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A salinity front in the southern East China Sea separating the Chinese coastal and Taiwan Strait waters from Kuroshio waters

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Abstract

While the current in the entire cross section of Taiwan Strait has been considered for a long time to flow northward in summer, in this paper the observational results are presented to indicate that only the western three-quarters of the northernmost part of the Taiwan Strait is occupied by the Chinese coastal and Taiwan Strait waters, and the remaining part by the lower temperature and higher salinity Kuroshio subsurface waters which have circumvented the northern tip of Taiwan. Chinese coastal and Taiwan Strait waters are separated from Kuroshio waters by a salinity front. In fact, the waters are vertically well-mixed near the front where the surface waters show a clear horizontal salinity maximum but a weak temperature minimum. These surface waters are in sharp contrast to the bottom waters which show a horizontal salinity minimum but a strong temperature maximum. Subsurface waters near the front are distinctively warmer and lighter but less saline and less oxygenated than the waters on either side. The warm, fresh, light, low-oxygen characteristics of these subsurface waters are attributed to the downwelling of waters from the east which have upwelled earlier near the shelf-break northeast of Taiwan. These waters can be traced along the isobath of about 75-m to at least 30°N in the East China Sea (ECS). Similarly, the water column-integrated nutrients, chlorophyll *a* and primary productivity also show a horizontal minimum near this depth. Such an unusual subsurface warm temperature ridge but low salinity trough correctly delineates the seaward boundaries of the coastal and Taiwan Strait waters in the ECS. The salinity maximum at the surface also seems to define the seaward boundaries of the fresh ($S<33$) coastal waters.

Keywords: Salinity front; East China Sea; Taiwan Strait; Kuroshio; Upwelling; Downwelling

1. Introduction

Oceanic fronts are defined as a region with clear-cut horizontal contrasts of water properties. As they are often associated with vertical mixing and upwelling of nutrient-rich deep waters, valuable fishing ground is formed near the front (Atkinson et al., 1987; Paffenhöfer et al., 1987). In addition to its river plumes and coastal fronts, the East China Sea (ECS) region is known to have several thermal fronts (Liu and Pai, 1987; Hickox et al., 2000), with one — under focus here — extending to the Taiwan Strait throughout the fall, winter and, to a lesser degree, the spring (the yellow colored band off the Chinese coast in Fig. 1). Almost all the areas west of

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this front are occupied by fresher, cooler, more nutrient-rich and more productive water than those east of the front (Fig. 2; Chen, 2003). In late spring and summer, on the other hand, the surface waters on both sides are heated to such an extent that warm waters prevail, and the thermal front extending to the Taiwan Strait all but disappears.

The objectives of this paper are to demonstrate with field observations that in summer, a salinity front exists in the southern ECS and in the northern end part of the Taiwan Strait but not in the central or southern parts of the Taiwan Strait, and that this front separates the northward-flowing Taiwan Strait waters from the intruding subsurface Kuroshio waters which have earlier circumvented the northern tip of Taiwan. And besides this, it is proposed that the front is formed by the vertical mixing of downwelled subsurface Kuroshio waters which have previously upwelled near the shelf break northeast of Taiwan.

2. Sampling locations and methods

The present authors conducted research on five cruises in the vicinity of the Taiwan Strait roughly over a span of 13 years: the Ocean Researcher I-179 (ORI-179) cruise between 11 and 14 September 1988, the ORI-418B cruise from 8 to 17 May 1994, the ORI-508 cruise from 15 to 26, November 1997, the ORII-806 cruise from 27-28 August, 2001, as well as the ORIII-721 cruise from 6 to 7 August 2001. The relevant station locations are given in Fig. 3.

The shipboard temperature (T) and salinity (S) were determined with an SBE 911 plus Conductivity–Temperature–Depth Pressure (CTD) units manufactured by Sea-Bird, while surface T and S were continuously measured with an autosalinograph. Discrete samples were collected at various depths with a Rosette sampler fitted with 2.5-l Niskin bottles that were mounted on the Sea-Bird CTD unit for the determination of S, dissolved oxygen (DO), nitrite (NO_2^-), nitrate (NO_3^-), phosphate (PO_4^{3-}) and silicate (SiO_2). Data from the sensors on the CTD unit were obtained during both the downcast and the upcast periods. Discrete water samples were picked up during the upcast. The CTD unit was lowered as well as raised at a rate of about 1.0 m/s.

Salinity in the discrete samples was determined by measuring conductivity with an AUTOSAL salinometer, which was calibrated with IAPSO standard seawater (batch No. P128) with a precision of 0.003. Dissolved oxygen in the discrete samples was measured by direct spectrophotometry (Pai et al., 1993), with a precision of about 0.32% at the 190 $\mu mol\,kg^{-1}$ level. Nitrate plus nitrite was measured by reducing nitrate to nitrite, and then identifying nitrite by means of the pink azo dye method (Strickland and Parsons, 1972) using a flow injection analyzer with an on-line Cd coil. The precision of this method was about 1% at 35 $\mu mol\,kg^{-1}$, and 3% at 1 $\mu mol\,kg^{-1}$. Nitrite was determined following the pink azo dye method (Strickland and Parsons, 1972; Pai et al., 1990a) with a flow-injection analyzer with a precision of 0.02 $\mu mol\,kg^{-1}$. Phosphate was studied under the molybdenum blue method (Murphy and Riley, 1962; Pai et al., 1990b) again using a flow-injection analyzer with a precision of about 0.5% at 2.8 $\mu mol\,kg^{-1}$ and 3% at 0.1 $\mu mol\,kg^{-1}$. Silicate was measured in accordance with the silicomolybdenum blue method (Fanning and Pilson, 1973) once again with a flow-injection analyzer with a precision of about 0.6% at 150 $\mu mol\,kg^{-1}$ and 2% at 5 $\mu mol\,kg^{-1}$.

pH was measured at $25\pm0.05\,^{\circ}C$ with a Radiometer PHM-85 pH meter and a GK 2401C combination electrode. The electrode and the electrode shift were, respectively, calibrated using a TRIS seawater buffer and IAPSO Standard seawater as the running standard. Precision was better than ±0.003 pH units. Total alkalinity (TA) was measured using a titration system composed of a Radiometer PHM-84 pH meter, a PHC-2401 combination electrode, an ABU- 80 autoburet, a 150-ml titration cell and a temperature-controlled water bath set at $25\pm0.05\,^{\circ}C$. For the TA values, until 1997, the end points had been determined from the Gran function with a precision of $\pm3\,\mu mol\,kg^{-1}$ (Chen et al., 1996), but thereafter, they were determined following the mass and charge balance method, as pioneered by Butler (1992), and again, with a precision of $\pm3\,\mu mol\,kg^{-1}$. Total CO_2 (dissolved inorganic carbon, DIC) was measured by employing the coulometric method with a precision of $\pm0.05\%$. CO_2 gas was extracted from acidified seawater by using a single operator multiparameter metabolic analyzer (SOMMA) system; then the CO_2 gas was measured with a coulometric detector (model 5011 from UIC, Coulometrics, Inc.) (Dickson and Goyet, 1994). For calibration, the reference material prepared by A. Dickson was