frontiers in Marine Science

REVIEW
published: 16 February 2021
doi: 10.3389/fmars.2021.620910

Progress of Studies on Circulation Dynamics in the East China Sea: The Kuroshio Exchanges With the Shelf Currents

Zhiqiang Liu[1,2], Jianping Gan[3,4], Jianyu Hu[5], Hui Wu[6], Zhongya Cai[7] and Yongfei Deng[1]*

[1] *Department of Ocean Science and Engineering, Southern University of Science and Technology, Shenzhen, China,* [2] *Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou, China,* [3] *Department of Ocean Science, The Hong Kong University of Science and Technology, Hong Kong, China,* [4] *Department of Mathematics, The Hong Kong University of Science and Technology, Hong Kong, China,* [5] *State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, China,* [6] *State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai, China,* [7] *State Key Laboratory of Internet of Things for Smart City and Department of Civil and Environmental Engineering, University of Macau, Macau, China*

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***Correspondence:**
Zhiqiang Liu
liuzq@sustech.edu.cn

Specialty section:
This article was submitted to Physical Oceanography, a section of the journal Frontiers in Marine Science

Received: *24 October 2020*
Accepted: *04 January 2021*
Published: *16 February 2021*

Citation:
Liu Z, Gan J, Hu J, Wu H, Cai Z and Deng Y (2021) Progress of Studies on Circulation Dynamics in the East China Sea: The Kuroshio Exchanges With the Shelf Currents. Front. Mar. Sci. 8:620910. doi: 10.3389/fmars.2021.620910

This paper reviews recent advances in the circulation dynamics of the Kuroshio and its interaction with shelf currents in the East China Sea (ECS). The annually averaged Kuroshio volume transport varies between 19 and 24 Sv, based on different observations, but there is no consensus on which season its volume transport peaks. The Kuroshio is intensified over the central slope of the ECS from that off the northeast of Taiwan. The total Kuroshio intrusion into the ECS shelf is estimated to be 1.3–1.4 Sv, deduced from the observed volume transport of exchange flow in the Taiwan and Tsushima Straits, based on the assumption of volume conversation over the shelf. However, the uncertainty regarding this estimation remains due to the absence of sufficient observations and understanding of the Kuroshio dynamics. The Kuroshio intrusions over the shelf off the northeast of Taiwan and southwest of Kyushu are stimulated by planetary or topographic β -effect associated with the alongshore variations in the ECS slope topography and altered by variations in the Kuroshio intensity, shear stress, and baroclinicity. Multilayered exchanges between the Kuroshio and shelf currents were found between 100- and 200-m isobaths along the central ECS slope. The spatial variations in these exchanges are governed by cross-isobath transport by geostrophy, whereas bottom Ekman transport may play a predominant role in altering the integrated exchange flow along the slope. Although the intrusion is greatly modulated along the path of the Kuroshio in the ECS by variable slope topography, there are few observations on the spatial variations of these exchange flows. The characteristics and variations in the circulation and hydrographic properties of waters between 100- and 200-m isobaths significantly determine the general ECS circulation, about which consensus has still not been attained.

Keywords: Kuroshio, East China Sea, geostrophic adjustment process, shelf currents, Ekman transport

INTRODUCTION

The Kuroshio is a strong western boundary current originating from the northward branch of the meridionally bidirectional bifurcating North Equatorial Current (NEC) at about 12–15°N to the east of the Philippine coast (Qu et al., 2016). Along its pathway toward higher latitudes in the Northwest Pacific Ocean (NWPO), the Kuroshio bypasses the Luzon Strait (18–22°N) between Taiwan and Luzon Islands and exchanges waters and momentum with the South China Sea (SCS) (Gan et al., 2016, 2020). The Kuroshio mainly enters the East China Sea (ECS) through the East Taiwan Channel between the northeast of Taiwan and Yonaguni-Jima Island—an island at the southwestern tip of the Ryukyu Islands (**Figure 1**). A small portion of Kuroshio can also intrude into the ECS shelf through the Luzon and Taiwan Straits (Hu et al., 2010), although the dynamics underlying the exchange flows in these two straits have not been well proposed. The Kuroshio plays a critical role in altering not only the meridional heat transport in the NWPO but also the circulation in the seas to the land side of its pathway due to the enormous amount of heat and momentum it transports (Zhang et al., 2002; Nakamura, 2020).

The ECS is located at the mid-latitude of the NWPO. It is bounded by the Chinese mainland, Taiwan, the Ryukyu and Kyushu Islands, and the Korean Peninsula (**Figure 1**). The ECS shelf widely opens to the southern Yellow Sea to the northwest and connects to the northern SCS to the southwest through the Taiwan Strait. The currents in the Tsushima/Korea Strait convey the ECS waters to the Japan Sea to the northeast (Senjyu, 2020). The Ryukyu Islands separate the ECS from the deep NWPO to the east. The total ECS area is approximately 0.77×10^6 km^2, where the continental shelf shallower than 200 m accounts for about 66% of the ECS area. The maximum water depth of over 2,000 m is in the central Okinawa Trough, where a large topography gradient exists in both the cross-slope direction.

The Kuroshio is crucial in regulating not only the circulation dynamics of the shelf (Lie and Cho, 2016; Wei et al., 2020) but also the associated biogeochemical processes (Zuo et al., 2019; Chen et al., 2020; Zhai et al., 2020). The intrusion of the Kuroshio subsurface waters from the shelf off the northeast of Taiwan characterizes the bottom waters of the ECS shelf (Zhou et al., 2018a). These waters intrude further northeastward into the coastal seas off the Zhejiang coast (Yang et al., 2013). The Kuroshio intrusive waters carry high concentrations of phosphorus to support the primary production over the ECS shelf (Wang et al., 2018). The stimulated production regulates the dissolved oxygen concentrations (Zuo et al., 2019) and the hypoxia conditions (Qian et al., 2017; Chen et al., 2020) in the shelf waters seaward of the Changjiang Estuary. The multiscale variations in the Kuroshio intrusion superimpose complex forcings over the shelf to regulate the ECS circulation (Su, 2001; Lie and Cho, 2002; Guan and Fang, 2006; Isobe, 2008; Matsuno, 2020). However, because of the complexity of this interactive and dynamic circulation system, the associated processes and driving mechanisms, which control the variability and interlinkage of multiscale circulations in the ECS, are still poorly known.

This paper gives a review of the publications on the interaction between the Kuroshio and shelf currents published in recent decades (from the 1990s to the 2010s) and synthesizes the discoveries and understanding of circulation dynamics. The Kuroshio dynamics, including its multiscale temporal and spatial variabilities and its interaction with the ECS shelf circulation, are synthesized. We also aim to identify the uncertainties and knowledge gaps that merit further study. Following this introduction, we present the findings related to the nature and variability of the Kuroshio over the ECS continental slope in Section "Mean State and Variability of Kuroshio Volume Transport." The Kuroshio exchanges with major ECS shelf currents are synthesized in Section "Water Exchanges Between the Kuroshio and the ECS Shelf." We explore the dynamics underlying the interactive Kuroshio and shelf currents in Section "Dynamics Underlying the Exchange Flows," and Section "Schematic of the Interactive Kuroshio and Shelf Currents" updates the schematics of the interactive Kuroshio and ECS shelf current. Section "Summary and Prospects" concludes this paper. Several earlier complementary review papers are available for reference (Su, 2001; Lie and Cho, 2002, 2016; Isobe, 2008; Qu et al., 2016). Unlike previous reviews that presented mainly the characteristics of the Kuroshio and its exchange flows with the ECS shelf current, our focus is on the underlying dynamics of the Kuroshio.

MEAN STATE AND VARIABILITY OF KUROSHIO VOLUME TRANSPORT

To facilitate our review, we present the annual mean and depth-averaged velocity vectors in the vicinity of the ECS shelf (**Figure 2A**). This velocity was obtained from the validated climatological simulation by Gan et al. (2016). In order to better represent the spatial characteristics of the cross-shore water exchanges in the later contents, we further project the velocities to the cross-isobath direction and illustrate the Kuroshio intrusion by positive values in **Figure 2B**. The exchange between the Kuroshio and other shelf currents is composite of the Kuroshio intrusion into the ECS and the extrusion of shelf waters into the Kuroshio.

The Kuroshio is the most energetic current in the ECS (**Figure 2A**). It flows northeastward along the 200-m isobath until approximately 30°N in the Okinawa Trough, where its mainstream veers eastward to exit the ECS through the Tokara Strait (**Figure 1**) to the south of Kyushu Island (Ichikawa and Beardsley, 1993; James et al., 1999). The width of the Kuroshio mainstream in the ECS reaches 200 km (Liu and Gan, 2012). **Table 1** shows the Kuroshio volume transport estimations along its stream in the ECS (**Figure 2A**). To compile **Table 1**, we mostly regarded the studies with explicitly shown seasonality of the Kuroshio intensity and separately illustrated the results from observations (mostly based on geostrophic calculations) and numerical simulations. The published observations/simulations confirmed that the annually averaged Kuroshio volume transport is approximately 22.35/22.81 Sv. The reviewed studies also showed that, although the mainstream over the Okinawa Trough

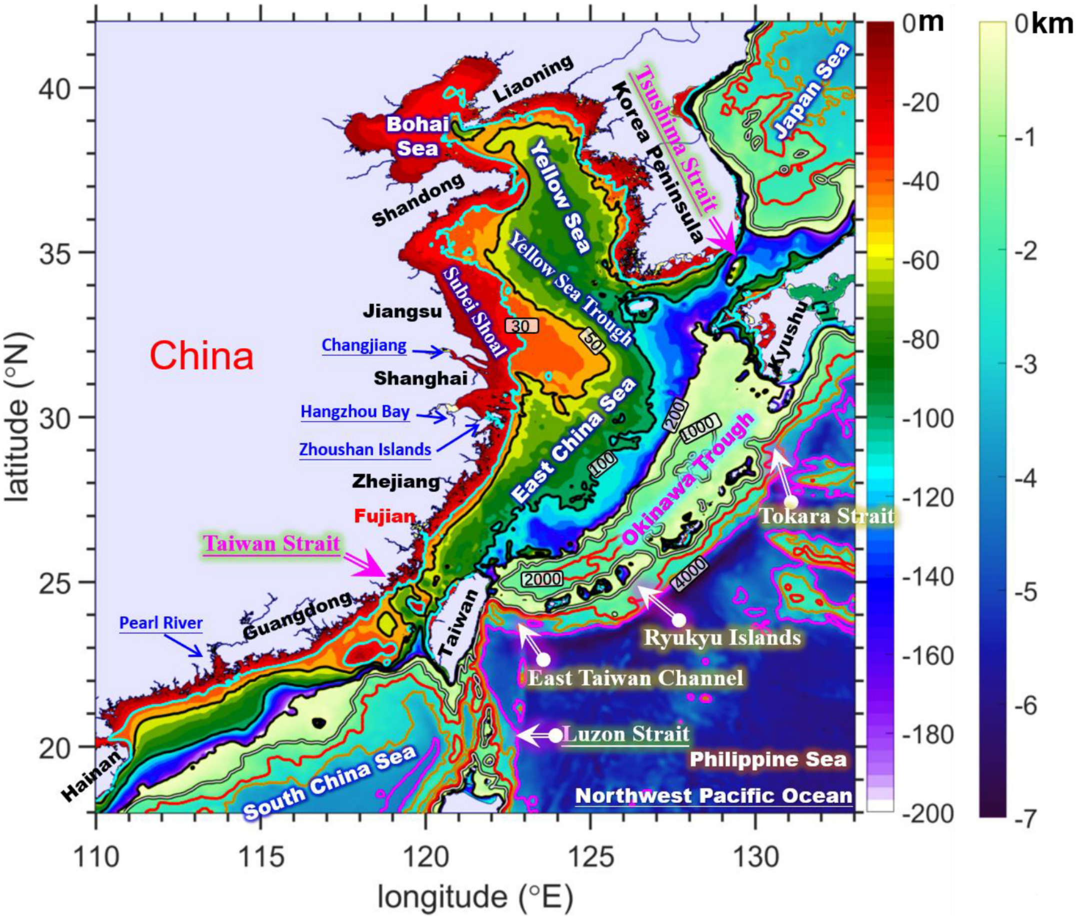

FIGURE 1 | Topography in the vicinity of the ECS shelf with the waters deeper and shallower than 200 m illustrated by different colormaps. The 30-, 50-, 100-, and 200-m isobaths over the shelf and the 1, 000-, 2, 000-, 3, 000-, and 4,000-m isobaths in the deeper seas, as well as the names of the seas, rivers, troughs, and straits discussed in this paper, are also shown. The bathymetry is composed from the digitalized navigation map in the coastal areas and the ETOPO1 arc-minute global relief model (Amante and Eakins, 2009).

is relatively stable, remarkable fluctuations in the Kuroshio volume transport are shown.

On a seasonal scale, majority of the observations suggests that the Kuroshio volume transport reaches its maximum in the warm half of the year and its minimum in the cold half of the year, except those estimations over the PCM-1 section in the East Taiwan Channel in Lee et al. (2001) and Johns et al. (2001). Nonetheless, no consensus exists for the Kuroshio volume transport peak season (**Table 1**). For example, Su et al. (1990) reported that the Kuroshio was stronger in the spring and weaker in the autumn, supported by the recent observations and simulations by Yang D. et al. (2018) and (Wei et al., 2013), while the other simulations, e.g., Guo et al. (2006), Li et al. (2013), and Zhang et al. (2017), and the observation-based estimations by Tang et al. (2000) and Liu X. H. et al. (2014) showed that the Kuroshio was stronger in the summer and weaker in the winter.

It has long been recognized that the Kuroshio volume transport fluctuates widely from days to decades (James et al., 1999; Hsin et al., 2008, 2011, 2013; Zhu et al., 2015). The observations by Qiu and Imasato (1990) and Ichikawa and Beardsley (1993) showed high-frequency fluctuations in the Kuroshio volume transport that propagated downstream with a period of 8–32 days and a wavelength of 100–300 km. The characteristics of these disturbances were further detailed by James et al. (1999) and Tang et al. (2000), indicating that the Kuroshio volume transport fluctuates both seasonally and intra-seasonally (Jan et al., 2015), and the estimated phase speed of these waves ranges between 10 and 30 km/day (James et al., 1999). These Kuroshio fluctuations are excited by the frontal waves through baroclinic instabilities over the slope, where the bottom topography changes abruptly (Isobe and Beardsley, 2006).

The Kuroshio volume transport also experiences low-frequency fluctuations in the scales of interannual and decadal variabilities, as recently summarized in Nakamura (2020) and Matsuno (2020). Chang and Oey (2011) reported that fluctuations in the Kuroshio volume transport in the interannual period are modulated by extensive eddy activities in the Philippine Sea to the east of Taiwan and the Philippines, as also shown in, for example, Hsin et al. (2013) and Shen et al. (2014).

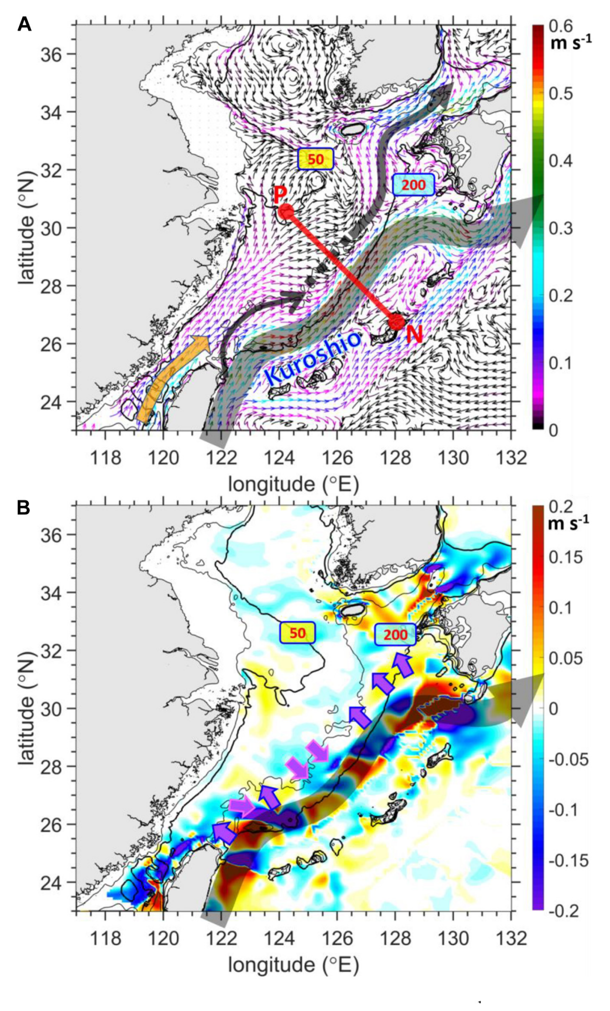

FIGURE 2 | (A) Annual mean and depth-averaged velocity (in meters per second) and **(B)** cross-isobath velocity (in meters per second) in the vicinity of the East China Sea (ECS) shelf and from the simulation in Gan et al. (2016). The 50- and 200-m isobaths over the ECS shelf and the PN line (*red line*) as well as the general features of the Kuroshio mainstream (*bold gray arrow*) are illustrated. The *thin gray lines* in panel **(A)** exhibit the circulations between the 100- and 200-m isobaths, and the *orange arrow* denotes the circulation in the Taiwan Strait. The *arrows* in panel **(B)** indicate the location where the onshore and offshore velocities are observed.

In the recent two decades, the Kuroshio mainstream showed an onshore decadal trend, coincident with a warming trend over the ECS shelf (Wang and Oey, 2014). These eddies impose multidecade changes of the Kuroshio to the east of Taiwan (Hsin, 2015). They cause convergence and divergence in the neighboring ocean currents and modulate the Kuroshio volume transport (Yan et al., 2016). It is recently found that both cyclonic and anticyclonic eddies could weaken/strengthen the Kuroshio volume transport (Yan et al., 2016), although there is still recent argument stating that the cyclonic eddies are responsible for a weakened Kuroshio volume transport (Ren et al., 2020). Liu X. H. et al. (2014) noted that the Kuroshio volume transport in the ECS is stronger during the El Niño years than the La Niña years. This conclusion indicates that the interannual variations of the Kuroshio volume transport in the ECS are opposite to those in its upstream part, to the east of the Philippines (Hu et al., 2015). The eddy activity to the east of Taiwan, with a timescale of 70–120 days (Hsin et al., 2011) and a spatial scale of 100–200 km (Jan et al., 2017), blurs the correlation between the fluctuations in the Kuroshio volume transport and those of the Pacific Decadal Oscillation (PDO) (Andres et al., 2008b; Soeyanto et al., 2014) that is considered to critically alter the wind stress curl over the NWPO. The greatly increased zonal variations of wind over the NWPO after 1999 also greatly deteriorate the associations of the Kuroshio variability and PDO (Wu et al., 2019). The long-term observations analyzed in Wei et al. (2013) showed that the dominant period of interannual fluctuations (±2.8 Sv) in the Kuroshio volume transport is 2–5 years. Shen et al. (2014) found that the annually averaged intensity of the Kuroshio is regulated by the volume transport in the northward-branching NEC to the east of the Philippines. This NEC branching differs substantially between the El Niño and La Niña years, and its variability in the East Taiwan Channel is regulated by eddy activities in the basin to the east of Taiwan, as also recently confirmed by Jan et al. (2017).

In addition to the temporal variabilities, considerable spatial variations in the Kuroshio volume transport are noted in the ECS (**Table 2**), even though the spatial variations in the Kuroshio volume transport are less studied than its temporal variability. The Kuroshio intensifies from the East Taiwan Channel to the central ECS slope (e.g., PN line in **Figure 2A**) and then weakens further downstream toward the Tokara Strait (Ichikawa and Chaen, 2000). This spatial variation in the ECS volume transport with a strengthened Kuroshio along the central ECS slope was modeled by Guo et al. (2006), Wei et al. (2013), and Liu X. H. et al. (2014) and observed using satellite remote sensing of surface elevation along the ECS slope (Liu and Gan, 2012).

WATER EXCHANGES BETWEEN THE KUROSHIO AND THE ECS SHELF

It has long been recognized that it is difficult to estimate the water exchange between the Kuroshio and the ECS shelf currents in three dimensions sufficiently and synchronously. The indirect estimation of the water exchange between the Kuroshio and the ECS shelf currents is based on volume conservation over the ECS shelf and numerical simulations (Yang et al., 2013). Isobe (2008) summarized field estimations at the entrance/exit of the ECS (the Taiwan/Tsushima Straits) to quantify the water exchanges between the ECS shelf and the Kuroshio based on the law of mass (volume) conservation. This conservation showed an annually averaged northeastward transport in both the Taiwan Strait and the Tsushima Strait. The estimated annually averaged volume transport of the northeastward current in the Taiwan Strait, the so-called Taiwan Strait Current (TSC), equals approximately 1.2 Sv. The flow pattern and the variability of this TSC are synthesized in Hu et al. (2010). The annually averaged volume transport of the northeastward current in the Tsushima Strait, the so-called Tsushima Warm Current (TSWC), is approximately 2.6 Sv (Yang et al., 2011). The consensus on

TABLE 1 | Summary of the observed and simulated annually and seasonally averaged Kuroshio volume transport in the ECS (Sv = 10^6 m^3/s), in which PCM-1 is 24.5°N, 122.17°E to 24.06°N, 123°E and PN line is 30°N, 124.5°E to 27.5°N, 128.5°E.

Annual (Sv)	Spring (Sv)	Summer (Sv)	Autumn (Sv)	Winter (Sv)	References	Location
Observation						
21.5	21.2	22.4	21.5	**22.5**	Lee et al., 2001	PCM-1
21.5	23.3	23	21.9	**23.9**	Johns et al., 2001	PCM-1
21.25	**22.6**	22	19.1	21.3	Su et al., 1990	PN line
23.7	16.5	**36.0**	25.5	21.7	Ichikawa and Beardsley, 1993	PN line
23.03	25.88	**28.54**	23.52	14.17	Ichikawa and Chaen, 2000	PN line
18.7	18.8	**19.0**	18.1	18.9	Andres et al., 2008a	PN line
18.5					Andres et al., 2008b	
22.48	**23**	22.56	21.29	21.15	Wei et al., 2013	PN line
23.20	23.63	**24.46**	21.94	22.76	Wei et al., 2015	PN line
25.84	24.63	**27.17**	24.83	26.49/26.73	Liu et al., 2019	Tokara Strait
22.35	**22.17**	**25.01**	**21.96**	**21.4**	Mean value	
Simulation						
23.46	23.17	**25**	23.67	22	Lee and Chao, 2003	Off the east of Taiwan
21.84	21.25	**22.5**	21.3	22.3	Lee and Takeshi, 2007	Off the east of Taiwan
24.7	26.2	**26.6**	23	22.9	Li et al., 2013	Off the east of Taiwan
23.11	23.92	**24.89**	21.08	22.55	Zhou et al., 2015	Off the east of Taiwan
21.52	21.5	**22.0**	20.7	21.9	Zhang et al., 2017	PN line
22.24	**23.98**	23.67	20.11	21.18	Li et al., 2013	Tokara Strait
22.81	**23.34**	**24.11**	**21.64**	**22.14**	Mean value	

The bolded values denote the largest volume transport among seasons.

the Kuroshio volume transport intrusion into the ECS seems to proceed with the Isobe (2008) conclusions, and the TSC annually averaged volume transport is recently estimated to be approximately 1.32 Sv (Chen et al., 2016) by the ship-boarded Acoustic Doppler Current Profilers (ADCP). Therefore, the annual mean Kuroshio intrusion intensity equals almost 1.3 Sv. The numerical simulation by Gan et al. (2016), in which the transports in the Taiwan Strait and the Tsushima Strait were determined by internal dynamics in the NWPO, was consistent with the estimations. The recent numerical simulation in Yang et al. (2020) presents that the wind stress to the east of Japan, instead of the regional wind stress over the ECS shelf, established a southward transport (2.2 Sv) in the NWPO, which could impose a northward shelf current to stimulate the Kuroshio intrusion toward the ECS shelf along its mainstream. This finding is partially consistent with the observations and simulations by Liu X. H. et al. (2014), which proposed that the regional wind stress mainly functions to modulate the heat flux to alter the Kuroshio intrusion.

It is also worth noticing that the estimations based on the conservation of water masses over the ECS shelf can only present the intensity of the integrated exchange flows. The pathway of the Kuroshio intrusion and extrusion of the ECS shelf current, and the respective intensity of those exchange flows, cannot be presented. The recent simulation based on the passive-tracers method suggested that the annually averaged intensity of the Kuroshio intrusion is ~1.85 Sv, while the volume transport of the extrusive shelf waters is ~0.42 Sv (Hu et al., 2020). It should also be noted that this Kuroshio intrusion is actually composed by extensive outflows and inflows along the ECS slope, as shown in Zhang et al. (2017). The magnitude of these outflows and inflows reduces from that over the 200-m isobath to over the 50-m isobath in the central ECS shelf. Given the importance of the along-shelf variabilities of the pathway and the intensity of the exchange flows critically determines the budget of, for example, biogeochemical substances over the ECS (Chen et al., 2020; Hu et al., 2020). The spatial variabilities of the interactive Kuroshio and the ECS shelf currents should be further investigated.

Kuroshio Intrusion Into the ECS Shelf

Along the northeastward mainstream in the Okinawa Trough (**Figure 2A**), the Kuroshio intrudes into the ECS shelf (<200 m) through two branches, which are located over the shelf off the northeast of Taiwan and the southwest of Kyushu (**Figure 2B**). An extensive exchange of the shelf currents and the Kuroshio are shown by the arrows in **Figure 2B** between the 100- and 200-m isobaths. The general nature of currents and hydrography is typically determined by the characteristics of both the Kuroshio and the shelf currents in the ECS between the 100- and 200-m isobaths and those in the central ECS.

Most previous studies, for example, Lie et al. (1998), focused on the characteristics of the Kuroshio intrusion following the two pathways: over the shelf off the northeast of Taiwan and southwest of Kyushu. However, few direct quantitative estimations of the intensity of these intrusions exist, except for the field observations by Katoh et al. (2000) in July 1995, describing how the intrusive Kuroshio bifurcates into two branches near the 100-m isobath over the shelf off the northeast of Taiwan. The main branch extends northeastward along the 100-m isobath toward the Tsushima Strait further downstream, with a volume transport of approximately 0.3 Sv. The estimation by Liu et al. (2000) based on chemical hydrography and velocity records

TABLE 2 | Summary of the estimated Kuroshio volume transport off the east of Taiwan, over the central East China Sea (ECS) and in the Tokara Strait (Sv = 10^6 m^3/s), in which PCM-1 is 24.5°N, 122.17°E to 24.06°N, 123°E; KTV-1 is 23.88°N, 121.72°E to 23.62°N, 123.0°E; KTV-2 is 22.75°N, 121.20°E to 22.75°N, 123.00°E; KTV-3 is 22.00°N, 121.00°E to 22.00°N, 123.00°E; PN line is 30°N, 124.5°E to 27.5°N, 128.5°E; PN1–PN5 is 27.5°N, 128.25°E to 28.7°N, 126.47°E; and Yakushima to Amamioshima is 30.5°N, 130.5°E to 28.5°N, 129.5°E.

	Averaged Kuroshio volume transport (Sv)	Estimated Kuroshio volume transport (Sv)	References	Methods	Time period	Location	Maximum depth	
Off the East of Taiwan	22.3	**23.83**	Guo et al., 2006	(1/18)° model	1995–1998	˜24.5°N; Taiwan coast to 124.5°E	\	Numerical Simulation
		25.8	Hsin et al., 2008	(1/8)° model	1982–2005	PCM–1	1,000 m	
		21.37	Yang et al., 2011	˜8 km model	2000–2010	˜24.5°N; Taiwan coast to 124.5°E	Entire water column	
		25.75	Li et al., 2013	(1/4)° model	1959–2007	˜24.5°N; Taiwan coast to 123.5°E	\	
		25.88	Soeyanto et al., 2014	(1/12)° model	1993–2012	Transect that connects Keelung and Ishigaki	\	
		20.03	Zhu et al., 2015	(1/18)° model	1993–2003	PCM–1	\	
		20.63	Yang D. et al., 2018	˜4 km model	Jan 1993–Dec 2015	˜24.5°N; Taiwan coast to 124.5°E	\	
		22.6	Liu et al., 1998	ADCP	Oct 1990–May 1995	I-lan ridge (˜24.5°N)	Entire water column	Observation
		21.5	Johns et al., 2001	Current meters	Sep 1994–May 1996	PCM–1	Entire water column	
		23	Teague et al., 2003	Climatological mean based on previous estimations (Hsueh et al., 1992; Ichikawa and Chaen, 2000; Johns et al., 2001)				
		10.46-22.92	Jan et al., 2015	ADCP	Sep 2012–Sep 2014	KTV–1	Entire water column	
		9.5-23.5	Mensah et al., 2015	CTD and ADCP	Nov 2012–Sep 2014	KTV–1, 2, 3	26.1 kg/m^3 isopycnal	
		21.4	Yan et al., 2016a	ADCP and current meters	Sep 1994–Jun 1996	PCM–1	Entire water column	
		26.5	Jan et al., 2017	Pressure-sensor equipped inverted echo sounders	Nov 2012–Oct 2014	KTV–1	800 m	
Central ECS	24.37	**24.44**	Guo et al., 2006	(1/18)° model	1995-1998	PN	\	Numerical Simulation
		24.1	Hsin et al., 2008	(1/8)° model	1982–2005	PN	1,000 m	
		26.31	Liu X. H. et al., 2014	(1/18)° model	1993–2011	PN	1,000 m	
		21.47	Zhang et al., 2017	(1/12)° model	1993-2009	PN	700 m	
		27.2	Yuan et al., 1998	ADCP and current meters	May-Jun 1996	PN	1,200 m	Observation
		24.61	Zhang et al., 2012	Observation	1955–2003	PN1-PN5	700 dbar	
		22.48	Wei et al., 2013	In-situ hydrographic data	1955–2010	PN	\	
Tokara Strait	20.68	**19.47**	Guo et al., 2006	(1/18)°model	1995-1998	Yakushima to Amamioshima	\	Numerical Simulation
		20.66	Yang et al., 2011	˜8 km model;	2000–2010		Entire water column	
		23.19	Li et al., 2013	(1/4)°model;	1959–2007		\	
		30.11	Soeyanto et al., 2014	(1/12)°model;	1993–2012		\	
		19.22	Zhu et al., 2015	(1/18)°model	1993–2003		\	
		20	Teague et al., 2003	Mass balance		Yakushima to Amamioshima	\	Observation
		21.9	Bingham and Talley, 1991	CTD	31 May–3 Jun 1985		1,400 m	
		23.4	Feng et al., 2000	CTD and ADCP	Mar 1992–Mar 1996		1,000 m	
		23.03	Zhu et al., 2017	Shipboard ADCP	2003–2011		500 m	
		25.84	Liu et al., 2019	Shipboard ADCP	2003–2012		700 m	

Gray shading is used to differentiate the numerical simulated and observed values. Bold values indicate the main points should be highlighted. The others indicate details related to the methods to get the value.

suggested that the onshore intrusions of the Kuroshio subsurface waters were 0.6–0.8 Sv in August 1994 and March 1995. Similarly, even though the northward Kuroshio intrusion over the shelf off the southwest of Kyushu has long been recognized using satellite-tracked surface drifters (Ma et al., 2009; Liu and Gan, 2012; Lie and Cho, 2016), its intensity has been rarely estimated. The satellite observations by Guo et al. (1991) indicated that northward branching of the Kuroshio toward the Tsushima Strait was stronger in January 1988, with volume transport of approximately 1.45 Sv, and weaker in July 1987, with about 0.29 Sv. Lie and Cho (1994) also observed that the Kuroshio waters intruded across the 200-m isobath over the central ECS slope and traveled farther north toward the Tsushima Strait. Their estimations using hydrographic data suggested that the average intensity of this intruding current was approximately 4.0 Sv during the two observational periods of December 1993 and late April–early May 1995 (Lie et al., 1998). However, the field observations by Katoh et al. (1996) in the summers of 1991 and 1994 showed that the intensity of this intrusion was approximately 0.5 Sv.

The aforementioned estimations then present a wide range of the northward-branching Kuroshio volume transport due to the complexity of the circulations in these two pathways (Lie and Cho, 2016). Great uncertainty still exists among those few presented observations about the Kuroshio intrusion intensity. As such, these estimations cannot contribute to quantifying the relative importance of the Kuroshio intrusion along the ECS shelf slope. The strength and relative importance of intrusions along these two pathways are thereby still debated (Isobe, 2008). These disagreements, together with those on the volume transport in the Taiwan Strait, lead to debates on the general flow patterns over the outer shelf of the ECS.

We synthesized the findings of the previous studies concerning the dynamics underlying the Kuroshio intrusion over the shelf off the northeast of Taiwan, off the southwest of Kyushu, and the less studied intrusion over the central ECS slope in the following contents.

Over the Shelf Off the Northeast of Taiwan

A year-round upslope intrusion of the Kuroshio across the 200-m isobath over the shelf off the northeast of Taiwan has been frequently observed and simulated (Chang et al., 2009; Yang et al., 2011, 2012; Li et al., 2013; Wu et al., 2014; Yang D. Z. et al., 2018; Zhou et al., 2018a). Although rarely quantified, previous studies consider that the dynamics underlying this year-round intrusion are primarily imposed by the adjustment of the Kuroshio to the regional topography setup and the frictional transport associated with the extensive northeastward-flowing Kuroshio.

The setup of coastlines and bottom topography over the shelf off the northeast of Taiwan has long been considered to excite this intrusion, which is stimulated by the β -effect of the Earth's rotation. The intrusive currents bend around Taiwan and enter the ECS shelf (Qiu and Imasato, 1990). The reduced-gravity simulation over simplified topographies by Hsueh et al. (1992) further suggested that this intrusion is sensitive to the incident angle of the Kuroshio with the slope topography and the ratio of step depth (depth of the shelf) to depth of the upper-layered ocean. The subsequent observations and reduced-gravity simulations showed that the Kuroshio intrusion over the shelf off the northeast of Taiwan is induced by the blocking effect of the zonally running isobaths (Hsueh et al., 1993).

Given the fact that the Kuroshio extensively flows northeastward along the continental slope, the associated bottom Ekman transport beneath the northeastward-flowing Kuroshio was also considered to regulate this intrusion (Jacobs et al., 2000). However, the relative contribution of the bottom Ekman transport to the integrated Kuroshio intrusion into the ECS is still disagreed upon. The high-resolution numerical simulation by Guo et al. (2006) exhibited that Ekman transport modulates the integrated volume transport across the entire ECS slope, while the change in the density field predominantly regulates the Kuroshio intrusion intensity over the shelf off the northeast of Taiwan. Ding et al. (2016) have recently analyzed the long-term satellite altimetry and *in situ* hydrographic measurements for the years 1993–2014 and found that the Kuroshio intrusion over the shelf off the northeast of Taiwan is the dominant component of the integrated Kuroshio intrusion (1.7 ± 2.0 Sv) along the continental slope in the Okinawa Trough. They stated that this intrusion is induced by the combined surface (0.6 ± 0.6 Sv) and bottom (2.7 ± 1.0 Sv) Ekman transport, while the geostrophic transport, integrated along the 200-m isobath over the shelf, is seaward (-1.5 ± 1.7 Sv). This conclusion is consistent with that of Wang and Oey (2016), who analyzed the Kuroshio exchange with the ECS shelf waters using satellite-tracked surface drifters. The numerical simulation in Zhang et al. (2017) further showed that the seasonality of surface Ekman transport is consistent with that of the Kuroshio intrusion in the upper 60 m (0.38 ± 0.41 Sv) over the 200-m isobath in the ECS, while the bottom Ekman transport (0.60 Sv) explains part of the Kuroshio intrusion (1.27 Sv). The authors also proposed that over the 100-m isobath, the bottom Ekman transport plays a predominant role in contributing to the integrated intensity of the exchange flows (∼1.39 Sv) over this isobath.

The Kuroshio intrusion shows notable seasonality (**Figure 3**). A stronger upslope intrusion occurs in the cold half of the year, and a weaker one takes place in the warm half of the year (Chuang and Liang, 1994; Hu et al., 2008; Ma et al., 2009; Zhou et al., 2017). Su (2001) synthesized the observed hydrographic properties over the shelf off the northeast of Taiwan for the 1980s and 1990s and concluded that the Kuroshio branches over the 200-m isobath in the winter when extensive northeasterly monsoon prevails, and the mainstream of Kuroshio migrates shoreward toward the ECS shelf (Ichikawa et al., 2008; Liu and Gan, 2012). The conceptual simulation over simplified topography by Oey et al. (2010) indicated that spatial irregularity in heat flux, especially due to cooling in the winter, could also greatly alter the intrusion intensity by stimulating the downslope transport of shelf waters through the joint effect of baroclinicity and relief (JEBAR). The Kuroshio intrusion over a sharply eastward-deflecting slope is thereby generated to compensate for this downslope transport.

In the summer, when the Kuroshio is stronger and its mainstream departs from the 200-m isobath, the Kuroshio intrusion is mostly compiled by the extensive upwelling of the subsurface Kuroshio waters. This upwelling forms a cold

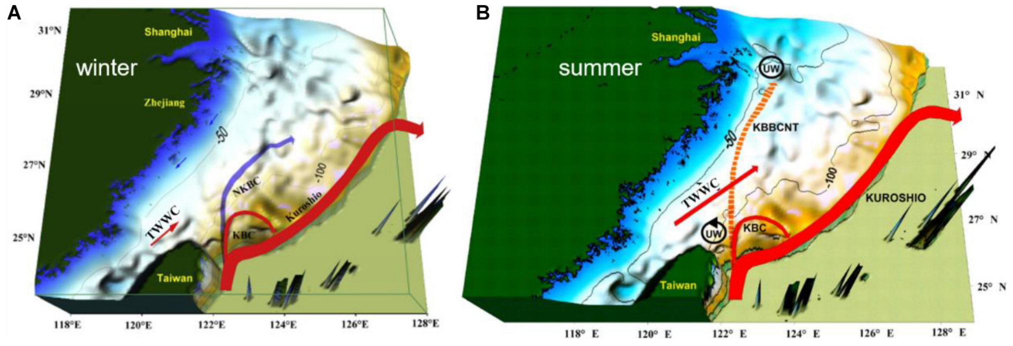

FIGURE 3 | Schematic maps of the **(A)** nearshore Kuroshio branch current in winter (Yang D. et al., 2018) and the **(B)** Kuroshio Bottom Branch Current off the northeast of Taiwan in summer (Yang et al., 2011), where the Taiwan Warm Current (TWWC) overlaps. KBC stands for Kuroshio Branch Current in Qiu and Imasato (1990). In panel **(A)**, NKBC stands for nearshore Kuroshio Branch Current. In panel **(B)**, UW denotes upwelling and KBBCNT stands for Kuroshio Bottom Branch Current off the northeast of Taiwan.

dome (i.e., cyclonic eddy) over the shelf off the northeast of Taiwan (Chern et al., 1990; Tang et al., 1999; Wong et al., 2000; Wu et al., 2008; Liu et al., 2015; Zhang et al., 2015; He et al., 2019). The succeeding observations and numerical modeling studies (Yang et al., 2011, 2012, 2013; Li et al., 2013; Zhou et al., 2018a) suggested that those intrusive Kuroshio waters travel further shoreward to feed coastal upwelling on the lee side of the Zhoushan Islands because of the irregularities in the along-slope topography (Liu and Gan, 2014). Recent observations and numerical simulations by Yang D. Z. et al. (2018) and Yang D. et al. (2018) further disclosed that the Kuroshio intrusion is established through a topographic β -spiral associated with a topographically induced upwelling in the stratified ocean in the summer. The numerical simulation by Liu X. et al. (2020) also revealed that non-linear advection determines not only the integrated Kuroshio intrusion but also its variability in the water column by modulating the bottom pressure torque of the depth-integrated potential vorticity dynamics.

In the intra-seasonal and interannual timescales, the Kuroshio intrusion variability over the shelf northeast of Taiwan is intensified when a weaker Kuroshio volume transport is present and the Kuroshio mainstream is closer to the shelf (Zhang et al., 2001; Zhuang et al., 2020). The high-frequency radar observations by Takahashi et al. (2009) showed biweekly (10–20 days) onshore–offshore migration of the Kuroshio mainstream. It is initiated by the biweekly fluctuations of the currents to the east of Taiwan in the form of interior shelf waves and due to the northeastward propagation of eddies. These variations modulate the intruding current over the shelf off the northeast of Taiwan through regulating the onshore and offshore displacement of the Kuroshio mainstream (Zhang et al., 2001). Yin and Huang (2019) have recently confirmed the universality of these short-term biweekly variations by using high-frequency satellite remote sensing data.

The Kuroshio intrusion also shows extensive interannual variabilities, which are related to the El Nino-Southern Oscillation (ENSO) (Hwang and Kao, 2002) and the PDO (Wu, 2012; Hsin et al., 2013; Wu et al., 2014). The extensive eddy activities in the Pacific Subtropical Countercurrent (STCC) area greatly regulate the interannual variabilities of the Kuroshio intrusion by regulating the fluctuation of the Kuroshio mainstream and intensity (Chang and Oey, 2011; Ren et al., 2020), and a stronger Kuroshio onshore intrusion occurred between 2002 and 2013, when the Kuroshio volume transport was suppressed (Wu et al., 2017). Yin et al. (2017) proposed that the arrival of cyclonic eddies, through strengthening the positive potential vorticity flux, facilitates the Kuroshio intrusion. Liu X. H. et al. (2014) and Liu et al. (2015) studied the long-term variations in the trajectories of satellite-tracked surface drifters and reconstructed their motions using numerical simulations. They elucidated that the Kuroshio intrusion is regulated by a secondary maximum current core over the shelf to the shoreward of the Kuroshio mainstream. The core of this current fluctuates on the interannual timescale, and together with regional variations in the Kuroshio heat flux and inertia, it determines the Kuroshio intrusion over the shelf off the northeast of Taiwan. The high-resolution numerical simulations by Liu C. Y. et al. (2014) also indicated that the interannually fluctuating Kuroshio volume transport regulates its intrusion over the shelf off the northeast of Taiwan, and a strengthened Kuroshio volume transport weakens the intrusion.

Over the Shelf Off the Southwest of Kyushu

When the Kuroshio mainstream in the central Okinawa Trough veers eastward at approximately 30°N, a northward branch toward the Tsushima Strait is formed (**Figure 2A**). This eastward-veering Kuroshio is governed by the advection of the geostrophic potential vorticity and the JEBAR due to along-slope variations in the bottom topography and the baroclinicity of the Kuroshio (Guo et al., 2003, 2006). Northward branching of the Kuroshio happens in the shoreward direction of its mainstream because of the existence of Kyushu Island (Hsueh et al., 1996; Hsueh, 2000). These intruding Kuroshio waters impact not only the circulation in the Tsushima Strait (Isobe, 1999, 2000; Takahashi and Morimoto, 2013; Zhang et al., 2017) and the Japan Sea (Chang et al., 2004; Senjyu, 2020) but also in the Yellow Sea (Hwang et al., 2014; Gan et al., 2016; Lie and Cho, 2016).

Over the Central ECS Slope

Although most published studies have focused on the Kuroshio intrusions over those previous two branches (off the northeast of Taiwan and southwest of Kyushu), more recent studies have discussed the exchange between the ECS shelf currents and the Kuroshio across the central ECS slope. For instance, Ito et al. (1995) measured the cross-slope velocity profiles in the central ECS in September 1991 and proposed an extensive upslope intrusion of Kuroshio waters, probably induced by the meandering of the shelf break front. This onshore Kuroshio intrusion was also indicated by their earlier measurements of silicon distributions along the ECS slope and the recent analyses based on the dissolved inorganic iodine species (Zhou et al., 2017, 2018a,b). The high-resolution numerical simulation by Zhou et al. (2015) revealed two additional intrusion streams at approximately 26°N and 28°N in the central ECS slope, where the Kuroshio intrudes across the 200-m isobath. Zhang et al. (2017) simulated the cross-slope velocity over the 200-m isobath in the ECS and found an extensive exchange of flow between the Kuroshio and the ECS shelf waters in the central ECS (**Figure 4**). They suggested that the Kuroshio upslope intrusion across the 200-m isobath in the central ECS mainly occurs in the bottom layer. In the water column, the exchange velocity (averaged along the 200-m isobath) shows a not well-defined three-layer structure with shoreward flows in both the surface and bottom layers and an offshore current in the intermediate layer, especially in the winter (**Figure 5**). Wei (2018) established a conceptual simulation by solving the sectional two-dimensional primitive equations driven by temperature and salinity observations over the PN section. They proposed that the horizontal shear stress of the Kuroshio induces the upslope intrusion of the Kuroshio waters into the central ECS.

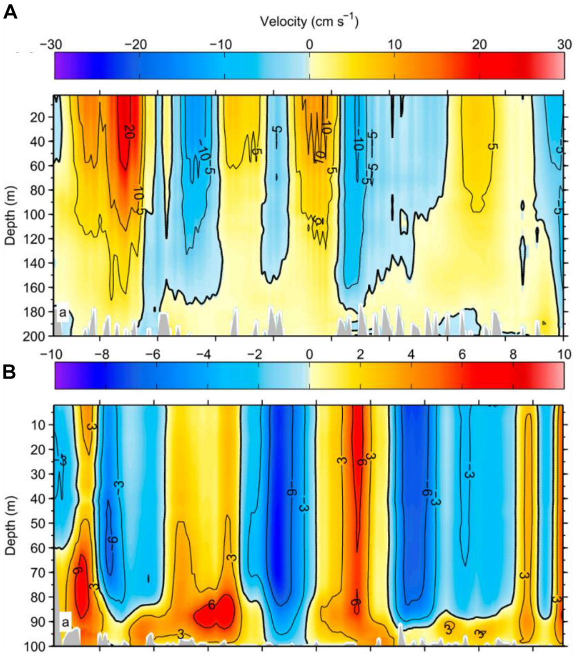

FIGURE 4 | Vertical distribution of the annually averaged velocities (in centimeters per second) perpendicular to the **(A)** 200-m and **(B)** 100-m isobaths in the East China Sea (ECS). A positive value indicates shoreward intrusive currents (Zhang et al., 2017).

Intrusion of Shelf Waters Into the Kuroshio

The ECS shelf current was found to intrude into the Kuroshio mainstream across the central ECS slope. The high-resolution numerical model by Yuan and Hsueh (2010) showed that a strong northerly winter monsoon over the ECS could increase the surface elevation in the southern ECS to be greater than that in the northern ECS and the southern Yellow Sea (YS). The shelf waters then flow eastward across the shelf slope to intrude into the Kuroshio in the Okinawa Trough. This offshore transport is also indirectly evidenced by the similar composition of sediments in the Okinawa Trough and the ECS and YS coastal areas (Yuan et al., 2008; Bian et al., 2013; Li et al., 2016). In fact, **Figure 2B** demonstrates that, although there is strong Kuroshio intrusion along the 200-m isobath over the shelf off the northeast of Taiwan, most of the intruded waters recirculate back into the Kuroshio mainstream over the shelf between the 100- and 200-m isobaths and flow further downstream (Qiu and Imasato, 1990; Liu and Gan, 2012; Zhou et al., 2015). The observations by Tang et al. (1999) and the numerical simulations by Wu et al. (2008), Chang et al. (2009), and Yang et al. (2013) showed an apparent eastward export of shelf waters along the coast of northeastern Taiwan, especially in the winter (**Figure 6**) (Tang et al., 2000), but the Kuroshio recirculation intensity in the central ECS and its net effect on the shelf circulation have not been estimated sufficiently yet.

The exchanges of the Kuroshio with the ECS shelf waters and their underlying dynamics have been extensively studied in the recent decades. It is now commonly accepted that these exchange flows occur in multiple layers in the water column. The topography setup and the baroclinicity of the Kuroshio are important for regulating the Kuroshio intrusion. Thereby, the intrusion occurs not only over the shelf off the northeast of Taiwan and southwest of Kyushu but also over the ECS mid-shelf. No observations of the exchange flow along the ECS slope exist, so numerical simulations are frequently used to investigate the exchange flow details. The relative importance of the Kuroshio intrusions among those three pathways and, correspondingly, the general circulation patterns over the ECS shelf are still debatable. Section "Mean State and Variability of Kuroshio Volume Transport" also remarks that the interannual variability in the Kuroshio volume transport is stronger than its seasonality. The interannual variability of the exchange flows between the Kuroshio and the ECS shelf currents should be further investigated.

DYNAMICS UNDERLYING THE EXCHANGE FLOWS

In recent decades, there is still no consensus on the relative importance of cross-isobath transport contributed by the Ekman

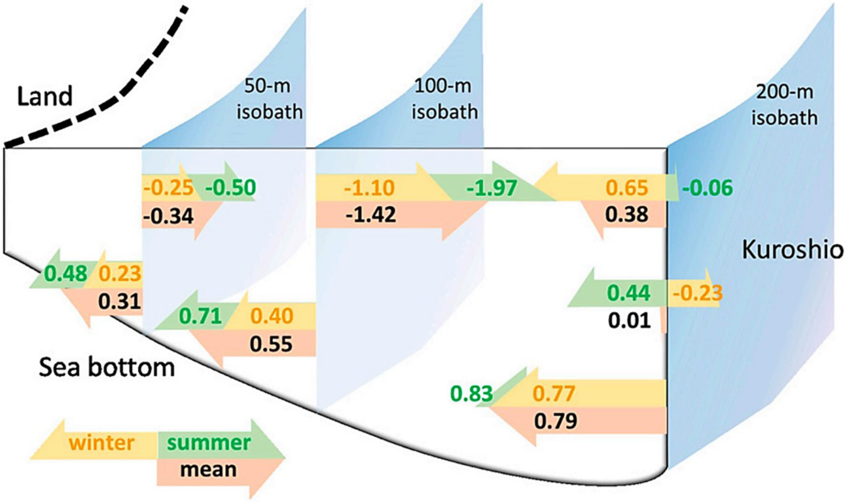

FIGURE 5 | Schematic diagram of the water exchange across isobaths over the continental shelf of the East China Sea (ECS). The three isobath areas are denoted by *light blue* sections. The horizontally averaged cross-section currents at the 50- and 100-m isobaths represent a two-layer structure and the currents at the 200-m isobath a three-layer structure. The depth ranges of the surface, mid-, and bottom layers of the 200-m isobath are 0–60, 60–140, and 140–240 m, respectively. The depth ranges of the surface and bottom layers of the 100-m isobath are 0–80 and 80–100 m, respectively. The depth ranges of the surface and bottom layers of the 50-m isobath are 0–34 and 34–50 m, respectively. The *pink arrow* represents the direction and magnitude of the annual mean net volume transport integrated along the respective isobaths in each layer. The *green* and *yellow arrows* represent those in the summer and the winter, respectively. *Numbers near arrows* denote the values of the net volume transport (in Sverdrup, Sv). This figure and caption is from Zhang et al. (2017).

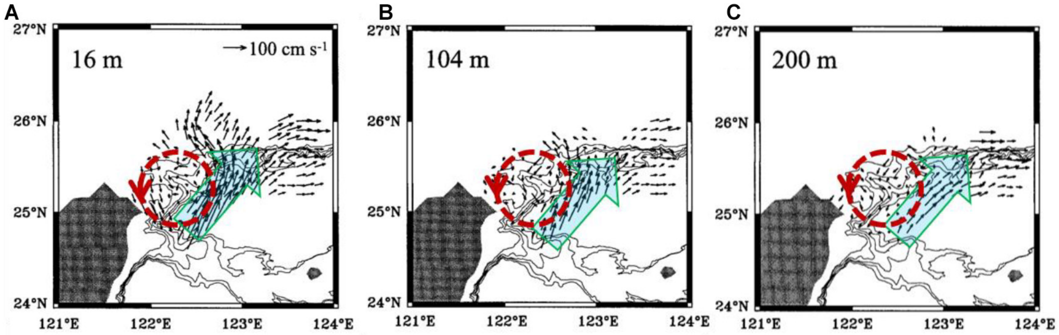

FIGURE 6 | Averaged current vectors from ship-boarded ADCP observations at depths of **(A)** 16 m, **(B)** 104 m, and **(C)** 200 m. The bathymetry is shown with thin depth contours from 200 to 1,000 m at intervals of 200 m. The data is averaged within 68.31 h (5.5 times the period of the M_2 tide). The *thick green arrow* indicates the Kuroshio and the *dashed red circle* represents the observed cyclonic circulation over the shelf off the northeast of Taiwan (revised from Tang et al., 1999).

dynamics and that induced by the geostrophic current in those three pathways. It is generally accepted that the spatial variabilities of the cross-shore exchanges should be mainly contributed by the geostrophic current. We discuss the dynamics underlying the cross-isobath velocities (**Figure 2B**) by using the depth-integrated potential vorticity equations (Liu Z. et al., 2020), which, also according to Mertz and Wright (1992) and Gan et al. (2013), can be written as:

$$\mathrm{PGF}_{y*} = \mathrm{JEBAR} + \mathrm{PGF}^{b}_{y*} \qquad (1)$$

$$\mathrm{PGF}^{b}_{y*} = \mathrm{BSC} + \mathrm{SSC} + \mathrm{RVA} \qquad (2)$$

in which PGF_{y*} stands for the depth-averaged along-isobath pressure gradient force and PGF^{b}_{y*} is the along-isobath pressure gradient force in the bottom layer. BSC/SSC denotes the bottom/surface stress curl and RVA represents the non-linear advection of relative vorticity, respectively. The negligible gradient of momentum flux (Gan et al., 2013) is excluded, and the calculation is based on the annual average model results from the climatological simulation by Gan et al. (2016). The respective contributions of terms in Eqs 1 and 2 to the cross-isobath velocities (**Figure 2B**) are divided by the Coriolis parameter and shown in the **Figure 7**.

It is readily demonstrated that the cross-shore component (**Figure 7A**) of the geostrophic velocities (PGF_{y*}) between the 100- and 200-m isobaths shows great similarity to the cross-isobath velocities in **Figure 2B**. The major contributor to this extensive PGF_{y*} in the mainstream of the Kuroshio

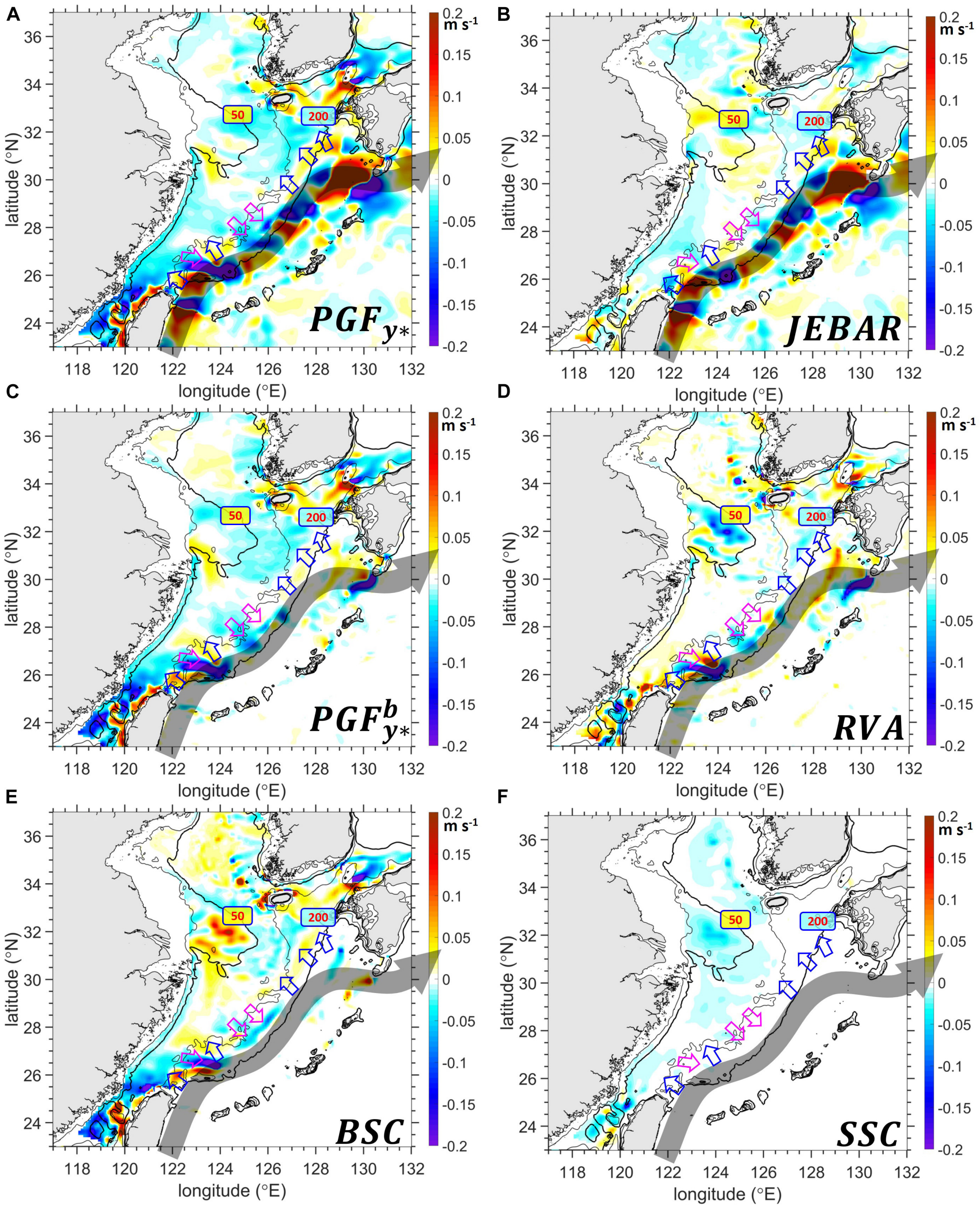

FIGURE 7 | Maps of the annual mean cross-isobath velocities by PGF_{y*}, JEBAR, PGF^b_{y*}, RVA, BSC, and SSC in Eqs 1 and 2. Positive values indicate the onshore velocities. The model results are from the climatological simulation by Gan et al. (2016). The *thick gray curve* indicates mainstream of the Kuroshio (**Figure 2A**), and the *arrows* indicate the locations where the onshore and offshore velocities are observed in **Figure 2B**. The 30 m, 50 m, 100 m, and 200 m isobaths are shown in **(A–F)**, and the 50 m and 200 m isobaths are labeled.

(to the seaward of the 200-m isobath) is JEBAR (**Figure 7B**). This finding is consistent with Guo et al. (2003). However, over the ECS shelf between the 100- and 200-m isobaths, the PGF_{y*} (**Figure 7A**) shows greater similarity to the PGF^b_{y*} (**Figure 7C**). Although JEBAR still plays a critical role in governing the cross-isobath velocities over the shelf off the northeast of Taiwan, its contribution, referring to that of the PGF^b_{y*}, becomes weaker over the shelf further onshore toward the 100-m isobath. The Kuroshio intrusions over the shelf off the northeast of Taiwan are jointly governed by the JEBAR (**Figure 7B**), RVA (**Figure 7D**), and BSC (**Figure 7E**). These latter two terms are associated with the changes of the relative vorticity of the Kuroshio. The intrusion over the shelf off the southwest of Kyushu is mainly contributed by the BSC (**Figure 7E**). Over the central ECS slope and between the 100- and 200-m isobaths, there is not extensive onshore intrusion of the Kuroshio imposed, and the cross-isobath velocities show export of shelf waters to the Kuroshio. Also consistent with Liu X. H. et al. (2014), there are not extensive exchange flows imposed by the local SSC (**Figure 7F**).

These analyses evidenced that the interactions between the Kuroshio and shelf currents in those three pathways are governed by variant mechanisms, which should be interpretated in a unified dynamics framework. Moreover, the 200-m isobath is most frequently used as the reference interface to address the location and intensity of the Kuroshio intrusion. This reference interface contributes to the debate about the relative importance of those three pathways in connecting the Kuroshio and ECS shelf currents, as the Kuroshio is merely under geostrophic balance that is strongly regulated by the conservation of potential vorticity and, thereby, by the orientation of isobaths (**Figure 2A**). The intrusion, indicated by the trajectory of surface drifters over the shelf off the southwest of Kuroshio, is unlikely to be represented by this 200-m isobath.

SCHEMATIC OF THE INTERACTIVE KUROSHIO AND SHELF CURRENTS

The disagreements on how the Kuroshio influences shelf circulation in the ECS have existed since the 1930s, when the first ECS circulation schematic was proposed. The respective intensities of the Kuroshio intrusion over the shelf off the northeast of Taiwan and southwest of Kyushu have long been debated. The existence, intensity, and variability of these intrusions as well as of other intrusive currents in the central ECS slope, which were recently proposed by Zhou et al. (2015); Ding et al. (2016), and Zhang et al. (2017), are still arguable. No consensus exists on the intensity and pathway of the shelf waters intruding into the Kuroshio, according to the previous overview by Isobe (2008), in which the progress in understanding the interaction between the Kuroshio and the ECS shelf currents was comprehensively summarized in a partially accomplished schematic.

Although the three-dimensional characteristic of the general circulation in the ECS has not been constructed yet, it has been progressively updated. **Figure 8** summarizes the ECS circulation schematics from representative studies conducted in the recent decades and after the schematics in Isobe (2008). The advances in understanding the dynamics underlying the Kuroshio intrusions over the shelf off the northeast of Taiwan, off the southwest of Kyushu, and in the central ECS have been synthesized in Sections "Water Exchanges Between the Kuroshio and the ECS Shelf" and "Dynamics Underlying the Exchange Flows."

In the recent decade, the underlying dynamics of the exchanging flows between the 100- and 200-m isobaths of the ECS shelf are better studied. It is generally confirmed that the arrival of the eddies, to the east of Taiwan and associated with the strongly meandering STCC, could contribute to the variabilities of the Kuroshio and its intrusion over the shelf off the northeast of Taiwan (**Figure 8**). These eddies function through regulating not only the Kuroshio volume transport but also the displacement of the Kuroshio mainstream from the shelf slope. They impact the variabilities not only in the intra-seasonal timescale but also in the interannual and decadal

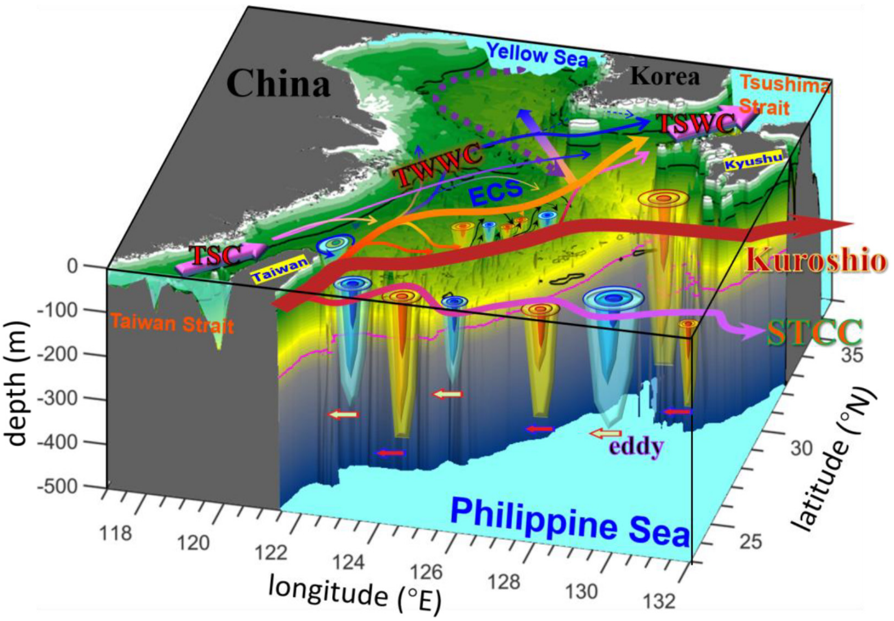

FIGURE 8 | Three-dimensional schematic of the interactive Kuroshio and ECS shelf currents. *TSC*, Taiwan Strait Current; *TWWC*, Taiwan Warm Current; *TSWC*, Tsushima Warm Current; *STCC*, Pacific Subtropical Countercurrent. It should be noted that we removed the Ryukyu Islands from the demonstration and focused more on the mainstream of the Kuroshio in the ECS, STCC to the east of Taiwan, and the associated eddies. The detailed flow patterns of TSC and TSWC, the coastal and estuarine circulations in the waters shallower than 30 m, as well as the buoyant waters from Changjiang and the cold water mass in the Yellow Sea trough are excluded from this demonstration.

timescales. In the recent decade, the third pathway of the Kuroshio intrusion in the central ECS shelf is better investigated, and the role of winds in altering the Kuroshio intrusion is further clarified. The winds over the NWPO are proposed to critically govern the intensity of the Kuroshio intrusion and characterize the general flow pattern of the ECS shelf circulation. The local winds, however, indirectly influence the Kuroshio intrusion through modulating the heat flux and the baroclinicity of the shelf current. It is also recently confirmed that the spatial variabilities of the interactive Kuroshio and shelf currents are mainly imposed by the geostrophic dynamics. The contribution from Ekman transport plays a secondary role in altering the spatial variability of the interactive Kuroshio and shelf currents, although it may critically affect the integrated Kuroshio intrusion along the ECS slope.

SUMMARY AND PROSPECTS

This overview synthesized the studies on the Kuroshio's multiscale variability and its exchange with the ECS shelf currents. The schematics of this interactive current system over the shelf between the 100- and 200-m isobaths have been updated.

Summary

The Kuroshio mainstream and its volume transport over the ECS slope to the east of the 200-m isobath are relatively stable, and the observed and simulated intensities of the current are approximately 22.35 Sv and 22.81 Sv, respectively, although there is still no consensus when the Kuroshio volume transport peaks because of its predominant interannual and decadal variability. The Kuroshio is intensified from its entrance in the East Taiwan Channel toward the central ECS slope and then weakened toward its exit in the Tokara Strait. As reflected by the fluctuations in the position of the mainstream and volume transport, the Kuroshio also experiences multiscale temporal variabilities, ranging from weeks to decades. The intensity and occurrence frequency of eddies in the Philippine Sea off the east coast of Taiwan are crucial for regulating the interannual variability of the Kuroshio volume transport in the ECS. In short, although most previous studies have focused on the seasonality of the Kuroshio volume transport and its flow patterns, the spectrum of the studied Kuroshio variability is progressively widened.

As recently recognized, the Kuroshio intrudes into the ECS shelf through three pathways: over the shelf off the northeast of Taiwan, over the central slope of the ECS, and over the shelf off the southwest of Kyushu. The long-term records of exchange flow in Taiwan Strait are of approximately 1.2–1.3 Sv and Tsushima Strait of almost 2.6 Sv. The intensity of the Kuroshio intrusion into the ECS shelf is now considered to be approximately 1.3–1.4 Sv. However, the relative importance and the interplay of these three intrusion pathways are not well documented yet. Consensus on the ECS circulation schematics has not been attained in this decade, as the respective intensities of the three intrusive Kuroshio currents have been rarely quantified.

The mechanisms governing the Kuroshio intrusion over the shelf off the northeast of Taiwan are better understood. Stronger intrusions occur when the Kuroshio volume transport is weaker and the Kuroshio mainstream is located closer to the slope. The bottom Ekman transport beneath the Kuroshio mainstream likely plays a critical role in determining the Kuroshio intrusion integrated along the ECS slope. However, it has been progressively recognized that the spatial variability of the Kuroshio intrusion is also regulated by the geostrophic current in the cross-shore direction. The zonally running isobaths and the non-linearity of the Kuroshio over the shelf off the northeast of Taiwan probably induce onshore climbing and intrusion of the Kuroshio. Topographic β -spirals facilitate the Kuroshio shoreward transition in the water column. The effective Kuroshio intrusion is formed by a secondary maximum current core to the shoreward of the Kuroshio mainstream. Furthermore, the joint effects of the Kuroshio baroclinicity and the topography (JEBAR) stimulate an extensive Kuroshio intrusion over the shelf off the northeast of Taiwan and southwest of Kyushu. The Kuroshio intrusion is altered by the meandering of the shelf break front in the central ECS slope, where the intrusion functions in a three- or multiple-layered manner in the water column.

Prospects

Although the currents between the 100- and 200-m isobaths, in general, unidirectionally flow northeastward, the characteristics, variability, and the dynamics of the circulation between these isobaths are complicated and not thoroughly investigated in the past decades. Numerical simulation and satellite remote sensing are helpful for understanding the underlying dynamics. The absence of observations with sensible spatial coverage and the complexity of the circulation system, however, handicap the thorough interpretation of the cross-scale dynamics in the region. A cross-district cooperation of observations with sufficient spatial and temporal coverage is essential. Autonomous underwater observations, a stationary mooring system, and high-resolution satellite remote sensing will facilitate the extraction of multiscale variabilities associated with the meanders of the Kuroshio, the wide-spectrum variabilities of the Kuroshio volume transport, and the interactive processes between the Kuroshio and the ECS shelf currents. It should also be noted that the selection of pathways of water exchanges and stations to deploy the observation systems and ship-boarded or autonomous samplings could be guided by well-calibrated numerical simulations, whose horizontal resolution should be further increased to better reveal the slope topography and fluctuation of the Kuroshio, as preliminarily indicated by Isobe and Beardsley (2006). These higher-resolution simulations can also be used to diagnose the underlying dynamics that govern the interactive Kuroshio and shelf currents.

Kuroshio experiences multiscale variabilities, and those three pathways of intrusions are merely governed by the cross-shore intrusion induced by the geostrophic current associated with the alongshore irregularity of the topography and the baroclinicity of the Kuroshio. The generation mechanism of the alongshore pressure gradient should thereby be observed by measuring the high-frequency velocities in the water column. Topographic arrestment of the propagating waves associated with the Kuroshio is one of the possible mechanisms since the pathways of these intrusions, according to numerical simulations, are relatively stable over the ECS slope. This latter structure shows the characteristics of standing waves possibly resultant from the arrested waves. Long-term observations of the velocities can better reveal the variabilities of the recently proposed multilayer exchanges between the Kuroshio and the shelf current and the dynamics connection between the Kuroshio intrusion with the local and remote winds.

In this overview, we summarized recent advances in the multiscale variability of the Kuroshio volume transport and the governing processes of the Kuroshio intrusion along the ECS slope. The ECS circulation characteristics over the shelf shoreward of the 100-m isobath and those of the exchange flow in the Taiwan and Tsushima Straits will be further investigated in our future work.

AUTHOR CONTRIBUTIONS

ZL wrote this manuscript by taking the suggestions and comments by JG, HW, JH, ZC, and YD. All authors contributed to the article and approved the submitted version.

FUNDING

This study was supported by the National Natural Science Foundation of China (41942034 and 41906016), the National Key R&D Program of China (2018YFC1406302 and 2016YFA0601903) and Science, Technology and Innovation Commission of Shenzhen Municipality (JCYJ20190809144411368), and The Science and Technology Development Fund, Macau SAR (SKL-IOTSC2018-2020).

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.