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Nutrient flux and transport by the Kuroshio east of Taiwan

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ABSTRACT

The Kuroshio is the western boundary of the North Pacific Ocean. To estimate the nutrient flux and transport in the upper 250 m, measurements were conducted along a transect across the Kuroshio at 23.75° N, east of Taiwan. The results showed that the Kuroshio flowed northward at a maximum velocity varying between 0.7 and 1.4 m s^{-1} at a depth of 100 m. The flow volume transport in the upper 250 m ranged from 13.43 to 17.51 *Sv*, accounting for 51–67% of the transport above 1000 m. The shoreward sloping isopycnals were revealed to be favorable for carrying nutrients onto the East China Sea shelf. The “nutrient stream” was located primarily at depths from 300 to 600 m, and the maximum flux ranged from 4.2 to 7.9 mmol m^{-2} s^{-1} for nitrates and from 0.4 to 0.7 mmol m^{-2} s^{-1} for phosphates. Nutrient transport in the upper 250 m varied within the range of 16.8–31.1 kmol s^{-1} for nitrates and 0.8–3.9 kmol s^{-1} for phosphates. This study suggests that 1) nitrate transport in the upper 250 m increases and 2) phosphate transport above 1000 m decreases during downstream transport, implying that the Kuroshio interacts with nearby ecosystems during its downstream journey.

1. Introduction

The Kuroshio Current (hereafter referred to simply as the Kuroshio) forms the western boundary of the subtropical gyre in the North Pacific Ocean (see the insert in Fig. 1) and is the counterpart of the Gulf Stream in the North Atlantic Ocean. It originates in the northward bifurcation of the North Equatorial Current off the east coast of the Philippines and becomes a pronounced current that crosses the Luzon Strait and flows along the east coast of Taiwan and the shelf break of the East China Sea (ECS) before it reaches the southeastern coast of Japan (Nitani, 1972). Liang et al. (2003) and Rudnick et al. (2011) reported that the Kuroshio is a relatively stable current east of Taiwan. However, based on shipboard measurements, Jan et al. (2015) observed large variations in the Kuroshio east of Taiwan. The contradictory conclusions in these previous studies may exist because of the limited amount of field data in this region (Jan et al., 2015). Regardless of the variability at the synoptic time scale, the axis of the Kuroshio shifts shoreward during the northeast winter monsoon and seaward during the southwest summer monsoon (Liang et al., 2003; Liu and Gan, 2012).

This current transports a tremendous amount of water and associated materials (e.g., dissolved inorganic nutrients), and it has significant effects on downstream environments, such as the ECS, the seas southeast of Japan, and even the Tsushima Strait (e.g., Kwak et al., 2013; Liu and Gan, 2012; Oka and Kawabe, 1998). For example, a substantial quantity of nutrients upwells from the intermediate waters associated with the Kuroshio off northeastern Taiwan onto the ECS shelf (Chen, 1996; Mensah et al., 2015). Hence, the Kuroshio may serve as a major nutrient source for primary production in the southern ECS (Chen et al., 2015; Chen, 1996). These factors imply that this current has significant effects on nearby ecosystems along its route.

The Kuroshio has also been known to carry oligotrophic water. However, several physical processes bring nutrient-rich subsurface Kuroshio water to the surface, such as upwelling, vertical mixing induced by typhoons, strong northeast winter monsoons, and cyclonic mesoscale eddies (Chen et al., 2015; Hsu et al., 2010; Hung and Gong, 2011; Sukigara et al., 2014). For example, previous studies suggested that subsurface waters (100–200 m) upwelled to the surface water (0–65 m) within the cold dome induced by the Kuroshio on-shelf intrusion northeast of Taiwan (Chen et al., 2015; Jan et al., 2011). Primary production could therefore be enhanced by the enrichment of nutrients in the subsurface water (Chen, 1996; Liu et al., 2000). In addition, the shoreward intrusion of the Kuroshio subsurface waters may also affect the ECS shelf ecosystem, and these subsurface waters normally deviate from the nutrient core to around the 200 m isobaths of the Kuroshio (Liu and Gan, 2012; Nitani, 1972). The subsurface maximum core of the nutrient fluxes at downstream of the Kuroshio has been suggested to exist at a depth from 400 to 500 m (Guo et al., 2013 and citations therein). However, the depth of maximum velocity of the Kuroshio east of Taiwan varies from 20 to 100 m (Jan et al., 2015). These results suggest that at a depth of approximately 200 m in the Kuroshio, the upper ocean and its associated materials may have important effects on the surrounding ecosystems.

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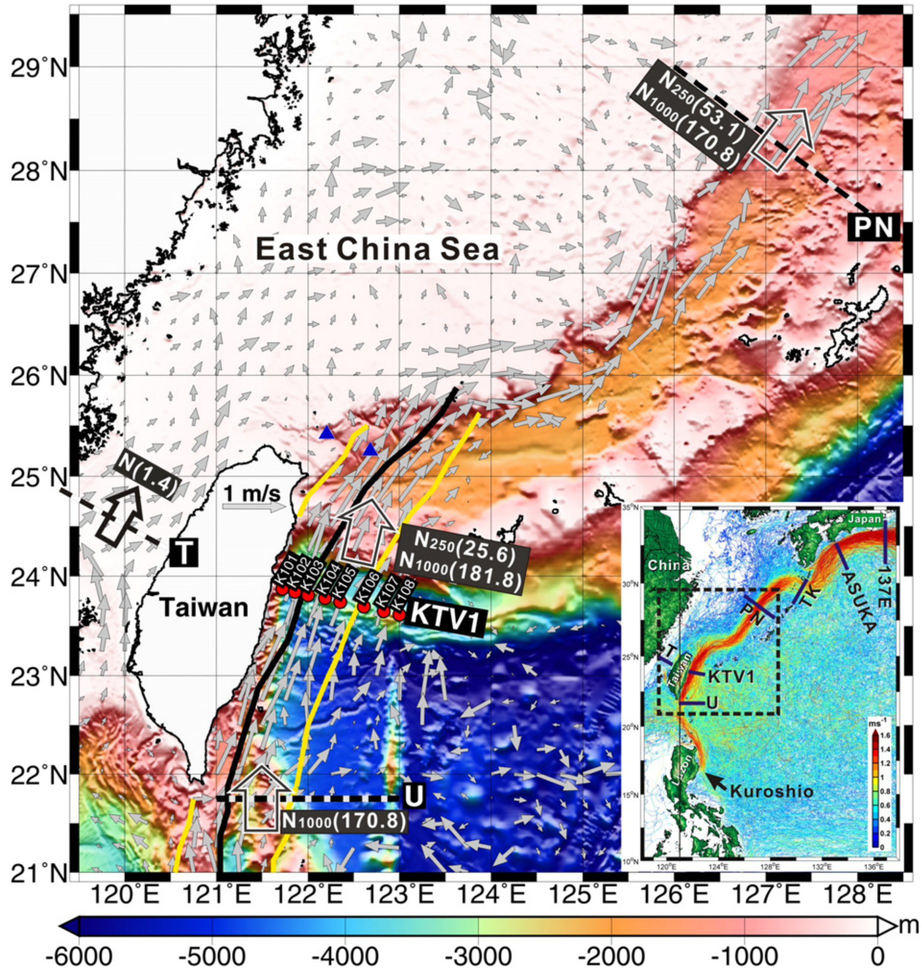

Fig. 1. Sampling stations (K101–K108) along the KTV1 transect of the Kuroshio east of Taiwan. The climatological current velocity (grey arrows) at a depth of 30 m was computed from the historical ADCP dataset available from Taiwan's Ocean Data Bank. The bold black line indicates the maximum velocity axis at 15 m depth obtained from the surface drifter data. The solid yellow line indicates the 0.2 m s^{-1} isotach at 30 m depth obtained from the historical ADCP dataset (Jan et al., 2015). The nitrate transport (kmol s^{-1}) across transects is also shown (please refer to Table 2 for details.). Both blue triangles off northeastern Taiwan were sampling stations from our previous cruise, and their data were used as a comparison (see Fig. 7.). The path of the Kuroshio with velocity > 1 m s^{-1} is indicated by surface drifter trajectories and speeds (data available at http://www.coriolis.eu.org/Data-Products/Data-Delivery/Data-selection) in the lower right inset where the black dotted rectangle marks the map area. For comparison, the solid lines in the inset represent the upstream (i.e., U) and downstream (i.e., PN, TK, ASUKA, and 137E) regions of the Kuroshio and Taiwan Strait (T), as derived from previous studies (Chen et al., 1995; Chung et al., 2001; Guo et al., 2013; Guo et al., 2012).

In the Gulf Stream, nutrient flux and nitrate transport in the order of 1000 kmol s^{-1} were reported over two decades ago (e.g., Pelegrí and Csanady, 1991; Pelegrí et al., 1996). The on-shore intrusion of the Gulf Stream onto the shelf has important effects on shelf circulation, biogeochemistry, and fisheries (Zhang and Gawarkiewicz, 2015 and citations therein). Surprisingly, even though the importance of the Kuroshio has been emphasized, studies have tended to focus on physical characteristics such as current velocity and heat and salt transport as well as on water masses (Jan et al., 2015 and citations therein). In comparison with the Gulf Stream, only a few studies have focused on nutrient flux and transport downstream of the Kuroshio off northeastern Taiwan, the shelf edge of the ECS, and the seas southeast of Japan (e.g., Guo et al., 2013; Kodama et al., 2014; Liu et al., 2000; Zhao and Guo, 2011). Additionally, over the past two decades, there have been almost no studies on the region where the Kuroshio becomes a pronounced current (e.g., east of Taiwan), though a few studies have focused on the Kuroshio east of the Luzon Strait (Chen et al., 1995; Liu et al., 1988). This lack of research makes it challenging to 1) understand the nutrient cycle on the scale of the basin and 2) evaluate the effects and connectivity of nutrients on the downstream ecosystems of the Kuroshio. Therefore, it would be worthwhile to estimate nutrient fluxes in the Kuroshio, particularly in the region to the east of Taiwan.

To explore this topic, the flux and transport of nutrients in the upper ocean (≤250 m) were calculated using comprehensive data taken from six shipboard measurements made east of Taiwan along a transect across the Kuroshio at 23.75° N. The flux and transport of nutrients in the water above 1000 m were also estimated using an empirical calculation. To better understand the nutrients' spatial variation during transport, the results were compared to values documented upstream and downstream of the Kuroshio.

2. Materials and methods

2.1. Study area, sampling, and hydrographic measurements

To estimate the nutrient flux and transport across the Kuroshio east of Taiwan, eight stations (K101–K108) along a transect (KTV1) between 121.72° and 123° E at 23.75° N were repeatedly surveyed (Fig. 1), which provided a wide enough area where to capture the Kuroshio. Samples were collected from six shipboard measurements taken from the R/V *Ocean Researcher I* between September 2012 and July 2014: September and November 2012, June and October 2013, and March and July 2014. These sampling periods covered the northeast winter monsoon (i.e., October to February), the southwest summer monsoon (i.e., May to