Spring of no Kuroshio intrusion in the southern Taiwan Strait

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[1] The Taiwan Strait connects the East China Sea (ECS) to the South China Sea (SCS). Typically, in spring, the water in the SCS and a branch of the Kuroshio occupy the eastern part of the strait while the China coastal waters, including a large contribution from the Changjiang (Yangtze River), occupy the western part. During spring 2008, when the Taiwan Strait was under the influence of La Niña, and according to field observations, the Kuroshio branch did not contribute much to the waters in the southern Taiwan Strait. A numerical model verifies this observation. The China coastal waters also seem to have had less effect than in typical years. Since the SCS waters contain more nutrients than the Kuroshio branch, more nutrients may be transported from the SCS to the ECS in a La Niña spring than at other times.

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1. Introduction

[2] The South China Sea (SCS), with an area of 3.5×10^6 km^2, is the largest marginal sea in the world, while the East China Sea (ECS), at 7.7×10^5 km^2, ranks 11th largest. Warm, saline, and oligotrophic surface waters occupy the SCS while cooler, fresher, and euphotic surface waters occupy the ECS. Apart from the complex teleconnection between these seas via the area east of Taiwan [*Chen*, 2005, 2008], the Taiwan Strait is the only direct link between these two seas, and large amounts of heat, freshwater, and nutrients flow through it [*Beardsley et al.*, 1985; *Chang and Isobe*, 2003; *Chen and Sheu*, 2006; *Teague et al.*, 2003; *Wu et al.*, 2007].

[3] The Taiwan Strait, with a mean depth of 60 m, is much shallower than the 2200 m deep Luzon Strait, which is the major passage that connects the SCS to the West Philippine Sea (WPS). Relative to the ECS and SCS some of the warmest, saltiest, and most oligotrophic surface waters of the Kuroshio enter the SCS through the Luzon Strait. Most of the incoming Kuroshio branch either enters the SCS proper or forms a loop current west of the Luzon Strait and then rejoins the Kuroshio, but part of it enters the Taiwan Strait [*Centurioni et al.*, 2004; *Chu and Li*, 2000; *Hu et al.*, 2000; *Metzger and Hurlburt*, 1996; *Qu et al.*, 2000, 2004; *Shaw*, 1991; *Y. Wang et al.*, 2006; *C. Wang et al.*, 2006; *Xue et al.*, 2004].

[4] The coldest, least saline, but most eutrophic Fujian-Zhejiang Coastal Water occupies the coast of China mainland between fall and spring [*Chen*, 2008, 2009; *Naik and Chen*, 2008]. Except for this coastal water, various investigations have found that the SCS water and the Kuroshio branch occupy the Taiwan Strait [*Fang et al.*, 2003; *Jan et al.*, 2002, 2006a; *Song*, 2008; *Wang and Chern*, 1988]. Yet, few have attempted to differentiate the SCS water from the Kuroshio water. The authors believe that this issue is important for several reasons. In particular, the SCS water contains more nutrients than the Kuroshio [*Chen*, 2008]. Accordingly, the relative contributions of the SCS and Kuroshio waters may be major determinants of the biological productivity in the Taiwan Strait, and perhaps in the southern ECS. In this work, SCS, Kuroshio, and a mixture of these two waters in the Taiwan Strait will be studied, and the Kuroshio waters will be shown to have been all but absent from the southern Taiwan Strait during the La Niña spring of 2008.

2. Study Area and Methods

[5] Cruise 861 of *Ocean Researcher I* (ORI-861) took place on 7–8 April 2008. Figure 1 displays the locations of the stations. The shipboard temperature and salinity were determined with an SBE 911*plus* conductivity-temperature-depth (CTD) unit, manufactured by Sea-Bird. Seawater samples were collected using a CTD/Rosette sampler, which had been fitted with 20 L Niskin bottles. Seawater pH was measured to a precision of ±0.002 at 25° ±0.05°C with m-cresol purple and a UV-visible spectrophotometer [*Clayton and Byrne*, 1993]. Nitrate plus nitrite concentration was measured by 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 μmol L^{-1} and ±3% at 1 μmol L^{-1}. Nitrite concentration was also determined by the pink azo dye method [*Pai et al.*, 1990a; *Strickland and Parsons*, 1972] and a flow injection analyzer to a precision of ±0.02 μmol L^{-1}. Silicate concentration was measured by the silicomolybdenum blue method [*Fanning and Pilson*, 1973; *Pai et al.*, 1990b] using a flow injection analyzer. The pre-

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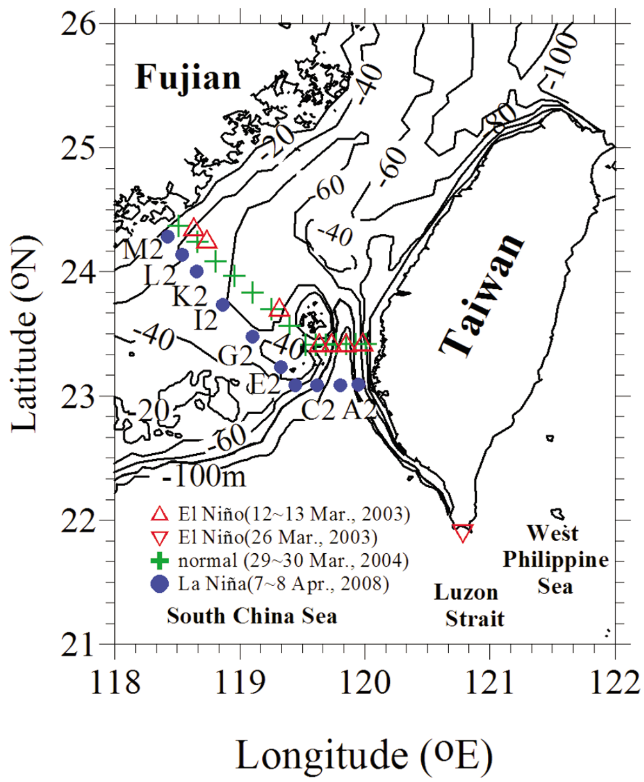

Figure 1. Station locations in the southern Taiwan Strait.

cision was approximately 0.6% at 150 μmol L^{-1} and 2% at 5 μmol L^{-1}.

[6] A duo-grid North Pacific Ocean model, based on a DieCAST (Dietrich/Center for Air Sea Technology) model [*Dietrich*, 1997; *Dietrich et al.*, 2004; *Tseng et al.*, 2005], was adopted to elucidate the unusual strong blocking effect of wind on the Kuroshio branch. The model covered 30°S to 60°N and 100°E to 80°W with horizontal grid resolutions of 1/8° and 1/4°, respectively; the west and east domains bordered each other at 150°E. *Jan et al.* [2006b] and *Tseng et al.* [2009] described in detail and validated the model. Moreover, to facilitate the inference of the modeled flow patterns, absolute geostrophic velocities, computed from sea surface height (SSH) measured using a satellite altimeter, were collected from Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) data at http://las.aviso.oceanobs.com/las/servlets/dataset. The altimeter products were produced by Ssalto/Duacs and distributed by AVISO with support from Centre National d'Etudes Spatiales (CNES).

3. Results and Discussion

[7] Figure 2 displays cross sections of potential temperature (θ), salinity (*S*), sigma θ (σ_θ), nitrate (NO_3), silicate (SiO_2) and pH. Remnant cold (θ = 17°–20°C), fresh (*S* = 32–34), high-nutrient (NO_3 = 0.2–18 μmol L^{-1}; SiO_2 = 1–16 μmol L^{-1}) Fujian-Zhejiang Coastal Waters can still be found west of station K2. However, the exceptionally cold water (~12.6°C) found at Penghu Island [*Chang et al.*, 2009; *Hsieh et al.*, 2008] (near stations D2 and E2] in mid-February 2008 have retreated. Measured temperatures at stations D2 and E2 were 10°C warmer in early April than in February, reaching 26.5°C at station B2 in the central Penghu Channel (Figure 2a). This warm water must come from the south but temperature alone can not be used to differentiate the SCS water from the Kuroshio water. The colder but highly saline and high-σ_θ water found at the bottom of stations C2–E2 is present because of upwelling (Figure 2a–2c) [*Chen et al.*, 2004]. The influence of the SCS and Kuroshio waters on the seawater properties in the study area is discussed below.

[8] The NO_3 and SiO_2 concentrations are typically low at the surface and increase with depth, except close to the China mainland coast (Figures 2d–2e); however, pH exhibits an opposite trend (Figure 2f). High nutrient concentrations but low pH (stations L2 and M2) are indicative of the Fujian-Zhejiang Coastal Current, which can be traced to the nutrient-rich Changjiang diluted water. The Fujian-Zhejiang Coastal Current begins to flow southward in the autumn and begins to retreat in the spring [*Chen*, 2008]. As stated above, only a remnant of that current was observed in this investigation. The upwelling feature at the bottom of stations C2–E2 is accompanied by high nutrient concentrations but low pH, as expected [*Naik and Chen*, 2008].

[9] Figure 3 presents a θ/*S* plot, which is a powerful tool for differentiating various water masses. In this work, the typical WPS waters exhibit a shallow salinity maximum (Figure 3; *S* = 35). The water with maximum salinity is sometimes called the Kuroshio Tropical Water [*Chen*, 2005]. The Kuroshio Intermediate Water has a minimum in salinity (*S* = 34.1; not shown). Strong vertical mixing and upwelling in the SCS reduces the magnitude of these salinity extremes. Accordingly, the salinity maximum in the SCS has a lower salinity than the salinity maximum of the Kuroshio water, whereas the salinity minimum in the SCS has a higher salinity than the salinity minimum of the Kuroshio water (Figure 3).

[10] Figure 3a presents the θ/*S* plot at stations K2, L2, and M2. The Fujian-Zhejiang Coastal Current causes all salinities to fall below the values for Kuroshio and SCS. Importantly, the θ/*S* plots for stations A2–I2 are almost completely consistent with the typical SCS plot (Figure 3b). This fact is the first indication that, except when under the influence of the Fujian-Zhejiang Coastal Current, the study area was completely occupied by SCS water, with little or no direct effect by Kuroshio water. Supporting evidence is presented below.

[11] Figure 3b plots our unpublished data from three other spring (March–May) cruises, one in a normal year and the other two in an El Niño year. Since there is a delay of several months after the effects of the El Niño–Southern Oscillation (ENSO) appear in the SCS [*Y. Wang et al.*, 2006; *C. Wang et al.*, 2006; *Wu and Chang*, 2005], we have used the CTD data for 9–12 months after the occurrence of each phase, based on ENSO information provided by NOAA (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/enso_evolution-status-fcsts-web.pdf). These non–La Niña data are scattered between the SCS and WPS curves and are clearly affected by the Kuroshio. Furthermore, the cross sections of θ, *S*, σ_θ, NO_3, SiO_2, and pH along 21°45′N south and southeast of Taiwan are plotted (Figure 4). Without exception, the contours shoal toward the west, mainly because of upwelling and vertical mixing in the SCS [*Chen et al.*, 2006]. At any particular depth, the subsurface SCS

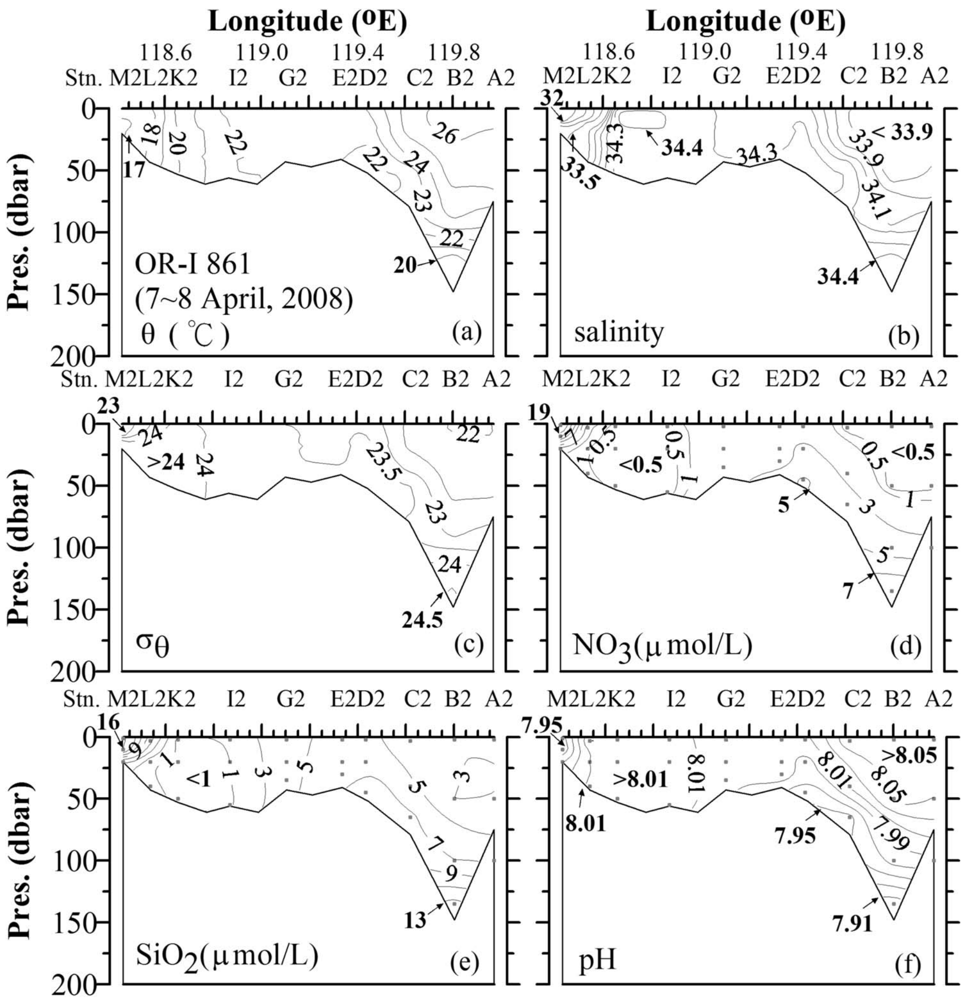

Figure 2. Cross section of (a) θ, (b) S, (c) σ_θ, (d) NO_3, (e) SiO_2, and (f) pH in the southern Taiwan Strait.

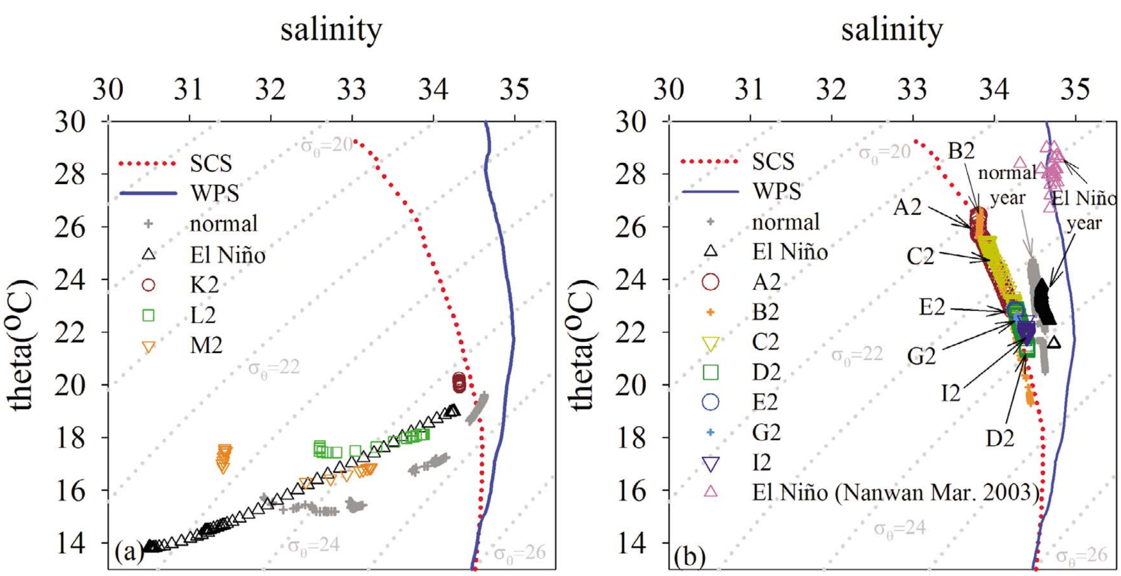

Figure 3. The θ/S plots for (a) stations K2–M2 and (b) A2–I2 for the ORI-861 cruise. The typical plots for SCS and WPS waters and data from three other spring cruises are also shown.

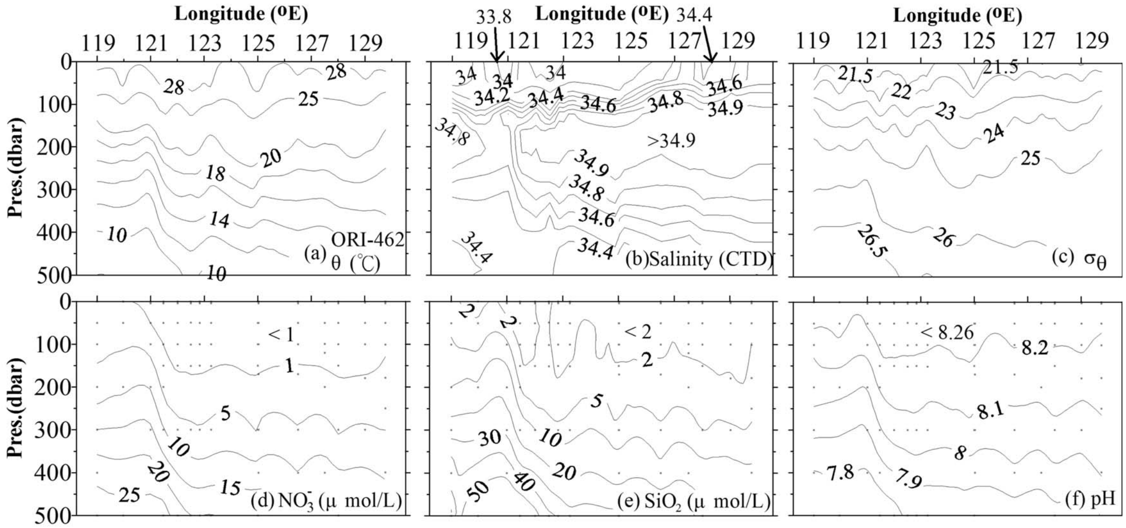

Figure 4. Cross section of (a) θ, (b) S, (c) σ_θ, (d) NO_3, (e) SiO_2, and (f) pH at 21°45′N off SE Taiwan [from *Chen et al.*, 2006].

waters are colder, saltier, heavier, and higher in NO_3 and SiO_2 concentrations but lower in pH than the Kuroshio waters. Indeed, in spring 2008, the study area was occupied by waters that were colder, saltier, heavier, and higher in NO_3 and SiO_2 concentrations but lower in pH than the Kuroshio. Notably, the θ/S plots for the Fujian-Zhejiang Coastal Waters have a positive slope (Figure 3a) whereas those for the upper waters in the SCS and the Kuroshio have a negative slope (Figure 3b). Accordingly, water temperatures increase with depth in the Fujian-Zhejiang Coastal Current.

[12] Figure 5 plots 10 day averaged model results for the top two levels (28 m thick layer), based on the wind data collected from the European Centre for Medium-Range Weather Forecasts (ECMWF). In the circulation that is driven by the wind during 1–10 April 2006, a prominent branch current that is separated from the west flank of the Kuroshio deflects northwestward then turns anticyclonically and intrudes into the southeastern Taiwan Strait (see velocity vectors in the rectangle in Figure 5a). The warm Kuroshio water (>24°C) is thus carried to the strait. Unlike Figure 5a, in the circulation that is driven by the wind during 1–10 April 2008 the Kuroshio branch is impeded by a stronger northeast monsoon than present in a similar period of 2006 and associated warm water is absent from the region off southwestern

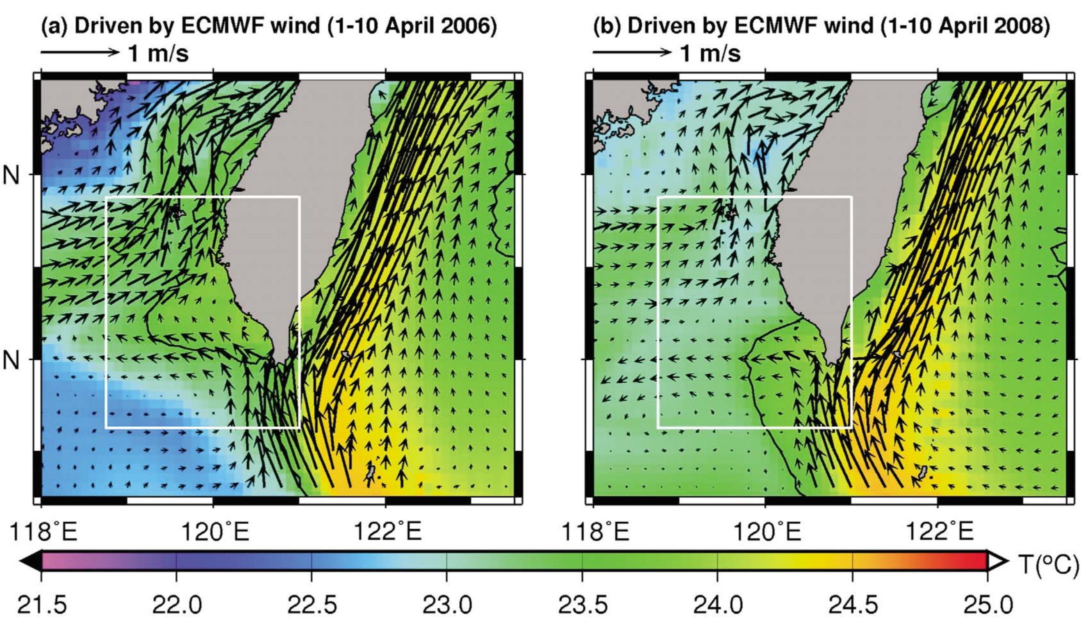

Figure 5. Model produced 10 day mean current velocity and temperature distributions in the upper 28 m thick layer, driven by European Centre for Medium-Range Weather Forecasts (ECMWF)-produced winds during (a) 1–10 April 2006 and (b) 1–10 April 2008.

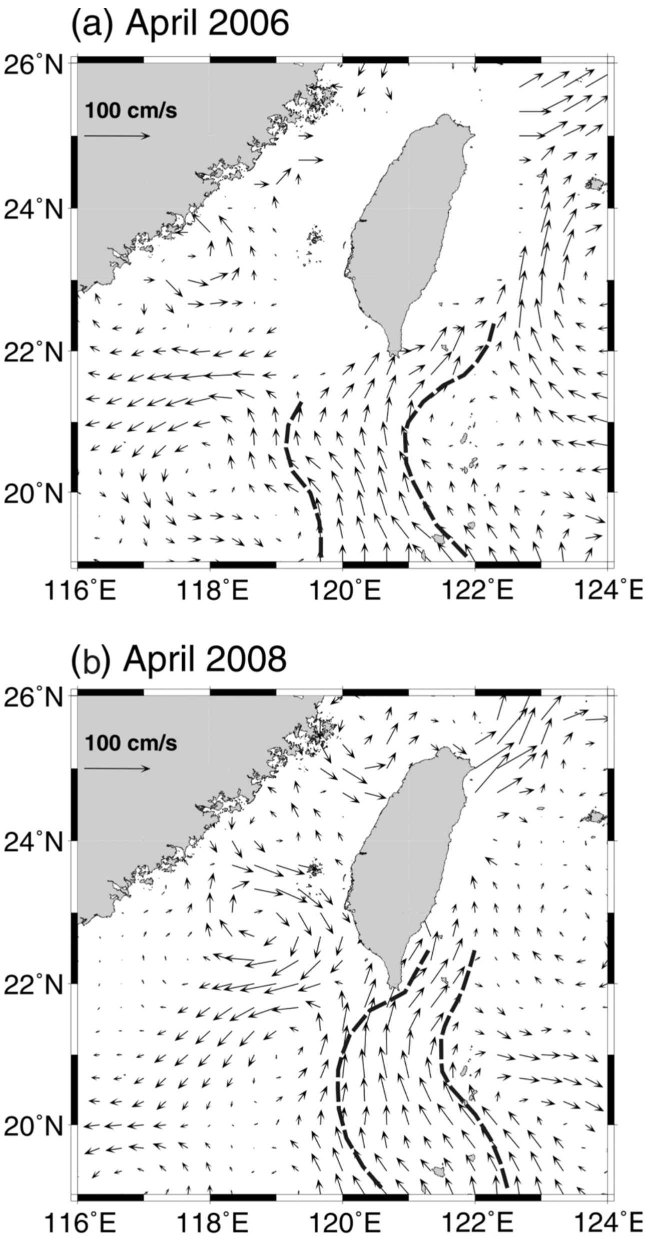

Figure 6. Monthly mean absolute geostrophic velocities (from AVISO) for April (a) 2006 and (b) 2008. The blanking regions indicate no sea surface height (SSH) data. The dashed lines in each figure mark the plausible pathway for the Kuroshio in the Luzon Strait.

Taiwan (Figure 5b). Note that the spatial resolution of the ECMWF wind cannot resolve fine structure variation in the wind field, particularly a pair of negative and positive wind stress curls in the downwind side, during northeast monsoons over the mountain range of Taiwan Island. However, associated evaluation of the flow patterns below the synoptic scale warrants further study and is beyond the scope of this paper.

[13] Indeed, the East Asian monsoon system dominates the climate of the ECS and the SCS, and the top-layer circulation is driven primarily by the monsoon [*Wyrtki*, 1961]. For comparison, *Chao et al.* [1996] used a regional ocean model to simulate the 1982–1983 El Niño and found that a weakening of the East Asian monsoon weakened upwelling in the SCS. *Y. Wang et al.* [2006]; *C. Wang et al.* [2006] employed a global ocean model to demonstrate that in the El Niño winter of 1997–1998, cyclonic circulation in the SCS was weaker than in other years because the wind stress was lower. The opposite effect was observed, as could have perhaps been expected, in the 2007–2008 La Niña winter, because the winds were stronger (http://www.cwb.gov.tw/). As a result, the upwelling in the SCS proper was thus relatively intense. Note that the effect of wind curl was not analyzed in this preliminary research.

[14] Although the above mentioned basin scale processes are correct, how these processes influence the water properties off SW Taiwan is not clear. It is speculated that while the basin-wide circulation intensified the thermocline was lifted in the SCS basin, that deeper waters with lower temperature and lower pH, but higher salinity, density, NO_3 and SiO_2 moved toward the surface. These upwelling waters were subsequently transported to the study area.

[15] Figure 6 plots the monthly mean absolute geostrophic currents for April of 2006 and 2008. Note that due to the lack of reliable satellite SSH data east of Taiwan, the Kuroshio is unfortunately not seen there in Figure 6. The currents in shallow seas such as the Taiwan Strait may also not be approximated well by the geostrophic flow. Leaving these deficiencies aside, the meso-scale current patterns indicate that the Kuroshio looped more to the west in the Luzon Strait during April 2006 (Figure 6a) than it did during the same period in 2008 (Figure 6b). The aforementioned comparison between Figures 6a and 6b supports the results from the numerical model shown in Figure 5. A stronger winter northeast monsoon in La Niña years than in normal years impedes the intrusion of the Kuroshio branch current to the southeastern Taiwan Strait, which in turns considerably affects the biogeochemical properties of seawater in the Taiwan Strait (this study). In addition, the pathway of Kuroshio may be shifted by the unusually strong NE monsoon during a La Niña year, and it may also be affected by the strength of the North Equatorial Current (NEC). *Kim et al.* [2004] concluded that the bifurcation point of NEC east of Luzon Island shifts northward during El Niño and southward during La Niña periods, meaning that the flow volume transport of the NEC is larger in the latter than in the former periods. Conceivably, it leads to a stronger Kuroshio in La Niña years than in El Niño or "normal" years. A stronger Kuroshio results in a straighter path in the Luzon Strait [*Metzger and Hurlburt*, 1996, and references therein], which does not favor the intrusion of the Kuroshio branch into the west reaches of the Luzon Strait. The abnormally strong northeast monsoon further prevents the warm and saline water carried by the Kuroshio to be transported to the southeastern Taiwan Strait. This situation may apply in the spring of 2008.

4. Conclusion

[16] Model results in the literature show that the SCS basin-wide surface circulation and its vertical advection rate are reduced during an El Niño event, warming the surface water of the SCS [*Chao et al.*, 1996; *Kuo and Ho*, 2004; *Liu et al.*, 2004; *Shang et al.*, 2005; *Wang et al.*, 2002]. On the other

hand, a numerical model was employed to confirm the field observations that in the La Niña spring of 2008, colder, fresher, denser waters with higher NO_3 and SiO_2 concentrations but lower pH occupied the southern Taiwan Strait, except for a small region that was affected by the Fujian-Zhejiang Coastal Current close to the China mainland coast. This result is the opposite of that expected for an El Niño year. Additionally, the Kuroshio branch did not appear to enter the southern Taiwan Strait.

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