Current observations on and around a deep-ocean island/reef: northern Palau and Velasco Reef

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Abstract

Current and hydrographic measurements were made in the equatorial Pacific Ocean between the westward-flowing North Equatorial Current and the eastward-flowing North Equatorial Counter Current. Nine moorings containing current profilers and hydrographic sensors were deployed on and around Velasco Reef, just north of Palau Island, from May 2016 to March 2017, when the Pacific Ocean was relaxing after the 2015/16 El Niño. Currents and their interactions with this abrupt bathymetric feature are characterized on spatial scales of 10–30 km, and frequencies from semidiurnal to intraseasonal. Currents near the reef displayed a two-layer structure and were not stationary due to the shifting of the major currents and eddy passages. Energy was significant at tidal and inertial periods, and at periods longer than ten days. Tides and higher frequency currents were responsible for about half the energy on the reef but for only about 20% of the energy in the deep water. Cyclonic (anticyclonic) vorticity occurred on the western (eastern) side of the reef during westward (eastward) flows, indicating recirculation on the leeward side of the reef. Vorticity west of the reef was much stronger than vorticity on the east side. When the cyclonic vorticity was large, the divergence flow patterns supported strong upwelling in the upper layer. Differences in both vertical and horizontal velocity coherences and correlations between moorings indicated that the reef affected the currents. The reef seemed to significantly impact water exchange. Currents near the reef are difficult to be described, particularly at depth by satellite products, making their prediction problematic.

Keywords Currents · Velasco Reef · Palau · Vorticity · Tides · Hydrography · Salinity · El Niño · Intraseasonal · Wavelet · EOF

1 Introduction

There are many islands and groups of islands in the central to western equatorial Pacific Ocean (e.g., Johnston Atoll, Hawaiian island chain, Wake Island, Marshall Island, Federated States of Micronesia, Palau, and Guam) that are situated along the paths of major equatorial current systems. There have been few observational studies near these islands (e.g., Barkley 1972) and the circulation is predicted only from large-scale ocean models (Gopalakrishnan and Cornuelle 2019 and Simmons et al. 2019, for example). The deeper currents and current interactions with ocean ridges and island archipelagos are believed to be not well-represented by large-scale ocean models partly due to lack of representation of subgrid scale processes.

Palau is an island chain of about 200 volcanic islands located in the western Pacific Ocean at a latitude of about 7.5° N, about 650 km southeast of the Philippines (Fig. 1a). Collectively, Palau has a footprint of about 466 km². The topography ranges from mountains to low coral islands that are surrounded by large barrier reefs. Velasco Reef is about 65 km north of the islands of Palau (Fig. 1a, b). The surrounding seafloor, over 4000-m deep, rises abruptly to depths approaching 10 m at the outer edges of the reef. The reef is oval in shape, and is oriented north–south, about 30 km by 15 km in size. The reef is located in an area of active and diverse ocean currents. Heron et al. (2006) provided an early depiction of the surface circulation near Palau using in situ and model data and found that the circulation is
influenced by major equatorial currents and eddies, and varies seasonally with the Asian monsoon. The reef is located near the Mindanao Eddy (Kashino et al. 2013). Its unique location lies between the westward flowing North Equatorial Current (NEC) and the eastward flowing North Equatorial Counter Current (NECC). The North Equatorial Undercurrent (NEUC) flows eastward beneath the NEC (Zhang et al. 2017; Qiu et al. 2013a, b). Using Argo Float data (Rom mich and Gilson 2009), zonal geostrophic velocities were computed between 130° E and 135° E and between 2° N and 30° N by Qiu et al. (2013a, b). They found the NEC between 7.5° N and 25° N and the NECC between 2.5° N and 7.5° N. Beneath the NEC, they also observed three eastward-flowing subsurface jets (NEUC) centered around 9° N, 13° N, and 2.5° N and 18° N. Using an eddy-resolving ocean model, Li et al. (2018) suggest that these NEUCs vary on interannual time scales. Ishizaki et al. (2019) found that the NEUCs vary on interdecadal time scales based on an analysis of a 48-year series of hydrographic observations.

North–south meandering of these currents can impact currents off Palau and the Velasco Reef. Interactions of the currents with Palau Island and associated ridges and reefs make the small-scale currents much more complicated. The westward-flowing NEC is divided into northward and southward branches, upon encountering the east side of Palau (https://coralreelfpalau.org/research/oceanographyweather/ocean-observations/). These branches, which then encounter the reefs located north and south of Palau, are also impacted by the NECC. As the currents flow between the islands and over the reefs, complicated flow patterns, including eddies and lee waves, are likely. The footprints of these islands and reefs are small, but their impacts on the circulation and current variability are large, and complicate modeling efforts. Geostrophic velocities computed from sea-surface-height anomalies from satellite altimetry data do not have the resolution to describe the effects of the island/reef/ridge on the current patterns, and are not adequate to adjust the models on small scales. Some coarse-resolution numerical simulations indicate that the inclusion of Palau Island does not make a significant change in regional-scale circulation (Gopalakrishnan and Cornuelle 2019). However, they recognize that the low-resolution (1/12° × 1/12°) model does not represent form drag around Palau due to lack of island wakes, lee waves and eddies. Simmons et al. (2019) numerically simulated the flow around Palau using the Regional Ocean Modeling System (ROMS), and noted that to capture the wake behind Palau requires a model resolution of 800 m or less. Apart from modeling challenges around Palau, we know little about the current variability in this region near the thermocline and below, due to the scarcity of direct long-term observations. Similarities and differences of the currents just west and east of Palau and the effects of the island/reef are not known.

To advance the understanding of flow disturbances around steep-sided islands in the western equatorial Pacific Ocean, an extensive observational and modeling study was conducted around Palau Island/Velasco Reef (Fig. 1a) as part of the Office of Naval Research’s Flow Encountering Abrupt Topography (FLEAT) program (Johnston et al. 2019). Variability of currents around Palau Island/Kyushu-Palau Ridge and their impact on the regional circulation through flow separation and eddy shedding are relatively unknown. A better understanding of the currents and vorticity around
Palau though from situ observations is necessary to improve predictions and modeling of circulation around this island/ridge region. The goal of the FLEAT research initiative is to determine the effects of topography on major current systems and their downstream structure. The Naval Research Laboratory (NRL) undertook an intensive measurements program as part of the FLEAT program. The main objectives are to understand and quantify the processes due to the impact of the reef on the current variability, vorticity generation, and recirculation around Palau Island/Velasco Reef. The study also focuses on a better understanding of the subthermocline currents and hydrographic variability, their relation to the surface currents, and their variability in the vicinity of the Kyushu-Palau Ridge.

With these objectives in mind, the NRL deployed 9 moorings, consisting of acoustic Doppler current profilers (ADCPs) and acoustic current meters on and around the Velasco Reef (Fig. 1b), from May 2016 through March 2017. Velocity profiles were measured in the upper 600 m of the water column at 5 deep-water moorings and profiles for nearly the full water column were measured at 4 moorings on the reef. Conductivity, temperature, and depth (CTD) measurements (Fig. 1a, b) were made during the deep-water moorings. Conductivity, temperature, and depth (CTD) measurements (Fig. 1a, b) were made during mooring deployment and recovery cruises, and during a middle cruise (November 25–December 08, 2016). In addition, shipboard ADCP transects and microstructure measurements (not discussed here), utilizing a vertical profiler, were conducted during the middle cruise (Wijesekera et al. 2020). Here, the concentration is on the effects of Velasco Reef on the currents. We focus mainly on a description of the currents around the reef, vorticity formation, intraseasonal variability, similarities and differences of currents west and east of the reef, the relationship of the subthermocline currents with the near-surface currents, and the current conditions during the recovery phase of the major 2015/2016 El Niño event, and return to normal ocean conditions. The 2015/16 El Niño was comparable in strength and dynamics to the major 1997/98 El Niño (L’Heureux et al. 2017; Jacox et al. 2016; Santoso et al. 2017; https://www.cpc.ncep.noaa.gov/).

The paper is structured as follows. Section 2 provides a brief description of the data and instrumentation along with background wind field. Temperature and salinity variability from CTDs is discussed in Sect. 3. A description of the currents using time, spectral, and wavelet domain analyses is given Sect. 4. Vorticity generated by multiple-time-scale currents (low-inertial, near-inertial, and tidal) is presented in Sect. 5. Empirical-orthogonal-function (EOF) analyses, including vertical and horizontal coherences of the low-frequency current variability around the reef/ridge, are presented in Sect. 6. In Sect. 7, we discuss our results in conjunction with modeling efforts, the significance of upwelling and downwelling associated with the vorticity patterns, as well as the impact of stronger currents observed during the El Niño transition period on vorticity generation and transports. Finally, a summary and conclusions are presented in Sect. 8.

2 Instrumentation and data

Five deep ADCP moorings for recording current profiles were deployed around the Velasco Reef (Fig. 1b) in May 2016. Two of the moorings (M1 and M3) were deployed west of the reef in the deep water (greater than 2600 m) and two moorings (M2 and M5) were deployed east of the reef at similar water depths. M4 was deployed north of the reef plateau between M3 and M5 at a depth of 1350 m. These deep moorings contained an upward-looking ADCP operating at 300 kHz (Teledyne RD Instruments Workhorse) and a downward-looking ADCP operating at 75 kHz (Teledyne RD Instruments Long Ranger), both ADCPs mounted within a 45-inch-diameter, Flotation Technology buoy, at water depths between 64 and 91 m. They contained Edge Tech acoustic releases for location and recovery. These moorings were designed to measure current velocities in the upper 600 m of the water column.

Three additional moorings were deployed in trawl-resistant bottom mounts near the top of the reef (B1–B3) on the bottom at water depths ranging from 53 to 135 m. These moorings utilized dome-shaped mounting pods, called Barnys because of their barnacle-like shape (Perkins et al. 2000), that are highly resistant to trawling. Each Barny was equipped with an upward-looking Workhorse ADCP, Sea-Bird Electronics Model 26 wave/tide gauges, and Edge Tech acoustic releases for location and recovery. The ADCP heads were approximately 0.5 m off the bottom. These B moorings required a recovery and redeployment in November 2016 due to power constraints. B1 and B2 were successfully recovered and redeployed but B3 was stuck on the bottom. An additional mooring, B4, was then deployed near the B3 position. All of the moorings were routinely recovered via acoustic release during April, 2017, except for B3 which was successfully recovered a few months later using a remotely-operated vehicle. The battery for B3 expired, as expected, before the final recovery. These B moorings measured near-full water-column current profiles on top of the reef. Bathymetry in the vicinity of Palau and Velasco Reef is shown in Fig. 1. Table 1 provides positions, measurement depths, measurement times, sampling intervals, water depths, and instrument types. In addition, the inertial periods (ranging from 80 to 84 h) at each mooring location are provided in Table 1.

Each deep mooring also contained a variety of sensors mounted along the wire beneath the ADCP buoy: 20 temperature (T) sensors, 2 temperature, pressure (TP) sensors, 3 temperature, conductivity (TC) sensors, and 3 temperature,
Table 1: ADCP mooring summary; 300-kHz ADCP is upward looking and 75-kHz Long Ranger ADCP is downward looking. RCM9 is an Aanderaa acoustic current meter.

| Site | Start date | End date | Decimal day | Lat °N | Lon °E | Depth m | Δt Min | Δz m | Zn m | Zl m | Type kHz | Tl h |
|------|------------|----------|-------------|-------|-------|---------|--------|------|------|------|---------|-----|
| M1   | 05-22-16   | 04-01-17 | 144–458     | 8.44  | 134.43| 2600    | 60     | 8    | 64   | 8    | 600     | 75  |
| M2   | 05-19-16   | 03-29-17 | 141–455     | 8.26  | 134.79| 2610    | 60     | 8    | 80   | 8    | 600     | 75  |
| M3   | 05-21-16   | 03-31-17 | 143–457     | 8.62  | 134.49| 2846    | 60     | 4    | 66   | 8    | 600     | 75  |
| M4   | 05-20-16   | 03-30-17 | 142–456     | 8.61  | 134.60| 1350    | 60     | 8    | 91   | 8    | 600     | 75  |
| M5   | 05-20-16   | 03-29-17 | 142–455     | 8.52  | 134.87| 3610    | 60     | 4    | 73   | 8    | 600     | 75  |
| B1   | 05-23-16   | 04-03-17 | 145–460     | 8.38  | 134.55| 110     | 20     | 4    | 12   | 105  | 300     | 30  |
| B2   | 05-23-16   | 04-03-17 | 145–460     | 8.40  | 134.67| 135     | 20     | 4    | 14   | 119  | 300     | 30  |
| B3   | 05-24-16   | 02-25-17 | 146–423     | 8.47  | 134.62| 53      | 20     | 2    | 5    | 47   | 300     | 30  |
| B4   | 11-25-17   | 03-23-17 | 331–449     | 8.48  | 134.64| 78      | 10     | 4    | 8    | 68   | 300     | 30  |

Zn is the depth of the top buoy, the ADCP ball. Depth is the water depth. Δt is the sampling period of the ADCP or RCM9 and Δz is velocity bin size of the ADCP. Zl is the depth of the first ADCP bin and Zn the depth of the last bin of or of the RCM9. Z0 is the depth of the Long Ranger Ball. 300-kHz ADCPs are mounted on the bottom at B moorings. All depths are in meters. Start day and end day are given as month-day-year and decimal day where day 0 is January 1, 2016. Mooring position is given by decimal latitude and longitude in degrees. Tl is the inertial period in hours. Site locations of the moorings are marked by squares in Fig. 1b.

Conductivity, and pressure (TCP) sensors. The instruments consisted of MicroCats (SBE37, SBE39, and SBE56), manufactured by Sea Bird Electronics, that recorded temperature and/or conductivity with or without pressure (P), and Vemco temperature data loggers. The sampling rates were 10 min for the SBE37 and 10 s for the SBE39 and SBE56. The sampling rates for the Vemco temperature data loggers were 1 min. These sensors were unevenly spaced and were more numerous within about 200 m of the buoy, where strong stratification was expected. A summary of these recorders, sensor depths, and sampling rates are provided in Table 2. The ADCPs at M1–M5 and the RCM9s at M2–M5 (Fig. 1b and Table 1) recorded P and T apart from velocity measurements, and those T and P records were included in the final processing of the T field. By interpolating known P records from SBE sensors, ADCPs, and RCM9s, we inferred P for sensors which did not record P. The resulting T and P fields were then interpolated into uniform depth-time series with 10-m vertical spacing and 10-min temporal resolution.

The Long Ranger and Workhorse ADCP data were merged into single profiles and interpolated to 8-m vertical intervals between 8 and 600 m. The accuracy of the Workhorse is 0.5% of the water velocity ± 0.5 cm s⁻¹ and the accuracy of the Long Ranger is 1% of the water velocity ± 0.5 cm s⁻¹. Four Aanderaa RCM9 current meters were deployed deeper in the water column between 838 and 1098 m (see Table 1) at M2–M5 and recorded current speed, current direction, temperature, and pressure. Accuracies of the corresponding velocities were well under 1 cm s⁻¹.

The quality of the current data was generally good and little editing was required for the recorded velocity data. Mostly-full data records were returned except for the Workhorse ADCP component of M4 which stopped recording after October 6, 2016, the Workhorse at B3 stopped recording about a month early (February 25, 2017) due to battery exhaustion, and the RCM9 at M4 which stopped on December 17, 2016.

Meteorological observations were collected from an autonomous XMet weather station on the Kayangel Atoll, at the northern end of the Palau Islands (made available by E. Terrill at the Scripps Institution of Oceanography and P. Colin at the Coral Reef Research Foundation in Palau). During the mooring observation period, winds (Fig. 4a) were relatively moderate to weak, with pulses of high winds associated with the passage of cold fronts and low pressure events. Winds were slightly above 5 m s⁻¹, mainly westerly (from west) to northwesterly (from northwest) during the shipboard survey between November 26 and December 4, 2016. A pulse of westerly-northwesterly winds of magnitude ~ 12 m s⁻¹ that lasted nearly 3 days occurred about three weeks prior to the ship survey. Similar events occurred in early July and the middle of August.
Temperature ($T$) and salinity ($S$) are presented to show the water-mass properties near Palau. Vertical profiles of potential temperature ($\theta$), salinity, potential density ($\sigma_\theta$), and buoyancy frequency ($N$) are shown in Fig. 2. Distinct differences of water-mass properties and stratification in the upper 200 m were found between deployment and recovery of the mooring array. These profiles are from deep CTD casts collected in May 2016, November 2016 (not shown in Fig. 2), and March 2017 around northern Palau (Fig. 1b). The depths of salinity maxima (34.8 psu) in May 2016 and March 2017 were about 150 m and 75 m, respectively. The pycnocline was deep (~ 150 m) in May when the El Niño relaxed and a pulse of warm/salty water passed through the mooring array. A shallow pycnocline was reestablished as flow transitioned back to normality in March 2017. Although the pycnocline depth fluctuated between 75 and 150 m, the magnitude of the density stratification remained unchanged below 300 m. The buoyancy frequency at the pycnocline was as large as a 15 cycles per hour (cph).

The potential-temperature-salinity structure was examined from deep CTDs collected during May 2016, November 2016, and March 2017, and also from limited $T$ and $S$ measurements at M moorings (Table 2). Note that the ship-based CTDs provide high vertical resolution with limited temporal variability, whereas the moored observations provide high temporal resolution with limited vertical resolution. Water-mass properties were steady below 200 m, but there is a significant variation in $T$–$S$ properties in the upper 200 m. The $T$–$S$ diagram for March 2017 (black dots in Fig. 3a) is somewhat similar to typical water-mass properties near 8°N in the western equatorial Pacific Ocean for a non-El Niño year. These water masses include North Pacific Intermediate Water (NPIW), North Pacific Tropical Water (NPTW), and North Pacific Tropical Surface Water (NPTSW) (Schönau et al. 2015; Qiu et al. 2015; Maes et al. 2002; Kashino et al. 1996; Fine et al. 1994; Lukas et al. 1991). NPIW is identified by a subsurface salinity minimum between $\sigma_\theta$ = 26 kg m$^{-3}$ and $\sigma_\theta$ = 27 kg m$^{-3}$ (Fig. 3). NPTW contains a subsurface salinity maximum at $\sigma_\theta$= 24 kg m$^{-3}$. NPTSW is a low-salinity, shallow layer encompassing the southern edge

| Variable | Sensor | dZ (m) | M1 (m) | M2 (m) | M3 (m) | M4 (m) | M5 (m) | Sampling rate |
|----------|--------|--------|--------|--------|--------|--------|--------|--------------|
| $T$      | Vemco  | 0      | 64     | 80     | 66     | 91     | 73     | 1 min        |
| $T, C$   | SBE37  | 5      | 69     | 85     | 71     | 96     | 78     | 10 min       |
| $T$      | Vemco  | 10     | 74     | 90     | 76     | 101    | 83     | 1 min        |
| $T$      | Vemco  | 20     | 84     | 100    | 86     | 111    | 93     | 1 min        |
| $T, C, P$| SBE37  | 30     | 94     | 110    | 96     | 121    | 103    | 10 min       |
| $T$      | Vemco  | 40     | 104    | 120    | 106    | 131    | 113    | 1 min        |
| $T$      | Vemco  | 50     | 114    | 130    | 116    | 141    | 123    | 1 min        |
| $T$      | Vemco  | 60     | 124    | 140    | 126    | 151    | 133    | 1 min        |
| $T, C, P$| SBE37  | 70     | 134    | 150    | 136    | 161    | 143    | 10 min       |
| $T$      | Vemco  | 80     | 144    | 160    | 146    | 171    | 153    | 1 min        |
| $T$      | SBE56  | 90     | 154    | 170    | 156    | 181    | 163    | 10 s         |
| $T$      | Vemco  | 100    | 164    | 180    | 166    | 191    | 173    | 1 min        |
| $T, C$   | SBE37  | 110    | 174    | 190    | 176    | 201    | 183    | 10 min       |
| $T$      | Vemco  | 120    | 184    | 200    | 186    | 211    | 193    | 1 min        |
| $T$      | Vemco  | 130    | 194    | 210    | 196    | 221    | 203    | 1 min        |
| $T, P$   | SBE39  | 140    | 204    | 220    | 206    | 231    | 213    | 10 s         |
| $T$      | Vemco  | 150    | 214    | 230    | 216    | 241    | 223    | 1 min        |
| $T$      | Vemco  | 175    | 239    | 255    | 241    | 266    | 248    | 1 min        |
| $T, C$   | SBE37  | 200    | 264    | 280    | 266    | 291    | 273    | 10 min       |
| $T$      | Vemco  | 300    | 364    | 380    | 366    | 391    | 373    | 1 min        |
| $T, P$   | SBE39  | 400    | 464    | 480    | 466    | 491    | 473    | 10 s         |
| $T$      | SBE56  | 506    | 570    | 586    | 572    | 597    | 579    | 10 s         |
| $T$      | SBE56  | 606    | 670    | 686    | 672    | 697    | 679    | 10 s         |
| $T, C, P$| SBE37  | 706    | 770    | 786    | 772    | 797    | 779    | 10 min       |
| $T$      | SBE56  | 806    | 870    | 886    | 872    | 897    | 879    | 10 s         |
| $T$      | SBE56  | 906    | 970    | 986    | 972    | 997    | 979    | 10 s         |
of the NEC and northern part of the NECC. NPTSW was found in a shallow layer where $\sigma_\theta < 22 \text{ kg m}^{-3}$, and salinity $< 34.1$ psu. At the beginning of May 2016, high-salinity, cold water with broad salinity maxima was found between 24.5 kg m$^{-3}$ and 23.5 kg m$^{-3}$ in the upper 200 m (Fig. 3).

**4 General description of currents**

Current observations are described here during the adjustment phase or transition period of the El Niño (end of May to end of August, 2016) and when ocean conditions returned to normal (September 2016–March 2017). Further details of ocean conditions during the transition period at the end of the 2015/2016 El Niño are provided by Schönau et al. (2019) and Andres et al. (2019). Schönau et al. (2019) used thermistor, glider, and satellite observations of sea-surface-height anomaly along with some of these same mooring observations to describe the ocean response. Andres et al. (2019) looked at currents near Palau with focus on the abyssal circulation and on the deep expression of mesoscale eddies, using different moorings equipped with ADCPs and current meters, pressure-sensing inverted-echo sounders (CPIES), drifters, gliders and satellite observations of sea-surface height anomaly,
during the 2015/16 El Niño and its transition period, and the return to neutral ocean conditions.

Time-depth sections of eastward velocity ($U$), northward velocity ($V$), and temperature ($T$) at M3 at raw, 1-h resolution are provided in Fig. 4b–d. Since salinity observations were limited on the mooring line (Table 2), a scatter plot of salinity as a function of sensor depth and time is presented in Fig. 4e. Here, current velocities were averaged over 1 h and 8-m vertically in depth, and the temperatures were averaged over 10-min and 10-m vertically in depth. Multiple timescale flows ranging from tidal to low-frequency oscillations (periods of 10 days and longer) are indicated by the observations. Large isothermal displacements can be found in the deeper part of the thermocline (depths greater than 300 m) which are closely associated with low-frequency motions of $U$ and $V$. The salinity has a maximum, roughly at 150-m depth. For some of the following analyses, high-frequency currents were removed from the current records by applying a low-pass filter with a half-amplitude point at a period of 10 days (240 h). Other analyses, e.g. for spectra, tides and inertial currents, used the one-hour resolution data.

Time-depth sections of the $U$ and $V$ components for the filtered (10-day low-passed) currents for each of the moorings are provided in Figs. 5 and 6. Current fluctuations with periods between about 30 and 75 days are readily apparent in all of the sections for the deep M moorings, and in sections for the B3 and B4 reef moorings. Significant horizontal shear is evident between B3 and B4, where the records overlap (December 2016–February 2017), particularly in the $V$ component (Fig. 5). Currents are weak (less than about 5 cm s$^{-1}$) at B1. Currents were generally greater than about 10 cm s$^{-1}$ at B2–B4, but currents greater than 50 cm s$^{-1}$ were sometimes observed. B3 and B4 were deployed in close proximity (see Sect. 2) at the northern tip of the reef at water depths of 53 m and 78 m, respectively. B4 was located northeast of B3 where bathymetry was oriented more north–south than at B3. Average northward currents near the surface at B4 were 19 cm s$^{-1}$, about twice as large as the average northeastward currents near

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**Fig. 4** Stick plot of wind speed (Wspd) from a XMET weather station on the Kayangel Atoll near northern Palau (a). Raw data at 1 h resolution at M3 for $U$ (b), $V$ (c), $T$ (d), and $S$ (e)
Fig. 5  Velocity time series for the east–west ($U$) and the north–south ($V$) velocity components for the B moorings on Velasco Reef. Data were smoothed using a 10-day low-pass filter, removing tidal and inertial currents.

Fig. 6  Velocity time series for the east–west ($U$) and the north–south ($V$) velocity components for the M moorings in the deep water off of Velasco Reef. Data were smoothed using a 10-day low-pass filter, removing tidal and inertial currents.

The major tidal components at B3 were also stronger than at B3 (Table 3). Currents at the deep-water M moorings often exhibit a two-layer flow in the $V$ component, with reversing flow pattern above and below the thermocline (~125 m, Fig. 2). The current patterns at the M moorings (Fig. 6) as well as temperature records (Fig. 7) exhibited multiple time-scale processes, that are suggestive of intraseasonal motions and mesoscale eddies.
Kashino et al. (2005) and (2015) found intraseasonal variability on time scales of 50–100 days in this region. Low-pass-filtered velocities from the RCM9 records, placed deeper on moorings M2–M5, are plotted in Fig. 8. The deeper RCM9 velocities show similar fluctuations to those from the deepest ADCP velocities, but RCM9 amplitudes range from 30 to 60% of corresponding deep ADCP amplitudes. Significant northward mean velocities occurred at M2 and M5, and northwestward at M4. Mean northward velocity at M3 was negligible.

### Table 3 Tidal ellipse parameters from the deepest bins of the ADCPs and from the RCM9s (*) are listed with measurement depths

| Site depth | Period (h) | K1  | O1  | P1  | Q1  | N2  | M2  | S2  |
|------------|------------|-----|-----|-----|-----|-----|-----|-----|
| 23.93      | 25.82      | 24.07 | 26.87 | 12.66 | 12.42 | 12  | 11.97 |

| Semi-major axis (cm/s) | B1 | B2 | B3 | B4 | M1 | M2 | M2* | M3 | M3* | M4 | M4* | M5 | M5* |
|------------------------|----|----|----|----|----|----|-----|----|-----|----|-----|----|-----|
| K1                     | 105| 119| 47 | 68 | 600| 600| 1095| 600| 838 | 600| 600 | 1098|     |
| O1                     | 1.47| 0.61| 1.08| 3.17| 2.41| 1.16| 1.04| 1.4 | 2.03| 1.31| 1.53| 0.71 |     |
| P1                     | 1.83| 0.29| 1.43| 4.5 | 1.89| 0.89| 0.45| 1.3 | 1.3 | 1.48| 1.76| 1.13 |     |
| Q1                     | 0.23| 0.38| 0.76| 1.88| 0.97| 0.54| 0.36| 0.5 | 0.55| 0.99| 0.33| 0.45 |     |
| N2                     | 1.21| 0.19| 1.04| 0.74| 0.71| 0.19| 0.5  | 0.92| 0.45| 0.85| 0.71| 0.85 |     |
| M2                     | 4.07| 1.82| 4.47| 5.99| 2.28| 0.4 | 0.5  | 4.44| 0.21| 6.18| 3.17| 2.29 |     |
| S2                     | 2.42| 1.82| 2.85| 3.33| 1.75| 1.17| 2.29| 3.17| 1.56| 4.57| 5.51| 1.39 |     |
| K2                     | 0.77| 0.53| 1.97| 2.31| 0.76| 0.24| 1.39| 0.57| 0.38| 0.99| 0.67| 0.59 |     |

| Semi-minor axis (cm/s) | B1 | B2 | B3 | B4 | M1 | M2 | M2* | M3 | M3* | M4 | M4* | M5 | M5* |
|------------------------|----|----|----|----|----|----|-----|----|-----|----|-----|----|-----|
| K1                     | 0  | 0.01| 0.04| 0.03| 0.1 | 0.17| 0.07 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |     |
| O1                     | 0  | 0.05| 0.01| 0.01| 0.1 | 0.28| 0.05 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |     |
| P1                     | 0  | 0.01| 0.17| 0.09| 0.09| 0.09| 0.09 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |     |
| Q1                     | 0  | 0.04| 0.28| 0.07| 0.16| 0.16| 0.09 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |     |
| N2                     | 0  | 0.0 | 0.3  | 0.07| 0.3 | 0.3 | 0.3  | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |     |
| M2                     | 0  | 0.0 | 0.5  | 0.05| 0.0 | 0.05| 0.05 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |     |
| S2                     | 0  | 0.0 | 0.5  | 0.05| 0.0 | 0.05| 0.05 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |     |
| K2                     | 0  | 0.0 | 0.5  | 0.05| 0.0 | 0.05| 0.05 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |     |

| Ellipse orientation (°CCW from East) | B1 | B2 | B3 | B4 | M1 | M2 | M2* | M3 | M3* | M4 | M4* | M5 | M5* |
|--------------------------------------|----|----|----|----|----|----|-----|----|-----|----|-----|----|-----|
| K1                                   | 105| 119| 47 | 68 | 600| 600| 1095| 600| 838 | 600| 600 | 1098|     |
| O1                                   | −127| 99 | 21 | 4  | 35 | 75 | −75 | −2 | 95  | −56| 95  | 87  |     |
| P1                                   | 53 | 61 | 0  | 1  | 56 | −59| 82  | 95 | −62 | −4 | 95  | 20  |     |
| Q1                                   | 41 | 41 | 18 | −9 | 40 | 136| 136 | 95 | −62 | −9 | 95  | 87  |     |
| N2                                   | 55 | 55 | 15 | −4 | 95 | −82| 88  | 65 | −25 | −2 | 65  | 123 |     |
| M2                                   | −126| 92 | 15 | 8 | 41 | 87 | 136 | 41 | −25 | −9 | 41  | 15  |     |
| S2                                   | 57 | 57 | 6  | 2 | 19 | 123| 123 | 19 | −25 | −6 | 19  | 12  |     |
| K2                                   | 51 | 51 | 6  | 7 | 37 | 16 | 16  | 37 | −25 | −13 | 37 | 16  |     |

Negative semi-minor axes indicate CW rotations of the velocity vectors.
Geographical pictures of the mean current field and its variability are shown by mapping the depth-averaged currents and their principal standard deviation ellipses at each of the moorings (Fig. 9). The center of the standard-deviation ellipse is at the tip of the arrowhead and reflects the area that is within one standard deviation of the mean. The mean currents are well-determined when the mean vectors are not encompassed by their respective deviation ellipses. In the top layer (Fig. 9a), mean currents in the deep water had magnitudes from about 5–10 cm s\(^{-1}\) and were towards the north-northwest, north and east of the reef at M3–M5, and M2, respectively, but were towards the north-northeast, west of the reef at M1. Mean currents on the reef were similar in magnitude to those in the deep water but were steered by the reef topography. Generally, the orientations of the ellipses in both upper and lower layers were along the mean flow direction, except orientation of the ellipses at B3, B4, and M3, were cross-mean flow in the top layer. For the deep layer (Fig. 9b), mean currents are just a few cm s\(^{-1}\) and are not well-determined. Generally, all of the mean flow directions in both layers ranged from northwest to northeast except southwestward for B1. Currents were steered towards the north by the ridge topography and mean currents were different west of the reef (M1), with smaller variance, than east (M2) of the reef.

### 4.1 Spectra

To examine overall frequency content, autospectra were calculated for the ADCP and RCM9 current time series. Spectral energy levels were estimated by averaging sample spectra of 50%-overlapping 100-day segments of each time series. This resulted in 6 degrees of freedom (NDOFs) in most cases; some of the series were shorter, so had fewer NDOFs. The results presented here are total spectral energy:\(\frac{(\Phi_U(\omega) + \Phi_V(\omega))}{2}\), where \(\Phi_U(\omega), \Phi_V(\omega)\) are spectral magnitudes of \(U\) and \(V\) velocities, respectively, and \(\omega\) is the frequency.

The spectrum for the RCM9 current meter record from 838 m depth on mooring M3 appears in Fig. 10a. The RCM9 spectra at the other locations are similar, considering the 95% confidence limits shown on the plot. The salient features are the diurnal and semidiurnal tidal peaks and broad rise starting near the inertial period of about 3.4 days (0.3 cycles per day, herein after cpd). Significant energy is evident at lower frequencies, where the resolution is inadequate to separate signals with periods longer than about 50 days, due to the short sample segments.

Spectra for each depth level of the ADCP data were calculated at each location. Figure 10b shows the result for M3, contoured as a function of depth and frequency. Spectral levels of tidal and inertial peaks and higher energy at low frequencies are similar to those in the RCM9 record. There are hints of tidal harmonics near 3 cpd, 4 cpd, and beyond (note vertical striping), but the levels are not significant with 95% confidence. Some vertical intensification in the diurnal and semidiurnal energy occurred with decreasing depth. There are also significant vertical structures in and above the inertial band. The profiles of spectra at the other deep locations (M1, M2, M4, and M5) show similar patterns. Shallow moorings closer to the Velasco Reef (B1–B4) show similar spectral levels as found at the deeper locations (e.g. at B2, Fig. 10c), except at B1 (Fig. 10d) on the western side of Velasco Reef, where energies are significantly lower, particularly for periods longer than the tidal band. As with the RCM9 spectra, there are lower-frequency peaks around 0.1 cpd.

Note that the dominant tidal constituents were generally the \(M_2\) and \(S_2\) constituents. Their magnitudes were less than about 5 cm s\(^{-1}\). Significant variability was found among the moorings, and with depth. Tides and higher frequency
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Fig. 8 RCM9 U (black) and V (red) velocity-components series; mooring, depth, average speeds and standard deviations are noted on the plots. Data were smoothed using a 10-day low-pass filter, removing tidal and inertial currents.

Currents contributed about 20% of the total current energy at the deep-water moorings, on average for the 11-month observation period, while their contributions to the total current energy at the moorings on the reef ranged from about 40 to 60% of the total current energy. Significant tidal currents near Palau are expected, since tidal height differences between low and high tides from observations at Palau tide stations can be as large as 2 m (https://coralreefpalau.org/research/oceanographyweather/ocean-observations/). Tidal ellipse parameters were computed, using harmonic analysis, for eight primary constituents, consisting of four diurnal (K1, O1, P1, Q1), and four semidiurnal (N2, M2, S2, K2) constituents, for the ADCP and RCM9 velocity data. Tidal ellipse parameters from the deepest bins of the ADCPs and from the RCM9s are presented in Table 3. Significant variability is evident among the moorings, and with depth. The ellipse orientations for the M2 and S2 constituents are guided by the ridge, approximately along the isobaths, except at B1. Tidal ellipses were largest at M4 in the deep water, likely due to shallower depth on the ridge, and at B4 on the reef. The tidal
variability changed throughout the observed current profiles, and hence, the barotropic tide could not be computed.

4.2 Wavelet analysis

The currents in this region are often not stationary due to passing of eddies and shifting of major current patterns. Conventional Fourier spectrum analysis, which presumes that the data are stationary, provides information about the average energy content in each harmonic, for the entire time span of the data. In order to better describe the nonstationarity of these currents, and to estimate variability over time as a function of period, a continuous wavelet transform analysis (Torrence and Compo 1998; Mallat 1989; Liu and Miller 1996) was applied to the high-resolution RCM9 and ADCP (for selected depths) time series. Figure 11 shows total current-velocity energy at mooring M3, at depths 8, 152, 400, 600, and 838 m. The dominant, persistent feature is in the 12-h band, with considerable variation over time; this shows the presence of the M2 (and other semidiurnal) tides, and likely nonstationary internal-tidal variability. The bursts of elevated energy in the 12-h band occur with a quasi-fortnightly period, which correspond to the spring-neap cycle. The diurnal band also shows persistent energy over the record. Energies generally decrease with increasing depth. Inertial-band (~3 days) energies are more episodic, and tend to be concentrated in the second half of the record. The shallowest bin (8 m, Fig. 11) exhibits broadband energy levels; in particular, note the persistent peak near 30 days. Peaks near 50 days occur at the deeper levels (152 m, 600 m, and 838 m). Bursts of energy occur between 2 and 10 days, and longer (after October; Fig. 11). The energies become concentrated around the tidal, inertial, and specific low-frequency bands at and deeper than 150 m. The energy levels at mooring B2 (Fig. 12), which was located near the east slope of the Velasco Reef, show similar patterns to those at M3, but fall off quickly with depth. Most of the energy at periods longer than the tidal band is gone at ~100 m.

Wavelet analyses produced similar results at all of the deep moorings (M1–M5) and for the reef moorings (B2–B4), with the exception of the mooring at B1 where there was little energy at periods longer than inertial. At all locations, variability at periods longer than about 40 days is difficult to assess in this wavelet analysis due to the relative shortness of the series, as shown graphically by the green-shaded areas in Figs. 11 and 12, which represent the truncations of the filtering implicit in the analysis.

5 Vorticity

Multiple time-scale low-frequency motions with large velocities occurred off the Velasco Reef. Variability of currents was largest in the upper 100 m compared to current measurements below 100 m, where tides, near-inertial waves, and intraseasonal oscillations (ISOs) dominate (Figs. 4, 5, 6, 7 and 11). These reversing currents passing over the northern tip of the Velasco Reef generate vorticity on both sides of the reef. Vorticity was determined for the deep water surrounding Velasco Reef using the deep moorings. The vertical component of vorticity was computed using the M1–M3–M4 and M4–M5–M2 triangular mooring distributions for the west side and east side of reef/ridge, respectively, where
The average vorticity over each triangular array, denoted \( \zeta \), can be estimated using Stokes' theorem:

\[
\zeta = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} \tag{1}
\]

The average vorticity over each triangular array, denoted \( \zeta \), can be estimated using Stokes' theorem:

\[
\int_A \zeta_0 dA = \oint_C \mathbf{V} \cdot d\mathbf{r}, \tag{2}
\]

where \( A \) is the area of each triangle, and \( \mathbf{V} \cdot d\mathbf{r} \) is velocity parallel to the path around \( C \); in this case around the perimeters of the triangles. The deep mooring setup allows us to compute spatial gradients of velocity at 13–30 km scales, where the zonal separations between M4 and M3, and M5 and M4 are 12.7 km and 29.3 km, respectively, and the meridional separations between M3 and M1, and M5 and M2 are 20 km and 29.4 km, respectively. Vorticity associated with 13–30 km scales was computed from 10-day, 40-h, and 6-h low-passed velocity records. Time-depth sections of vorticity for west (\( \zeta_{West} \)) and east (\( \zeta_{East} \)) of the reef/ridge were computed and \( \zeta_{West}/f \) and \( \zeta_{East}/f \) are plotted in Fig. 13, where \( f \) is the inertial frequency at 8° N. There are no vorticity estimates in the upper 100 m after October 9, 2016 (Fig. 6) due to the failure of the 300 kHz ADCP unit at M4. The basic time-depth structure of vorticity reflects low-frequency variability, even though the inclusion of near-inertial and tidal motions enhanced the strength of vorticity. The vorticity showed a two-layer structure with subseasonal variability similar to the velocity field discussed in Sect. 4 (Fig. 6). We further examined the basic structure of the low-frequency vorticity using EOF analysis in Sect. 6.

In general, cyclonic (or positive) vorticity dominated on the west side extending throughout the upper 600 m during September–November 2016, and in the upper 200 m during November–December 2016, and April 2017 (Fig. 13). Strong anticyclonic (or negative) vorticity events lasting ~10–30 days occurred in the upper 100 m, on the east side during August 2016, and below 200 m on the west side during June 2016 (Fig. 13). These high vorticity events coincided with reversing flows associated with ISOs (Fig. 6). The
strongest vorticity occurred in the presence of inertial and tidal currents. The maximum vorticity in the upper 200 m for 6-h low-passed currents is about a factor of 1.5 or ~50% larger than that of the 10-day low-passed filtered currents.

Recirculation flow patterns formed on the leeward side of the reef. Cyclonic vorticity on the west side occurred when the flow was westward over the ridge, and anticyclonic vorticity on the east side occurred when the flow was eastward (Fig. 14), indicating that the meridional gradient of zonal currents was an important term in vorticity and a correlation of the vorticity with the zonal flow. Figure 14 further illustrates a strong correlation between zonal flow and vorticity in the upper 200 m. Significant correlations were found for the west-side vorticity with the zonal current at M4, where correlation coefficients for upper and lower layers are about −0.63 and −0.53, respectively. The correlation coefficients of east-side vorticity for the upper and lower layers are smaller, and are about −0.34 and −0.17, respectively. Linear least-squares fits to the data are shown in Fig. 14. Correlations with the zonal flows were high where the vorticities were high. The upper and lower layers represent layers of strong and weak stratification (Fig. 2), respectively. Stratification was strongest between 75 and 150 m during the experiment, and weak below 200 m.

6 EOF analyses

6.1 EOF analysis of horizontal currents, and vertical and horizontal coherences

In order to measure the similarities of the velocities between the moorings, vertical and horizontal EOF analyses were conducted using the 10-day, low-passed-filtered ADCP data from M1-M5 moorings. The vertical analysis provides a measure of coherence over depth of current velocities. The results, with findings in other sections of this paper, suggest a two-layer structure of low-frequency variability of currents. The upper layer has a rapidly varying stratification with $N^2 \sim 10^{-4} - 10^{-3}$ s$^{-2}$ on the top of the pycnocline near 175 m, and the lower layer has a slowly varying stratification with $N^2 \sim (1-2) \times 10^{-4}$ s$^{-2}$ below 200 m (Fig. 2). The flow reversal took place just below the pycnocline (Fig. 6). Subsequently, depth-averages of velocities, in each of these two layers, at the 5 mooring locations are compared horizontally with a second EOF analysis. This provides a measure of variability which is coherent temporally around the Velasco Reef.

To examine vertical coherence, principal component (PC) analysis (more commonly termed...
empirical-orthogonal-function (EOF) analysis was applied to the 10-day, low-passed ADCP time series. At each mooring location, the ADCP velocity, $U(z, t)$ (and $V(z, t)$), can be expressed as:

$$U(z, t) = \sum_{j=1, 2} E_j(z) P_j(t)$$

where $n$ is the number of orthogonal modes, in this case, the number of depth samples. $E_j$ are the orthonormal eigenfunctions (EOFs) and the $P_j$ are the orthogonal principal components, which carry the variance, $\lambda_j$, of mode $j$. For the data analyzed here, mode 1 accounts for 70% to 90% of total variance (vertically-integrated) for all mooring locations, for both $U$ and $V$. Mode 2 accounts for 10–20% of the variance; the remaining modes are considerably less important. Profiles of the mode-1 and mode-2 scaled eigenfunctions (multiplied by the square root of respective modal eigenvalues, to indicate actual magnitudes) appear in Fig. 15. The plots indicate that mode 1 represents primarily the deeper part of the water column while mode 2 is focused on the upper part. The mode-1 profiles are similar to those shown by Zhang et al. (2017), at their southernmost mooring (~10° N), just north of the Velasco Reef. The $U$ eigenfunction mode-1 amplitudes (Fig. 15) for M1 and M2 are about half those of M3-M5; note that M1 and M2 are located just east and west of the Velasco Reef, where topographic effects might attenuate the east–west velocity components. M3-M5 are north of the reef. For $V$, the amplitude at M2 (east of the reef) is the highest, while those at M1 and M3 (west of the reef/ridge) are the lowest, with those at M4 and M5 (north of the reef) between. These differences could be a result of blockage of westward flowing currents by the reef. Additionally, a blockage could also be indicated by the average temperature in the thermocline higher at M1 and M3 (Fig. 7) than at the other moorings. Correspondingly, mode 1 differences among the moorings are largest below about 200 m and are perhaps indicative of reef impact.

From Figs. 6 and 15, two regimes of motion, or layers, are suggested: surface to 200 m (layer 1); 200–600 m (layer 2). Then, depth-averages, $(U_1, V_1)$, $(U_2, V_2)$ were calculated for each mooring; these are functions of time only. As a check, correlation coefficients of the depth-averaged velocity components with corresponding principal component series ($P(t)$ in Eq. 3), were computed for several modes. Layer 2 showed correlation coefficients of virtually 1.0 at all locations, for $U_2$ and $V_2$ with the mode 1 PCs; correlation coefficients with the other modes were essentially zero. For layer 1, correlation coefficients were high for mode 2, with values ranging from 0.70 to 0.92 for all except $U_1$ at M1, where it was 0.50 (here, energy was spread over modes 1–3). In general, the layer 1 correlations were not as robustly represented by a single mode, which indicates somewhat lower vertical coherence in the upper layer.

To evaluate horizontal coherence among the 5 moorings, a second EOF analysis was conducted using the depth-averaged series; this was done for each of the layers. Here, the $z$ coordinate in Eq. (3) is replaced with horizontal position, $i = 1.5$. Furthermore, a vector EOF calculation (Preisendorfer 1988; Kaihatu et al. 1998) is done by concatenating $U$ and $V$, yielding a data matrix $[U_i(t), V_i(t)]$, $i = 1.5$; or a 10x$N_t$ matrix, where $N_t$ is the number of samples in time. For each location, $i$, we define $Y_{ik}(t)$, such that

$Y_{i1}(t) = U_i(t), i = 1, 5; Y_{i2}(t) = V_i(t), i = 1, 5$,  

where $k = 1, 2$. Then $Y_{ik}(t)$ consists of 10 time series, or 5 series of the vector ($U$, $V$). $Y$ is then expressed as a sum of 10 EOF modes as:

$$Y_{ik}(t) = \sum_{j=1}^{10} E_{ijk} P_j(t).$$

The eigenfunctions for $U$ and $V$ are then $E_{i1j}$, and $E_{i2j}$, respectively, or vector eigenfunctions $E_{ij}$. The index $j$
indicates mode, ranging from 1 to 10 (note: these modes should not be confused with the vertical EOF modes discussed in previous paragraphs). Eigenvalues for the first 3 modes show total horizontally-integrated variances of: 48%, 33%, 10%, for layer 1, and 50%, 29%, 10%, for layer 2; hence, modes 1 and 2 account for about 80% of the total variance. Scaled eigenfunctions ((\bar{E}_{ij}/\lambda_j)^{1/2}\lambda_j) are plotted as maps in Fig. 16, for layers 1 and 2. The plots represent magnitude and direction of velocity vector variability over the 5 locations, for modes 1 and 2. The vectors represent fluctuations about temporal means; their magnitudes (and signs) are modulated by the principal component series \(P_j(t)\). The percent of explained variance for these modes, at each site, are included with mooring labels in Fig. 16. The normalized principal component series for modes 1–2 are plotted in Fig. 17, for the 2 layers.

The upper layer EOF amplitudes (Fig. 16a) show NNW-SSE mode-1 variability, dominant east of the reef (M2, M5), while mode 2 shows motions generally around the north end of the reef. In the lower layer (Fig. 16b), where the bathymetry of the reef is likely influential, mode 1 shows motions generally conforming to the topography of the reef and shows mostly NE-SW fluctuations north of the reef, but N-S on the east side, and NNE-SSW on the west. Mode 2 shows fluctuations nearly orthogonal to those of mode 1; at M2, the mode-2 vector is oriented partially toward the reef.
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**Fig. 14** Vorticity west (red dots) and east (blue dots) of Velasco Reef versus zonal velocity (at M4) for the upper (a, c) and lower (b, d) layers. The thick lines represent a linear least-squares fit to the data.

**Fig. 15** Scaled vertical-eigenfunction profiles for deep moorings.
The temporal variability associated with the maps of Fig. 16 is shown in Fig. 17. The first feature of note is the presence of shorter periods in the upper layer. Also present in both layers are small fluctuations with a fortnightly period, possibly related to tidal effects. Fluctuations in the upper layer have periods ranging from about 20 to 50 days. Larger amplitudes are near the beginning and end of the observation period, with a more quiescent period between September and November 2016.

6.2 EOF analysis of vorticity

Vorticity estimates may be improved by removing spatial variability on scales smaller than the horizontal spacing in the triangular arrays, west and east of the ridge, described in Sect. 5. Using an approach described in Zeiden et al. (2020) and Fischer et al. (2002), velocity series at locations in each triangular array were calculated from one or more horizontal EOF modes computed from the original velocities. Each mode represents correlated variability among the 3 locations. Zeiden et al. (2020) apply a further constraint originating with Okubo (1970) and Weiss (1991), or OW parameter, which is defined using the strain and vorticity as

\[
\text{OW} = \sigma^2 - \zeta^2, \]

where \(\sigma^2 = (\partial U/\partial x - \partial V/\partial y)^2 + (\partial V/\partial x + \partial U/\partial y)^2\) and \(\zeta\) is the vorticity. Vorticity is the result of vortex motion and strain. A negative value for OW indicates predominantly vortex flow on the scale of the observing array.

As in Sect. 5, vorticities were calculated, using the 10-day-low-passed data, for the upper and lower layer depth-averaged velocities, in the western (M1, M4, M3) and eastern (M2, M5, M4) triangles of moorings. Both the total vorticities, and those based on selected EOF modes, were computed for the eastern and western arrays. At least 55\% of total velocity variance is accounted for in mode 1 for both arrays; modes 1 and 2 account for over 80\%.

Note that these EOF analyses were calculated separately for the eastern and western arrays, for each layer. Figure 18 shows time series of \(\text{Ro} (=\zeta/f)\) and \(\text{OW}/f^2\) (normalized to simplify the plot) based on original velocities (black) and those reconstructed from selected EOFs (red). In the latter, OW is mostly negative, indicating the presence of vortices at the scales of the arrays. The positive values of OW exhibited by results using the original velocities indicate dominance of straining motion over pure rotation, or vortex motion (see, e.g., Gill 1982, Sect. 7.9). The largest vorticity variance occurred in the upper layer, from the western array (Fig. 18). Furthermore, in this case, the greatest similarity occurred between vorticity calculated directly from the velocity series and that based on the reconstructed series, strongly indicating the presence of eddying motions. On the other hand, the anticyclonic vorticity period during June, 2016, below 200 m west of
the reef was primarily the result of strain as opposed to eddying motion: the reconstructed vorticity (Fig. 18) was near zero until the beginning of July, when it became positive (cyclonic).

7 Discussion

The reef and ridge can significantly impact the current patterns in their vicinity. The smaller-scale current variability cannot be represented by satellite products, and hence the larger-scale current variability may not be accurately depicted near the reef and ridge due to aliasing, both near the surface and at depth, without accounting for their local impact. The effects of the steep topography and ridges associated with Palau Island have been the subject of investigations based mainly on modeling and snapshots of the in-situ oceanography. Recently, model simulations were performed by Gopalakrishnan and Cornuelle (2019) that used the same forcings but with and without Palau Island and ridge. Their results indicated that the island and ridge effects were localized and small. They do warn that their study is limited by not resolving the fine-scale circulation features around the island ridge such as eddies, lee waves, and island wakes. They did not have observations to validate their findings. Simmons et al. (2019) looked at the vortex wakes caused by the interactions of the equatorial currents with the Palau Island chain. They concluded that ocean models require considerably-higher resolution than those in standard use to capture the wakes. Vorticity, over a wide range of scales, generated by flow interactions with Palau Island and the ridge was studied by Rudnick et al. (2019) using satellite products, glider observations, and three closely-spaced moorings. They found that understanding the vorticity associated with the interactions of eddies on different temporal and spatial scales is important for ocean forecasting and more work needs to be done. Seasonal recirculation of the NECC to the NEC in relation to the Mindanao Dome (Masumoto and Yamagata 1991; Kashino et al. 2011) and eddies associated with the recirculation patterns around Palau add to the complexity of the circulation (Kashino et al. 2013; Andres et al. 2019; Schönau et al. 2019). These recent studies suggest that in situ observations are required for understanding the physical processes associated with flow past topography and for comparison with the models. Most importantly, these processes must be properly depicted by the models and not overly simplified. The mooring observations presented in this paper provide a description of 10–30 km spatial scales and semidiurnal tides to intraseasonal variabilities of currents and vorticities around an abrupt bathymetric feature, which are building blocks for future studies and model development. In-situ observations are expensive and hence are limited in scope. Models for studying flow-topographic interactions are limited by the resolution of the bathymetry, and likely need increased grid resolution. Hence, models and observations must be economically used together for a realistic depiction oceanographic conditions.

Formation of cyclonic vorticity on the west side during November–December 2016 (Figs. 13, 18) is consistent with the vorticity formation over the northern edge of Velasco Reef reported by Wijesekera et al. (2020), based on ship-based ADCP surveys. They reported that vorticity computed at 8–12 km scales over the northern tip of the Velasco Reef was (2–4)f. Here, vorticities estimated at 13–30-km scales on east- and west-sides of the ridge were at least a factor of 2–5 smaller than those found off the edge of the northern Velasco Reef. However, the cyclonic vorticity west of the ridge, shallower than 200 m, was primarily due to vortex motion at these larger scales (Fig. 18). The anticyclonic vorticity found in August 2016 (Fig. 13) is also consistent with the timing of anticyclonic circulation on the east side of Palau reported by Merrifield et al. 2019. Furthermore, moored vorticity estimates are qualitatively similar to model simulations reported by Simmons et al (2019). They discussed the generation of submesoscale cyclonic eddies on the west side and over the reef during May and December 2016, and anticyclonic circulation on the east side during August 2016. They noted that a high-resolution model grid (~800 m) is required in order to capture tidal-flow separation and formation of small-scale eddies.

Furthermore, significant upwelling and downwelling may be associated with the formation of the stronger vorticity patterns. From horizontal divergence calculated as a function of depth, using the divergence theorem within each triangle, with the 10-day low-passed current data, vertical velocity, W(z), was inferred between the surface and 200 m in the western and eastern triangular-station arrays, by integrating ∫(deptU/dept + deptV/depy) between the surface and 200 m, setting W to zero at the surface. This was done for the first portion of the record, since data were missing shallower than 10 m after this, due to instrument failure (see Fig. 6). This calculation provides area averages, <W>, over the west and east triangular arrays at 200 m. Figure 19 shows time series of <W> for east and west sides of the reef. In Fig. 19, the positive upwelling peak in late June and the broader, somewhat smaller peak throughout September are consistent with periods of strong cyclonic vorticity (Fig. 18). In the east, mostly downwelling is evident, but is weaker than the upwelling in the west. Vorticity in the east was significantly weaker, and primarily anticyclonic during the period shown in Fig. 19. Upwelling transports within each triangle can be estimated as W × A, where A is the area of the triangle of stations. Since the area of the east triangle (473.8 km²) is significantly greater than
that of the west triangle (130.8 km²), comparisons may be misleading. In the west, transports ranged from ~ − 0.1 to −0.25 Sv (1 Sv is 10⁶ m³ s⁻¹). However, these estimates may be affected by smaller-scale processes that are unresolved by the triangular arrays, particularly the easternmost one (Simmons et al. 2019).

Fortuitously, the beginning of the mooring deployment overlapped with the relaxation of the 2015/2016 major El Niño event. At the end of May 2016, warm water during the El Niño adjustment period began to cool. Currents collected during the adjustment phase of the El Niño (end of May to end of August), exceeded 50 cm s⁻¹ and revealed ISOs with periods of 15–30 days (Fig. 8). Schönau et al. (2019) report, based on sea surface height analysis, packets of westward-moving waves with phase speeds of about 16–18 cm s⁻¹, which lie between phase
speeds of linear baroclinic Rossby waves for mode 1 and mode 2. Hydrographic observations (not shown) revealed vertical displacements of isotherms exceeding ~150 m in the deeper part of thermocline. Unfortunately, the moorings only partly recorded the ISO due to the timing of the mooring deployment. The current flows in June-July (Fig. 6) produced positive vorticity in the upper layer and large negative vorticity in the lower layer on the western side of Velasco Reef (Fig. 13). In July–August, currents in the upper 100 m at M4 and M5 were southwestward (Fig. 6), and generated strong anticyclonic vorticity in the eastern side of Velasco Reef (Fig. 13) which overlapped with anticyclonic circulation found east of Palau (Merrifield et al. 2019). Although anticyclonic vorticity on the eastern side was infrequent, the anticyclonic circulation occurring in July–August was primarily due to anomalous circulation patterns associated with the El Niño transition period (Schönau et al. 2019). More importantly, these current and thermocline motions are associated with large transports, which could be a major factor for water exchanges between the NEC and NEUC with the NECC. Schönau et al. (2019) estimated east–west (zonal) transport and north–south (meridional) transports using currents at M1-M5. They found that during the El Niño transition period, meridional transports ranged from about −6 to 4 Sv while the east–west transports were generally less than about 1.5 Sv. After the transition period, southward transports were generally less than 1 Sv. These reversing 15–30 day oscillations during the May–August period produced large transports and vorticity, which in turn suggests the transfer of NEC and NEUC waters to the NECC and vice versa could most effectively occur during the El Niño transition period.

8 Summary and conclusions

The mooring observations revealed some insight into the current processes around Velasco Reef. Significant energy at tidal and inertial frequencies, and at periods of ten days and longer were found. Tides contributed about half of the current energy on the reef. The dominant tides were M\(_2\) and S\(_2\) but there was significant variability among the moorings, and with depth. Tides were affected by the ridge. The vertical structure of tidal energy was intensified at shallower depths. Vertical structure was also found in the inertial band over time. Significant variability was found among all of the moorings. Inertial-band energies were episodic. Long-period fluctuations between about 30 and 75 days occurred in the deep water and on the reef. Two-layer flows were found in the deep water, which often reversed below the thermocline, and occurred on multiple scales that ranged from seasonal to intraseasonal. The current energy was not stationary. Currents in the deep water were highly variable and their means were not well determined. Average velocities for the low-frequency currents (periods of 10 days and longer) in the deep water in the upper 200 m ranged from about 10 to 15 cm s\(^{-1}\). Velocities for the low frequency currents on the reef were generally less than 10 cm s\(^{-1}\) but sometimes exceeded 25 cm s\(^{-1}\). Flow was steered by reef/ridge topography and was generally towards the north but more northwestward east of the ridge and northeasterly west of the ridge.

The interactions of the NEC, subseasonal currents and other high-frequency flows with the island-ridge topography formed different vorticity patterns to the west and east of the reef/ridge. The vorticity field was examined for multiple time scales using the 10-day, 40-h, and 6-h low-passed ADCP currents. The strength of the vorticity increased with inclusion of high-frequency motions; the strongest vorticity occurred in the presence of inertial and tidal currents. The maximum vorticity in the upper layer (upper 200 m) for 6-h low-passed currents is about a factor of 1.5 or ~50% larger than that of the10-day low-passed filtered currents. Cyclonic (anticyclonic) vorticity formed on the leeward side when the flow was westward (eastward) over the ridge, indicating recirculation flow patterns on the leeward side of the reef, perhaps indicating wake-eddy vorticity formation. Although the currents were strong, there was less rotation, and much- weaker vorticity was found on the eastern side. Vorticity correlations with the zonal flows were high where the vorticities were high. The large positive vorticity or cyclonic circulation on the western side was associated with upwelling. The currents in the transition period at the end of El Niño appeared to enhance the cyclonic (upwelling) and anticyclonic (downwelling) vorticity patterns that formed on the western and eastern sides of the reef, respectively. The maximum upwelled transport of the exchange of water

![Fig. 19 Time series of <W>, the area-averaged, vertical velocity at 200 m. Black (red) curves are west (east) of the ridge](image-url)
between equatorial currents appears to be at least 50% greater during the El Niño transition period than after the transition period during normal ocean conditions.

To help gauge the effects of the ridge on the current field vertical and horizontal coherences around and across the ridge were computed. EOF analyses made clear the vertical coherences of the current structure. The first two modes accounted for 80% to 90% of the variance. Mode 1 represented the deeper part of the water column and mode 2 represented the shallower upper layer (thermocline and above). The modes behaved differently across the ridge as topographic effects may attenuate the velocity components. The causes for the differences in the vertical modes are not clear, but the differences in mode 1 were most pronounced below depths of 200 m. Horizontal EOF analyses were performed using depth-averaged velocities in each of the layers revealed that the first two modes accounted for about 80% of the variance. EOF analyses suggests that the ridge impacted the velocity correlations between moorings with modes most highly correlated east of the ridge. Mode-1 fluctuations were dominant in the upper layer (8–200 m) east of the reef and were oriented in a NNW–SSE direction. Mode-2 fluctuations were related to currents flowing around the north end of the reef. In the lower layer (200–600 m) mode 1 indicated NE–SW fluctuations north of the reef, NNE–SSW fluctuations on the west side of the reef, and N–S fluctuations on the east side. Mode-2 fluctuations were mostly orthogonal to mode-1 fluctuations and indicated currents flowing generally around the north end of the reef. Fluctuations in the upper layer mostly ranged from about 20 to 50 days while in the lower layer fluctuations ranged from 50 days to longer scales. One-hundred day fluctuations and longer were found in modes 1 and 2. The reef appears to have affected both the vertical and horizontal coherences of the current variability. Vortices occurred at the scales of the mooring arrays.

Recirculation flow patterns on each side of the reef/ridge were complicated by the current variability and by the effects of the ridge topography, but were highly correlated with the current direction. Stronger currents occurring during the El Niño transition period further complicated the current processes. This study suggests that the reef can impact the local currents differently along opposite sides of the reef to an extent that is important to the local circulation on scales of 10–30 km. The impact of current interactions with the reef/ridge on the broader general circulation have yet to be determined but results here suggest that the water exchange within the water column and between equatorial currents could be significantly impacted. Identifying and understanding of the current processes requires observations that are tailored to the specific complexities of the island ridges and may take several iterations to determine the appropriate spatial and temporal resolutions.

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