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Episodic events imposed on the seasonal nutrient dynamics of an upwelling system off northeastern Taiwan

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ABSTRACT

An upwelling center has been frequently observed on the shelf break of the East China Sea (ECS) off northeastern Taiwan, where the Kuroshio encounters an abrupt shoaling topography. The region is also located under the track of Asian dust (AD) storms and frequently disturbed by typhoons. To examine the seasonal nutrient dynamics of the upwelling and the potential impacts of these episodic events, transect stations across the upwelling center were visited at intervals of 1–3 months from November 2003 to January 2005. The results of the water temperature profiles indicated that the upwelling persisted throughout the year with the most intensified events occurring in winter. Seasonally, a higher nitrate concentration was observed during the stronger upwelling period. The highest nitrate value was however observed during an AD storm, with an average value of 8.3 μM for the top 30 m. Interestingly, the N/P ratio was larger than 16 during these episodic events, and the N/P ratios were equal to or smaller than 16 during other periods. On average, the estimated values from wet deposition constituted 17.3% of the total estimated nitrogen input. This suggests that atmospheric deposition, particularly during the episodic events, might be an important external nutrient source.

1. Introduction

Upwelling phenomena have been frequently observed in the coastal and marginal seas. The effects of upwelling on ecosystems vary depending on the intensity and frequency of such events. They may occur annually, seasonally, monthly, or daily (Chen et al., 2005, 2006b; Summerhayes et al., 1995). Generally, in all cases, nutrient-rich cold water upwells to the shoal water column and enhances the primary productivity of the ecosystem. Understanding the properties (e.g., the intensity and frequency) of an upwelling is key to assessing its effects on the ecosystem.

A cold dome induced by the Kuroshio Water (KW) on-shelf intrusion has been often observed across the shelf edge of the East China Sea (ECS) northeast of Taiwan, with a center over the Mien-Hua Canyon (Fan, 1980; Liu et al., 1992a, 1992b; Tang et al., 1999). The dome, which is approximately 100 km in diameter, has drawn much attention due to its high fishery yield in the nearby region and its association with the permanent eddy facilitating the exchange of water between the KW and the ECS (Liu et al., 2000). Upwelled intermediate KW has been suggested as a major source of nutrients that support primary production in the ECS (Chen, 1996; Liu et al., 2000). Based on observations and model simulations, this upwelling persists throughout the year (Liu et al., 1992b), with seasonal variation (Gong et al., 1995), but with a stronger magnitude in the winter than in the summer at 100 m from the surface (e.g., Chang et al., 2009; Wu et al., 2008). There are limited physical and chemical hydrographic data to validate its seasonal variation and to estimate how it affects biogeochemical cycles in nearby ecosystems (Gong et al., 1997).

Episodic events, including Asian dust (AD) storms in late winter and early spring and typhoons in summer, also influence the upwelling region (Hsu et al., 2008; Tsai et al., 2008; Zhang et al., 2011). During such events, air-borne nutrients and materials are deposited to the upper water column, often accompanied by wind induced vertical mixing (Hsu et al., 2010; Hung and Gong, 2011). These events make it difficult to discriminate the contributions to the ecosystem from upwelling or episodic atmospheric events. Therefore, this study was designed to investigate the seasonal variation and intensity of upwelling as well as the respective contributions of upwelled water and/or episodic events to the ecosystem.

2. Materials and methods

2.1. Study area, sampling, and hydrographic measurements

This study is a part of the Long-term Observation and Research of the East China Sea (LORECS) program. To cover the potential upwelling

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region, six water sampling stations are located on a transect across the shelf break of the ECS extending to the Kuroshio (i.e., over the Mien-Hua Canyon, northeast of Taiwan; Fig. 1), and the water depths of the stations were in the range of 133–1683 m. Samples were collected on board the R/V *Ocean Researcher II* between November 2003 and January 2005 to detect seasonal dynamics and episodic events, with sampling intervals of 1–3 months (Fig. 2). Seawater at each station was collected at 6 water depths, which were surface water (2, 3 or 5 m), 10, 20, 50, 75, and 100 m, by using Teflon-coated Go-Flo bottles (10 l, General Oceanics Inc., USA) mounted on a General Oceanic rosette assembly. Hydrographic data (temperature, salinity, and density) were recorded up to a water depth of 200 m with a SeaBird CTD (SBE 9/11 puls, SBE Inc., USA). The depth of the mixed layer was based on a 0.125 unit potential density criterion (Levitus, 1982).

2.2. Nutrient analyses and hydrographic measurements

Water subsamples for dissolved inorganic nutrient (i.e., NO_3^- and PO_4^{3-}) analyses were collected with 100 ml polypropylene bottles and frozen immediately in liquid nitrogen. It should be noted that ammonium in the water column was not measured in this study. However, this will probably have only a trivial influence on further data interpretation since its concentration is usually limited in the surface water. A custom-made flow-injection analyzer was used for nitrate and phosphate analysis, with a detection limit of 0.3 and 0.01 μM, respectively (Gong et al., 2003). Integrated values of nutrients in the water column above 30 and 100 m were estimated by trapezoidal methods, whereby depth-weighted means are computed from vertical profiles and then multiplied by 30 and 100 m, respectively (Chen et al., 2013). The average nutrient concentrations (per m^3 basis) over 30 m and 100 m were estimated from the integrated value divided by 30 m and 100 m, respectively (Chen et al., 2003, 2006a, 2009).

2.3. Weather stations, AD definition, and rain chemistry

For the sake of convenience, a major AD storm was defined as an event with an aluminum (Al) aerosol concentration greater than 3000 ng m^{-3} (Fig. 2c; Hsu et al., 2008). The Al aerosol samples were collected from the Central Weather Bureau in Taipei, northern Taiwan, which is approximately 20 km away from the northern coast (Fig. 1). Wet deposition (rain) samples were collected from another site (the campus of Academia Sinica in Taipei, 15 km away from the northern coast of Taiwan) for measurements of dissolved inorganic nutrients (e.g., nitrate and ammonium). The study area is frequently disturbed by typhoons in the summer. During the study, three typhoons – namely Mindulle, Aere, and Haima – with variable magnitudes were observed (Fig. 2c). For details on these typhoons, please refer to the website of the Central Weather Bureau, Taiwan (http://rdc28.cwb.gov.tw/data.php).

To evaluate the contribution of inorganic nutrients from atmospheric deposition to the water column, wet deposition of nutrients was estimated by the daily nutrient flux (i.e., daily precipitation × daily nutrient concentration) of the rainfall. The daily precipitation data were obtained from Pengchia Islet and Keelung, which are the weather stations closest to the water sampling stations (Figs. 1 and 2b). To account for the cumulative effect of atmospheric deposition on the shelf water, we use the average data on precipitation and the nutrient concentration of the rainfall over the one week before the water sampling.

2.4. Nutrient estimation of the water column

To estimate the nutrient concentration of the upwelled water, a linear function derived from nitrate concentration and potential temperature was applied (Gong et al., 1995). Pooled data were used for this linear regression, excluding the data obtained during the AD storm and typhoon periods (i.e., April, May, and September 2004). It should be noted this approach might thus under-estimate the predicted nitrate concentration during the AD storm. The nitrate levels at different temperatures were estimated, and then were integrated over water depth of 30 m

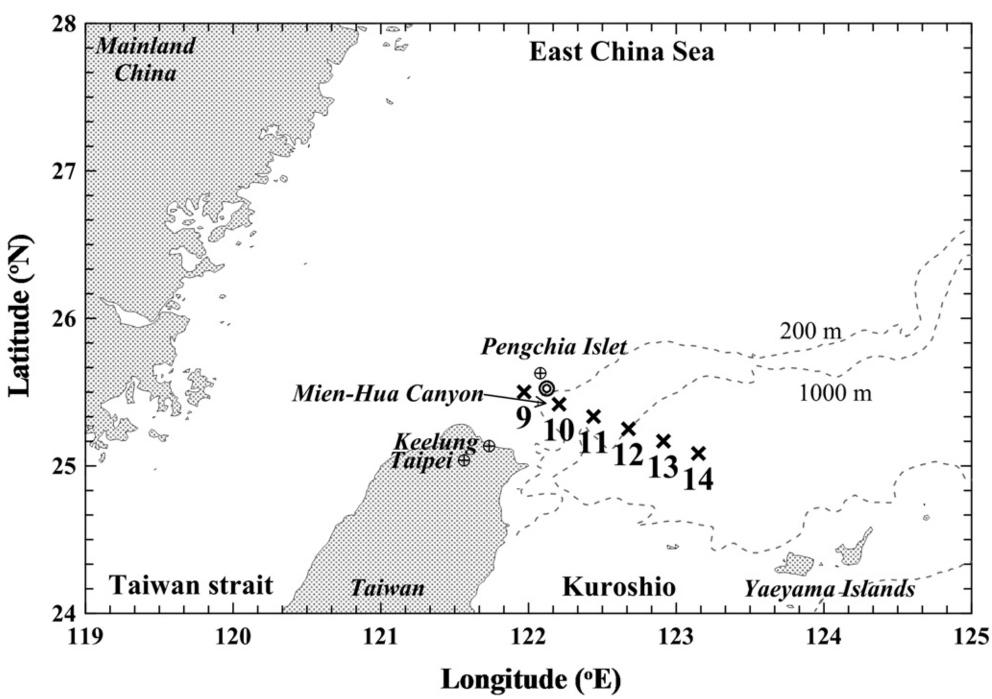

Fig. 1. Map of sampling stations (×) across the shelf break on the East China Sea to the Kuroshio Water off northeastern Taiwan. The station numbers are indicated below the marks. The bottom depth contours (dashed lines; 200 and 1000 m) are also shown. The locations of the weather stations (⊕; Pengchia Islet, Keelung, and Taipei) and the observed historical upwelling center (⊚, Jan et al., 2011) are labeled for reference.