

Studying the Origin of the Kuroshio with an Array of ADCP-CTD Moorings

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LONG-TERM GOALS

Our long-term scientific goals are to understand the dynamics and identify mechanisms of small-scale processes—i.e., internal tides, inertial waves, nonlinear internal waves (NLIWs), and turbulence mixing—in the ocean and their interaction with mesoscale processes such as western boundary currents. We aim to develop improved parameterizations of mixing for ocean models. For this study, our focus is on the origin of the Kuroshio, the interaction among internal tides, internal waves, meso-scale eddies and the Kuroshio, and the interaction of oceanic processes with the complex topography in Luzon Strait.

OBJECTIVES

The primary objectives of this observational program are to quantify Kuroshio properties at its origin and as it evolves downstream.

APPROACH

An array of six subsurface moorings was deployed in June 2012 northeast of the Philippines, where the strong Kuroshio enters Luzon Strait. All moorings were recovered in June 2013. Each mooring had an Acoustic Doppler Current Profiler (ADCP) to measure the velocity field in the upper 450 m. The long-term mooring velocity observations were complemented by a shipboard survey to identify the origin of the Kuroshio and its properties before it enters Luzon Strait. Our mooring observations as well as glider and HPIES observations and downstream mooring observations east of Taiwan are used to quantify the evolution of the Kuroshio.

WORK COMPLETED

During 2013 and 2014 we continued scientific analysis of the integrated data sets of measurements taken by moorings, Seagliders, and HPIES south of Luzon Strait. Results were presented at the ONR workshop in Seattle (2013), at the ONR review in Chicago (2013), and at the Ocean Sciences Meeting in Honolulu (2014). A paper “Modulation of Kuroshio transport by mesoscale eddies at the Luzon Strait entrance” has been published in the *Journal of Geophysical Research* (Lien et al., 2014). We

worked closely with Taiwanese colleagues on data taken east of Taiwan. A paper entitled “Evolution of the Kuroshio tropical water east of Taiwan” has been published in *Deep-Sea Research* (Mensah et al., 2014). A graduate student, Vigan Mensah, of National Taiwan University also visited APL-UW for two months to work on PIES data processing and comparison with mooring and Seaglider measurements.

RESULTS

Kuroshio Velocity and Transport

Six moorings were deployed along $18^{\circ}45'N$ in a zonal section between $122^{\circ}E$ and $122^{\circ}52'E$, each roughly 16 km apart, spanning ~ 80 km at the Kuroshio’s entrance to Luzon Strait (Fig. 1). The mooring array was located on the main path of the Kuroshio, and captured most of the Kuroshio transport. Eddies were often observed in this area.

The monthly averaged meridional current is mostly northward in the observed depth range (Fig. 2). The maximum northward current (the Kuroshio core) often exceeds 1 m s^{-1} . The Kuroshio core is located at $\sim 122^{\circ}24'E$ at the surface, and tilts eastward with increasing depths. The zonal current is about 30–60% of the meridional current.

Rossby number, $Ro = \frac{\zeta}{f}$, is computed where the relative vorticity ζ is approximated by the zonal gradient of the meridional current $\partial_x v$. On the Kuroshio western flank and at shallow depths, $Ro \sim O(1)$, where the ageostrophic component becomes important (Fig. 3). Elsewhere, Kuroshio Ro is near 0.2.

Meso-scale Eddy Effects on Kuroshio Transport

We compute the Kuroshio transport by integrating the northward current from the surface to its maximum depth across the moored array. The annual average northward transport is 15 Sv with a standard deviation of 3 Sv (Fig. 4). Rapid changes in Kuroshio transport greater than 10 Sv were observed. Between 24 June and 4 July 2012, the transport increased from 7 Sv to 22 Sv in 10 days. Between May and June 2013 transport variations greater than 10 Sv were observed on a $O(10 \text{ days})$ time scale.

The variation of the sea level anomaly (SLA) slope across our moored array fluctuates in unison with the observed Kuroshio transport. Eight anomalous transport events greater than 3 Sv, one standard deviation, are identified. Kuroshio transport increases when the SLA slope is large, and transport decreases when the SLA slope is small.

Six eddies within 200 km of the eastern Kuroshio boundary, nominally $18^{\circ}45'N$ $123^{\circ}E$, are identified (Fig. 5). They are tracked as far east as $130^{\circ}E$. Six anomalous Kuroshio transport events can be explained by the detected eddies. In particular, the large changes in transport of more than 10 Sv in June–July 2012 and in May–June 2013 are caused by consequent pairs of cyclonic and anticyclonic eddies. These eddies have a typical Rossby number, relative vorticity normalized by the planetary vorticity, of ~ 0.2 . The area integrated eddy kinetic energy is of order $TJ \text{ m}^{-1}$ and the mean current speed is about 0.4 ms^{-1} . The anomalous transport event 6 in April 2013 may be explained by the low SLA to the west of $122^{\circ}E$, and not the westward propagating eddies.

Internal Waves

We are continuing our analysis to understand the effects of the Kuroshio on the propagation of internal waves at Luzon Strait. Mooring observations from a period in early January 2013 are used to calculate horizontal kinetic energy and vertical shear squared, which are weakest within the Kuroshio core (Fig. 6).

Kuroshio Watermass Properties

Watermass origins for the Kuroshio Current and Luzon Undercurrent (LU) are identified using moored and Seaglider measurements (Figs. 7). The upper layer of the Kuroshio is composed mostly of waters from the Western Philippine Sea (WPS) and North Equatorial Current (NEC). The intermediate layer of the Kuroshio is composed primarily of North Pacific Tropical Water (NPTW) originating from NEC. The bottom layer of the Kuroshio carries North Pacific Intermediate Water (NPIW). The southward flowing Luzon Undercurrent also carries NPIW. Watermass origins and transports within the Kuroshio and LU are summarized in Fig. 8.

IMPACT/APPLICATION

The Kuroshio is well defined north of Luzon Strait as a strong western boundary current. Nonetheless, its origin and the dynamics of its initiation are not well understood. The potential origin of the Kuroshio is complicated by a rich spectrum of oceanic processes, e.g., remotely and locally generated eddies. The Kuroshio carries significant mass, heat, and energy from the tropics to the subtropics and interacts with marginal seas. Therefore it is crucial to understand its origin and dynamics.

RELATED PROJECTS

Generation and Evolution of Internal Waves in Luzon Strait (N00014-09-1-0279) as a part of IWISE DRI: The primary objectives of this observational program are to quantify 1) the generation of NLIWs and internal tides in the vicinity of Luzon Strait, 2) the energy flux of NLIWs and internal tides into the Pacific Ocean and South China Sea (SCS), 3) the effects of the Kuroshio on the generation and propagation of NLIWs and internal tides, 4) the seasonal variation of NLIWs and internal tides, and 5) to study other small-scale processes, e.g., hydraulics and instabilities along internal tidal beams and at the Kuroshio front.

PUBLICATIONS (wholly or in part supported by this grant)

- Lien, R.-C., B. Ma, C. Lee, T. B. Sanford, V. Mensah, L. Centurioni, R. D. Cornuelle, G. Gopalakrishnan, J. L. McClean, A. Gordon, M.-H. Chang, S. R. Jayne, Y.-J. Yang, (2015). The Kuroshio and Luzon undercurrent east of Luzon Island, *Oceanography*. [submitted, refereed].
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- Lien, R.-C., B. Ma, Y.-H. Cheng, C.-R. Ho, B. Qiu, C. M. Lee, and M.-H. Chang (2014). Modulation of Kuroshio transport by mesoscale eddies at the Luzon Strait entrance, *J. Geophys. Res. Oceans*, 119, 2129-2142, doi:10.1002/2013JC009548. [published, refereed]

Mensah, V., S. Jan, M.-D. Chiou, T. H. Kuo, and R.-C. Lien (2014). Evolution of the Kuroshio Tropical Water East of Taiwan, *Deep Sea Res.*, **86**, 68–81, <http://dx.doi.org/10.1016/j.dsr.2014.01.005>. [published, refereed].

Rudnick, D. L., S. Jan, L. Centurioni, C. M. Lee, R.-C. Lien, J. Wang, D.-K. Lee, R.-S. Tseng, Y. Y. Kim, and C.-S. Chern (2011). Seasonal and mesoscale variability of the Kuroshio near its origin. *Oceanography* **24**(4), 52–63, [doi:10.5670/oceanog.2011.94](https://doi.org/10.5670/oceanog.2011.94). [published, refereed]

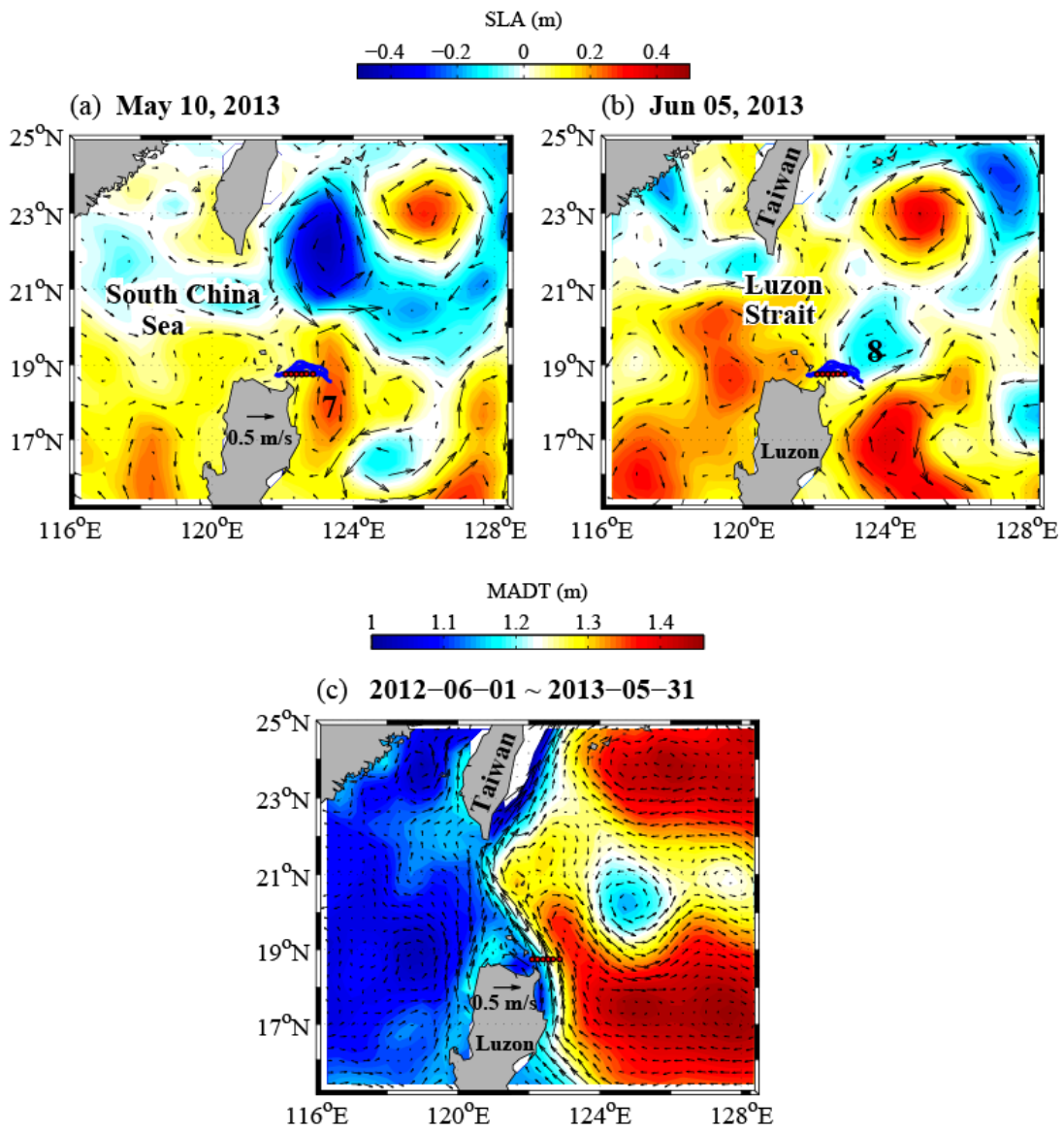


Figure 1: Positions of six moorings at the entrance to Luzon Strait (red dots), Aviso sea level anomaly (SLA) (color shading), and Aviso surface current anomaly (vectors) on 10 May 2013 (a) and 5 June 2013 (b). Velocity reference scale of 0.5 m s^{-1} is labeled in panel (a). Two eddies leading to Kuroshio transport anomaly events 7 and 8 (see Fig. 4) are labeled in panel (b). Blue curves northeast of Luzon represent Seaglider tracks. Panel (c) shows the map of absolute dynamic topography (MADT) and Aviso surface current.

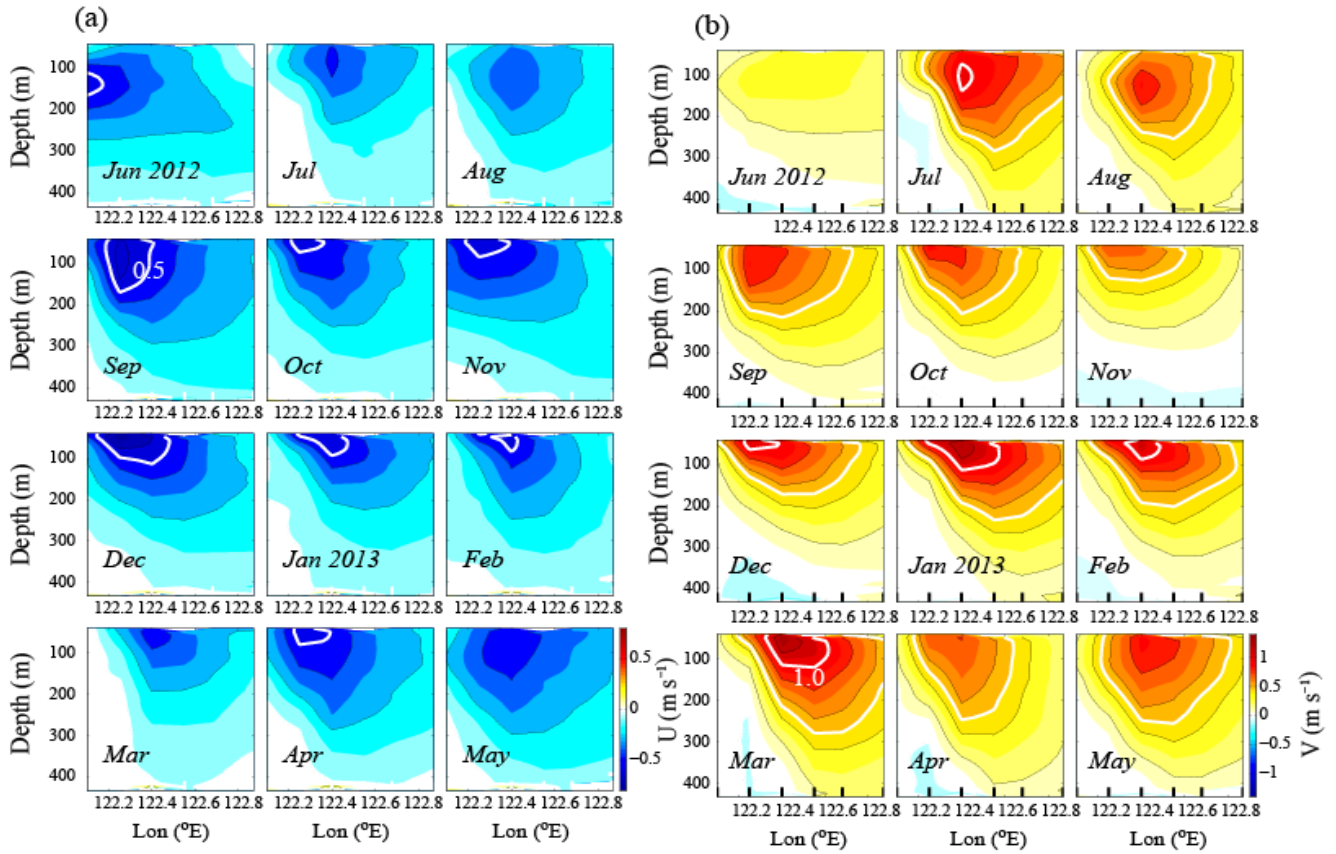


Figure 2: Monthly mean (a) zonal velocity and (b) meridional velocity measured by the moored ADCP array between June 2012 and May 2013. The black curves are constant velocity contours at a 0.2 m s^{-1} interval. The white curves are 0.5 and 1.0 m s^{-1} velocity contours. Vertical tick marks at the bottom of panel (b) label the mooring positions.

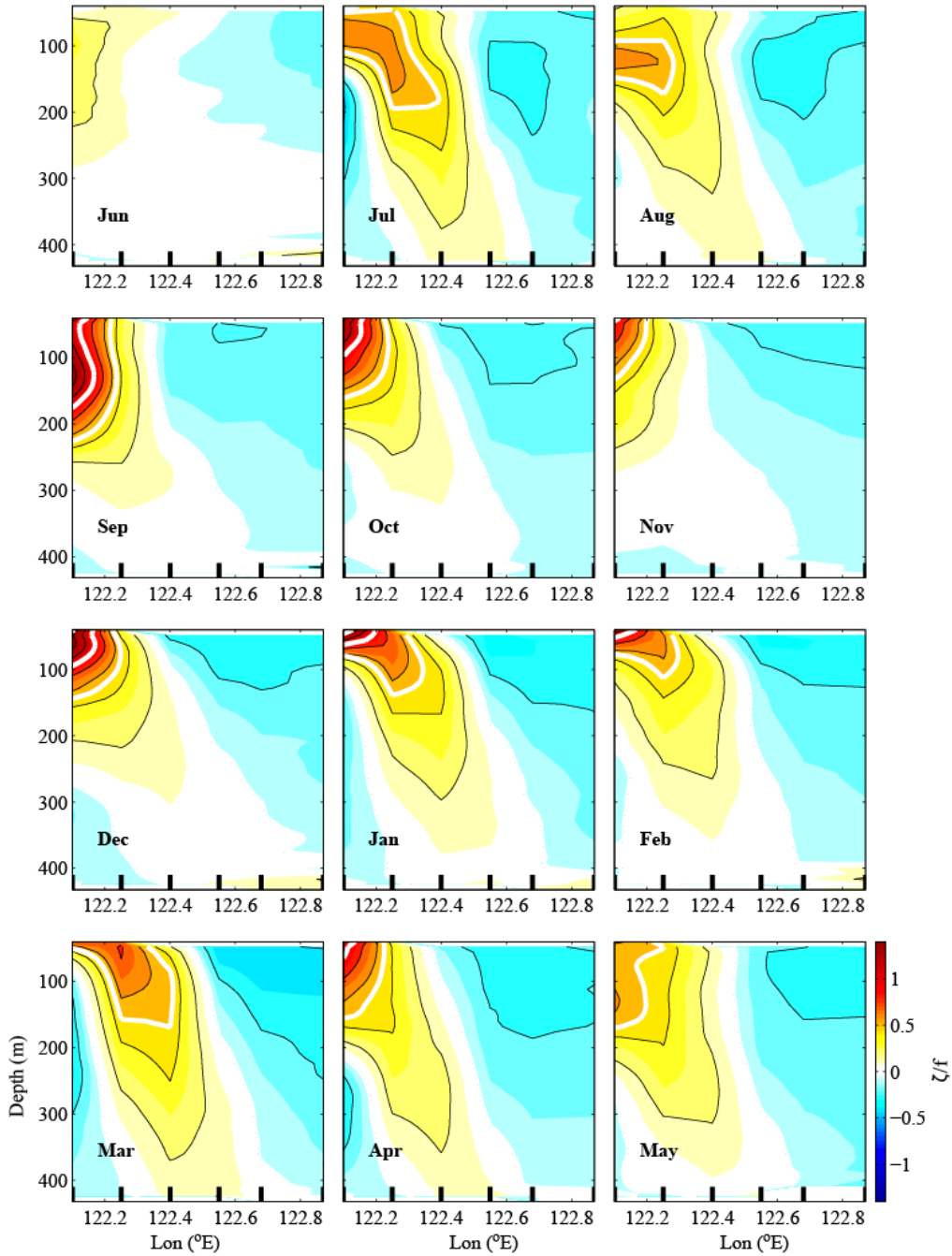


Figure 3: Monthly averaged relative vorticity ζ , normalized by the planetary vorticity f , approximated as the zonal gradient of the meridional velocity $\partial_x v$ measured by the moored ADCP array June 2012 – May 2013. The black curves are constant contours of ζ/f at 0.2 interval. The white curves are 0.5 and 1.0 ζ/f contours. Vertical ticks at the bottom of panels label the mooring positions.

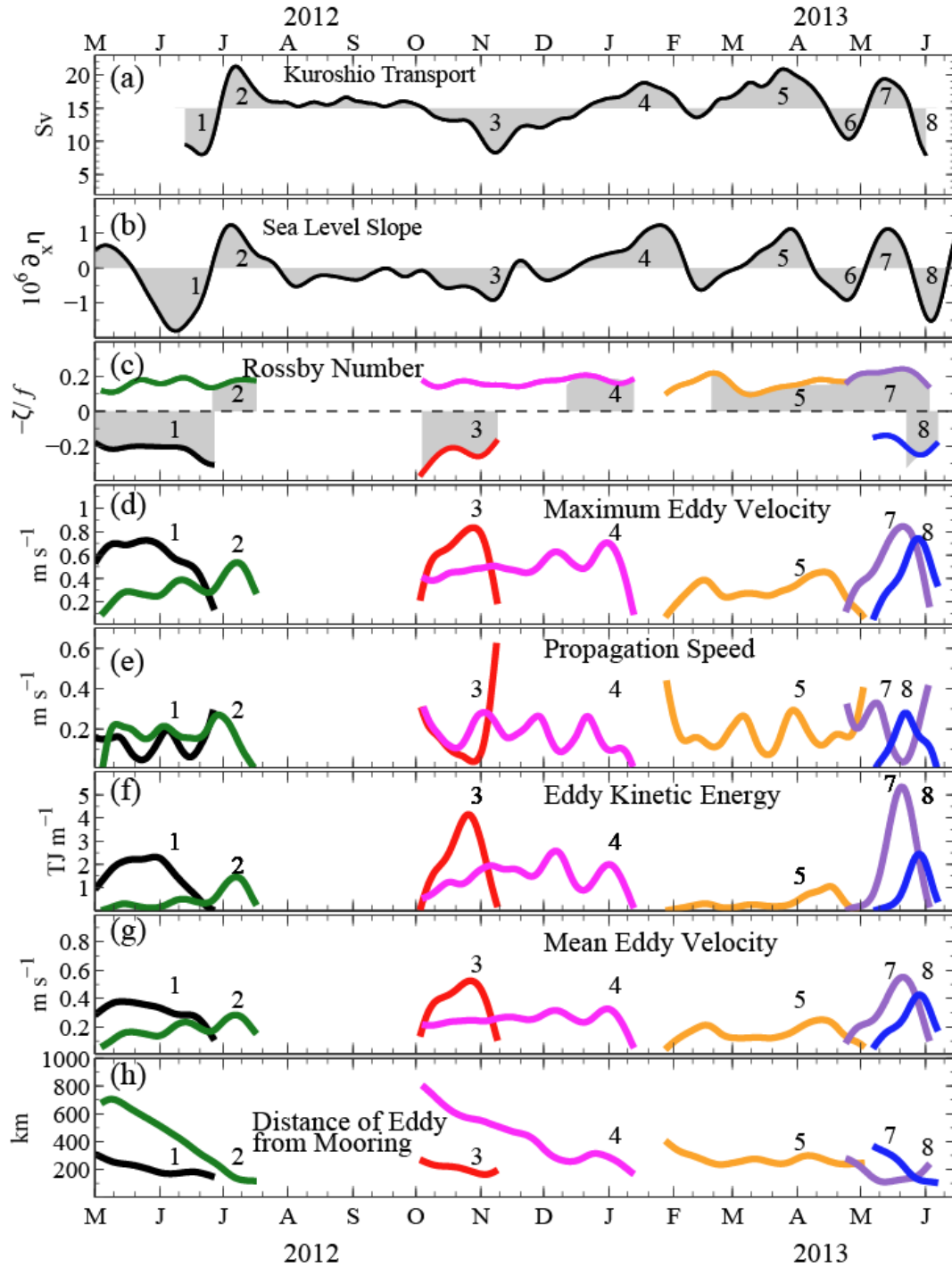


Figure 4: Time series of (a) observed Kuroshio transport computed from mooring measurements south of Luzon Strait (black curve) and (b) SLA slope between 122°E and 123°E across the mooring array south of Luzon Strait. Time series of eddy properties impinging within 250 km from the mooring south of Luzon Strait: (c) minus Rossby number, (d) maximum eddy current speed, (e) eddy propagation speed, (f) area integrated eddy kinetic energy, (g) area averaged eddy current speed, and (h) distance between the eddy center and the eastern Kuroshio boundary, $\sim 18.75^{\circ}\text{N}$ 123°E . Kuroshio transport anomaly events and corresponding SLA slope events and eddies are labeled. All variables have been low-pass filtered at a 10-day time scale.

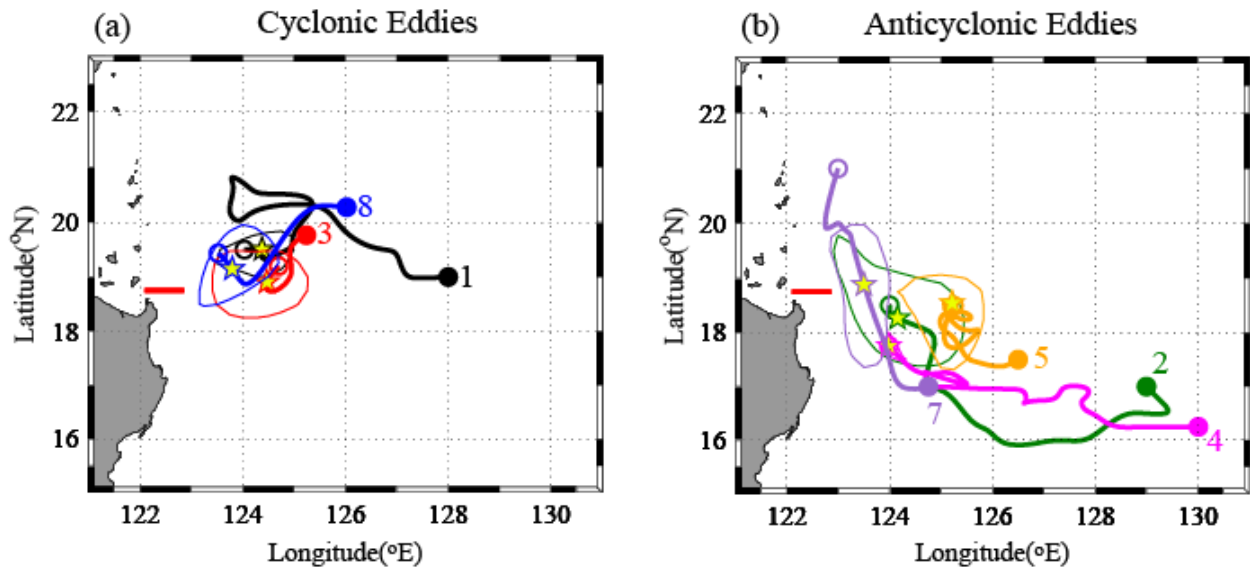


Figure 5: Three cyclonic eddies (a) and four anticyclonic eddies (b) between June 2012 and June 2013. Eddies are labeled corresponding to the anomalous events in Kuroshio transport from Figure 7c. Horizontal red line marks the mooring array position. Color lines show eddy tracks. Dots and circles represent the beginning and end of eddy tracks, respectively. Yellow stars mark positions of eddies when SLA slopes between 122°E and 123°E are the largest corresponding to the anomalous events of Kuroshio transport and the large closed color loops represent the outer boundary of eddies, defined by the boundary of maximum eddy current speed.

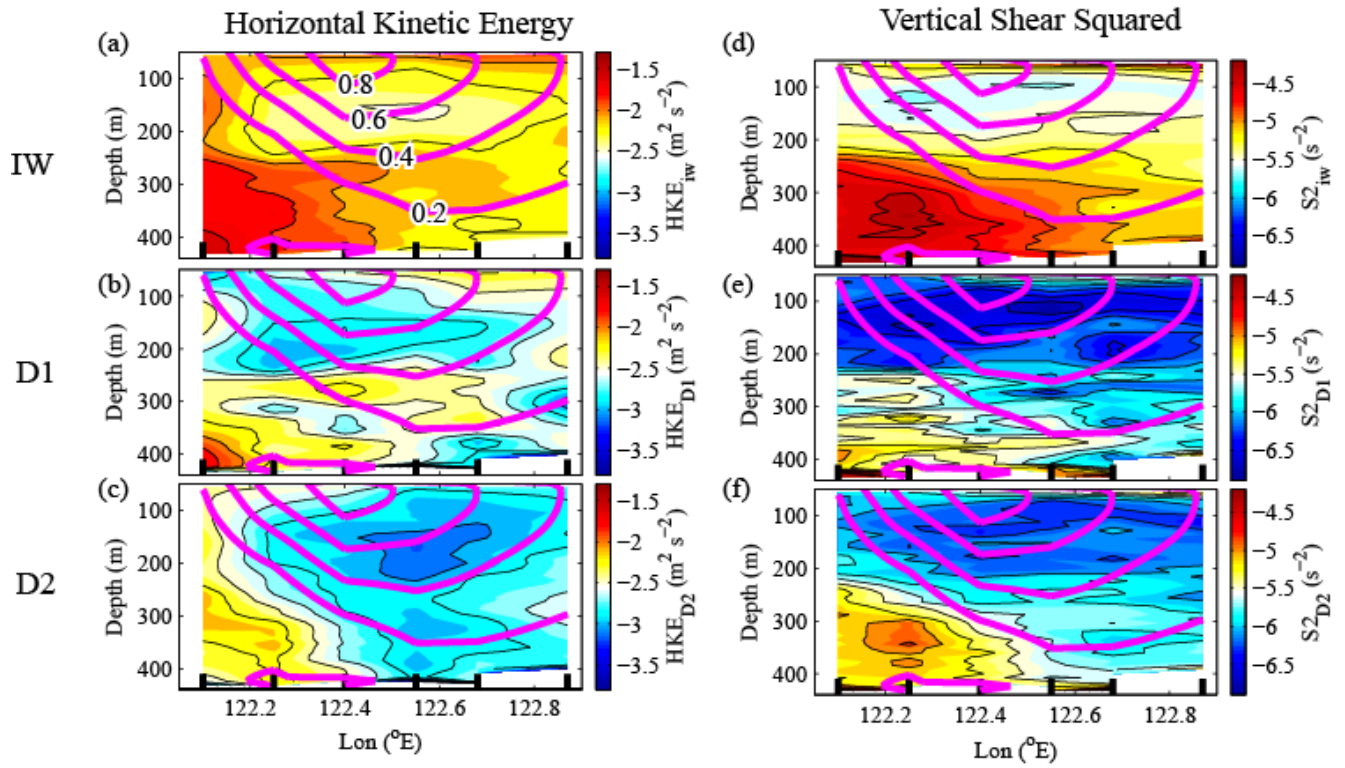


Figure 6: Wentzel–Kramers–Brillouin (WKB) scaled horizontal kinetic energy (a–c) and vertical shear squared (d–f) in internal wave frequency band (IW), diurnal frequency band (D1), and semidiurnal frequency band (D2) across the Kuroshio averaged between 1 and 16 January 2013. Magenta curves show the contours of northward velocity.

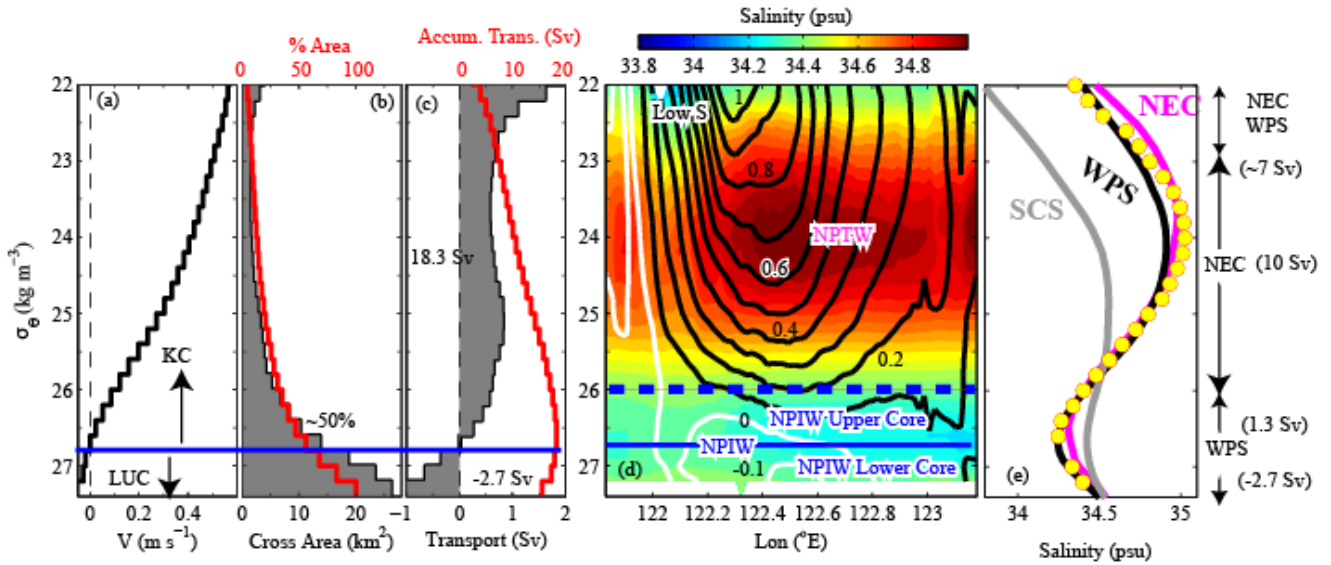


Figure 7. Temporal mean of Seaglider estimates of (a) meridional geostrophic current, (b) crossing area, product of layer thickness and zonal span (shading), and the accumulated crossing area (red), (c) northward transport (shading), and the accumulated transport from the surface (red). (d) Salinity on the isopycnal coordinate. Black and white contour lines represent northward and southward velocity. Horizontal blue line represents the isopycnal surface dividing the northward flowing Kuroshio and the southward flowing Luzon Undercurrent and is also the center of the low salinity North Pacific Intermediate Water (NPIW). (e) Salinity properties of the North Equatorial Current (NEC, magenta), Western Philippine Sea (WPS, thick black), and South China Sea (SCS) (grey). Yellow circles indicate salinity of maximum transport observed by Seagliders. The Kuroshio transport 50% of the total volume, labeled in (b). The total transports of the Kuroshio and Luzon Undercurrent are labeled in (c). The high salinity North Pacific Tropical Water (NPTW) is labeled in (d). The low salinity SCS water west of the Kuroshio is labeled. The blue horizontal dashed line represents the upper bound of the NPIW upper core. The transports of different water masses identified by the TS analysis are summarized on the right side of panel (e).

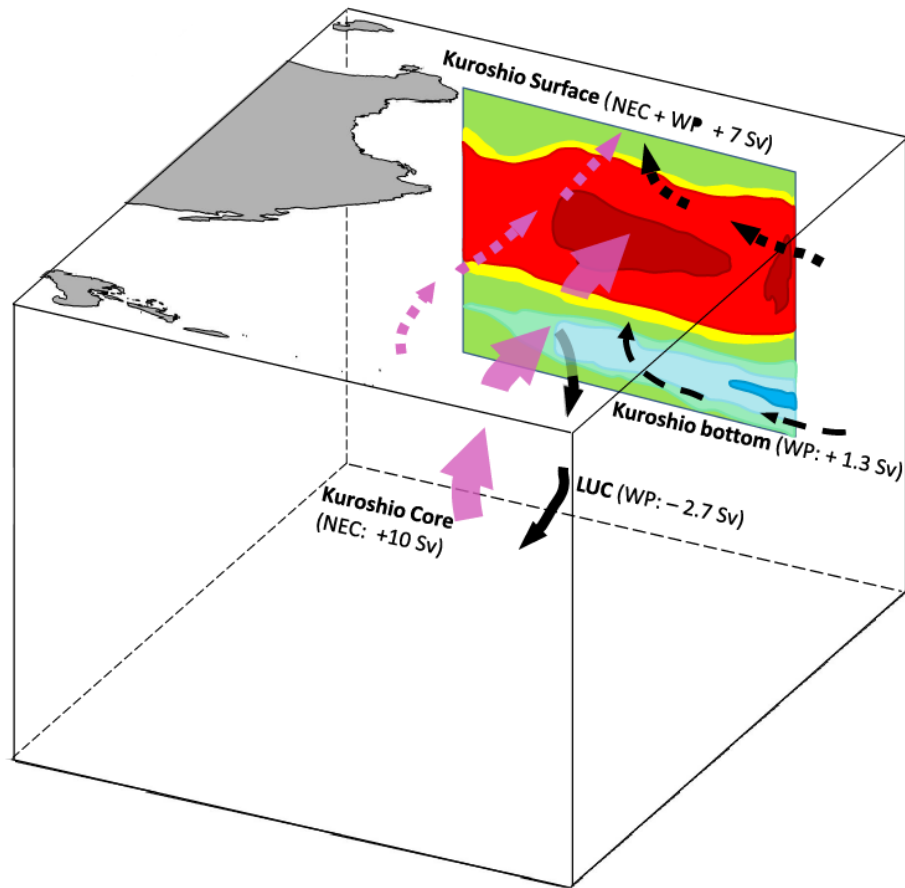


Figure 8: Illustration of water mass transports of the Kuroshio and Luzon Undercurrent east of Luzon Island summarized from Fig. 7e.