Glider-based Observations of Kuroshio Seasonal Variability and Loop-Current Intrusion into the South China Sea

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LONG-TERM GOALS

This study contributes to long-term efforts toward understanding:

- Origins of the Kuroshio Current.
- Circulation of the Western Pacific.

OBJECTIVES

The proposed observational program focuses on understanding:

- Characterize the annual cycle of the Kuroshio and its associated mesoscale variability.
- Quantify Kuroshio spatial structure and temporal evolution.
- Investigate Kuroshio and mesoscale response to strong monsoonal forcing.

APPROACH

Data availability limits understanding of Kuroshio formation, with the upstream Kuroshio having received far less attention than the regions to the northeast, offshore of Japan. Although observations reveal a distinct Kuroshio Current east of Taiwan, its upstream structure appears less well defined. The Kuroshio typically flows northward from Luzon with a slight westward incursion through the deep channels (2400 m sill depth) of Luzon Strait, but occasionally turns westward to form significant intrusions into the South China Sea. These intrusions modify Kuroshio structure through entrainment of South China Sea waters and impact mesoscale and internal wave climate within the South China Sea. Competing theories attempt to explain the dynamics governing these intrusions, ranging from arguments based on seasonal changes in Ekaman transport (Farris and Wimbush, 1996) to gap-

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jumping governed by the current's inertia (Sheremet, 2001). Estimates of Kuroshio volume, transport also exhibit significant seasonal and interannual variability, with Gilson and Roemmich (2002)

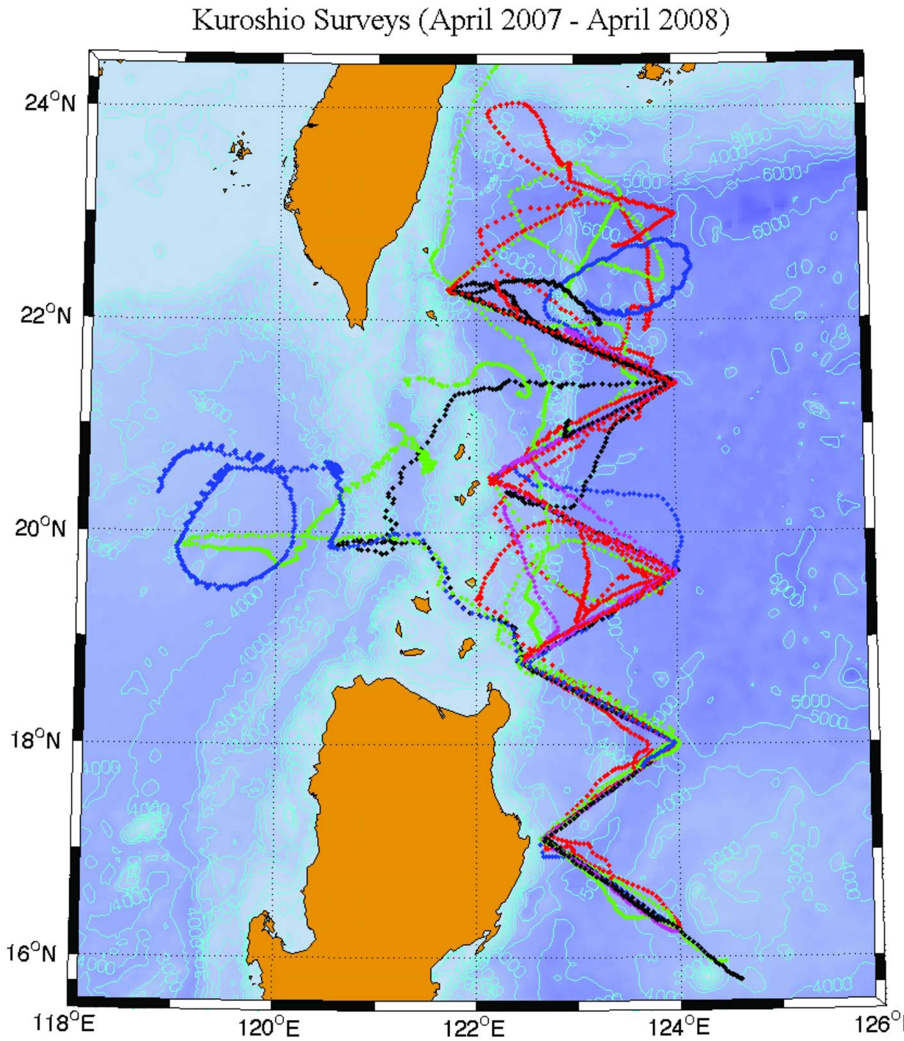

Figure 1. All tracks occupied by Kuroshio gliders (13 trajectories total). Dots mark profile locations. Deployments cycle through a set of 5 colors with red, green and blue representing three gliders and pink and black representing two.

reporting annual mean volume transport (1993 – 2001) of 22±1.5 Sv with 8±6 Sv seasonal variation, with the strongest currents confined close to the Taiwan coast, in the upper 700 m of the water column. Kuroshio transport is strongest in winter/spring and weakest in autumn, but also exhibits 12±6 Sv interannual variability, well in excess of its seasonal range.

This project employs autonomous, long-endurance gliders to characterize the seasonal cycle and downstream evolution of Kuroshio structure. Gliders occupy multiple cross-current sections along ~750 km of the Kuroshio's pathway to capture changes in structure and watermass properties between Luzon and Taiwan. Typical missions last ~3 months, with multiple deployments providing repeat occupations to document a complete annual cycle. Energetic, highly variable mesoscale currents present a challenging environment for glider operations, requiring the vehicles to move rapidly at significant cost to mission endurance. Currents within the Kuroshio often exceed maximum glider speeds, dictating a strategy that involves collecting sections across the current while being carried downstream. Gliders occupy a sawtooth track beginning at ~16° N, off the east Luzon coast (Fig. 1). Rather than expending energy fighting strong currents, gliders use the Kuroshio to distribute themselves along the entire pathway, executing repeated sections across the flow while being carried downstream. Although sections across the Ilan Ridge (northeast of Taiwan, where the Kuroshio passes

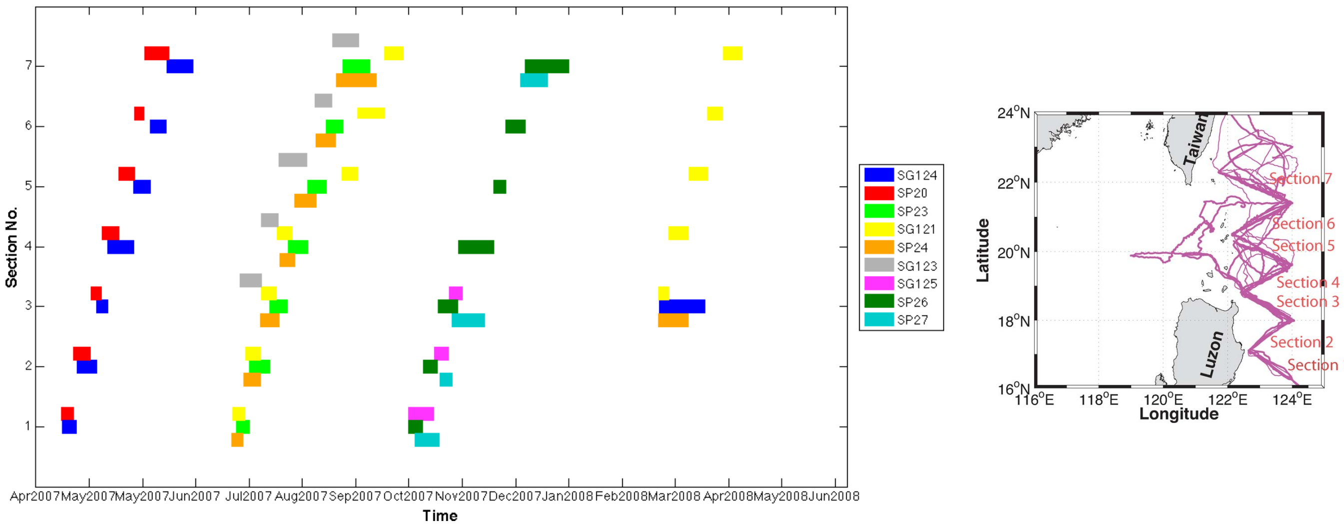

Figure 2. Timing chart (left) depicting when gliders occupied each of the seven repeated sections marked on the accompanying chart (right). Each color represents a single glider, with three of the vehicles deployed twice. The South China Sea sections are not included here, and one additional glider that sampled primarily within the South China Sea has been omitted from the chart.

into the East China Sea) were desirable, EEZ constraints and the lack of a suitable recovery platform for retrieving gliders from the East China Sea dictated that sampling end further to the south.

WORK COMPLETED

Glider operations began in April 2007 and continued through April 2008, supported by R/V Melville and vessels from the Taiwanese research fleet. Successful operation within the strong Kuroshio currents required high speeds that limited mission endurance to roughly three months, dictating the deployment tempo (Fig. 2). The initial survey employed two vehicles (one APL-UW Seaglider and one SIO Spray) to demonstrate that gliders could overcome the various operational challenges to maintain control and execute sections across the Kuroshio. To improve coverage, the second survey used four gliders with staggered deployment sites and flight plans designed to better distribute the vehicles along the survey path. After demonstrating the gliders' ability to navigate across the Kuroshio the third and fourth surveys sent three vehicles through the Luzon Strait, seeking the western edge of the boundary current during its intrusion into the South China Sea (Fig.1). Sections collected over the four deployments provide seasonal resolution across most of the lines east of Luzon/Taiwan, with a smaller number of sections extending into the South China Sea.

Experience gained through this year-long effort provided several operational lessons. Foremost is confirmation that gliders can provide persistent sampling across strong boundary currents. Even when currents prevented gliders from navigating directly to desired waypoints, accepting deflection allowed vehicles to achieve their targets by traversing a more circuitous path. Gliders also demonstrated the ability to pass through relatively hazardous, topographically-constrained regions. This was, to a large degree, achieved by allowing the vehicles to be carried with the swift current, which sweeps around the hazards as it passes through Luzon Strait. The narrow shelves and steep slope regions east of Luzon and Taiwan allow the Kuroshio to extend far inshore. This forces gliders to navigate close to the shoreline, a risky undertaking given the strong, unpredictable currents, in ordered to resolve the

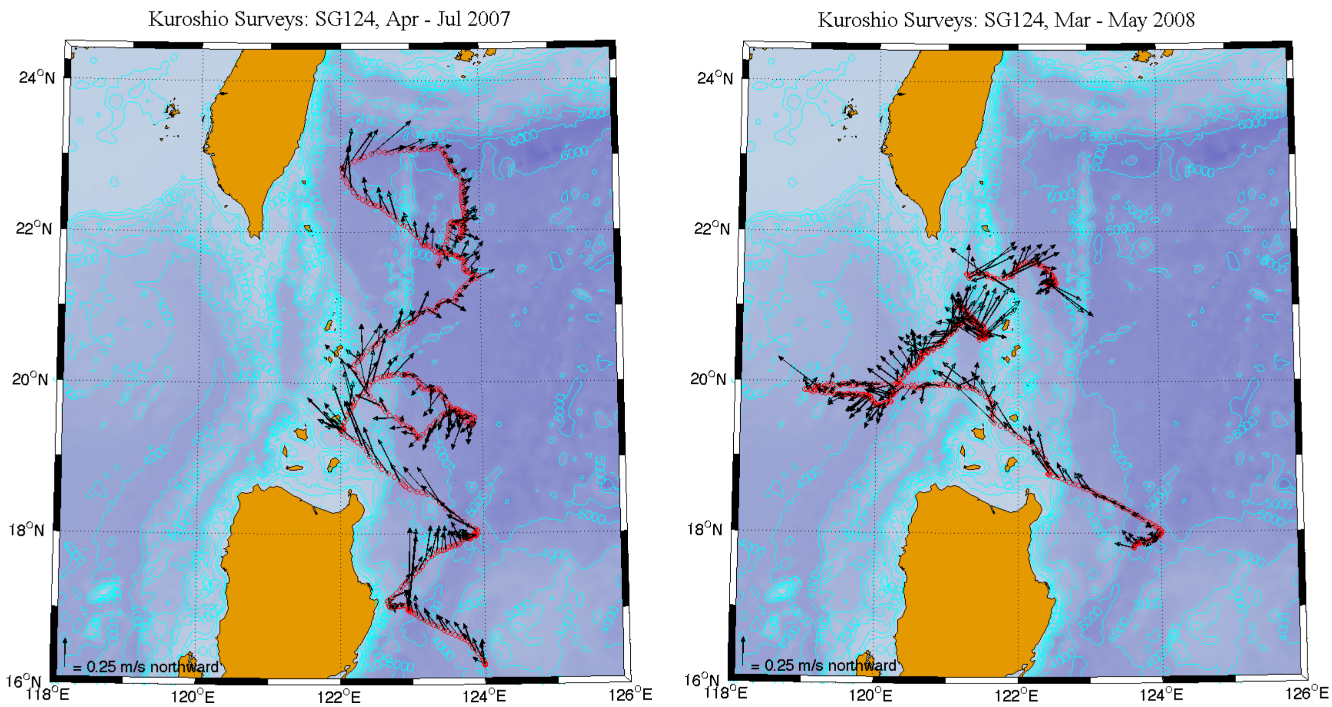

Figure 3. Example glider tracks (red) with depth-average velocities (upper 1000 m, black vectors). Energetic eddies dominate the region south of Luzon Strait (left), though the Kuroshio is distinct, appearing to enter Luzon Strait at ~19° N. In July 2007, sg124 successfully navigated upstream by exiting the eastern edge of the Kuroshio before steering southward. This suggests that gliders could hold station over a smaller region by executing triangular patterns, repeatedly occupying two sections across the boundary currents and moving upstream outside the strong flow. Mesoscale eddies and internal waves dominate variability in the South China Sea (right).

Kuroshio's western edge. The resulting tradeoff between platform safety and resolution of the current's inshore edge should be weighed in the design of future sampling programs.

RESULTS

Glider surveys reveal a Kuroshio current often obscured by mesoscale variability. Energetic eddies often dominate from Luzon Strait southward, with the Kuroshio becoming more distinct off the east coast of Taiwan (Fig. 3a). The measurements suggest that the Kuroshio makes a slight westward intrusion through Luzon Strait, though the surveys did not typically characterize the extent of penetration into the South China Sea. Sampling within the South China Sea revealed strong eddy and internal wave variability that might mask the Kuroshio's signature (Fig. 3b). Sections depicting the seasonal cycle of absolute geostrophic velocity (calculated by combining the baroclinic component derived from along-track density gradients with the glider estimate of depth-averaged velocity) show predominantly northward currents during all seasons but fail to capture a distinct Kuroshio (Fig. 4). Both depth average currents (Fig. 3a) and geostrophic velocity sections (Fig. 4) suggest that the strong flows extend inshore of the sampled regions. Although depth average velocities define a distinct Kuroshio Current, especially north of Luzon Strait, the structure is far less apparent in the geostrophic flow. This discrepancy might be partly explained by the fact that estimated geostrophic velocities are normal to the section, while the strongest currents are often oriented obliquely.

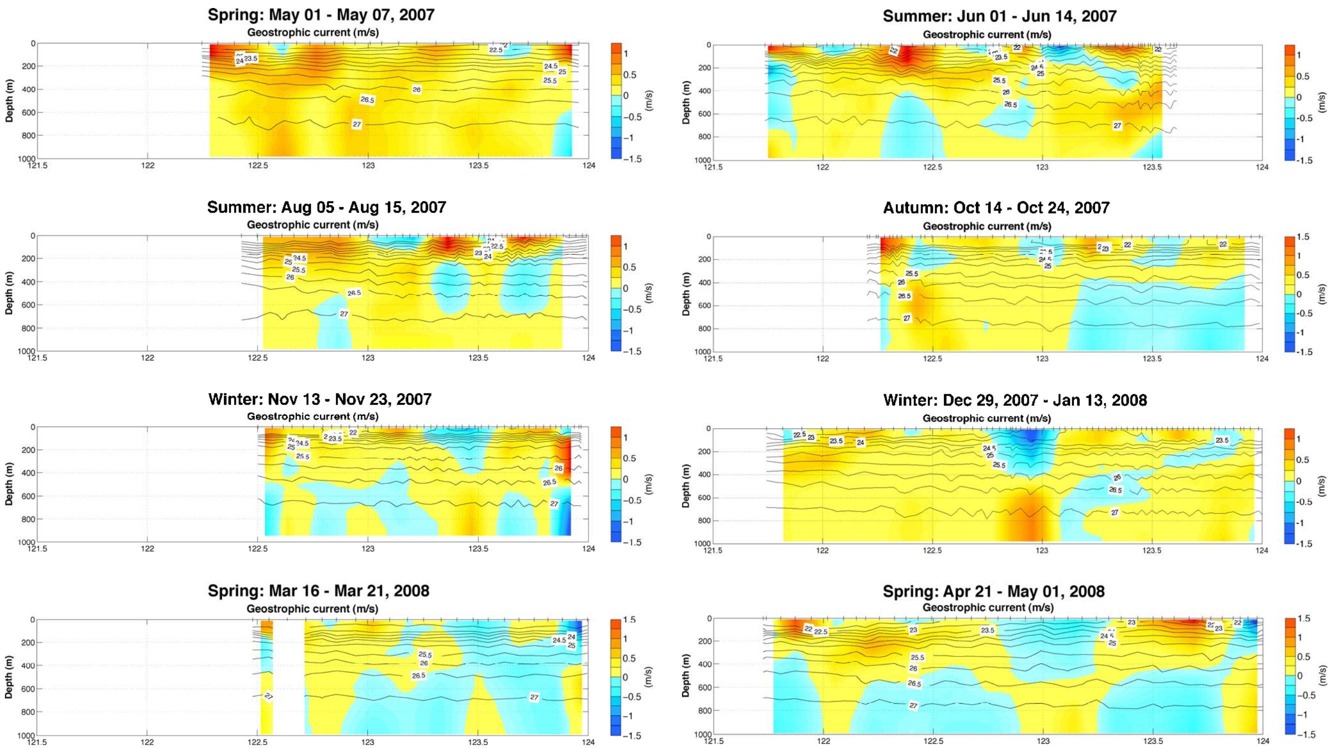

Figure 4. Absolute geostrophic velocity (normal to the section) for Sections 3 (south of Luzon Strait, left) and 7 (north of Luzon Strait, right). Black contours mark potential density. Panels depict occupations in various seasons.

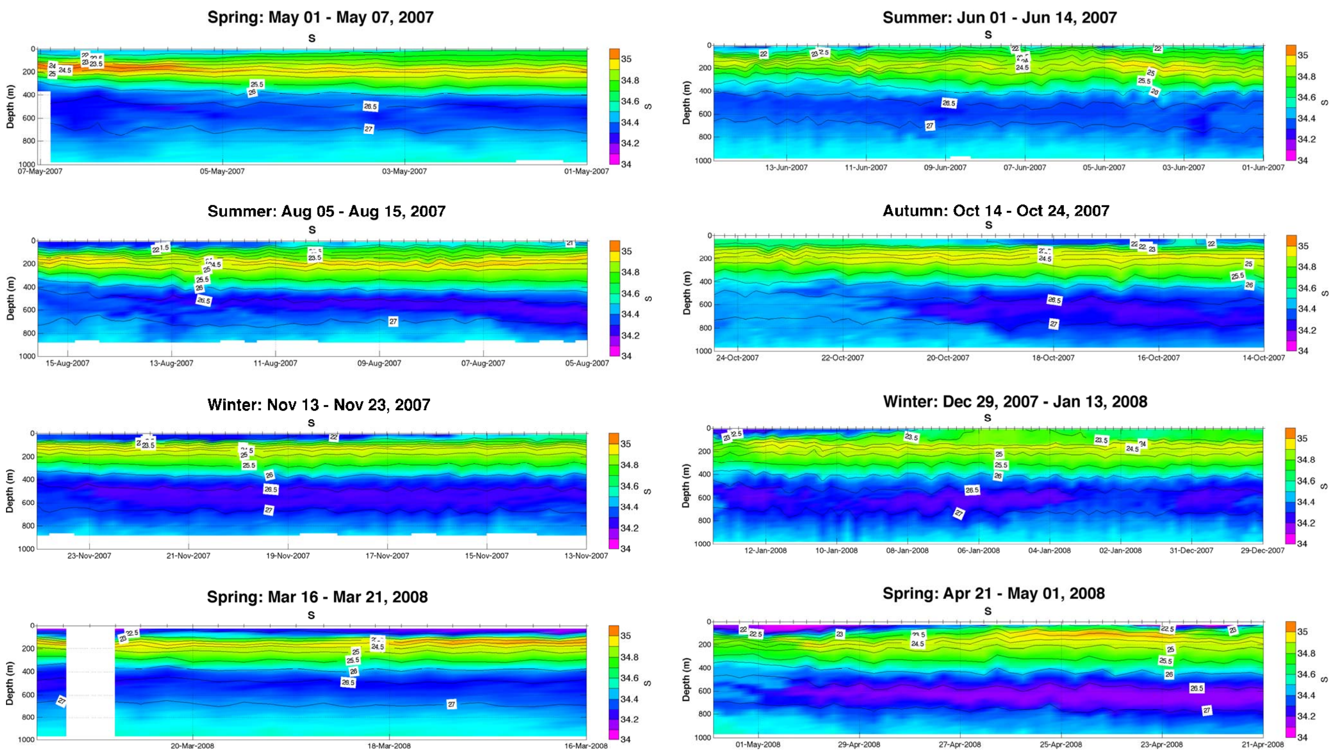

Figure 5. Salinity for Sections 3 (south of Luzon Strait, left) and 7 (north of Luzon Strait, right). Black contours mark potential density. Panels depict occupations in various seasons.

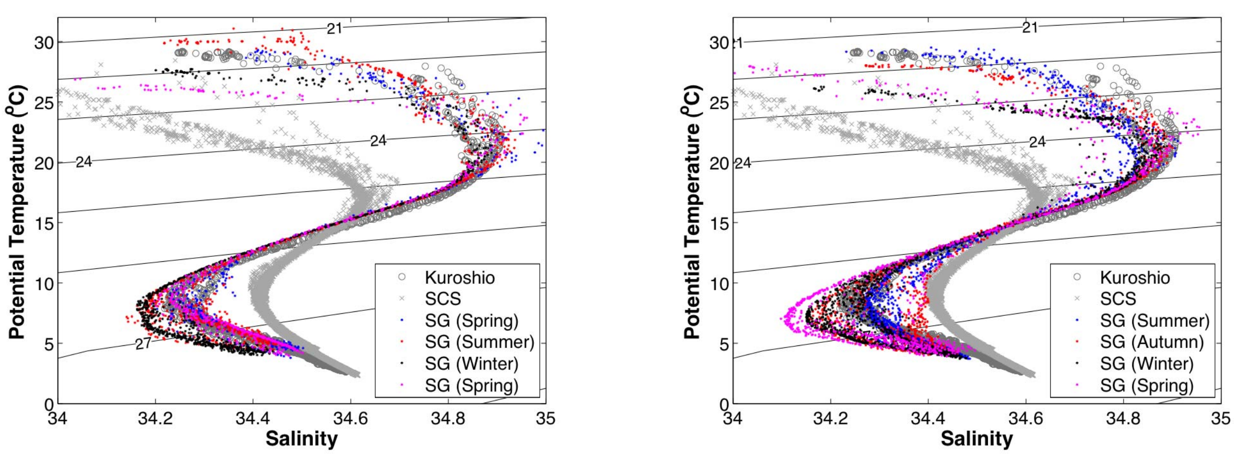

Figure 6. Potential temperature – salinity diagrams for Sections 3 (left) and 7 (right). Different color dots mark water properties during various seasons, with the light grey crosses (circles) indicating climatological profiles in the South China Sea (Kuroshio, east of Northern Luzon).

Vertical structure and watermass properties exhibit seasonal changes and downstream evolution. Sections reveal a distinct subsurface salinity maximum and a deeper (600 m) layer of fresh, North Pacific Intermediate Water (NPIW) both south and north of the Luzon Strait (Fig. 5). South of Luzon Strait, the NPIW layer appears weakest in spring while to the north it is prominent in all but the summertime section. A fresh surface layer extends over much of the southern section (section 3) with weaker signatures to the north. In both sections, salinities within the upper 400 m appear highest in spring, with fresher conditions through the rest of the year. Comparing sections taken before and after the Kuroshio's excursion into the South China Sea, stratification within the upper 200 m appears to weaken to the north. To the south, watermass properties (Fig. 6, left) reflect those of the climatological Kuroshio (as defined by historical casts collected east of Northern Luzon), with the distinctive NPIW salinity minimum and shallower salinity maximum. Springtime near-surface conditions appear cooler and fresher than climatology. North of Luzon Strait (Fig. 6, right), watermass properties largely follow those of the Kuroshio climatology, though in autumn and summer the NPIW layer exhibits elevated salinities consistent with mixing during the current's passage through the South China Sea. As for the southern section, winter- and springtime near-surface conditions are cooler and fresher than climatology, perhaps indicating near-surface mixing with South China Sea waters.

IMPACT/APPLICATION

Developed techniques for using gliders to sample strong boundary currents.

TRANSITIONS

None.

RELATED PROJECTS

Glider-based Observations of Kuroshio Seasonal Variability and Loop-Current Intrusion into the South China Sea, D. Rudnick (SIO).

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PUBLICATIONS

None.