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Intrusion pattern of the Kuroshio Subsurface Water onto the East China Sea continental shelf traced by dissolved inorganic iodine species during the spring and autumn of 2014

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ABSTRACT

The Kuroshio has an important influence on the circulation systems and ecological environment of the East China Sea (ECS), but the intrusion pattern of the Kuroshio on the ECS continental shelf and its seasonal variability are still debated. Our study shows that evidence from both hydrographic data and dissolved inorganic iodine species (DIIS) suggest that a cold (< 19 °C), saline (> 34.4 PSU), dense (> 24.5 kg/m^3), R-iodate-rich (> 0.35 μM) and R-iodide-poor (< 0.10 μM) water (R-iodate and R-iodide are represented by iodate and iodide concentrations normalized to a salinity of 35) occurs at the bottom of the ECS continental shelf (depth < 100 m). The characteristics of this water are similar to those of the Kuroshio Subsurface Water (KSSW), and the intrusion pattern of the KSSW onto the ECS shelf consists of an intrusion from the northeast of Taiwan and another intrusion at ~28.5°N along the 100-m isobaths. In the spring of 2014, the KSSW intrusion northeast of Taiwan flowed northwestward then bifurcated into a nearshore branch and an offshore branch at ~27.5°N. The nearshore branch flowed approximately northward and finally appeared in the subsurface layer within the 50-m isobath off the Zhejiang coast (~29.5°N). In addition, the offshore branch flowed along the 100-m isobath and reached ~29.5°N. The KSSW intrusion northeast of Taiwan was obviously weaker in autumn than in spring. In autumn, the nearshore branch was not observed, and the offshore branch reached only ~28°N. In addition to the main intrusion center northeast of Taiwan, the DIIS concentrations indicate that another weaker intrusion from the KSSW occurs at ~28.5°N along the 100-m isobaths. However, this phenomenon could not be observed via hydrographic data alone. Moreover, seasonal fluctuation in this additional KSSW intrusion was observed. In spring, this water flowed northwestward and reached 29.5°N, whereas this water was confined along the 100-m isobath in autumn. Overall, DIIS can be used as complementary tracers of the KSSW intrusion, and more details of the intrusion pattern of the KSSW were well revealed.

1. Introduction

The East China Sea (ECS) is a highly dynamic oceanic region with complex circulation systems and is influenced by the Changjiang (Yangtze River) Diluted Water (CDW), the Yellow Sea water via the Yellow Sea Coastal Current (YSCC), the South China Sea (SCS) water via the Taiwan Strait warm water (TSWW), and the Kuroshio, which is the western boundary current of the North Pacific subtropical gyre (Fig. 1). The Kuroshio is one of the largest ocean currents in the world and has an average water flux of > 1 Sv (1 Sv = 10^6 m^3/s) to the ECS continental shelf (Guo et al., 2006; Isobe, 2008), and this value is 1–2 orders of magnitude larger than that of the Changjiang. In addition, the amount of nutrients that are contributed to the ECS continental shelf by the Kuroshio is much larger than that by the Changjiang (Chen, 1996; Zhang et al., 2007). Thus, the Kuroshio considerably influences the hydrology, circulation systems and ecological environment of the ECS.

The Kuroshio has been known to be an oligotrophic water. However, the nutrient-rich Kuroshio Subsurface Water (KSSW) could enter the ECS shelf via upwelling. The KSSW mainly upwells and intrudes onto the ECS continental shelf off the northeast of Taiwan at

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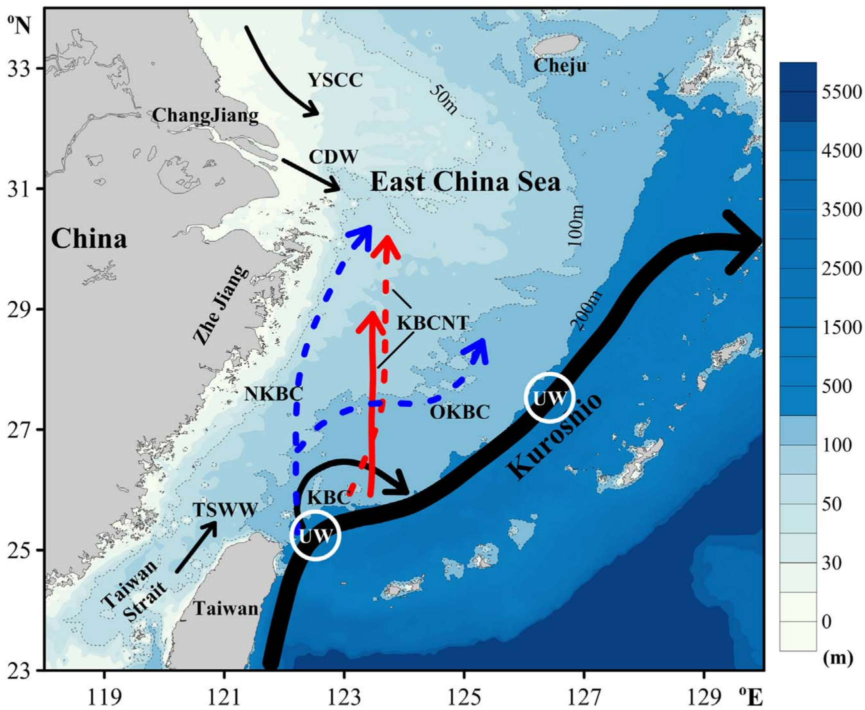

Fig. 1. Bottom topography and schematic of circulation pattern in the ECS. YSCC, CDW, and TSWW denote the Yellow Sea Coastal Current, Changjiang Diluted Water, and Taiwan Strait warm water, respectively. UW denotes upwelling water. KBC is the Kuroshio Branch Current (Qiu and Imasato, 1990), and KBCNT is the Kuroshio Branch Current northeast of Taiwan (red dashed arrow: Kondo, 1985; red solid arrow: Ichikawa and Beardsley, 2002). NKBC and OKBC denote the Nearshore and Offshore Kuroshio Branch Currents, respectively (Yang et al., 2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

25.5°N (Chen et al., 1995; Hsueh et al., 1992; Liu et al., 1992; Wong et al., 2000; Wu et al., 2008). However, modeling exercises (Lee and Chao, 2003) and field observations (Wong et al., 2004) suggest that, in addition to the well-documented upwelling center off the northeast of Taiwan, another weaker upwelling center may occur at the shelf edge at ~27°N. This other upwelling center requires further examination, and the occurrence, pathway and variation of the upwelling KSSW northeast of Taiwan onto the ECS continental shelf remain debated.

Kondo (1985) suggested that a nearly northward current separated from the Kuroshio northeast of Taiwan and flowed roughly along the meridian of 123.5°E as far as 30°N in summer. This current is called the Kuroshio Branch Current northeast of Taiwan (KBCNT). However, Qiu and Imasato (1990) and Ichikawa and Beardsley (2002) proposed that the KBCNT turned to the ESE near 27°N to rejoin the mainstream of the Kuroshio (KBC), and the KBCNT does not occur north of 29°N but flows toward the northeast. However, most studies on the intrusion pattern of the Kuroshio onto the ECS continental shelf did not separate the KSSW from the Kuroshio water or clarify the characteristics and structure of the deep water of the ECS. Yang et al. (2011, 2012) proposed that the summer intrusion pattern of the Kuroshio was mainly composed of an Offshore Kuroshio Branch Current (OKBC) and a Nearshore Kuroshio Branch Current (NKBC) in the bottom water of the ECS based on the modeling exercises together with observations and found that the NKBC and the OKBC mostly originated from the KSSW northeast of Taiwan, with the NKBC flowing along the ~60-m isobath and reaching 30.5°N. Recent modeling exercises (Wang and Oey, 2016) and field observations of $\delta^{18}O$ (Lian et al., 2016) also showed that the intrusion from the KSSW northeast of Taiwan could reach the area off the Zhejiang coast (~30°N). Nevertheless, work on the intrusion pattern of the KSSW requires further confirmation by additional field observations of the hydrography and chemistry parameters and more studies on the temporal variations in the intrusion.

To determine the intrusion pattern of the KSSW on the ECS continental shelf, we chose dissolved inorganic iodine species (DIIS) as a complementary tracer to the hydrographic data. Dissolved inorganic iodine is generally present in seawater as iodate and iodide, at a total concentration of approximately 0.45 μM (Campos et al., 1996; Elderfield and Truesdale, 1980; Truesdale, 1994b; Wong, 1991). According to thermodynamic considerations, iodate should predominate in oxic seawater, although iodide is commonly found in significant quantities of up to 0.3 μM in surface oceans (Campos et al., 1996; Tian and Nicolas, 1995; Truesdale and Upstill-Goddard, 2003; Tsunogai and Henmi, 1971; Wong, 1991; Wong, 1995). However, below the euphotic zone, iodate likely represents the exclusive form of dissolved inorganic iodine, and the concentration of iodide is low and close to its detection limits (Truesdale and Bailey, 2002; Truesdale et al., 2000; Wong, 1995; Wong and Zhang, 2003). Thus, deeper seawater, such as upwelling water, should be iodide-poor and iodate-rich relative to surface water, and the DIIS can be used to differentiate surface water and deeper water. Furthermore, the biological uptake and conversion rates of iodate to iodide are significantly lower than that of nutrient elements, and the residence time of iodate is on the order of 10^0–10^1 years (de la Cuesta and Manley, 2009; Edwards and Truesdale, 1997; Moisan et al., 1994; Wong et al., 2002), which is similar to or longer than the residence time of the water on the ECS continental shelf (Nozaki et al., 1991). Relative to the influence of physical processes, non-conservative behaviors resulting from the biologically mediated reductions of iodate (Tsunogai and Sase, 1969; Wong, 1991) or photochemically induced reduction of iodate (Spokes and Liss, 1996) can be neglected, especially in the upwelling water (Wong et al., 2004). Therefore, DIIS can be used as quasi-conservative tracers to indicate the movement of seawater, especially upwelling activities, and fieldwork on this topic in different seas around the world has been reported (Bluhm et al., 2011; Truesdale and Bailey, 2002; Wong, 1995; Wong et al., 2004; Wong and Zhang, 2003). Wong et al. (2004) proposed that the discrete upwelling centers at the ECS shelf edge could be traced by DIIS, although this work focused on the area outside the 100-m isobath and did not reveal the pathway of the KSSW on the shelf. Here, evidence from in situ observations of DIIS and conservative hydrography (temperature, salinity and density) are used to evaluate the intrusion pattern of the KSSW onto the ECS continental shelf and describe its seasonal variability.

2. Materials and methods

Sample collection was conducted across the ECS and Kuroshio east