Kuroshio subsurface water feeds the wintertime Taiwan Warm Current on the inner East China Sea shelf

Ergang Lian1, Shouye Yang1,2, Hui Wu3, Chengfan Yang1, Chao Li1, and James T. Liu4

1State Key Laboratory of Marine Geology, Tongji University, Shanghai, People’s Republic of China, 2Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao, People’s Republic of China, 3State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai, People’s Republic of China, 4Department of Oceanography, National Sun Yat-sen University, Kaohsiung, Taiwan

Abstract The Taiwan Warm Current (TWC) has an overwhelming influence on the heat, salt, and nutrients balance on one of the broadest shelf in the world, the East China Sea shelf. In winter, the TWC flows in an unusual upwind direction and reaches the Changjiang (Yangtze River) Estuary, but its origin and pathway are intensely debated. Here combined evidences from current measurement, hydrographic, and stable isotopic data all suggest that the wintertime TWC intrusion off the Changjiang Estuary mainly originates from the Kuroshio subsurface water northeast of Taiwan, rather than from the Taiwan Strait warm water. The Kuroshio-branched water northeast of Taiwan can intrude into the inner shelf near the Zhe-Min Coast via bottom layer, manifesting by a pronounced boundary at 50 m isobath around 28°N, and thereby feeds the TWC intrusion into the Changjiang Estuary. The intrusion complicates the hydrological process in the estuary and shelf sea, and its impact on marine environment deserves more research attentions.

1. Introduction

The East Asia continental margin is characterized by well-developed shelf seas and strong land-sea interactions. Among these marginal seas, the East China Sea (ECS) is unique in terms of its wide continental shelf linking the Changjiang (Yangtze River), one of the largest rivers in the world, with the Okinawa Trough, a back-arc basin formed by the collision between Asian continent and Pacific Plate. The complex shelf circulation system in the ECS has long been recognized by previous studies [Uda, 1934; Mao et al., 1964; Fang et al., 1991; Guan, 1994; Ichikawa and Beardsley, 2002; Guan and Fang, 2006; Chen, 2009], and the Changjiang Diluted Water (CDW), Taiwan Warm Current (TWC), Zhe-Min Coastal Current (ZMCC), and the Kuroshio are the dominant currents in the ECS (Figure 1). Although many studies have attempted to investigate the temporal and spatial variations of the ECS circulation systems [Guan, 1994; Ichikawa and Beardsley, 2002; Chen, 2009], some basic questions relating to the origins and pathways of these major currents remain to be answered. For instance, the origin and temporal and spatial variability of the TWC is always a key question for physical oceanographic study in the ECS.

The TWC, named by its high temperature and origin [Mao et al., 1964], flows northward between 50 and 100 m isobaths off the Zhe-Min Coast all year around [Weng and Wang, 1984; Guan, 1994], and then intrudes into the submerged river valley off the Changjiang Estuary [Zhu et al., 2004; Guan and Fang, 2006]. Particularly, compared to the southward flowing ZMCC, the direction and velocity of the TWC are relatively stable, flowing northeastward with annual mean speed about 14 cm s⁻¹, and seasonal mean speed about 13 and 17 cm s⁻¹ in winter and summer, respectively [Guan and Fang, 2006]. As one of major currents in the ECS, the TWC has an overwhelming influence on the heat, salt, and nutrients balance on the ECS shelf [Fang et al., 1991; Guan and Fang, 2006; Chen, 2009], and to some extent results in upwelling, hypoxia, and algal bloom in the Changjiang Estuary and adjacent shelf areas [Qiao et al., 2006; Wei et al., 2007; Wang, 2009; Dai et al., 2013]. Despite the significant influence of the TWC on the shelf environment and ecosystem, its origin and flow pathway have been intensely debated over the last several decades.

Early hydrographic surveys suggest that the TWC originates from the branching of Kuroshio Current northeast of Taiwan [Uda, 1934; Mao et al., 1964], while Guan [1984] pointed out that in summer it should stem in the Taiwan Strait and flows northeastward based on the historical current data from 1932 to 1977 (Figure 1a).
Nevertheless, Weng and Wang [1984] argued that in summer, the upper layer water of the TWC is derived from the Taiwan Strait, while the lower layer originates from northeast of Taiwan where the Kuroshio sub-surface water (KSSW) upwells and intrudes onto the ECS shelf [Wong et al., 1991; Chen et al., 1995b]. Afterward, Su and Pan [1987] furthered the issue that the TWC has an inshore branch (IB) and an offshore branch (OB) in addition to the upper and lower structure, which was examined by the three-dimensional diagnostic calculation of circulation over the ECS by Yuan et al. [1987]. The inshore branch flows northward near 50 m isobath and turns to the northeast off the Changjiang Estuary, whereas the offshore branch flows anticyclonically and then turns eastward around 28°N off the Zhe-Min Coast (Figure 1a). As for the origin of upper layer of the TWC, the inshore branch comes from the Taiwan Strait in both summer and winter, while the offshore branch comes mostly from the Kuroshio sub-surface water northeast of Taiwan (i.e., KSSW), and the Taiwan Strait warm water (TSWW) accounts for a significant portion in summer. For the lower layer of the TWC, both branches originate from the KSSW northeast of Taiwan throughout the year [Su and Pan, 1987]. Recently, Yang et al. [2011] proposed that a Kuroshio-derived bottom branch current northeast of Taiwan (KBBCNT) exists in the deep and bottom layer of the southern ECS in summer (Figure 1b), which confirms the views of Weng and Wang [1984] and Su and Pan [1987].

In summary, it is now widely accepted that in summer the TWC originates from both the Taiwan Strait warm water and the shelf-intrusion water of Kuroshio northeast of Taiwan [Guan, 1994]. However, the origin of the TWC in winter is still controversial because of its complex structure and the ambiguous Kuroshio intrusion northeast of Taiwan [Ichikawa and Beardsley, 2002; Isobe, 2008]. Shipboard Acoustic Doppler Current Profiler (ADCP) observations by Fang et al. [1991] and Wang et al. [2003] estimated that the volume transport flux through the Taiwan Strait is about 1 Sv in winter, indicating the northward flow existing all year around in the Taiwan Strait [Guan and Fang, 2006]. Zhu et al. [2004] suggested that the episodic intrusion of the TWC into the submerged valley off the Changjiang Estuary does exist in winter, and speculated the intrusion water originates from the TSSW. In favor of this argument, Kim et al. [2005] assumed that the δ18O-depleted water in Tsushima Strait originates in the Taiwan Strait. Nevertheless, Chen and Sheu [2006] argued that the northward flowing TSSW is, in fact, only a rare event when there is a relaxation in NE monsoon. Hydrogeochemical data such as historical nutrients and stable isotopes as well as hydrographic observations by Chen [2003] and Chen and Sheu [2006] provide evidences that the TWC does not originate from the TSSW in winter but comes from the KSSW. Current measurements and model simulation [Jan et al., 2002; Wu et al., 2007; Jan et al., 2010] also suggest that the monthly mean volume transport across the Taiwan Strait declines and reverses its direction to south during winter, implying a lack of persistent northward warm current in the Taiwan Strait. This suggests that the overall
contribution of the TSWW to TWC is small in winter when the NE monsoon prevails. Rather, the persistent upwind current does exist in lower layer along Zhe-Min Coast with the strengthening of NE monsoon as frequently reported [Zhu et al., 2004; Guan and Fang, 2006; Wu et al., 2013; Huang et al., 2016], indicating another feeding for the TWC. Therefore, the origin of the TWC in winter needs further clarifications. To address this question, the present study combines the evidence from in situ observations of hydrography and water stable isotopes in the ECS and the Taiwan Strait. The major purpose of this study is to clarify whether the intrusion water of the TWC into the Changjiang Estuary in winter mostly originates from the KSSW or from the TSWW, and to further interpret the linkage between the TWC intrusion off the Changjiang Estuary and Kuroshio Current northeast of Taiwan.

2. Data Sources and Methods

2.1. Field Survey and In Situ Measurements

Three hydrographic surveys were carried out on board of R/Vs Science III, Runjiang I, and Ocean Researcher V (OR-5) cruising the Changjiang Estuary, ECS, and Taiwan Strait (Figure 2 and Table 1). The cruises are all conducted in February and March when northerly wind prevails. According to the Remote Sensing Systems (REMSS) and Quick Scatterometer (QuikScat) data set, the monthly zonal and meridional wind components from February to March around the survey region are relatively stable (−1.24 ± 0.92 and −4.41 ± 1.39 m s⁻¹, respectively).

The seawater salinity and temperature were measured by Seabird 911plus CTD (Conductivity-Temperature-Depth Sensor). To determine the boundary of the Kuroshio subsurface water intrusion off the Zhe-Min Coast, the underway seawater property (3 m deep below the sea surface) was measured at 10 min interval using a Seabird 21 thermosalinograph on board of R/V OR-5 during a roundtrip cruise from the southern Taiwan Strait to the Changjiang Estuary (Figure 2a). The underway measurements were corrected to Seabird 911plus CTD measurements if drift was noted.

Figure 2. Sampling stations in the East China Sea, Taiwan Strait, and surrounding areas, with 20, 50, 100, 200, and 500 m isobaths in light gray lines. The dark gray arrow denotes the flow direction of Kuroshio in winter [Guan, 1994]. The symbols indicate locations of samples in March 2013 and February 2014, including literature sources (data from Horibe and Ogura [1968], Kang et al. [1994], Lin [2000], Chang [2000], Kim et al. [2005], and Chen and Sheu [2006]). YS, ECS, TS, and NT denote the Yellow Sea, East China Sea, Taiwan Strait, and Nantong Station, respectively. The red line in Figure 2b marked as the TWC according to the water masses classification in Figures 3 and 4.
The vertical profile of current was taken in an anchored site M1 (30°36.47′N, 123°14.69′E), which is located in the submerged valley region off the Changjiang Estuary (Figure 5a), using a shipboard Acoustic Doppler Current Profiler (ADCP) with 2.23 s intervals for a period of 27 h during 15–17 March 2013. The subtidal current of each level was obtained by a tidal filter method [Chen et al., 1995a] after the quality control.

### 2.2. Stable Isotopic Data

A total of 397 seawater samples in the Changjiang Estuary and adjacent area, Zhe-Min Coast and Taiwan Strait were collected using a CTD Rosette sampler during the 2013 open ECS cruise and OR-5 cruise (Figures 2a and 2b and Table 1, supporting information Data set S1). For comparison, four river water samples were collected from the lower Changjiang mainstream at Nantong station (i.e., NT in Figure 2b) [Li et al., 2016], and seven rainwater samples were collected in Shanghai (31°17′13″N, 121°29′49″E) during March 2013. All the above water samples were filtered through precleaned 0.45 μm pore cellulose acetate filters immediately after collection, and then stored in 50 mL acid cleaned polyethylene vials which were filed and sealed with screw caps topped with parafilm as soon as possible (to avoid evaporation). Finally, the samples were refrigerated at 4°C for isotopic analysis.

The stable hydrogen (δD) and oxygen (δ18O) isotopes were measured following the procedures of Berman et al. [2013] with the Isotopic Water Analyzer (IWA-45EP, LGR Co.). The isotopic data are reported relative to Vienna-Standard Mean Ocean Water (V-SMOW), and the precisions of δ18O and δD measurements are better than ±0.1‰ and ±0.5‰, respectively. Additionally, the published isotopic data of the water masses in the ECS are referred from Horibe and Ogura [1968], Zhang et al. [1990], Kang et al. [1994], Lin [2000], Chang [2000], Kim et al. [2005], and Chen and Sheu [2006]. The δ18O data from Horibe and Ogura [1968] were converted from δD data via the formula: δ18O = δD/7.5
The data of seawater temperature, salinity, and stable isotopes are given in supporting information Data set S1.

3. Results

3.1. Hydrography

According to the previous studies [Mao et al., 1964; Liu et al., 2000; Chen, 2009] and our observational data, three major water masses can be recognized off the Changjiang Estuary during the cruise period (Figure 3). The CDW has low salinity (6.5–12.5°C, 19–31 PSU) in the coastal area, while the Yellow Sea Coastal Current (YSCC) is characterized by low temperature and high salinity (<8°C, 31–31.8 PSU). Particularly, the TWC located offshore has typically high temperature and high salinity (>13.5°C, 34.0–34.4 PSU) contrasting sharply with the other two water masses (Figure 3).

Figure 4. Distribution patterns of temperature (T), salinity (S), and δ¹⁸O in surface (2 m) and bottom (with water depth ranging from 7 to 75 m following the topography) water off the Changjiang Estuary taken from 4 to 20 March 2013. Isobaths of 20 and 50 m are shown in gray lines. All distribution patterns obviously show that the saline (S > 33.5 PSU), warm (T > 12.5°C), and δ¹⁸O-enriched (δ¹⁸O>0‰) water flows northward along ~50 m isobath and intrudes into the submerged valley off the Changjiang Estuary in winter.

The distribution patterns of temperature and salinity in both the surface (2 m) and bottom (with water depth ranging from 7 to 75 m, i.e., following the topography) layers are shown in Figure 4. The low-salinity CDW expands southward and is confined to the coastal area (west of 122.5°E) by the warm and saline TWC intrusion in the offshore area (Figures 4a, 4b, 4d, and 4e). The colder YSCC is also restricted to the shallow regions (north of 31.75°E) along the coast. It is notable that a warm and saline water tongue, which is usually identified as the TWC intrusion, spreads northward along ~50 m isobath and intrudes the submerged valley off the Changjiang Estuary as far as 30.5°N. This feature is consistent with the previous observation in winter [Zhu et al., 2004]. Besides, both temperature and salinity are well vertically mixed, without obvious stratifications, due to stronger water mixing, except the region around 122.5°E, 31.25°N.
3.2. Current Measurement

The direct short-term measurement of currents was carried out at the selected anchored site M1 (Figure 5a). The monthly average wind data show that the northerly winds prevailed in the ECS during the cruise period (Figure 5a), while the hourly wind data at Shengshan near the site M1 indicate that the southerly wind prevailed episodically during the ADCP survey (Figure 5c). Vertical spirals of the current profiles are measured above 30 m, which are consistent with the surface Ekman theory [Huang et al., 2016], and the Ekman depth can be calculated by following formula [Pond and Pickard, 1983]:

\[
D = \frac{4.3}{\sqrt{\sin \phi}} W
\]  

where \(D\) is the Ekman depth, \(\phi\) is the latitude, and \(W\) is the wind speed. The mean wind speed is 4.8 m s\(^{-1}\) during the ADCP survey, and the Ekman depth is estimated to be 28.9 m, which is consistent well with the vertical current distribution. The subtidal currents below 30 m flow northward, with a mean speed of 9 cm s\(^{-1}\) and extreme speed of 17.5 cm s\(^{-1}\) at 55 m depth, which are within the range of 9–30 cm s\(^{-1}\) reported by Zhu et al. [2004], Guan and Fang [2006], Wu et al. [2013], and Huang et al. [2016]. Therefore, the TWC end-member is identified by the properties of \(S > 34.0\) PSU and depth > 30 m (Figures 3 and 4, and 5b and supporting information Data set S1).

3.3. Stable Isotopic Data

3.3.1. Stable Isotopic Composition of Water Masses

The coupling of salinity and stable isotopes has been widely used as a powerful tool to discriminate different water masses and their contributions to the formation of mixed water bodies [Craig and Gordon, 1965;
The stable isotope of seawater is relatively conservative, weakly affected by biochemical processes, and provides more information about physical processes of water masses [Craig and Gordon, 1965; Fairbanks, 1982; Hoefs, 1997].

In this study, the correlation between $\delta^{18}O$ and salinity was estimated (Figure 6a) by combining our measured data with the published historical data of the ECS and adjacent sea (supporting information Data set S1). Most of the Changjiang effluent water samples fall on one linear line ($\delta^{18}O = 0.235 - 7.67$, $R^2 = 0.87$, $p < 0.001$), suggesting the mixing between two end-members, i.e., the riverine input contributed by the Changjiang and the saline water derived from the TWC. The obtained slope of $\delta^{18}O$—salinity relationship in this study is similar to those previous results [Zhang et al., 1990; Kim et al., 2005; Ye et al., 2014], but the mixing line has a slightly higher intercept, which is attributed to relatively enriched $\delta^{18}O$ value of the freshwater end-member. In addition, it is interesting to note that some surface seawater samples (at 2 and 5 m depths) from the region (122.5°E, 31.25°N) have the isotopic and salinity values off the mixing line and point to the $\delta^{18}O$ values of precipitation collected in Shanghai (Figure 6a), which falls within the range of $\delta^{18}O$ values previously observed ($-3.78^{\circ/o}$ to $-1.88^{\circ/o}$ [Peng et al., 2010]; $-4.3^{\circ/o}$ to $-1.61^{\circ/o}$ [Uemura et al., 2012]) for wintertime precipitation in western pacific monsoon region. Such trend probably indicates the precipitation influence on the coastal water during the cruise period, consistent with the trend of surface water in eastern equatorial pacific [Benway and Mix, 2004].

Given that the $\delta^{18}O$ values of Kuroshio water are relatively constant on interannual time scale [Lin, 2000], we compare the stable isotopic composition of the TWC off the Changjiang Estuary with those potential
end-members including the TSWW and Kuroshio water. Figure 6b shows that the TWC samples have more enriched $^{18}$O values than the TSWW samples, closer to the Kuroshio intrusion water samples northeast of Taiwan. Note that all samples in the transect B, representing the water through the northern Taiwan Strait, have more depleted $^{18}$O values than the warm and saline TWC samples off the Changjiang Estuary (Figure 6b). In addition, the $^{18}$O values of water samples became more depleted from G2 station to B4 and B3 stations, while the samples at B3 and B4 overlap with the samples at transect B, which suggests that the TSWW cannot flow through the northern Taiwan Strait to supply $^{18}$O-enriched water.

Based on Figure 6c, the estuarine samples are clearly clustered into three groups (dots of i, ii, and iii regions), and display two different mixing patterns, i.e., one mixing between the TWC and YSCC (black line) and another mixing between the TWC and CDW (red line). However, the samples in B3, B4, and G2 stations deviate from the CDW–TWC mixing trend by extending to the Kuroshio surface water end-member (blue dash line), while the YSCC-TWC mixing trend links to the end-member of KSSW. This distinct feature is consistent with previous hydrographic observations [Jan et al., 2006], indicating the wintertime water masses of the Taiwan Strait influenced by the Kuroshio mainly come from the surface layer.

3.3.2. Spatial Distribution of $^{18}$O

The lateral variations of $^{18}$O related to the advection among different water masses at the surface and bottom layers are shown in Figure 4c, f. Similar to the hydrographic observations, the $^{18}$O values gradually decrease from the offshore to coastal area due to the proportionate dilution by fresh Changjiang River water, and increase in the southern region owing to the TWC intrusion. The enriched $^{18}$O regions (>0‰) well match with high-salinity region by the 33.5 PSU isohalines, although the enriched $^{18}$O values are unevenly distributed (Figures 4c and 4f). A slightly isotopic depletion occurs toward the east and forms some $^{18}$O-enriched patches, which may be attributed to the complex hydrological and atmospheric conditions, such as commonly episodic relaxation of the NE monsoon.

3.4. Underway Thermosalinograph Survey

Combined with the simultaneous routine CTD profiles data, the underway thermosalinograph survey was taken to describe the property of water column profile along ~50 m isobath from the Taiwan Strait to the

Figure 7. (a) Schematic diagram of routine CTD and underway sea surface thermosalinograph survey (TSG); (b) potential temperature versus salinity plot with reference historical curve of water masses of the South China Sea (SCS, red line), Kuroshio origin (black line) [Mensah et al., 2014], and historical data (1985–2003) in the northern Taiwan Strait in winter (shaded patches) [Jan et al., 2006]. The red and black squares represent the TWC end-member off the Changjiang Estuary (this study) and the shelf-intruded KSSW end-member northeast of Taiwan [Chen et al., 1995b; Liu et al., 2000], respectively. Gray rectangle denotes the range of historical data of the TSWW from Jan et al. [2006]. Light contours represent the isopycnal. High-resolution hydrographic data enable the delineation of water mass boundaries as well as revealing insights into Kuroshio subsurface water intruding position at 28°N off the Zhe-Min Coast (black arrow).
Changjiang Estuary, considering well vertical mixing in winter. A pronounced trend, which is subparallel to
the isopycnals beginning near the $\sigma = 24$ isopycnal, is confined to south of 25°N in the Taiwan Strait (Figure
7b). Such trend is the character of typical Taiwan Strait water [Liu et al., 2000; Jan et al., 2006]. Figure 7b also
shows that the TSWW originates from the mixing water between the South China warm water and Kuroshio
branch water south of Taiwan, which is consistent with previous hydrographic observations and isotopic
evidences [Chang, 2000; Liu et al., 2000; Jan et al., 2006; Chen, 2009]. It was slightly influenced by the
Zhuoshui River diluted water (ZDW in Figure 7b) at 24°N.

In contrast to the wintertime TSWW (gray rectangle) and northern Taiwan Strait water (color shaded patches
in Figure 7b), the TWC is much denser and could be the source of the warm and saline water north of 29°N.
Note that the salinity at B1 station is higher than B3 and B4 stations, and falls on the mixing curve between
the ZMCC and the TWC, rather than the TSWW, suggesting different water masses merging into the TWC
near 28°N, and linking to the intruding KSSW upwelled northeast of Taiwan (with a properties of $T = 15°C$
and $S = 34.6$ PSU to 34.7 PSU) [Chen et al., 1995b; Liu et al., 2000]. Comparatively, the higher salinity at 28°N
than its southern area off the Zhe-Min Coast has been widely reported in summer [Yang et al., 2012; Zhou
et al., 2015] but is overlooked in winter. Simply put, two water mass boundaries (~25°N: between ZMCC
and TSWW, ~28°N: between ZMCC and KSSW) can be clearly observed during the study period. Besides, as
for water masses off the Changjiang Estuary, Figure 7b shows that temperature sharply reduces from the
south to north area off the Changjiang Estuary (i.e., from dark gray dots to light gray dots in Figure 7b.),
indicating the increasing influence by the YSCC. This pattern indicates the CDW, TWC, and YSCC involve
the water mixing processes off the Changjiang Estuary.

4. Discussions

4.1. The TWC Intrusion Off the Changjiang Estuary

Based on hydrography, the northward intrusion of the TWC, featured by a high-temperature, high-salinity,
and $\delta^{18}$O-enriched water tongue, extends northward to the 30.5°E off the Changjiang Estuary during the
cruise periods (Figure 4). The vertical profile of the subtidal currents also shows that the TWC intrudes
the submerged valley of the Changjiang Estuary via the lower layer (Figures 5a and 5b), where it has been
reported to be the main route of the wintertime TWC intrusion off the Changjiang Estuary [Zhu et al., 2004].
Unfortunately, the situation of the TWC intrusion under the northerly wind is not captured this time, due to
the southerly wind prevails by chance before the ADCP survey. However, the calculated Ekman depth is
shallower than 30 m (actually about 22 m) under southerly wind condition (Figure 5b), implying that the TWC
intrusion below 30 m is rarely affected by the eventful wind conditions. In addition, the current measure-
ments at one anchored site off the Changjiang Estuary by Zhu et al. [2004] showed that the northward intru-
sion of the TWC likewise occurs when NE monsoon prevails, with a velocity of 30 cm s$^{-1}$ at depth of 30 m
below the surface. Long time serial of bottom-mounted ADCP measurement deployed throughout the win-
ter also reports the robust upwind TWC flows northward [Huang et al., 2016], supporting above viewpoint.
Therefore, the TWC intrusion off the Changjiang Estuary keeps northward under different weather condi-
tions, implying an unfailing supply for the TWC.

4.2. Discriminating the Sources of the TWC Intrusion Off the Changjiang Estuary

4.2.1. Residence Time of the TWC Off the Changjiang Estuary

Assuming that the total warm, saline, and $\delta^{18}$O-enriched water (CJESW, $S > 33.5$ PSU) volume off the Chang-
jiang Estuary is renewed by the TWC intrusion water and regardless of the tidal effect, the mean water resi-
dence time ($\tau$) can be computed as follows by one-dimensional, steady state model [Bowden, 1967]:

$$f = S_{CJESW}/S_{TWC}$$  \hspace{1cm} (2)

$$V_{TWC} = \int f dv \approx f_{mean}V_{CJESW}$$  \hspace{1cm} (3)

$$\tau = V_{TWC}/F_{TWC}$$  \hspace{1cm} (4)

where $S_{CJESW}$ is salinity of the CJESW; $S_{TWC}$ is salinity of the TWC; $f$ is the TWC content at observed point;
$V_{TWC}$ is total inventory of the TWC intrusion water accumulated off the Changjiang Estuary and $F_{TWC}$ is the
flux of the TWC through that volume; \( \tau \) is the residence time of the relatively \( \delta{}^{18}O \)-enriched TWC off the Changjiang Estuary.

In the same way as Rabouille et al. [2008], if the geometry of the CJESW is rectangular, then

\[
V_{CJESW} = A_{box} \cdot L
\]

and

\[
F_{TWC} = A_{box} \cdot \omega
\]

where \( A_{box} \) is the lateral surface area of the box considered, \( \omega \) is the TWC speed (cm s\(^{-1}\)), and \( L \) is the extension of the CJESW alongshore (km). The residence time is therefore written as:

\[
\tau = \frac{f_{\text{mean}} \cdot L}{\omega}
\]

Given that the mean \( f \) value is 0.98 \( \pm \) 0.01 calculated from observed CTD data (salinity of the CJESW and the TWC are 33.7 \( \pm \) 0.27 PSU and 34.4 PSU, respectively), the \( L \) is about 250 km and the \( \omega \) is 10–30 cm s\(^{-1}\) throughout the year [Zhu et al., 2004; Guan and Fang, 2006]. The annual mean speed of 14 cm s\(^{-1}\) is referred for calculation. The mean residence time \( \tau \) is estimated to be about 20.2 days, which is somewhat higher than previously reported times of 7.0–11 days [Rabouille et al., 2008; Gu et al., 2012]. In this case, the relatively \( \delta{}^{18}O \)-enriched water off the Changjiang Estuary is the renewed intrusion water from the TWC, rather than the residual TSWW brought in by the TWC in late autumn. On the other hand, the \( \delta{}^{18}O \)-enriched signal observed off the Changjiang Estuary during March comes from the intrusion water on the southern shelf in December, considering the response time of the TWC to Kuroshio intrusion is about two months [Zhou et al., 2015]. Thus, the comparison of the potential source end-members of the TWC is reasonable and valid on intraseasonal time scale. Nevertheless, the estimation still contains some uncertainties, because the exact inventory of the TWC off the Changjiang Estuary is unclear due to complex hydrological dynamics, and inherent uncertainties of the calculation method. More accurate estimation is required in further studies.

### 4.2.2. Source of the TWC Off the Changjiang Estuary

The plot of \( \delta{}^{18}O \) versus salinity (Figure 6b) indicates that the saline and \( \delta{}^{18}O \)-enriched TWC off the Changjiang Estuary predominantly originates from the Kuroshio intrusion northeast of Taiwan. And the plot of \( \delta{}D \) versus temperature (Figure 6c) provides more constraints on the source of the TWC. Note that the samples in B1 and G1 stations fall on the YSCC-TWC-KSSW mixing line, confirming that the saline water in these two stations originates from the KSSW. Therefore, the TWC inherits the physical properties of the KSSW intrusion northeast of Taiwan (Figure 7b), which accounts for the above observations. Our observation again suggests the intrusion of the KSSW into the Changjiang Estuary in winter, which is also supported by the supply of abundant nutrients from the intrusion-induced upwelling off the Changjiang Estuary [Zhao et al., 2001]. In addition, the passive tracer experiments further indicate that the Kuroshio-derived water dominates the bottom layer of the ECS shelf throughout the year [Guo et al., 2006], in favor of our isotopic data.

Even though, the above tracer data cannot thoroughly rule out the possibility that part TSWW were mixed into the TWC water. However, hydrographic data and numerical studies suggest that there is no persistent northward flowing current against the strong NE monsoon in winter [Jan et al., 2002, 2006], which causes that the nutrient-rich and \( \delta{}^{18}O \)-depleted water coming from the Zhe–Min Coastal Current occupies the northern Taiwan Strait in winter [Chen, 2003; Chen and Sheu, 2006]. A zonal oceanic front in the central Taiwan Strait in winter is likely to occupy the whole water column [Jan et al., 2002; Li et al., 2006], rendering stable by salinity and blocking the northward flow of the TSWW [Jan et al., 2002]. This is well consistent with the simulated trajectories of drifters releasing from Luzon Strait that just reach the southern Taiwan Strait in January and February [Jan et al., 2010]. In addition, even when NE monsoon relaxed, the cross-strait flow related to occurrence of the front also favors the blocking effect [Oey et al., 2014]. This circulation pattern basically controls the habitat of Calanus sinicus, a cold-water copepod species abundant in the Yellow Sea and the Zhe–Min Coast but rare in the water with high temperature and salinity. The abundance of Calanus sinicus exhibits seasonal peaks in winter and early spring, from East China Coast to the north Taiwan Coast in winter [Dur et al., 2007].

In summary, various lines of evidences suggest that in most winter time the TSWW only influences the southern Taiwan Strait and cannot flow through the strait into the open ECS shelf. The TWC intrusion off
the Changjiang Estuary predominantly originates from the Kuroshio subsurface water northeast of Taiwan, rather than directly from the Taiwan Strait warm water.

4.3. Boundary of the KSSW Intrusion Onto the Zhe-Min Coast
Although a great amount of routine hydrographic observations on oceanographic cruises were conducted, rare studies show the boundary of Kuroshio water intruding into the Zhe-Min coastal area in winter. Yang et al. [2011] observed a Kuroshio bottom branch current northeast of Taiwan intruding into the Zhe-Min Coast around 28°N in summer, which has been confirmed by numerical model [Yang et al., 2012]. Interestingly, this intruding boundary of the KSSW off the Zhe-Min Coast is in agreement with previous transect hydrographic observation in winter in 1999 [Qiao et al., 2006, Figure 2], which demonstrated that the water mass around 28°N off the Zhe-Min Coast is saltier than in the Taiwan Strait. Nevertheless, no details are given as to the water mass boundary between the cold ZMCC and the warm currents, i.e., the TSWW and/or KSSW in winter. In the present study, the continuous hydrographic data clearly indicates an apparent intruding boundary of the KSSW at 28°N off the Zhe-Min Coast (Figure 7b), confirming by the isotopic imprint (Figure 6c). A direct inference is that the KSSW can intrude into the Zhe-Min Coast at 28°N and thereby feeds the northward flowing TWC elucidated above.

In addition, the obvious KSSW intruding boundary also closely matches the tidal phase-divergent zone where tide-inducing mixing is weaker and vertical viscosity is much smaller as reported by Wu [2015, Figures 10]. Meanwhile, the intrusion area corresponds well with the observed KSSW intrusion pathway in summer [Yang et al., 2011], indicating there exist some intrinsic oceanic dynamics that drive the KSSW intrusion.

4.4. Intrusion Pathway of the KSSW
So far, both models and observations have revealed that the KSSW intrudes onto the ECS shelf via upwelling northeast of Taiwan [Su and Pan, 1987; Hsueh et al., 1992; Liang and Su, 1994; Tang et al., 1999]. The puzzle is the KSSW may not intrude into the inner ECS shelf considering the NE monsoon is downwelling favorable. However, the isotopic signal of the KSSW captured off the Changjiang Estuary (Figures 6b and 6c) implies a close linkage between the Changjiang Estuary and the KSSW upwelling from the depth of 200–300 m at northeast of Taiwan in winter (Figure 7b). Similarly, the particle tracking experiment also suggests that the one of main sources of Kuroshio on-shelf intrusion northeast of Taiwan is from the same depths of 200–300 m [X. Liu et al., 2015], where the cyclonic eddy and resulting upwelling exist year round [Liu et al., 1992; Wu et al., 2008]. In addition, both models of Yang et al. [2012] and X. Liu et al. [2015] show that the relative strong upwelling at depth between 200 and 300 m coincides with positive vorticity, suggesting that the topography effect dominates the upwelling. Hence, when the KSSW passes the sharp steep slope northeast of Taiwan, it upwells and intrudes on-shelf by the cyclonic vortex-tube stretching [Pedlosky, 1979]. It also benefits from an intense anticyclonic loop separating from the Kuroshio due to decreasing upstream volume transport [C. Liu et al., 2014, X. Liu et al., 2014] and the combined effect of baroclinicity and relief (JEBAR) associated with cooling [Oey et al., 2010].

Subsequently, weak tide mixing in the southern ECS [Wu, 2015, Figure 10] may sustain the KSSW intruding into the 80 m isobath via the bottom layer as its relative higher density [Guo et al., 2006; Lee and Matsuno, 2007]. The KSSW penetrates into the shelf off the Zhe-Min coast as far as the 50 m isobaths (Figure 7b), as also proven by the enriched δ18O signal (Figures 6b and 6c). In fact, the high-salinity (S = 34.4 PSU) water observed off the Zhe-Min Coast (Figure 7b, gray dots) directly indicates the KSSW intrusion pathway similar to that situation in summer [Yang et al., 2012]. Interestingly, Wu [2015] speculated that the along-isobath thermocline variation induced by the nonuniform tidal mixing could intensify the KSSW onshore intrusion at 28°N off Zhe-Min Coast by the JEBAR analogous to mechanism proposed by Oey et al. [2010], though no details were given. However, the recent hydrographic observations suggest that in winter the thermocline exists around 28°N off the Zhe-Min Coast [S. Liu et al., 2015, Figures 5 and 8], unlike ambient intense vertical mixing area, indicating the nonuniform thermocline likely exists along the Zhe-Min Coast. These assertions agree well with our statements above. In brief, we propose an intrusion pathway that the KSSW can intrude onto the Zhe-Min Coast at 28°N via the bottom layer as far as 50 m isobath, thereby feeds the TWC and finally extends as far north as 30.5°N off the Changjiang Estuary in winter.
Recently, based on the 25 years of drifter data and modeling, Wang and Oey (2016) demonstrated that the Kuroshio water intrudes into the inner ECS shelf as far north as ~30°N. The mechanism they proposed is the geostrophic current owing to northward downsloping of sea level that is steepest for 25°N–28°N. Such a barotropic process should work as well for the bottom water, although was not discussed in Wang and Oey (2016), due to the lack of data. Our observation, however, provides clear evidences of the subsurface Kuroshio water intrusion near the bottom, with the enriched $\delta^{18}O$ signal can be found on the inner ECS shelf and Changjiang Estuary (Figures 4 and 6b, 6c, and 7b). However, observations in present work were limited in both temporal and spatial coverage, more investigations are necessary to address the relevant dynamics of the bottom intrusion of Kuroshio northeast of Taiwan and upwind nature of the TWC in winter, and further study its significant effect on the ecosystem of the shelf area.

5. Conclusions

The field hydrographic observations and current measurements all clearly suggest that the TWC intrudes the Changjiang Estuary along the submerged valley in winter. The stable isotopic data together with under-way hydrographic observation reveal the wintertime TWC is primarily sourced from the Kuroshio subsurface water rather than from the Taiwan Strait warm water. Our study sheds new light on the linkage that the Kuroshio subsurface water can intrude into the Zhe-Min Coast at 28°N via bottom layer, as far as 50 m isobath, feeding the TWC which spreads as far north as 30.5°N off the Changjiang Estuary in winter. Nevertheless, the actual processes involved were elusive beyond the scope of this study, and the long-term continuous physioceanographic observations as well as isotopic data and numerical model are therefore strongly recommended. In particular, the KSSW has to be paid intensive research attention because it not only directly affects heat and salt balances of the Chinese marginal seas [Oey et al., 2013], but also carries nutrient-rich and warm water to the shelf and the Changjiang Estuary to support the fishing grounds [Zhao et al., 2001; Chen, 2009].

Appendix A

The acronyms and full name of seas and water masses are listed in Table A1 below.

### Table A1. List of Acronyms

<table>
<thead>
<tr>
<th>Acronyms</th>
<th>Full Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDW</td>
<td>Changjiang Diluted Water</td>
</tr>
<tr>
<td>CIESW</td>
<td>Changjiang Estuary Saline Water</td>
</tr>
<tr>
<td>ECS</td>
<td>East China Sea</td>
</tr>
<tr>
<td>KSW</td>
<td>Kuroshio surface water</td>
</tr>
<tr>
<td>KSSW</td>
<td>Kuroshio subsurface water</td>
</tr>
<tr>
<td>SCS</td>
<td>South China Sea</td>
</tr>
<tr>
<td>SMW</td>
<td>Shelf Mixing Water</td>
</tr>
<tr>
<td>TS</td>
<td>Taiwan Strait</td>
</tr>
<tr>
<td>TSWW</td>
<td>Taiwan Strait warm water</td>
</tr>
<tr>
<td>TWC</td>
<td>Taiwan Warm Current</td>
</tr>
<tr>
<td>YS</td>
<td>Yellow Sea</td>
</tr>
<tr>
<td>YSCC</td>
<td>Yellow Sea Coastal Current</td>
</tr>
<tr>
<td>ZMCC</td>
<td>Zhe-Min Coastal Current</td>
</tr>
</tbody>
</table>

References


Berman, E. S., N. E. Levin, A. Landais, S. Li, and T. Owano (2013), Measurement of $\delta^{15}N$, $\delta^{17}O$, and $\delta^{18}O$-excess in water by off-axis integrated cavity output spectroscopy and stable isotope ratio mass spectrometry, Anal. Chem., 85(21), 10,392–10,398.


Chang, C.-C. (2000), Spatial and temporal variation of $\delta^{18}O$ in the sea water from the Taiwan Strait, MS thesis, Dep. of Oceanogr., Natl. Sun Yat-sen Univ., Kaohsiung, Taiwan.


Hseuh, T.-J., J. Wang, and C. S. Chen (1992), The intrusion of the Kuroshio across the continental shelf northeast of Taiwan, J. Geophys. Res., 97(C9), 14,323-14,330.


Li, C., Y. Yang, C. Tang, and Z. Liu (2016), Damping effect on the Changjiang (Yangtze River) river water cycle based on stable hydrogen and oxygen isotopic records, J. Geochim. Explor., 165, 125–133.


