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Varying intensity of Kuroshio intrusion into Southeast Taiwan Strait during ENSO events

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ABSTRACT

The Taiwan Strait is the only direct passage between the South China Sea (SCS) and the East China Sea. Variations in the intensity of Kuroshio Branch and surface currents in the SCS result in seasonal and interannual variability in the hydrography of the SE Taiwan Strait, where the northwardly pointing funnel-like Penghu Channel is located. These currents vary with the intensity and direction of monsoons. The teleconnection between air-sea interaction of the east Pacific and west Pacific reportedly has time differences. The data in this study reveal that the salinity of the seawater in the Penghu Channel is highest during El Niño events with a seven-month lag to the monthly Niño 3.4 index, and lowest during La Niña periods, also with a lag of seven months to the monthly Niño 3.4 index. The chemical parameters also vary with these events. The concentrations of apparent oxygen utilization, nutrients, and hydrogen ions vary with the mixing ratio of SCS water and Kuroshio Branch water. The maximum concentrations of nutrients are significantly higher during the summer, seven months after a La Niña event (La Niña-7), than in other seasons. However, biological activities also affected these chemical parameters. In spring, active photosynthesis consumes more nutrients and hydrogen ion concentrations in La Niña-7 periods than in normal-7 periods.

1. Introduction

The Taiwan Strait (TS) is the only direct connection between the South China Sea (SCS) and the East China Sea (ECS), which are the largest and the 11th largest marginal seas in the world. Unlike the 2200 m-deep Luzon Strait, the TS is a shallow channel with a mean depth of only 60 m. The water in the TS mainly consists of SCS water and Kuroshio Branch water, except in the winter, when the China Coastal Current water exists. These currents, which are dominated by the monsoons, affect the relative fractions of these water masses. These fractions can further influence the salinity, temperature, and biogeochemical properties of nearby regions (Chen et al., 2010; Jan et al., 2006).

As the intensity of the NE monsoon increases from late autumn to winter, the cold, fresh, eutrophic and southward flowing China Coast Current water occupies the western TS; this water retreats with the diminishing of the NE monsoon during spring (Chen, 2003, 2008; Jan et al., 2006; Naik and Chen, 2008; Wu et al., 2007). The extent of the Kuroshio intrusion into the Luzon Strait also varies seasonally, with maximum transport in winter and minimum transport in summer (Chu and Li, 2000; Fang et al., 2005; Qu et al., 2000; Yaremchuk et al., 2009; Yaremchuk and Qu, 2004). The South Asian monsoon winds also influence the circulation in the northern part of the SCS. At the beginning of the NE monsoon in autumn, the current in the upper layer flows westward owing to Ekman transport, but during the SW monsoon, it flows eastward (Shaw and Chao, 1994). The warm, salty and oligotrophic Kuroshio Branch water from the West Philippine Sea (WPS), enters the SCS through the Luzon Strait. Part of Kuroshio Branch forms a loop current southwest of Taiwan, then flows out of the SCS and rejoins the Kuroshio. The surface and subsurface SCS waters are colder, fresher and more eutrophic than the Kuroshio Branch water, and mix with some of the water in the Kuroshio Branch before entering the TS in the northeast SCS. Usually, the mixed water flows northward towards the eastern TS and even traverses the whole TS in the summer. Most of the northward flow is through the Penghu Channel (PHC), which is funnel-shaped and opens to the southeast TS, contributing approximately 60% of the volumetric inflow into the TS (Lin et al., 2005; Wang, 1999).

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The Luzon Strait is the boundary between the WPS and the SCS. The upper and deep WPS water flow into the SCS, but the intermediate water flows into the WPS from the SCS (Chen et al., 2001). Although most of SCS water originates in the WPS, the SCS seawater has a lower salinity (*S*) at the S_{max} level and a higher *S* at the S_{min} level than WPS water because of the vertical mixing in the SCS. The vertical mixing also moves considerable amounts of nutrients from the subsurface water to the surface layer (Liu et al., 2002). SCS water is older than WPS water and the longer residence time corresponds to greater decomposition of organic matter and higher oxygen consumption. SCS water receives a great deal of terrestrial material from rivers, groundwater and the erosion of beaches, causing it to have higher nutrient concentrations than Kuroshio Branch water (Chen et al., 2001, 2010; Gong et al., 1992; Peng et al., 2008). The higher nutrient concentrations support the higher primary production in the SCS than in the WPS. Since the chemical and physical characteristics of SCS and WPS waters are useful tools for distinguishing between these two water masses (Chen, 2005), sigma-T and multiple parameter plots were utilized herein to determine the proportions of these water masses.

El Niño and La Niña events are known to have a variety of effects in Southeast Asia, reflecting the effect of teleconnection between the air–sea interaction in central Pacific and Southeast Asia. Some of these conditions, such as varied Kuroshio transport off southeast of Taiwan may arise 9–10 months before the onset of El Niño and La Niña events, but some of these conditions, such as sea surface temperature anomaly occur 3–6 months after the onset of these events. (Lin et al., 2011; Qu et al., 2004; Tozuka et al., 2009; Wu, 2013; Wu and Chang, 2005; Xie et al., 2003). These interannual transport variations are related to several associated phenomenon, such as fluctuations of the North Equatorial Current Bifurcation Latitude (NECBL; Kashino et al., 2009; Kim et al., 2004) and interannual variation of local wind speed (Kuo and Ho, 2004). The compositions of TS water changes interannually owing to the differential mixing ratios of seawaters from the Kuroshio and SCS. Zhang et al. (submitted for publication) identified a strong correlation between local wind stress and the Kuroshio intrusion, which affects the ecosystem and primary production in the TS and possibly in the southern ECS. This study investigates the variation in the hydrography in the PHC to evaluate the magnitude of the Kuroshio intrusion.

2. Methods

The bottled water data and shipboard CTD (Conductivity–Temperature–Depth) data were obtained during 19 cruises (Fig. 1) on board R/V Ocean Researchers I and III (OR-1 and OR-3) to the PHC from June 2000 to October 2011. In addition, shipboard CTD data were adopted from the Ocean Data Bank (http://www.odb.ntu.edu.tw/). CTD data from 2863 sampled profiles that covered the area from 119.5°E to 120.5°E and from 22.5°N to 23.5°N from 1991 to 2011 (Fig. 1; Table 1) were obtained. These CTD data were monthly averaged over 0.5 sigma-T layers and classified into 12 categories (El Niño, La Niña, and normal events with a seven-month lag to the monthly Niño 3.4 index during each of the four seasons; the definition would be explained in the following discussion). Notably, some CTD data do not cover the whole sigma-T range between 22 and 26 (Fig. 2). To quantify the contribution of the typical Kuroshio Branch to the PHC, mixing in a sigma-T layer was assumed to involve only horizontal mixing between the Kuroshio Branch and the SCS seawater. Seasonal typical Kuroshio Branch and the SCS seawater are calculated with the similar statistical process. We adopted 7925 and 1456 CTD profiles from the world ocean database (sampled area: 126–131°E and 19–24°N for the Kuroshio Branch water, and 112–117°E and 10–14°N for the SCS water; sampled period: 1970–2014). The values of seasonal salinity in the sigma-T=24.5 layer of the typical Kuroshio Branch (spring: 34.858 ± 0.064, summer: 34.887 ± 0.059, autumn: 34.810 ± 0.058, winter: 34.865 ± 0.066) and the SCS seawater (spring: 34.445 ± 0.062, summer: 34.478 ± 0.055, autumn: 34.456 ± 0.059, winter: 34.450 ± 0.052) were set as the end members in the horizontal mixing to calculate the percentage of the typical Kuroshio Branch water in the PHC.

Seawater samples were collected using a CTD/Rosette sampler, which had been fitted with 2.5 L Niskin bottles. The concentration of dissolved oxygen was measured by direct spectrophotometry (Pai et al., 1993) to a precision of approximately 0.32% at

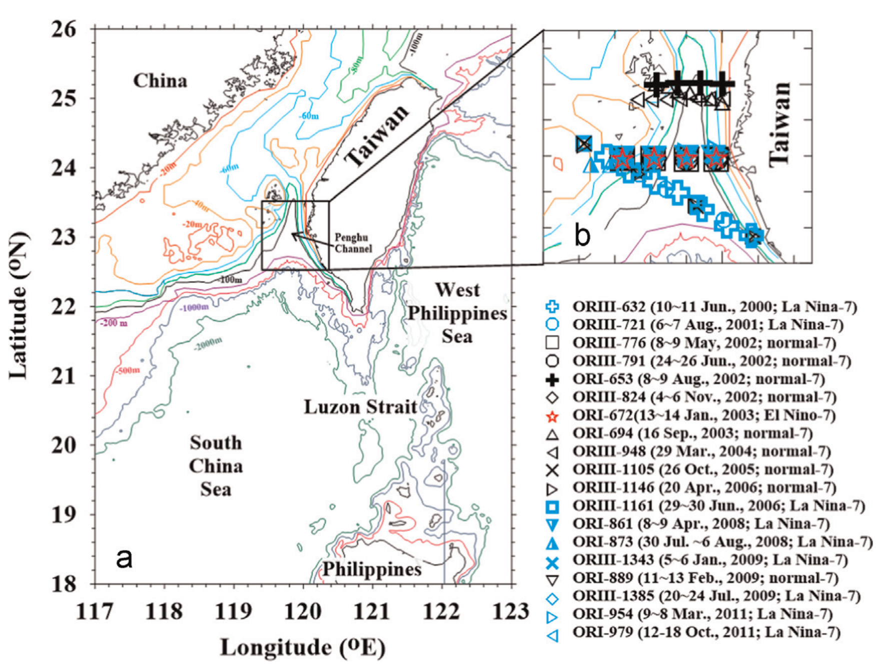

Fig. 1. (a) Black square delineates CTD sampling area; and (b) symbols represent stations where water is bottled.