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Flow Encountering Abrupt Topography

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LONG-TERM GOALS

To understand oceanic flow around islands and to better predict them using basin-scale observations.

OBJECTIVES

To obtain spatial surveys of currents and hydrography around a large (with respect to the Rossby radius) island in the North Equatorial Current (NEC) and small islands in the North Equatorial Countercurrent (NECC).

APPROACH

One cruise was completed in June–July 2013. The scientific goal of this cruise was to observe major low-latitude zonal current systems in the western Pacific and their encounters with topography. While steaming at 10 knots, a spatial survey of currents, temperature, and salinity were obtained from R/V *Revelle*'s Doppler sonars and an Underway CTD (UCTD, details below). Multibeam bathymetry was collected with coverage of the slope and abyssal areas adjacent to Palau. This survey covered much of the area near the main islands (from 6.5–8.5°N) as well as smaller islands to the south (2.5–5.5°N). The cruise comprised (Figures 1–2): bathymetry and current surveys circumnavigating the main islands; transects to the minor islands with multibeam bathymetry, currents from the ship's Doppler sonars, and hydrographic data from the UCTD; similar surveys around the minor islands (2 or 3 laps around each island); and similar surveys made in a cross-shore direction from the main islands.

Another cruise for March 2014 is planned on *Revelle* with SeaSoar, a towed vehicle which can obtain high-resolution CTD data similar to the UCTD data described here.

From these data, it appears the westward NEC impinges on the main islands of Palau and diverts around the south and north ends of the island group (Figure 1, left and right; Section). At Helen Reef and Toby Island (both near 3°S), the eastward NECC deflects around the topography may drive upwelling on the upstream side and accelerate over the flanks as in a Venturi (Figure 1, middle).

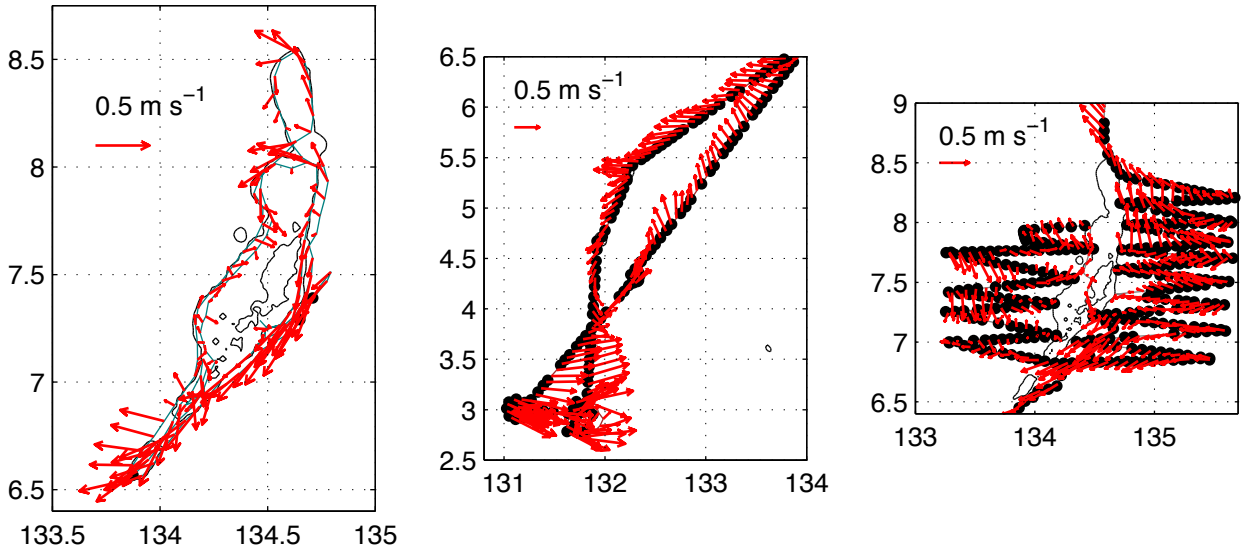

Figure 1: **Left:** ***Two circumnavigations of the main islands were made to obtain bathymetry over the slope and nearshore currents, which form a southward western boundary current and a weaker northward one. Red vectors denote mean currents from 28–125 m from the OS75 ADCP.*** **Middle:** ***The southern lines and around island surveys obtained currents, hydrography, and bathymetry.*** **Right:** ***The cross-shore surveys focussed on the current and density structure of major zonal currents encountering the main islands. Black circles denote ∼500 UCTD profiles to 500 m.***

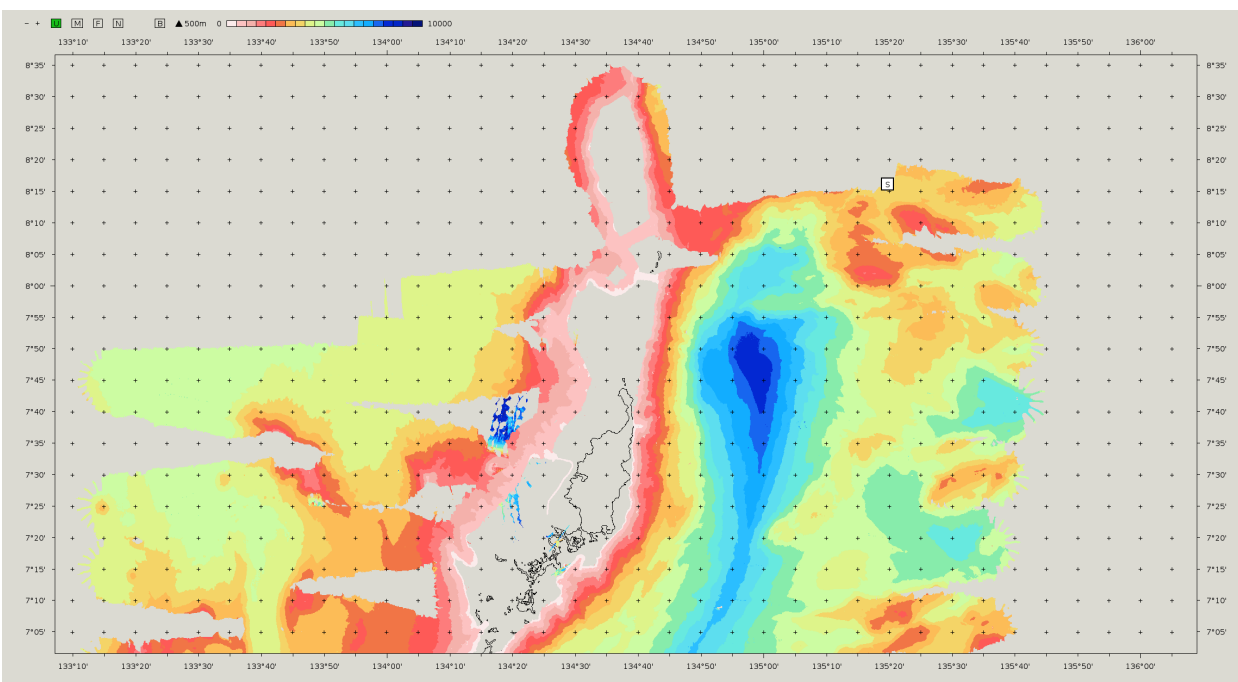

Figure 2: A portion of the bathymetry survey from around the main islands from a combination of two circumnavigations and a number of cross-shore lines. This map was produced by the Hawaii Mapping Research Group's Mosaic system. The small "s" in a white box denotes the ship's position at the time the image was made on 14 July just prior to the northern leg of the survey and the transit to Guam.

The UCTD was loaned by Oceanscience and is a compact, research-quality CTD with Seabird temperature (T) and conductivity sensors, which can be deployed every <30 minutes from a ship at 10 knots to depths exceeding 500 m. Further details are found in Rudnick and Klinke (2007). About 500 profiles with an RMS spacing of ∼10 km were obtained during the cruise. Preliminary averaging has taken place for plotting purposes, but no effort has yet been made to remove salinity (S) spikes due to any lag or thermal mass effects.

The ship's EM122 multibeam system obtained reliable bathymetry and backscatter signal (perhaps useful to assess the type of substrate) for depths below 500 m. Shallower data were obtained but will need further scrutiny since this system is intended for deep waters.

Doppler sonars included the Hydrographic Doppler Sonar System (HDSS) with 50 and 140 kHz systems for profiling to ∼700 and 200 m as well as an RDI Ocean Surveyor (OS) 75 kHz ADCP and an older, narrowband 150 kHz ADCP. The OS75 was operated in narrowband mode only to provide better statistics over the depth range of UCTD profiles.

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 1 m.

WORK COMPLETED

Bathymetry

The initial focus of the multibeam survey was on obtaining data over the slope, which is of considerable interest to the government and local scientists for habitat mapping and planning further research. Essentially two circumnavigations of the main islands were made. Since the slopes are very steep, mapping close to the reef fringe was done during daylight hours. At each of the southern islands, two or three circumnavigations of each were done for bathymetry mapping. During the cross-shore surveys, additional deep water bathymetry was obtained with a majority of the area around the main islands mapped from the 500-m isobath to ∼100 km offshore (Figure 2). This work is done in conjunction with Palau-based scientists (Pat Colin at the Coral Reef Research Foundation and Paul Collins, who has extensive experience with such data).

Helen Reef

Concerted UCTD measurements began on this southern leg in addition to the ongoing current and bathymetric measurements. In addition, humanitarian assistance was rendered by *Revelle* to the inhabitants of Helen Reef at the request of the governments of Palau and Hatohobei State.

The current and T-S data suggest the incident eastward flow splits upon encountering Helen Reef and Hatohobei Island (Figure 3). An objective map shows the density at a depth of 78 m shows denser water on the upstream/west side and lighter water on the downstream/east sides of the two islands (Figure 4). Shoaling isopycnals on the upstream side suggest current-driven up-/downwelling is occurring above/below 200 m. Stagnation points are found on the west and east sides of Helen Reef. Flow appears to be constricted and intensified on the north and south sides, where isopycnals squeeze together (Figures 3–4). This situation suggests a Venturi effect (i.e., flow constriction leads to faster flow and lower dynamic pressure) and the possibility of applying the Bernoulli equation. At deeper depths near 350 m at Helen Reef, northward flow of relatively salty water is seen. This salty water may serve as a tracer and may indicate similar flow constriction and acceleration at 350 m. With 2 or 3

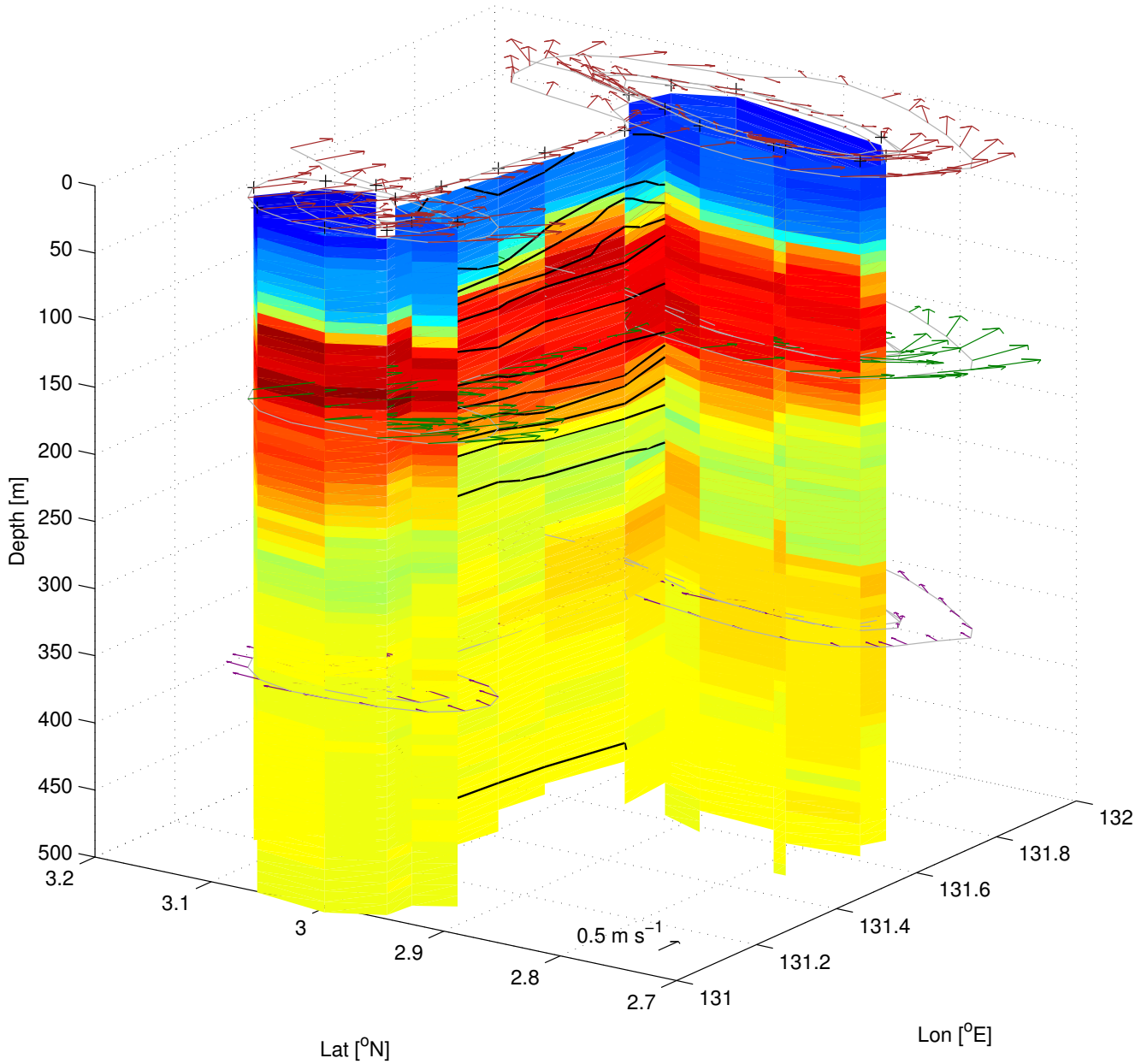

Figure 3: Two circular patterns of UCTD salinity profiles around Hatohobei Island (left) and Helen Reef (right) use a portion of the data to show a widening of the S maximum on the upstream side of the two islands and a constriction over the flanks. Vectors denote mean currents from the OS75 over three levels: 28–100, 100–200, and 300–400 m. Isopycnals (black lines) are plotted on the transect between islands at 0.5 kg m^{-3} intervals. Similar results are seen for eastward/northward flows and the S maxima near 150/350 m especially at Helen Reef. Black plus signs at the surface denote UCTD casts.

circumnavigations of the atoll it may be possible to make mixing estimates from the salinity distribution. Similar results are found at Hatohobei Island, but perhaps the effects are smaller due to the smaller extent of the island across the flow. Note only some of the UCTD data are plotted in Figure 3.

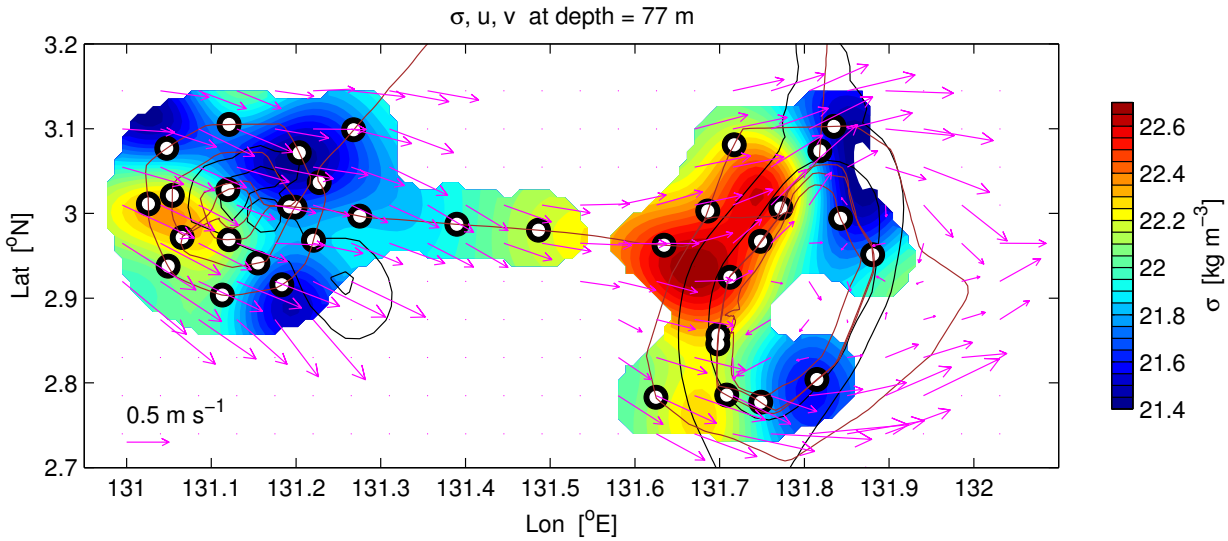

Figure 4: Two sets of UCTD/current surveys around Hatohobei Island (left) and Helen Reef (right) show σ_θ maxima on the upstream side of the two islands and minima over the flanks before returning to undisturbed levels downstream. Data are objectively mapped using a Gaussian length scale of 10 km and a noise-to-signal ratio of 0.1. Smith-Sandwell bathymetry at 500 m and 1000 m (black lines) are plotted. However, multibeam bathymetry shows all UCTD profiles (dots) were in water deeper than 600 m. Brown lines denote cruise tracks.

Helen Reef comprises a large atoll and a small island which is essentially a sand bar and only a few feet above sea level. The island is experiencing eastward motion across the reef: roughly 100 m in 20 years. This movement appears consistent with the eastward direction of the NECC and the principal direction of waves breaking on the reef.

Two scientists (Johnston and Travis Schramek- graduate student with Eric Terrill, SIO) went ashore to set up a meteorological station as part of network of stations in Palau maintained by Terrill. Also a GPS survey of the low tide line and the vegetation line of the island were made by Johnston and Brandon Patris, a citizen of Hatohobei State. This is only the second such survey. The intention is for the Palauans to do further surveys whenever the island is visited to document the island's motion.

Schramek and Kasia Zaba (graduate student on a project with Dan Rudnick and Johnston at SIO) prepared 6 simple moorings (T sensors, weights, 45 m of line, and a float) which were arrayed around Helen Reef nominally on the 90-m isobath using *Revelle*'s workboat. Colin (CRRF) will return in 2 years to retrieve the T loggers.

Currents and hydrography

Palau is located across a sea level ridge (7–11°N, 135°E) which extends across most of the Pacific (Figure 5). These sea surface height anomalies suggest that basin-scale observations may be useful in predicting regional currents. Eastward NECC flow between the sea level ridge and trough (3–5°N, 133°E) is found in the ship-based current measurements (Figures 1 and 6). Analysis of our ship-based

observations extending over the region in the context of basin-scale altimetry and wind products is warranted.

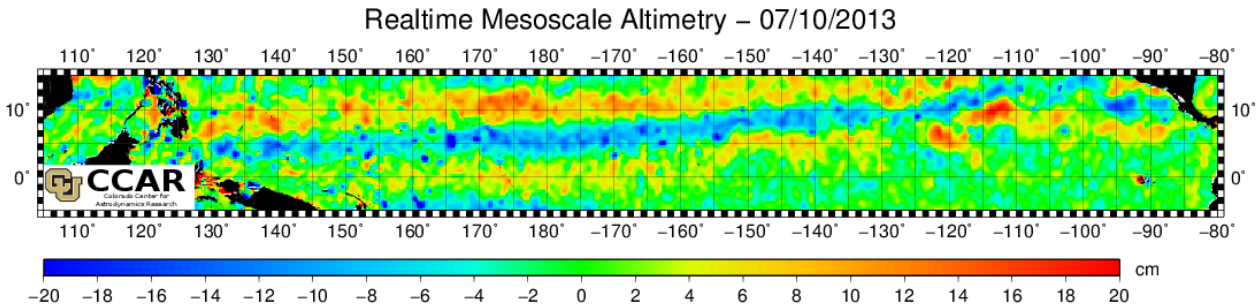

Figure 5: A sea level ridge near the main islands of Palau and a sea level tough further to the south near Helen Reef from altimetry data for 10 July 2013 extend across the entire Pacific. Figure downloaded from http://eddy.colorado.edu/ccar/ssh/nrt_global_grid_viewer.

Westward NEC flow incident on the coast of Palau near 7.5°N appears consistent with the sea level ridge (Figure 6). The NEC flow splits into a northward and southward, coastal intensified currents (Figure 6). These stronger currents are especially evident in Figure 1 in the left panel where the ship surveyed within 1-2 miles of the reef crest. Lastly, strong flows go through the deep gaps to the north and south of the fringing reef (Figure 6). Some suggestions of an anticyclonic/cyclonic eddy are found to the west of the main islands in the south/north (Figure 6).

RESULTS

Only preliminary analysis of the data has been done at this point. The main features are NEC flow around Palau with a possible strong southward western boundary current near the main islands, eddies in the lee of the main islands, and accelerated flow over the flanks of the the smaller , southern islands. Some possible avenues for further investigation include: (a) relating the NEC and NECC flow near Palau to basin-scale sea level and winds, (b) explaining the partition of incident westward flow into northward and southward currents, (c) interpreting the flow around Helen Reef and Hatohobei Island in terms of the Bernoulli equation (Gove et al., 2006, and references therein), and (d) examining mixing indicators such as Thorpe scale or reduced shear around Helen Reef. Gradients in sea level from tide gauges maintained by the University of Hawaii Sea Level Center may also be helpful in placing the observed currents in the context of basin-scale fluctuations of geostrophic currents (Johnston and Merrifield, 2000).

Existing glider observations by Rudnick (SIO) during the OKMC DRI may be useful for assessing the variability of the flow patterns observed on this cruise around the main islands of Palau. Also two gliders have made repeated lines near the passages north and south of the main islands of Palau.

A cruise with SeaSoar in March 2014 is planned. Closer examination of the incident NEC flow on the main islands and NECC flow on Helen Reef will be made. After a dense spatial survey with SeaSoar, some time series with the ship's CTD could be done on the slopes of Helen Reef- on the flanks as well as upstream and downstream.

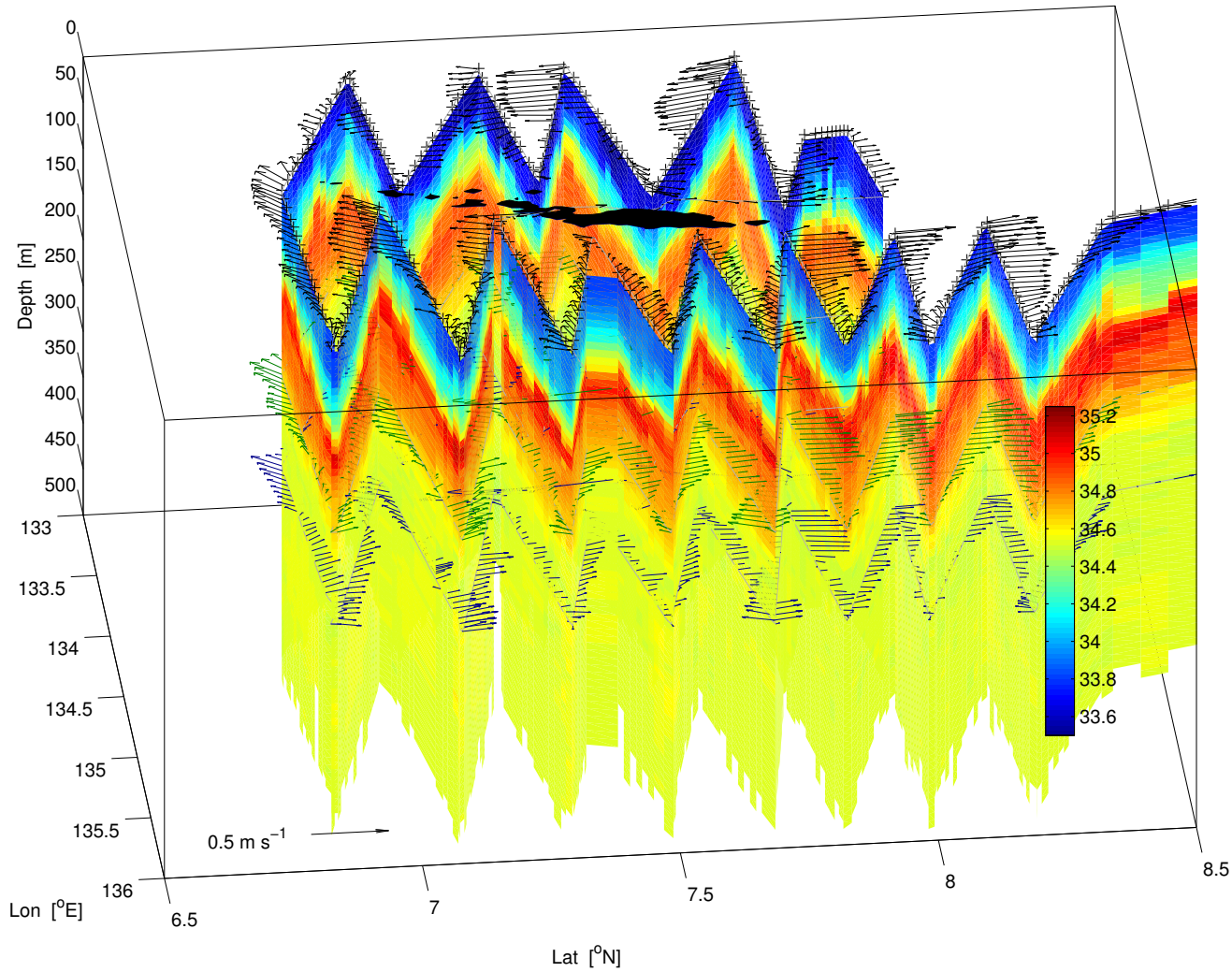

Figure 6: A 3D view of the salinity (colours) and currents (vectors from OS75) during the cross-shore surveys around the main islands of Palau (black shading). At 100 km distance to the east of Palau, flow is roughly westward. Closer to the coast the flow diverts northward and southward with a stagnation point near 7.5°N (also in Figure 1). Black plus signs at the surface denote UCTD casts.

IMPACT/APPLICATIONS

These data will be useful for assessing state estimates of the tropical Pacific produced by Bruce Cornuelle (SIO) using data obtained upstream of the islands in this study.

RELATED PROJECTS

During the Origins of the Kuroshio and Mindanao Currents DRI, gliders have repeated westward and northward sections from Palau on many occasions. Data from that study will be used to assess variability of the currents and complements the spatial survey done here.

Large internal waves have been previously reported near Palau (Wolanski et al., 2004) and are a

common feature near steep topography (e.g. Johnston et al., 2013, and references therein). The Internal Waves In Straits Experiment is related to this topic and has its own annual report. Also the NSF-funded Tasmanian Tidal Dissipation Experiment (TTIDE) with many IWISE PIs (Pinkel, Alford, Johnston, MacKinnon, Nash, Rainville, Rudnick, and Simmons) is investigating dissipation of an incident low-mode internal tide impinging on the steep continental slope of Tasmania. Preliminary results from one glider's spatial survey over $\sim$4 months shows a region of elevated tidal amplitudes and stable phase, which bears resemblance to preliminary model results. An analysis of incident and reflected waves, shows a stronger incident wave and weaker reflected one, which implies wave transmission onto the shelf and/or dissipation on the shelf.

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