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Vertical Migration of the Along-Slope Counter-Flow and Its Relation with the Kuroshio Intrusion off Northeastern Taiwan

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Abstract: Based on satellite and analysis data and in situ observations acquired during May 23, 2017 to May 19, 2018, the spatiotemporal variations of the along-slope counter-flow off northeastern Taiwan were investigated. It was observed that the along-slope counter-flow in the subsurface layer was uplifted and lowered significantly during the study period. The counter-flow was significantly uplifted (lowered) while the sea surface was during an interval of positive (negative) geostrophic velocity anomaly (GVA) curl. The vertical migration of the counter-flow was also found closely linked with the Kuroshio intrusion (KI) to the northeast of Taiwan. The depths of both the upper boundary and the axis of the counter-flow were found proportional to the KI variance along the western continental slope off northeastern Taiwan. More importantly, it was established that the variation of the KI to the northeast of Taiwan had better correlation with the counter-flow than the Kuroshio derived from altimetry data. Thus, further study of the variation and mechanism of the along-slope counter-flow is needed to improve the understanding and prediction of the KI in the area of northeastern Taiwan, as well as the biochemical systems and marine economy in the East China Sea in the future.

Keywords: ocean modeling; counter-flow; vertical migration; Kuroshio intrusion; marine economy

1. Introduction

The Kuroshio is the strongest western boundary current in the Pacific Ocean, transporting warm, salty and nutrient-rich water from the seas off eastern Philippines northward to the seas off eastern Japan [1,2]. The Kuroshio has significant influence on the marginal seas, atmosphere and climate while traveling northward along the continental shelf west of the Pacific Ocean [3–7]. It is a unique and significant phenomenon that the Kuroshio current intrudes onto the East China Sea shelf off northeastern Taiwan [5,8–10]. Recent studies indicate that the seas to the northeast of Taiwan are the source regions of the Kuroshio branch currents on the East China Sea shelf [11,12], which have considerable influence on the regional circulation [13–15], chemical hydrography [16,17], and biological systems [18–20]. Therefore, it is essential to investigate the detailed flow structures and their variations



in the region off northeastern Taiwan. Despite the northward-flowing Kuroshio water, a unique along-slope counter-flow exists in the subsurface layer below the depth of 150 m [21,22]. As illustrated in Figure 1, this counter-flow is directed towards the southwest along the steep continental slope from the North Mien-Hwa Canyon (NMHC) to the Mien-Hwa Canyon (MHC) [22–24] before flowing southward into the I-Lan Bay [25].

The southwestward flow was first observed during a hydrographic survey [26] and the existence of a counter-flow in the subsurface layer was first proposed by Chuang and Wu [27]. The year-round existence of the counter-flow was later confirmed by further observations [22,23] and numerical simulations [21,28,29]. Based on multiple historical observations, the counter-flow was initially considered part of a cyclonic eddy in the subsurface layer off northeastern Taiwan [23,24,30,31], and the cyclonic eddy was found to be closely related with the upwelling systems off northeastern Taiwan [25,29–31]. Observational studies have indicated that this counter-flow is a quasi-steady phenomenon that exhibits considerable seasonal and intraseasonal variations [22–24]. Earlier cruise observations revealed that the along-slope counter-flow extends to the surface layer above the depth of 50 m during summer months and descends to depths below 150 m during winter months [23]. In addition, substantial intraseasonal variability has also been reported based on previous in situ observations [22,23,32,33] and numerical simulations [21].

However, the uplift and lowering of the counter-flow in the subsurface layer remain confusing and unresolved. Furthermore, flowing along the western continental slope (D1-D2, Figure 1), where the Kuroshio branches intrude onto the East China Sea shelf [12,34], to the northeast of Taiwan and showing considerable variation in the extent of its vertical migration, the southwestward counter-flow should be linked closely with the variation of the Kuroshio intrusion (KI); however, the relationship between the along-slope counter-flow and the KI off northeastern Taiwan remains unclear. Above all, it is important that the specifics of the variations of the counter-flow be revealed because this could help improve the understanding of the local flow structure and KI variances off northeastern Taiwan.



Figure 1. Location of the study area, the bathymetry off northeastern Taiwan, location of the mooring (25.51°N, 122.59°E; acoustic Doppler current profiler (ADCP) marked by yellow star), sections used in data analysis and a sketch of the horizontal flow pattern below the water depth of 200 m. The gray solid lines are isobaths of ETOPO1 [35], the blue solid line denotes the 200-m isobath and the red dots (D1 (25.03°N, 122.03°E), D2 (25.75°N, 122.72°E) and D3 (25.83°N, 124.10°E)) indicate segment points along the 200-m isobath. The red dashed line (NL) and the black dashed line (K) denote sections used in the data analysis. The panel in the lower-left corner shows the horizontal flow patterns off northeastern Taiwan in the subsurface layer below the water depth of 200 m. The deep red arrow denotes the main Kuroshio Current and the magenta arrows denote the counter-flow and the cyclonic eddy in the subsurface layer. The panel in the upper-left corner shows the location of the study area (red box).

2. Materials and Methods

2.1. Materials

2.1.1. Study Area

The East China Sea is one of the marginal seas west of the North Pacific Ocean, and seas off northeast Taiwan located at the southern East China Sea (Figure 1). The bathymetry as well as the flow structure in this area is complex. The sea water depth in the Okinawa Trough is deeper than 1000 m, while the sea water depth of the continental shelf is shallower than 200 m. Sea valleys (NMHC and MHC) are found on the steep continental slope off northeastern Taiwan. The Kuroshio current flows northward into the study area through the I-Lan ridge, and then collides with the continental slope off northeastern Taiwan, resulting in the significant Kuroshio water intrusion onto the East China Sea shelf. Although the Kuroshio waters intrude onto the shelf across the entire slope off northeastern Taiwan, the Kuroshio branches on the East China sea shelf were usually considered to intrude westward or northwestward onto the continental shelf mainly through the western continental slope (D1–D2) both during the summer months [9,12] and during the winter months [9,34].

2.1.2. In Situ Observations

In situ observations were carried out on the continental slope between the MHC and NMHC (Figure 1), where the angle of the local isobaths is approximately 30° from north. An acoustic Doppler current profiler (ADCP) mooring was deployed at a water depth of about 500.2 m with a standard deviation of 0.7 m, and first bin depth of 483.5 m from 23 May, 2017 to 19 September, 2017. The ADCP was again deployed at a water depth of 495.4 m with a standard deviation of 0.6 m and first bin depth of 478.6 m from 19 September, 2017 to 19 May, 2018; the bathymetry measured by ship at the in situ measurement sites was 621.0 m. The ADCP provided horizontal velocity records for 62 layers of the water column in 8 m vertical bins with a 1 h sampling interval. The uppermost six bins were excluded from the analysis because the data were contaminated by sidelobe reflection. Focusing on the circulation off northeastern Taiwan, a 36 h low-pass filter was applied to the remaining 56 vertical bins to remove tidal signals and other high-frequency fluctuations.

2.1.3. Satellite Altimeter Data

The all-satellite merged absolute dynamic topography (ADT), geostrophic velocity (GV), sea level anomaly (SLA) and geostrophic velocity anomaly (GVA) data from the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) dataset were used to provide geostrophic velocities off northeastern Taiwan. The AVISO dataset were derived from 15 altimeter missions: the TOPEX/Poseidon and Jason series; ERS-1, ERS-2, and ENVISAT; and Geosat Follow-On, Cryosat-2, Saral/AltiKa, Sentinel-3A, Sentinel-3B, and Haiyang-2A, CFOSAT. The resolution of the AVISO dataset is sufficient to resolve mesoscale eddy activity and mesoscale patterns off northeastern Taiwan [36] with 1-d temporal resolution and 0.25° spatial resolution. The daily satellite altimeter data are available from the Copernicus Marine Environment Monitoring Service (CMEMS) [37], the version of the datasets used in this study is "Global Ocean Gridded L4 Sea Surface Heights and Derived Variables Reprocessed (1993-ongoing)".

2.1.4. MODIS SST Data

The sea surface temperature (SST) level 3 datasets derived from the Moderate-resolution Imaging Spectroradiometer (MODIS) [38] observations were used to compare the surface temperature distribution patterns with the satellite altimeter data in the study. The first MODIS Flight Instrument, ProtoFlight Model or PFM, is integrated on the Terra (EOS AM-1) spacecraft. Terra successfully launched on 18 December, 1999. The second MODIS flight instrument, Flight Model 1 or FM1, is integrated on the Aqua (EOS PM-1) spacecraft; it was successfully launched on 4 May, 2002. These

MODIS instruments offer an unprecedented look at terrestrial, atmospheric, and ocean phenomenology for a wide and diverse community of users throughout the world. The weekly (8-d) daytime SST data with 4 km spatial resolution were used in this study.

2.1.5. The Analysis Data

The realistic ocean analysis datasets generated by the data assimilative global Hybrid Coordinate Ocean Model (HYCOM) [39] were also used to reveal the spatiotemporal patterns of the counter-flow in the region to the northeast of Taiwan, the version of the datasets used in this study is "GOFS 3.1 Global Analysis". The HYCOM data applies the Navy Coupled Ocean Data Assimilation (NCODA) system, which assimilates available satellite altimeter, sea surface wind stress, sea surface temperature observations, in situ sea surface temperatures, vertical temperature and salinity profiles from expendable bathythermographs (XBTs), Argo floats, and moored buoys. The three vertical diffusion mixing sub-models of the HYCOM are capable of resolving both geostrophic shear and ageostrophic wind-driven shear in the upper ocean [40]. The daily data are available with 0.08° horizontal resolution and 40 vertical z-levels, which are considered suitable for revealing accurate variation of the counter-flow and providing reliable detailed flow fields. The analysis data were validated, as shown in Figures 2 and 3.

2.2. Methods

The counter-flow is an along-slope current in the subsurface layer [21,23], and the direction of the local isobaths is about 30° from north (Figure 1). The cross-shelf shoreward direction is 150° (0° towards east, and 90° towards north), and the southwestward direction in Figure 2b,d are 240°. The along-isobath southwestward velocities reveals the along-slope counter-flow, and distinguish it from the surface velocities. To reveal and make quantitative estimation of the vertical migration of the observed along-slope counter-flow, we applied a formula to calculate the axis depth (D_a) of the counter-flow at the in situ site. The method was also used in the calculation of Kuroshio axis position [41]. The analysis velocities shallower than the sixth uppermost bin depth of the observation velocities were also excluded in the calculation.

$$D_a = \frac{\int_{z_{\rm B}}^{z_{\rm U}} v_{sw}(z) \cdot z dz}{\int_{z_{\rm R}}^{z_{\rm U}} v_{sw}(z) dz},\tag{1}$$

where v_{sw} denotes the observed southwestward counter-flow velocity, z denotes water depth, and z_U and z_B denote the upper boundary and bottom depth of v_{sw} , respectively.

To make quantitative estimation of the Kuroshio mainstream, the Kuroshio intensity (INT) [41] derived from the altimeter data along the section K (Figure 1) during the observation period were calculated as follows.

$$INT = \int_{x_{w}}^{x_{E}} v_{g}(x) dx,$$
(2)

where v_g denotes the normal geostrophic velocity of section K derived from the satellite altimeter data; *x* denotes distance from the western integral limits of section K, the x_w and x_E . are the western and eastern integral limits, respectively.

To make quantitative estimation the Kuroshio cross-shelf intrusion off northeastern Taiwan, the integral KI off northeastern Taiwan derived from the analysis data and integral surface Kuroshio intrusion (SKI) off northeastern Taiwan derived from the satellite altimeter data were given below.

$$KI = \int_{S_1}^{S_n} v(s) ds, \tag{3}$$

$$SKI = \int_{x_w}^{x_E} v_g(x) dx,$$
(4)

where v(s) denotes cross-isobath (200-m isobath) component of horizontal velocity, *s* denote area of vertical grid cell from bottom to the surface along the 200-m isobath section; v_g indicates the normal geostrophic velocity of section D1–D2 and section D2–D3 derived from the satellite altimeter data; *x* denotes distance from the western integral limits of section D1–D2 and section D2–D3, the x_w and x_E are the western and eastern integral limits, respectively.

The least square regression method [42] was applied to review the linear trend of the Kuroshio Current, the along-slope counter-flow with the Kuroshio intrusion intensity off northeastern Taiwan.

$$\hat{y}_i = a + bx_i,\tag{5}$$

$$\min \sum_{i=1}^{n} \delta_i^2 = \min \sum (y_i - \hat{y}_i)^2,$$
(6)

$$R = \frac{Cov(x, y)}{\sqrt{var(x)var(y)}},\tag{7}$$

where the x_i is the independent variable and y_i is the dependent variable, \hat{y}_i is the fitting dependent variable, and δ_i is the error or residual. a and b are the linear regression coefficient satisfied the minimum δ_i^2 . *R* is the related coefficient. Cov(x, y) is the covariance of variable x and y, and var(x), var(y) are variance of variable x and y, respectively.

In addition, to reveal the surface cyclonic or anti-cyclonic GVA field variations, the GVA curl at the in situ site were calculated as follow.

$$V_{\rm ga} curl = \frac{\partial v_{\rm ga_y}}{\partial x} - \frac{\partial v_{\rm ga_x}}{\partial y}, \tag{8}$$

where v_{ga} indicates the geostrophic velocity anomaly; x and y are the zonal and meridional direction.

3. Results

3.1. Vertical Migration of the Counter-Flow

The one year's in situ observations confirmed that the depths of the upper boundary and axis of the counter-flow experienced substantial fluctuations (Figures 2 and 3). The depth of the bottom of the counter-flow at the in situ observation sites was deeper than the depth of the deployed ADCP and therefore it could not be determined in this study. The depths of the upper boundary and axis of the counter-flow rose during the summer months (May–October) and fell during the winter months (November–April); the transition times were at the end of April and at the end of October (Figure 3). During the observation period, the mean depth of the upper boundary of the counter-flow was 141.9 (\pm 84.4) m and the mean depth of the axis was 307.4 (\pm 51.8) m. Specifically, during May–October 2017, the mean depths of the upper boundary and axis of the counter-flow were 102.0 (\pm 70.5) m and 269.6 (\pm 41.3) m, respectively. During November 2017 to April 2018, the mean depths of the upper boundary and axis of the counter-flow were 182.3 (\pm 77.9) m and 339.6 (\pm 37.4) m, respectively.



Figure 2. Current velocity distribution as a function of depth and time derived from (**a**,**b**) in situ observations and (**c**,**d**) analysis data. Panels a and c represent cross-shelf velocities, where red (blue) color indicates shoreward (seaward) velocity; panels b and d represent along-shelf velocities, where red (blue) color indicates northeastward (southwestward) velocity. Black contour denotes 0 m/s.



Figure 3. The power spectrum of the observed (**a**) counter-flow upper boundary depth, (**b**) counter-flow axis depth and (**c**) geostrophic velocity anomaly (GVA) curl at the in situ site, and time series of the observed (**d**) counter-flow upper boundary depth and (**e**) counter-flow axis depth. A 5-d filter was applied to the primary data. The red (blue) solid line was derived from in situ observations (analysis data).

In addition to the seasonal pattern, the depths of the counter-flow upper boundary and axis also rose and fell frequently within periods of tens of days (Figure 3); the 5-d smoothed daily time series showed near periodicity of 10, 15 and 20 d (Figure 3a,b). The near 10-d periodicity could be attributed to Kuroshio baroclinic instability waves, which are a characteristic of the Kuroshio current in the East China Sea [43,44]. The signal observed by James [43] in the East China Sea was 11-day, and they also pointed out that the continental shelf depth and core location attributed as well to their effects on the "stiffness" of the systems, and the model result reproduced was near 12-d. The near 15-d periodicity could be attributed to the lunisolar synodic fortnightly component of the tidal signal, which was not excluded in the 5-d low-pass filtering process. As for the near 20-d periodicity, the same signals were revealed in the daily GVA curl time series at the in situ site (Figure 3c). Furthermore, intraseasonal variations of the vertical migration of the counter-flow were also revealed in the GVA curl time series. The sea surface was during an interval of positive (negative) GVA curl while the counter-flow was significant uplifted (lowered). For instance, the counter-flow was uplifted significantly during June 2017 during an interval of positive GVA curl (Figures 2 and 4), while the counter-flow was lowered significantly during July 2017 during an interval of negative GVA curl. There are a total of five intervals of positive GVA curl and four intervals of negative GVA during the analysis period. Additionally, as revealed in Figure 4, the counter-flow could also be uplifted during winter months with significant positive GVA curl in the sea surface. A previous study [21] indicated that the flow field in the seas northeast of Taiwan fluctuates in a wide range of timescales, for the intraseasonal scale, the local structure was strongly influenced by the intraseasonal forces, such as westward-propagating mesoscale eddies east of Taiwan [36,45]. The significant counter-flow uplifted case during the winter months indicates that the intraseasonal forces imposed on the counter-flow off northeastern Taiwan is also significant during winter months.



Figure 4. The daily sea level anomaly (SLA) (black lines), GVA curl (blue lines), and depths of the upper boundary and axis of the counter-flow (red lines). A 9-d low-pass filter was applied to the primary data. The SLA and GVA curl at the in situ site were derived from satellite altimeter data, and the depths of the upper boundary and axis of the counter-flow were derived from in situ observations. The SLA was defined as a deviation from mean sea level for the analysis period, and the seasonal variation was removed.

3.2. Horizontal and Vertical Patterns

The horizontal GV field, SST field, GVA field and the vertical velocity field during an uplifted case and a lowered case are presented in Figures 5 and 6, respectively. During June (July) 2017, a significant cyclonic (anti-cyclonic) GVA field covered the western continental slope off northeastern Taiwan, and the SST distribution variations (Figures 5b and 6b) fit with the surface GVA field variations. The vertical distribution of normal horizontal velocity along section NL (Figures 5d and 6d) indicates that the surface cyclonic or anti-cyclonic GVA fields near the western slope were dominant in the surface layer above the thermocline, while the along-slope counter-flow was dominant in the subsurface layer below the thermocline. Previous studies [46–48] have also highlighted that the positions of cyclonic and anticyclonic eddies in the surface layer off northeastern Taiwan can shift substantially. The horizontal distribution of the surface GVA field (Figures 5c and 6c) also helps us to distinguish the surface flow structures from the along-slope counter-flow in the subsurface layer. The variation and duration of each of the surface processes over the western continental slope to the northeast of Taiwan were revealed by the GVA curl, and it was found that the vertical migration of the counter-flow varies with the surface GVA curl (Figure 4).



Figure 5. The horizontal absolute dynamic topography (ADT), geostrophic velocity (GV), sea level anomaly (SLA), geostrophic velocity anomaly (GVA) and sea surface Temperature (SST) distribution off northeastern Taiwan and the normal velocity distribution along section NL during an uplift case. (a) The horizontal ADT (colors) and GV (black arrows) distributions derived from satellite altimeter data. (b) The horizontal SST (colors) distributions derived from MODIS data, the white contours denote the 26.5 °C isotherm, and the black contours denote the 28 °C isotherm. (c) The horizontal SLA (colors) and GVA (black arrows) distributions derived from satellite altimeter data; the black line denotes the 200-m isobath, the in situ site is marked by a yellow star and the cyclonic GVA field center to the northeast of Taiwan is marked by a white '+' symbol. (d) Vertical distribution of normal velocity (colors) along section NL (Figure 1) derived from the analysis data; the black solid lines denote isotherms, the black bold solid line denotes the 18 °C isotherm, and the purple dashed line denotes the ADCP mooring site.



Figure 6. The horizontal absolute dynamic topography (ADT), geostrophic velocity (GV), sea level anomaly (SLA), geostrophic velocity anomaly (GVA) and sea surface temperature (SST) distribution off northeastern Taiwan and the normal velocity distribution along section NL during a lowered case. (a) The horizontal ADT (colors) and GV (black arrows) distributions derived from satellite altimeter data. (b) The horizontal SST (colors) distributions derived from MODIS data, the white contours denote the 27.5 °C isotherm, and the black contours denote the 29 °C isotherm. (c) The horizontal SLA (colors) and GVA (black arrows) distributions derived from satellite altimeter data; the black line denotes the 200-m isobath, the in situ site is marked by a yellow star and the anti-cyclonic GVA field center to the northeast of Taiwan is marked by a white '+' symbol. (d) Vertical distribution of normal velocity (colors) along section NL (Figure 1) derived from the analysis data; the black solid lines denote sthe ADCP mooring site.

4. Discussion

The Kuroshio Current transports warm, salty and nutrient-rich waters to the marginal seas west of the Pacific Ocean [3,16,17,49,50], and marine organisms and species in the seas are substantially sensitive to temperature, salinity, nitrate and phosphate [18–20,51,52]. Thus, the Kuroshio intrusion water onto the shelf is important for the biochemical systems and ecological environment in the East China Sea [50–53]. Previous studies indicate that the Kuroshio intrusion across the continental slope off northeastern Taiwan is closely related with the upwelling systems and the marine fishery off northeastern Taiwan [12,30,31,54]. Specifically, the nutrient-rich surface upwelling waters northeast Taiwan was supplied by the subsurface Kuroshio intrusion waters [55,56]. What is more, the near-shore Kuroshio branch current (NKBC) intrudes to the inner side of the East China Sea shelf and reaches

the seas off eastern Zhejiang and Changjiang River estuary [54,57]. The Kuroshio subsurface water was observed in the upwelling systems off the Changjiang river estuary [54,58]. The off-shore branch current also transports nutrient-rich waters to the offshore regions in the East China Sea [49]. Both the phytoplankton, zooplankton and fish diversity in the East China Sea were significantly influenced by the Kuroshio bottom branches [19,58,59]. In addition, the nutrient supplement of Kuroshio intrusion waters is not only important for the prediction of the fisheries, but also important for the harmful algal blooms and red tides in the coastal area of the East China Sea [59,60].

The continental slope to the northeast of Taiwan is the source region of the Kuroshio branch currents on the continental shelf. Although the Kuroshio water intrude onto the shelf across the entire slope off northeastern Taiwan, and the cross-shelf intrusion across the eastern slope is also strong (Figure 7), previous studies indicate that the waters of the Kuroshio branch currents mainly intrude onto the East China Sea shelf through the western slope (D1-D2, Figure 1) of northeastern Taiwan [9,13,34,61]. Strong westward intrusion velocities were observed all year round in the subsurface layer of the MHC Chanel (Figure 1) [62,63]. During the winter months, the strong anticyclonic Kuroshio branch current intrude onto the East China Sea shelf close to the coast of northeastern Taiwan [9,34]. During the summer months, the surface velocity across the western slope is weak, while, the Kuroshio intrusion in the subsurface layer is strong [9]. The Kuroshio horizontal velocities in the subsurface layer were considered to be colliding with the western continental shelf in westward or northwestward direction, and the interior horizontal velocities \vec{u}_k rotates clockwise with depth following the topography beta spiral [12,47].

Generally, The KI across the continental slope to the northeast of Taiwan shows significant seasonal variation [9,64]. The KI volume transport across the western continental slope becomes weak (strong) during summer (winter) months, although the subsurface Kuroshio intrusion is relatively strong, whereas the KI across the eastern continental slope becomes strong (weak) during summer (winter) months (Figure 7). The intraseasonal variation of the KI across the western and eastern continental slope is also in negative phase (Figure 7). Previous studies [36,65] have indicated that intraseasonal variation of the KI can be attributed to mesoscale eddies off eastern Taiwan, cyclonic (anticyclonic) mesoscale eddies off eastern Taiwan induce a strong (weak) KI across the western continental slope to the northeast of Taiwan, while the Kuroshio Current volume transport east of Taiwan is weakened (enhanced) [45,66]. Therefore, the KI to the northeast of Taiwan is strongly modulated by the Kuroshio Current off northeastern Taiwan. The INT time series and the SLA variations east of Taiwan during the analysis period was shown in Figure 8. The cyclonic mesoscale eddies were found east of Taiwan during July 2017, last third (LT) of October to LT of November 2017, LT of December 2017 to LT of February 2018, and LT of April to May 2018, whereas, anti-cyclonic mesoscale eddies east of Taiwan were found during Juny 2017, August to LT of September 2017, LT of November to LT of December 2017 and LT of February to middle third (MT) of March 2018. The INT time series was in response to the SLA east of Taiwan during the analysis period, namely, an anti-cyclonic (cyclonic) mesoscale eddy east of Taiwan induce a PE (NE) of the Kuroshio intensity. However, it worth noting that during LT of December 2017 to LT of February 2018, the INT revealed a slight increase while a significant cyclonic mesoscale eddy propagating westward east of Taiwan (Table 1), this is different from the rules above. Generally, the KI and surface GVA field northeast of Taiwan was in response to the Kuroshio and mesoscale eddies east of Taiwan, namely, an anti-cyclonic (cyclonic) mesoscale eddy east of Taiwan induce NE (PE) of KI through the western slope and cyclonic (anti-cyclonic) GVA field over the western slope northeast of Taiwan. However, it worth noting that there are significant cases different from this rules. The GVA field variation northeast of Taiwan is more complex, for instance, during case L2 (U4). The GVA field over the western slope were anti-cyclonic (cyclonic) while an anti-cyclonic (cyclonic) mesoscale eddy was found east of Taiwan (Table 1). These abnormal cases indicate that other undetermined seasonal and intraseasonal factors strongly influence the flow field off northeastern Taiwan.



Figure 7. The KI across the western continental slope (D1–D2 in Figure 1) and across the eastern continental slope (D2–D3 in Figure 1). (a) The magnitude of the KI was derived from analysis data and calculated based on the vertical integral of the volume transport; (b) the magnitude of the SKI was derived from altimeter data and calculated based on the horizontal integral of the geostrophic velocity. A 15-d low-pass filter was applied to the primary data.



Figure 8. (a) The Kuroshio intensity (INT) and Kuroshio intensity anomaly through the K section derived from the altimeter data. The Kuroshio intensity anomaly was defined as a deviation from mean INT for the analysis period, and the seasonal variation was removed. (b) The ADT was the mean ADT derived from sea area of 22°N–24°N and 122°E–124°E east of Taiwan during the analysis period; the SLA was defined as a deviation from mean ADT for the analysis period, and the seasonal variation was removed. A 15-d low-pass filter was applied to the primary data.

Case	Period	GVA Curl	Counter Flow Occurred (Yes, no)		Integral Kuroshio Intrusion (KI) (Sv)		Integral Surface Kuroshio Intrusion (SKI) (10 ⁴ m ² /s)		INT (10 ⁴ m ² /s)	Mesoscale Eddy East of Taiwan	
			<100 m	subsurface	West (D1–D2)	East (D2–D3)	West (D1–D2)	East (D2–D3)	(/-/		
U1	1 June–12 July, 2017	+	Yes	Uplifted	NE	PE	NE	PE	PE	Anti-cyclonic (June)	
U2	29 July–16 September, 2017	+	Yes	Uplifted	NE	PE	NE	PE	PE	Anti-cyclonic (August-LT of Oct)	
U3	3-26 October, 2017	+	Yes	Uplifted	NE	PE	NE	PE	PE	Anti-cyclonic (August-LT of October)	
U4	3–11 January, 2018	+	Yes	Uplifted	NE	PE	NE	PE	PE	Cyclonic (LT of December–LT of February)	
U5	24 March–7 April, 2018	+	Yes	Uplifted	NE	PE	NE	PE	PE	Anti-cyclonic (LT of February-MT of April)	
L1	13–28 July, 2017	-	No	Lowered	PE	NE	PE	NE	NE	Cyclonic (July)	
L2	17 September–2 October, 2017	-	No	Lowered	PE	NE	PE	NE	PE (slight decrease)	Anti-cyclonic (August-LT of October)	
L3	27 October–2 January, 2017	-	No	Lowered	PE	NE	PE	NE	NE PE	Cyclonic (LT of October–LT of November) Anti-cyclonic (LT of November–LT of December)	
L4	12 January–23 March, 2018	-	No	Lowered	PE	NE	PE	NE	PE PE	Cyclonic (LT of December–LT of February) Anti-cyclonic (LT of February–MT of April)	

Table 1.	The inf	formation (on different	cases of th	e counter-fl	low and H	Kuroshio in	trusion.
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The PE (NE) denotes Positive (Negative) Extremums, symbol "-" and "+" indicates "Negative values" and "Positive values LT denotes "The Last Third", MT denotes "The Middle Third".

It is worth noting that previous observations [22–25], and observations in this study, as well as the simulations [21] supported the year-round existence of the strong along-slope counter-flow off northeastern Taiwan below the water depth of 150 m. The counter-flow flows southwestward along the western continental slope (D1–D2, Figure 1) in the subsurface layer, and more importantly, the counter-flow is a quasi-steady phenomenon in the subsurface layer that shows significant variation in its vertical scope. Therefore, it is essential to reveal the relationship between the along-slope counter-flow and the KI off northeastern Taiwan.

The least square regression method was applied to show the linear regression of the counterflow depths with the Kuroshio intrusion intensity off northeastern Taiwan (Figures 9 and 10). The related coefficient R of the standardized INT across section K (Figure 1) with the Western KI (D1–D2) was –0.643, while the R of the standardized depths of the upper boundary and axis of the counter-flow at the in situ site with the western KI were –0.750 and –0.791, respectively (Figure 9a). The West SKI between D1 and D2 derived from altimetry data was also used as validation in Figure 9b. The related coefficient R of the standardized INT across section K with the SKI was -0.678, respectively, while the R of the standardized applies of the upper boundary and axis of the counter-flow at the in situ site with the western SKI were –0.815 and –0.852, respectively (Figure 9b).

The related coefficient R of the standardized INT across section K (Figure 1) with the Eastern KI was 0.494, while the R of the standardized depths of the upper boundary and axis of the counter-flow at the in situ site with the East KI were 0.696 and 0.703, respectively (Figure 10a). The East SKI between D2 and D3 derived from altimetry data was also used as validation in Figure 10b. The related coefficient R of the standardized INT across section K with the East SKI was 0.624, respectively, while the R of the standardized depths of the upper boundary and axis of the counter-flow at the in situ site with the East SKI were 0.768 and 0.750, respectively (Figure 10b).



Figure 9. Scatter plots of standardized Kuroshio Intensity (INT), counter-flow upper boundary depth and counter-flow axis depth with the KI across the western continental slope (D1–D2, Figure 1) The INT was derived from satellite data along section K (Figure 1). The depths of the upper boundary and axis of the counter-flow were derived from in situ observations. (a) The West KI was derived from analysis data; (b) the West SKI was derived from satellite altimeter data. A 15-d low-pass filter was applied to the primary data. Locations of each section, segment points and in situ measurement sites are shown in Figure 1.



Figure 10. Scatter plots of standardized Kuroshio intensity (INT), counter-flow upper boundary depth and counter-flow axis depth with the KI across the Eastern continental slope (D2–D3, Figure 1). The INT were derived from satellite data along section K (Figure 1). The depths of the upper boundary and axis of the counter-flow were derived from in situ observations. (a) The East KI was derived from analysis data; (b) the East SKI was derived from satellite altimeter data. A 15-d low-pass filter was applied to the primary data. Locations of each section, segment points and in situ measurement sites are shown in Figure 1.

The results indicate that the depths of the upper boundary and axis of the counter-flow at the in situ site were proportional to the variance of the West KI and West SKI (Figure 9). The East KI and East SKI also showed high linear relation with the counter-flow depths (Figure 10). Moreover, the variation of the KI to the northeast of Taiwan had better correlation with the counter-flow than the Kuroshio derived from altimetry data. Although the INT derived from altimetry data exhibited linear trends with the KI, and the altimeter data are updated regularly on the open platform, the variable is inadequate for using as a linear index for the KI to the northeast of Taiwan.

The quasi-steady counter-flow is directed southwest along the western continental slope to the northeast of Taiwan in the subsurface layer and is frequently uplifted and lowered. This study has found that the vertical migration of the counter-flow was in well response to the local surface GVA curl, and that the vertical migration of the counter-flow exhibited reasonable linear correlation with the KI across the western continental slope off northeastern Taiwan, where the Kuroshio branch currents intrude onto the East China Sea shelf both during the summer and winter months [9,12,34]. Thus, further study of the variation and mechanism of the counter-flow variations would be helpful for oceanographers to make a better prediction of the KI off northeastern Taiwan, the KI and Kuroshio branch currents on the East China Sea shelf as well as the fisheries in the seas off northeastern Taiwan, eastern Zhejiang, and in the East China Sea.

5. Conclusions

Based on one year's sustained mooring observations, in conjunction with satellite and validated analysis data, this study revealed the vertical migration characteristics of the along-slope counter-flow to the northeast of Taiwan. The mean depths of the upper boundary and axis of the counter-flow at the in situ site were 141.9 (\pm 84.4) m and 307.4 (\pm 51.8) m, respectively. Specifically, during the summer half year, the counter-flow was uplifted with mean upper boundary depth of 102.0 (\pm 70.5) m and mean axis depth of 269.6 (\pm 41.3) m. During the winter half year, the counter-flow was lowered with mean upper boundary depth of 182.3 (\pm 77.9) m and mean axis depth of 339.6 (\pm 37.4) m. In addition to the seasonal pattern, the depths of the upper boundary and axis of the counter-flow also rose and fell frequently over periods of tens of days, e.g., with near 10-d and 20-d periodicity. The 20-d signal was revealed in the GVA curl time series, more importantly, the intraseasonal variation of the vertical migration of the counter-flow was also revealed in the sea surface GVA curl time series. There are five intervals of positive GVA curl and four intervals of negative GVA during the analysis period, and the counter-flow was significant uplifted during an interval of positive (negative) GVA curl in the sea surface. The sea surface GVA curl near the western slope well revealed the variations of the along-slope counter-flow in the subsurface layer. Additionally, the observations in this study also indicates that the strong intraseasonal forces imposed on the counter-flow can uplift the along-slope counter-flow to the surface layer during the winter months.

The depths of the upper boundary and axis of the counter-flow were also found closely linked with the KI off northeastern Taiwan, i.e., as the counter-flow became closer to the sea surface, the KI across the western continental slope (D1–D2, Figure 1) became weaker. The depths of the upper boundary and axis of the counter-flow were found to be proportional to the magnitude of the KI across the western continental slope to the northeast of Taiwan. Moreover, the variation of the KI to the northeast of Taiwan showed better correlation with the counter-flow than the Kuroshio derived from altimetry data. Thus, further study of the variation and mechanism of the along-slope counter-flow is needed to improve the understanding of the KI off northeastern Taiwan, and, a step further, the prediction of the biochemical systems and marine economy in the East China Sea.

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References

- 1. Andres, M.; Jan, S.; Sanford, T.B.; Mensah, V.; Centurioni, L.R.; Book, J.W. Mean Structure and variability of the Kuroshio from northeastern Taiwan to southwestern Japan. *Oceanography* **2015**, *28*, 84–95. [CrossRef]
- 2. Hsueh, Y. The Kuroshio in the East China Sea. J. Mar. Syst. 2000, 24, 131–139. [CrossRef]
- Hu, D.X.; Wu, L.X.; Cai, W.J.; Gupta, A.S.; Ganachaud, A.; Qui, B.; Gordon, A.L.; Lin, X.P.; Chen, Z.H.; Hu, S.J.; et al. Pacific western boundary currents and their roles in climate. *Nature* 2015, 522, 299–308. [CrossRef] [PubMed]
- 4. Isobe, A. Recent Advances in Ocean-Circulation Research on the Yellow Sea and East China Sea Shelves. *J. Oceanogr.* 2008, *64*, 569–584. [CrossRef]
- 5. Wu, C.R.; Wang, Y.L.; Lin, Y.F.; Chao, S.Y. Intrusion of the Kuroshio into the South and East China Seas. *Sci. Rep.* **2017**, *7*, 7895. [CrossRef]

- 6. Nitani, H. Variation of the Kuroshio South of Japan. J. Oceanogr. Soc. Jpn. 1975, 31, 154–173.
- 7. Matsuno, T.; Lee, J.S.; Yanao, S. Influence of the Kuroshio on the water properties in the shelf. *Ocean Sci. Discuss.* **2009**, *6*, 741–764. [CrossRef]
- 8. Gawarkiewicz, G.; Jan, S.; Lermusiaux, P.F.J.; Mcclean, J.L.; Centurioni, L.; Duda, T.F.; Wang, J.; Yang, Y.J.; Sanford, T.; Lien, R.C.; et al. Circulation and intrusions northeast of Taiwan: Chasing and predicting uncertainty in the cold dome. *Oceanography* **2011**, *24*, 111–121. [CrossRef]
- 9. Liu, X.H.; Dong, C.M.; Chen, D.K.; Su, J.L. The Pattern and Variability of Winter Kuroshio Intrusion Northeast of Taiwan. *J. Geophys. Res. Oceans* **2014**, *119*, 5380–5394. [CrossRef]
- Lee, J.S.; Matsuno, T. Intrusion of Kuroshio Water onto the Continental shelf of the East China Sea. J. Oceanogr. 2007, 63, 309–325. [CrossRef]
- Yang, D.Z.; Yin, B.S.; Liu, Z.L.; Bai, T.; Qi, J.F.; Chen, H.Y. Numerical study on the pattern and origins of Kuroshio branches in the bottom water of southern East China Sea in summer. *J. Geophys. Res. Oceans* 2012, 117. [CrossRef]
- Yang, D.Z.; Huang, R.X.; Yin, B.S.; Feng, X.R.; Chen, H.Y.; Qi, J.F.; Xu, L.J.; Shi, Y.L.; Cui, X.; Gao, G.D.; et al. Topographic Beta Spiral and Onshore Intrusion of the Kuroshio current. *Geophys. Res. Lett.* 2018, 45, 287–296. [CrossRef]
- Yang, D.Z.; Yin, B.S.; Chai, F.; Feng, X.R.; Xue, H.J.; Gao, G.D. The Onshore Intrusion of Kuroshio Subsurface Water from February to July and a Mechanism for the Intrusion Variation. *Prog. Oceanogr.* 2018, 167, 97–115. [CrossRef]
- 14. Lie, H.J.; Cho, C.H. Recent advances in understanding the circulation and hydrography of the East China Sea. *Fish. Oceanogr.* **2002**, *11*, 318–328. [CrossRef]
- Lie, H.J.; Cho, C.H. Progress in Oceanography Seasonal circulation patterns of the Yellow and East China Seas derived from satellite-tracked drifter trajectories and hydrographic observations. *Prog. Oceanogr.* 2016, 146, 121–141. [CrossRef]
- 16. Zhou, P.; Song, X.X.; Yuan, Y.Q.; Wang, W.T.; Cao, X.C.; Yu, Z.M. Intrusion pattern of the Kuroshio Subsurface Water onto the East China Sea continental shelf traced by dissolved inorganic iodine species during the spring and autumn of 2014. *Mar. Chem.* **2017**, *196*, 24–34. [CrossRef]
- 17. Guo, X.Y.; Zhu, X.; Long, Y.; Huang, D.J. Spatial variations in the Kuroshio nutrient transport from the East China Sea to south of Japan. *Biogeosciences* **2013**, *10*, 6403–6417. [CrossRef]
- 18. Shiah, F.K.; Liu, K.K.; Kao, S.J.; Gong, G.C. The coupling of bacterial production and hydrography in the southern East China Sea: Spatial patterns in spring and fall. *Cont. Shelf Res.* **2000**, *20*, 459–477. [CrossRef]
- 19. Xu, Y.; Ma, L.; Sun, Y.; Li, X.Z.; Wang, H.F.; Zhang, H.M. Spatial variation of demersal fish diversity and distribution in the East China Sea: Impact of the bottom branches of the Kuroshio current. *J. Sea Res.* **2019**, 144, 22–32. [CrossRef]
- Zhao, Y.; Yu, R.C.; Kong, F.Z.; Wei, C.J.; Liu, Z.; Geng, H.X.; Dai, L.; Zhou, Z.X.; Zhang, Q.C.; Zhou, M.J. Distribution Patterns of Picosized and Nanosized Phytoplankton Assemblages in the East China Sea and the Yellow Sea: Implications on the Impacts of Kuroshio Intrusion. *J. Geophys. Res. Oceans* 2019, 124, 1262–1276. [CrossRef]
- 21. Wu, C.R.; Lu, H.F.; Chao, S.Y. A numerical study on the formation of upwelling off northeast Taiwan. *J. Geophys. Res. Oceans* **2008**, *113*. [CrossRef]
- 22. Chuang, W.S.; Li, H.W.; Tang, T.Y.; Wu, C.K. Observations of the Countercurrent on the Inshore Side of the Kuroshio Northeast of Taiwan. *J. Oceanogr.* **1993**, *49*, 581–592. [CrossRef]
- 23. Tang, T.Y.; Tai, J.H.; Yang, Y.J. The Flow Pattern North of Taiwan and the Migration of the Kuroshio. *Cont. Shelf Res.* **2000**, 20, 349–371. [CrossRef]
- 24. Wong, G.T.F.; Chao, S.Y.; Li, Y.H.; Shiah, F.K. The Kuroshio Edge Exchange Processes (KEEP) Study—An Introduction to Hypotheses and Highlights. *Cont. Shelf Res.* **2000**, *20*, 335–347. [CrossRef]
- 25. Hsu, P.C.; Zheng, Q.A.; Lu, C.Y.; Cheng, K.H.; Lee, H.J.; Ho, C.R. Interaction of coastal Countercurrent in I-Lan Bay with the Kuroshio Northeast of Taiwan. *Cont. Shelf Res.* **2018**, *171*, 30–41. [CrossRef]
- 26. Miyaji, K.; Inoue, N. Characteristics of the flow of the Kuroshio in the vicinity of Senkaku Islands. *Bull. Seikai Reg. Fish. Res. Lab.* **1983**, *60*, 50–70, (In Japanese with English Abstract).
- Chuang, W.S.; Wu, C.K. Slope-Current fluctuations northeast of Taiwan winter 1990. J. Oceanogr. Soc. Jpn. 1991, 47, 185–193. [CrossRef]

- Hsueh, Y.; Chern, C.S.; Wang, J. Blocking of the Kuroshio by the Continental Shelf Northeast of Taiwan. J. Geophys. Res. 1993, 98, 12351–12359. [CrossRef]
- Shen, M.L.; Tseng, Y.H.; Jan, S. The formation and dynamics of the cold-dome off northeastern Taiwan. J. Mar. Syst. 2011, 86, 10–27. [CrossRef]
- Jan, S.; Chen, C.C.; Tsai, Y.L.; Yang, Y.J.; Wang, J.; Chern, C.S.; Gawarkiewicz, G.; Lien, R.C.; Centurioni, L.; Kuo, J.Y. Mean Structure and Variability of the Cold Dome Northeast of Taiwan. *Oceanography* 2011, 24, 100–109. [CrossRef]
- Xu, F.H.; Yao, Yuan.; Oey, L.; Lin, Y.L. Impacts of pre-existing ocean cyclonic circulation on sea surface chlorophyll-a concentrations off northeastern Taiwan following episodic typhoon passages. *J. Geophys. Res. Oceans* 2017, 122, 6482–6497. [CrossRef]
- 32. Tang, T.Y.; Hsueh, Y.; Yang, Y.J.; Ma, J.C. Continental Slope Flow Northeast of Taiwan. *J. Phys. Oceanogr.* **1999**, *29*, 1353–1362. [CrossRef]
- Tang, T.Y.; Yang, Y.J. Low frequency current variability on the shelf break northeast of Taiwan. J. Oceanogr. 1993, 49, 193–210. [CrossRef]
- 34. Oey, L.Y.; Hsin, Y.C.; Wu, C.R. Why Does the Kuroshio Northeast of Taiwan Shift Shelfward in Winter? *Ocean Dyn.* **2010**, *60*, 413–426. [CrossRef]
- Amante, C.; Eakins, B.W. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24; National Geophysical Data Center, NOAA. Available online: https://www.ngdc.noaa.gov/mgg/global/global.html (accessed on 1 September 2009). [CrossRef]
- 36. Yin, Y.Q.; Lin, X.P.; He, R.Y.; Hou, Y.J. Impact of Mesoscale Eddies on Kuroshio Intrusion Variability Northeast of Taiwan. *J. Geophys. Res. Oceans* **2017**, *122*, 3021–3040. [CrossRef]
- 37. SSALTO/DUACS Experimental Product Handbook. Available online: https://www.aviso.altimetry.fr/en/ data/product-information/aviso-user-handbooks.html (accessed on 1 September 2019).
- 38. NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. MODIS-Terra Ocean Color Data. NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group, 2014. Available online: https://modis.gsfc.nasa.gov/data/dataprod/mod28.php (accessed on 28 July 2015). [CrossRef]
- 39. Wallcraft, A.J. HYCOM and Navy ESPC Future High Performance Computing Needs. Available online: https://www.hycom.org/hycom/documentation (accessed on 1 November 2017).
- 40. Chassignet, E.P.; Hurlburt, H.E.; Martin, O.M.; Halliwell, G.R.; Hogan, P.J.; Wallcraft, A.J.; Baraille, R.; Bleck, R. The HYCOM (HYbrid Coordinate Ocean Model) data assimilative system. *J. Mar. Syst.* **2007**, *65*, 60–83. [CrossRef]
- 41. Hsin, Y.C.; Qui, B.; Chiang, T.L.; Wu, C.R. Seasonal to interannual variations in the intensity and central position of the surface Kuroshio east of Taiwan. *J. Geophys. Res. Oceans* **2013**, *118*, 4305–4316. [CrossRef]
- 42. Geladi, P.; Kowalshi, B.R. Partial Least-Squares Regression: A Tutorial. *Anal. Chim. Acta* **1986**, *185*, 1–17. [CrossRef]
- 43. James, C.; Wimbush, M.; Ichikawa, H. Kuroshio Meanders in the East China Sea. J. Phys. Oceanogr. 1999, 29, 259–272. [CrossRef]
- 44. Johns, W.E.; Lee, T.N.; Zhang, D.X.; Zantopp, R. The Kuroshio East of Taiwan: Moored Transport Observations from the WOCE PCM-1 Array. *J. Phys. Oceanogr.* **2001**, *31*, 1031–1053. [CrossRef]
- Lee, I.H.; Ko, D.S.; Wang, Y.H.; Wang, Y.H.; Centurioni, L.; Wang, D.P. The mesoscale eddies and Kuroshio transport in the western North Pacific east of Taiwan from 8-year (2003–2010) model reanalysis. *Ocean Dyn.* 2013, *63*, 1027–1040. [CrossRef]
- 46. Cheng, Y.H.; Ho, C.R.; Zheng, Z.W.; Lee, Y.H.; Kuo, N.J. An Algorithm for Cold Patch Detection in the Sea off Northeast Taiwan Using Multi-Sensor Data. *Sensors* **2009**, *9*, 5521–5533. [CrossRef] [PubMed]
- 47. Yin, W.; Huang, D.J. Short-Term Variations in the Surface Upwelling off Northeastern Taiwan Observed via Satellite Data. *J. Geophys. Res. Oceans* **2019**, *124*, 939–954. [CrossRef]
- 48. Qin, D.D.; Wang, J.H.; Liu, Y.; Dong, C.M. Eddy Analysis in the Eastern China Sea Using Altimetry Data. *Front. Earth Sci.* **2015**, *9*, 709–721. [CrossRef]
- 49. Wang, W.T.; Yu, Z.M.; Song, X.X.; Yuan, Y.Q.; Wu, Z.X.; Zhou, P.; Cao, X.H. Intrusion Pattern of the Offshore Kuroshio Branch Current and Its Effects on Nutrient Contributions in the East China Sea. *J. Geophys. Res. Oceans* **2018**, *123*, 2116–2128. [CrossRef]

- 50. Gong, G.C.; Shiah, F.K.; Liu, K.K.; Wen, Y.H.; Liang, M.H. Spatial and temporal variation of chlorophyll a, primary productivity and chemical hydrography in the southern East China Sea. *Cont. Shelf Res.* **2000**, *20*, 411–436. [CrossRef]
- 51. Lin, Y.H.; Nakamura, Y. Distribution of planktonic copepods in the Kuroshio area of the East China Sea to the southwest of Kyushu in Japan. *Acta Oceanol. Sin.* **1993**, *12*, 445–456.
- 52. Shiozaki, T.; Kondo, Y.; Yuasa, D.; Takeda, S. Distribution of major diazotrophs in the surface water of the Kuroshio from northeastern Taiwan to south of mainland Japan. *J. Plankton Res.* **2018**, *40*, 407–419. [CrossRef]
- 53. Shiozaki, T.; Takeda, S.; Itoh, S.; Kodama, T.; Liu, X.; Hashihama, F.; Furuya, K. Why is Trichodesmium aboundant in the Kuroshio? *Biogeosciences* **2015**, *12*, 6931–6943. [CrossRef]
- 54. Umezawa, Y.; Yamaguchi, A.; Ishizaka, J.; Hasegawa, T.; Yoshimizu, C.; Tayasu, I.; Yoshimura, H.; Morii, Y.; Aoshima, T.; Yamawaki, N. Seasonal shifts in the contributions of the Changjiang River and the Kuroshio Current to nitrate dynamics in the continental shelf of the northern East China Sea based on a nitrate dual isotopic composition approach. *Biogeosciences* **2014**, *11*, 1297–1317. [CrossRef]
- Liu, K.K.; Gong, G.C.; Lin, S.; Yang, C.Y.; Wei, C.L.; Pai, S.C.; Wu, C.K. The year-round upwelling at the shelf break near the northern tip of Taiwan as evidenced by chemical hydrography. *Terr. Atmos. Oceanic Sci.* 1992, 3, 243–275. [CrossRef]
- 56. Chang, Y.L.; Wu, C.R.; Oey, L.Y. Bimodal behavior of the seasonal upwelling off the northeastern coast of Taiwan. *J. Geophys. Res. Oceans* **2009**, *114*. [CrossRef]
- 57. Xu, L.J.; Yang, D.Z.; Benthuysen, J.A.; Yin, B.S. Key Dynamical Factors Driving the Kuroshio Subsurface Water to Reach the Zhejiang Coastal Area. *J. Geophys. Res. Oceans* **2018**, *123*, 9061–9081. [CrossRef]
- 58. Tseng, Y.F.; Lin, J.; Dai, M.; Kao, S.J. Joint effect of freshwater plume and coastal upwelling on phytoplankton growth off the Changjiang River. *Biogeosciences* **2014**, *11*, 409–423. [CrossRef]
- 59. Yu, R.C.; Zhang, Q.C.; Kong, F.Z.; Zhou, Z.X.; Chen, Z.F.; Zhao, Y.; Geng, H.X.; Dai, L.; Yan, T.; Zhou, M.J. Status, impacts and long-term changes of harmful algal blooms in the sea area adjacent to the Changjiang river estuary. *Oceanol. Limn. Sin.* **2017**, *48*, 1178–1186, (In Chinese with English Abstract).
- 60. Wang, J.H.; Wu, J.Y. Occurrence and potential risks of harmful algal blooms in the East China Sea. *Sci. Total Environ.* **2009**, 407, 4012–4021. [CrossRef]
- 61. Liang, X.S.; Su, J.L. A two-layer model for the circulation of the East China Sea. *Donghai Mar. Sci.* **1994**, *12*, 1–20, (In Chinese with English Abstract).
- 62. Guo, B.H. Cold water and upwelling in the area around some capes of Taiwan island. *Adv. Mar. Sci.* **1986**, *3*, 3, (In Chinese with English Abstract).
- 63. Guo, B.H.; Lin, K. Characteristics of Circulation in the Continental shelf Area of the East China Sea in Winter. *Acta Oceanol. Sin. V* **1987**, *6*, 51–60.
- 64. Liu, X.H.; Chen, D.K.; Dong, C.M.; He, H.L. Variation of the Kuroshio Intrusion Pathways Northeast of Taiwan Using the Lagrangian Method. *Sci. China Earth Sci.* **2016**, *59*, 268–280. [CrossRef]
- 65. Vélez-Belchí, P.; Centurioni, L.R.; Lee, D.K.; Jan, S.; Niiler, P.P. Eddy induced Kuroshio intrusions onto the continental shelf of the East China Sea. *J. Mar. Res.* **2013**, *71*, 83–107. [CrossRef]
- 66. Yin, Y.Q.; Lin, X.P.; Hou, Y.J. Seasonality of the Kuroshio Intensity East of Taiwan Modulated by Mesoscale Eddies. *J. Mar. Syst.* 2019, 193, 84–93. [CrossRef]



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