Interannual and seasonal variations of Kuroshio transport east of Taiwan inferred from 29 years of tide-gauge data

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[1] Twenty-nine years of tide-gauge data are analyzed in conjunction with wind and satellite-derived sea-surface height and ocean velocity data to study the interannual and seasonal variations of the Kuroshio transport off the northeastern coast of Taiwan. The data reveals an interannual variation of ±0.1 m (transport-variation of approximately ±3.5 Sv; 1 Sv = 10^6 m^3 s^{-1}), and a much weaker (5–10 times weaker) seasonal fluctuation that is minimum in May and maximum in November. The interannual fluctuations are not directly wind-driven by linear dynamics; rather, the Kuroshio strengthens in years of abundant eddies of the Subtropical Counter Current, which is related to the current's instability state driven by the slow fluctuations of the large-scale wind stress curl in the western Pacific. The seasonal transport fluctuation is also eddy-forced, but has weaker amplitude because the seasonal time scale is of the same order as the eddy-propagation time scale, and transport-producing eddy signals tend to overlap east of Taiwan. **Citation:** Chang, Y.-L., and L.-Y. Oey (2011), Interannual and seasonal variations of Kuroshio transport east of Taiwan inferred from 29 years of tide-gauge data, *Geophys. Res. Lett.*, *38*, L08603, doi:10.1029/2011GL047062.

1. Introduction

[2] The Kuroshio enters the East China Sea at 24°~25°N between Taiwan and Ishigaki Island (Japan; Figure 1, top left). *Johns et al.* [2001] measured a 20-month mean transport of 21.5 Sv (1 Sv = 10^6 m^3 s^{-1}) with 100-day fluctuations of ±10 Sv; the record was too short to infer a seasonal signal. *Zhang et al.* [2001] showed that the 100-day fluctuations were caused by westward-propagating eddies. Interannual variability of the Kuroshio transport at this important choke point between subtropical and tropical western North Pacific is poorly understood. *Johns et al.* [2001] suggest using tide-gauge for long-term Kuroshio monitoring. This work uses 29-year long tide-gauge records as a proxy to study transport variability and to explain its cause(s). Using satellite altimetry, wind stress and General Circulation Model (GCM) output - we show that eddies from the Subtropical Counter Current (STCC) [*Qiu and Chen*, 2010] play an important role in affecting the transports both at the interannual and seasonal time scales.

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2. Data

[3] Details of data sources and processing are given in the auxiliary material.[1] Monthly sea level (SL) data at Keelung (25.15N, 121.75E) and Ishigaki (24.3N, 124.15E; see stations in Figure 1) are used to compute sea level difference $\Delta\eta_{ik} = SL_{Ish} - SL_{Kee}$ as a proxy for Kuroshio transport (Tr_{ik}, in Sv). *Johns et al.* [2001] found good correlation (0.72~0.78) between $\Delta\eta_{ik}$ and Tr_{ik} and estimated approximately 0.35 Sv per 1 cm increase in absolute SL-difference across the current. A general circulation model (OFES, see below) is used to additionally confirm this relation between $\Delta\eta_{ik}$ and Tr_{ik} (see auxiliary material). Satellite sea-surface height (SSH) anomaly data (SSHA) and mean SSH are from AVISO (http://www.aviso.oceanobs.com/). Monthly-mean ECMWF wind stress data is used to compute the corresponding wind stress curl (WSC = $\nabla \times \mathbf{T}_o$; $\mathbf{T}_o$ = kinematic wind stress). The data were low-passed using either 90-day or 360-day Lanczos filter to study seasonal or interannual variation respectively.

3. Kuroshio Transport and Eddies

[4] The $\Delta\eta_{ik}$ has interannual variations with a range of ±0.1 m (Figure 1a; i.e., TR_{ik} = ±3.5 Sv); seasonal fluctuations are much less (Figure 1b) and will be discussed later. The $\Delta\eta_{ik}$ is generally larger (implying a stronger transport) in 1980~1991, 1995~1997 and mid2003~2005, and is weaker in 1992~1995, 1997~mid2003 and after 2005. Amongst the various Pacific indices, the PDO [*Zhang et al.*, 1997] shows the largest correlation with Tr_{ik}: Corr(PDO, TR_{ik}, 11) $\gg$ 0.47 (see Table S1 of the auxiliary material). Here, the Corr(A,B,lags) = maximum lagged correlation coefficient with lags in months, positive if A leads B. All quoted correlations are above the 95% significance level. When PDO is positive, negative WSC anomaly prevails over the western North Pacific, approximately west of 170°E and from 10~35°N [*Zhang et al.*, 1997], and TR_{ik} strengthens 1 year later, and vice versa for negative PDO. However, the correlation = 0.47 is not high, and PDO is ineffective in explaining EKE in the Subtropical Countercurrent (STCC): Corr(PDO,EKE,8) · 0.43. Here, EKE = eddy-kinetic-energy calculated from satellite-derived SSH assuming geostrophy (the same notation EKE is also used for EKE anomaly = ΔEKE = EKE − ⟨EKE⟩, where ⟨.⟩ = time-mean, unless it causes confusion). To make progress, we compute the correlations between $\Delta\eta_{ik}$ and SSHA (Figure 1c). Here we focus solely on the positive significant-correlation region east of Taiwan with maximum ≈ 0.6.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL047062.

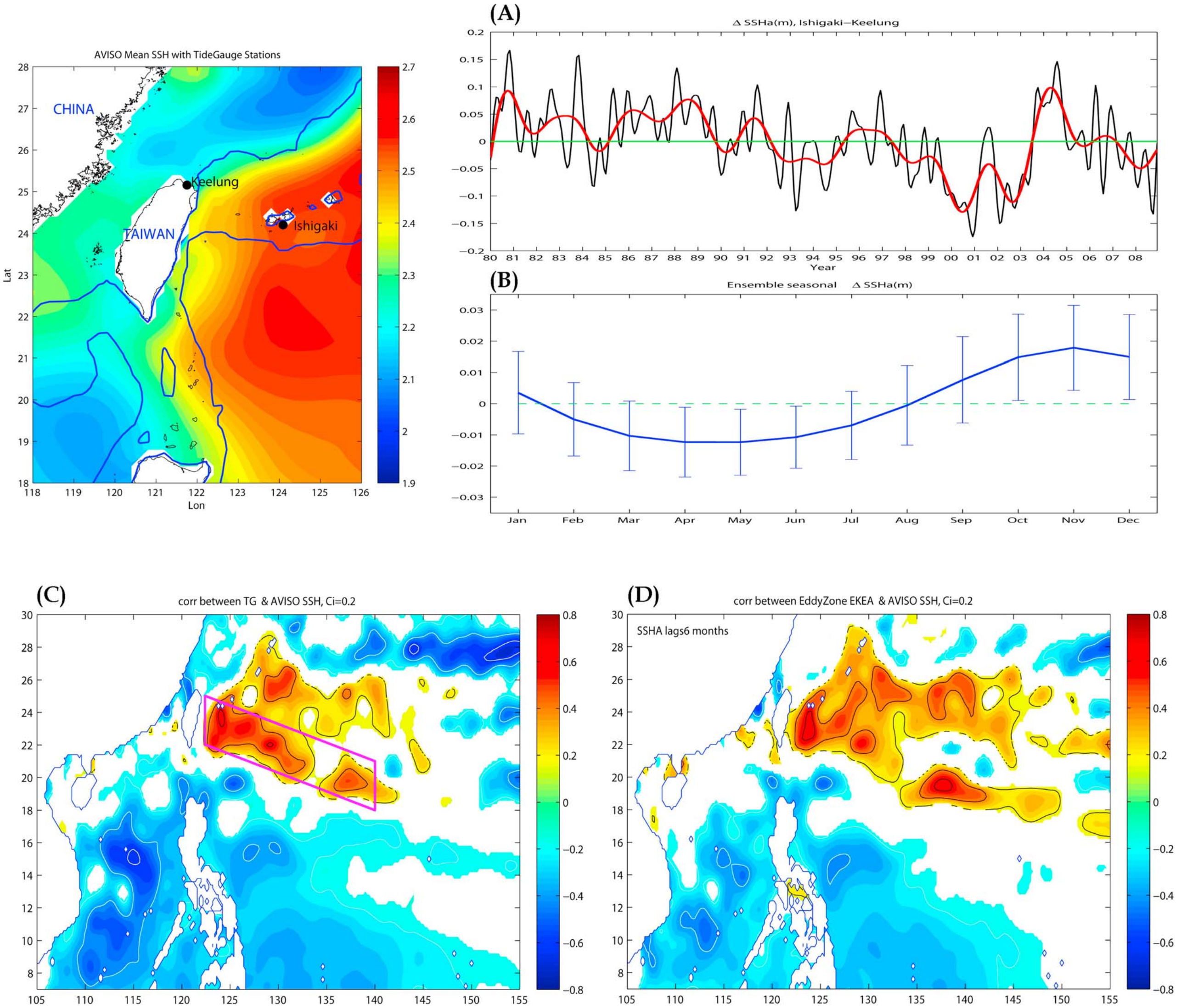

Figure 1. (top left) Mean SSH (m) from AVISO with Keelung and Ishigaki stations and 200 and 3000 m isobaths. (a) 90-day (black) and 360-day (red) low-passed $\Delta\eta_{ik}$ (m). (b) Seasonal $\Delta\eta_{ik}$ with error bars. (c) Colors and contours (interval = 0.2, zero omitted) are correlations between $\Delta\eta_{ik}$ and SSHA for values above the 95% significance level. Box indicates the "STCC eddy zone". (d) same as Figure 1c for correlations between SSHA and EKE in STCC eddy zone, with SSHA lagged by 6 months (see Corr($\Delta\eta$,EKE,−6)=0.83) in Table S1 of the auxiliary material).

[5] The STCC "eddy zone" lies between 20~23°N and extends east of Taiwan to approximately 145°E [see *Qiu and Chen*, 2010, Figure 1]. We define the eddy zone in a tilted parallelogram region of high correlation between $\Delta\eta_{ik}$ and SSHA (Figure 1c) east of Taiwan. *Qiu* [1999] and *Qiu and Chen* [2010] show that the STCC is baroclinically unstable. *Hwang et al.* [2004] found that the region is populated with eddies of both signs, and there appears to be seasonal as well as interannual variations in the number of eddies. *Zhang et al.* [2001] found that westward-propagating eddies generate 100-day fluctuations in the Kuroshio transport. On interannual time scales, $\Delta\eta_{ik}$ and eddy-zone-averaged SSHA and EKE are also highly correlated: Corr(SSHA,$\Delta\eta_{ik}$,5) ≈ 0.64 and Corr(EKE,$\Delta\eta_{ik}$,6) ≈ 0.83 (Table S1 of the auxiliary material; Figures 2a and 2b). Westward eddy-propagation is evident from the diminishing lags of maximum Corr(SSHA,$\Delta\eta_{ik}$,lags), from 8~9 months near 133°E to 3~4 months near 123°E (Figure 2c); propagation was further verified using Hoffmueller plots similar to *Zhang et al.*'s [2001] (not shown). These propagation signals indicate that higher and lower SSH's are caused by eddies, and not simply due to a uniform rise and fall of the sea surface over the STCC. A comparison of Figures 2a and 2b shows that eddy-zone-averaged SSHA and EKE are positively correlated, Corr(SSHA,EKE,3) = 0.73 (Table S1 of the auxiliary material). This is clear also from the correlation map of eddy-zone-averaged EKE with SSHA in Figure 1d, which shows that high EKE correlates with positive SSHA east of Taiwan. It follows that, since there is no reason why cold eddies (SSHA < 0) should be weaker (ΔEKE < 0) than warm ones, warm eddies outnumber cold eddies over interannual and longer periods. This conclusion

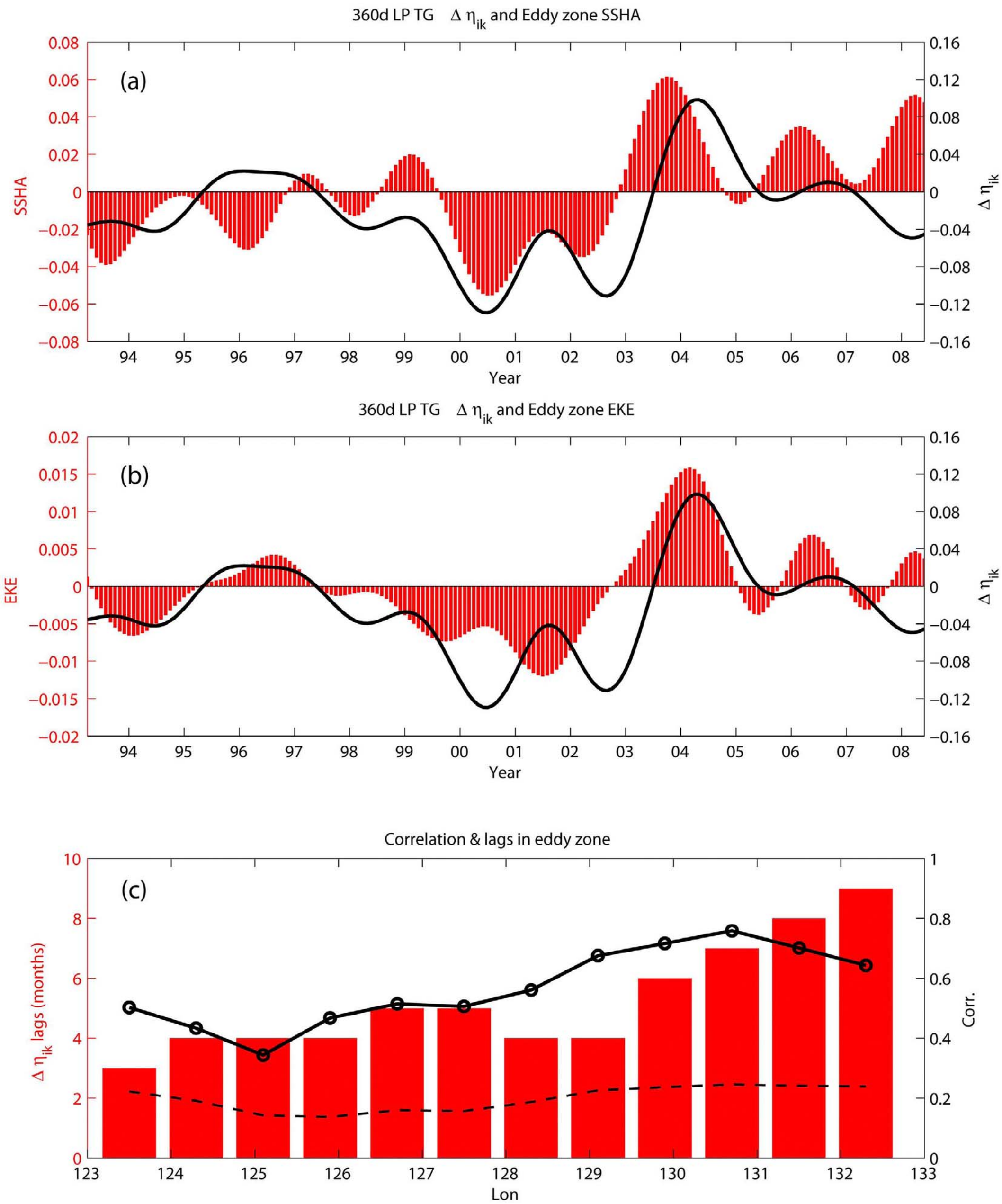

Figure 2. 360d low-passed (a) AVISO-SSHA (bars) and (b) ΔEKE (bars) averaged over the eddy zone, and compared with tide-gauge $\Delta\eta_{ik}$ (black lines). (c) Lags (bars) and maximum correlation coefficients (line; the 95% significance is shown as the dashed line) between SSHA averaged over meridional sections across the eddy zone and $\Delta\eta_{ik}$.

agrees with *Hwang et al.* [2004] who reported that in the STCC warm eddies are 40% more abundant. Periods of negative ΔEKE (or SSHA) in Figure 2 therefore indicate periods of less eddies. The positive correlation between $\Delta\eta_{ik}$ and SSHA in the eddy zone (Figure 1c) suggests then that eddies contribute to a stronger Kuroshio transport in eddy-rich years, and a weaker transport in eddy-weak years. Eddy-rich years are 1995~1996, 2003~2004 and 2006, and eddy-weak years are 1993~1994 and 1998~2002, and they are generally followed by (after 2~6 months lag) increased and decreased Kuroshio transports, respectively (Figures 2a and 2b). Finally, since warm eddies dominate, the positive correlation is explained by noting that eddies carry mass and anticyclones impinging upon a western wall migrate northward, and therefore tend to increase the Kuroshio transport. That anticyclones can produce increased transports was previously documented [e.g., *Kagimoto and Yamagata*, 1997; *Yang et al.*, 1999]; and is readily demonstrated in numerical models (see section II of the auxiliary material).

[6] *Qiu and Chen* [2010] demonstrate that interannual modulations of EKE (Figure 2b) are caused by variations in the baroclinic instability growth rate of the STCC under different WSC conditions. They show that eddy-rich years lag, by about 9 months, periods of stronger Ekman convergence caused by the strengthening of (negative) WSC in the band 18–25°N, 135–170°E due to mid-latitude wester-

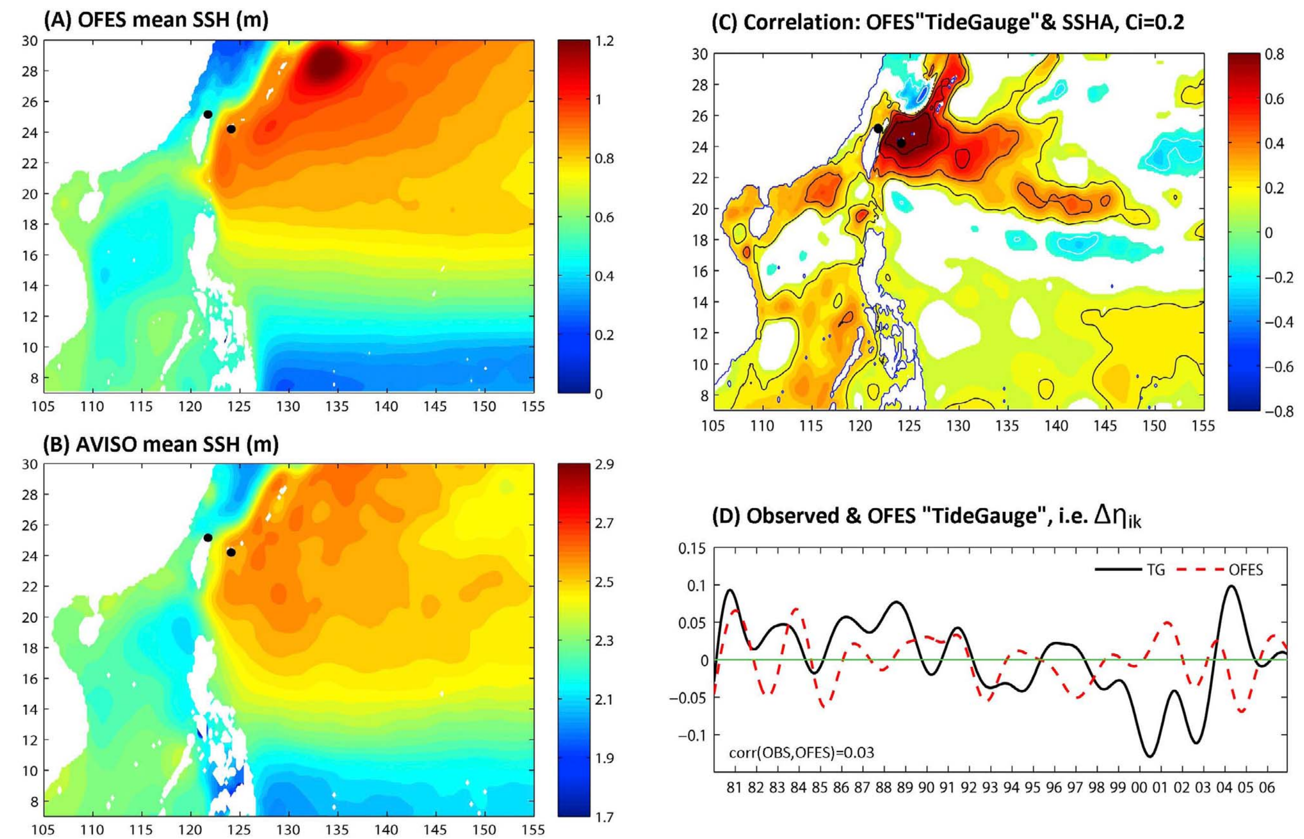

Figure 3. Mean SSH from (a) OFES and (b) AVISO; datum are arbitrary but color scales are the same for both. (c) correlation between OFES "tide-gauge" (i.e., OFES $\Delta\eta_{ik}$ = SSH-difference between Ishigaki and Keelung – see dots in Figure 3a) and OFES SSHA, plotted for values above the 95% significance level. This is to be compared with the corresponding observed map shown in Figure 1c. (d) 360-day low-passed time series of observed (solid line) and OFES (dashed line) "tide gauge" (i.e., $\Delta\eta_{ik}$) (see black dots in Figures 3a and 3b). The correlation between the two time series is shown at lower left, and is very small.

lies and trade winds. Since EKE and $\Delta\eta_{ik}$ are highly correlated (Table S1 of the auxiliary material), their conclusions support the above results that interannual variation of the Kuroshio transport is due to eddies.

[7] We mentioned previously that the Kuroshio transport may also be driven directly by the WSC fluctuations in the Pacific through the Sverdrup response. To further examine this, we computed $U_{SV}(x, y, t) \approx \int_x^{x_E} \frac{\partial}{\partial y}(\nabla \times \tau_o/\beta)dx'$, where U_{SV} (m^2 s^{-1}) is the zonal volume transport per unit latitudinal distance y, and x_E is the eastern boundary of the Pacific Ocean (ignoring islands), assuming that the steady Sverdrup formula is approximately valid at interannual periods. We find that the integral of U_{SV} from 14°–23°N is poorly correlated with Tr_{ik} from tide-gauge. We also calculated the sea-level and transport responses using a reduced-gravity model of the North Pacific Ocean. Since baroclinic instability is absent, no STCC eddies are produced, and the response is linear of (wind-forced) Rossby-wave/Sverdrup type. The modeled sea-level (and/or transport) time-series are again poorly correlated with the observed Dh_{ik} (see section III of the auxiliary material).

[8] We next confirm these findings by analyzing the simulation results from OFES (OGCM for the Earth Simulator: http://www.jamstec.go.jp/esc/ofes/eng/index.html). The model is based on GFDL's MOM3, with a resolution of 0.1° × 0.1° and 54 vertical levels. NCEP monthly wind was used to force the model, from 1950 to 2006. The mean SSH from OFES and AVISO agree quite well (Figures 3a and 3b), both showing western Pacific cyclonic and anticyclonic (tropical-subtropical) gyres separated by the westward-flowing north equatorial current (NEC) that bifurcates at approximately 13° N east of the Philippines. OFES sea-level difference $\Delta\eta_{ik}$ also correlates well with its own eddy field east of Taiwan (Figure 3c), consistent with an eddy-forced mechanism for the simulated Kuroshio transport. However, east and northeast of Taiwan, the OFES SSH contours are more tilted northeastward (Figure 3a), and details of OFES and observed STCC eddy fields are different (not shown). Time series of OFES and observed $\Delta\eta_{ik}$ (Figure 3d; also OFES transport which is proportional to $\Delta\eta$; see section I of the auxiliary material) are also very different, which (with Figures 1c and 3c) suggests that the observed and OFES Kuroshio transports are driven by their own (uncorrelated) eddy fields. The discrepancy between OFES and tide-gauge time series in Figure 3d suggests that the transport response cannot be due to linear wind-driven Sverdrup and Rossby-wave dynamics. These results agree with the above calculations based on reduced-gravity model and Sverdrup formula, and are consistent with our inference from tide-gauge and

altimetry observations that transport fluctuations are caused by interannual variations of STCC eddies.

4. Seasonal Variation

[9] Despite the strong monsoon, the tide-gauge data shows weak and barely significant (i.e., with large error bars) seasonal variations (Figure 1b), in contrast to the interannual variations (Figure 1a). This suggests that the monsoonal winds have little direct effects on the Kuroshio transport northeast of Taiwan. We therefore again look for an eddy-forced mechanism. Despite the different time scales, we argue here that the contribution of STCC eddies to Kuroshio transport is similar. *Qiu* [1999] shows that due to seasonal variation of STCC's instability, the EKE attains a maximum in May and a minimum in December [see *Qiu*, 1999, Figure 10]. Therefore, since the averaged time-duration of 4~6 months (Figure 2c) for eddies to arrive near the east coast of Taiwan is independent of time scales, the months when eddies are most effective in altering the Kuroshio transport is Sep~Nov. This agrees well with the time when the tide-gauge data shows an increased Kuroshio transport (Figure 1b). The minimum transport occurs in March~May when the STCC-NEC system begins to become unstable [*Qiu*, 1999], and eddies have not yet arrived. The eddy-forced mechanism is also consistent with *Hwang et al.*'s [2004] analysis of satellite observations that warm eddies over the STCC outnumber cold ones in summer, while in winter cold eddies outnumber warm ones. The weak seasonal transport variations with large error bars can now be explained since the arrival times of eddies originated over the large zonal extent (125°~145°E) of the STCC can range from 1~12 months, so that there is a considerable overlapping of eddies over a season as they arrive near the east coast of Taiwan.

[10] Although the seasonal variation is weak, the November's maximum transport is nonetheless consistent with *Oey et al.* [2010] that the Kuroshio tends to intrude further onto the East China Sea northeast of Taiwan during winter. However, the timing differs from existing estimates at other sections of the Kuroshio; in particular, from *Gilson and Roemmich*'s [2002] summer maximum transport estimated from ship data off the southeastern coast of Taiwan. Their plots of interannual variation also differ from Figure 1a. The discrepancy may be due to poor sampling in the 8.5-year ship-track data. It may also indicate different dynamics in the two regions, since the ship tracks [see *Gilson and Roemmich*, 2002, Figure 1] lie in the region of insignificant correlations between $\Delta\eta_{ik}$ and satellite-derived SSHA and EKE south of Taiwan (see Figures 1c and 1d).

5. Discussion

[11] While the interannual fluctuations of the Kuroshio transport are not directly wind-driven, the slow fluctuations of the wind stress curl east of Philippines and Taiwan play a crucial role (Y.-L. Chang and L.-Y. Oey, The Philippine-Taiwan Oscillation, manuscript in preparation, 2011). That is because these fluctuations affect both the STCC and NEC, which in turn affect the production of eddies. Kuroshio-transport fluctuations and eddies also affect transports through the Luzon Strait into South China Sea and account for the curious negative correlation between SSHA in South China Sea and tide-gauge data, as seen in Figure 1c (Chang and Oey, manuscript in preparation, 2011). Years of prolonged increased transport (1980~1989, Figure 1a) or weakened transport and decreased eddy activity (1998~2003, Figures 1a and 2) may be expected to affect water-mass exchanges between the Kuroshio and East and South China Seas. Increased Kuroshio transport has also been attributed to the initiation of the large Kuroshio meander south of Japan [e.g., *Akimoto et al.*, 1996], and eddies off Taiwan (and Philippines) can play a significant role in the process. *Miyazawa et al.* [2008] suggested that the northward propagation of a warm eddy that originated off Taiwan was responsible for the large Kuroshio meander south of Japan in 2004. This is a period of increased eddy activity and a major switch from low to high sea-level difference between the Ishigaki-Keelung tide-gauge stations (Figure 2b). We plan to explore these and other interesting topics in the near future.

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