Seasonal Exchanges of the Kuroshio and Shelf Waters and Their Impacts on the Shelf Currents of the East China Sea

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ABSTRACT

Previous in situ observations and modeling studies have indicated that, through mass and momentum exchanges across the shelf edge, the Kuroshio can significantly influence the shelf currents of the East China Sea (ECS). Here, instead of localized observations, this study uses 25 yr of drifter data, supported by satellite and other data to identify seasonal cross-shelf exchanges along the entire shelf edge. The authors show that Kuroshio meanders onshore from fall to winter and offshore from spring to summer, with the largest amplitude northeast of Taiwan. The influence is limited to the shelf edge when the Kuroshio meanders offshore in spring and summer. By contrast, strong onshelf intrusions and cross-shelf exchanges occur when the Kuroshio meanders onshore in fall and winter. Drifters intrude onshore northeast of Taiwan and spread as far north as 28°N against the strong northeasterly wind. The forcing on the shelf is identified as a northward downsloping of the sea level that is steepest north of Taiwan at 25°–28°N, but which is 3 times weaker farther north. The vorticity budget computed from a numerical model indicates that intrusion during fall and winter is primarily a result of balance between onshelf advection of ambient potential vorticity and vorticity production by the along-isobath pressure gradient acting on the changing mass of water column across the continental slope.

1. Introduction

We define the East China Sea (ECS) to be within the domain 23°–33.5°N and 118°–130°E in the western North Pacific Ocean (Fig. 1). It is separated from the Yellow Sea in the northwest by a line that joins the mouth of the Yangtze River to Jeju Island, Korea. In the northeast, the ECS shelf connects to the Japan Sea through the Korea Strait, and it connects to the South China Sea in the southwest through the Taiwan Strait. To the east, the ECS extends to the Ryukyu Islands. The Kuroshio enters the ECS through the Ilan Channel over the Ilan Ridge east of Taiwan, flows northeastward along the ECS shelf break, and leaves the ECS through the Tokara Strait (Fig. 1). Previous studies have shown that the Kuroshio path fluctuates over a wide range of time scales, from a few days because of frontal eddies to intraseasonal, seasonal, interannual, and longer time scales (Qiu et al. 1990; Hsueh et al. 1992; James et al. 1999; Tang et al. 1999; Feng et al. 2000; Guo et al. 2003; Liu and Gan 2012; Wang and Oey 2014). This work uses surface drifters to infer seasonal exchanges across the ECS shelf edge between the shelf and the Kuroshio and to relate them to the fluctuations of the Kuroshio path.

In summer, the so-called Kuroshio Branch Current north of Taiwan intrudes near the surface into the ECS shelf, from Taiwan to east of the Yangtze River (Changjiang) mouth (Su and Pan 1987; Ichikawa and Beardsley 2002; Yang et al. 2012); the onshore intrusion of surface Kuroshio water is less frequently observed in summer. In contrast, Kuroshio intrusions north of Taiwan occur in both the upper and lower layers in winter. Satellite images and ship observations indicate
that Kuroshio warm water northeast of Taiwan can extend over the continental shelf, and the warm water mass can sometimes reach the mouth of Yangtze River in winter (Qiu et al. 1990; Wang et al. 2003; Yuan et al. 2008).

Based on the work of Kondo (1985), and others, Ichikawa and Beardsley (2002) proposed that the Kuroshio Branch Current north of Taiwan also intrudes into the inner shelf of the ECS in winter. Yuan et al. (2008) and Yuan and Hsueh (2010) used observations and numerical model results to propose similar wintertime circulations in the ECS. Through water mass and momentum exchanges across the shelf edge, fluctuations of the Kuroshio influence the ECS circulation and water mass (Qiu and Imasato 1990; Guo et al. 2006; Isobe 2004, 2008). Onshore intrusions of Kuroshio waters together with the northward transport of water by the Taiwan Warm Current through the Taiwan Strait contribute to the net water transport of the Tsushima Current through the Korea Strait (Lie and Cho 1994; Isobe 1999, 2008; Ichikawa and Beardsley 2002; Guo et al. 2006). Intrusions of Kuroshio water also modify the biochemical characteristics of water on the shelf; for example, Chen (1996) estimated that the intrusion of Kuroshio subsurface water may be the major source of nutrients in the ECS. Northeast of Taiwan, studies have shown that the offshore (onshore) shift of the Kuroshio intensifies (suppresses) the cyclonic eddy in summer (winter), which increases (decreases) the upward nutrient supply by upwelling at the shelf break (Liu et al. 1992; Tang et al. 1999, 2000; Wu et al. 2008; Liu et al. 2014). Downstream, Kuroshio frontal eddies can facilitate exchanges of shelf and Kuroshio waters across the shelf break (Isobe 2004; Matsuno et al. 2009).

In summary, the Kuroshio tends to shift more offshore northeast of Taiwan in summer, and Kuroshio subsurface waters may intrude near the bottom to the ECS shelf. In winter, the Kuroshio shifts more onshore and the intruded warm water of the Kuroshio may extend farther into the shelf. Understanding the influence of the Kuroshio on the ECS is critical to an improved understanding of the circulation and transport as well as biogeochemical processes on the shelf. Because of the in situ and short-time nature of the previous observational studies, much of our understanding of the seasonal-mean circulation has relied on numerical model results, some of which have provided useful insights into the relevant dynamical processes (e.g., Guo et al. 2006; Yuan et al. 2008; Oey et al. 2010). On the other hand, a comprehensive, observation-based understanding of how water mass exchanges across the entire shelf edge of the ECS and the influence of the exchange on ECS shelf circulation is lacking. Based on concurrent measurements of velocities in the Taiwan and Korea Straits in October–December of 1999, Teague et al. (2003) estimated that nearly the entire 3.17-Sverdrup (Sv; 1 Sv = 10^6 m^3 s^-1) transport of the Korea Strait is supplied by water mass intrusion across the shelf edge from the Kuroshio, with very little contribution from flow through the Taiwan Strait. Is this estimate representative of the fall–winter period? Are there preference sites along the shelf edge where cross-shelf exchange of water mass is more prominent? What are the apportionments of transports across the shelf edge in spring–summer? What are the relevant dynamics?

In this study, we revisit the problem of Kuroshio intrusion, focusing on its impact on ECS shelf circulation shoreward of the 150–200-m isobaths at the seasonal time scale. We make inferences of the exchange processes across the shelf edge using drifter and satellite observations and provide dynamical support of our inferences using a numerical model. Wang and Oey (2014) have recently used satellite sea surface height (SSH) data to derive a mode-1 EOF index that characterizes the fluctuations of the Kuroshio path in the ECS. Here, we use the same index as the given Kuroshio forcing and attempt to connect it with cross-shelf exchange processes and shelf circulation. Section 2 describes the data

![Fig. 1. (a) East China Sea study region. Shading is mean absolute dynamic height (MADT; m) from AVISO, and vectors are the corresponding geostrophic currents. Thin contours are isobaths: 50, 100, 150, and 200 m. Black dashed line along the 150-m isobath indicates the section location where onshelf intrusions of drifters north of Taiwan (NTDs) are tracked as gray trajectories in Fig. 6. Numbers along the 150-m isobath indicate sections where cross-isobath drifters are calculated in Figs. 8a–d. The thick black line from east Taiwan over the Ilan Ridge and into the Tokara Strait indicates the mean KP, and the two dotted lines on either side are plus or minus one standard deviation (from Wang and Oey 2014); section numbers are indicated on the KP (see text).]
used. Section 3 discusses seasonal shelf circulation inferred from the drifter analysis. Section 4 then infers cross-shelf edge exchange using the vorticity balance from the results of a numerical model. Concluding summary and discussions are given in section 5.

2. Data

Satellite-tracked surface drifters from the Global Drifter Program dataset (Lumpkin et al. 2013; Available online at ftp.aoml.noaa.gov) are used in this study. According to the information provided, drifter locations were determined from 16 to about 20 satellite fixes per day per drifter, quality control was applied, and the data were then interpolated to 6-hourly intervals using the Kriging method (Krige 1951; see Goovaerts 1997). The data were available from February 1980 to March 2014, and the largest number of releases is for the region east of Taiwan and the Philippines (see the supplemental information, Fig. SM-1). However, over 95% of the data were after 1990; in this study, we therefore focus on trajectories from 1990 to 2014. The drifter drogue depth is at approximately 15 m below the surface, and this study focuses therefore on cross-shelf exchanges near the surface. Figure 2a plots the release locations (red asterisks) and trajectories of drifters that were either released within or entered the rectangular box shown northeast of Taiwan from 1990 to 2014. Fig. 2b shows their averaged lifetimes, and Fig. 2c shows the corresponding trajectory density. Apart from some exceptional cases (see the supplemental information, Fig. SM-2), most of the drifters entering the box are from the subtropical and tropical regions east of Taiwan and the Philippines as well as from farther locations generally following the Pacific Ocean’s basin-scale anticyclonic gyre circulation that carries them into the northward-flowing Kuroshio, and then into the ECS, at time scales of a few weeks to years. These trajectories constitute the majority of drifters used for this study.

The new daily gridded sea surface height anomaly (SSHA = η’) data from Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO) at \(\frac{1}{4}^\circ \times \frac{1}{4}^\circ\) resolution, from 1993 to 2014, were downloaded (AVISO 2013; http://www.aviso.oceanobs.com/); the product has been corrected for aliasing of tides. The mean dynamic topography (MDT; Rio et al. 2011) was also downloaded from the AVISO website and combined with SSHA to form a total sea surface height (SSH = η) time series. We use these AVISO data to calculate the geostrophic currents to determine the time-dependent Kuroshio Path (KP), following the method of Wang and Oey (2014). Briefly, along a mean Kuroshio path first estimated as the SSH = 1.1-m contour, local coordinates \((n, s)\) corresponding to axes across and along the local direction of the path were defined; positive \(n\) points to the right of the KP, generally toward the open Pacific basin, while positive \(s\) is generally poleward along the KP. We then defined 48 cross-jet sections at equal along-jet intervals, \(\Delta s = 25\) km, from east of Taiwan (section 1) to southwest of Kyushu (section 48; Fig. 1). The time-dependent Kuroshio position KP\((s, t)\) was then calculated at each cross section as the \(n\) coordinate of the center of the cubed geostrophic velocity computed from AVISO [see Wang and Oey (2014) for details]. The KP was time averaged to define a new path, and the process was repeated until convergence; two iterations were found to be sufficient. The KP has the same sign as “\(n\),” that is, positive to the right of the mean Kuroshio path. Note that the present KP is an extended and updated version of the one we published in Wang and Oey (2014). We will show that while its seasonal and interannual variations are similar, the new KP shows a clearer long-term trend.

In addition to the drifter and SSHA data, wind data from the cross-calibrated multiplatform (CCMP) product are also used (Atlas et al. 2009). The CCMP data are from 1987 to 2011 at 0.25° × 0.25° resolution (http://podaac.jpl.nasa.gov/). The model data from the Advanced Taiwan Oceanic Prediction System (ATOP; Oey et al. 2013b, 2014) will also be used to calculate vorticity balance. ATOP is based on the message passing interface (mpi) version of the Princeton Ocean Model (mpiPOM). In addition to the above two papers, the model has also been described and validated in the western North Pacific Ocean and process experiments by Chang and Oey (2014a,b), Xu and Oey (2014, 2015), Sun and Oey (2015), Sun et al. (2015), Huang and Oey (2015), and Xu et al. (2015), covering a wide range of topics. Briefly, the model domain encompasses the entire North Pacific Ocean (16°S–70°N, 98°E–73°W) at 0.1° × 0.1° horizontal resolution and 41 vertical sigma levels. The model was first run for 28 yr, from 1988 to 2014, forced by the NCEP monthly climatological surface fluxes, and then was repeated to cover the same period forced by the 6-hourly CCMP (1988–2011) and NCEP–GFS (2012–14) winds. In the present study, five daily mean model fields from 1993 to 2014 are used for the vorticity analysis (see below).

3. Results

a. Kuroshio path

The empirical orthogonal function (EOF; Kutzbach 1967) was computed for the KP. Mode 1 has a seasonal signal and accounts for 44% of the total variance (Fig. 3), which is more than 2 times stronger than mode 2 (18%).
which does not have a seasonal signal (not shown). In this work, we will focus on mode 1. The mode-1 eigenvector (EV$_1$; i.e., spatial pattern; Fig. 3a) is of one sign from southeast Taiwan (station 5) to Kyushu (station 48); it shows a distinct, delta function–like peak of amplitude of about 65 km near station 17 northeast of Taiwan, and the amplitude becomes weak (<20 km) south and north. The mode-1 principal component (PC$_1$; Figs. 3b,c) has a strong seasonal variation that is modulated interannually as well as showing a negative trend.
that is statistically more significant ($p$ value = 0.02) than previously found in Wang and Oey (2014; $p = 0.1$) using the weekly and shorter AVISO dataset. Since $EV_1$ is positive, the negative trend means that the Kuroshio has shifted more onshore over the past 22 yr. The interannual KP variations were discussed in detail by Wang and Oey (2014); here, we focus on the seasonal variation. In fall and winter, the $PC_1$ is negative (Fig. 3c), indicating an onshore

FIG. 3. EOF mode-1 (a) eigenvector ($EV_1$; km) of the KP’s cross-jet fluctuations as a function of distance along the Kuroshio from stations 1–48 (southeast Taiwan to Tokara Strait; see Fig. 1); (b) for the corresponding principal component ($PC_1$; dimensionless) from 1993 to 2014, blue is monthly and black is the 12-month running mean. Dashed line shows the linear trend that is significant at the 95% confidence level ($p = 0.02$; see legend on top right). Cross-jet fluctuations of KP are defined as positive offshore and negative onshore; (c) 22-yr monthly mean $PC_1$ and plus or minus one standard deviation, showing generally onshore KP in fall–winter and offshore KP in spring–summer. The negative trend in (b) indicates that the Kuroshio northeast of Taiwan has for the past two decades shifted shoreward by approximately 18 km. Since KP was determined by a method using the geostrophic current, Wang and Oey (2014) argued that the shift was not caused by the large-scale sea level rise in the western North Pacific Ocean (Merrifield 2011).
shift of the Kuroshio, while the PC$_1$ is positive in spring and summer, indicating an offshore shift of the Kuroshio.$^1$

**b. Shelf currents**

Figure 4 compares SSH and geostrophic currents from AVISO in February and August. The direct impact of the Kuroshio on outer-shelf circulation in winter can be clearly seen by the presence of currents stronger than 0.1 m s$^{-1}$ over the 100- to 200-m water depths, from north of Taiwan to about 28°N (Fig. 4a), whereas these strong currents are absent in summer (Fig. 4b). For depths shallower than 100 m, the SSH contours are seen to cross isobaths in winter but are generally along isobaths in summer. Thus, the along-shelf sea level gradient is strong in winter, especially in the region north of Taiwan; this fact will be shown to be dynamically consistent with the drifter results below. In agreement with the dominant EOF1 eigenvector (Fig. 3a), the largest deviation of the Kuroshio path occurs northeast of Taiwan. Because of this, the section shown in a thick dashed line along the 150-m isobath northeast of Taiwan (Figs. 1, 4) will be shown to be where strong cross-shelf exchanges of drifters tend to occur.

The mean October–March and April–September currents are computed from the drifter trajectories (Fig. 5). Unlike the AVISO data, there is not sufficient data to compute statistically significant mean monthly currents from the drifter trajectories. We will therefore use October–March to represent fall–winter and April–September to represent spring–summer, keeping in mind that during the former (later) period the KP is generally more onshore (offshore). The mean Kuroshio paths compare well with those derived from AVISO, as these paths coincide well with grid cells where the drifter-derived currents are strongest for both seasons. Consistent with the AVISO geostrophic currents, strong onshore currents can be seen northeast of Taiwan in fall and winter (Fig. 5a), while the currents remain offshore in spring and summer (Fig. 5b). Over the midshelf between the 50- and 100-m isobaths, the drifter-derived currents are poleward in spring and summer, while in fall and winter they are weakly poleward from 26.5°–28°N but are equatorward in the Taiwan Strait.

**c. Drifter trajectory analyses northeast of Taiwan**

Figures 6c and 6d show the trajectories of drifters that have crossed the 500-m isobath into ECS (cyan and orange); we call them the western Pacific drifters (WPDs). Cyan trajectories indicate those WPDs that remain offshore of the 150-m isobath, drifting northeastward along the western edge of the Kuroshio; we call them the Kuroshio drifters (KUDs). Orange trajectories show those WPDs that cross the dashed line on the 150-m isobath northeast of Taiwan (see Fig. 1), and after crossing onto the shelf they are colored gray and are called the north Taiwan drifters (NTDs; Figs. 6e,f). The red plus (+)
symbol indicates the beginning location of the gray drifter path, that is, where it enters the shelf across the 150-m isobath northeast of Taiwan, and the blue plus symbol indicates its end location, which may either be on the shelf or as the path crosses the 150-m isobath, back into the deeper ocean. Drifter trajectories are grouped into fall and winter (FaW; October–March) and spring and summer (SpS; April–September). In FaW, most NTDs turn northward after intruding onto the shelf, and only a few drift southward into the Taiwan Strait. Northward spreading follows a Y shape, with the northwestern (i.e., left) branch just offshore of the 50-m isobath and the northeastern branch sandwiched between the 100- and 150-m isobaths. By contrast, in SpS, very few drifters cross the 150 m onto the ECS shelf. The contrast between the numbers of intruding (i.e., NTDs) and nonintruding drifters (i.e., KUDs) is illustrated in the bar plots (Figs. 6a,b). The ratio of NTDs (gray bars) to KUDs (cyan bars) varies interannually. In general, however, the ratio is larger during FaW (61:100 = 61%; Figs. 6a,c) than SpS (23:94 = 25%; Figs. 6b,d).

The areal distribution of NTDs is shown in Figs. 7a and 7b by maps of the visitation frequency (Csanady 1983; Chang et al. 2011). The visitation frequency depends on both the number of drifters a particular grid is visited and their speeds. The patterns confirm the mostly rightward turning tendency (i.e., northward spreading) of NTDs after intrusion irrespective of the season. In SpS (Fig. 7b), most of the intruded drifters curve back into the Kuroshio, while in FaW they spread more extensively westward (i.e., inshore) and northward (Fig. 7a). For grids immediately next to the coast, the visitation frequency is significantly less during SpS compared to FaW. These behaviors of the NTDs are counterintuitive since during FaW, because of the prevailing northeasterly wind, most of the drifters might be expected to drift southwestward into the Taiwan Strait after intruding onto the shelf northeast of Taiwan, instead of spreading northward. During SpS, both southwesterly monsoon wind and the Taiwan Warm Current might be expected to carry NTDs farther northward into the northern ECS after the intrusion, instead of curving back into the Kuroshio. The observed behaviors therefore suggest the strong influence of the Kuroshio. We can check this by examining drifters that do not originate from the Kuroshio northeast of Taiwan. We therefore compare NTDs with drifters that originate from South China Sea (SCS); these SCS drifters are minimally influenced by the Kuroshio northeast of Taiwan. During SpS (Fig. 7d), the SCS drifters penetrate far northward consistent with, for example, Isobe (2008), who suggested that in spring and summer the Taiwan Warm Current flows northward into the Korea Strait. During FaW (Fig. 7c), the SCS drifters are confined to the Taiwan Strait, consistent with currents blocked in the Strait by the strong northeasterly monsoon in fall and winter (e.g., Oey et al. 2014). Since NTDs and SCS drifters are mutually exclusive, their distinct
patterns for the same season indicate the strong influence of the Kuroshio on the former. The strong contrast between the two groups of trajectories is clearly seen when they are plotted together using different colors (Figs. 7e,f).

d. Drifter trajectory analyses along the entire ECS shelf edge

We have focused above on drifters crossing the northeast Taiwan section (i.e., NTDs), composed almost
FIG. 7. Visitation frequency (=number of 6-hourly drifter data per 1° × 1° grid) of (a),(b) NTDs, and (c),(d) SCS drifters (i.e., those originating across the southwestern open boundaries of the domain) during FaW in (a),(c) and SpS in (b),(d). (e),(f) Trajectories of NTDs (blue) and SCS drifters (red). Black contours are the 50-, 100-, 150-, and 200-m isobaths. Thick red line shows the mean KP (see Fig. 1).
entirely (99%) of drifters that were carried northward by the Kuroshio from the east of Taiwan. The rationale is that cross-shore fluctuations of the Kuroshio northeast of Taiwan are strongest because of the strong peak in the mode-1 EOF eigenvector of KP near that location (Fig. 3), and one may therefore hypothesize that here is also where the dominant exchange of water mass can occur; the strong shelf edge exchange near that location is evident from the numerical model results of Guo et al. (2003). In FaW, the EOF-1 is negative (i.e., positive eigenvector but negative principal component; Fig. 3) so that the Kuroshio tends to shift onshore, while in SpS, the EOF-1 is positive and the Kuroshio tends to shift offshore. Thus, one may expect that onshelf (offshore) intrusions of drifters across the shelf edge northeast Taiwan occur mainly from fall to winter (spring to summer), with fewer contributions from cross-shelf exchanges at other portion of the shelf edge. To test this hypothesis, we plot the trajectories of all the drifters that crisscross the 150-m isobath along the shelf edge of ECS from Taiwan to southwestern Kyushu (Fig. 8). By comparing Fig. 8e with Fig. 6e for NTDs during FaW, it is remarkable that despite the nearly threefold increase in the total number of onshelf intruding drifters across the entire shelf edge in winter and fall, 169 in Fig. 8e versus 61 of Fig. 6e, drifter distributions over the shelf where depths <100 m are very similar. During FaW, when all of the drifters are considered (Fig. 8e), northward spreading still follows the Y shape whose left or shoreward branch is identical to that of Fig. 6e so that shelf spreading remains confined south of 30°N. The right or offshore branch is strengthened as many more—in fact 108 (=169 − 61) more—drifters now crisscross the 100–150-m isobaths toward the entrance of the Korea Strait. During SpS (Fig. 8f), the majority of trajectories still loop back into the western edge of the

Fig. 8. (a),(b) Number of all (1990–2014) onshore (positive; gray bars) and offshore (negative; cyan bars) intruding drifters across the 150-m isobath along the shelf edge of the ECS from Taiwan to Kyushu, from sections 1 to 13 (see Fig. 1 for section locations). (c),(d) Net number of drifters (onshore minus offshore; black), its accumulated sum along the section along the isobath (red), and the percentage of the accumulated sum (blue using the right-hand side y axis; shown only if onshore). (e),(f) Trajectories of all drifters that crossed the 150-m isobath along the shelf edge of the ECS plotted as gray for onshore and blue for offshore trajectories. The starting and ending locations of the onshore trajectories are indicated by red and blue + symbols. The end points of the 13 along-150-m isobath sections (see Fig. 1) are marked by green circles. (left) Fall and winter and (right) spring and summer, and the total numbers of onshore and offshore intruding drifters are shown in the legends in (e) and (f).
Kuroshio and crisscross northward following the 100–150-m isobaths. Near 124°E, the plot now shows a strong cross-shelf exchange that modifies the outer-shelf circulation near 28.5°N, 124°E, similar to the circulation noted previously by Hsueh et al. (1992).

The bar plots (Figs. 8a,b) confirm that the largest onshore (offshore) intrusion during FaW (SpS) does indeed occur northeast of Taiwan at sections 1 and 3 (1 and 4). (The section numbers along the 150-m isobath are indicated in Fig. 1). The net drifter flux (i.e., difference between onshore and offshore-intruding drifters), shown as black lines in Figs. 8c and 8d, is onshelf and largest at sections 1 and 3 in FaW and at section 4 in SpS. In FaW (Fig. 8c), the accumulated drifter flux (i.e., accumulated sum along the 150-m isobath of net flux from sections 1 to 13), shown as the red line, is onshelf at all sections. From sections 1–3, which encompass the northeast Taiwan section used to define the NTDs, the accumulated flux reaches ~60% of the total net onshore flux into ECS (blue lines in Figs. 8c,d) during FaW, consistent with the strong negative peak in the EOF-1 of KP northeast of Taiwan and demonstrating the unique contribution of NTDs in determining the circulation and water mass of ECS because of intrusions from the Kuroshio. Farther north, the accumulated onshelf flux first decreases at sections 5 and 6 before steadily increasing across the remaining sections 7–13, where the largest increase (~25%) is from sections 8–10 (Fig. 8c). Contrary to previous belief [see summary of literature in Ichikawa and Beardsley (2002)], the water intrusion northeast of Taiwan therefore makes up a substantial if not dominant portion of the water mass of the Tsushima Current through the Korea Strait. In SpS (Fig. 8d), the accumulated flux is offshore at sections 1–3 consistent with the strong positive peak in the EOF-1 of KP northeast of Taiwan. Thereafter, the accumulated flux steadily increases through section 13 (Fig. 8d). In terms of percentage, the onshelf intrusion across section 4, where strong cross-shelf exchange around 124°E was previously noted, accounts for 40% of the total net onshore flux.

e. Fall and winter: Identifying the Kuroshio influence

Thus, the NTDs in FaW intrude and spread more extensively onto the shelf; there are nearly 3 times more NTDs during FaW than SpS (61 vs 23; see Fig. 6), and they account for ~60% of the net onshore drifters across the entire shelf edge of the ECS (Fig. 8c). The relative importance of NTDs can be assessed by plotting the ratio of the visitation frequency of NTDs (i.e., Figs. 7a,b) to the visitation frequency of all drifters in each season (see the supplemental information, Fig. SM-4). Figure 9 shows that during FaW, the NTDs account for a significant fraction (35%–85%) of the total number of drifters in southern to central ECS. In contrast, the percentage is much smaller (<20%) during SpS. In FaW, the temperature contrast between the Kuroshio and shelf is large (Oey et al. 2015). The shelf heat (and other tracer) budgets can then be expected to be strongly regulated by the intruded warmer waters of the Kuroshio, consistent with Oey et al.’s (2013a, 2015) findings that strong air–sea coupled responses exist over the same region. In view of their importance, it is of interest to further
analyze the fall and winter NTDs to infer what their potential impacts are to the shelf circulation. We have noted above that the NTDs tend to spread north-northeastward against the strong northwesterly monsoon wind after they intrude onto the shelf. One way that the drifters may be “pushed” northward is through a pressure gradient caused by the sea level dropping northward along the shelf. Assuming a well-mixed ocean that may be applicable to fall and winter, a simple formula for the quasi-steady, along-shelf velocity near the surface \( v_o \), is given by (see detailed derivation in the supplemental information; also Oey et al. 2014):

\[
v_o = \tau^{\text{oy}} \left( (H_{rb})^{-1} + 2^{1/2} e^c \sin(\xi + \pi/4) (f\delta_E)^{-1} \right) - (g/\rho_o) \partial\eta/\partial y.
\]

(3.1)

Here, \( y \) is the along-shelf coordinate (taken to be positive poleward, approximately from southwest to northeast), \( r_o \) (\( \approx 1.66 \times 10^{-5} \text{s}^{-1} \)) is the bottom friction coefficient, \( g \) is the acceleration due to gravity, \( \eta \) is the sea surface height, \( \tau^{\text{oy}} \left( \text{m}^2 \text{s}^{-2} \right) \) is the along-shelf kinematic wind stress, \( f \left( \approx 8 \times 10^{-5} \text{s}^{-1} \right) \) is the Coriolis parameter, \( \delta_E \) (\( \approx 15 \text{m} \)) is the Ekman depth, \( \xi = z/\delta_E \), \( z \) is the vertical coordinate (\( z = 0 \) at the surface), and \( H \) is the averaged water depth. The values of \( r_o \) and \( \delta_E \) are taken from Oey et al. (2014). Depth \( H \) is taken to be 75 m, since the model is assumed to be valid over the midshelf between 50 and 100 m. The second term on the right-hand side (rhs) of (3.1) is the Ekman velocity correction near the sea surface assuming a constant eddy viscosity (Gill 1982). For shelf flow, the along-shelf, depth-averaged velocity may be assumed to be much larger than the cross-shelf, depth-averaged velocity (which equals 0 at the coast), while quasi steadiness requires that \( \partial/\partial t \ll f^{-1} \), that is, a time scale of two or more days, so that only the along-shelf component of the wind is considered (Csanyi 1982; alternatively, for ECS, the along-shelf northwesterly monsoon wind dominates). The first and third terms on the rhs of (3.1) then are the along-shelf geostrophic velocity \((g/\rho_o)\partial\eta/\partial x [\text{see SM.6}])\). Equation (3.1) shows that near the surface, the along-shelf velocity over the midshelf is proportional to the wind stress and the proportionality constant depends on parameters such as the \( r_o \) and \( \delta_E \). Most importantly, it shows that in the absence of wind (\( \tau^{\text{oy}} = 0 \)) the along-shelf velocity can be positive if sea level slopes downward along the shelf. The along-shelf pressure gradient is interpreted as being caused by the Kuroshio, analogous to the along-shelf pressure gradient along the Mid-Atlantic Bight off the U.S north-eastern coast, which is in part forced by the Gulf Stream (Xu and Oey 2011). The pressure gradient can be localized—for example, northeast of Taiwan—or it can be large scale over the entire ECS shelf.

We calculate the drifter velocity from the 6-hourly trajectories by finite differences, interpolate the CCCP wind to each trajectory, and then low pass the wind and velocities using a 48-h low-pass filter to remove high-frequency fluctuations (e.g., inertial oscillation and tides for the ocean velocity; Fan et al. 2004). We then convert the wind velocity to wind stress using the drag formula given in Oey et al. (2006, 2007), which modifies the Large and Pond (1981) formula with a maximum limit for the drag coefficient for very strong wind. We then regress the along-shelf component of the drifter velocity against the wind stress (Fig. 10), using the NTDs (\( v_{ntd} \)) and then repeat the procedure using all drifters except the NTDs (\( v_{shelf} \)), all for FaW. We only use \( v_{ntd} \) and \( v_{shelf} \) for trajectories over water depths shallower than 100 m (over 98\% of them were actually between the 50- and 100-m isobaths) so that the results may be compared against the simple equation (3.1) that is approximately applicable over the shelf. Figure 10a shows that 56\% of the time the \( v_{ntd} \) versus \( \tau^{\text{oy}} \) relation falls in the second quadrant, indicating northeastward drifter trajectories against the prevailing southwestward wind stress, while the NTDs were drifting in the same direction as the wind 42\% (2\%) of the time in the third (first) quadrant. The regression formula is

\[
v_{ntd} = 1.9 \times 10^3 \tau^{\text{oy}} + 0.2 \text{ (m s}^{-1})
\]

(3.2)

which gives a y intercept (i.e., \( \tau^{\text{oy}} = 0 \)) of 0.2 m s\(^{-1}\), yielding \((\partial\eta/\partial y)_{ntd} \approx -3.3 \times 10^{-7} \) from (3.1), which agrees reasonably well with the estimate from AVISO (\( \partial\eta/\partial y \)AVISO \( \approx -2.72 \times 10^{-7} \)) when averaged over the region of the NTDs (Fig. 10e). The observed regression slope of \( 1.9 \times 10^3 \text{s}^{-1} \text{m}^{-1} \) [from (3.2)] may be compared with the theoretical regression slope from (3.1), that is, \(( (H_{rb})^{-1} + 2^{1/2} e^c \sin(\xi + \pi/4) (f\delta_E)^{-1} \)\), which ranges from \( 1.1 \times 10^3 \text{s}^{-1} \text{m}^{-1} \) if velocity averaged over a drifter drogue depth of 15 m (\( \approx \delta_E \)) is assumed to 1.8 \( \times \) 10\(^3 \text{s}^{-1} \text{m}^{-1} \) if surface velocity (i.e., \( \xi = 0 \)) is used. These values are weaker than the observed regression slope of \( 1.9 \times 10^3 \text{s}^{-1} \text{m}^{-1} \) from (3.2). However, it may be argued that the theoretical estimate should be nearer the higher value of the range = \( \{1.1 \times 10^3, 1.8 \times 10^3\} \text{s}^{-1} \text{m}^{-1} \), since the velocity veering angle is generally observed to be less than that predicted by the constant eddy viscosity Ekman formula (Toba 1978). When all drifters except the NTDs were used in the regression analysis, the regression formula becomes

\[
v_{shelf} = 1.1 \times 10^3 \tau^{\text{oy}} + 0.063 \text{ (m s}^{-1})
\]

(3.3)

Figure 10b shows that the percentage of velocities in the second quadrant is now significantly decreased, from 56\% to 41\%, while the number of velocities in the third
FIG. 10. Regression of the 48-h low-pass filtered along-shelf (positive northeastward) velocities (m s\(^{-1}\)) vs the corresponding 48-h low-passed kinematic wind stresses (m\(^2\) s\(^{-2}\)), calculated from (a) drifter trajectories during fall and winter for the NTDs and (b) all ECS drifters except the NTDs. Only those trajectories that were over waters shallower than 100 m are used. (c), (d) The corresponding trajectories with red dots indicating those trajectories that are in the second quadrant in (a) and (b). Legends are discussed in text. Thin contours are the 50-, 100-, 150-, and 200-m isobaths. The regression is significant at the 99.9% confidence level (\(p = 0.001\)). (e) Northeastward (i.e., along shelf) SSH gradients from AVISO monthly mean dynamic height topography area averaged over the ECS shelf (<100-m isobath) from 1) 26°–28°N in the region of the NTDs; 2) 26°–34°N in the ECS shelf north of the region of the NTDs; and 3) 26°–34°N over the entire ECS shelf including the region of the NTDs. The October–March averaged SSH gradients for the 3 regions are, respectively, 1) \(2.72 \times 10^{-7}\), 2) \(1.26 \times 10^{-7}\), and 3) \(1.60 \times 10^{-7}\).
and first quadrants, which indicate current in the same direction as the wind stress, is more (48% + 10% = 58%). The along-shelf sea level slope \((\partial \eta / \partial y)_{\text{shelf}} = -1.04 \times 10^{-7}\) is less than a third as steep as \((\partial \eta / \partial y)_{\text{ntd}}\) but is also in agreement with the estimates based on AVISO, which give \((\partial \eta / \partial y)_{\text{AVISO}} = -1.26 \times 10^{-7}\) for the shelf region north of 28°N, that is, away from northeastern Taiwan. Thus, drifters that intruded from the Kuroshio northeast of Taiwan (i.e., the NTDs) experienced an acceleration \([g(\partial \eta / \partial y)_{\text{ntd}}]\) by a sea level slope that is on average steeper than the sea level slope experienced by other shelfwide drifters in the ECS. Another way of expressing the same idea is to compare the x intercept (i.e., \(u_{\text{ntd}}\) or \(u_{\text{shelf}} = 0\), which is \(-1.05 \times 10^{-4} \text{m}^2 \text{s}^{-2}\) for Fig. 10a and \(-0.57 \times 10^{-4} \text{m}^2 \text{s}^{-2}\) for Fig. 10b, meaning that it would require nearly 2 times stronger northeasterly wind stress to stop the NTDs from drifting northeastward than to stop other shelfwide drifters. It is clear that because we have distinguished NTDs from other drifters, the steeper slope is set up by the intrusion of warmer water of the Kuroshio. The additional acceleration enables the NTDs to more easily drift northward against the northeasterly monsoon wind, which explains the larger percentage of \(u_{\text{ntd}}\) in the second quadrant. In contrast, other shelfwide drifters tend to drift more readily with the wind, with \(u_{\text{shelf}}\) staying in the third or first quadrant.

4. Vorticity balance

We explain how onshelf intrusion can occur during fall and winter using the depth-integrated vorticity equation of the two-layer planetary geostrophic model of Salmon (1992) (see also Oey et al. 2010; Wang and Oey 2014):

\[
\mathbf{U} \cdot \nabla (f / H) = (g^2 / 2) \mathbf{k} \cdot [\nabla (-H^{-1}) \times \nabla (h_t^2)] + \mathbf{k} \cdot \nabla \times (\mathbf{\tau}^o / H) - \nabla \cdot (rH^{-1}\nabla \psi),
\]

(4.1)

where \(\mathbf{U} = (u_1 h_1 + u_2 h_2, v_1 h_1 + v_2 h_2) = \mathbf{k} \times \nabla \psi\) is the total volume transport vector, \(\mathbf{k}\) is the z-directed unit vector, \(\psi\) is the transport streamfunction, subscripts 1 and 2 denote upper and lower layers, \(u\) and \(v\) are zonal (x) and meridional (y) velocities, \(h\) is the layer depth, \(f\) is the Coriolis parameter, \(H = h_1 + h_2\) is the total water depth, \(g^2\) is the reduced gravity, \(\mathbf{\tau}^o\) is the wind stress divided by water density, and \(r\) is the friction coefficient. In this equation, the nonlinear advection of vorticity has been dropped. As we will see below, this term and the wind stress and friction terms on the right-hand side are generally smaller than the advection of ambient vorticity term on the left-hand side (lhs) and the first term on the rhs—the so-called joint effect of baroclinicity and relief (JEBAR) term. Thus, the main balance is

\[
\mathbf{U} \cdot \nabla (f / H) = (g^2 / 2) \mathbf{k} \cdot [\nabla (-H^{-1}) \times \nabla (h_t^2)].
\]

(4.2)

The JEBAR term can be interpreted as follows: Suppose the upper-layer \(h_1\) deepens along the Kuroshio off northeastern Taiwan. Since the Kuroshio is approximately along isobaths, an along-isobath pressure gradient force is therefore set up, directed southwestward. A shallower water column to the north and west (i.e., shoreward of the shelf edge) experiences the same pressure force as the deeper water column to the south and east (i.e., seaward). The shallower water column will therefore (in the absence of other effects) be pushed more rapidly than the deeper column, resulting in a net gain in vorticity, which if relative vorticity remains weak compared to the ambient vorticity [i.e., according to (4.2)] is balanced by onshore movement of water parcel to the shallower shelf where the ambient vorticity is higher. This interpretation of the JEBAR term is analogous to that for the \((\nabla \rho \times \nabla p)\) term of the vorticity equation of a stratified fluid (e.g., Pedlosky 1979). Oey et al. (2010) and Wang and Oey (2014) found that the along-Kuroshio or along-isobath increase in \(h_1^2\) may be caused either by the intense, localized cooling off northeastern Taiwan during fall and winter or by a localized cyclonic wind stress curl.

We now quantify the above explanation by computing the vorticity terms using the ATOP Pacific Ocean Model of Oey et al. (2013b). The counterpart of (4.1) for a continuously stratified ocean is the z component of the curl of the depth-averaged equations (Oey et al. 2014):

\[
\partial \xi / \partial t + \mathbf{U} \cdot \nabla [(f + \xi)/D] - [(f + \xi)/D] \partial \eta / \partial t = -J(D^{-1}, \chi) + \nabla \times [(\mathbf{\tau}^0 - \mathbf{\tau}_o) / D].
\]

(4.3)

Here, \(f\) is the Coriolis parameter; \(\xi = \nabla \times \mathbf{u}_A\) is the vertical component (unit vector \(\mathbf{k}\) in the z direction, \(z = 0\) at mean sea surface) of the curl of the depth-averaged velocity \(\mathbf{u}_A = (u_A, v_A)\); \(\mathbf{U} = D \mathbf{u}_A\) is the transport vector per unit length; \(\nabla = (\partial / \partial x, \partial / \partial y)\) is the horizontal gradient operator; \(b = gr / \rho_o\); \(r\) is density; \(\rho_o\) is reference density; \(H\) is undisturbed water depth; \(\eta\) is sea surface elevation; \(D = H + \eta\) is the total water depth; \(\mathbf{\tau}^o\) and \(\mathbf{\tau}_o\) are the (kinematic) wind and bottom stress vectors, respectively; \(\chi = \int^H_0 \xi dz\); and \(J(D^{-1}, \chi) = \partial D^{-1} / \partial \xi \partial \chi / \partial y - \partial \eta / \partial \xi \partial D^{-1} / \partial y\). Equation (4.3) is a generalization of (4.1) to a continuously stratified ocean including the full nonlinear advection on the lhs. The lhs is \((\partial \xi / \partial t + \mathbf{u}_A \cdot \nabla) \text{PV}\), where \(\text{PV} = (f + \zeta)/D\), so (4.3) expresses PV conservation if the rhs = 0. We compose each term for fall and winter and spring and summer using 25-yr model data from 1990 to 2014. The composites of \(\partial \xi / \partial t\) and \(\partial \eta / \partial t\) are
orders of magnitudes smaller than the other terms, so that (4.3) becomes

\[
\mathbf{U} \cdot \nabla (f/D) + \mathbf{U} \cdot \nabla (\zeta/D) + J(D^{-1}, \chi) + \nabla \times (\mathbf{u}')/D + \nabla \times (\tau_{b}/D) = 0,
\]

where symbols define terms (with sign included) in the line above. Contours of \( \mathbf{cpvf} \) and \( \mathbf{cjbar} \), as well as each term averaged between the 200- and 500-m isobaths (i.e., along the inshore side of the Kuroshio) are shown in Fig. 11; the 500-m isobath is chosen because both the model and observed mean Kuroshio paths lie closely along it. All along the Kuroshio, the main balance is between \( \mathbf{cpvf} \) and \( \mathbf{cjbar} \), while the next order terms are \( \mathbf{cadv} \) and \( \mathbf{ctsurf} \).
ctsurf, and the cthot is very small. Northeast of Taiwan, from 122° to ~123.5°E, Fig. 11 confirms the results of Oey et al. (2010) that the cpvf is mainly balanced by cjbar. The wind stress curl (ctsurf < 0) term also contributes, and together with the cjbar (<0), they contribute to a net (positive) PV production, which, because of the PV constraint, is balanced by the onshore transport (cpvf > 0). Further along the Kuroshio, from 123.5° to ~125°E, the cjbar becomes positive, and it is balanced by offshore transport (cpvf < 0) and other negative values of the other terms. The AVISO currents are superimposed in Figs. 11a and 11b and show an anticyclonic recirculation: onshore intrusion northeast of Taiwan between 122° and 123.5°E and offshore return flow between 123.5° and 125°E farther east-northeast along the Kuroshio, in agreement with the model prediction. Farther east, cjbar and cpvf remain in approximate balance, though weaker.

Figure 11c further shows that the $\nabla \times (\sigma / D) (\approx H^{-1} \nabla \times \sigma / \delta H$ along isobaths) term is positive immediately east of Taiwan then weakens to ~0 near 123.5°E. This is consistent with Oey et al. (2010) and Wang and Oey (2014) that show the updoming of the isopycnals (i.e., thinning of the upper-layer $h_1$) is produced near Taiwan due to Ekman pumping $\nabla \times (\sigma / \delta$). The Ekman pumping decreases to the east, thus setting up the along-isobath pressure gradient and contributing to the net production of vorticity through the $\nabla (-H^{-1} \times \nabla (h_1))$ term, as explained above in conjunction with (4.2).

5. Conclusions and discussion

In this paper, decades-long drifter, satellite sea surface height, and other supporting observations and modeling are analyzed to study the seasonal influence of the Kuroshio on the shelf currents of the East China Sea. The novel feature of the study is that the Kuroshio influence is examined over the entire length of the shelf edge from northeast Taiwan to southwest Kyushu, that drifters are selected to identify the influence of the Kuroshio, and that model results are used to determine the dominant vorticity balance of flow exchanges across the shelf edge. The main findings are the following:

1) The dominant seasonal change of the Kuroshio path is that its entire length shifts onshore from fall to winter and offshore from spring to summer; the largest cross-shelf shift occurs northeast of Taiwan.

2) Drifter trajectories indicate that exchange of water mass and flow momentum across the shelf edge occurs along the entire length of the Kuroshio; however, the strongest exchange takes place over a relatively small stretch of the shelf edge northeast of Taiwan, of approximately 200 to 300 km in length.

3) Onshelf intrusion of drifters is strongest in fall and winter, coincident with the onshore phase of the Kuroshio path; the intrusion northeast of Taiwan is not only the most dominant, accounting for 60% of the total intrusion across the entire shelf edge of the East China Sea, it also penetrates farthest onto the shelf, as far as the 50-m isobath.

4) Onshelf intrusion of drifters is weakest in spring and summer, coincident with the offshore phase of the Kuroshio path, and drifters from the Kuroshio are mostly confined along the shelf-edge between the 100- and 200-m isobaths.

5) In fall and winter, the influence of the Kuroshio northeast of Taiwan is to produce an along-shelf sea level that slopes down toward the north and northeast; the resulting pressure gradient force enables drifters to penetrate as far north as the 30°N against the prevailing northeasterly monsoon wind.

6) The strong intrusion northeast of Taiwan is a result of potential vorticity constraint that requires onshelf flow into the region of high ambient vorticity or shallower depths because the shelf-edge water columns are pushed to rotate cyclonically by the rising pressure force along the east-northeastward-flowing Kuroshio.

Our study shows that the cross-shelf shift in the Kuroshio path is correlated with intrusion and intensity of exchanges across the shelf edge. Onshelf intrusion is the largest and exchanges most vigorous in fall and winter when the Kuroshio shifts most onshore and vice versa in spring and summer. In the literature, there has been some debate as to the source of the Tsushima Current in the Korea Strait, especially in winter: whether it originates solely from the Kuroshio branch west of Kyushu or from a mixture of waters of the Taiwan Warm Current and the Kuroshio branch north of Taiwan [see reviews in Ichikawa and Beardsley (2002) and Matsuno et al. (2009)]. The drifter analysis shows that the Kuroshio branch north of Taiwan contributes substantially to the water mass of the Tsushima Current. Our analysis supports Guo et al.’s (2006) numerical model results that JEBAR plays an important role in the intrusion process.

The surface influence of the Kuroshio on the shelf is therefore largest in fall and winter, especially in the southern East China Sea south of approximately 30°N due to the dominant intrusion northeast of Taiwan. There the intrusion of warmer waters in fall and winter produces the strong, localized sea level slope north of Taiwan (finding 5 above); the sea level slope weakens farther north, however. Such slope variation along the shelf may explain why there tends to be shelf flow convergence near 28°N (seen in Fig. 5 and Fig. 9). Further
studies are necessary to explore the detailed dynamics using models. Moreover, the warm-water intrusion influences not only the regional circulation and ecosystem, but it also brings heat into the shelf that in turn can change the overlying winds in a coupled manner (Oey et al. 2013a, 2015). The winter warming of the shelf water just north of the Taiwan Strait has been documented by Wang and Oey (2014). It will be an interesting future study to examine the interannual changes of the intrusion processes and the corresponding circulation and ecosystem responses on the shelf.

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