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Research papers

Migration area of the Tsushima Warm Current Branches within the Sea of Japan: Implications from transport of ^{228}Ra

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ABSTRACT

We investigated lateral profiles of ^{228}Ra (half-life; 5.75 years) activity and ^{228}Ra/^{226}Ra (1600 years) activity ratio using 241 surface water samples collected in/around the Sea of Japan and the East China Sea (ECS) during June–October of 2009–2014. In the ECS, the ^{228}Ra/^{226}Ra ratio in the surface waters exhibited markedly wide variation (< 0.05–3.5) in June, predominantly reflecting the mixing between the ^{228}Ra-rich continental shelf water and the ^{228}Ra-depleted Kuroshio Current water. In July, the surface waters of the central Sea of Japan (135–138°E) became separated into three currents: the Offshore Branch of the Tsushima Warm Current (OBTWC) (^{228}Ra/^{226}Ra =0.7–1.2) at 39–41°N, the Coastal Branch of the TWC (CBTWC) (~0.7) on the southern side, and sub-Arctic Current (~0.7) on the northern side. From the central to northeastern Sea of Japan, the ^{228}Ra/^{226}Ra ratio at the surface (0.8–1.0) was within a range between that of the CBTWC and OBTWC. The fraction of continental shelf water in the CBTWC, OBTWC, and in their combined current was estimated to be 11–16%, ~8%, and 10–11%, respectively.

1. Introduction

The Sea of Japan is one of the largest marginal seas of the western Pacific Ocean. It is surrounded by the Eurasian continent and Japan Islands, and is connected to the Pacific Ocean and other marginal seas by the Tsushima, Tsugaru, and Soya straits. The circulation of the surface water within the Sea of Japan is often considered to be governed primarily by lateral movements of the branches of the Tsushima Warm Current (TWC). The migration patterns of the TWC have been studied using various techniques (Talley et al., 2004; Kim et al., 2008; Watanabe et al., 2009). However, because of its complicated pattern of migration through the East China Sea (ECS) and the Sea of Japan, the characteristics of the TWC have not been clarified comprehensively.

The ^{228}Ra isotope with a half-life of 5.75 yrs is mostly depleted in the Kuroshio Current water following its long migration in the Pacific Ocean. However, additional ^{228}Ra is supplied to the continental shelf water from the broad shallow shelf and coastal sediments along the continental side of the ECS (Nozaki et al., 1991; Inoue et al., 2012a) and from riverine water/particles and submarine groundwater discharge in estuaries and coastal/offshore areas (Kim et al., 2005; Gu et al., 2012). The ^{228}Ra-enriched continental shelf water, ^{228}Ra-depleted Kuroshio Current water, and Yangtze River water combine within the ECS, and the mixing ratios of these three components were estimated both on the continental side (Gu et al., 2012; Lee et al., 2014) and on the eastern side of the ECS (Inoue et al., 2012a). The mixture of waters is then transported into the Sea of Japan through the Tsushima Strait. Along the coastlines of the Japan Islands, the ^{228}Ra/^{226}Ra ratio of the surface waters exhibits minimum and maximum values in early summer and in autumn–winter, respectively (Inoue et al., 2007),

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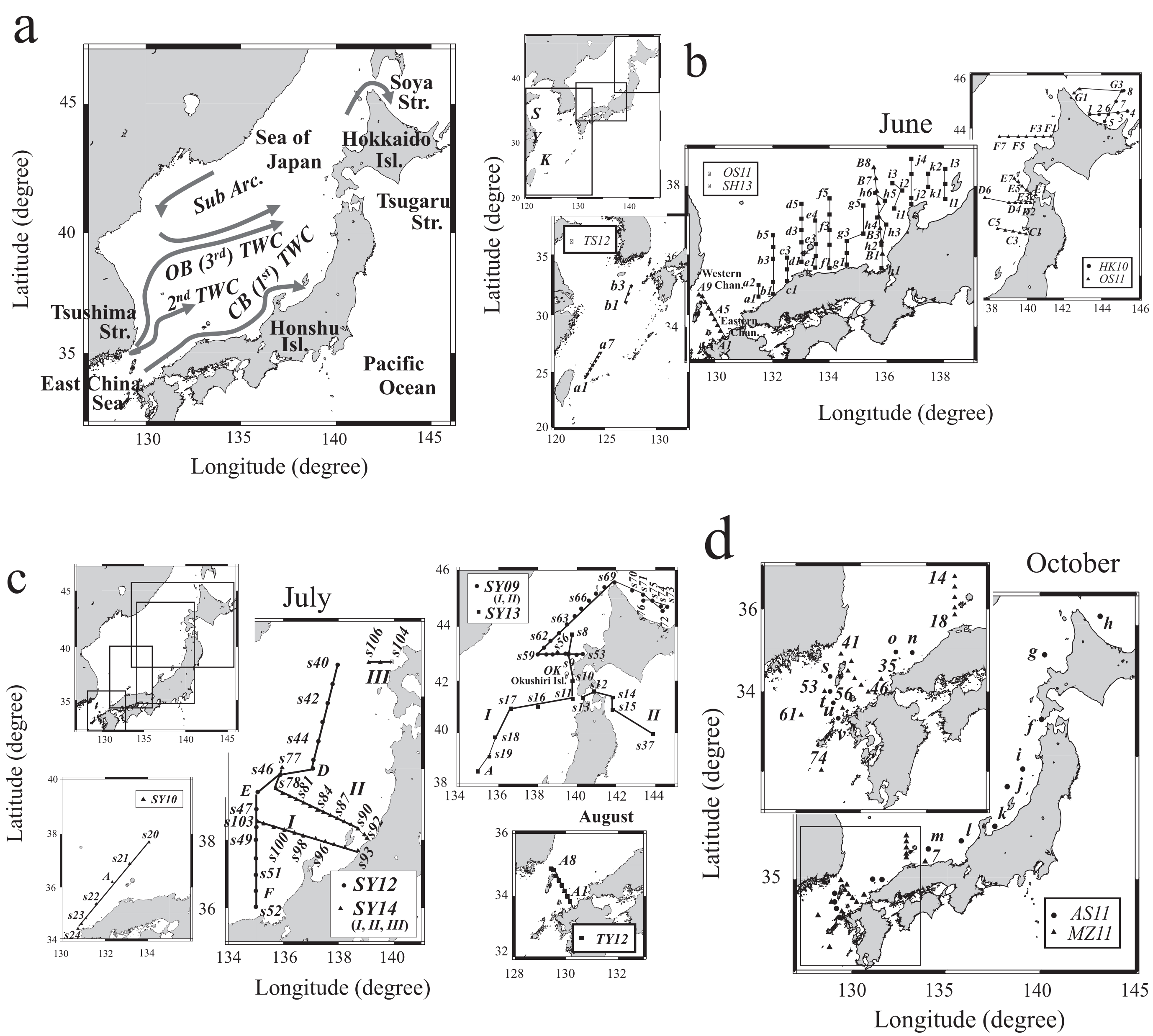

Fig. 1. Map showing (a) triple branch model of the Tsushima Warm Current (TWC): *CB (1st) TWC*, Coastal (First) Branch; *2nd TWC*, Second Branch; *OB (3rd) TWC*, Offshore (Third) Branch of the TWC; *Sub Arc.*, sub-Arctic Current (Katoh, 1994; Ito et al., 2014; Isobe and Isoda, 1997), and sampling locations for surface waters; (b) transects *HK10*, *OS11*, *TS12*, and *SH13* in June 2010–2014 with Kuroshio (*K*; *TS12a-3*; this study), shelf (*S*; *CB42*; Nozaki et al. (1991)), and Yangtze River waters (*Y*; *#1* and *#2*; Elsinger and Moore (1984)) (see text), (c) transects *SY09*–*SY14* in July 2009–2014 with *TY12A* in August 2012, and (d) *AS11* and *MZ11* in October 2011–2012.

depending on the seasonal variation of the mixing ratio of the shelf water. The distribution of the ^{228}Ra/^{226}Ra ratio (or ^{228}Ra and ^{226}Ra activities) in the surface waters also revealed the migration patterns of radiocesium derived from the Fukushima Dai-ichi Nuclear Power Plant accident in March 2011 in/around the Sea of Japan (Inoue et al., 2013, 2014a) and across the northwestern North Pacific Ocean (Inoue et al., 2016).

The present study observed the fine-resolution lateral profiles of ^{228}Ra (^{228}Ra activity and ^{228}Ra/^{226}Ra ratio) at the surface in/around the Sea of Japan in the latter half of July of 2009–2014. Based on comparisons with the values of ^{228}Ra at the surface in June and October (2010–2013), and in combination with salinity data, we assessed the origin and the migration areas of the CBTWC and OBTWC, and the surface flow patterns of various soluble contaminants released by human activities/accidents.

2. Water samples and experimental procedures

The locations of the surface water sampling sites are presented in Fig. 1 together with the main current systems. Overall, we collected 241 samples of surface water (i.e., ~20 L) at 0- or 5-m depths in/around the Sea of Japan. These were obtained in June (and end of May) of 2010–2013 during the *Hokkou Maru* (*HK10*), *Oshoro Maru* (*OS11*), *Shoyo Maru* (*SH13*), and *Tansei Maru* (*TS12*) expeditions (Fig. 1b). Samples were also collected in July of 2009–2014 during five expeditions of the *Soyo Maru* (*SY09*, *SY10*, *SY12*–*SY14*) and in August 2012 during the *Tenyo Maru* (*TY12A*) expedition (Fig. 1c). Additional samples were also obtained in October 2011–2012 during the *Mizuho Maru* (*MZ11*) and *Asuka-II* (*AS11*) expeditions (Fig. 1d). All water samples were unfiltered because the contribution of particulate matter is negligible for radium activities reflecting the solubility of radium isotopes (Inoue et al., 2013). The ^{228}Ra activity and ^{228}Ra/^{226}Ra ratios in some *SY09* samples have been reported previously by Inoue et al. (2014a, 2014b),