Does the Taiwan warm current exist in winter?

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[1] It has been argued for many years whether the Taiwan Warm Current (TWC) exists in winter, though there is no question about its existence in summer. A regional CTD survey and anchored ADCP measurements were conducted off the mouth of the Changjiang on the western shelf of the East China Sea from 24 February to 10 March 2001. Both hydrographic and current data showed an evidence of the TWC, which flowed northeastward along the 50-m isobath and intruded into the submerged river valley off the Changjiang. This current is sub-surface intensified, with a maximum velocity of 30 cm/s occurring at a depth of 30 m below the surface. This finding was consistent with the satellite-derived SST image received on 26–30 January 1986 and MODIS SST image received on 18 February 2001. It suggests that the TWC is at least an episodic feature in the East China Sea and its occurrence and duration might vary due to meandering of the Kuroshio around the Taiwan Strait. *INDEX TERMS:* 4528 Oceanography: Physical: Fronts and jets; 4568 Oceanography: Physical: Turbulence, diffusion, and mixing processes; 4283 Oceanography: General: Water masses; 4599 Oceanography: Physical: General or miscellaneous. **Citation:** Zhu, J., C. Chen, P. Ding, C. Li, and H. Lin (2004), Does the Taiwan warm current exist in winter?, *Geophys. Res. Lett.*, *31*, L12302, doi:10.1029/2004GL019997.

1. Introduction

[2] A composite of the general circulation in the East China Sea (ECS) was given based on previous observational events by *Ichikawa and Beardsley* [2002]. The Kuroshio enters the ECS on the eastern coast of Taiwan, flows northeastward along the 200-m isobath, and leaves the ECS from the southwest of Kyushu (Figure 1) [*Chen et al.*, 1992; *Chen et al.*, 1994]. In summer, the Taiwan Warm Current (TWC), which originates either in the Taiwan Strait or north of Taiwan due to a northward intrusion of the Kuroshio, flows northeastward parallel to the 50-m isobath and enters the submerged river valley off the Changjiang [*Beardsley et al.*, 1985].

[3] It has been argued for many years whether the TWC exists in winter. *Kondo* [1985] constructed a regional map of the winter- and summer-time circulation in the ECS and concluded that no evidence was found for TWC in winter. He believed that the northward intruding water found around the 50-m isobath in the ECS in winter was a result of the Kuroshio Branch Current originating from the north of Taiwan (KBCNT). *Qiu and Imasato* [1990] constructed a climatologic map of the surface current in the ECS by averaging GEK current data available over 1/5° × 1/5° resolution boxes from 1953 to 1984. They found no evidence of the northward intrusion of the TWC in winter, either. *Naimie et al.* [2001] used the climatologic hydrographic data to drive the East China/Yellow/Bohai Seas circulation model and also reported that no TWC could be resolved in winter due to the cancellation between wind- and buoyancy-induced baroclinic circulations. Similar argument was also given by *Lin et al.* [2001].

[4] These conclusions, however, are questioned by many snapshot regional observations undertaken in the ECS. *Beardsley et al.* [1985] conducted a regional survey over the western inner shelf of the ECS. According to the local evidence of temperature, salinity and currents, they suggested that there should be the TWC in winter, which originates in the Taiwan Strait, split northward along the 50-m isobath east of 120°E, and flows into the submerged river valley off the Changjiang. Similar findings were also reported by *Guan and Mao* [1982], *Pan et al.* [1987], *Chen* [1989], *Fang et al.* [1991], *Chen et al.* [1994], and *Su et al.* [1994]. Examining the evidences supporting these contrasting views, it is apparent that one view is based mainly on the climatologically averaged hydrographic data, while the other on the direct snapshot regional measurements. This raises a fundamental question on whether the TWC is an episodic wintertime feature in the ECS that could be erased after a climatological average.

[5] A regional CTD survey and three anchored ADCP measurements were conducted off the Changjiang over the inner shelf of the ECS during 24 February through

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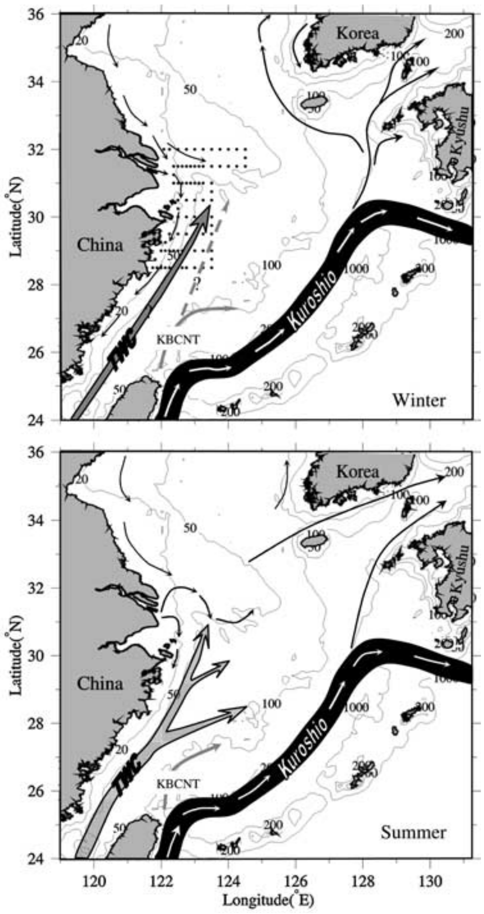

Figure 1. Schematic of the summer- and winter-time regional circulation patterns in East China Sea. The filled dots in the upper panel are the locations of the CTD survey.

10 March 2001. Temperature and salinity were obtained with a Seabird CTD along east-west transects through the study area, with a fine spacing of stations in the primary TWC passage. The research vessel was anchored at 122.9517°E and 31.0482°N during 5–6 March, at 122.6250°E and 30.5000°N during 6–7 March, and at 122.1005°E and 31.9947°N during 8–9 March, during which the vertical profiles of currents were taken with 2-minute intervals for a period of longer than 24 hours by an anchored ADCP mounted on the ship. A least-square fitting method, which was developed to filter tidal signals from ADCP data [*Chen et al.*, 1995], was used to remove tidal currents from the ADCP. The uncertainty of resulting averaged residual current was within 1–2 cm/s. Combined hydrographic and current data clearly showed an evidence of the TWC and a detailed description and discussion are given below.

2. Evidences of the TWC

[6] The hydrographic data clearly showed a northeastward intrusion of the warm and saline water that originated from the south over the western continental shelf of the ECS. At depths of 3 and 30 m, for example, this warm and saline water continued to extend northeastward and entered the submerged river valley off the Changjiang, with large cross-isobath gradients of temperature and salinity along the 50-m isobath (Figures 2a, 2b). Both temperature and salinity was relatively well mixed in the upper 30 m due to relatively strong wintertime local mixing. A temperature vs. salinity plot (TS-diagram) shown in Figure 3 indicated a quasi-linear trend between (T = 16°C, S = 34) and (T = 12°C, S = 31), implying energetic mixing between the northward intruded warm, saline water and the cold, less saline continental shelf water. The spatial distributions of temperature and salinity were very similar to those observed in summer [*Chen et al.*, 1994], though the winter- and summer-time TS distributions were remarkably different due to seasonal variability of vertical mixing.

[7] To find out the source of the relatively warm and saline water observed in the measurement area, we examined the validated 1-km resolution SST images from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the satellite Terra covering late 2000 to 2002. The MODIS SST received on 18 February 2001, two days before the regional CTD survey, clearly showed a warm water sourcing from the Taiwan Strait (Figure 4). This warm water could be traced along the 50-m isobath until the submerged river valley off the Changjiang. A similar feature was also detected in a composite AVHRR-derived SST image taken between 26–30 January 1986 (Figure 5). This image showed a continuous flow of the warm water from the Taiwan Strait to the submerged river valley off the Changjiang. Based on the satellite-derived SST images and the CTD survey data, we believe that the relatively warm and saline water observed off the Changjiang in winter was a part of the northward intrusion water of the TWC.

[8] This argument was supported by direct short-term measurements of currents at 3 selected anchored sites shown in Figure 1. According to the distribution of the wintertime circulation in the ECS, the tidally averaged water movement in the nearshore region shallower than 50 m off the Changjiang is characterized by southward

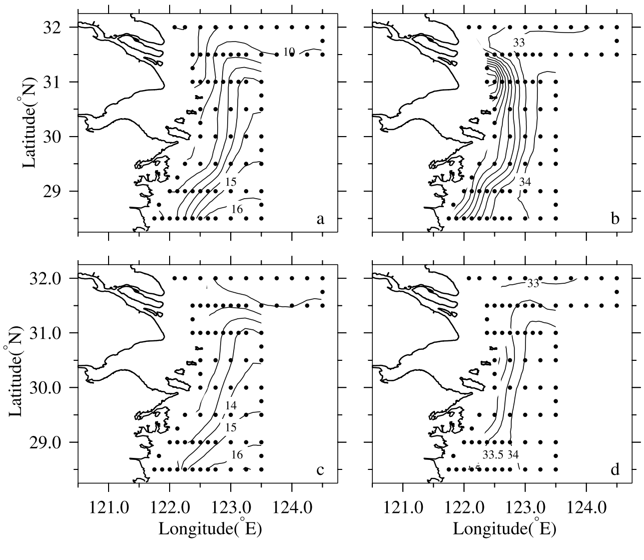

Figure 2. Distribution of temperature and salinity off the Changjiang constructed using the CTD survey taken from 24 February to 10 March 2001. a) Temperature at a depth of 3 m; b) Salinity at a depth of 3 m; c) Temperature at a depth of 30 m; d) Salinity at a depth of 30 m.

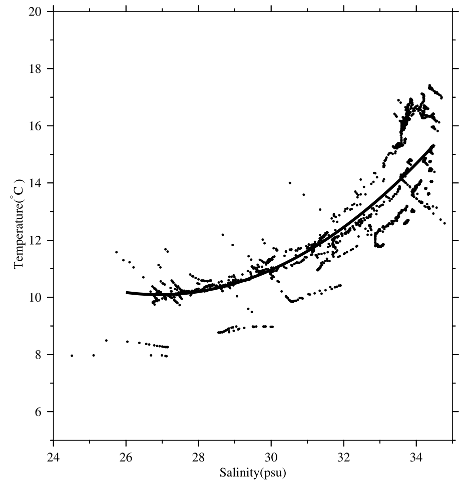

Figure 3. The TS diagram constructed using the February–March 2001 CTD data.

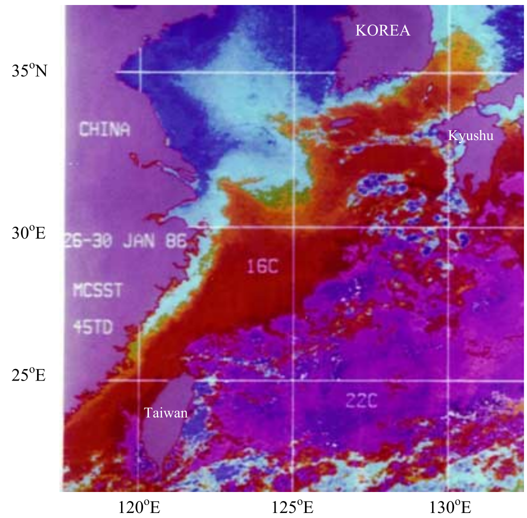

Figure 5. The NOAA-AVHRR satellite-derived SST received on 26–30 January 1986 in the East China Sea.

coastal currents induced by northerly monsoon to the north and Changjiang discharge to the south. These two currents were evident at sites F2 and F3, where southward currents of about 10 and 10–50 cm/s were observed on the northern and southern coast off the Changjiang (Figure 6). The northward intrusion of the TWC can be clearly seen at site F1, where the subsurface-intensified, northward subtidal current of about 24–31 cm/s was observed at the 50-m isobath in the onshore edge of the submerged river valley.

[9] A southward wind prevailed during the February–March 2001 CTD/ADCP survey. The averaged speed of the surface southward wind measured on the research vessel was about 6 m/s. The wind tended to move the water southward in an opposite direction to the movement of the TWC in the ECS. This suggests that the northward intrusion of the TWC parallel to the 50-m isobath found from anchored ADCP measurement at site F1 was not an occasional event that occurs only under wintertime wind conditions. The observed subtidal current, which was about 30 cm/s, near the submerged river valley off the Changjiang implies that the intensity of the TWC in winter could be comparable in order of magnitude to that observed in summer. Therefore, in addition to winds and freshwater discharge, the TWC could be an important physical process attributing directly to the wintertime circulation on the western shelf of the ECS.

3. Discussion and Conclusion

[10] The regional CTD survey plus current measurements from three anchored ADCPs clearly showed an evidence of the wintertime TWC, which flowed northeastward parallel to the 50-m isobath and intruded into the submerged river valley off the Changjiang. This current was sub-surface intensified, with a velocity of 30 cm/s occurring at a depth of 30 m below the surface. This evidence was supported by the MODIS SST received on 18 February 2001 and AVHRR-derived SST image taken between 26–30 January 1986, from which a warm water sourcing from the Taiwan

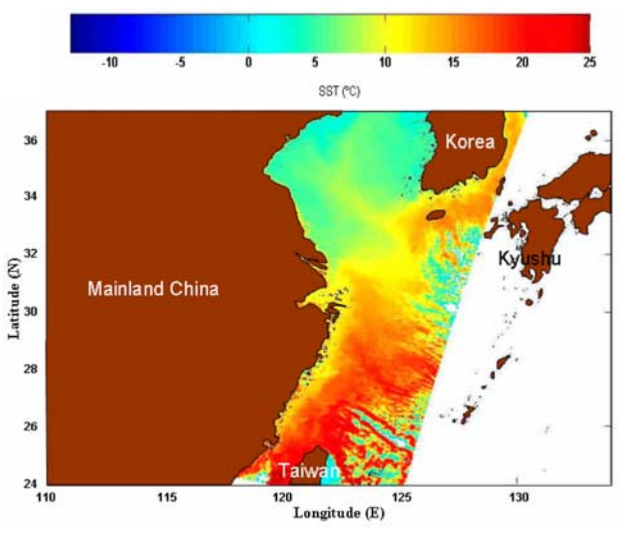

Figure 4. The MODIS SST image received on 18 February 2001 in the East China Sea.

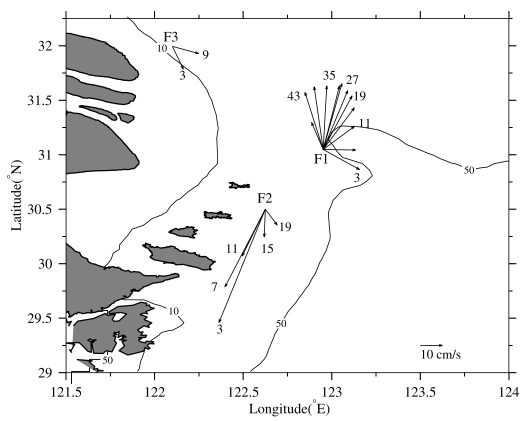

Figure 6. Vectors of the subtidal velocity at selected depths at measurement sites F1, F2, and F3. The currents were measured with an anchored ADCP mounted on the ship. Value near the end of the vector is the measurement depth (m) below the surface.

Strait and flowing continuously to the submerged river valley off the Changjiang was detected.

[11] The fact that no TWC was detected in the climatologically averaged wintertime hydrographic data but it was frequently observed in the snapshot regional surveys suggests that the TWC is an episodic wintertime feature in the East China Sea. The occurrence and duration of this current might be controlled by the onshore meandering of the Kuroshio around the Taiwan Strait. The northward intrusion of the TWC does not appear to be affected by the wintertime southward monsoon climate in the ECS.

[12] Previous observations have demonstrated the existence of a year-round KBCNT north of Taiwan [*Kondo*, 1985]. However, few observational evidences have been provided to verify the northward branch of this current. This water usually turns clockwisely following the local isobath and then flows northeastward parallel to the Kuriosho. The satellite images shown in Figures 4 and 5 suggest that the main source of the TWC might have originated from the Taiwan Strait and the northward intrusion current is guided by the sloping bottom along the 50-m isobath. The episodic scenarios of the TWC in the winter call for additional research on the physical mechanism for onshore meandering of the Kuroshio on the southern coast of Taiwan.

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