The Influence of A Cross-Reef Channel On the Wave-Driven Setup and Circulation at Ipan, Guam

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Abstract The influence of a deep (30 m), narrow (30 m) cross-shore channel on the circulation and wave-induced setup over a shallow (~0.5 m) and wide (~400 m) shore-attached fringing reef is examined using field measurements collected at Ipan, Guam. Mean currents on the reef flat over a 7-week study period during mid and high tides when the reef is submerged are directed toward the channel with the alongshore component of the current increasing with proximity to the channel. The cross-shore component of the reef flat current is directed onshore at the sensors in the far-field of the channel with a weak offshore flow at the current meter located closest to the channel (~760 m to the north). Low-frequency fluctuations of the alongshore reef flat current and offshore channel current are significantly correlated and with the incident significant wave height. Mean and low-frequency fluctuating currents are forced by the spatially variable wave-driven setup, modulated by tidal elevation, which creates a pressure gradient over the reef flat due to the channel where waves do not break. The dominant alongshore momentum balance on the reef flat is between the pressure gradient and bottom stress, with an inferred drag coefficient of $C_D \sim 0.01$. A simple analytical model is presented that is consistent with the observations and delineates the near- and far-field of the channel as a function of the aspect ratio of the reef. Observations from a longer deployment of channel currents are highly correlated with incident wave height in distinct tidal level bands.

Plain Language Summary Observations of waves, water levels, and currents at Ipan, Guam, are analyzed to determine how wave-driven flow on a shore-attached fringing reef is influenced by a cross-reef channel. Breaking waves at the outer reef cause elevated water levels over the reef flat. At the deep, narrow channel wave breaking is suppressed, resulting in a pressure gradient that forces a rip circulation toward and out the channel. The dominant physical balance between bottom friction and this pressure gradient leads to an estimate of a drag coefficient $C_D \sim 0.01$. The wave-driven channel current is modulated by tidal submergence of the reef flat, and the flow scales with offshore wave heights at high tidal levels. A simple analytical model describes the spatially variable pressure gradient and defines the region of influence of the channel as a function of the length to width ratio of the reef flat.

1. Introduction

Fringing reefs are common morphological features on tropical coastlines, consisting typically of a sloping reef face where waves break and a shallow reef flat shoreward of the surf zone. The reef flat may directly attach to the shoreline or may be separated from the shoreline by a lagoon which may be considerably deeper than the reef flat. Water exchange between a lagoon and the open ocean generally occurs through one or more deep channels that cut through the reef flat. Fringing reef currents are widely recognized to be significant for the transport of sediment, larvae, and nutrients on a variety of spatial scales, all of which can play an important role in the reef ecosystem (Hearn et al., 2001; Kraines et al., 1998; Presto et al., 2006). The diversity and abundance of coral and fish species make fringing reefs and their lagoons attractive sites for fisherfolk and tourists alike. Fringing reefs can play an important role in reducing coastal hazards by increasing wave attenuation, and reef conservation can be less expensive than building artificial structures (Ferrario et al., 2014; Elliff & Silva, 2017). Generally, variations in reef morphology have important effects on wave attenuation (e.g., Sheppard et al., 2005; Quataert et al., 2015). Man-made and natural reef channels can affect coastal...
hazard mitigation directly by decreasing wave attenuation and indirectly by altering erosion patterns and influencing coral health (Gelfenbaum et al., 2011; Xue, 2001; Reguero et al., 2018). Additionally, strong currents over the reef and through the channels can be dangerous, and permanent reef channels have been identified as a primary hazard for drowning (Lucas & Lincoln, 2010; Blay, 2011).

Forcing of reef circulation by winds (Symonds et al., 2011), tides (Taebi et al., 2011), and buoyancy effects (Hench et al., 2008) has been reported, but depth-limited wave breaking generally is observed to be the most important forcing mechanism for fringing reef circulation (Hench et al., 2008; Lowe et al., 2009b; Monismith, 2007; Taebi et al., 2011). The depth-averaged, steady momentum and mass balances for wave-driven flow over shallow reefs are described by

\[
g(h + \eta)\frac{\partial \eta}{\partial x_i} = -\frac{1}{\rho} \left( \frac{\partial S_i}{\partial x_i} - \tau_i^B + \tau_i^S \right),
\]

\[
\frac{\partial ((h + \eta)u_i)}{\partial x_i} = 0,
\]

where \(\eta\) is the mean sea-surface elevation, \(h\) is the mean water depth, \(u_i\) is the depth-averaged water velocity vector with cross-shore \((i = 1, x = x_i)\) and longshore \((i = 2, y = x_j)\) components, \(\rho\) is the water density, \(S_i\) is the radiation stress tensor (Longuet-Higgins & Stewart, 1964), \(\tau_i^B\) and \(\tau_i^S\) are the bed and surface stresses, and \(g\) is the gravitational acceleration. Advection of momentum and rotation are neglected in (1). Reef flat currents are forced by gradients in wave-driven radiation stress, primarily at the reef face and outer reef flat where waves break and transfer most of their momentum to the water column.

Analytic solutions of (1) and (2) for fringing reefs with a back lagoon have been developed to examine cross-shore currents over one-dimensional (1-D) reef transects (Hearn, 1999; Symonds et al., 1995; Gourlay & Colleter, 2005). Water level in the lagoon is set to the offshore water level assuming open communication between the lagoon and ocean. These studies demonstrate that the cross-shore gradient of radiation stress generated by breaking waves creates a positive sea-surface slope and the setup of the water level on the reef flat shoreward of the surf zone, followed by diminished wave amplitudes and a negative sea-surface slope on the reef flat toward the lagoon where setup is zero. The pressure gradient between the surf zone and lagoon, which drives a mean flow across the reef flat and into the lagoon, is balanced by bottom stress. Due to the relationship between the significant wave height and radiation stress \((H^2 \sim S_{xx})\), the magnitude of the current over the reef flat increases with offshore significant wave height (Hearn, 1999; Symonds et al., 1995; Gourlay & Colleter, 2005). More recently, Monismith (2014) developed an analytical model of steady two-dimensional (2-D) flow over a reef crest-lagoon system and found two limiting flow regimes, one with nearly uniform inflow across the reef face with alongshore flow that increases linearly toward an outflow channel, and a second with both flows localized near the outflow channel (suggestive of the circulation at Moorea, French Polynesia and Ofu, and American Samoa, respectively). For shore-attached fringing reefs with no back lagoon, the pressure gradient on the reef flat tends to be negligible resulting in weak cross-shore flows (Gourlay & Colleter, 2005).

A number of numerical modeling studies have been carried out for fringing reefs with lagoons, including Kaneohe Bay on the island of Oahu (Lowe et al., 2009a) and Ningaloo in Western Australia (Taebi et al., 2012; Van Dongeren et al., 2013). The Kaneohe Bay study utilized the Delft3D coupled wave and flow model to simulate the 2-D circulation within the bay. Hindcast model results showed good agreement with observations of both overall circulation patterns and wave setup on the reef (Lowe et al., 2009a). A numerical modeling study of Ningaloo utilized XBeach for both 1-D and 2-D simulations of the wave and circulation dynamics on the reef (Van Dongeren et al., 2013), which were in good agreement with observations described by Taebi et al. (2011). The model results of Van Dongeren et al. (2013) show alongshore variability of circulation features, with a prominent alongshore component of the current in the lagoon and toward the shoreward side of the reef flat. The Kaneohe Bay and Ningaloo reef studies illustrate the forcing mechanisms that drive the wave-driven circulation over fringing reefs; however, each of these studies considers a reef with a back lagoon, and flow over the shallow reef flat is primarily in the cross-shore direction.

Here we consider the second common morphological class of fringing reef for which the reef flat is directly attached to shore without a separating back lagoon. For shore-attached fringing reefs, 1-D (cross-shore)
dynamics often adequately represent the waves and water level variability on the reef flat (e.g., Vetter et al., 2010; Quataert et al., 2015); however, when outflow channels cut through the reef flat, both cross- and alongshore dynamics may be important. The effects of cross-reef channels on reef-flat circulation have been noted in previous field observations. At Pago Bay, Guam, just north of the study site considered here, appreciable alongshore and cross-shore flows directed toward a cross-reef channel were measured using dye-tracking experiments (Marsh et al., 1981). Alongshore flows also have been detected using dye measurements at Kapa’a reef, on the island of Kaua‘i in the Hawaiian Islands, and were hypothesized to be primarily wave driven and linked to a cross-reef channel (Inman et al., 1963; Köhn & Helfrich, 1957).

Based on a more extensive set of field measurements than available in the previous dye studies, we examine the drivers of alongshore current variability on a fringing reef flat. For the experiment considered here, the radiation stress gradients are negligible on the reef flat and wind stress is weak; hence, the alongshore component of (1) may be reduced to

$$g(h + \eta) \frac{\partial \eta}{\partial y} = -C_D |u|v.$$  

In (3), \(u = (u_1, u_2)\equiv(u, v)\), and we have invoked a quadratic drag law for the bed stress where \(C_D\) is a dimensionless drag coefficient that is determined typically from observations (Monismith, 2007; Rosman & Hench, 2011). We evaluate this dominant balance based on the field observations and find that an alongshore gradient in sea-surface elevation may occur on a reef flat if wave setup is not alongshore uniform, for example, at the mouth of a deep channel where wave breaking is suppressed. We note here that for the steep reef at Ipan where breaking is localized, the wave setup that drives this alongshore pressure gradient scales with incident wave height following the point break model of Vetter et al. (2010) and Becker et al. (2014).

We use statistical and analytical techniques to examine the dynamics of the circulation on the shallow reef flat at Ipan, Guam. We first describe the study site and outline the observational results. We then present an idealized analytical model that demonstrates how spatially variable breaking wave setup leads to an alongshore pressure gradient that is consistent with the observations. The simple analytical model provides an estimate of the near-field of the channel, taken here as the distance over which the wave-driven free surface elevation varies from 90% of its far-field value to zero and where the induced pressure gradient is largest. The analytical model suggests that the extent of the near-field scales as \(y_{90} = 1.62\delta\) for \(\delta<0.4\), where \(\delta\) is the aspect ratio (ratio of reef width to length) of the reef flat domain. From the observations informed by the analytical model, we estimate a drag coefficient, \(C_D \sim 0.01\), using a finite difference approximation to (3). The more sophisticated drag coefficient estimate of Lentz et al. (2017) is not utilized here as the water level on the shallow reef flat that is exposed at low tide does not vary significantly. We also demonstrate, using a longer observational record of currents in the channel, that the channel currents may be predicted in terms of offshore wave height at high tidal levels.

2. The Field Experiment

The reef in this study is on the southeast coast of Guam (Figure 1). The northern reef flat (north of the reef channel) is \(\sim400\) m wide and spans \(\sim2\) km from the channel to a small peninsula that separates it from another reef just to the north. To the south of the channel is a reef of roughly the same dimensions. The reef flat is shallow, the average depth is \(\sim0.5\) m during the experiment. We estimate the tidal elevation, \(h'\), by detrending the water level at the reef face sensor S8 yielding a tidal range of \(\sim0.6\) to 0.4 m over the 7-week deployment. During low tides, much of the reef flat is exposed. The reef flat is relatively smooth and composed mostly of algae-covered coral, which is generally flat and featureless, but does have some coherent ridge-like structures, which are \(\sim0.25\) m tall. Sandy areas and sea grass beds are interspersed among the coral, particularly in areas close to shore. The reef flat directly attaches to the shoreline, which is mostly rocky with some areas of narrow sandy beach. The reef face is steep, with a slope of \(\sim0.06\), and is characterized by a rugged spur and groove topography. At the reef rim, in the surf zone, the reef is slightly shallower than the reef flat, about 0.3 m, and is also very rugged, with both protruding rocks and deep holes in the surf zone.
The ~30-m-wide channel extends from the shore to the fore reef (30 m deep), with a wedge-shaped cross-reef profile. The channel has a sandy bottom and very steep sides, which can overhang and occasionally collapse, resulting in the deposition of scattered large boulders. The channel is a drowned river, and the Togcha River continues to drain a small watershed (5.72 km²) through the channel. The larger Ylig watershed drains into Pago Bay located approximately 3 km north of the channel (Luo & Khosrowpanah, 2012).

From August 2005 until the present, bottom-mounted pressure sensors (Seabird SBE26plus) and acoustic velocimeters with pressure sensors (Nortek Aquadopp and AWAC) have been deployed in numerous sampling configurations across the reef flat, reef face, and in the channel at Ipan as part of the PILOT project (Boc & Hathaway, 2011). This study focuses on the S-deployment that occurred from mid-December 2011 to early February 2012, when sensors were deployed in both a cross-shore and alongshore array, including a profiling current meter (Nortek AWAC) in the reef channel. We also consider the channel current over a longer 6-month deployment from mid-August 2011 to early February 2012 to compare with incident wave heights and tidal elevation in section 3.3. Sampling was conducted in either 1 -Hz bursts over one depth cell, or as 2-min averages with an average interval of 1 min over a number of depth cells. Details regarding sampling schemes are found in Table 1. The study site and sensor locations are shown in Figure 1.

Currents on the reef flat were measured using upward-looking Aquadopps. Measurements on the reef flat are considered when the water level above the center of the cell exceeds 15 cm, which takes into account blanking distance and acoustic backscatter thresholds. Velocity time series are depth averaged and time averaged over 30-min intervals centered on 15-min time stamps. As the North-South (NS) and East-West (EW) depth-averaged currents on the reef flat are only weakly correlated, the reef flat currents are used in...
geographic coordinates. In the deep channel, however, the depth-averaged currents are strongly correlated, and hence are presented both in geographic coordinates, and referenced to their principal axes. For the pressure sensors, the significant wave height is computed at 4 times the standard deviation of surface elevation over a 30-min burst band-passed between 0.04 and 0.3 Hz with the surface elevation obtained from bottom pressure based on linear wave theory. Local water level is calculated from 30-min averages of local pressure converted to meters, and, as mentioned above, the tide is approximated by the detrended water level at S8. These data may be found in “Data from: The influence of a cross-reef channel on the wave-driven setup and circulation at Ipan, Guam (2019).” Offshore conditions during the study period are obtained from the Coastal Data Information Program (CDIP) Datawell Waverider MkIII directional wave buoy, Ipan 121, deployed in 200-m water depth. All of the CDIP offshore wave data met quality control standards, and check factors and bulk wave parameters were computed from 30-min segments of time series data. Meteorological data are taken from the National Oceanographic and Atmospheric Administration (NOAA) weather station at Pago Bay. Wind and water velocity data follow the north/east positive convention for the u and v components, respectively. Wave direction is specified in compass format with 0° corresponding to waves traveling from the north.

3. Observations

3.1. Wind and Wave Observations

Offshore wave conditions during the deployment, which are typical for this region, are characterized by significant wave heights, \( H_{\text{buoy}} \), of ~2–3 m at CDIP buoy 121 with refraction leading to ~73% weaker incident wave heights, \( H_s \), at S8 on the reef face of the main array (Figure 2). Moderate to large amplitude wind and swell events frequently occur during winter, for example, the event that started around 7 January 2012 with \( H_{\text{buoy}} \) peaking at 3.6 m (\( H_s = 2.7 \) m at S8) on 10 January. A mixed diurnal and semi-diurnal tide prevails at Guam, with three spring-neap cycles occurring during the experiment. Persistent northeasterly trade winds with speeds of ~2 m s\(^{-1}\) occur throughout the deployment (Figure 2).

Wave breaking in a narrow zone over the steep reef face and reef edge reduces the incident significant wave height, \( H_s \), by an order of magnitude on the reef flat (Péquignet et al., 2011). Depth-limited breaking is evident through the significant high correlation (\( r > 0.9 \), where here and subsequently, \( r \) is the Pearson correlation coefficient, and significant implies a p value of 0.05 or less) between local wave height and water level at the pressure sensors across the reef face (Figure 3, the reef flat current meters do not sample in wave-burst mode). Pressure sensors along the main transect (see also Figure 4 of Becker et al., 2014) demonstrate that active breaking may occur at the reef crest (S6) with additional dissipation affecting the local wave height to water level relationship shoreward (S4). At the shoreline at the northern end of the study site (S2n), wave heights are reduced further than observed at midreef. While wave heights are not available at the shoreline of the main transect, S1, we find that wave height-water level estimates from other PILOT deployments at the location of S1 are consistent with those to the north at S2n. In contrast to the alongshore uniformity of the wave height to water level dependence of the shoreline sensors, the slope of the wave height to water level differs significantly for the two pressure sensors located near the middle of the reef flat (S5s and S4). The sensor closest to the channel (S5s) has the smallest wave height to water level ratio of all of the sensors consistent with its location in the near-field of the deep channel.
We estimate breaking wave setup at the reef flat sensors relative to the reef face sensor (S8, with significant wave height $H_s$) following Becker et al. (2014) here using 30-min average water levels and excluding water levels less than 10 cm. The point break setup model of Becker et al. (2014) for normally incident waves may be written as

$$\eta_i = \frac{5\gamma_s}{32}(H_s - 1.2H_r),$$

where $H_r$ is the residual significant wave height at a reef flat sensor where the setup is estimated, $\gamma_s$ is an empirical breaking parameter, and the factor of 1.2 multiplying $H_r$ is due to accounting for the setdown, $\eta_b \approx -\frac{1}{32}\gamma_s H_s$ at the reference sensor (see also Merrifield et al., 2014, equation 3). The regression removes trends in the pressure data and determines an offset so that setup is zero when $H_s - 1.2H_r = 0$ following (4).

We remark that for Ipan, $H_r$ at the reef flat sensors typically is small due to the shallow reef flat, and the setup estimates do not differ significantly from those obtained assuming $H_r$ is negligible as in Vetter et al. (2010).

For the current meters S1 (shoreline), S1n, and S3c (midreef), wave height estimates are not available for the setup regression offset; hence, we estimate $H_r$ from the local water level at those sensors using the wave height-water level relationship determined from 10 years of data at shoreline (IP1) and midreef (IP4) sensors at the main transect at Ipan (sensors from additional deployments at the shoreline and midreef on the main transect are designated as IP1 and IP4, respectively). For the main transect shoreline current meter S1, we perform a quadratic regression and find $H_r = -0.2h_e + 0.19h_t^2$ which, as mentioned above, is consistent with the wave height to water level dependence at the shoreline sensor (S2n) to the north of the main line (Figure 3). At the midreef sensor S4, we find that the residual wave height may be estimated by $H_r = 0.06h_e + 0.27h_t^2$. We use the regression for IP1 to estimate $H_r$ for the main transect shoreline current meter S1, and
Figure 3. The spatial variability of depth-limited breaking, $H_r$ versus local water depth $h_r$ at the sensors indicated (top panel), and breaking wave setup, $\eta_r$ (bottom panel) over the reef flat. The solid gray lines in the top panel are used for $H_r$ in the setup estimates at the current meters. For the shoreline current meter S1, the estimated $H_r$ from IP1 used in the setup estimates is shown in the gray line through S2n showing alongshore uniformity in depth-limited breaking. For the midreef current meters S1n and S3c, the estimated $H_r$ from IP4 used in the setup estimates is shown in the gray line through S4. The pressure sensor nearest the channel, S5s, demonstrates how the breaking wave setup decreases toward the channel (bottom panel).

Table 2

| Sensor | Correlation | Slope | Model | $\Delta y$ |
|--------|-------------|-------|-------|-----------|
| S1n   | 0.99        | 1.12  | 1.00  | 2,160 m   |
| S3c   | 0.98        | 0.96  | 0.99  | 1,280 m   |
| S6    | 0.95        | 0.56  | 0.99  | 730 m     |
| S4    | 0.93        | 0.87  | 0.97  | 740 m     |
| S1    | 0.94        | 0.90  | 0.92  | 760 m     |
| S5s   | 0.37        | 0.24  | 0.45  | 160 m     |

Note. Correlation and regression slope for setup estimated at the northern most shoreline sensor (S2n) and at the sensor locations listed. The correlation for the Model is between setup from the analytical model in the far-field ($\eta_0$) and at the approximate sensor locations. The approximate alongshore distance from each sensor to the channel sensor is indicated by $\Delta y$.

The regression for IP4 to estimate $H_r$ at the mid reef sensors S1n and S3c assuming alongshore uniformity north of the main transect. We note that the $H_r$ estimates only contribute to an offset in the setup estimates. Similar results are obtained taking $H_r = 0$ in the setup estimates at all sensors.

We extend the 1-D setup analyses of Vetter et al. (2010) and Becker et al. (2014) to assess the 2-D spatial variability of the setup over the fringing reef bounded at the south by the outflow channel using the $S$ deployment instrument array. As described previously (Becker et al., 2014; Vetter et al., 2010), the cross-shore variability of the setup along the main instrument line has setup increasing through the narrow break zone where radiation stress gradients are large with the setup tending to a near constant value across the reef flat shoreward (Figure 3 [bottom panel], S6 and S4). The setup estimate at the shoreline sensor S1 (not shown) approximates what observed at S4 (Table 2) consistent with weak cross-shore currents along the main instrument line (Vetter et al., 2010). At the northern sensors, we find the setup estimates at sensors S1n and S2n are highly correlated, but the setup decreases slightly shoreward (Table 2). The approximately 10% decrease in setup shoreward between sensors S1n and S2n is qualitatively consistent with an onshore current contributing to the setup balance through bottom stress (Apotsos et al., 2007).

The observations from the $S$ deployment reveal an alongshore gradient in setup due to the channel to the south where breaking of incident waves is inhibited and radiation stress gradient forcing is negligible. North of the main transect, the observed setup is largely uniform, with a strong decrease in setup south of the main array near the channel. To demonstrate this spatial variability, we compare the estimated setup at sensors over the reef referenced to the shoreline setup at the northern end of the study site (S2n). The estimated setup on the reef flat is highly correlated with that at S2n at all sensors except at S5s near the channel (Table 2). The far-field setup (S2n) decays gradually to the main sensor line and more rapidly toward the channel (S5s) where the estimated setup is the smallest observed (Figure 3). The regression coefficients between the estimated far-field shoreline setup at S2n and the highly correlated reef flat sensors (Table 2) show that the observed setup is nearly uniform alongshore between the northern end of the study site and S3c and decays to approximately 90% of the far-field shoreline setup at the main transect (S1, S4). The reef flat setup (Figure 4, S4) also shows tidal dependence with more setup observed at low tide than high for the same incident wave height (Becker et al., 2014). In contrast, the setup observed near the channel (S5s) is highest at high tide demonstrating the decreased importance of wave breaking (Figure 4). We remark that the setup estimates are obtained assuming alongshore uniform incident wave heights, $H_s$, which likely is not valid seaward of sensor S5s due to the channel. We find, however, that the setup estimate at sensor S5s is insensitive to decreasing the value of the incident wave height with only a small change in the offset of the setup estimate found.

3.3. Current Observations

The depth-averaged mean currents over the reef flat, time averaged over the 7-week deployment are $<u,v> = (−0.19,−0.10) ± (0.005,0.006)$, $(−0.12,−0.20) ± (0.002,0.004)$, and $(0.05,−0.34) ± (0.004,0.003)$ m s$^{-1}$ at sensors S1n, S3c, and S1, respectively (Figure 5). The standard errors in the mean currents are estimated assuming that current observations...
12 hr apart are independent. As described in section 2 above, the currents considered here exclude low reef flat water levels when the reef is exposed. These mean reef flat currents reveal a circulation pattern where the flow transitions from predominantly alongshore at the current meter nearest the channel (sensor S1) to dominantly cross-shore (onshore) at the current meter farthest from the channel (S1n). In the channel (Sch), the deployment-averaged, depth-averaged mean current in geographic coordinates is \( \langle u, v \rangle = (0.20, -0.14) \pm (0.002, 0.001) \). As the channel currents in geographic coordinates are significantly correlated, we rotate the channel currents into principal axes and define the along-channel current in these principal axes as \( u_{ch} \). We find that \( u_{ch} = 0.25 \pm 0.002 \text{ m s}^{-1} \) over the full range of tidal levels during the 7-week deployment. We remark that the angle of rotation of the channel current in its principal axes is \( -123^\circ \) which does not align with the bathymetric channel axis and may be due either to the local bathymetry of the channel at the position of the AWAC or to uncertainties in the bathymetry. Consistent with the reef flat circulation pattern, 30-min mean along-channel currents, \( u_{ch} \), are significantly correlated with the alongshore currents at sensors S1 and S3c (\( r = -0.60 \) and \(-0.66\), respectively) but are not significantly correlated with the alongshore current at the northern current meter S1n. A weak significant correlation (\( r = 0.20 \)) between \( u_{ch} \) and the cross-shore current at sensor S1n, however, is observed (Figure 6, top panel).

The reef flat and channel currents that make up the circulation pattern described above also are significantly correlated with the buoy wave height, \( H_{buoy} \) from CDIP 121 (and the incident wave height \( H_s \) at S8). The correlation between \( H_{buoy} \) and the alongshore currents at S3c and S1 is \( r = -0.72 \) and \( r = -0.78 \), respectively. The correlation between \( H_{buoy} \) and the cross-shore current is weak (\( r = -0.11 \)) at S1n, consistent with the weak correlation between this cross-shore current and \( u_{ch} \) as described above. The 30-min depth-averaged, along-channel current is related to wave height as well as tidal level (Figure 6, bottom panel, and Figure 7). For high tidal elevations (\( h' > 0 \)), the along-channel current \( u_{ch} \), defined as the principal axis of the vector current, is significantly correlated with \( H_{buoy} \) (\( r = 0.93 \)), with \( u_{ch} = a H_{buoy} + b \), \( a = 0.21 \pm 0.02 \text{ s}^{-1} \), and \( b = -0.08 \pm 0.06 \text{ m s}^{-1} \) (95% confidence intervals, assuming independent data points every 12 hr). Thus, at high tide, the seaward flowing channel current increases by 0.21 m s\(^{-1}\) for every 1 m increase of the incident significant wave height.

## 4. Analytical Model

We next demonstrate that the observed 2-D spatial variability of the reef flat setup described in section 3.2 is consistent with an idealized analytical model that depends upon the aspect ratio of the reef (the ratio of the reef width to length) and the far-field setup. As the observed mean circulation is significantly correlated with wave height (section 3.3), and consequently, the breaking wave setup, we use the simple model to complement the sparse observations and to inform estimates of the pressure gradient at the locations where current observations are available. The pressure gradient estimates and current observations then are used to obtain an estimate of the drag coefficient for Ipan reef using (3).
A simple analytic model also provides an estimate of the near-field of the channel as a function of the aspect ratio. The near-field of the channel is defined here as that region where the water level is less than 90% of its far-field value.

The alongshore variations in breaking wave setup over the reef flat due to reduced wave breaking at the channel may be described by the steady-state dynamics (1) and (2) and boundary conditions for an idealized rectangular reef of length $L_r$, width $W_r$, and constant depth $h_r$. On the reef flat, we neglect radiation stress gradients and surface wind forcing in (1) and force the model through the inhomogeneous boundary conditions specified below. For simplicity, we approximate the bottom stress with linear drag following (Monismith, 2007) to obtain

$$g\nabla \eta = -r_d \frac{u}{h},$$

where $h = h_r + \eta$ is the total water level on the reef flat and $r_d$ is a drag coefficient. In section 5.2 below, we show that the bottom stress $r_b$ from (1) is significantly correlated with the observed pressure gradient when modeled with a quadratic drag law as in (3) or with the linear drag law of (5). Approximating $h \approx h_r$, taking the divergence of (5) and invoking (2), we obtain

$$\nabla^2 \eta = 0, \quad 0 < x < W_r, \quad 0 < y < L_r.$$  

The effect of the channel is to reduce the setup to zero at the southern end of the reef flat where wave breaking is inhibited. We impose the boundary conditions of uniform (far-field) setup, $\eta_0$, at the northern and eastern boundaries of the reef flat with zero setup at the southern boundary due to the channel and nonnormal flow at the shoreline (western boundary) yielding

Figure 6. Time series of the 30-min mean, depth-averaged along-channel (Sch: $u_{ch}$), cross-shore (Sn1: $u$), and alongshore (S3c: $u$, S1: $v$) reef flat currents over the 7-week deployment (top panel) and time series of the along-channel current (Sch: $u_{ch}$) and the CDIP buoy 121 significant wave height over the 6-month deployment (bottom panel). The gray shading on the bottom panel delineates the 7-week deployment.

Figure 7. Thirty-minute mean depth-averaged along-channel currents as a function of CDIP buoy wave height, $H_{buoy}$, colored with the tidal level, $h'$. 

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\[ \eta = \eta_0, \quad (x = W_r, \quad 0 < y < L_r, \quad y = L_r, \quad 0 < x < W_r), \]
\[ \eta = 0, \quad (y = 0, \quad 0 < x < W_r), \quad \frac{\partial \eta}{\partial x} = 0, \quad (x = 0, \quad 0 < y < L_r). \]

We nondimensionalize the dynamics according to
\[ x = W rx, \quad y = L ry, \quad \eta = \eta_0 \eta_s, \]

to obtain
\[ \frac{\partial^2 \eta_s}{\partial x^2} + \delta^2 \frac{\partial^2 \eta_s}{\partial y^2} = 0, \quad (7) \]

where \( \delta = \frac{W_r}{L_r} \) is the aspect ratio of the reef, subject to the boundary conditions
\[ \eta_s = 1, \quad (x_s = 1, \quad 0 < y_s < 1, \quad y_s = 1, \quad 0 < x_s < 1), \]
\[ \eta_s = 0, \quad (y_s = 0, \quad 0 < x_s < 1), \quad \frac{\partial \eta_s}{\partial x_s} = 0, \quad (x_s = 0, \quad 0 < y_s < 1). \quad (8) \]

We solve (7) and (8) as a function of aspect ratio, \( \delta \), to determine the spatial variability of the setup and to estimate the region of influence (near-field) of the channel. The steady-state linear model is straightforward to solve by separation of variables. We obtain the solution to (7) and (8) by superposing the uniform solution of (7), \( \eta_s = 1 \) everywhere, and the solution of (7) subject to
\[ \eta_s = 0, \quad (x_s = 1, \quad 0 < y_s < 1, \quad y_s = 1, \quad 0 < x_s < 1), \]
\[ \eta_s = -1, \quad (y_s = 0, \quad 0 < x_s < 1), \quad \frac{\partial \eta_s}{\partial x_s} = 0, \quad (x_s = 0, \quad 0 < y_s < 1), \quad (9) \]

yielding the solution of (7) and (8) as
\[ \eta_s = 1 + \sum_{n=1}^{\infty} A_n \cos k_n x_s \sinh k_n y_s (y_s - 1), \quad (10) \]

where
\[ A_n = \frac{2(-1)^{n+1}}{k_n \sinh k_n}, \quad k_n = \frac{(2n - 1)\pi}{2}, \quad k_n = \frac{k_n}{\delta}. \quad (11) \]

Color maps of \( \eta \) and its partial derivatives are shown in Figure 8 for an aspect ratio representative of Ipan (\( \delta = 0.2 \)). For the boundary conditions chosen here, the Gibbs phenomenon (e.g., Greenberg, 1998, p. 854) is evident at the southern (channel) boundary. In Appendix A, we consider alternative boundary conditions that suppress the Gibbs phenomenon and demonstrate the robustness of the analytical solution.

The idealized model is qualitatively consistent with the reef flat setup observations (Table 2 and Figure 8) with sensor S3c located in the far-field approximately 1.3 km to the north of the channel. The observed setup at S3c is \( \sim 96\% \) of the far-field setup taken as that observed at northern most shoreline sensor S2n. The model predicts that the setup at the approximate location of S3c is \( \sim 99\% \) of the far-field setup \( \eta_s \). Sensor S1, approximately 760 m to the north of the channel is located near the edge of the near-field with the observed setup \( \sim 90\% \) of far-field value observed at S2n. For S1, the model predicts a setup that is \( 92\% \) of the far-field setup consistent with that observed. Near the channel at the approximate location of S5n, the model predicts setup that is \( 45\% \) of the far-field value which is larger than that observed (24\%) but consistent with the S5s being located in the near-field of the channel.

The idealized model of the effect of a channel on the reef flat setup next is used to provide a measure of the alongshore distance from the channel for which the setup exhibits significant spatial variability. We define the near-field of the channel as that alongshore distance for which the setup is less than \( 90\% \) of the far-field
value. For an aspect ratio similar to the present study site (Figure 8, \( \delta \sim 0.2 \), e.g., \( L_r \approx 2,000 \text{ m}, W_r \approx 400 \text{ m} \)), the near-field of the channel for the shoreline setup (\( x_0 = 0 \)) is approximately 32\% of the reef length (Figure 8). As is intuitively obvious, for smaller aspect ratios, the effect of the channel on the setup is localized to the vicinity of the channel, whereas for an aspect ratio of 0.5, the shoreline position of the near-field of the channel extends to \( \sim 74\% \) of the reef length (Figure 9). The shoreline position (\( x_0 = 0 \)) of the near-field as a function of aspect ratio may be approximated from (10) and (11) according to

\[
\eta_*(0, y_*) \approx 1 + A_1 \sinh k_{1d} (y_* - 1) \approx 1 \frac{2}{k_1} \exp(-k_{1d} y_*). \tag{12}
\]

For \( \eta_*(0, y_*) = 0.9 \), (12) yields \( y_* \approx 1.625 \) which is within 3\% of the exact solution for \( y_* \) obtained from (10) and (11) for \( \delta \leq 0.4 \) (Figure 9).

5. The Alongshore Momentum Balance

The observations suggest that the dominant alongshore balance on the reef flat is between the pressure gradient due to the spatially varying setup and the bottom stress, here assumed to follow a quadratic drag law, (3), as the wind stress and other forcing terms are unlikely to be important. Wind velocities during the deployment are \( \sim 2 \text{ m s}^{-1} \) from the northeast (Figure 2). The calculated alongshore surface stress is two orders of magnitude smaller than the estimated bed stress and thus not considered further. Tides may influence currents on the reef flat either by generating an ebb-flood circulation or by tidal modulation of the wave-driven currents (Hearn, 1999; Symonds et al., 1995; Taebi et al., 2011). Because the reef flat at Guam is exposed at low tide, it is difficult to assess the importance of tidal forcing based solely on the observations, however, the significant correlations between incident wave height, and the reef flat and channel currents suggest that the alongshore flow is driven by pressure gradients due to the spatially varying setup, described in (3).

5.1. Alongshore Pressure Gradients

We estimate the alongshore derivative of the setup \( \frac{\partial \eta}{\partial y} \) at the current meters S3c and S1 first by considering the analytic solution for the reef flat setup (Figure 8, right panel). The simple model reveals that the alongshore pressure gradient is larger near the channel and is negligible far from the channel. For \( \delta = 0.2 \), the analytic solution suggests that the ratio of the pressure gradient at the approximate location of the mid reef sensor S3c is \( \sim 1/3 \) of that at S4 along the main deployment line for \( \delta = 0.2 \) (Figure 8). We approximate the alongshore pressure gradient from the observations using a center-difference approximation with the pressure gradient at sensor S3c estimated by differencing the setup at sensors S1n and S4 and that at sensor S1 by differencing the setup at sensors S3c and S5s and dividing by the alongshore separation of the sensors. The pressure gradients estimated at S3c and S1 are significantly correlated \( (r = 0.84) \), with a slope of approximately 0.3, suggesting that the center-difference approximation provides a reasonable estimate of the local pressure gradients at the current meters S3c and S1.

5.2. Friction on the Reef Flat

To determine an empirical drag coefficient for Ipan, a regression analysis is carried out for the terms in the alongshore momentum balance with the quadratic drag law, (3), estimated from the observations. The alongshore derivatives of the setup on the left-hand side (lhs) of (3) for sensors S3c and S1 are estimated with center differences as described in section 5.1, with \( h \) replaced by the local 30-min average water level at each sensor, respectively. The 30-min average currents at S3c and S1 are used in the right-hand side (rhs) of (3). These estimates of the rhs and lhs of (3) are significantly correlated \( (r = 0.90) \), and we find \( C_D = 0.01 \pm 0.001 \) (Figure 10) which is similar to a previous estimate of the drag coefficient at Ipan \( (C_D \approx 0.006) \) based on an

![Figure 8. Color maps of the free surface elevation and its partial derivatives obtained from (10) to (11) for an aspect ratio \( \delta = 0.2 \). Gibbs phenomena is evident at the southern boundary due to the discontinuity in the inhomogenous boundary conditions (but see Appendix A). Approximate locations of the sensors used in the estimates of the drag coefficient are indicated on the free elevation color map.](image-url)
assessments of the cross-shore momentum balance during larger wave conditions and hence larger reef flat water levels due to breaking wave setup (Vetter et al., 2010). We remark that the linear drag law used in (5) also reveals significant correlation ($r = 0.82$) between the pressure gradient estimated at S3c and S1 and the observed $v/h$ at these current meters with an inferred linear drag coefficient $r_d = 0.003 \pm 0.0003$ m s$^{-1}$.

The $C_D$ value estimated here is similar to that reported for other reefs (Rosman & Hench, 2011). For example, estimates based on turbulent Reynolds stress measurements at a fringing reef in the Gulf of Aqaba, Red Sea ranged from 0.009 to 0.015 (Reidenbach et al., 2006). Larger estimates of the drag coefficient have been found based on field measurements of pressure gradients at Kaneohe Bay, where $C_D = 0.02$ (Hearn, 1999; Lowe et al., 2009b) and at PaoPao Bay, Moorea, where $C_D = 0.1$ (Hench et al., 2008). Recently, Lentz et al. (2017) synthesized new observations with existing estimates and found that coral reef drag coefficients range from 0.4 to 0.005, with the lower values occurring in deeper water or for smoother reefs. The estimated $C_D = 0.01 \pm 0.001$ for Ipan for the average reef flat water level of 0.5 m is consistent with those drag coefficients for a coral reef, albeit on the lower end.

The lower value of the drag coefficient estimated for Ipan likely is due to the smoothness of the reef flat compared to other reef locations. As noted previously, although the reef face at Guam has live coral with a rugged spur and groove structure, the reef flat is primarily composed of algae-covered dead coral. It is relatively flat and featureless, with only small ridges crossing the reef flat. Coral heads and other coral structures that increase friction on other reef flats (Monismith, 2007) are absent at Ipan.

6. Summary and Discussion

Reef flats similar to Ipan are common throughout Guam and may be found in other parts of the world as well. Although wave-driven currents on shallow reef flats are predominantly in the cross-shore direction, with alongshore flows constrained to deeper back-reef lagoons (e.g., PaoPao, Moorea Hench et al., 2008), the mean currents at Ipan across the reef flat are dominated by the alongshore current due to the presence of the cross-shelf channel. Elevated water levels on the reef flat due to breaking wave setup force flow along the reef and out the channel for all wave conditions sampled. Current observations indicate that the flow as far as 2.2 km away is affected by the channel, with a reef flat circulation pattern significantly correlated with incident wave height and revealing onshore flow in the far-field, and alongshore flows directed toward the channel, regardless of wave conditions. A steady rip circulation thus is established, modulated by wave height, that is active except when the water level falls below the level of the reef flat during low tides. A longer, 6-month record of channel currents reveals that buoy wave heights at high tidal elevations may be used to predict the along-channel currents at Ipan.

Estimates of breaking wave setup over the 2-D sensor array reveal a slight decrease in setup shoreward at the northernmost sensors due to the onshore current. The setup is largely uniform in the far-field of the channel and decreases sharply at the sensor nearest the channel. A simple analytical model is presented that is consistent with the observed spatial variability of the setup and also informs the estimates of the alongshore pressure gradients from the sparse observations. The analytical model provides an approximation to the near-field of the channel, here defined as the region where the setup is less than 90% of its far-field value. In the near-field of the channel, the setup decreases to zero over an alongshore shoreline position that

Figure 9. The near-field as a function of aspect ratio for the analytic model. Contours where the analytic free surface elevation given by (10) and (11) is 90% of its far-field value are presented for various aspect ratios. For $\delta < 0.4$, the shoreline position delimiting the near-field is well approximated by $y_\ast = 1.62\delta$. The dashed lines are from the Appendix A solution with (A2) replacing (11) in (10) that limits the effects of Gibbs phenomena.
may be approximated by \( y = 1.62 \delta \), for \( \delta < 0.4 \), where \( \delta \equiv \frac{W}{L_r} \) is the aspect ratio of the reef flat. We note here that the blocking headland to the north of the study site sets the alongshore length scale, \( L_r \), used here.

The dominant momentum balance on the reef flat between the alongshore pressure gradient and bed stress, assuming a quadratic drag law (3), yields a drag coefficient of \( C_D = 0.01 \pm 0.001 \) that is at the lower end of

![Figure 10](image1.png)

**Figure 10.** Estimating the drag coefficient. The left-hand side of (3) as a function of the right-hand side of (3) without \( C_D \) at the current meters S3c and S1 (left panel). The black line is the least squares fit yielding \( C_D = 0.01 \pm 0.001 \) where the error is the 95% confidence interval assuming observations separated by 12 hr are independent. Time series of the right- and left-hand sides of (3), respectively, for S3c: magenta/red and S1: cyan/blue with \( C_D = 0.01 \) (right panel).

![Figure 11](image2.png)

**Figure 11.** Satellite photo of the reef flat at Ipan, showing lines of reef substrate running in the approximate direction of the observed circulation.
values obtained in previous reef studies (Lowe et al., 2009b; Taebi et al., 2011; Lentz et al., 2017). The value of $C_D$ is consistent with the smooth, featureless nature of the the Ipan reef flat, as well as with that estimated previously from the cross-shore momentum balance during a large wave event at Ipan (Vetter et al., 2010). The simple analytical model presented here captures the spatial variability of the alongshore pressure gradients over the shallow fringing reef. Our analytical model differs from the 2-D circulation model of Monismith (2014) and others notably in the way that the boundary condition is applied at the offshore edge of the reef platform. Monismith (2014) prescribes the incident volume flux over the reef crest, which is well suited for a channelized flow along the lagoon and out the channel. At Ipan, the presence of a reef platform makes it difficult to specify the incident transport without additional observations. For example, the net transport is weak in the far-field of the channel, where the dynamics approach 1-D. Lacking observations of how the shoreward transport varies along the outer reef from the channel to the far-field, we instead specify the setup height along the outer reef, which is assumed to be constant based on direct observations. This allows a mapping of the setup elevation over the reef, from which flow characteristics can be inferred.

We remark that a cross-reef channel is effective at decreasing residence times of water parcels over a reef flat. Over long time scales, the strong alongshore flows established may lead to scouring and the eventual establishment of a prototypical back-reef lagoon morphology (Xue, 2001). Aerial photographs show lines in the substrate running across the reef flat approximately in the direction of the measured currents in this study, indicating the ability of the steady alongshore flows to affect the back reef geomorphology (Figure 11). Finally, given even weak incident wave conditions, it is likely that flows in cross-reef channels similar to that at Ipan will be directed offshore, in the form of a permanent rip cell. The strength of the channel flow will be modulated by water level on the reef, and a combination of high waves and high tides yield particularly dangerous flow conditions in these reef channels.

**Appendix A**

For the simple analytic model, we note that the solution (10) exhibits Gibbs phenomena (Figure 8) at the southern boundary as $\eta_s = 0,(y_s = 0,x_s \to 1)$ and $\eta_s = 1,(x_s = 1,y_s \to 0)$ for the boundary conditions (8). To assess the effects of Gibbs phenomena at the southern boundary on the spatial variability of the setup, we impose an alternative southern boundary condition to (9) that takes the imposed setup at the southern boundary smoothly to $-1$ at the eastern boundary:

$$\begin{align*}
\eta_s &= 0, \quad (x_s = 1, \quad 0 < y_s < 1, \quad y_s = 1, \quad 0 < x_s < 1), \\
\eta_s &= x_s^m - 1, \quad (y_s = 0, \quad 0 < x_s < 1), \quad \frac{\partial \eta_s}{\partial x_s} = 0, \quad (x_s = 0, \quad 0 < y_s < 1),
\end{align*} (A1)$$

where $m$ is an integer. For $m = 4$, for example,

$$A_n = \frac{2(12k_n^2 - 24)(-1)^n+1}{k_n^5 \sinh k_{nd}} \quad (A2)$$

in (10) provides the solution of (7) subject to (A1) that is quantitatively similar to the solution of (7) and (9). In Figure 9, we present the contour lines for comparison for which $\eta$ is 0.9 of its far-field value for (10) with (A2) in place of (11) to demonstrate the small effect of the Gibbs phenomena on the spatially variable setup.

**Data Availability Statement**

The Pago Bay wind data are available from the National Data Buoy Center (Station PGBP7), and the buoy wave data are available from the Coastal Data Information Program (CDIP, Station 121). The wave heights, water level, currents, and sensor locations used in this study may be obtained from the UCSD Data Repository, Digital Collections, “Data from: The influence of a cross-reef channel on the wave-driven setup and circulation at Ipan, Guam (2019),” https://doi.org/10.6075/J01V5C9V.
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