Flow encountering abrupt topography

Cruise report, R/V *Revelle*, 17 Mar to 11 Apr 2014

Shaun Johnston
Scripps Institution of Oceanography
http://www-pord.ucsd.edu/%7Eshaunj/

1 Overview

The scientific goal of this cruise was to observe major low-latitude zonal currents in the western Pacific and their encounters with topography. A cruise in June–July 2013 in Palau waters (a) found a southward western boundary current and a weaker northward one; (b) observed the North Equatorial Countercurrent (NECC) impinging on Helen Reef; and (c) obtained multibeam bathymetry. The main islands are larger than a deformation radius and so can support a boundary current, while flow at smaller islands appear to produce upwelling on the upstream side and flow acceleration over the flanks. Lee waves are also found emanating from a submarine ridge near Merir Island.

On this cruise, while steaming at 8 knots, a spatial survey of currents, temperature, and salinity were obtained from R/V *Revelle*'s Doppler sonars and SeaSoar, a towed, undulating vehicle equipped with a conductivity-temperature-depth (CTD) instrument (Section 2). The cruise comprised: a meridional section southward to Palau (8.5–11.5°N), cross-shore sections off the east coast of the main islands of Palau (from 6.5–8.5°N), a section across the NECC (4–6.5°N), a short survey around Helen Reef (∼3°N), and intensive surveys of NECC flow around Merir (4–5°N). A repeat of the main islands' survey was shorter due to tropical storm Peipah.

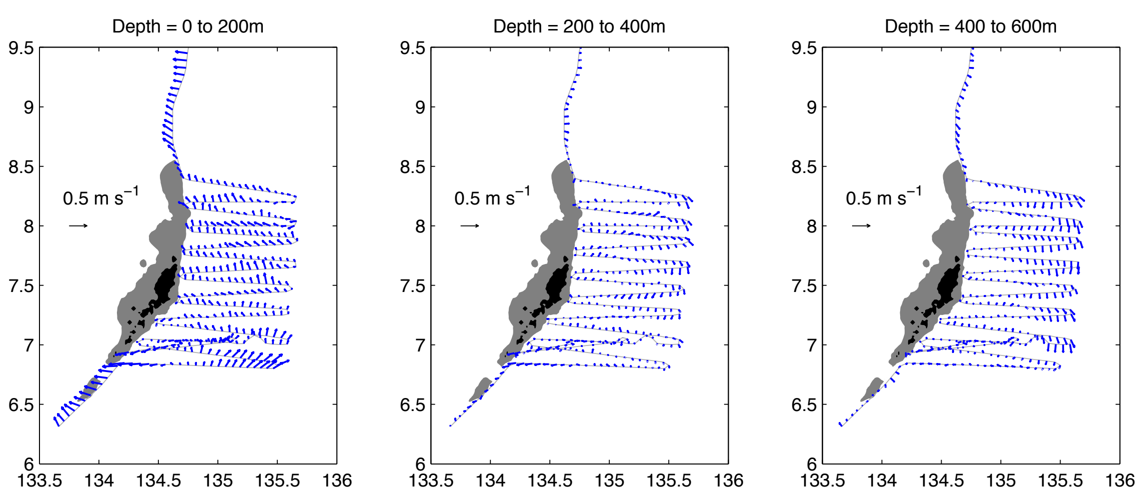

Figure 1: **Left:** During survey 1, currents in the upper 200 m were mainly northward along the east coast of Palau roughly consistent with geostrophic estimates from AVISO SSH (Fig. 2). Flow below Peliliu was westward. Between these flows, a possible stagnation point near the southeast coast is seen. **Middle and right:** Southward flow is found offshore with weaker flows inshore.

2 Methods

SeaSoar, is an undulating vehicle equipped with a CTD, which completes a dive cycle from 5–400 m every ∼10 minutes or ∼3 km while being towed at 8 knots. Shipboard Doppler sonars included the Hydrographic Doppler Sonar System (HDSS) with 50 and 140 kHz systems for profiling to ∼700 and 300 m as well as an RDI Ocean Surveyor (OS) 75 kHz acoustic Doppler current profiler (ADCP) and an older, narrowband 150 kHz ADCP. The OS75 was operated in narrowband mode only to provide better statistics over its maximum depth range. Currents are denoted u and v, which are positive east- and northward. An X-band radar was used to obtain surface wave measurements and statistics throughout the cruise during which seas were quite calm with significant wave heights of about 2 m. Multibeam bathymetry covered a similar area to the 2013 cruise, but some gaps were filled in and some more coverage was obtained especially near Merir Island.

3 Main islands

The SeaSoar was put in the water at the north end of Palau's EEZ near 11°N and towed southward (Fig. 1). Westward flow of ∼0.2 m s^{-1} in the upper 200 m was seen. Currents in the upper 200 m were mainly northward along the east coast of Palau (Fig. 1, left) roughly consistent with geostrophic estimates from AVISO sea surface height (Fig. 2) but different from the 2013 cruise. Flow south of Peliliu was westward. Between these flows, a possible stagnation point near the southeast coast is seen (Fig. 1, left). Deeper southward flows are found in the offshore area (Fig. 1, right, and Fig. 3).

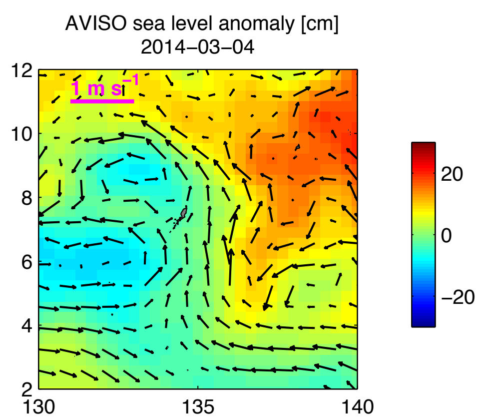

Figure 2: Sea surface height anomaly from the AVISO satellite altimetry product from a period prior to the cruise is high/low east/west of Palau and produces northward flow along the east coast and westward flow south of the main islands qualitatively similar to observed currents (Fig. 1).

A portion of the main islands survey was repeated at the end of the cruise and similarities were noted with the 2013 cruise. During the 2013 cruise, the upstream zonal flow in the offshore area separated near the coast into a stronger (∼0.5 m s^{-1}) southward boundary current and weaker (∼0.3 m s^{-1}) northward boundary current. Similar to the 2013 cruise, a southward boundary

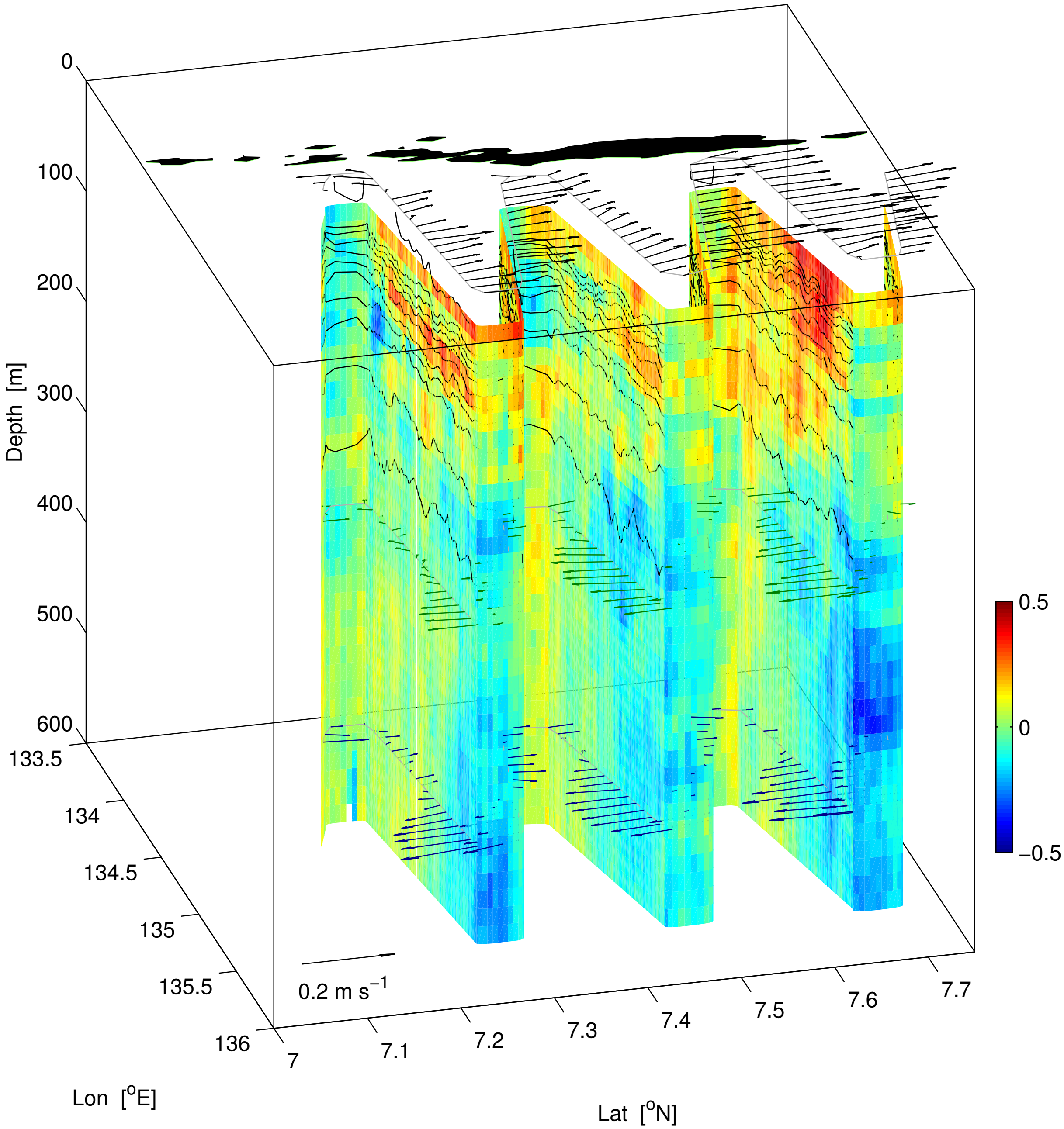

Figure 3: Some depth/cross-shore sections of v in m s^{-1} from survey 1 are shown with northward flow in the upper 200 m and southward flow below 200 m in the offshore area. Current vectors are means from 28–200 m, 200–400 m, and 400–600 m. Black lines are isopycnals at 0.5 kg m^{-3} intervals. The topography of the main islands of Palau are shaded black.

currents was present (Fig. 4–5). In the offshore area, flow varies from northward to northwestward. Southward flow is found at depth.

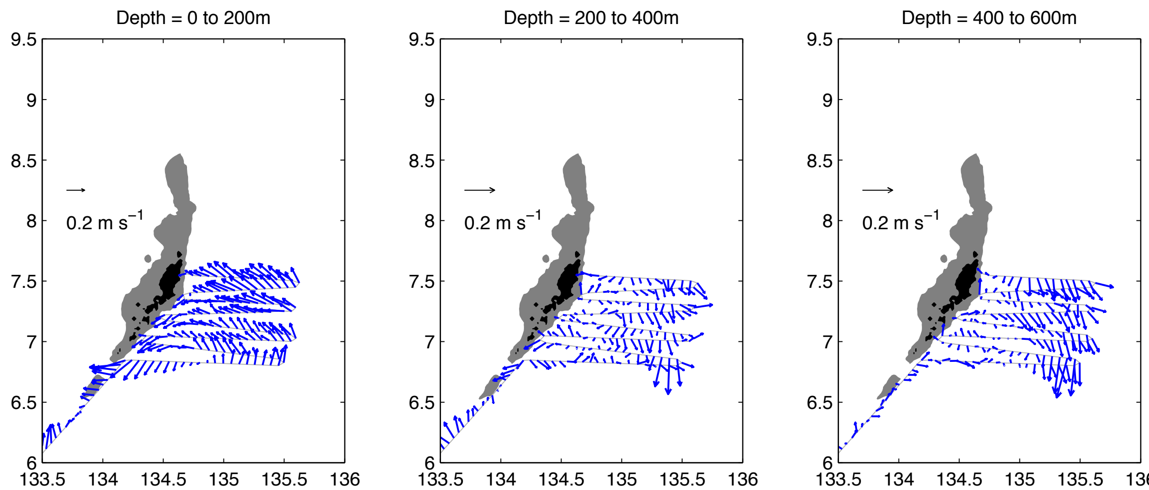

Figure 4: **Left:** During survey 2, a southward boundary current in the upper 200 m was found. Flow below Peliliu was westward. Currents were northward further offshore. **Middle and right:** At depth, maximum southward flow is found offshore.

4 Helen Reef and Merir Island

On this cruise, the NECC was maximum near 4.5°N, which is about 1° further north than the previous cruise (Fig. 6). A mainly zonal current with a maximum of 1.2 m s^{-1} was incident on Merir Island, similar to the situation on the previous cruise when the NECC was flowing around Helen Reef.

While surveying around Helen Reef, *Revelle* received a radio call from the rangers on the island asking for water. Since the ship had not yet cleared into the country, we obtained an exception from the government of Palau to allow us to deliver some water and food to the rangers. Governor Patris of Hatohobei State and the Coral Reef Research Foundation were helpful in obtaining the necessary permissions.

Since the currents around Helen were not as strong as those by Merir, the spatial survey near Helen Reef was shifted to Merir Island (Fig. 6). Current shear around the island was visible from the ship in north-south bands of roughened water extending in straight lines for kilometres suggestive of lee waves (Fig. 7).

Two surveys around Merir were done to examine how the flow goes around the island and the submarine ridge. Preliminary objective maps in the horizontal plane were made of the density data from SeaSoar and currents from the OS75 ADCP. Isopycnals show the presence of lee waves with a wavelength of about 0.1° or 10 km (Fig. 8) (Baines, 1995). The waves are present throughout the survey area. A zonal slice through these objective maps also shows upward and upstream phase propagation of the lee waves both in isopycnals and velocities (Fig. 9). Flow convergence near the surface is at least 0.5 m s^{-1} over a wavelength of about 10 km (Fig. 9, middle and bottom). To

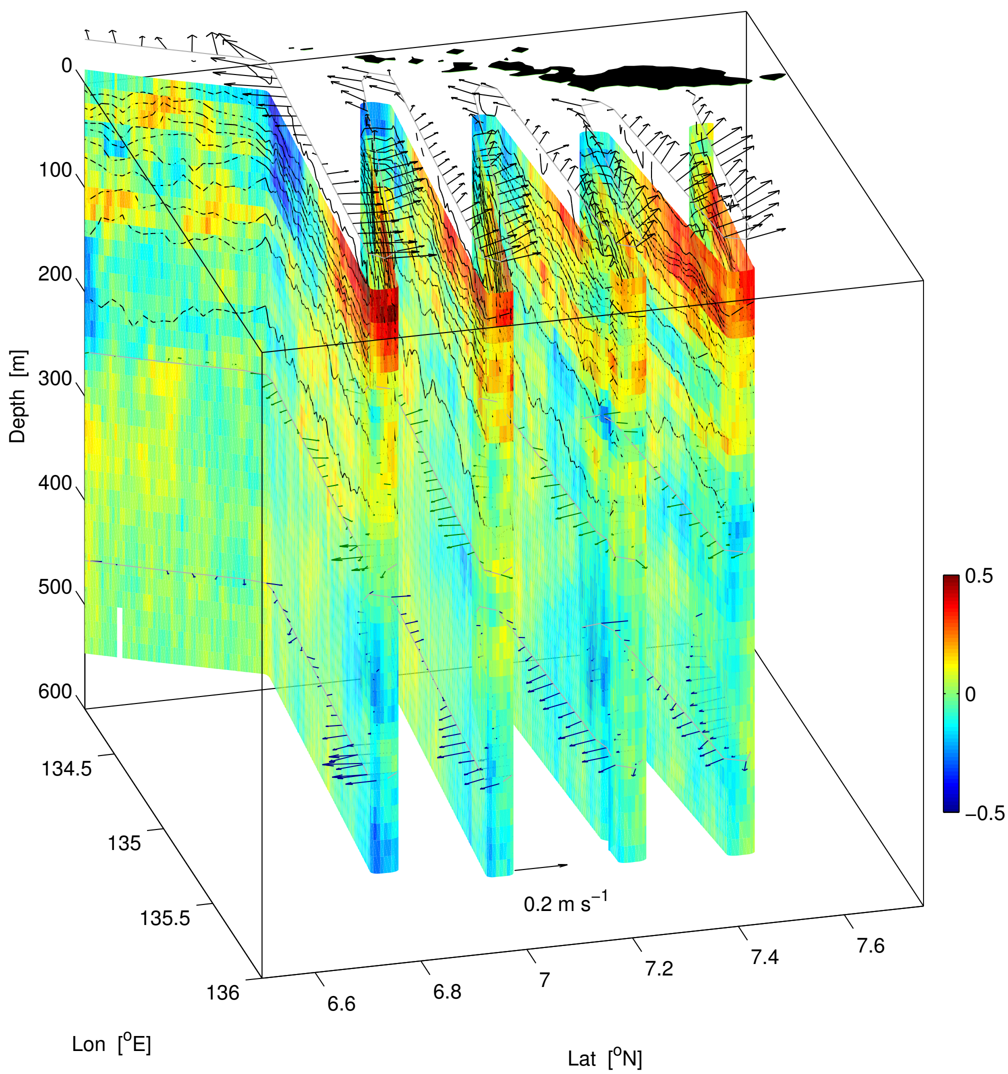

Figure 5: Some depth/cross-shore sections of v in m s^{-1} from survey 2 are shown with a southward boundary current in the upper 200 m and northward/northwestward flow in the offshore area. Currents are southward further offshore and deeper. Current vectors are means from 28–200 m, 200–400 m, and 400–600 m. Black lines are isopycnals at 0.5 kg m^{-3} intervals. The topography of the main islands of Palau are shaded black.

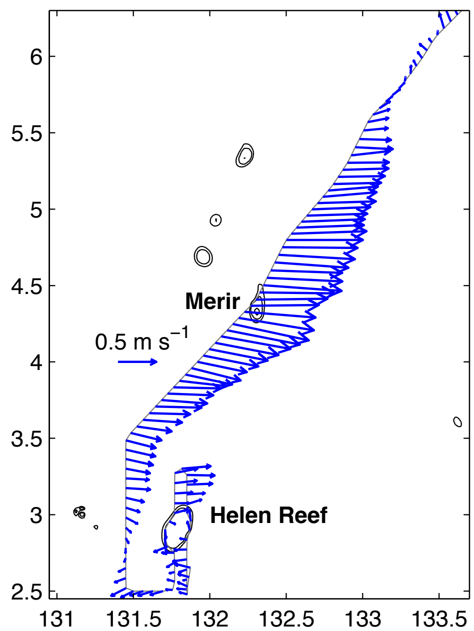

Figure 6: The NECC's depth-mean eastward currents from 28–200 m are maximum near Merir Island. The NECC extends from 3–5.5°N. Black lines are isobaths at 0, 500, and 1000 m.

obtain better horizontal resolution, a zonal tow along 4.4°N across the survey area was made at depths of 100–200 m. Reduced shear is obtained as $S_r^2 = S^2 - 4N^2$, where $S^2 = (\partial_z u)^2 + (\partial_z v)^2$ and N is the buoyancy frequency. Regions of positive reduced shear may be susceptible to shear instability and turbulence. Such regions are found in the north of our survey area where lee wave amplitudes may be larger and in the island/ridge wake (Fig. 10). Similar wake effects have been well studied (Chang et al., 2013, and references therein).

5 Future directions

While internal tides have energy conversion rates of $\mathcal{O}$(100 mW m^{-2}) in the western Pacific, little energy is lost from the barotropic tide in the vicinity of Palau (Egbert and Ray, 2003). However, geostrophic flow over the abrupt topography may input $\mathcal{O}$(0.1–100 mW m^{-2}) into lee waves in a patchy pattern below 10°N in the waters of Palau and the Federated States of Micronesia according to estimates by Nikurashin and Ferrari (2013). The lee wave energy estimates are based on modelled geostrophic flow and Smith-Sandwell bathymetry, which may underestimate the roughness on the scales of rough topography in the western Pacific (Smith and Sandwell, 1997). Further analysis of this cruise's data may help with understanding how relevant lee wave generation and propagation are in this region of rough topography (i.e. tall, isolated seamounts and ridges that extend into the thermocline). Lee wave effects may be quite important locally, but not resolved or visible on a global map.

Substantial differences in the boundary currents near the main islands of Palau and NECC flow by Helen Reef and Merir Island were noted between the 2013 and 2014 cruises. While some

Figure 7: A line of sheared current (indicated by white arrows) is visible, where the NECC is forced over a submarine ridge. Water depth at this time was >500 m, not much less than the ship's distance from the island. Similar straight, north-south lines extending for kilometres were also seen further downstream of the island, which suggest the presence of lee waves.

similarities are noted with geostrophic flow from altimetric SSH anomalies on both cruises, there are also considerable differences. Combining these data in state estimates by Bruce Cornuelle (SIO) is a necessary step. Measurements from the 2013 and 2014 cruises complement sustained observations from a coastal instrument array (Eric Terrill, SIO) and glider lines around Palau (Dan Rudnick, SIO) which can provide descriptions of temporal variability.

Acknowledgements

Capt. Murline and the crew of R/V *Revelle* helped us accomplish all our goals on an enjoyable and productive cruise. Carl Mattson, Rob Palomares, and Drew Cole (SIO STS) prepared the SeaSoar and provided technical and engineering support.

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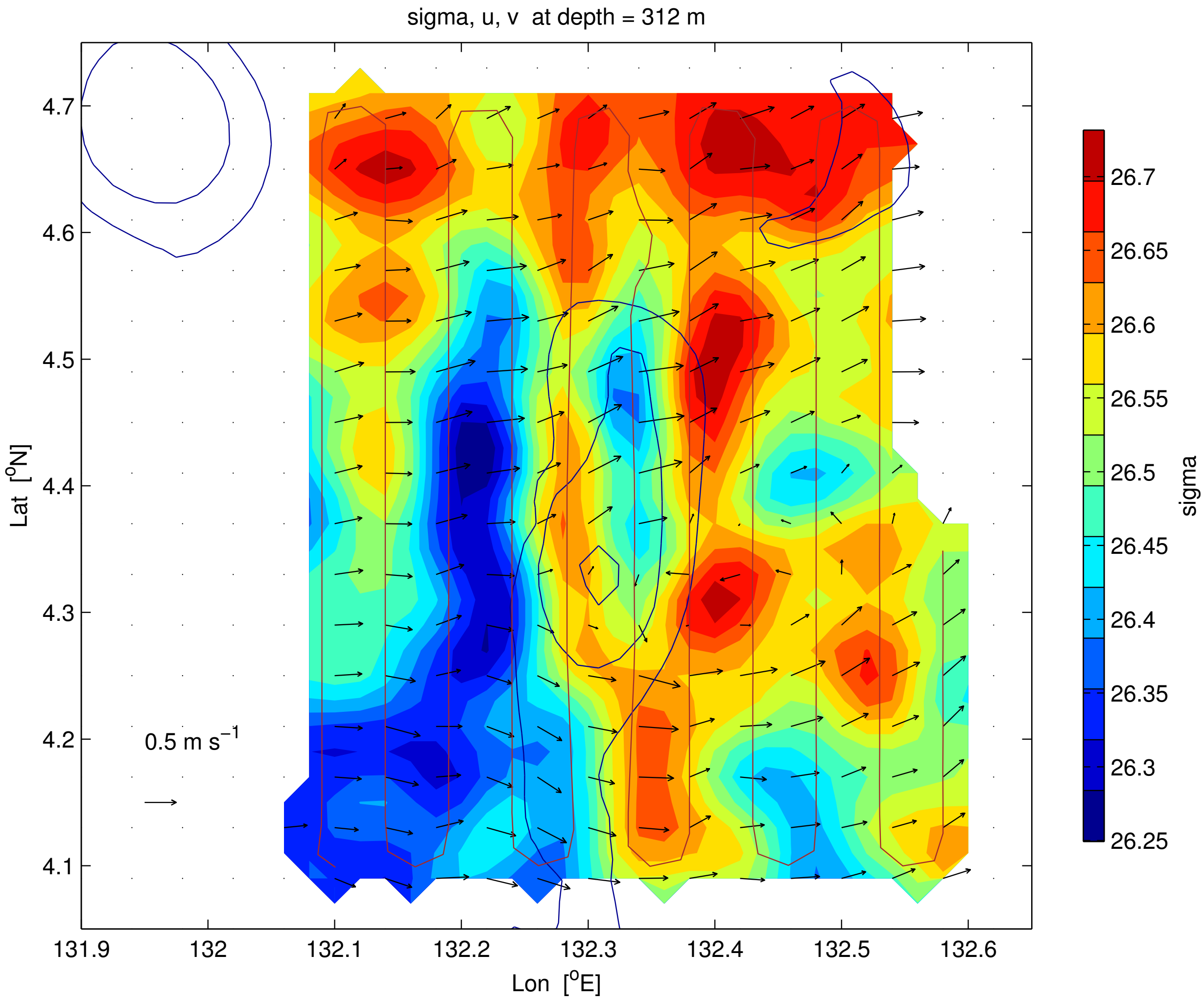

Figure 8: From survey 2 around Merir, an objective map at a depth of 312 m of potential density (σ_θ in kg m^{-3}, coloured shading) and currents (black vectors) shows crests and troughs of lee waves, which are oriented meridionally. The cruise track (brown line) parallels the north-south submarine ridge (bathymetry shown as blue lines: 0, 1000, and 2000 m) in the centre of the survey. Merir Island is at 4.3°N, 132.3°E.

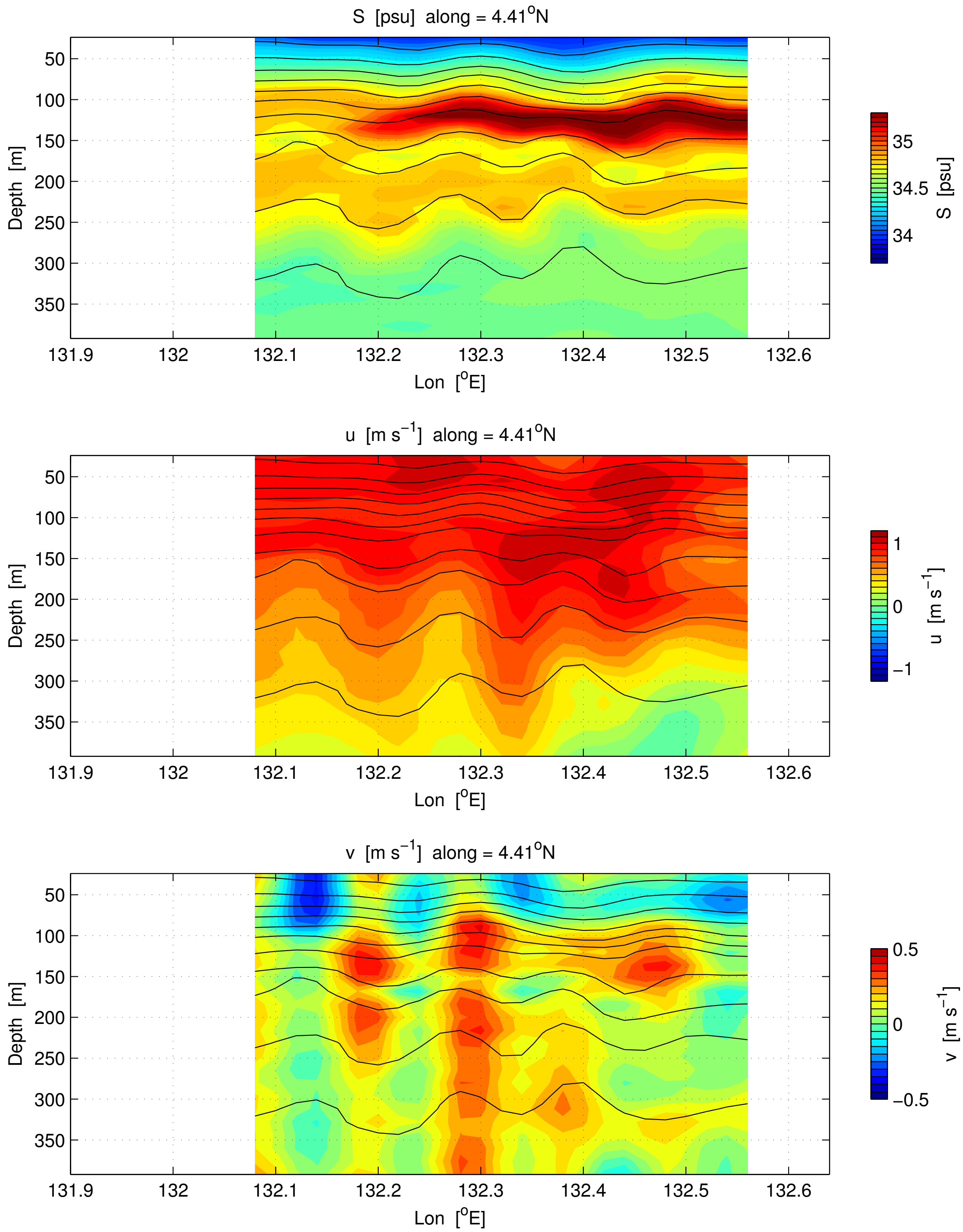

Figure 9: From survey 2 around Merir, a vertical slice along 4.41°N (see Fig. 8) displays upward and westward wave propagation particularly evident in σ_θ (black contours at 0.5 kg m^{-3} intervals). The ridge is near 132.3 °E. **Top:** S (coloured shading) displays two subsurface maxima, **Middle:** u is dominantly eastward with speeds of 1 m s^{-1}. **Bottom:** v has convergences in the upper 100 m exceed 0.5 m s^{-1} over 10 km or 0.1°, roughly the wavelength of the lee waves.

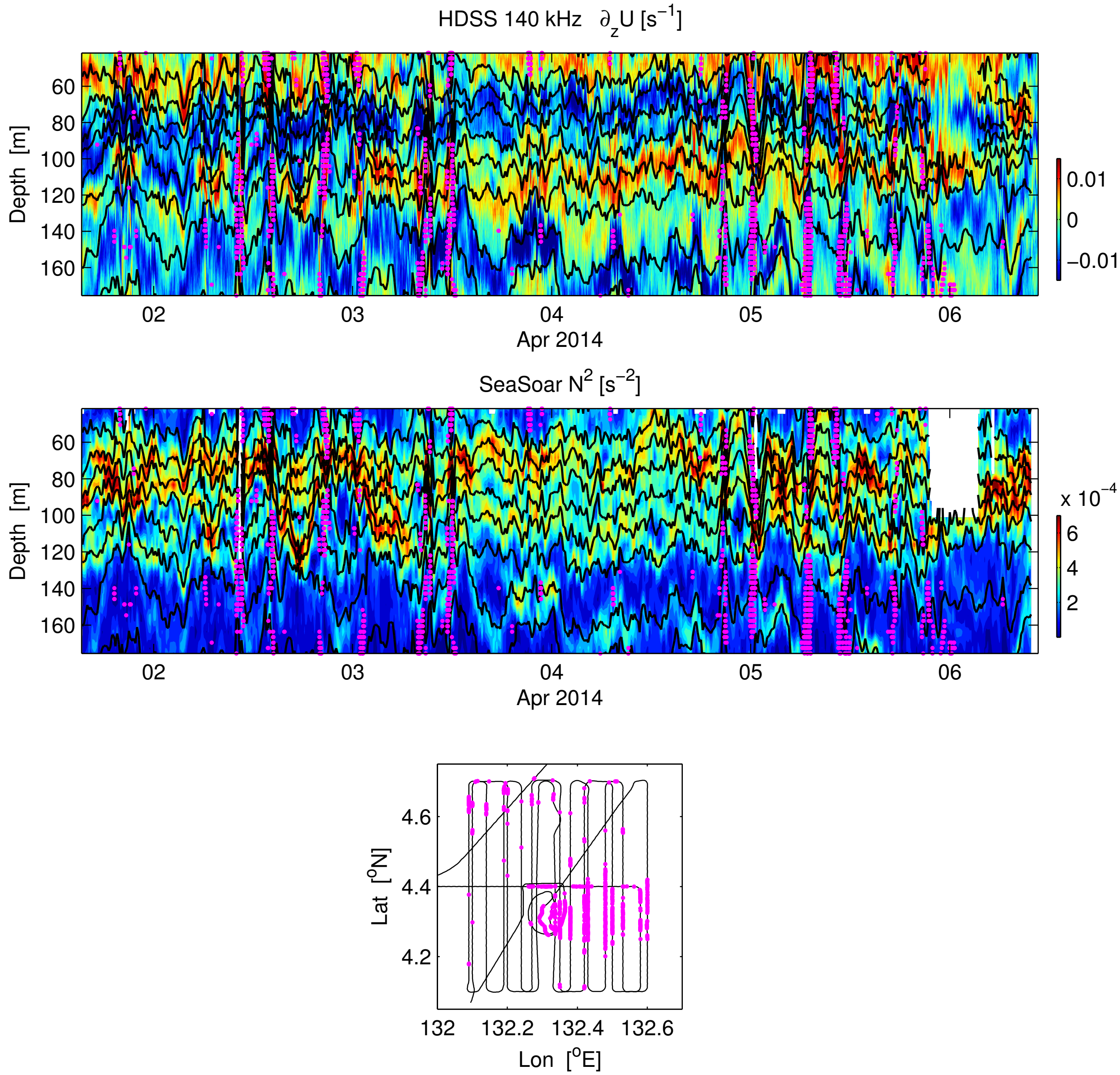

Figure 10: **Bottom:** During the surveys around Merir Island, regions where reduced shear is positive may develop shear instability (magenta dots). The island/ridge wake and the northern survey area show concentrations of positive reduced shear. Merir Island is at 4.3°N, 132.3°E. **Top:** Eastward shear from the HDSS 140 kHz in colour with isopycnals (black) in 0.5 kg m^{-3} intervals. **Middle:** Buoyancy frequency squared in colour with isopycnals.

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Appendix A Personnel

The personnel on the cruise included graduate students from Scripps, UCSD, and CICESE, who stood watches during SeaSoar operations. Technical and engineering personnel from SIO STS prepared SeaSoar and provided help with operations. Also two NAVMAR personnel deployed weather balloons.

Name	**Position**	**Affiliation**
Shaun Johnston	chief scientist	SIO
Lyndsay Bloom	graduate student	UCSD
Meredith Epp	graduate student	SIO
Esther Rodriguez	graduate student	CICESE
Laura Russell	volunteer	SIO
Bianca Soria	graduate student	CICESE
Drew Cole	research technician	SIO STS
Carl Mattson	development engineer	SIO STS
Rob Palomares	senior electronics technician	SIO STS
Stuart Hamilton	technician	NAVMAR
Brandon Treat	technician	NAVMAR

Table 1: Personnel on the cruise.

Appendix B Schedule

The cruise was from 17 Mar to 11 Apr 2014 and some events are noted in local time.

Date	Event
17 Mar	depart Kaohsiung, Taiwan
19 Mar	reach international waters begin weather balloon launches
21 Mar	deploy SeaSoar - leg 1 reach Palau EEZ - main islands - survey 1
28 Mar	recover SeaSoar deploy anchor at Hydrographer Bank deploy SeaSoar - leg 2
29 Mar	transit southward to Helen Reef
30 Mar	arrive Helen Reef - shortened survey
1 Apr	recover SeaSoar deliver water and supplies to rangers at Helen Reef deploy SeaSoar - leg 3
2 Apr	arrive Merir Island - survey 1
4 Apr	Merir - survey 2
6 Apr	tow along 4° 24’N at 100–200 m - survey 3 transit northward to main islands
7 Apr	arrive main islands - survey 2
11 Apr	recover SeaSoar arrive Malakal Harbor, Palau