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Turbulent Mixing of the Kuroshio Waters Southeast of Taiwan

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Abstract

Diapycnal diffusivity and energy dissipation rate of the Kuroshio waters off the southeastern coast of Taiwan have been inferred from more than 50 profiles of CTD measurements collected during different cruises from 2007 to 2011 at the latitude near 22^{O}N. Eddy diffusivity in the thermocline of the Kuroshio main stream is relatively small, about 10^{-5} m^2s^{-1}. The mixing is enhanced by one or two degrees of magnitude near the boundaries (land and ocean bottom). A front separating the northward Kuroshio and southward reverse flows can be detected along the east coast of Taiwan. Density overturns within the 100 m surface layer occur at this front. Wakes behind the Lanyu Island are evident due to the impingement of Kuroshio. Cold subsurface water is upwelled in the wakes, and as a result the turbulence is elevated significantly.

Key words: Kuroshio, turbulent mixing, Taiwan

1.Introduction

Kuroshio, the mighty western boundary current of the North Pacific, is originated from the westward-flowing North Equatorial Current (NEC). After running into the Philippine coast, the NEC bifurcates into the Kuroshio and the southward-flowing Mindanao Current. The current is not clearly defined at the bifurcation region. As Kuroshio flows northward along the Luzon and Taiwan islands it gradually becomes well established (Rudnick et al., 2011). Occasionally a branch of the Kuroshio penetrates into the South China Sea through the Luzon Strait. The current then continues its journey passing the Ryukyu Islands and south of Japan, and off it goes into the Kuroshio Extension and North Pacific Current. Figure 1 (a) is a compilation of all historical SVP drifter 6-hourly locations with color-coded to indicate speed for various stages of Kuroshio evolvement.

The flow field and volume transport of the Kuroshio off the east coast of Taiwan have been investigated previously from both in-situ field measurements and numerical simulation. Based on mooring current-meter data, Johns et al. (2001) concluded that the Taiwan Current (another name for Kuroshio as it passes near Taiwan) is a strong, coherent flow with a mean transport of 21 Sv (1 Sv is 10^6 m^3s^{-1}). Liang et al. (2003) compiled the shipboard ADCP (Sb-ADCP) velocity data of 1991 - 2000 and found that as the Kuroshio passes the northern tip of Luzon Island, it is sometimes separated into two branches. The main stream flows along the east coast of Taiwan, and the other branch flows into the South China Sea. Spatial and temporal variations of the Kuroshio east of Taiwan from 1982-2005 were investigated by a numerical model (Hsin et al., 2008). Their modeling results indicate that at southeast of Taiwan, the Kuroshio is mostly in the top 300 m in the inshore path but

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extends to 600 m in the offshore path. The effect of coastal topography and island on strong flow is an interesting topic and has drawn the attention of many investigators. Weak southward flows with a 50-km width were commonly found on the continental slopes off eastern Taiwan. Since 1985, scientists have found that the flow on the eastern slope is often southward from CTD data. The surface flows are generally northeastward or northwestward geostrophic currents, but the underlying westward flow is a balance of pressure gradient and friction, mid-waters and bottom waters in the West Philippine Sea through the Luzon Strait transporting into the South China Sea (Liu et al., 1995).

On the other hand, studies of the turbulence properties of the Kuroshio and surrounding waters of Taiwan were scarce. In the open ocean, as the Reynolds number exceeds a critical value, the inertial force will overcome the viscous force to break down the density structure of the water mass, and thus produce turbulent mixing. This process will change the characteristics of the water mass, and promote the exchange of heat and material by the mixing process. Analyzing data of 3,500 LADCP and CTD profiles from the database of the World Ocean Circulation Experiment, Kunze et al.,(2006) found that the turbulent mixing intensity varies in different topographies and latitudes from the finescale parameterization method. The eddy diffusivity near the equator is weak (3×10^{-3} m^2s^{-1}), and there is a relatively strong eddy diffusivity at high latitudes between 50 and 70 degrees (5×10^{-3} m^2s^{-1}).Nagai et al., (2009) used TurboMAP, XBT and ADCP to observe the Kuroshio flow and characteristics east of Japan (along 143°E), and found that the temperature of water mass at the Kuroshio edge is lower than the Kuroshio water. The eddy diffusivity of the thermocline is $10^{-4}m^2s^{-1}$ to $10^{-3}m^2s^{-1}$, which is stronger than that at the depth below the thermocline. Stober et al., (2008) analyzed hydrographical data of 2000 - 2005 in the region of western boundary current in the North Atlantic, and their results indicate that topography is the most important factor for the turbulent overturns and energy dissipation.

1. Observations and instruments

In this study, we used data collected from Sb-ADCP, CTD and Lowered ADCP (LADCP) by R/V OR3 during eight cruises of 2007 - 2011 to investigate the flow structure and turbulence properties of Kuroshio waters southeast of Taiwan. Listed in Table 1 are the cruise time, station locations and other information for all eight cruises. Most of the cruises were completed between 3 and 5 days. All stations of the eight cruises are situated mostly between Taiwan and Lan-yu (Figure 2). A ship board ADCP (Teledyne RDI) of 150 or 75 KHz is installed on the ship bottom. Mounted on the CTD package (Seabird 9-11 plus), the LADCP consists of two 300 kHz ADCPs (Teledyne RDI), one looking upward and the other downward. The vertical bin size was set to 8 or 10 m, the number of layers was set to 20, and the sampling frequency was set to 1 Hz for LADCP, which collected current velocity with an estimated uncertainty of 1 cms^{-1}. Velocity profiles were processed on 10-m-depth grid with software developed at Lamont-Doherty Earth Observatory, Columbia University based on the principle of inverse method (Visbeck, 2002). In some CTD casts the LADCP/CTD was lowered down to within 80 m above the seabed, and the full-depth velocity profiles can be obtained by the bottom tracking mode. In other casts the LADCP/CTD was lowered to only 200-300 m depth, primarily for phytoplankton study purpose. The accuracy of the CTD sensors was 0.002°C for temperature and 0.002-0.003 for salinity, respectively.

Table 1. Measurement time, stations and instrumentations for all eight cruises.

Cruise	Time	Location	Instrument
OR3-1217	2007 / 04	8 stations, 4 stations south of Lan-yu (21.9°N) and 4 stations north of Lan-yu (22.2°N), along 121°E~122°E.	L-ADCP and CTD
OR3-1234	2007 / 07	5 stations, all stations south of Lan-yu (21.9°N), along 121°E~122.2°E. Each station was occupied twice.	L-ADCP and CTD
OR3-1250	2007 / 10	6 stations between Taiwan and Lan-yu. Each station was occupied three times.	L-ADCP and CTD
OR3-1275	2008 / 03	4 stations between Taiwan and Lan-yu (22.08°N), along 121°E~121.5°E. Each station was occupied twice.	L-ADCP and CTD
OR3-1470	2010 / 06	7 stations, all north of Lan-yu (22.23°N), along 120.9°E~122.25°E.	L-ADCP and CTD
OR3-1489	2010 / 09	6 stations, all north of Lan-yu (22.23°N), along 121.1°E~122.25°E.	L-ADCP and CTD
OR3-1510	2010 / 12	6 stations, All stations off the southeast coast of Taiwan. One station at the Kuroshio front was repeated nine times.	L-ADCP and CTD
OR3-1544	2011 / 06	20 stations, located at 22°N ~ 22.37°N and 121°E ~ 121.7°E.	L-ADCP and CTD

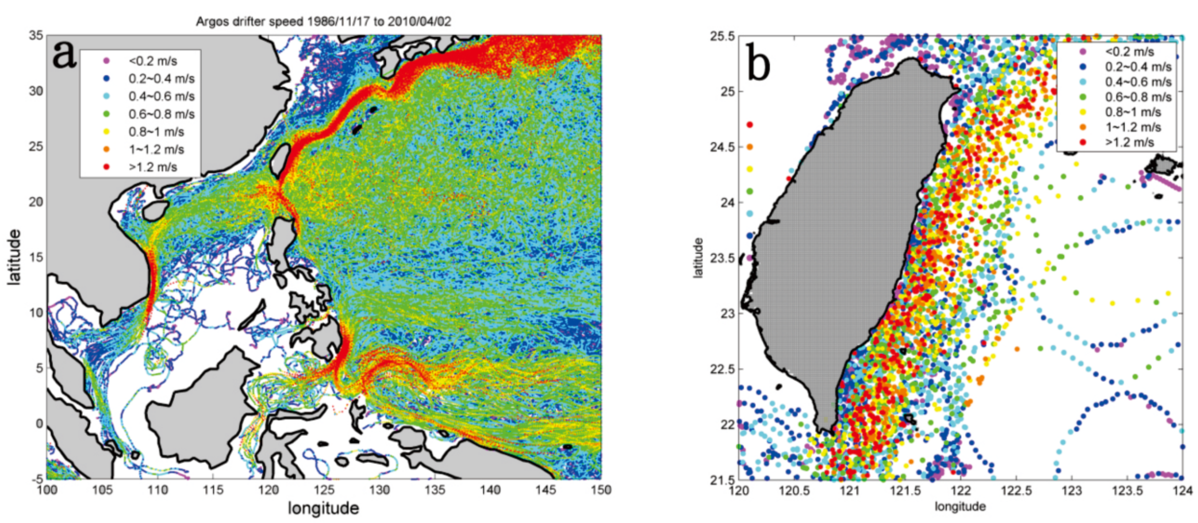

Fig. 1. Six-hourly drifter locations with color-coded to indicate speed of Kuroshio for the (a) larger area and (b) east of Taiwan for the period of 1988 to 2010.

2. Thorpe scale method

Thorpe scale can be used to infer the energy dissipation rate and eddy diffusivity of turbulence, which may contain inversions associated with turbulent overturns (Thorpe, 1977). This method is the application using potential density inversion ρ (z) to calculate the vertical displacement. In a stable stratified fluid, the potential density increases monotonically. Turbulent stirring results in overturning, and subsequently in density inversions. When overturn occurs, we can rearrange the potential density to monotonize the profile. The distance over which a given point in a profile has to be moved is called the vertical Thorpe displacement. The Thorpe scale Lt is defined as the root mean square of these Thorpe displacements within each turbulent patch, which is identified as the vertical segment over which the sum of the Thorpe displacements drop back to zero (Dillon,1982; Galbraith and Kelley, 1996). The vertical eddy diffusivity Kz can be written as (Park et al., 2008)

$$K_z = 0.128 L_t^2 N \qquad (1)$$

.where N is the Brunt- Vaisala frequency.

3. Results

1) Structure of the Kuroshio and velocity

The Kuroshio axis swings between 121°E and 122°E. Figure 1(b) shows all historical six-hourly SVP drifter locations at the east of Taiwan with color-coded to indicate near-surface speed. The data is downloaded from the Surface Velocity Program (SVP) drifter database from 1988 to 2010. The near-surface velocity of Kuroshio has a maximum of 1.2 ms^{-1} between Taiwan and Lan-yu Island (Figure 1b), and the subsurface velocity gradually weakened to 0.2 ms^{-1} at 400 m depth from the LADCP-measured velocity profiles (Figure 4). Due to the influence of the tides, the flow is toward the northwest or northeast(not shown).For the characteristics of the water masses, the Brunt-Vaisala frequency has a maximum in the surface layer, and a minimum in the bottom layer. The Brunt-Vaisala frequency varies rapidly at the depths between 700 and 1200 m, therefore the water layer is relatively unstable.Figure 3 is the T-S diagram of all measurement stations between Taiwan and Lan-yu. The characteristics of the upper layer near Lan-yu (blue line) shows a warmer temperature and a higher salinity, but the characteristics of a small percentage of water near Taiwan (red line) still has a warm temperature and high salinity. It implies that the main axis of Kuroshio swings between Taiwan and Lan-yu, a result consistent with that derived directly from the SVP drifters.

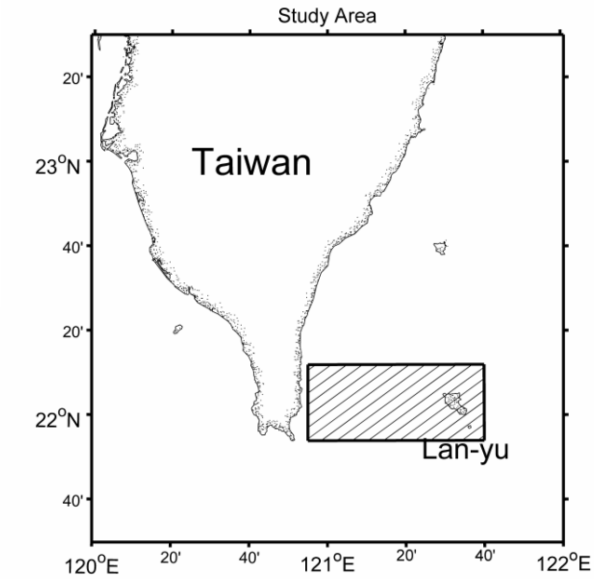

Fig. 2. Geographic map of the study area and measurement stations in this study.

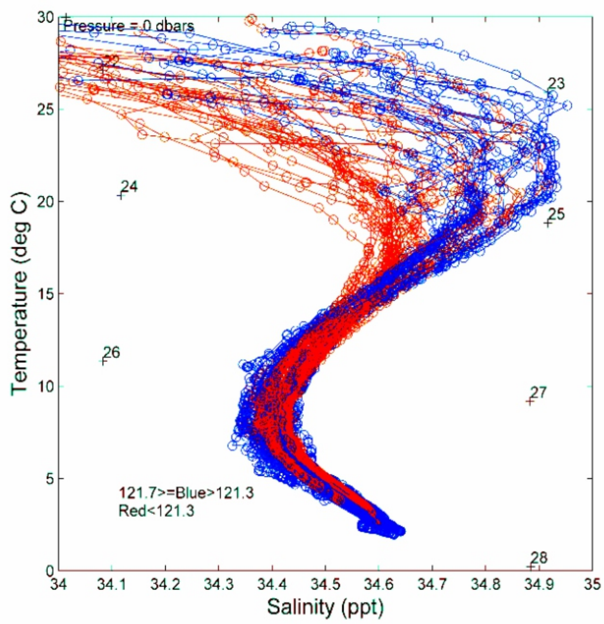

Fig. 3. Temperature-salinity diagram for CTD data collected from all eight cruises. The data near Lan-yu (east of 121.3°E) is plotted as the blue line, and the data near Taiwan (west of 121.3°E) is plotted as the red line.

2) Eddy diffusivity

Figure 4 shows a contour of the Kuroshio's north-south velocity and vertical eddy diffusivity Kz from the cruise 1250 which was conducted in October 2007 along 22°N between Taiwan and Lan-yu. At each of the six stations three CTD casts were conducted repeatedly, with the time interval set to be 16.5 hr apart. The average of the velocities over three repeated measurements can eliminate the tidal currents by the so-called 3-phase method (Chang et al., 2008), thus obtain the detided currents. Analysis of the Sb-ADCP data reveals that the Kuroshio has a maximum speed of approximately 1.0 ms^{-1} at 121.15°E, and a weak southward flow is found to exist near the Taiwan coast. Energy dissipation rates from the surface to a depth of around 1000 m are weak, approximately 10^{-7} W/kg. Stable, fast flows and strong stratification of the upper Kuroshio layer appears to inhibit turbulent mixing and overturns. A V-shaped basin exists between Taiwan and Lan-yu (121.25°E ~ 121.5°E) with rugged bottom, and the energy dissipation rate and eddy diffusivity are enhanced by two orders of magnitude in the bottom boundary layer. The maximum eddy diffusivity is about 10^{-2} m^2s^{-1}. Between the Kuroshio and the eastern Taiwan coast, the existence of a southward flow along with the northward-flowing Kuroshio main stream forms a frontal region, which is characterized by strong horizontal shear and instability.

In December 2010 cruise 1510 was conducted to investigate the Kuroshio front. Six stations of CTD casts were done off the southeast coast of Taiwan. Among them, station S1 was located in the southern part of frontal region and was occupied repeatedly for nine times to do CTD casts which was separated by one hour interval. Figure 5 shows the time-series plot of the north-south velocity contour and eddy diffusivity profiles at this station. Instability of the flow was found on the upper 200 m, especially evident within the upper 100 meters. As a result, Brunt-Vaisala frequency was small and stratification was unstable. In the ocean, it is uncommon to find a strong mixed layer in the middle and upper waters to achieve the magnitude of 10^{-2} m^2s^{-1}, but strong mixing of this order was found to exist almost consistently in this station during this cruise. At the Kuroshio front, turbulence intensity and eddy diffusivity in the surface layer was significantly greater than the lower layer. This result is consistent with a recent study by D'Asaro et al., (2011). Using the Lagrangian float to measure directly the vertical velocity, D'Asaro et al., (2011) noted that turbulent dissipation will be enhanced at the front. The vertical shear within 150 m of the surface layer is also affected by wind, but the impact is less than the frontal effect.

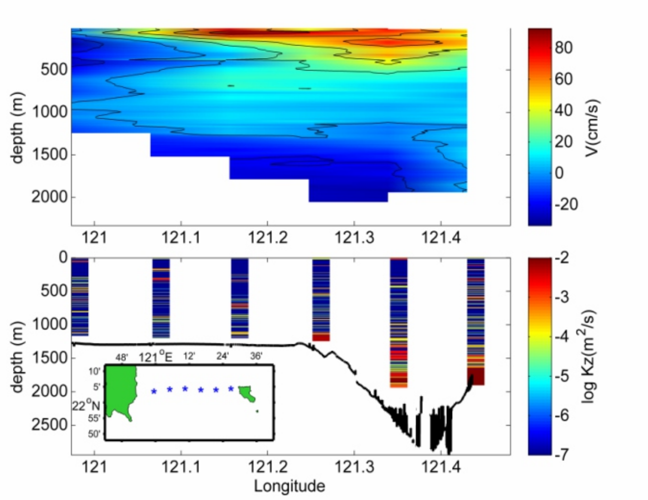

Fig. 4. The north-south velocity contour (upper panel), and vertical eddy diffusivity (Kz, lower panel) for the cruise 1250 of October 2007. A small figure inserted in the lower left corner indicates locations of the stations.

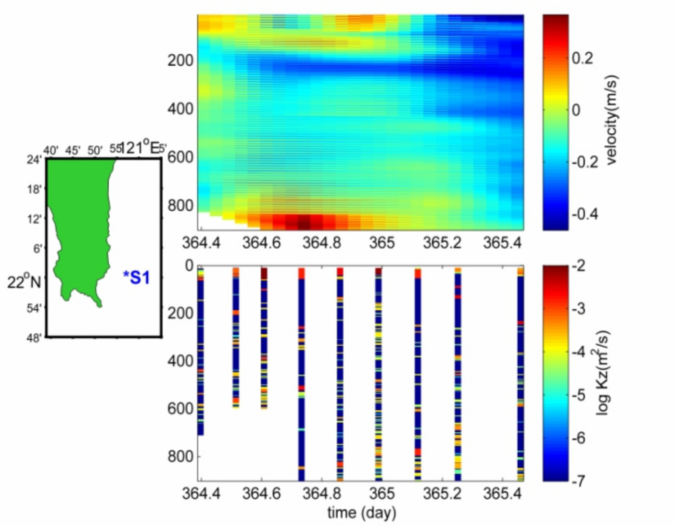

Fig. 5. Time series plot of north-south velocity profile (upper right panel) and vertical eddy diffusivity (Kz, lower right panel) in cruise 1510 of December 2010. Figure on the left is the location of the station S1.

3)Integrated energy dissipation and island wake

In order to compare the turbulence intensity among all stations, the total energy dissipation rate is obtained by vertical integration of the dissipation rate over a depth interval,

$$\varepsilon = \rho_0 \times \int_{min}^{max} \varepsilon(z)dz$$

where ρ_0 = 1024 kg m $^{-3}$ is the reference density of Kuroshio water. The minimum (min) depth is 10 m, and the maximum (max) is the lowest depth of each CTD cast. The calculations were done for all CTD casts in this study.

In the study area, most of the total energy dissipation rates are less than 100 mWm^{-1}, as shown in Figure 6. Larger values of (500 - 10000 mWm^{-1}) can be found near the coast and around the Lan-yu Island. In the Kuroshio main stream, turbulent mixing is generally weak due to stable stratification and strong uniform flows. The mixing is enhanced in the coastal area and around the island.

Island wakes were observed behind the Lan-yu Island during the cruise 1544 of June 2011. When Kuroshio impinges against the Lan-yu Island, the flow is significantly retarded, the island wakes makes the instability of water mass and generates an eddy. Using Sb-ADCP data, a pair of eddies can be observed behind the Lan-yu Island (Figure 7). Behind the left side of the Lan-yu Island a clockwise eddy was formed, and a counterclockwise eddy is generated on the right side. When the island wake appears, a mixed layer with 80-m thickness can be clearly visible between 10 - 90 m deep from the density profile (Figure 8a). The seawater in the mixed layer has warmer temperature, higher salinity and smaller density. Thus the wake causes a strong mixing in the mixed layer. This CTD station was reoccupied again about thirty hours later, and this time we were unable to see the presence of the eddy. A thinner mixed layer could be seen from the density profile for the second observation (Figure 8b). A comparison for the Thorpe displacement, Thorpe scale and the dissipation rate between the two CTD casts indicates that the inferred turbulent mixing intensity with the presence of island wakes is a hundred times stronger than that without. Recent study of island wakes from direct microstructure turbulence measurement by Lass et al., (2008) indicates that enhanced turbulent mixing by an order of tenfold can be clearly observed downstream of a bridge piles. In this study, when the swift Kuroshio flows meet the barrier of Lan-yu Island, high Reynolds number is formulated and strong island wakes can be clearly observed. This physical process results in enhanced turbulent mixing in the wakes.

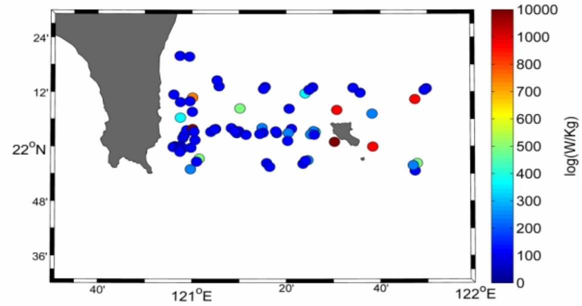

Fig. 6. Integrated energy dissipation rates for all stations in this study.

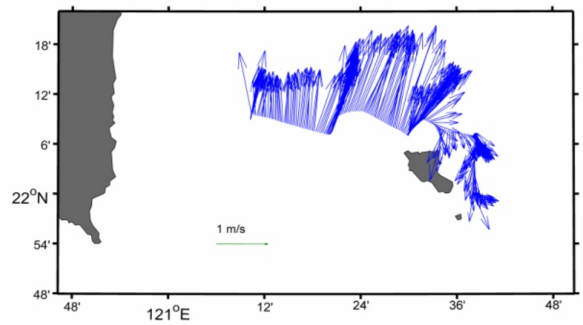

Fig. 7. Sb-ADCP observations behind the Lan-yu Island for cruise 1544.

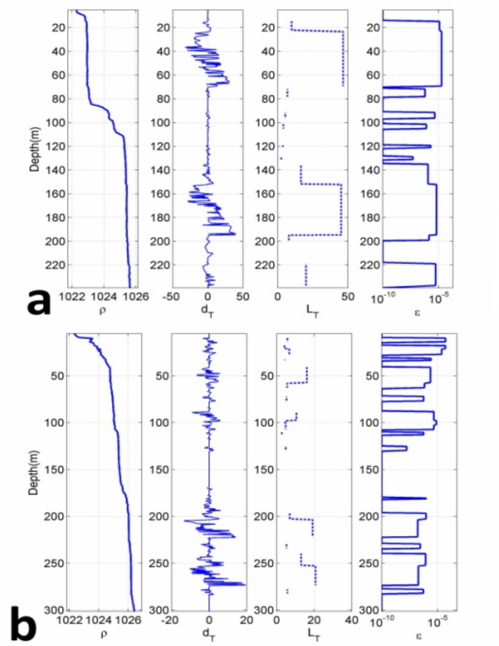

Fig. 8. Vertical profiles of density, Thorpe displacement, Thorpe scale and dissipation rate for the (a) first and (b) second CTD casts behind the Lan-yu Island during cruise 1544.

4. Summary

The Kuroshio is a strong western boundary current of the North Pacific Ocean. From all historical drifter data at 15 m depth and CTD/LADCP data of eight cruises conducted during 2007-2011 at east of Taiwan, some details about flow structure and turbulence properties of the Kuroshio were unveiled. Our results indicate that the Kuroshio has a maximum velocity of 1.2 ms^{-1}. SVP drifter and CTD hydrographical data both show that Kuroshio swings between Taiwan and Lan-yu. The main stream of Kuroshio is mostly centered near Lan-yu Island, which is evidenced either by the CTD data or velocity measurements. Turbulence mixing in the Kuroshio is generally weak, probably due to strong stratification and its swift, uniform flows. Steep slope and rugged seabed between Taiwan and Lan-yu enhance the vertical eddy diffusivity greatly, and reach a maximum value of Kz is about 10^{-2} m^2s^{-1} in the bottom layer. A front separating the northward-flowing Kuroshio and southward reverse flows was detected along the east coast of Taiwan. Density overturns within 100 m surface layer occur in this front. As the Kuroshio passes the Lan-yu Island, a pair of eddies is generated behind the island. The island wakes behind Lan-yu induce strong mixing in the mixed layer with a thickness of 80 m, and as a result cold, subsurface water is upwelled from below.

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References

Chen, C., M. Huang. 1996. A mid-depth front separating the South China Sea water and the Philippine Sea water. Journal of Oceanography, 52, 17-25.

Chang, Y. C., R. S. Tseng, C.T. Liu. 2008. Evaluation of tidal removal method using phase average technique from ADCP surveys along the Peng-hu Channel in the Taiwan Strait, TAO, 19, 433-443.

Dillon, T.M. 1982: Vertical overturns: a comparison of Thorpe and Ozmidov length scales. Journal of Geophysical Research, 87, 9601-9613.

D'Asaro, E., C. Lee, L. Rainville, R. Harcourt, L. Thomas. 2011: Enhanced turbulence and energy dissipation at ocean fronts. Science, 15, 318-322.

Galbraith, P.S., Kelley, D.E. 1996. Identifying overturns in CTD profiles. Journal of Atmospheric Oceanic Technologies., 13, 688-702.

Hsin, Y. C., C. R. Wu, P. T. Shaw. 2008. Spatial and temporal variations of the Kuroshio east of Taiwan, 1982-2005: A numerical study. Journal of Geophysical Research, 1 13, C04002, doi:10.1029/2007JC004485.

Johns, W.E., T.N. Lee, D.X. Zhang, R. Zantopp, C.T. Liu, Y. Yang. 2001. The Kuroshio east of Taiwan: Moored transport observations from the WOCE PCM-1 array. Journal of Physical Oceanography, 31:1,031-1,053.

Kunze, E. Firing, J.M. Hummon, T.K. Chereskin, A.M. Thurnherr. 2006. Global abyssal mixing inferred from lowered ADCP shear and CTD strain profiles. Journal of Physical Oceanography, 36, 1553-1576.

Lass, H.U., V. Mohrholz, M. Knoll, H. Prandke. 2008. Enhanced mixing down- stream of a pile in an estuarine flow. Journal of Marine Systems, 74, 505-527.

Liang, M. 2003. Upper-ocean currents around Taiwan. Deep-Sea Research II , 50, 1085-1105.

Nagai, T., A. Tandon, H. Yamazaki, M. J. Doubell. 2009. Evidence of enhanced turbulent dissipation in the frontogenetic Kuroshio Front thermocline. Geophysical Research Letters, 36, L12609.

Liu,C.T., Y. Yang, S.P. Cheng, C. Wang, Q. Liu. 1995. The counter current southeast of Lanyu Island. ACTA OCEANOGRAPHICA TAIWANICA, 34, 41-56.

Park Y.H., J.L. Fudab, I. Duranda, A.C. Naveira Garabato. 2008. Internal tides and vertical mixing over the Kerguelen Plateau. Deep-Sea Research II, 55, 582-593.

Rudnick, D.L., S. Jan, L. Centurioni, C.M. Lee, R. C. Lien, J. Wang, D. K. Lee, R. S. Tseng, Y.Y. Kim, C. S. Chern. 2011. Seasonal and mesoscale variability of the Kuroshio near its origin. Oceanography, 24, 52-63.

Stober, U., M. Walter, C. Mertens, M. Rhein. 2008. Mixing estimates from hydrographic measurements in the deep western boundary current of the North Atlantic. Deep-Sea Research I, 55, 721- 736.

Thorpe, S.A. 1977. Tubulence and mixing in a Scottish loch. Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences, 286, 125-181.

Visbeck, M. 2001. Deep velocity profiling using lowered acoustic doppler current profilers: Bottom track and inverse solutions. Journal of Atmospheric and Oceanic Technology, 19, 794-807.