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Mean Structure and Variability of the Kuroshio

from Northeastern Taiwan to Southwestern Japan

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ABSTRACT. In the subtropical western North Pacific Ocean, the Kuroshio delivers heat, salt, and momentum poleward, much like its North Atlantic analog, the Gulf Stream. Though the Kuroshio generally flows along the western boundary from Taiwan to southeastern Japan as an "attached" current, the Kuroshio's strength, vertical structure, and horizontal position undergo significant temporal and spatial variability along this entire route. Ubiquitous mesoscale eddies and complicated topography associated with a string of marginal seas combine to make the western North Pacific a region with complex circulation. Here, we synthesize results from the recent US Origins of the Kuroshio and Mindanao Currents and Taiwan Observations of Kuroshio Transport Variability observational programs with previous findings to build a comprehensive picture of the Kuroshio on its route from northeastern Taiwan to southeastern Japan, where the current finally transitions from a western boundary current into the Kuroshio Extension, a vigorously meandering free jet.

(background photo) A pressure-sensor-equipped inverted echo sounder (PIES) awaiting recovery onto R/V *Ocean Researcher I*. This instrument was deployed for two years at 6,000 m depth in the Philippine Sea east of Taiwan as part of an array of six PIESs supported through the companion programs Origins of the Kuroshio and Mindanao Current (OKMC) and Observations of Kuroshio Transport Variability (OKTV). *Photo credit: Sen Jan*

INTRODUCTION

The swift Kuroshio is a critical component in the global heat pump and a key element of the North Pacific's upper-ocean wind-driven circulation. On its 3,500 km route between the Philippines and southeastern Japan (Figure 1a), this current plays a role in transport of larval fish such as Pacific bluefin tuna, strongly influences internal waves in the South China Sea, and helps shape the stratification and material budgets on the continental shelf in the East China Sea through cross-shelf exchange (e.g., Kitagawa et al., 2010; Park and Farmer, 2013; Jan et al., 2011).

Along the Kuroshio's poleward course, mesoscale eddies that are generated in the ocean's interior and propagate westward impinge on it, resulting in strong temporal variability in the structure and strength of this western boundary current (Johns et al., 2001; Vélez-Belchí et al. 2013; Lien et al., 2014, and 2015, in this issue). Notably, this strong variability is not confined to those sections of the Kuroshio that are exposed directly to the interior ocean's eddies; it also occurs along the Kuroshio within the East China Sea (Figure 1a, pink shaded region) behind the protective arc of the Ryukyu island chain that largely separates this marginal sea from the North Pacific interior (Andres et al., 2008a,b).

Despite a first order understanding of western boundary current dynamics, open questions have remained about the mean and time-varying state of the Kuroshio. Recently, its connectivity (i.e., the degree to which Kuroshio structure and variability at one latitude is related to those at other latitudes) has been investigated in the joint Origins of the Kuroshio and Mindanao Currents and the Observations of Kuroshio Transport Variability (OKMC and OKTV) programs through a US-Taiwanese collaboration supported by the US Office of Naval Research (ONR) and the Ministry of Science and Technology of Taiwan, respectively (Rudnick et al., 2011; Jan et al., 2015). OKMC/OKTV builds on a series of in situ experiments conducted in the western North Pacific over the past decades, many of them supported by ONR, that have focused on different sections along the Kuroshio (Table 1). Here, we summarize some of these earlier field programs and synthesize them with OKMC/OKTV results to describe the downstream evolution of the Kuroshio along its route from the western Philippine Basin through the East China Sea to south of Japan (Figure 1a).

MEASURING THE KUROSHIO

Due to the rich eddy field in the western North Pacific (Figure 2a), individual synoptic sections across the Kuroshio from shipboard measurements are often not representative of the current's mean state. Longer duration measurements (or many crossings) are needed to estimate the current's mean transport and velocity structure. Since 1991, arrays of inverted echo sounders (IESs) have been deployed at various sections across the Kuroshio (e.g., Table 1 and the green lines in Figure 3a) to measure variability at hourly resolution for durations of one year or more. In most cases, the IESs were also equipped with pressure sensors (PIESs) and additional current sensors (CPIESs) or horizontal electric field sensors (HPIESs) to help establish the Kuroshio's time-varying position, absolute geostrophic transport, and velocity structure (see Meinen et al., 2002; Donohue et al., 2010; and Szuts, 2012, for reviews of the methodologies and the title page photo [opposite] for an image of a PIES). One of these experiments was along the Affiliated Surveys of the Kuroshio off Cape Ashizuri (ASUKA) Line, which extends 1,000 km southeastward from Shikoku, Japan, into the Philippine Basin (Figure 3a). A full array of instruments was deployed there from 1993 to 1995 (Book et al., 2002) with a reduced two-IES array maintained through 2004 (Kakinoki et al., 2008). Two IES arrays were also deployed along the PN Line, a repeat hydrographic line in the East China Sea northwest of Okinawa (labeled in Figure 4), the first from 1991

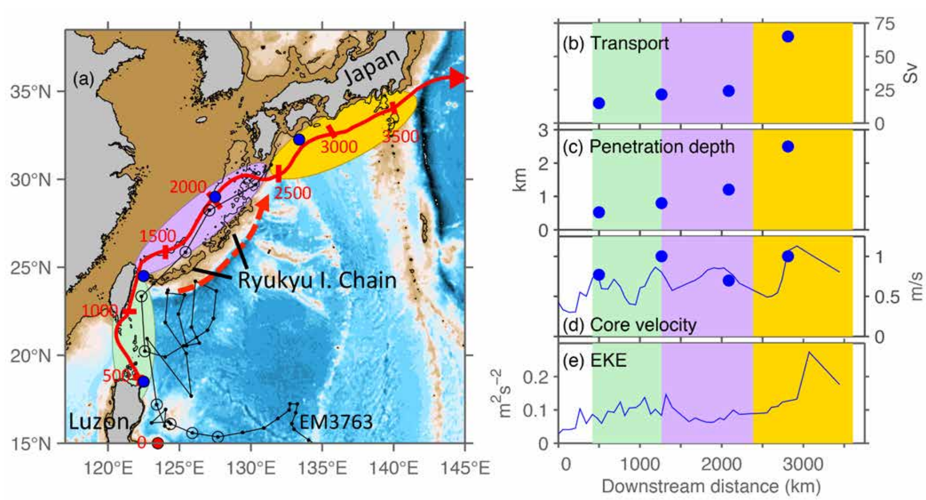

FIGURE 1. (a) Map of the western North Pacific highlighting the mean path of the Kuroshio (red curve) and downstream distance from 15°N, 124°E (red dot) near the Kuroshio's origin as indicated with red ticks at 500 km intervals. The thin black line traces the track of EM-APEX float EM3763. The red dashed line indicates the Ryukyu Current, a subsurface-intensified current, which joins the Kuroshio as it exits the East China Sea. Blue dots indicate locations of the mooring experiments where mean Kuroshio properties are plotted in panels b to e. Shaded regions in (a) indicate the Kuroshio's route through different regimes: the western Philippine Basin (green shading), the East China Sea (pink), and the area south of Japan (orange). These regions correspond to the highlighted areas on the subsequent panels. (b)–(e) show the downstream evolution of mean Kuroshio properties as deduced from moored arrays (blue dots) and drifters (solid lines).

to 1992 (James and Wimbush, 1995) and the second from 2002 through 2004 (Andres et al., 2008b). Most recently, two arrays were deployed by the OKMC/OKTV programs. In the "Taiwan Array," PIESs and CPIESs were deployed across the Kuroshio east of Taiwan along the Yaeyama Ridge (Figure 4) from 2012 to 2014. This location is about 100 km south (upstream) of the Kuroshio's entrance into the East China Sea. In the "Luzon Array," HPIESs were deployed in the western Philippine Basin northeast of Luzon, Philippines, from 2012 to 2013 (C. Tsai et al., 2015) near the origin of the Kuroshio (Gordon et al., 2014).

In addition to these measurements made with several iterations of inverted echo sounders, time series measurements across the Kuroshio have included arrays with acoustic Doppler current profilers (ADCPs), current meters, and tide gauges spanning the current (e.g., Kawabe, 1988; Johns et al., 2001; Lien et al., 2014; Y. Yang et al., 2015, in this issue; Table 1). The long duration, high temporal resolution records from in situ moored arrays (e.g., IESs, ADCPs) provide a Eulerian framework for observing the Kuroshio. A nearly Lagrangian perspective of the current is given by measurements from surface drifters and profiling floats that are advected with the currents. Drifters are drogued at 15 m depth and report their positions at nearly hourly intervals (Niiler, 2001). A focused effort to increase the number of drifters sampling in and around the Kuroshio resulted in deployment of a total of 536 ONR-funded Surface Velocity Program (SVP) drifters in the Kuroshio in the western Philippine Basin upstream of the East China Sea between 2003 and 2014. The same number of drifters was provided as a matching contribution from the National Oceanic and Atmospheric Administration (NOAA)-funded Global Drifter Program (GDP) for deployment in the same region. Drifter data are available from NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) GDP Drifter Data Assembly Center and from the enhanced data set (Pazan and Niiler, 2001) from the Lagrangian Drifter Laboratory at the Scripps Institution of Oceanography.

Drifter-derived speeds reveal a strong

TABLE 1. Summary of time series measurements across the Kuroshio.

Project Name	Region	Duration	Instruments	References
OKMC/Luzon Array	Western Philippine Basin ~18.75°N	2012–2013	ADCPs, HPIESs	Lien et al. (2014)
OKTV/Taiwan Array	Western Philippine Basin ~23.5°N	2012–2014	PIESs, CPIES, ADCPs	Tsai et al. (2015)
PCM-1 Line	East China Sea ~24°N	1995–1996	Current meters	Johns et al. (2001)
PN Line	East China Sea ~28°N	1991–1992	IESs	James and Wimbush (1999)
		2002–2004	CPIESs, PIESs	Andres et al. (2008)
Tokara Strait	East China Sea ~30°N	1965–ongoing	Tide gauges	Kawabe (1988)
ASUKA Line	South of Japan ~133.5°E	1993–1995	IESs, current meters	Book et al. (2002)
		1995–2004	IESs	Kakinoki et al. (2008)

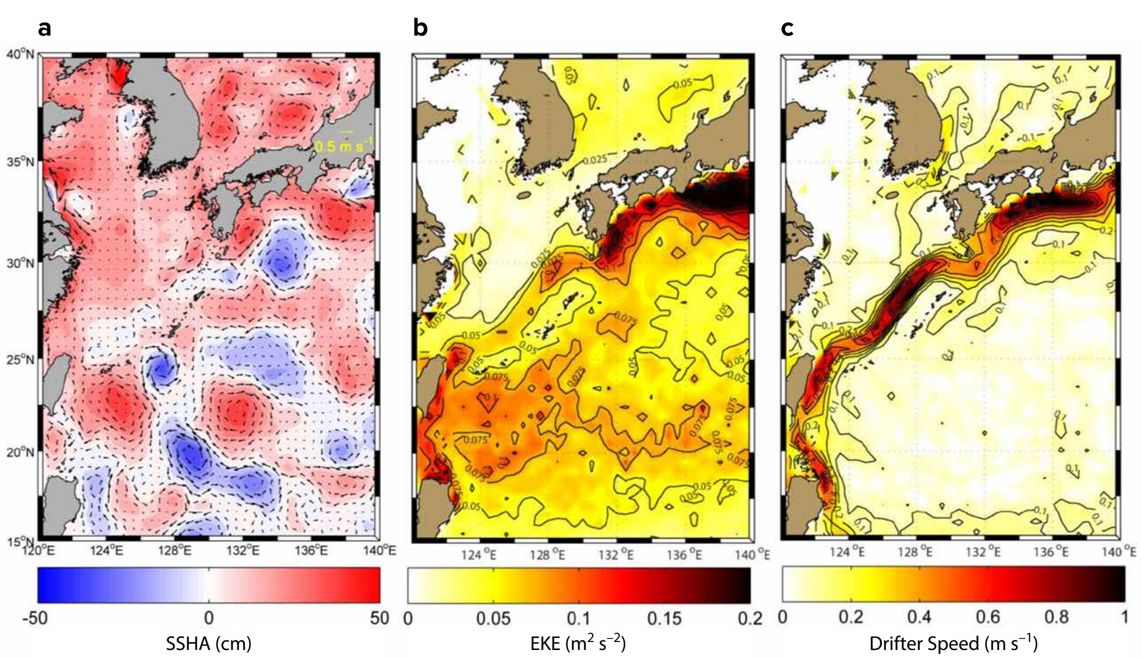

FIGURE 2. (a) A representative snapshot of the satellite sea surface height anomaly (SSHA) on October, 23, 2014, showing the "eddy soup" in the western North Pacific. (b) Mean eddy kinetic energy calculated for drifters from 1987 through 2014. (c) Mean current speed as deduced from drifters.

mean circulation with a swift ribbon-like Kuroshio along the western boundary from northeastern Luzon to southeastern Japan (Figure 2c). As with the Eulerian means derived from moored array data, this mean circulation emerges only after averaging over many drifters because of the high eddy variability in the western North Pacific (demonstrated by the map of mean eddy kinetic energy, Figure 2b).

In addition to the drogued drifters, nine Electromagnetic Autonomous Profiling Explorer (EM-APEX) floats (Sanford et al., 2005) were deployed near 135°E in the tropical North Pacific through the OKMC program. These floats profiled to 800 m depth and collected temperature, salinity, and velocity profiles at one-half the local inertial period. The thin black line in Figure 1a shows the track of one of the EM-APEX floats (EM3763), which was entrained into the nascent Kuroshio. This float's trajectory closely follows the Kuroshio mean path along the western boundary from the North Equatorial Current bifurcation region near 15°N to the Tokara Strait (except for a diversion into the eddy field in the western Philippine Basin where the float was ejected from and then re-entrained into the Kuroshio). The yellow vectors in Figure 3a show the depth-averaged velocities along the float's track, and Figure 5 shows the downstream evolution of subsurface properties and velocity profiles for the portion of the track where the float was within the Kuroshio (black circled dots in Figure 1a).

DOWNSTREAM EVOLUTION OF THE MEAN KUROSHIO

Figure 1b summarizes the downstream evolution of Kuroshio properties (its transport, penetration depth, core velocity, and eddy kinetic energy). Mean sections of the downstream (poleward) absolute geostrophic velocities across the current (Figure 3b–d) indicate that the Kuroshio, as defined by the area within the 0 m s^{-1} isotach, penetrates to greater depths and carries more water as it progresses downstream from the western Philippine Basin, through the East China Sea, and to the region south of Japan (see also Figure 1b,c). While the Kuroshio is only 520 m deep in the western Philippine Basin east of Luzon (Figure 3b), it extends to the seafloor at the 1,200 m isobath in the East China Sea at the PN Line (Figure 3c) and is even deeper south of Japan along the ASUKA Line where it penetrates to the seafloor over the 1,500 m to 2,000 m isobaths (Figure 3d). This mean view from the mooring lines is consistent with the subsurface information provided by the EM-APEX float that was entrained into the Kuroshio (black dots in Figure 1 and yellow vectors in Figure 3). Along EM3763's trajectory (neglecting the portion of the track when the float was outside of the Kuroshio and circulating in the eddy field), the

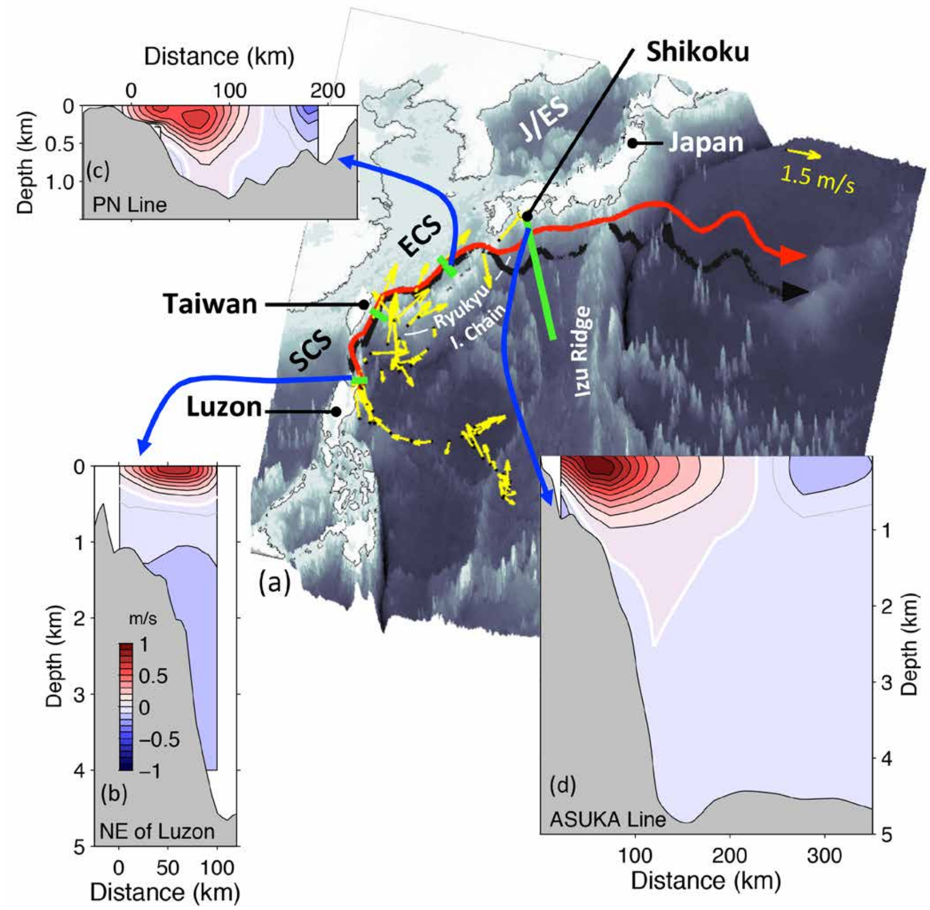

FIGURE 3. (a) Complex bathymetry largely separates the western North Pacific from a string of marginal seas: the South China Sea (SCS), the East China Sea (ECS), the Japan/East Sea (J/ES), and the Sea of Okhotsk (north of the region shown here). The Kuroshio—shown schematically with the red arrow—sometimes loops into the South China Sea and enters the East China Sea over I-Lan Ridge between northeastern Taiwan and the southwestern end of the Ryukyu island chain. Green lines indicate locations of mooring arrays across the Kuroshio that included inverted echo sounders (IESs, see text). Yellow lines with arrowheads denote the depth-averaged velocity of EM-APEX float EM3763 (whose trajectory is also shown in Figure 1a). (b–d) These panels compare the mean downstream velocity structure from three of these experiments: (b) the mean from a 13-month HPIES (IES with pressure and horizontal electric field sensors) array northeast of Luzon (this study) agreed with nearby acoustic Doppler current profiler data (ADCPs; Lien et al., 2014), (c) a 13-month mean from six CPIESs (PIES with current sensors) and five PIESs within the East China Sea at the PN Line (a repeat hydrographic line in the East China Sea northwest of Okinawa; Andres et al., 2008a), and (d) a 153-day mean from IESs along the ASUKA (Affiliated Surveys of the Kuroshio off Cape Ashizuri) Line (Book, et al., 2002). Red shading indicates downstream (poleward) flow; the contour interval is 0.1 m s^{-1} (black contours). The gray contour is the −0.05 m s^{-1} isotach to highlight the negative (equatorward) flow structure, and the white contour is the 0 m s^{-1} isotach. The spatial scale is the same for panels b–d.

depth of the 0.2 m s^{-1} isotach deepens in the downstream direction. It is at about 100 m depth near 16°N and more than 800 m depth in the East China Sea near 28°N (Figure 5c). In contrast, isopycnals do not deepen in the downstream direction along the Kuroshio core axis (see Figure 5a,b in which the 30 kg m^{-3} isopycnal surface is between 400 m and 500 m depth along the whole trajectory).

Local recirculation adjacent to the Kuroshio may contribute to the measured downstream (poleward) flow across a section without adding to the net throughput (e.g., see Imawaki et al., 2001). If a moored array does not sample across the entire recirculation, however, decomposing the downstream flow into net throughput and recirculated flow is ambiguous. Further, when the Kuroshio is not bound between landmasses as it is in a marginal sea, another ambiguity can occur in distinguishing the time-varying offshore boundary between locally recirculating flow and the general Sverdrup transport that both move in the same direction. Despite the "endpoint problem" and the resulting difficulty in finding the Kuroshio's throughput from long-term means measured at individual sections, Kuroshio downstream (poleward) transport does intensify along its downstream route (Figure 1b). Integrating over the regions of contiguous positive velocity (i.e., the red shaded areas in the sections shown in Figure 3b–d) indicates that the Kuroshio strengthens from a mean downstream transport of about 15 Sv east of Luzon to 24 ± 0.9 Sv in the East China Sea. The Kuroshio further strengthens to 65 ± 6 Sv at the ASUKA Line, fed in part by the Ryukyu Current (Zhu et al., 2003), a subsurface intensified current that flows along the southwestern side of the Ryukyu Islands and joins the Kuroshio as it exits the East China Sea through Tokara Strait (indicated with the red dashed line in Figure 1a). (Transport values are based on HPIES and ADCP data collected east of Luzon [Lien et al., 2014, and 2015, in this issue], Andres et al. [2008b], and Book et al. [2002], with the ASUKA Line mean calculated over two years rather than from the 153-day mean sections shown in Figure 3d.)

In contrast to the Kuroshio mean penetration depth and downstream (poleward) transport, which both increase downstream, the Kuroshio's mean velocity structure does not evolve downstream in such a regular fashion (Figure 2c). Kuroshio mean core speeds derived from mooring measurements (Figure 1d, blue circles) and from drifters (Figure 1d, solid line) vary irregularly with downstream distance. At the locations of the mooring arrays, the mooring-derived means are in good agreement with the local drifter-derived means speeds.

The number of velocity cores present in a given mean section (single core versus dual core) also varies spatially (K.-C. Yang et al., 2015, in this issue). The mean velocity sections have a single core with mean speeds of 0.9 m s^{-1}, 1.0 m s^{-1}, and 1.0 m s^{-1}, respectively, (1) east of Luzon, (2) over I-Lan Ridge where the Kuroshio passes from the western Philippine Basin

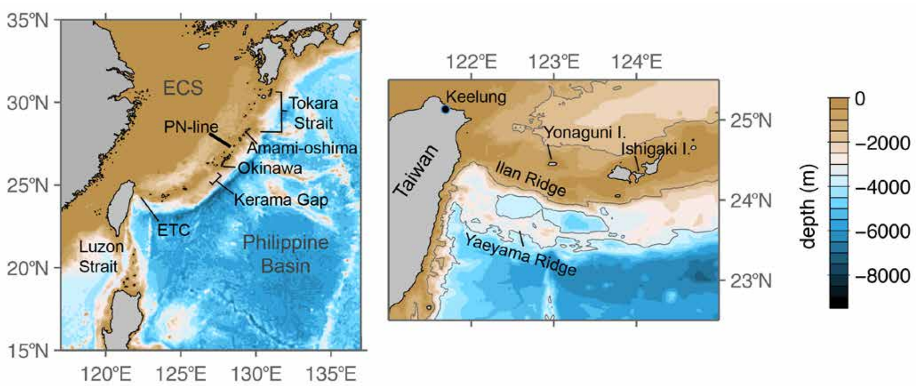

FIGURE 4. Some of the straits, gaps, islands, and ridges between the East China Sea and the Philippine Basin. Gray contours in the right panel show 3,500 m and 1,500 m isobaths.

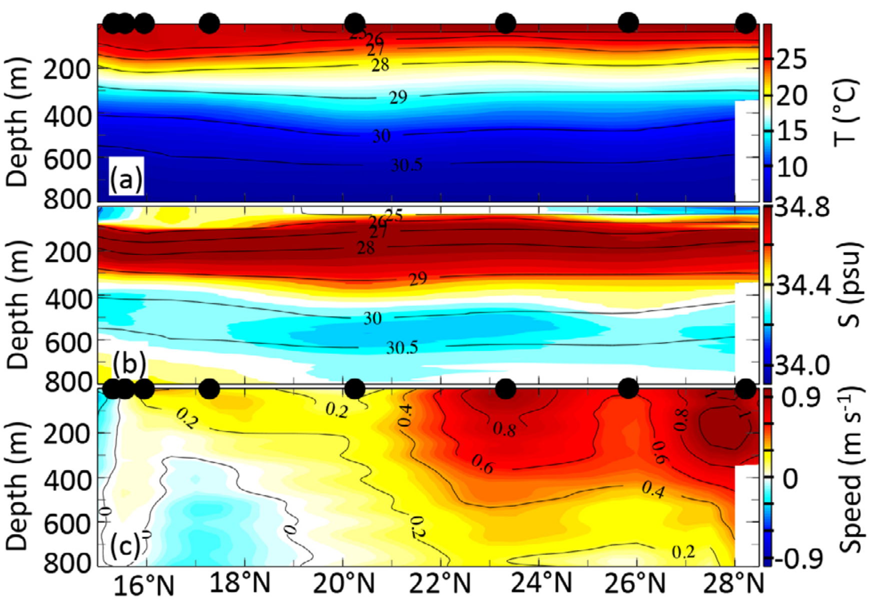

FIGURE 5. Downstream evolution of the subsurface profiles of (a) temperature, (b) salinity, and (c) speed observed with EM-APEX float EM3763 within the core of the Kuroshio (i.e., for the portion of the trajectory along the western boundary; see circled black dots in Figure 1a, which correspond to the black-filled circles in this figure). Solid contours in (a) and (b) show isopycnal surfaces.

into the East China Sea (Johns et al., 2001, section not shown here), and (3) at the ASUKA Line. However, at the Yaeyama Ridge (which is in the Philippine Basin east of Taiwan) and within the East China Sea at the PN Line, the Kuroshio can have a dual-core velocity structure, both in synoptic cross sections and in the mean. East of Taiwan, nine individual velocity sections from synoptic lowered-ADCP measurements across the Kuroshio at the Yaeyama Ridge reveal a dual-core Kuroshio in one-third of the crossings (Jan et al., 2015). Concurrent sea surface height anomaly (SSHA) maps from altimetry confirm that these dual cores are not simply instances of sampling through the western half of an anticyclonic eddy. Within the East China Sea, at the PN Line, the 13-month mean Kuroshio (Figure 3c) exhibits a surface velocity maximum over the 500 m isobath (0.6 m s^{-1}) and a slightly stronger subsurface maximum over the 1,200 m isobath (0.7 m s^{-1}; Andres et al., 2008b). Though two cores are not present in every individual section that constitutes the mean, individual velocity sections (from two-day lowpass filtered data) do exhibit a clear double velocity core, confirming that the dual core in the mean is not simply an artifact of the Eulerian average across a single-core, meandering current (as it is, for example, in the meandering Gulf Stream downstream of Cape Hatteras; Andres et al., in press, their Figure 4).

In some locations, a dual core may be directly related to topography. For example, a mean section in the East China Sea along 25°N just downstream of Yonaguni Island (Figure 4), compiled from 25 years of shipboard observations, shows a dual core (Figure 6). Also, in Tokara Strait, a 10-year mean section of Kuroshio geostrophic velocity locates dual cores north and south of a seamount (Kawabe, 2005). However, along other sections with a dual core, like that at the PN Line in the East China Sea, there is no nearby island that could cause the dual core, and the dynamical reason for the dual core remains unclear.

CONNECTIVITY ALONG THE KUROSHIO

In the East China Sea and south of Japan, Kuroshio transport, velocity structure, and position exhibit temporal variability at scales ranging from high-frequency frontal meanders, to seasonal variations in Kuroshio intrusions onto the shelf, to interannual transport variability, to multiyear path shifts of the Kuroshio south of Japan (Kawabe, 1995, 2005; James et al., 1999; Andres et al., 2011). Variability at eddy time scales (~100-day period) is particularly pronounced and often swamps any interannual signals or an annual cycle (Johns et al., 2001; Zhang et al., 2001; Andres et al., 2008b).

The mesoscale eddies, ubiquitous in the western North Pacific (Figure 2a), may be formed by baroclinic instability where the eastward-flowing Subtropical Countercurrent rides over the westward-flowing North Equatorial Current (Qiu, 1999) or by individual typhoons (e.g., I. Lee et al., 2003), or by other processes. At a given latitude, eddies arriving from the interior drive strong variability in the measured flow along the boundary (Zhang et al., 2001; Lien et al., 2014). Observations suggest that the eddy-induced transport variability in the western Philippine Basin is rarely communicated downstream from Luzon to Taiwan; a clear downstream connection due to advection of transport anomalies by the Kuroshio here is the exception rather than the rule (C. Tsai et al., 2015).

At the latitudes of the East China Sea, the strongest transport variability is within the Ryukyu Current along the southeastern side of the Ryukyu Islands (Figure 1a, red dashed line), which is directly exposed to eddies arriving from the ocean interior (Zhu et al., 2003; Andres et al., 2008a). However, there is also Kuroshio transport variability within the East China Sea (at the PN Line) that is driven by these eddy arrivals outside of the island chain (Andres et al., 2008a). This 100-day period variability is communicated through the deepest passage connecting the Philippine Basin to the East China Sea (Figure 4), the Kerama Gap southwest of Okinawa (Choi, 2002). This passage is narrow (50 km wide), and in sequences of satellite altimetry maps (like that shown in Figure 2a), eddies generally do not appear to pass through the island chain into the East China Sea. Rather, the observations suggest that indirect eddy effects drive the transport variability at the PN Line, possibly via eddy-induced "streamers" that flow around the islands due to conservation of circulation (Andres and Cenedese, 2013). Depending on the direction of circulation

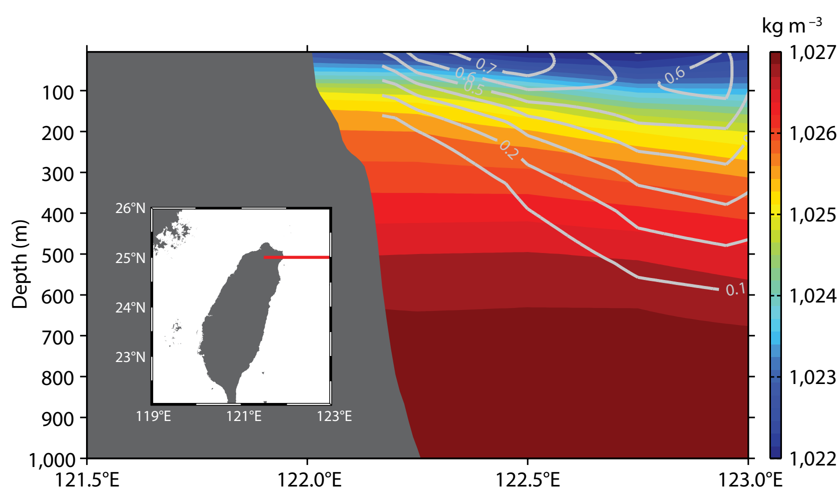

FIGURE 6. Mean downstream velocity (solid gray lines) and density (shaded) section just downstream of I-Lan Ridge and Yonaguni Island. This section is based on 25 years of shipboard velocity, temperature, and salinity data from the region, obtained from the Ocean Data Bank of Taiwan through http://www.odb.ntu.edu.tw.

in the eddy (cyclonic or anticyclonic), these streamers add to or subtract from the net Kuroshio transport at the PN Line. This idea of eddy-induced flow through the island chain is also consistent with strong flow variability observed in the Kerama Gap in data from an array of CPIESs and current meter moorings (Na et al., 2014) that show transport variability through the gap correlates with the presence of cyclones and anticyclones in the Philippine Basin adjacent to the islands just southwest of the Kerama Gap.

In contrast to the western Philippine Basin, transport variability observed at the PN Line (with CPIESs) is well correlated with transport variability in the Kuroshio where it exits the East China Sea through Tokara Strait (from eight hydrographic sections; Nakamura et al., 2006). The lag is less than one week (Andres et al., 2008a), suggesting rapid advection of transport anomalies along the 350 km distance in the East China Sea between the PN Line and Tokara Strait. The estimated advection speed (~0.6 m s^{-1}) is consistent with the speeds of the velocity cores in the mean cross section here (Figure 3c). The strong correlation suggests that the islands in the northeastern part of the Ryukyu island chain (i.e., downstream of the Kerama Gap, from Okinawa to Amami-oshima) provide a more robust barrier to additional eddy influences than do the islands in the southwestern part of the chain (from Ishigaki, across the Kerama Gap, to Okinawa). These spatial differences in eddy influences on the island chain, as suggested by the in situ observations, are consistent with findings from a data assimilative model (Soeyanto et al., 2014) and are presumably related to the depth and width of passages between islands.

MEANDERS AND INTRUSIONS DRIVE EXCHANGE

The Kuroshio's path within the East China Sea (e.g., Figure 2c) is largely controlled by the steep topography along the continental slope seaward of the shelf break near the 200 m isobath. This slope constrains the current to flow along f/h contours, where f is the Coriolis parameter and h is water depth, to conserve potential vorticity. However, variability in the Kuroshio's path here results in exchange across the shelf break between Kuroshio waters and shelf waters (e.g., Zhou et al., 2015). This exchange may be at least partially responsible for dramatic temperature increases on the East China Sea shelf: reconstructions of global sea surface temperatures (SSTs) suggest that the Kuroshio (and other subtropical western boundary currents) have warmed more rapidly than the global average rate of SST increase over the last century (Wu et al., 2012), and the neighboring East China Sea shelf is also a region of intense SST increase (see their Figure 1).

Cross-isobath exchange in the East China Sea can be associated with Kuroshio frontal meanders (James et al., 1999) and with so-called small and large Kuroshio intrusions onto the shallow shelf (Gawarkiewicz et al., 2011; Vélez-Belchí et al., 2013). Observations from long-term ADCP measurements at the Taiwan and Korea/Tsushima Straits suggest there is about 1.2 Sv of net transport onto the shallow East China Sea shelf from the Kuroshio (Jan et al., 2006; Isobe, 2008), but net flow onto the shelf has also been inferred to be as high as 3.0 Sv in the fall (Teague et al., 2003).

The Kuroshio frontal meanders along the East China Sea shelf break have been observed with IESs deployed along and across the Kuroshio near the PN Line (James et al., 1999). These persistent 11-day period meanders have wavelengths of about 210 km and propagate downstream at 20 km day^{-1}. The Kuroshio frontal meanders are related to baroclinic instability (James et al., 1999) and may be excited near abrupt changes in bottom slope (Isobe and Beardsley, 2006). These meanders drive cross-shelf exchange by drawing low-salinity shelf waters into the subsurface Kuroshio (Isobe et al., 2004). A similar exchange process operates in the Gulf Stream due to frontal meanders in the South Atlantic Bight between the Straits of Florida and Cape Hatteras, albeit with shorter period and faster phase speeds (T. Lee and Atkinson, 1983; Bane and Brooks, 1979).

Two locations along the East China Sea shelf break are considered particularly susceptible to the small and large Kuroshio intrusions (Guo et al., 2006). This view is consistent with drifter tracks that show a tendency to pass across the

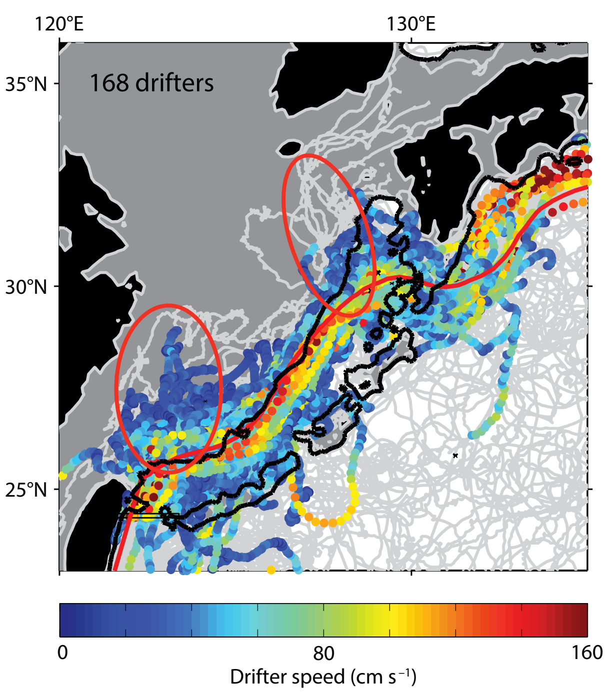

FIGURE 7. Trajectories of drifters that pass over I-Lan Ridge and into the East China Sea. For each drifter (track shown in gray), its trajectory for the first 50 days after passing into the East China Sea is highlighted with the color indicating the drifter's speed. The red circles show areas that are considered particularly subject to small and large Kuroshio intrusions. The 500 m isobath (black) and the typical Kuroshio path from altimetry (red line) are also shown. Regions shallower than 200 m are shaded dark gray. This analysis of drifter tracks available through the end of 2014 was accomplished with the JLAB software and data v 1.5 developed by J. Lilly and freely available at http://www.jmlilly.net/jmlsoft.html.

200 m isobath at preferred sites (Figure 7, red circles). The first location is in the southern Okinawa Trough northeast of Taiwan where the Kuroshio encounters the continental slope and is steered anticyclonically from north-northeastward to east-northeastward along the bathymetry (see Figure 4). The second location is in the northern Okinawa Trough near 30°N where the current turns anticyclonically (eastward) and crosses the isobaths to flow toward Tokara Strait. Though not all drifters that intrude onto the shelf past the 200 m isobath are permanently lost from the Kuroshio, many are, and they either die on the shelf or are eventually advected to the Korea/Tsushima Strait and into the Japan/East Sea (Lie et al., 1998).

The intrusions of Kuroshio waters onto the shelf in the northern Okinawa Trough near 30°N have been related to wind-driven events (e.g., Hsueh, 1988; Teague and Jacobs, 2000). However, despite extensive study of the intrusions occurring in the southern Okinawa Trough northeast of Taiwan, the underlying processes are still debated; it is likely that multiple processes operate simultaneously, thereby making attribution challenging. The momentum imbalance between Taiwan Strait water (west of Taiwan) and Kuroshio water, subsidence of shelf surface water, inertia and topographic interactions and associated baroclinic effects, as well as vorticity dynamics have each been investigated individually as the potential primary driver responsible for Kuroshio intrusions (Chao, 1991; Hsueh et al., 1992; Tang and Yang, 1993; Chuang and Liang, 1994; Chern and Wang, 1994; Oey et al., 2010; Vélez-Belchí et al., 2013). A cyclonic Kuroshio meander found by Jan et al. (2015) east of Taiwan in the winter of 2014 may also provide an upstream condition for Kuroshio intrusions onto the East China Sea shelf, and this remains to be investigated further.

Satellite altimetry suggests that some of the Kuroshio intrusions onto the shelf northeast of Taiwan that have been observed with drifters result from an indirect eddy effect. These observations are correlated with arrivals of cyclonic eddies east of Taiwan and concomitant weak Kuroshio transport entering the East China Sea over I-Lan Ridge between Taiwan and Ishigaki Island (Vélez-Belchí et al., 2013). Typhoons that pass near this region may also trigger Kuroshio intrusions at a time scale of about two days (Tsai et al., 2013).

Superimposed on these eddy- or typhoon-driven intrusions, there appears to be seasonality in the Kuroshio path (and shelf intrusions) at this southern boundary of the East China Sea shelf. The paths of drifters deployed east of Taiwan at a rate of two per week from April 2008 to January 2009 and one per week from January 2009 to September 2009 (Vélez-Belchí et al., 2013) suggest that the surface currents of the Kuroshio tend to flow mostly along the 200 m isobath in summer (i.e., March through August, Figure 8a), but sometimes flow shoreward and across the shelf break onto the shelf northeast of Taiwan in winter (i.e., September through February, Figure 8b). In summer, the mean flow into the East China Sea from Taiwan Strait west of Taiwan is 1 Sv (Jan et al., 2002), and this water floods the shelf north of Taiwan and largely prevents the Kuroshio from intruding onto the shelf (Hsueh et al., 1993). In contrast, in winter when the strong northeast monsoon dominates, the Taiwan Strait flow into the East China Sea diminishes (Jan et al., 2002), and the surface shelf water becomes cold and dense and subsequently sinks. These conditions are essential for allowing the warmer and lighter Kuroshio surface water to intrude onto the shelf in winter.

Recent coastal sea level and temperature observations at a station on Peng-jia-yu Island (Figure 8, triangle) on the shelf north of Taiwan (Jan et al., 2013) suggest that the seasonal Kuroshio intrusions onto the shelf in winter result from two distinct processes. Figure 8c shows time series of 20-day low-pass-filtered sea level and temperature records from September of one year to March of the following year for 2008 to 2015. In addition, SVP drifter trajectories (http://www.coriolis.eu.org/Data-Products/Data-Delivery/Data-selection) selected during each temperature increase/decrease period (marked by 1 and 2 in Figure 8c) are shown in Figure 8d and 8e, respectively. The first-order seasonal signal in winter is a temperature decrease from late fall to early spring (yellow lines in Figure 8a). Superimposed on this general six-month cooling period, most years exhibit two distinct temperature increase events: one from October to December and the other from December to March.

In most years, the first of these temperature increase events (i.e., 1 in the panels in Figure 8c) tends to occur about one month after the onset of the northeast monsoon. This event may be associated with a Kuroshio intrusion caused by the decrease in northward transport through Taiwan Strait flowing from the South China Sea into the East China Sea and the cooling of shelf water (Chuang and Liang, 1994) through a process similar to that of the typhoon-induced Kuroshio intrusion (Tsai et al., 2013). Sea level increases concurrently with rising temperature (blue lines in Figure 8c). This intrusion is presumably maintained because the Kuroshio is continuously cooled by the atmosphere and well mixed by winds and swift tidal currents (Lien et al., 2013). These processes induce downwelling across the shelf break that is compensated by enhanced Kuroshio intrusion over the shelf (Oey et al., 2010). (We note that impinging cyclonic eddies east of Taiwan, like one identified in September 2008 by Vélez-Belchí et al. [2013], likely also contribute to the Kuroshio intrusions even as these seasonal scale processes progress.) After about one month of this temperature increase, the climatological wintertime temperature decrease commences, presumably enabled by the new momentum balance between the intruding Kuroshio and the surrounding shelf circulation, and the continuous atmospheric cooling. According to the definitions of Vélez-Belchí et al. (2013), this intrusion associated with "Event 1" is classified as small (see the drifter tracks in Figure 8d).

The second wintertime temperature increase superimposed on the overall six-month cooling (2 in Figure 8c) is associated with another seasonal Kuroshio intrusion but with different dynamics. In contrast to the first intrusion, the second one is classified as large, and the intruding surface currents can reach onto the shelf north of Peng-jia-yu Island (cf. Figure 8d,e). The change in upstream Kuroshio stratification, which is strong in summer and weak in winter, and associated vorticity variation over the abrupt topography between I-Lan Ridge (called Su-Ao Ridge in Chern and Wang, 1994) and the East China Sea shelf is likely related to this Kuroshio intrusion, which is only weakly correlated to the northeast monsoon (Tang and Yang, 1993). The surface mixed layer of the Kuroshio east of Taiwan is typically thicker in winter than in summer. Using numerical experiments, Chern and Wang (1994) find that as the Kuroshio with a thick mixed layer flows over I-Lan Ridge, it induces a disturbance with anticyclonic relative vorticity due to the decrease in bottom depth (h), and this disturbance can extend to the surface layer. North of I-Lan Ridge, the bottom is deep and the water column is stretched as the Kuroshio flows from the ridge into this deeper water. As a consequence, the flow acquires cyclonic relative vorticity. This change in sign of relative vorticity, which induces a vorticity disturbance, favors shoreward movement of the Kuroshio. Some warm and saline surface water, particularly onshore of the Kuroshio, could move across the isobaths onto the shelf. By comparison, in summer, the stronger thermocline tends to decouple the movement above and below the thermocline. The disturbance generated over I-Lan Ridge is confined below the thermocline, and the shoreward migration of the Kuroshio in the upper layer is absent off northeastern Taiwan (Hsueh et al., 1993; Chern and Wang, 1994).

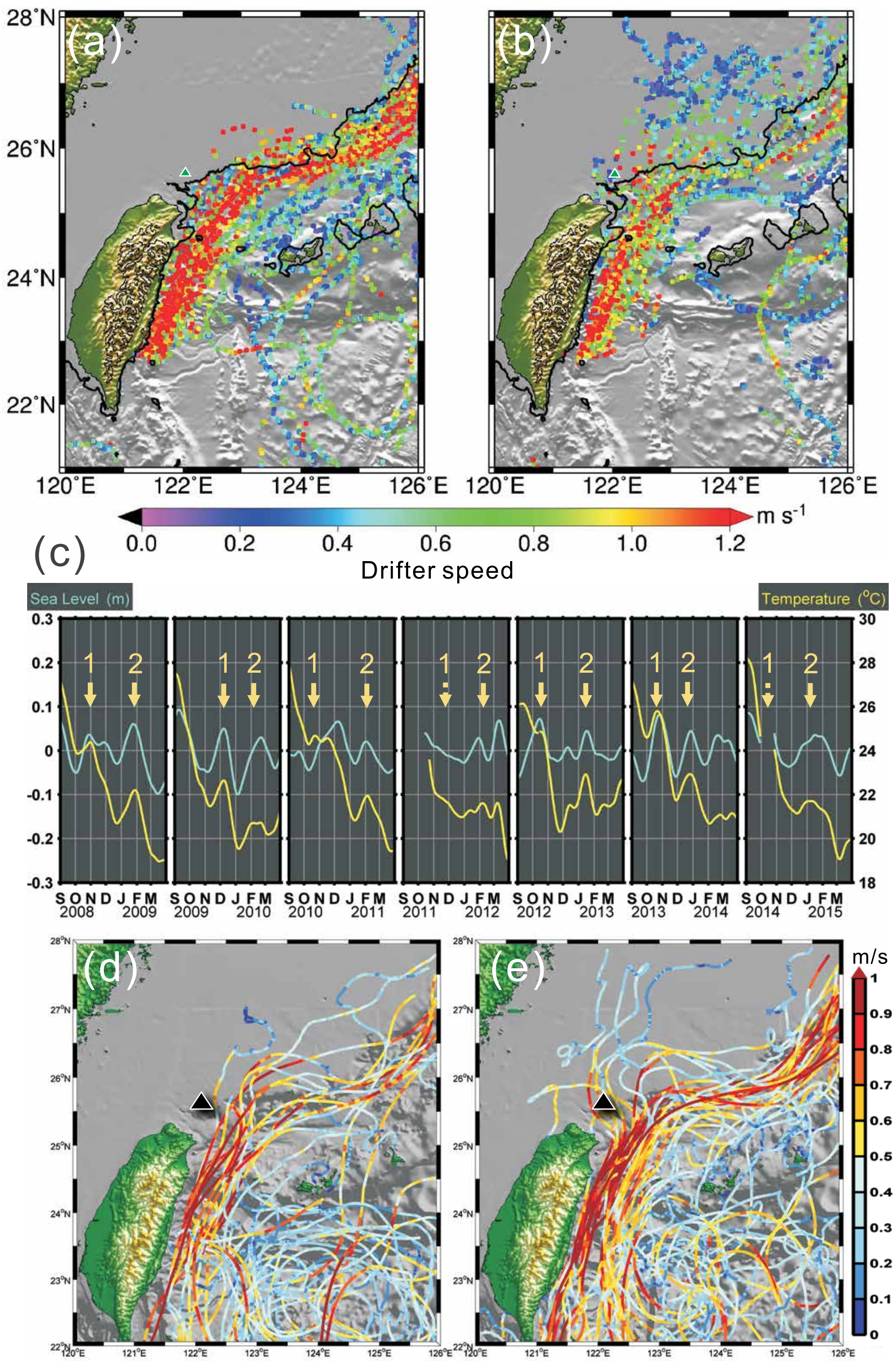

FIGURE 8. Trajectories and speeds of Surface Velocity Program (SVP) drifters deployed east of Taiwan in (a) summer (April to August 2008 and March to August 2009), and (b) winter (September 2008 to February 2009 and Sept. 2009). (c) Twenty-day low-pass-filtered sea level (blue) and temperature (yellow) measured from September through March for each year from 2008 through 2013 at a station on Peng-jia-yu Island north of Taiwan. Trajectories of drifters that cross I-Lan Ridge into the East China Sea during temperature rise/drop periods marked by 1 and 2 are plotted in (d) and (e), respectively. The black triangles in the maps indicate the location of Peng-jia-yu Island.

THE KUROSHIO SOUTH OF JAPAN

Kuroshio path variations within the East China Sea (whether associated with frontal meanders or the small and large Kuroshio shelf intrusions) are small relative to the 300 km offshore shift of the current axis that may occur downstream of the East China Sea in the region south of Japan between Tokara Strait and Izu Ridge (Kawabe 1995). This so-called Kuroshio large meander state may dominate for years or decades, as from 1975 through 1991 (e.g., Kawabe 1995). In contrast to its large meander path, the Kuroshio may persist in a non-large meander state, either paralleling the coast south of Japan all the way to Izu Ridge, hugging the narrow shelf and steep slope there (i.e., the "normal" non-large meander state), or paralleling the coast until the Kii Peninsula and then taking an offshore (~170 km shifted) path to cross over Izu Ridge south of Hachijo-jima (i.e., the "offshore" non-large meander state). The Kuroshio persisted in the non-large meander state from 1991 through June 2004 (Ambe et al., 2004; Kawabe, 2005) and then again from August 2005 to 2010 (Usui et al., 2013). A large meander state from September 2004 through January 2005 (Usui et al., 2011) was first observed in satellite altimetry records (which began in late 1992) and is thus far the only large meander reported in satellite altimetry data. It is interesting to note that the Kuroshio path suggested by drifter mean speed mapping (Figure 2c) indicates a non-large meander state south of Japan. This feature is presumably observed because the time period sampled by the drifters (1987–2014) is largely dominated by a Kuroshio in the non-large meander state.

The onset and decay of the large meander state have received much attention in the literature. However, since this 2004/2005 event is thus far the only large meander period observed in the satellite era, most studies have relied heavily on numerical models to identify this state (e.g., Endoh and Hibiya, 2001; Douglass et al., 2012; Usui et al., 2013).

Even when the large meander state is absent, there are frequent transitory meanders that occur in the Kuroshio between Tokara Strait and Izu Ridge (Solomon, 1978; Book et al. 2002; Ambe et al., 2004; Kakinoki et al., 2008). One mechanism for the creation of these short-term eastward-propagating meanders is direct interactions between the Kuroshio and westward-propagating mesoscale eddies as investigated by Ebuchi and Hanawa (2003). These meanders are in turn an important initiating mechanism for the transition from a non-large meander state to a large meander state (Kawabe, 2005). Thus, they are sometimes referred to as "trigger meanders" (Solomon, 1978), although very few of these meanders actually succeed in triggering such a transition.

CONCLUSION

Our understanding of the Kuroshio's mean and time-varying state has evolved over the last 25 years of in situ measurements. The recent focus of the OKMC/OKTV programs on the low-latitude western North Pacific has expanded our view by installing moorings at upstream sections in the western Philippine Basin (e.g., the Luzon and Taiwan Arrays) and releasing drifters and floats that can trace the current's connectivity from the western Philippine Basin to the downstream mooring sections examined in previous studies of the Kuroshio (e.g., from its entrance to the East China Sea at the World Ocean Circulation Experiment PCM-1 Line, across the PN Line, and through Tokara Strait to the region south of Japan at the ASUKA Line).

Mean sections derived from the moorings clearly show that the Kuroshio is connected across latitudes in the sense that it grows in mean strength and penetration depth along its downstream route. However, since the current is patchy in terms of mean core speed, eddy kinetic energy, and velocity structure (dual versus single core), some of this downstream increase in strength and depth is likely associated with spatially variable local recirculations rather than downstream increase in throughput. Whether (and how) spatial and temporal variability in these local recirculations is related to arrivals of mesoscale eddies remains to be investigated further. The direct impingement of eddies on the western boundary in the Philippine Basin is so strong that eddy arrivals make it difficult to observe coherence in transport variability at different latitudes in the Philippine Basin. To find latitudinal coherence at low frequencies (due, for example, to low-frequency changes in the bifurcation latitude of the North Equatorial Current) will require long-duration time-series measurements. Inside the East China Sea, the Kuroshio is insulated from direct eddy effects and some coherence is evident (e.g., between transport anomalies at the PN Line and Tokara Strait), but even here, the island chain serves only as a partial barrier to eddy influence, and details of where eddies arrive along the island chain is critical to predicting the Kuroshio's response inside the East China Sea.

Studies of Kuroshio variability—from its frontal meanders and intrusions onto the East China Sea shelf to its large-scale path shifts south of Japan—have elucidated underlying mechanisms, but many important open questions remain. (1) Is SST variability on the East China Sea shelf, which is increasing faster than global mean SST, driven by changes in the Kuroshio and cross-shelf exchange? (2) Does the "missing" large meander south of Japan in satellite altimetry data simply represent the intrinsic variability of the system or is this due to a regime shift in the system? (3) How is variability at different temporal scales related (e.g., do eddy arrivals at the boundary drive internal waves and mixing there, and do low-frequency changes in the numbers and paths of eddies drive low frequency change in Kuroshio strength)?

Continued measurement programs, particularly those that leverage the complementary capabilities of different instrument types, are essential for further elucidating the processes underlying observed Kuroshio variability. Progress in improving the predictive capabilities of numerical models will require continued commitment to in situ measurements even as remote sensing and modeling capabilities improve.

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