Submesoscale Dynamics of the South China Sea

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LONG-TERM GOALS

This study contributes to long-term efforts toward understanding:

- Dynamics of sub-kilometer fronts, eddies and filaments – the oceanic submesoscale.
- The role of submesoscale physics in governing evolution of the upper ocean and its interaction with the atmosphere.
- Circulation and watermass structure of the South China Sea.

OBJECTIVES

Investigate evolution of submesoscale eddies and filaments in the Kuroshio-influenced region off the SW coast of Taiwan. Questions include:

- What role does the Kuroshio play in generating mesoscale and submesoscale variability modeled/observed off the SW coast of Taiwan?
- How does this vary with atmospheric forcing? (This could be phrased as a contrast between opposing monsoons, but we will not be out there to sample the summer monsoon. We should witness significant variations in winter monsoon wind and heat flux, though, especial if we extend into the late winter/early spring.)
- How do these features evolve in response to wintertime (strong) atmospheric forcing?
- What role do these dynamics play in driving water mass evolution and interior stratification in the South China Sea?
- What role do these dynamics/features have on the transition of water masses from northern SCS water into the Kuroshio branch water/current and local flow patterns?

APPROACH

Strong lateral density gradients and deep mixed layers associated with Kuroshio Current intrusions and monsoon forcing, combined with complex topography and strong tidal forcing, drive energetic mesoscale and submesoscale variability in the northern South China Sea. This motivates a new focus on submesoscale dynamics and their role in the energy cascade in the South China Sea. In preparation for a more intensive, future program, this program planned and executed two exploratory field programs in contrasting forcing regimes. Observations focused on the region off the southwest coast of Taiwan, where the Kuroshio Branch Current often intrudes into the South China Sea (Fig. 1). The first

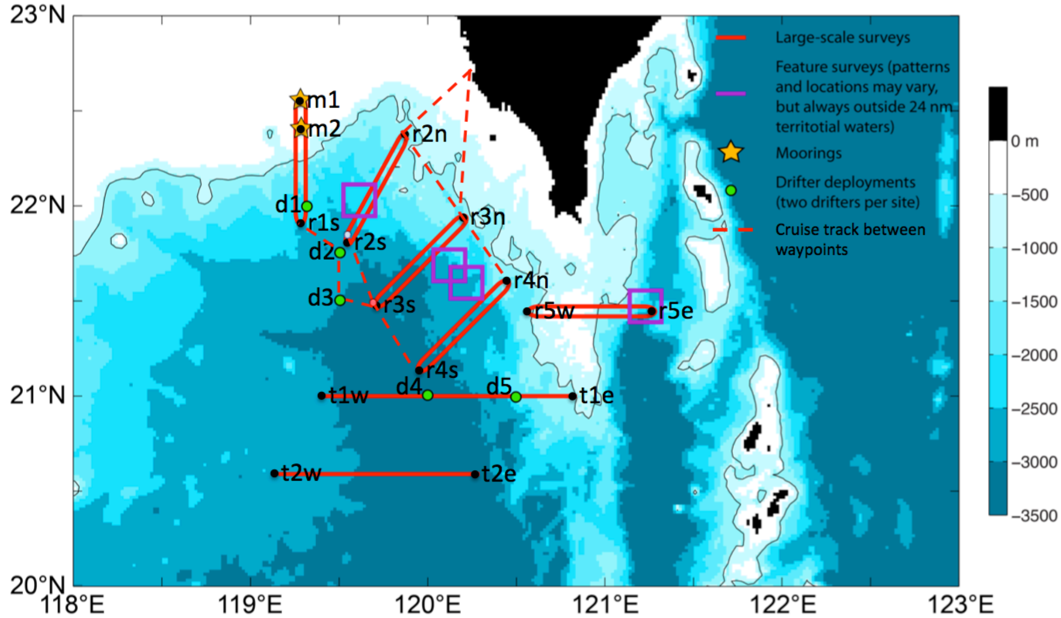


Figure 1. *Planned sampling activities. Red lines mark survey tracks, with labels indicating waypoints. Green dots mark drifter launch positions (leg 1) and yellow stars indicate mooring positions. Purple squares mark notional intensive surveys sites.*

cruise sampled springtime conditions, with weak winds and relatively shallow mixed layers. A second cruise focused on winter, to sample under strong wind-forcing with deeper mixed layers. A mix or rapidly-repeated synoptic sections, time series collected by moored instruments, continuous sampling with autonomous gliders and drifting surveys were used to characterize submesoscale variability.

WORK COMPLETED

Pilot Program- 2013

A pilot program conducted 18-27 May 2013 focused on a period of weak wind forcing, using R/V Revelle to conduct rapidly-repeated sections with an Underway CTD (UCTD, Lee), targeted microstructure sections using a Rockland Vertical Microstructure Profiler (VMP, Shroyer, St Laurent), persistent sections with two Slocum gliders (one equipped with microstructure sensors, Shearman, St Laurent) and time series collected by two mooring deployed over the shelf (Kirincich, Gawarkiewicz)

Moored Observations

Moorings (Gawarkiewicz, Kirincich) were deployed over the northern shelf for the duration of the cruise. These instruments focused on characterizing temporal statistics and observing Kuroshio branch currents and shelf/slope exchange.

- Two moorings were deployed in shelf/slope region (Fig. 2).

Repeat Surveys

Conduct repeat survey patterns to provide statistics on submesoscale/mesoscale variability.

- Underway CTD (UCTD, Lee, Rainville) and VMP (St Laurent, Shroyer) used to repeatedly sample selected sections at tidally-resolving timescales.
- Sections sample several regions to provide maps of the distribution

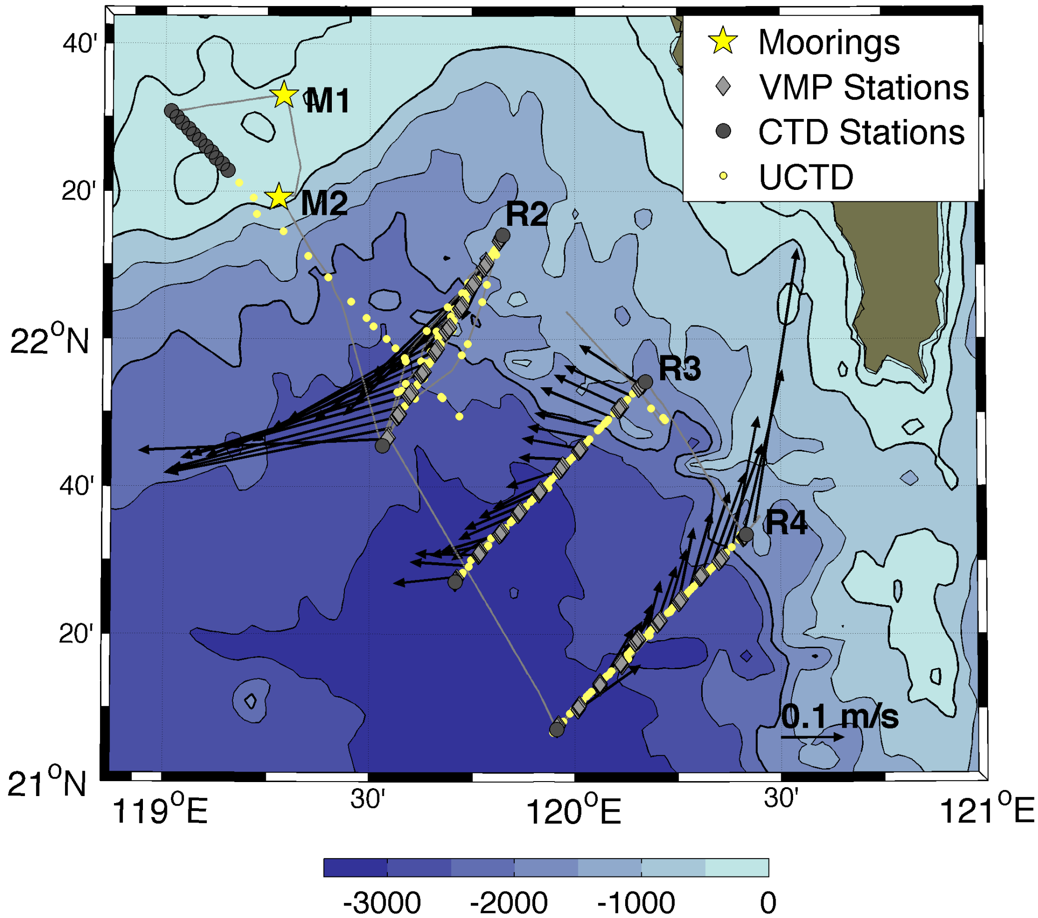


Figure 2. *Cruise track for RR1306. Yellow dots marked repeat UCTD survey lines (36 hours for R2, R3 and R4, 24 hours for the NW-SE line, designated 'R0'). Vectors mark depth-average (0-200 m) velocities, time-averaged over the entire ~48-hour occupation of each line. Note the scale vector in the lower right corner.*

Glider-Based Surveys
Continuous sampling along selected sections using autonomous gliders.

- Persistent sampling along line R3 by gliders 'Husker' (St Laurent) and'Jane' (Shearman).

Wintertime Study- 2014
R/V Revelle returned in January 2014 to conduct a second cruise, targeting at a period of relatively deep mixed layers and strong wind-forcing. Specific goals included characterizing mesoscale and submesoscale variability and relationship to Kuroshio strength/position and atmospheric forcing and capturing submesoscale processes (e.g. MLE restratification, symmetric instability) and their imprint.

In situ sampling from R/V Revelle was divided into two legs, 24 Jan – 9 Feb and 9 Feb – 20 Feb to allow for changes in science personnel and to facilitate participation of Taiwanese students following the New Year holidays. Elements of the 2014 field effort included:

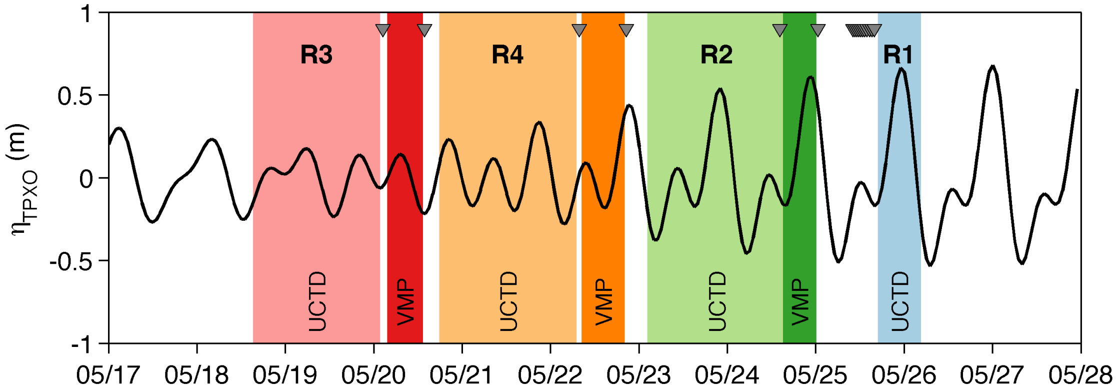


Figure 3. *Spring 2013 cruise. Tidal displacement from TPXO. Colored bars mark UCTD (light) and VMP (dark) survey periods, with grey triangles marking the timing of CTD casts.*

Characterization of Large-Scale Circulation- context and targeting
Prior to and during the cruise, the following efforts were undertaken to capture Kuroshio position and strength, water mass variations, basic spatial statistics.

- Regular drifter deployments (Centurioni) upstream in the Kuroshio, designed to maintain a stream of drifters passing through the region.
- Repeated occupation of one section (R3) with a Seaglider deployed in December 2013 by Prof Sen Jan (NTU) from OR5.
- Real-time maps of surface currents (produced using the Taiwanese HF radar array), satellite remote sensing and dedicated near-term weather forecasts provided by collaborators Prof. Sen Jan, Prof. Y-J Yang (National Taiwan University) and Prof. Ming-Huei Chang (National Taiwan Ocean University).

Moored Observations
Moorings (Gawarkiewicz, Kirincich) were deployed over the northern shelf at the start of RR1401 and recovered at the end, augmenting the Taiwanese array (Jan, Yang) deployed over the eastern shelf (Fig. 4). These instruments focused on characterizing temporal statistics and observing Kuroshio branch currents and shelf/slope exchange.

- Two moorings (Fig. 4) were deployed along line R0 (Fig. 1) in shelf/slope region Moored observations at northern end of domain, in shelf/slope region near the 2013 mooring sites.
- These link with NTU moorings deployed at the inshore ends of R2, R3 and R4 (Fig. 4), extending the arc of shelf measurements along the northern rim.
- The three NTU sites provide an inshore anchor for survey sections R2, R3 and R4, collecting measurements in a region that R/V Revelle cannot access.

Small-Scale Drifting Surveys
A mix of small-scale surveys (5-20 km span) were conducted following drifting wirewalkers.

- Wirewalkers (Lucas) deployed at targeted locations (e.g. frontal regions) for multi-day drifts. Wirewalker drifts do not define Lagrangian reference frames, but a small number of drifting surveys were carried out to provide spatial context for Wirewalker time series observations.
- Gliders (St Laurent, Shearman, Shroyer) surveyed within a small domain around the Wirewalkers.

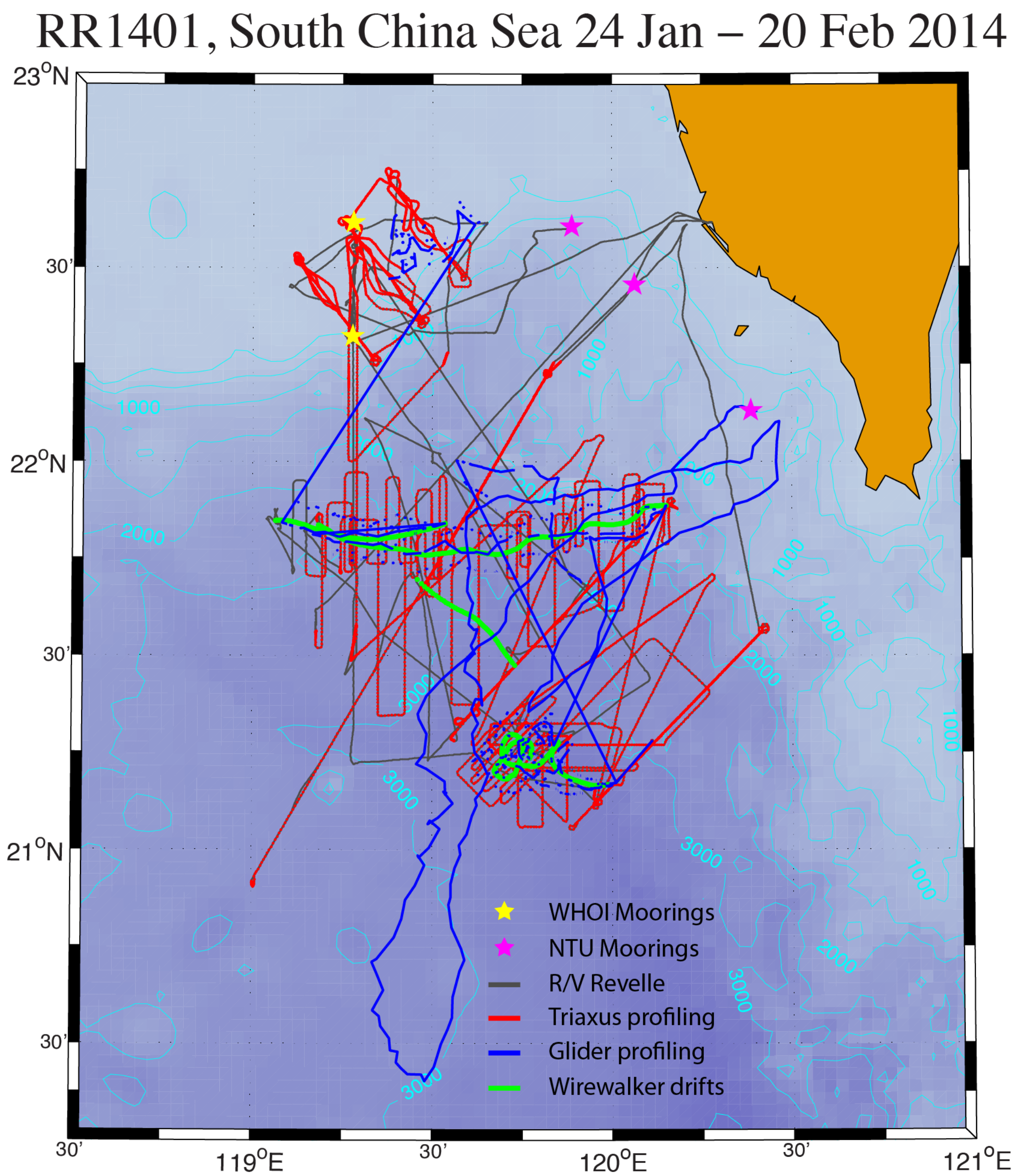


Figure 4. *Cruise track for RR1401. Light gray lines mark R/V Revelle's track, with red indicating where Triaxus survey operations were conducted. Blue lines mark the tracks of the four autonomous gliders, while green lines indicate Wirewalker drift paths. Yellow start mark WHOI mooring sites, while magenta start indicate the positions of the three NTU moorings.*

- The Triaxus towed profiler (Lee, Rainville) executed survey patterns in and around the Wirewalkers, punctuated periodically by longer sections radiating away from the drift track. These surveys were intended to provide mesoscale context for submesoscale observations and to capture a broad range of spatial and temporal scales.

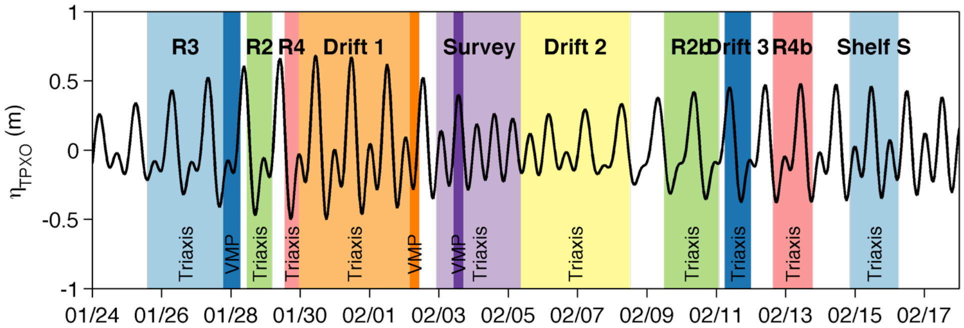


Figure 5. *Winter 2014 cruise. Tidal displacement from TPXO. Colored bars mark Triaxus (light) and VMP (dark) survey periods.*

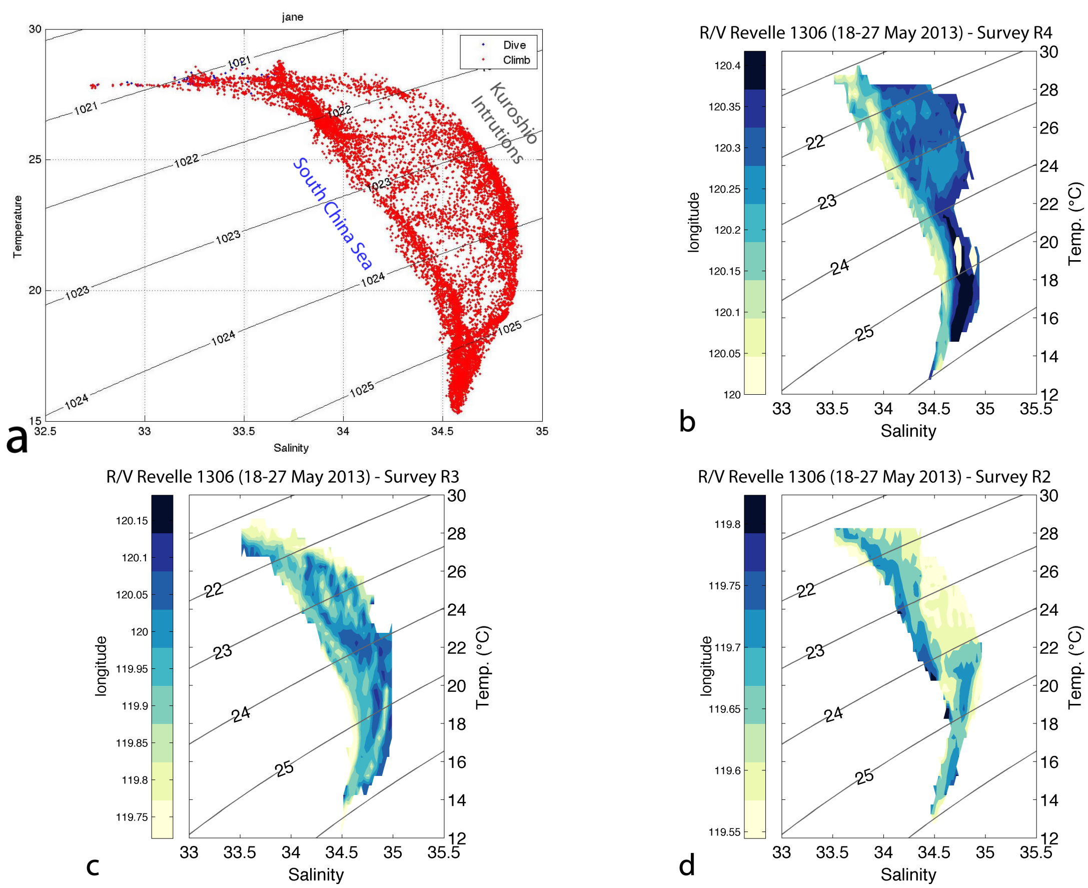


Figure 6. *θ-S from (a) gliders at R3, (b) R4, closest to Luzon Strait, (c) R2 and (d) R2, farthest from Luzon Strait. In b-c, colors indicate longitude, with blues being furthest east.*

Repeat Surveys

Conduct repeat survey patterns to provide statistics on submesoscale/mesoscale variability.

- Triaxus towed profiler (Lee, Rainville) and VMP (St Laurent, Shroyer) used to repeatedly sample selected sections at tidally-resolving timescales.
- Sections sample several regions to provide maps of the distribution

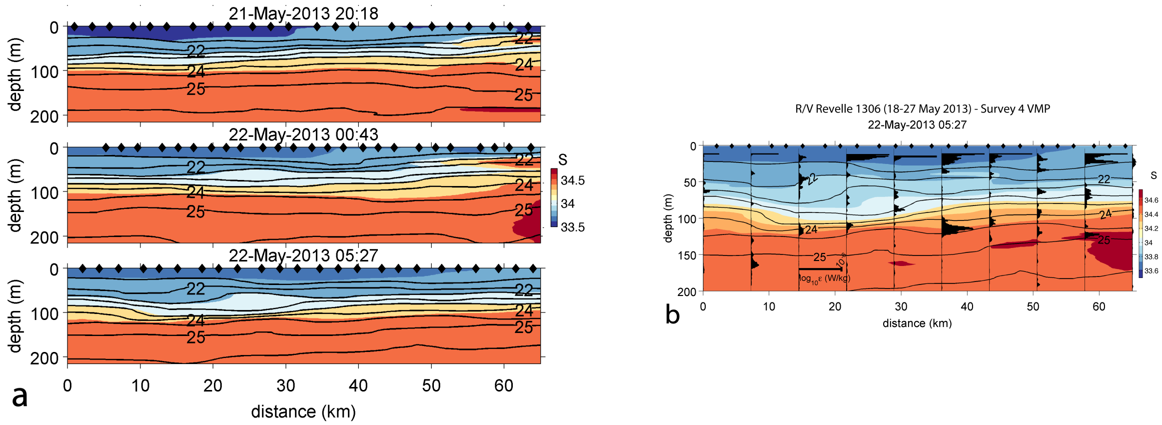


***Figure 7.** Example sections (R4) from (a) UCTD and (b) VMP. Color indicates salinity, contours σ_θ and vectors dissipation rate ε.*

Drifters Deployments
Three drifters supplied by TORI were deployed within the footprint of the Taiwanese CODAR array.

- Evaluate HF array performance.

Glider-Based Surveys
Continuous sampling along selected sections using autonomous gliders.

- Four gliders ('Bob' & 'Doug', Shearman, and 'Helo' & 'Saul', St Laurent) provided continuous sampling throughout the cruise period.

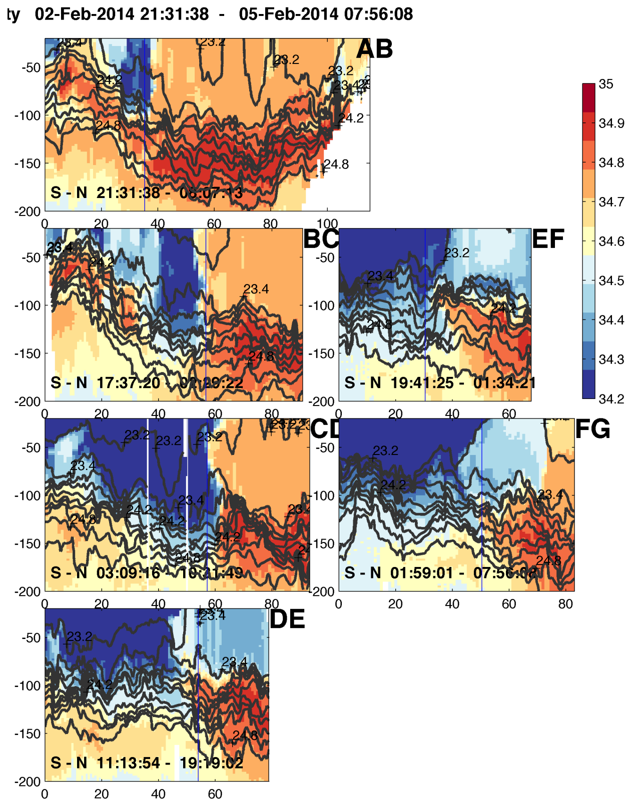
RESULTS

Analysis of observations from the May 2013 and January 2014 efforts is ongoing, with most effort to-date focused on the 2013 observations.

The survey lines (R4, R3, and R2) sampled the slope and deep basin region of the northeastern South China Sea at increasing distance from Luzon Strait and the influence of the Kuroshio. A fourth line (R0) sampled across westward and southwestward mean currents observed along R2 (Fig. 2). Repeat surveys show 48-h mean currents (Fig. 2) to the north at R4, northwest at R3 and west at R2 (roughly following the bathymetry at R2 and R3).

Winds remained weak throughout the May 2013 cruise, and TPXO tidal displacements show that R3 was occupied during neap tide, with R2 and R0 sampled during the spring tide and R4 during the transition (Fig. 3).

Warmer, more saline Kuroshio-influenced waters appear in all sections (Fig. 6). The separation between Kuroshio and South China Sea watermasses, along with mixing lines between them, is especially clear in θ-S diagrams derived from glider-based profiles (Fig. 6a). Kuroshio waters appear more concentrated in the eastern basin (Fig. 6b,c), with some presence even in the northern sections (Fig. 6c,d).



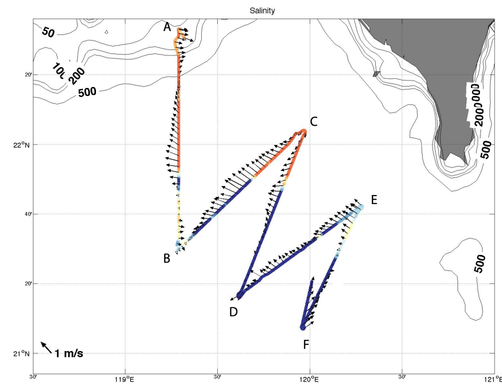


Figure 8. *Kuroshio Branch Current survey from February, 2014. Satellite remote sensing identified a Kuroshio intrusion, motivating a broad survey to refine targeting for intensive sampling. Upper layer velocities ranged between 0.5-1 ms^{-1} within the Branch Current. The right-hand panel displays sections of salinity (color) and potential density (contours), coded to the letters in the chart above. Note the steep isopycnal slopes, fresh water and prominent interleaving associated with the Branch Current.*

Individual sections of velocity, potential temperature, salinity and potential density show prominent isopycnal displacements that may be associated with internal tides or solitary waves (Fig. 7). Relatively weak fronts also appear in these sections, along with interleaving (Fig. 7a) that may be the signature of mixing and subduction driven by the strong atmospheric forcing experienced in the weeks prior to the springtime cruise. Shallow mixed layers were observed across the entire section. Microstructure profiles hint at elevated turbulence associated with the interleaving layers (Fig. 7b).

Sections of salinity and potential density across the wintertime Kuroshio Branch Current (Fig. 8) provide sharp contrast with springtime conditions. Strong currents (0.5-1 ms^{-1}) and anomalously fresh waters mark the Kuroshio intrusion. Mixed layer depths range from less than 50 m in the central basin to over 100 m on the northern (warm) side of the Branch Current. Regions of strong lateral density contrast also exhibit extensive vertical interleaving, suggestive of small-scale mixing and vertical exchange associated with these highly-sheared frontal zones.

IMPACT/APPLICATIONS

None yet.

RELATED PROJECTS

Pleas see reports from Drs. Luca Centurioni, Glenn Gawarkiewicz, Lou St Laurent, Andrew Lucas, R. Kipp Shearman, and Emily Shroyer that detail other aspects of these field programs.

REFERENCES

None.

PUBLICATIONS

None yet.