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Study of the Kuroshio/Ryukyu Current System Based on Satellite-Altimeter and *in situ* Measurements

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Data from satellite altimeters and from a 13-month deployment of *in situ* instruments are used to determine an empirical relationship between sea-level anomaly difference (ΔSLA) across the Kuroshio in the East China Sea (ECS-Kuroshio) and net transport near 28°N. Applying this relationship to the altimeter data, we obtain a 12-year time series of ECS-Kuroshio transport crossing the C-line (KT). The resulting mean transport is 18.7 ± 0.2 Sv with 1.8 Sv standard deviation. This KT is compared with a similarly-determined time series of net Ryukyu Current transport crossing the O-line near 26°N southeast of Okinawa (RT). Their mean sum (24 Sv) is less than the mean predicted Sverdrup transport. These KT and RT mean-flow estimates form a consistent pattern with historical estimates of other mean flows in the East China Sea/Philippine Basin region. While mean KT is larger than mean RT by a factor of 3.5, the amplitude of the KT annual cycle is only half that of RT. At the 95% confidence level the transports are coherent at periods of about 2 years and 100–200 days, with RT leading KT by about 60 days in each case. At the annual period, the transports are coherent at the 90% confidence level with KT leading RT by 4–5 months. While the bulk of the Kuroshio enters the ECS through the channel between Taiwan and Yonaguni-jima, analysis of satellite altimetry maps, together with the transport time series, indicates that the effect of mesoscale eddies is transmitted to the ECS via the Kerama Gap southwest of Okinawa. Once the effect of these eddies is felt by the ECS-Kuroshio at 28°N, it is advected rapidly to the Tokara Strait.

Keywords:
· Kuroshio,
· Ryukyu Current,
· volume transport,
· East China Sea,
· Tokara Strait,
· Kerama Gap,
· eddies,
· inverted echo sounder,
· ADCP,
· satellite altimeter.

1. Introduction

According to Sverdrup theory, the North Pacific subtropical gyre transports water southward in response to the integrated wind-stress curl. Convergence in this southward flow feeds the broad North Equatorial Current (NEC) which, in the mean, carries about 60 Sv westward across 137°E, roughly in accord with the transport expected from the basin-wide North Pacific wind-stress curl (Qiu and Joyce, 1992). This current bifurcates east of the Philippines. The Kuroshio is the branch of the bifurcation that returns water northward as a swift western boundary current (Nitani, 1972). On reaching Taiwan, most of the Kuroshio enters the East China Sea (ECS) over a ~775 m deep sill (Choi *et al.*, 2002) between Taiwan and Yonaguni-jima, the southernmost island of Japan's Ryukyu Island chain. This current, the ECS-Kuroshio, exits the ECS through the Tokara Strait. A branch, the Ryukyu Current, sometimes flows on the seaward side of the Ryukyu Islands (Yuan *et al.*, 1998; Kawabe, 2001). The Ryukyu Current is ephemeral near the southern-most Ryukyu Islands (e.g., Yuan *et al.*, 1991, 1994, 1996) and it is unknown how much of it comes from the Kuroshio east of Taiwan and how much from the ocean interior. There is evidence that the Ryukyu Current intensifies as it flows northeastward along the Ryukyu Islands (e.g.,

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You and Yoon, 2004; Ichikawa *et al*., 2004; Nagano *et al*., 2007, 2008; Zhu *et al*., 2008b). South of Kyushu, the Ryukyu Current joins the ECS-Kuroshio as it leaves the Tokara Strait. Finally, the Kuroshio leaves the Japan coast as an eastward flowing free jet, the Kuroshio Extension, closing the North Pacific subtropical gyre.

The ocean regions east of Taiwan and the Ryukyu Islands are characterized by the frequent arrival of mesoscale eddies from the ocean interior at intervals of about 100 days (Yang *et al*., 1999; Zhang *et al*., 2001; Konda *et al*., 2005). These eddies originate in a zonal band of high eddy kinetic energy between 19°N and 25°N and may be generated by baroclinic instability associated with the vertical shear between the shallow, eastward flowing Subtropical Countercurrent (STCC) and the underlying portion of the NEC (Qiu, 1999). There is also evidence that some eddies may be generated by the passage of typhoons (e.g., Lee *et al*., 2003). Typical eddies, which can be cyclonic or anticyclonic, are about 500 km in diameter (Roemmich and Gilson, 2001) with westward propagation speeds of 7–8 cm/s (e.g., Konda *et al*., 2005), temperature anomalies of ±3°C, flow velocities around 20–40 cm s^{-1} and surface height anomalies around 20–30 cm (e.g., Zhu *et al*., 2008a). Eddies hamper the evaluation of ECS-Kuroshio and Ryukyu Current mean transports from isolated hydrographic sections. Moreover, when these eddies arrive off Taiwan, they may change the proportions of transport flowing in the ECS-Kuroshio and the Ryukyu Current (Yang *et al*., 1999; Zhang *et al*., 2001; Liu *et al*., 2004).

Previous studies of Kuroshio transport suggest that the annual range of variability on entering the ECS is less than 10 Sv (Lee *et al*., 2001, and references therein), which is small compared to that expected from non-topographic, time-dependent Sverdrup theory. The seasonally varying wind-stress curl integrated over the Philippine Basin predicts a 20 Sv peak-to-peak annual range in Sverdrup transport (from Lee *et al*., 2001 based on COADS data integrated from 125°E to 142°E) and that integrated over the entire North Pacific predicts about 50 Sv annual variation in transport (Sakamoto and Yamagata, 1996; their figure 1 based on climatological winds of Hellerman and Rosenstein, 1983). An additional enigma is that North Pacific winds are strongest in winter (e.g., Hellerman and Rosenstein, 1983) but the highest ECS-Kuroshio transport is typically observed in summer (e.g., Ichikawa and Beardsley, 1993).

A significant portion of the Sverdrup return flow may be carried as a western boundary current on the eastern side of the Ryukyu Islands (Hautala *et al*., 1994; Lee *et al*., 2001). Lee *et al*. (2001) suggest such a scenario based on a 20-month time series of flow entering the ECS and the Sverdrup transport calculated from integrated wind-stress curl over the Philippine Basin. With their observed 4 Sv annual variation of transport entering the ECS, they suggest that the Ryukyu Current should carry about 12 Sv in the mean, with a 16 Sv (peak-to-peak) annual range. Others suggest that, while Sverdrup flow does prevail in the interior (Kagimoto and Yamagata, 1997), the reduced seasonal signal in the ECS arises from "JEBAR rectification" (Sakamoto and Yamagata, 1996; Sakamoto, 2005).

Time series of velocity structure and transport of the ECS-Kuroshio north of Okinawa were calculated from November 2003–November 2004 using data from 11 inverted echo sounders (IESs) and 2 ADCPs (Andres *et al*., 2008). Here we employ a technique similar to that of Zhu *et al*. (2004) and Imawaki *et al*. (2001a) to determine an empirical relationship between this ECS-Kuroshio transport and satellite altimeter data, in order to extend the transport time series using the altimeter data. We analyze the long period (>60 days) variability in this extrapolated time series and compare ECS-Kuroshio transport with the time series of Ryukyu Current transport and other regional signals.

To date, ECS transport studies have relied mainly on snapshots taken over many years (e.g., Ichikawa and Beardsley, 1993; Yuan *et al*., 1998; Isobe, 2008), or data collected quarterly (Ichikawa and Chaen, 2000). Thus, the month-by-month seasonal signal of the ECS-Kuroshio has not been well resolved. In addition, a long-term comparison between concurrent ECS-Kuroshio and Ryukyu Current transports has not been possible since the combined flow in these two Kuroshio branches has been reported only for isolated snapshots (e.g., Yuan *et al*., 1991, 1994, 1996; Zhu *et al*., 2006). The role of eddies in steering the Kuroshio has not been thoroughly examined. The following questions are addressed in this paper.

- How are the ECS-Kuroshio and Ryukyu Current transports related at intra-annual to interannual periods?
- What is the annual range in ECS-Kuroshio and Ryukyu Current transports and how do these compare with theoretical predictions?
- How does the Ryukyu Current/ECS-Kuroshio system respond to the arrival of mesoscale eddies from the east?
- Is the combined mean transport of the ECS-Kuroshio and Ryukyu Current equal to the expected mean Sverdrup transport?

2. Data

2.1 *Transport and velocity structure time series*

Time series of the ECS-Kuroshio's net absolute transport and velocity structure in the ECS north of Okinawa are available for 13 months, from November 2003 to November 2004 (Andres *et al*., 2008). This flow was measured for a 210 km span, referred to as the C-line (close to the so-called PN-line), from a point 15 km shore-

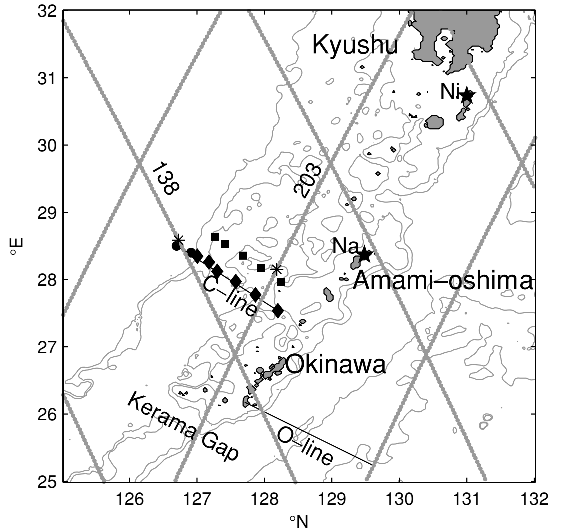

Fig. 1. Map showing CPIESs (diamonds), PIESs (squares) and ADCPs (circles). Jason-1 satellite tracks are shown. Depth contours are shown for 500, 1000 and 5000 m. Asterisks show locations (126.727°E, 28.586°N and 128.184°E, 28.151°N) of satellite altimeter measurements used in determining the empirical relationship between ΔSLA and net transport (see Methods). Stars show locations of Naze (Na) and Nishinoomote (Ni).

ward of the continental shelf-break (taken as the 170 m isobath) to a site near the Ryukyu Island chain (see Fig. 1). These time series were determined using data from inverted echo sounders equipped with pressure sensors (PIESs) and from ADCPs. The eleven PIESs measured hourly round-trip, bottom-to-surface acoustic-travel-time, τ, and bottom pressure. The six PIESs deployed along the C-line were further equipped with current sensors moored 51 m above the seafloor (CPIES). Hourly τ data were two-day low-pass filtered and then used to determine time series of specific volume anomaly profiles, $\delta(z)$, by the GEM method (e.g., Watts *et al.*, 2001; Book *et al.*, 2002). Using the thermal wind equation, velocity shear was then calculated from $\partial\delta/\partial x$. Finally, this shear was referenced with deep pressure and current data to obtain absolute velocity and transport according to the method described by Andres *et al.* (2008). The two bottom-mounted ADCPs measured the portion of ECS-Kuroshio flow shoreward of the 550 m isobath on the western edge of the Okinawa Trough which was not captured by the IESs.

2.2 *Satellite altimetry*

During the PIES/ADCP deployment, the Jason-1 satellite (J1) occupied an orbit with tracks 138 and 203 passing 5.3 km and 26.2 km from the western and eastern ends of the C-line, respectively (Fig. 1). The repeat cycle for satellite passes was 9.9156 days. On each cycle, track 138, a descending track, was followed 2.5375 days later by the ascending track 203. From October 1992 until August 2002, these same tracks were occupied by the TOPEX/Poseidon satellite (T/P).

Along-track sea-level anomaly (SLA) data, produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes, are used in this study. Aviso's Reference Product is used to assure continuity in the time series. Aviso reports SLA data corrected for the following: dry and wet troposphere, ionosphere, sea state bias, ocean and pole tides, and a combined atmospheric (including inverse barometer) correction; the data are not corrected for the Large Wavelength Error (for details, see the Aviso website: www.aviso.oceanobs.com).

In addition to the along-track SLA data, merged SLA maps at 7-day intervals from Aviso are used to track eddies in order to study their effects on the ECS-Kuroshio and the Ryukyu Current.

2.3 *Ryukyu Current*

We analyzed ECS-Kuroshio transport crossing the C-line (KT) in conjunction with Ryukyu Current transport crossing the O-line (RT) calculated by Zhu *et al.* (2004). During November 2000–August 2001, 9 PIESs and an upward looking ADCP were deployed southeast of Okinawa (Zhu *et al.*, 2003) to obtain a transport time series. Zhu *et al.* (2004) obtained an empirical relationship between the net northeastward volume transport (their NVT) between Okinawa and 129.5°E (O-line, see Fig. 1) and the sea-level anomaly difference (ΔSLA) across the current, where ΔSLA was determined with a combination of tide-gauge data and satellite-altimeter data. This technique provided a temporal extrapolation, resulting in a time series of NVT beginning in 1992 (Zhu *et al.*, 2004). Here we refer to this NVT as RT to distinguish it from the northeastward Kuroshio flow inside the ECS. Note that this RT had a strong eddy component. Its associated error was 5.9 Sv (2.1 Sv for the 10-month low-pass filtered values).

2.4 *Other regional signals*

Absolute transport entering the ECS through the East Taiwan Channel (ETC) between Taiwan and the Ryukyu Islands was measured by Johns *et al.* (2001) from September 1994 until May 1996 with a line of moored current meters and ADCPs located across the channel (the PCM-1 array of the World Ocean Circulation Experiment). Transport, relative to 700 dbar, exiting the ECS through the Tokara Strait determined four times per year from 12 CTD stations across the strait was reported in Nakamura *et al.* (2006).

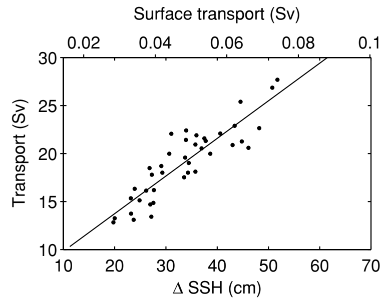

Fig. 2. Correlation between observed surface transport in top 10 m and total transport along the C-line between November 2003 and November 2004 at 10-day intervals. ΔSSH shown is computed from surface transport assuming geostrophy using Eq. (1).

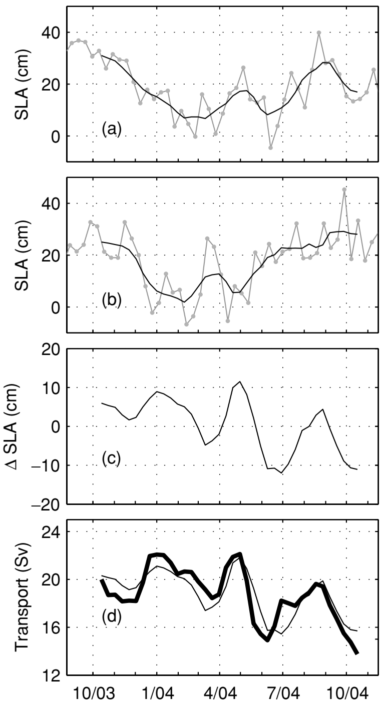

Fig. 3. (a) J1 SLA near the offshore end of the C-line (raw data = gray line, 5 point boxcar-filtered data = black line). (b) As in panel a, but for a point near the onshore end of the C-line, (c) ΔSLA ((a)–(b)), (d) 40-day boxcar-filtered transport measured along the C-line by CPIES/PIESs and ADCPs (heavy line) and satellite-derived transport (thin line) determined from ΔSLA of panel (c) using the empirical relationship: Transport (Sv) = 0.27 ΔSLA (cm) + 18.69. Vertical dotted lines mark beginnings of indicated months.

3. Methods

In this section, we first use C-line velocity cross-sections, determined from 2-day lowpass filtered *in situ* measurements taken hourly over 13 months (Andres *et al*., 2008), to demonstrate that sea surface height difference (ΔSSH) across the Kuroshio can be used as a proxy for full-water-column transport. Next we determine the empirical relationship between full-water-column transport from the *in situ* measurements and ΔSLA from satellite altimetry. Finally, the resulting empirical relationship between these two is used with satellite altimeter data to generate a 12-year time series, beginning in 1992, of ECS-Kuroshio transport crossing the C-line.

In a layered ocean, assuming geostrophy, the net transport in the uppermost layer, VT_{surf}, is proportional to ΔSSH across the current,

$$VT_{\text{surf}} = \frac{gD}{f}\Delta\text{SSH}, \qquad (1)$$

where g is gravity, D is the thickness of the uppermost layer, and f is the Coriolis parameter. Furthermore, if upper-layer transport is well correlated with full-water-column (total) transport, ΔSSH can be used to infer the total transport.

Andres *et al*. (2008) calculated a time-series of absolute geostrophic velocity cross-sections, determined in 10 m thick layers from the surface to the sea floor, along the C-line. Analysis of this velocity structure time series shows that ΔSSH calculated from net transport in the uppermost layer (Eq. (1)) is in fact well correlated with net transport in the entire water column (Fig. 2). The correlation coefficient, r, for values sub-sampled every 10 days (approximately the transport time-series integral time scale) is 0.88 with an rms error in total transport of 1.7 Sv. This demonstrates that ΔSSH can be used as a proxy for transport in this region. For comparison, the correlation coefficient between surface and total transport for the area-integrated eastward flow in the Kuroshio south of Japan along the ASUKA line is 0.90 with an rms error in transport of 5.6 Sv (Imawaki *et al*., 2001a).

During the entire T/P deployment, there are no SLA data from the sites on track 203 falling closest to the offshore end of the C-line. Data at these sites become available only when this orbit is occupied by J1. Nevertheless, as demonstrated below, it is still possible to determine a robust empirical relationship between satellite-derived ΔSLA and C-line transport. The locations of the satellite points used are shown in Fig. 1 (asterisks).

In order to determine an empirical relationship between low-frequency variations in satellite-derived ΔSLA and C-line transport, the following procedure is used for the November 2003–November 2004 time period. Time series of satellite-measured SLA at the two satellite points are passed through a 5 point boxcar filter resulting in SLA time series which are essentially 40-day lowpass filtered since the satellite repeat cycle is almost 10 days (Figs.

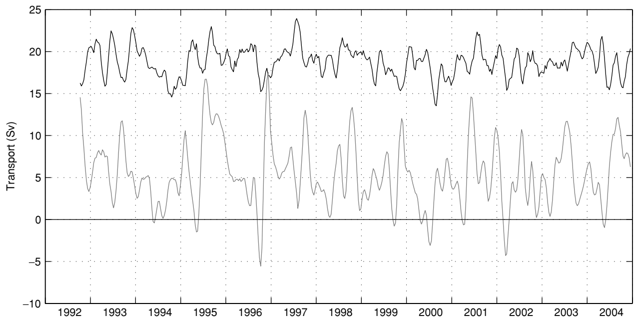

Fig. 4. Satellite-derived transports. Black = KT, gray = RT.

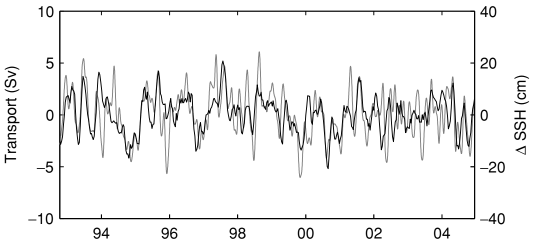

Fig. 5. Comparison of 40-day lowpass filtered Tokara Strait ΔSSH (gray) with KT (black). Means have been removed from both time series. X-axis marks indicate beginnings of indicated years.

3(a) and (b)). Next the filtered SLA time series are interpolated to a common time base with an exact 10-day interval and differenced to calculate ΔSLA across the C-line (Fig. 3(c)). The seasonal signal due to surface warming and cooling, which is apparent in each of the two SLA time series, is assumed to be spatially uniform in this small region and thus cancels out in the ΔSLA calculation. The net absolute ECS-Kuroshio transport across the C-line, determined from the *in situ* instruments (CPIES/PIESs and ADCPs), is also 40-day boxcar filtered (Fig. 3(d), heavy line). An empirical linear relationship between the resulting ΔSLA and the transport is determined by least-squares fitting, and this relationship is used to calculate satellite-derived transport (Fig. 3(d), thin line). Net absolute transport, from the *in situ* instruments, and ΔSLA (or satellite-derived transport) are well correlated with r = 0.83. Using this empirical relationship, rms difference between satellite-derived transport and transport determined from *in situ* instruments is 1.2 Sv. For the Ryukyu Current crossing the O-line, the correlation coefficient between satellite-derived transport (from ΔSLA) and that from *in situ* instruments was 0.91 with 2.8 Sv rms difference (Zhu *et al*., 2004), although we note that the calibration procedure of Zhu *et al*. (2004) was slightly different from that used here (e.g., they smoothed the satellite data spatially, whereas we smoothed them temporally).

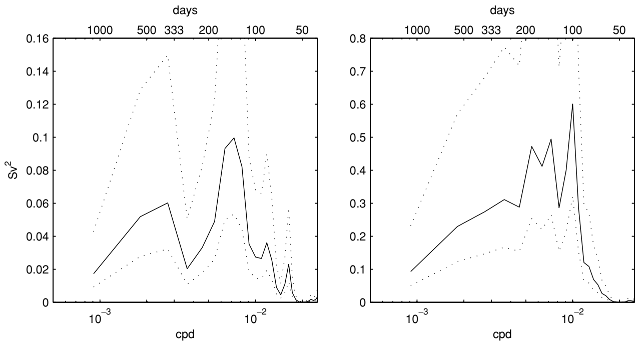

Fig. 6. Variance-preserving transport power spectra for KT (left) and RT (right). Dashed lines are 95% confidence intervals. Spectra are calculated with Hanning windows, 1100 days wide with 50% overlap (7 overlapping segments). Note the y-scales differ by a factor of 5.

Using the empirical relationship between ΔSLA and net absolute transport, satellite altimeter data extending back to October 1992 are used to produce a 12-year time series of ECS-Kuroshio transport crossing the C-line (Fig. 4, black line). We refer to this transport as KT.

To support the extrapolation method, the 12-year KT time series is compared to ΔSSH across the Tokara Strait calculated using detided sea levels from Naze and Nishinoomote (locations are shown in Fig. 1). Tokara Strait ΔSSH is a proxy for transport exiting the ECS through the Tokara Strait (Kawabe, 1995; Ichikawa, 2001). In order to make the comparison, the Tokara Strait ΔSSH is 40-day low pass filtered. The two time series (Fig. 5) show moderately good agreement with r = 0.55.

4. Results and Discussion

The 12-year mean KT is 18.7 Sv with ±0.2 Sv standard error, compared to 5.4 ± 0.4 Sv for the RT in the same period. Standard errors were calculated using the "blocking" method for correlated data described by Flyvbjerg and Petersen (1989). Transport of the ECS-Kuroshio is less variable than that of the Ryukyu Current with KT standard deviation about half that of RT (1.8 Sv vs. 3.9 Sv). Variance-preserving power spectra of the two transports are shown in Fig. 6. KT shows two significant energy peaks, one at periods of 300–600 days and the other at 100–170 days. Also, a small, though significant, peak appears near 60 days. RT is broadly energetic at periods of about 100–500 days, with a couple of peaks between 100 and 200 days.

4.1 Annual cycle

Power spectra contain energy at the annual period in

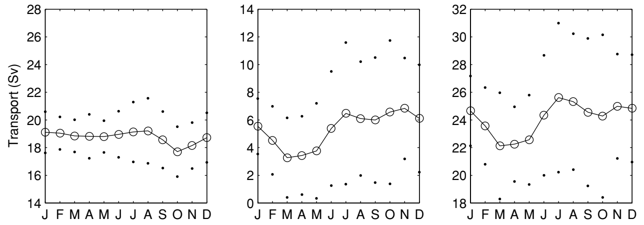

Fig. 7. Monthly mean transport in KT (left), RT (middle) and total transport (right). Circles represent monthly means for the 12-year ΔSLA-derived transports. Dots represent ± standard deviation of transport each month.

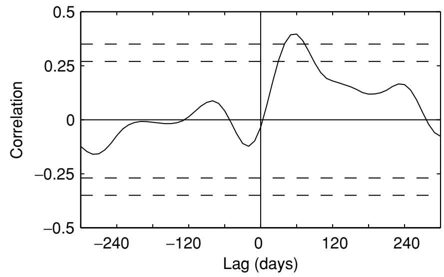

Fig. 8. Cross correlation function of KT and RT with time lag. Positive lag indicates KT lagging RT. The RT time series has 54 degrees of freedom (DOF) while the KT time series has 73 DOF. Dashed lines show the 95% and 99% confidence levels (±0.273 and ±0.354, respectively) for a correlation with 50 DOF (Emery and Thomson, 2001).

both the KT and the RT, although only the KT has a well-defined peak (Fig. 6). In order to investigate the annual cycle further, transport data for the two currents are averaged by month over the 12 year time series for the two currents. These annual cycles and their sum are plotted in Fig. 7 together with the standard deviation of transport for each month (dots). Even though KT is stronger than RT in the mean by a factor of 3.5, the annual range in RT is about 3.5 Sv, while that of KT is only about 1.6 Sv. Both currents show significant variability in the monthly transport, particularly from July to October (Fig. 7, dots). This probably reflects not only interannual variations in the annual cycle, but also the effect of mesoscale eddies.

The KT monthly-averaged signal has a maximum in August, followed by a sharp minimum in October. From December through August there is only 0.5 Sv variation in the KT monthly averages. The RT annual cycle has a maximum in November and a minimum in March. When the two currents are added together, the resulting combined western boundary current transport has an annual range of almost 4 Sv (peak-to-peak) with a minimum in March and a secondary minimum in October. Maxima occur in July and December. These results are similar to reported seasonal transports 1000 km upstream and downstream from our region: east of southern Taiwan, Gilson and Roemmich (2002) report 8 ± 6 Sv annual range with minimum in April and maximum in July; at the ASUKA line, Imawaki *et al.* (2001b) report ~5 Sv annual range with minima in March and September and maxima in July and December. Kakinoki *et al.* (2008) report 8.3 Sv annual range along the ASUKA line.

An October minimum in ECS-Kuroshio transport has been noted previously in other work (e.g., Kawabe, 1988; Ichikawa and Beardsley, 1993). Moreover, 21 months of transport measurements just upstream of the ECS (Johns *et al.*, 2001) averaged by month also exhibit an October minimum. Nevertheless, this minimum is absent in RT, which supports the possibility that the KT minimum results from local wind forcing (Ichikawa and Beardsley, 1993) or the baroclinicity (Kagimoto and Yamagata, 1997) rather than integrated wind-stress over the Pacific or Philippine Basin. Ichikawa and Beardsley (1993) found that transport in the ECS is positively correlated with the downstream component of wind-stress.

4.2 Co-variation of ECS-Kuroshio and Ryukyu Current

KT and RT shown in Fig. 4 are uncorrelated: r is not significantly different from zero. But this changes when one introduces a lag between the two currents (Fig. 8): with KT lagging RT by 60 days, the two currents become positively correlated at the 99% confidence level (r = 0.40).

The coherence spectrum between KT and RT is plotted in Fig. 9 (upper panel). Transports are coherent (at the 95% confidence level) at periods of 110 days, 160 days and 2-years. A 2-year spectral peak was also found by Zhu *et al.* (2004) who report a quasi-biennial oscillation in RT. In addition, Kawabe's (1988) analysis of 18 years of sea-level difference across the Tokara Strait has a spectral peak at 2.1 years. Phases at frequencies of significant coherence are plotted in Fig. 9 (lower panel) and show KT generally lagging RT by 33–62 days. This suggests that the previously-noted strong correlation between the two currents occurring at 60 day lag arises from processes occurring over a range of periods from about 100 days to 2 years. Further, the 60-day phase lag at 2-year period is relatively short, suggesting that the 2-year-period component in the ECS-Kuroshio and the Ryukyu Current is caused by the same driving force, possibly wind-stress over the North Pacific (Zhu *et al.*, 2004).

There is an annual peak in coherence (Fig. 9), but it falls below the 95% confidence level. It is significant only at the 90% confidence level (0.68). Nevertheless it is worth noting that the phase of the annual peak differs by approximately 180° from that of the other coherence peaks, indicating that annual KT variation *leads* that of

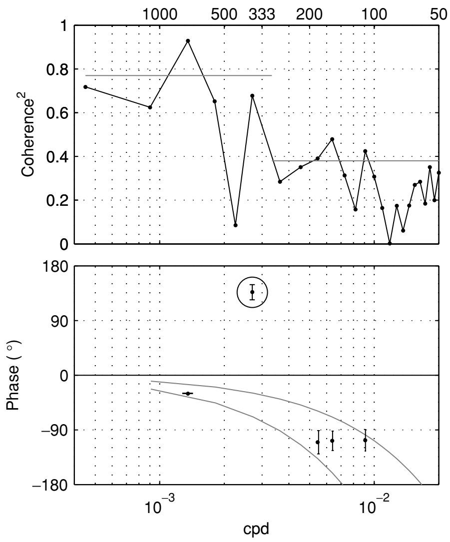

Fig. 9. Squared-coherence and phase lag spectra between KT and RT. For periods longer than 300 days, a 2220-day window was used. For shorter periods a 1100-day window was used. Gray lines on the coherence plot show the 95% confidence level. Phase (with standard error) is shown for frequencies which are coherent at the 95% confidence level. Additionally, the circled dot is the phase for 1-year period coherence (see text). Positive phase indicates RT lagging KT. Gray curves on the phase plot denote phase boundaries for transport lags between 30 and 70 days.

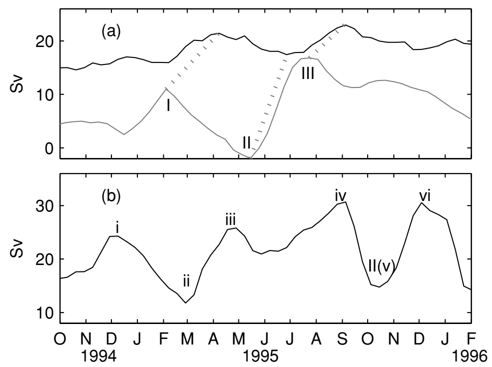

Fig. 10. (a) KT (black line) and RT (gray line) as in Fig. 4 but for period from October 1994 to January 1996. Influences of three eddies are apparent: Events I (anticyclonic), II (cyclonic), and III (anticyclonic)—see text. (b) The concurrent Kuroshio transport through the ETC from Johns *et al.* (2001) and 40-day lowpass filtered. Eddies i through vi are discussed in the text. Marks indicate beginning of designated month.

the RT by 137° ± 13°, which corresponds to a lead of 4.6 months (or a lag of 7.4 months). This is consistent with the 5 month time difference in the monthly-average minima shown in Fig. 7 (October for KT vs. March for RT).

4.3 Eddy effects

The Kuroshio enters the ECS over the Ilan ridge between Taiwan and the Ryukyu Islands. Zhang *et al.* (2001) suggest eddies arriving east of Taiwan can steer some of the transport either into the ECS or to the east of the Ryukyu Islands. This should result in Ryukyu Current and ECS-Kuroshio transport variations which are *negatively* correlated at periods typical of mesoscale eddies. However, Fig. 9 shows that KT and RT are coherent with 30–70 lag at these eddy-periods and the observed maximum-magnitude correlation is *positive* with a 60 day lag (Fig. 8). While eddy-steering east of Taiwan may occur in some instances, it does not seem to play a significant role in our observed 60-day lagged correlation between KT and RT. Rather, these transport co-variations appear to be the effect of many eddies communicated through the Kerama Gap, which lies southwest of Okinawa near 26°N, 127°E (Fig. 1) and has a sill depth of ~1050 m (Choi *et al.*, 2002). The associated lag likely arises from the time it takes an eddy to travel from the O-line to the Kerama Gap. Since the O-line lies about 200 km east of the Kerama Gap, this 60-day lag suggests eddies slow down from typical propagation speeds of 7–8 cm/s (Konda *et al.*, 2005) to ~4 cm/s. This reduction in propagation speed as eddies approach the Kerama Gap is consistent with a numerical model for inviscid barotropic flow of the interaction of a vortex with a gap in a wall (Johnson and McDonald, 2004, their figure 8); it may also be a result of advection by the Ryukyu Current.

Current-meter data suggest there is a net mean flow through the Kerama Gap into the ECS (Morinaga *et al.*, 1998). Generally, eddies themselves are not observed to pass through the gap into the ECS, but they appear to induce changes in the flow through the gap. The interaction of eddies with gaps has been treated numerically and analytically (e.g., Simmons and Nof, 2002; Johnson and McDonald, 2004, 2005) and with laboratory tank experiments (e.g., Cenedese *et al.*, 2005; Tanabe and Cenedese, 2008). Results depend on numerous parameters, such as the ratio of gap diameter to eddy diameter, G/d, relative position of eddy and gap, values of f and β ($=\partial f/\partial y$), orientation of the boundary, whether or not there is background flow, and whether the problem is inviscid (numerical and analytical models) or includes friction (tank experiments). There is great "richness in dynamics," but, in tank experiments with $G/d < 0.4$, eddies are often observed to "funnel" water through gaps between cylinders without themselves passing between the cylinders (Cenedese *et al.*, 2005, their figure 9). Unfortunately, the parameters used in these studies are not good representations of eddies near the Kerama Gap, so we could not use them to

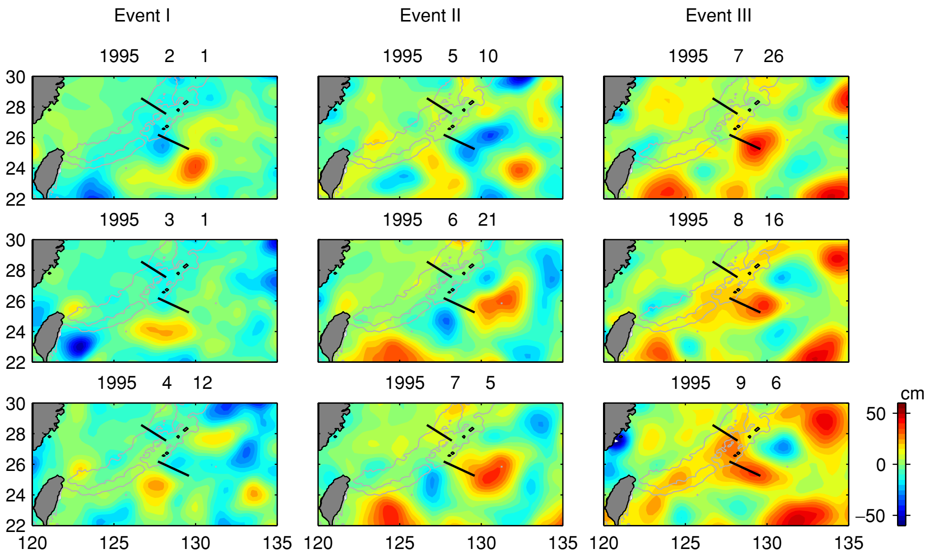

Fig. 11. Merged satellite SLA maps. Each column tracks a different event (I, II, III) identified in Fig. 10(a). Heavy black lines show C-line (north of Okinawa) and O-line (southeast of Okinawa). Gray contours show the 900 m isobath. In each panel the area-mean SLA was first removed to eliminate the effect of seasonal heating and cooling.

anticipate what we observed. In the context of the present observations, the eddy-effect on ECS-Kuroshio transport is demonstrated below by comparing the transports (Fig. 10) with satellite altimetry maps (Fig. 11) for 1995, when a series of strong cyclonic and anticyclonic eddies passed through the region.

Figure 10(a) shows KT and RT from October 1994 through January 1996. During this time there is a series of transport maxima and minima. Three events (I, II, and III) are highlighted and in each case show an extremum first in RT and then in KT.

Figure 11 shows merged SLA maps from February through September 1995. In February 1995, coincident with a RT maximum (Event I), an anticyclonic eddy on the offshore side of the O-line (southeast of Okinawa, crossing the Ryukyu Current) is coupled with an onshore cyclonic eddy. This eddy pair transports water northeastward across the O-line. The anticyclonic eddy moves westward and by March 1995 it reaches the Kerama Gap, where it stalls until May. While it is stalled, a maximum is observed in KT, suggesting that the eddy by the Kerama Gap is adding to flow through the gap into the ECS. This water flows northward in the ECS and crosses the C-line, increasing the net transport. The maximum in transport across the C-line (KT) lags the O-line transport maximum (RT) by roughly 2 months (Fig. 10).

In mid-May a cyclonic eddy on the offshore end of the O-line manifests itself as a minimum in RT (Fig. 11, Event II). This eddy moves west and arrives at the Kerama Gap around mid-June where it stays until mid-July. Its effect is felt along the C-line as a minimum in KT at the end of June, suggesting that the cyclonic eddy is reducing (or even reversing) flow through the Kerama Gap into the ECS. In this case, the lag between RT and KT minima is about 1.5 months (Fig. 10).

Meanwhile, an anticyclonic eddy arrives at the O-line coincident with a RT maximum at the end of June (Fig. 11, Event III). It remains there, but elongates towards the Kerama Gap and into the ECS during August/September coincident with a maximum in KT such that the maximum in KT lags that in RT by about 2 months (Fig. 10).

During this time period, Kuroshio transport entering the ECS through the ETC was measured by Johns *et al.* (2001) with an array of current meters and ADCPs. A portion of their 21 month (September 1994–May 1996) time series (40-day lowpass filtered for compatibility) is shown in Fig. 10(b). The correlation coefficient between this ETC transport and the corresponding 21 months of KT has its maximum at zero lag with value 0.43, but this correlation is not significant, even at the 90% confidence level. In contrast, the correlation coefficient for the same 21 months between KT and RT, has its maximum at 40 days lag with value 0.63, and this correlation is significant at the 95% confidence level. Thus while the main Kuroshio transport passes into the ECS through the ETC, transport variations at the C-line occurring over time scales on the order of 1.5 years or less are related mainly to variations of flow through the Kerama Gap rather than those through the ETC.

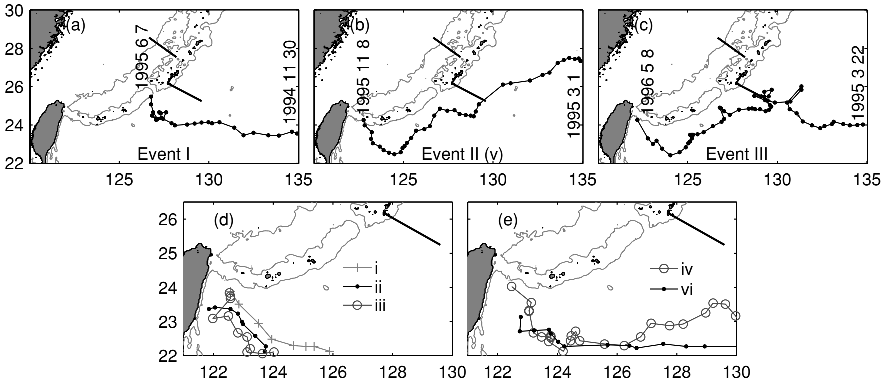

Fig. 12. Eddy-center tracks determined from merged satellite SLA maps. Positions are marked at 7-day intervals. Panels (a), (b), and (c) show Events I, II, and III, respectively, with dates of first and last position indicated. Panels (d) and (e) show tracks of eddies which do not cross the O-line or approach the Kerama Gap. Last plotted positions of i, ii, and iii are on 1994 12 7, 1995 3 29, and 1995 5 10, respectively. Last plotted positions of iv and vi are on 1995 9 20 and 1995 12 17, respectively. Event II(v) and ii are both cyclonic, the rest are anticyclonic.

To discern the effect of eddies on ETC transport, KT, and RT, we tracked eddies using merged SLA maps available at 7-day intervals (Fig. 12). While ETC-transport shows many extrema during the period from October 1994 through January 1996 (e.g. Events i through vi in Fig. 10(b)), only one of these (Event v, the minimum in October 1995) can be clearly related to an event affecting transport across the O- and C-lines (Event II, track shown in Fig. 12(b)). Event I appears to decay near the Kerama Gap around June 1995 (Fig. 12(a)) and thus never reaches the region east of Taiwan. While Event III does eventually make it to the region east of Taiwan (Fig. 12(c)), it does not arrive until May 1996, which is after Johns *et al.*'s (2001) ETC-transport measurements.

Five of the six pronounced extrema in ETC-transport appear to be related to eddies which never encounter the O-line or the Kerama Gap (Figs. 12(d) and (e)). The ETC-transport maximum in December 1994 (i), minimum in March 1995 (ii), and maximum in May 1995 (iii) appear to be related to eddies coming from the southeast (Fig. 12(d)). ETC-transport maxima in September 1995 (iv) and December 1995 (vi) appear to be caused by anticyclonic eddies approaching from the east (Fig. 12(e)). For all six of these eddy-associated events at the ETC, there is a consistent pattern: transport maxima are associated with anticyclonic eddies and minima with cyclonic eddies, regardless of the direction of eddy arrival. This pattern is in agreement with the findings of Yang *et al.* (1999) who based their conclusion on analysis of tide gauge-derived sea-level difference across the ETC, satellite altimetry and surface drifting buoys. There is one exception to this overall pattern: a weak ETC transport minimum in June 1995 (Liu *et al.*, 2004) appears to be due to the same anticyclonic eddy which eventually causes a transport maximum in September 1995 (Event iv). This unusual eddy has a large diameter and stalls for about 1 month in June 1995 near 124.5°N, 22.5°E (Fig. 12(e)). During that month the eddy appears to cause an offshore deflection of the Kuroshio away from the ETC resulting in the weak minimum in ETC transport. This scenario is consistent with coincident drifter tracks (Yang *et al.*, 1999, their figure 9).

All three transport records shown in Fig. 10 have strong oscillations with 3–5 month periods. In each case the oscillations appear to be caused by eddies arriving in the region from the east. Moreover a single eddy, like Event II, can be responsible for transport changes, at different times, in all three places, the O-line, the C-line, and the ETC line. However, many eddies arrive at the ETC from the east or southeast rather than from the northeast. These affect ETC-transport without first influencing transports across the C- and O-lines.

The influence of eddies on the flow in the ECS may be communicated through the Kerama Gap with a typical time lag (relative to the Ryukyu Current crossing the O-line) of 60 days. The peak correlation ($r = 0.4$) between RT and KT at 60-day lag represents a mean condition over the 12-year period. When correlation is calculated over a moving 2-year window, the lag resulting in the highest correlation coefficient (optimal lag) varies with time. This 2-year correlation coefficient and optimal lag are plotted in Fig. 13. In each case, p (the probability that there is no correlation) is less than 0.05. From mid-1993 to mid-1994 the optimal lag gradually drops from 100 to 50 days. From mid-1996 to mid-1997 the highest correlation coefficient is less than 0.4, implying that the Ryukyu Current transport crossing the O-line and ECS-Kuroshio transport crossing the C-line are behaving somewhat independently.

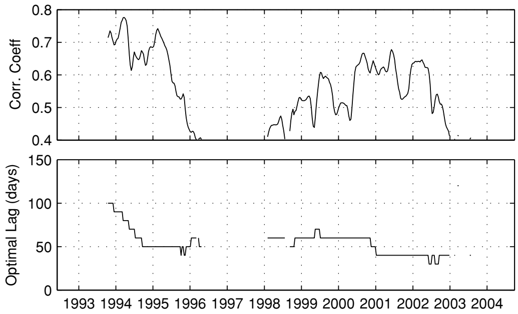

Fig. 13. Correlation coefficient, r, at optimal lag (top) between RT and KT. Optimal lag (bottom). Values are shown only for $r > 0.4$.

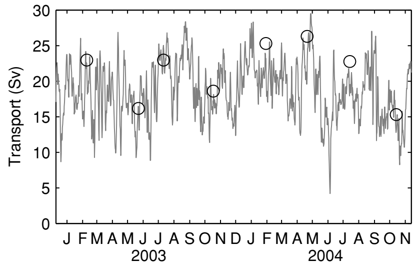

Fig. 14. Gray line is 2-day lowpass filtered transport across the C-line as determined from *in situ* instruments deployed from December 2002 to November 2004 (Andres *et al.*, 2008). Open circles are the volume transport relative to 700 dbar through the Tokara Strait determined from hydrographic casts (see text).

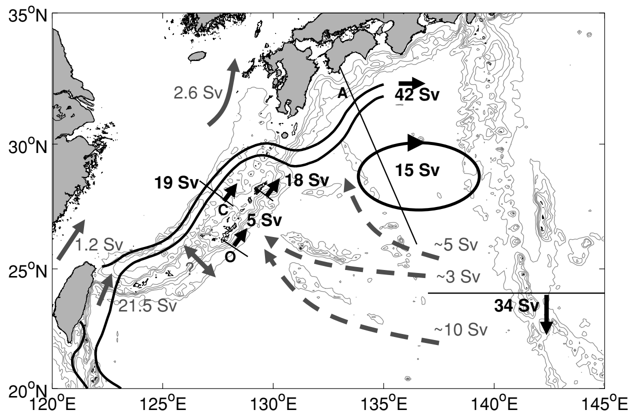

Fig. 15. Diagram of mean transports in the ECS and Philippine Basin. Dashed arrows show transports (joining the western boundary current system) which are inferred in this study: flow joining between (1) Okinawa and Amami-oshima (~10 Sv + ~3 Sv) and (2) Amami-oshima and the ASUKA line (~5 Sv). The mean transports used to infer these flows are shown as black solid arrows: mean transport across the C-line (19 Sv, this study), O-line (5 Sv, Zhu *et al.*, 2004), ASUKA line (42 Sv, Imawaki *et al.*, 2001a), in the recirculation south of Japan (15 Sv, Imawaki *et al.*, 2001a), across 24°N from the eastern boundary to 137°E (34 Sv, Hautala *et al.*, 1994), and east of Amami-oshima (18 Sv, Ichikawa *et al.*, 2004). Other regional flows not used directly in these calculations are shown for reference as solid lines: Taiwan Strait (1.2 Sv, Isobe, 2008), Korea/Tsushima Strait (2.6 Sv, Isobe, 2008), and between Taiwan and Yonaguni-jima (21.5 Sv, Johns *et al.*, 2001). Flow through the Ryukyu Islands south of Okinawa is not well constrained. Flow through the Ryukyu Islands north of Okinawa is assumed negligible here (<1 Sv, You and Yoon, 2004).

This may be related to anomalous ECS-Kuroshio transport during 1997–1998 when an El-Niño event occurred (Yuan *et al.*, 2001). From 1998 to 2001 the optimal lag is 60 days; thereafter it drops to 40 days. We do not know what causes these changes in optimal lag, but they suggest that the propagation speed of eddies between the O-line and the Kerama Gap is variable.

From the preceding analysis of satellite SLA maps, it seems that rather than entering the ECS as coherent eddies, eddies sit at the Kerama Gap and add to or subtract from the mean flow through the gap into the ECS. The ~5 Sv variations in KT induced by these eddies would require flow variations through the Kerama Gap on the order of 20 cm/s (assuming uniform flow through the top 500 m of a 50 km-wide gap). How this eddy-induced change in transport is propagated within the ECS (i.e., from the C-line to the Tokara Strait) can be investigated by comparing transport crossing the C-line (determined from the *in situ* instruments) with transport passing through the Tokara Strait. Figure 14 shows C-line net transport (2-day low pass filtered, determined with CPIESs and ADCPs). Also shown is net geostrophic transport relative to 700 dbar through the Tokara Strait which is determined four times per year from 12 CTD stations (Nakamura *et al.*, 2006). The eight Tokara Strait transports measured during the CPIES/ADCP deployment are well correlated with the contemporaneous C-line transport (r = 0.87), and this correlation drops rapidly with lags (or leads) greater than one week implying that eddy-induced transport variations are advected rapidly inside the ECS. This is in contrast to the slow advection (~60 days) of eddies from the O-line to the Kerama Gap.

4.4 *Comparison with regional mean flows and Sverdrup transport*

The 12-year mean net transports crossing the C- and O-lines (KT and RT, respectively) sum to 24 Sv. This total transport is low compared to the throughflow across the ASUKA line south of Japan (42 Sv, Imawaki *et al.*, 2001a). Figure 15 is a diagram of the region. The 12-year mean transports across the C-, O-, and ASUKA lines are shown, as is the 4-year (1998–2002) mean of the current east of Amami-oshima determined by Ichikawa *et al.* (2004) with moored current meters. We note that the respective 4-year means of KT, RT and throughflow across the ASUKA line calculated for 1998–2002 are each within 1 Sv of their full 12-year-means. Thus we can use C-, O-, and ASUKA line means in conjunction with the 4-year mean east of Amami-oshima to deduce a consistent mean-transport picture.

A mass balance using the mean transports on this diagram suggests the following. An 18 Sv increase in transport between the sum of the mean RT and KT (~24 Sv) and the ASUKA line throughflow transport (~42 Sv) arises from a strengthening of the Ryukyu Current as it flows east of the Ryukyu Islands. This western boundary current intensification is independent of the recirculation south of Japan (~15 Sv, Imawaki *et al.*, 2001a) and must be fed by North Pacific interior flow. The mean flow east of Amami-oshima (18 Sv) suggests about 13 Sv of this interior flow joins the Ryukyu Current between Okinawa and Amami-oshima and ~5 Sv joins between Amami-oshima and the ASUKA line. This ~5 Sv estimate represents a lower bound, if leakage from the ECS-Kuroshio between the C-line and the Tokara Strait feeds some of the flow through the Korea/Tsushima Strait. But the location of leakage from the ECS-Kuroshio is not well constrained (Isobe, 2008, and references therein), so it is not known what proportion occurs downstream of the C-line. Additionally, the preceding mass balance assumes that flow through the Ryukyu Islands between Okinawa and Amami-oshima is negligible; modeling by You and Yoon (2004) suggests the exchange there is <1 Sv.

Additional information about the mean flows in this region can be inferred using the results of Hautala *et al.* (1994) who found that the southward flow across 24°N between the eastern boundary and 137°E is 34 Sv (consistent with Sverdrup flow induced by climatological winds over the North Pacific). By mass balance arguments, about 10 Sv of the 13 Sv-intensification between the O-line and Amami-oshima probably originates south of 24°N. The result is C-line flow (19 Sv), O-line flow (5 Sv) and interior flow (10 Sv) balancing the 34 Sv southward flow. The remaining 3 Sv of the 13 Sv-intensification between the O-line and Amami-oshima and the 5 Sv-intensification occurring between Amami-oshima and the ASUKA line presumably both come from the ocean interior north of 24°N. The inferred transports are shown as dashed gray lines in Fig. 15.

This is consistent with a snapshot of the region based on 9 hydrographic sections throughout the region and an inverse technique (Zhu *et al.*, 2006). Their figure 5 shows strengthening of the current between Okinawa and Amami-oshima which could be fed by interior flow, rather than recirculation. This intensification is qualitatively consistent with the 1/6° model of You and Yoon (2004) and the 1/12° model of You (2005). The 1/12° model has ~8 Sv of flow from the interior joining the current between Okinawa and Amami-oshima.

5. Summary

Using satellite data calibrated with *in situ* transport measurements we have obtained a 12-year time series of net transport crossing the C-line (KT) and compared it to simultaneous transport crossing the O-line (RT). Our study confirms what previous studies have suggested, that the annual variation in KT is smaller than that predicted by the non-topographic, time-dependent Sverdrup balance and the wind-stress curl over the entire North Pacific. In addition, while the annual variation in RT is stronger than that of KT by a factor of 2, RT does not provide the 16 Sv annual variation predicted by Lee *et al.* (2001) for transport calculated using the Sverdrup balance over just the Philippine Basin. Our study provides more observational evidence to support the model of Sakamoto and Yamagata (1996) in which the annual range in transport is suppressed (relative to that predicted by Sverdrup theory) by the interaction of stratified flow with topography.

Despite the presence of the Ryukyu Island chain which shields the ECS from the Philippine Basin, arrival of eddies appears to cause much of the variability in the ECS-Kuroshio. The Kerama Gap, which is the deepest passage into the ECS, may be the conduit for communication of much of this eddy-influence to the ECS even though the bulk of the Kuroshio transport enters the ECS near Taiwan. Maps of satellite SLA, together with positive correlation between RT and KT with ~60-day lag suggest the following portrayal. Eddies approach the Ryukyu Islands from the east with typical speeds of 7–8 cm/s (e.g., Konda *et al.*, 2005). Their speeds are reduced to about 3–4 cm/s when they encounter the Ryukyu Island chain and the Gap. Once eddies encounter the Kerama Gap they induce flow changes through the gap into the ECS resulting in KT variations along the C-line which are about half as strong as those felt in RT along the O-line. These observations (slowing of eddies near a gap and eddies inducing flow through a gap) are consistent with numerical and laboratory studies (Johnson and McDonald, 2004; Cenedese *et al.*, 2005). Some of these eddies then move to the southwest reaching the region east of Taiwan after many months, but their effect on the C-line transport is more clearly communicated through the Kerama Gap than through the ETC as demonstrated by comparison of correlation coefficients between the various transport time series. Once transport variations are felt along the C-line, they are advected quickly to the Tokara Strait by the fast-moving ECS-Kuroshio. This conclusion is consistent with the findings of other authors who have noted a 60-day lag between the Ryukyu Current transport and sea surface height anomalies in the Tokara Strait (Zhu *et al.*, 2004) and between sea surface height outside the Ryukyu Islands and volume transport through the Tokara Strait (Ichikawa, 2001). Furthermore, modeling in the region (You and Yoon, 2004) demonstrates the likelihood of communication through the Ryukyu Islands, particularly through the Kerama Gap, and Yuan *et al.* (1994) provide observational evidence with a salinity section through the Gap suggesting intrusion of water from east to west (their figure 6b).

Finally, the combined KT and RT mean transports are less than the throughflow across the ASUKA line and less than the southward Sverdrup transport across 24°N from the eastern boundary to 137°E. These mismatches in mean flow each independently suggest that intensification of the Ryukyu Current downstream of Okinawa must be fed from the ocean interior rather than simply the recirculation south of Japan.

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