Flow encountering abrupt topography

Cruise report, R/V Revelle, 29 June to 17 July 2013

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1 Overview

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, Section 2). Multibeam bathymetry was collected with coverage of the slope and abyssal areas adjacent to Palau (Section 3). 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.



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 \sim 500 UCTD profiles to 500 m.

From these data, it appears the westward North Equatorial Current (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 5). At Helen Reef and Toby Island (both near 3°S), the eastward North Equatorial Countercurrent (NECC) deflects around the topography may drive upwelling on the upstream side and accelerate over the flanks as in a Venturi (Figure 1, middle; Section 4).



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.

With little impact on the scientific work, we were able to provide logistical assistance to Governor Thomas Patris of Hatohobei State in the transport of conservation officers and supplies to Helen Reef and Toby Island. Resupply missions to these islands are usually accomplished sporadically due to the small number of inhabitants and the distance from the main island group. Furthermore, R/V *Revelle* offered humanitarian assistance to some residents of Helen Reef. The wife of one of the conservation officers and their three young children had been left without transportation for over a month due to cancelled resupply missions and none in the foreseeable future. With permission from the US Coast Guard and the US Office of Naval Research, *Revelle* was able to transport the family to the main islands. The efforts of Dr Bruce Appelgate, Captain Tom Desjardins, and the crew of *Revelle* in helping the family are greatly appreciated not only by the stranded family, but also Palau's national and Hatohobei State governments. By providing multibeam and other data, helping with logistics, rendering humanitarian assistance, and hosting tours of the ship for former and current government officials, considerable goodwill in Palau has been generated for ONR and Scripps.

2 Methods

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.

3 Multibeam survey

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 \sim 100 km offshore (Figure 2).

Two Palau-based scientists (Pat Colin, director of the Coral Reef Research Foundation- CRRFand Paul Collins, who has experience with multibeam and GIS data) were onboard for the multibeam mapping portion of the cruise and will process and distribute preliminary data to interested parties in Palau. Mekeruul Ueki, a representative from the government's PALARIS agency (Palau Automated Real-time Information System), participated in this portion of the cruise and took some preliminary data with him on behalf of PALARIS. The Palau-based scientists and PALARIS officials were delighted with the bathymetric survey.

4 Helen Reef

For the southern leg of the cruise, another group including Gov. Patris and several conservation officers boarded the ship for the leg to Helen Reef. As noted in Section 1, supplies for the personnel at Helen Reef and Hatohobei Island were also transported by *Revelle* at the request of Gov. Patris. Humanitarian assistance was provided to the stranded family members of one of the conservation officers (Section 1). Concerted UCTD measurements began on this leg in addition to the ongoing current and bathymetric measurements.



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.

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 3–5). 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 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 these figures.



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 Schramek) went ashore to set up a meteorological station as part of network of stations in Palau maintained by Eric Terrill (SIO). 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. 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 (a graduate student with Terrill) and Zaba (graduate student with 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.

5 Currents and hydrography

Palau is located across a sea level ridge (7–11°N, 135°E) which extends across most of the Pacific (Figures 6–7). 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 8). Analysis of our ship-based observations extending over the region in the context of basin-scale altimetry and wind products is warranted.

Westward NEC flow incident on the coast of Palau near 7.5°N appears consistent with the sea level ridge (Figure 8). The NEC flow splits into a northward and southward, coastal intensified cur-



Figure 5: The 3D picture (Figure 3) is unwrapped in sections going around the north (upper) and south (lower) sides of the two islands. Coloured dots (middle) denote positions of UCTD profiles in the upper and lower panels encircling Hatohobei Island (\sim 131.1°E) and Helen Reef (\sim 131.8°E). Isopycnals (black lines) are plotted at 0.5 kg m⁻³ intervals.

rents (Figure 8). 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 8). Some suggestions of an anticyclonic/cyclonic eddy are found to the west of the main islands in the south/north (Figure 8).

The depth-time record of currents and shear from the HDSS again shows another view of the circulation near Helen Reef and the main islands. Westward flow in the NEC was seen near the main islands (Jul 2–3 and 6–8) and during the cross-shore surveys on the east side of Palau (Jul



Figure 6: The sea surface height anomaly in the region around Palau from altimetry data for 10 July 2013 shows a sea level ridge near the main islands of Palau and a sea level tough further to the south near Helen Reef. Figure downloaded from http://eddy.colorado.edu/ccar/ssh/nrt_global_grid_viewer.



Figure 7: The sea level ridge and trough seen in the region around Palau (Figure 6) 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.



Figure 8: A 3D view of the salinity (colours) and currents (vectors from OS75) during the crossshore 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.

11–14) in Figure 9a. Eastward flow (U > 0) in the NECC near Helen Reef (Jul 3–5) in Figure 9b. Coherent patterns in one component of vertical shear (U_z) are found near Helen Reef (Jul 3–5) and the cross-shore surveys on the east side of Palau (Jul 11–14). Regions of possible mixing, where the reduced shear is $U_z^2 + V_z^2 - 4N^2 > 0$, are denoted with magenta dots and are clustered around Helen Reef. These regions of positive reduced shear appear to surround a current maximum near 150 m coincident with the S maximum in Figure 3.



Figure 9: Top: Zonal flow (U) from the 140 kHz HDSS is positive eastward and shows the NEC and NECC. Bottom: One component of vertical shear (U_z) has coherent features near Helen Reef and the main islands. Isopycnals (black lines) are plotted at 1 kg m⁻³ intervals. Magenta dots denote regions where reduced shear is positive and mixing is possible. Short black lines on the top axes denote UCTD casts.

6 Future work and analysis plans

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 Hato-hobei 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) may be useful for assessing the variability of the flow patterns observed on this cruise around the main islands of Palau. Also one glider had \sim 20 days of remaining battery life at the time of this cruise and is repeating a line between Peliliu and Angaur Islands to help with the scientific goals of this cruise.

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.

Acknowledgements

Capt. Desjardins and the crew of R/V *Revelle* helped us accomplish all our goals on an enjoyable and productive cruise. Oceanscience generously loaned a UCTD system for this cruise on short notice and Jochen Klinke from Oceanscience trained the science party in UCTD use. Woody Sutherland and Bud Hale (SIO SOMTS) provided able technical assistance as needed. Pat Colin (CRRF) helped with logistics for this cruise and provided interesting scientific insights.

References

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Appendix A Personnel

The personnel on the cruise included scientists from US institutions and Palau-based scientists, an engineer who trained the science party in the use of the UCTD, observers from the Palau national and Hatohobei state governments, conservation officers who were transported to Helen Reef, other observers from Hatohobei state, and a mother and her three young children who were transported from Helen Reef to Koror.

Name	Position	Affiliation
Shaun Johnston	chief scientist	SIO
Anna Merrifield	graduate student	SIO
Travis Schramek	graduate student	SIO
Sarah Shackleton	graduate student	SIO
Katherine Zaba	graduate student	SIO
Stephanie Nebel	graduate student	U Delaware
Marissa Van Hoeven	graduate student	U Delaware
Pat Colin	scientist	director, CRRF
Paul Collins	scientist	consultant
Jochen Klinke	engineer	Oceanscience
Mekeruul Ueki	observer	PALARIS
Thomas Patris	observer	governor, Hatohobei State
Hercules Emilio	observer	conservation officer, Hatohobei State
Frano Eusobio	observer	conservation officer, Hatohobei State
Max Imbir	observer	conservation officer, Hatohobei State
Petra Tkel	observer	conservation officer, Hatohobei State
Brandon Patris	observer	resident, Hatohobei State
Hanna Muegge	observer	volunteer, Hatohobei State
Grace Sabadoquia	mother	resident, Hatohobei State
Dean Juanito	son	resident, Hatohobei State
Katrina Juanito	daughter	resident, Hatohobei State
Abigail Juanito	daughter	resident, Hatohobei State

Table 1: Personnel on the cruise.

Appendix B Schedule

The cruise was from 29 June to 17 July 2013 and some events are noted.

Date	Event		
28 Jun	tour of <i>Revelle</i> for former Palau government officials		
29 Jun	depart Malakal Harbor		
	begin multibeam and current surveys		
2 Jul	Colin, Collins, & Klinke depart via small boat		
	local observers and others arrive via small boat		
	continue multibeam and current surveys		
	begin UCTD work		
3 Jul	arrive Sonsorol and Pulowana Islands		
4 Jul	arrive Helen Reef		
	transfer supplies		
	establish met station		
	GPS survey of island		
	some conservation officers depart		
	mother and children arrive		
	deploy thermistors		
5 Jul	arrive Hatohobei Island		
	transfer supplies		
6 Jul	arrive Merir Island		
7 Jul	transfer observers to Koror via small boat		
	begin cross-shore survey southward on the east coast		
8 Jul	continue cross-shore survey northward on the west coast		
11 Jul	arrive Malakal Harbor		
	tour of <i>Revelle</i> for PALARIS officials		
	clear out of Palau		
	continue cross-shore survey northward on the east coast		
14 Jul	begin survey along ridge extending north of Palau		
	complete UCTD operations		
	comparison cast to 600 m with ship's CTD		
	begin transit for Guam		
17 Jul	arrive Guam		

Table 2: Cruise events.