Eulerian and Lagrangian measurements of water flow and residence time in a fringing reef flat-lined embayment: Faga’alu Bay, American Samoa

by

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Abstract

Water circulation is an important control on nutrient cycling, larval dispersal, and temperature variability in nearshore ecosystems, and interacts with terrestrially-derived sediment, nutrients, and contaminants to determine watershed impacts on coral reef ecosystems. We characterized water circulation patterns and residence times in relation to end-member forcing conditions in a reef-fringed embayment in American Samoa. Lagrangian GPS-enabled drifters were deployed at 5 different locations 30 times over a 2 week period. Current profilers installed at fixed locations collected continuous Eulerian flow data during different forcing conditions. Mean current speeds (residence times) varied widely, from 1-20 cm s-1 (2.8-0.14 h), 1-19 cm s-1 (2.8-0.15 h), and 1-36 cm s-1 (2.8-0.08 h) under strong wind, tidal, and large wave forcing, respectively. Flow speeds were highest and residence times shortest over the exposed southern reef near the reef crest. The slowest flow speeds and longest residence times occurred over the sheltered northern reef, close to shore, and in the deep paleostream channel incised in the reef. During large wave forcing, flows followed a clockwise pattern: onshore over the exposed southern reef, onto the sheltered northern reef, and out to sea through the channel. Flow directions during tidal forcing were the most variable, with some seaward transport from the reef flat to the fore reef. Under onshore wind forcing, flow directions were mostly into the embayment. Lagrangian estimates of mean flow speeds were 51-195% higher than Eulerian estimates. The discrepancy between methods was attributed to spatial heterogeneity of flows sampled by the drifters, the difference between surface and depth-averaged flow speeds, Stokes drift, or a combination of all of these. The results demonstrate a hybrid Lagrangian-Eulerian measurement scheme to understand long-term, spatially-distributed flow patterns and residence times for biophysical studies in geomorphically-complex embayments that characterize many reef-lined coasts.

Keywords:

coral reefs, Lagrangian drifters, water circulation, residence time, tides, waves, winds

Introduction

Water circulation and residence time control the chemistry, biology, and sediment dynamics of coral reefs (Lowe and Falter 2015). Biologically-important processes like nutrient cycling, larval dispersal, and temperature regimes are affected by the residence time and flow paths of water, which interacts with benthic organisms to alter water quality (Falter et al. 2004; Wyatt et al. 2012; Herdman et al. 2015). By influencing orbital velocities, bed shear stress, and suspended sediment transport, hydrodynamic conditions are a primary control on the spatial distribution of deposition, resuspension, and dispersal of terrigenous sediment discharged from streams (Hoitink and Hoekstra 2003; Storlazzi et al. 2004; Presto et al. 2006; Draut et al. 2009; Hoeke et al. 2013). The response of corals to terrestrial sediment stress is primarily a function of the magnitude of sediment concentration and the duration of time the corals are exposed (Erftemeijer et al. 2012), which is controlled by hydrodynamic conditions.

Spatially-distributed flow patterns under variable forcing conditions are logistically difficult to quantify, so conservation planning and remediation studies often use coarse estimates of pollutant discharge and distance-based plume models that assume symmetry in flow fields (Klein et al. 2012). Hydrodynamic conditions can exacerbate or limit the impacts of terrestrial sediment from disturbed watersheds on coral reefs (Hoitink and Hoekstra 2003). An improved understanding of the spatial patterns and temporal variability in flows and residence times of water over corals is needed for understanding sedimentation patterns and their impacts to coral health.

Studies in various fringing reefs adjacent steep volcanic islands have shown that current speeds, directions, and residence times over reef flats are controlled by wave, wind, and tidal forcing (Storlazzi et al. 2004; Presto et al. 2006; Hench et al. 2008; Storlazzi and Field 2008; Hoeke et al. 2011). Variations in reef morphology relative to the orientation of meteorological and oceanographic forcing can generate heterogeneous waves and currents over small (hundreds of meters) spatial scales, unlike those observed along linear sandy shorelines (Storlazzi et al. 2009; Hoeke et al. 2011, 2013). Currents over reefs exposed to remotely generated swell are generally dominated by wave forcing (Hench et al. 2008; Vetter et al. 2010; Hoeke et al. 2011), whereas wind forcing dominates reefs protected from swell (Yamano et al. 1998; Presto et al. 2006). Tidal elevation modulates both wave-driven currents by controlling wave energy propagation onto the reef flat (Storlazzi et al. 2004; Falter et al. 2008; Taebi et al. 2011), and wind-driven currents by regulating water depth for wind-driven wave development (Presto et al. 2006). Flows over wave-driven, fringing reefs typically exhibit a pattern of rapid, cross-shore flow near the reef crest that slows moving shoreward and turns along-shore towards a deep channel where water returns seaward (Hench et al. 2008; Lowe et al. 2009a; Wyatt et al. 2010). In wind-driven systems, current directions are more predominantly in the direction of the wind with possible cross-shore exchange over the reef crest (Storlazzi et al. 2004). In reality, forcing conditions can operate in combination, and areas near the reef crest may be strongly controlled by wave-forcing while lagoon areas may be unaffected by waves, and flushed only by tidal or wind-forcing (Lowe et al. 2009b).

Water flow can be quantified in two ways: 1) the Lagrangian perspective observes a fluid parcel as it moves through space and time, whereas 2) the Eulerian perspective observes flow past a fixed location over time. Eulerian methods are well-suited to characterizing flows over long periods to sample a large range of forcing conditions using bottom-mounted instruments to measure tides, waves, and currents (Presto et al. 2006; Storlazzi et al. 2009; Vetter et al. 2010). Research on rip currents in beach surf zones used large numbers of GPS-logging drifters to collect high-density flow observations and synoptic measurements of small-scale flow patterns (Johnson et al. 2003; MacMahan et al. 2010) and the approach is becoming more common in shallow fringing-reef environments (Falter et al. 2008; Wyatt et al. 2010; Pomeroy et al. 2015).

Lagrangian drifter studies in nearshore environments have generally been limited in number of drifters, number of deployments, and the range of oceanic and meteorological conditions experienced during deployments, making it uncertain whether they describe the dominant patterns, or short-lived anomalies (Storlazzi et al. 2006; Wyatt et al. 2010). Storlazzi et al. (2006a) and Andutta et al. (2012) successfully combined Eulerian and Lagrangian methods to investigate transport patterns between adjacent reefs and islands by comparing Lagrangian drifter tracks with progressive vectors of cumulative flow calculated from Eulerian current meters to determine if short-term observations from drifters were representative of the dominant patterns.

Our objective was to apply both Eulerian and Lagrangian methods in a rapid assessment technique to understand the spatial flow patterns, residence times, and their responses to different forcing conditions in a bathymetrically-complex, fringing coral reef-lined embayment. The study uses a spatially and temporally dense set of drifter deployments to characterize flow patterns across a reef. The measurements were sufficiently dense to produce gridded data on flow velocities and residence times at a 100 x 100 m resolution, which were then used to identify dominant circulation patterns under different wind, wave and tidal conditions. The research questions were: How are currents and residence times influenced by high waves, high winds, or calm conditions? How do currents and residence times vary spatially on the reef flat?

Materials and Methods

*Study Area*

Faga'alu Bay is situated on the western side of Pago Pago Bay on the island of Tutuila, American Samoa (14.290 S, 170.677 W) (Figure 1). The bay is surrounded by high topography that blocks wet-season northerly winds from October-April, but is exposed to dry-season southeasterly trade winds and accompanying short-period wind waves during May-September (Craig 2009). A semi-diurnal, microtidal regime exposes parts of the shallow reef crest and reef flat at extreme low tides. Faga'alu Bay is only open to south to southeast swell directions, and the more southerly angled swell must refract to the west, reducing their energy. Offshore significant wave heights (*Hs*) are generally less than 2.5 m and rarely exceed 3.0 m. Peak wave periods (*Tp*) are generally about 9 s or less, rarely exceed 13 s, but occasionally reach 25 s during austral winter storms (Thompson and Demirbilek 2002). Vetter (unpublished data) recorded *Hs* up to 1.7 m on the fore reef in Faga'alu, but *Hs* greater than 1.0 m were rare. Tropical cyclones typically occur in the South Pacific from November-April (Militello et al. 2003), impacting American Samoa every 1-13 years since 1981 (Craig 2009).

Faga’alu Bay is a V-shaped embayment adjacent a small (2.48 km2), steep-sided watershed that discharges large amounts of sediment during storm events from a single stream in the northwest corner of the Bay (Messina and Biggs, In Press). The bathymetrically complex reef is characterized by a shallow reef flat extending from shore to the reef crest, where it descends at an approximately 1:1 slope to an insular shelf at approximately 20 m depth. Near the reef crest, the reef flat is primarily cemented reef pavement, but within a few 10s of m, transitions into thickets of primarily *Acropora spp.*; closer to the shore in the southern back-reef there are areas of deeper (1-5 m) sediment-floored pools with coral bommies (“back-reef pools” in Figure 1). An anthropogenically-altered, vertical-walled, 5-15 m deep paleostream channel (Figure 1) extends from the mouth of Faga'alu Stream eastward to Pago Pago Bay; this channel divides the reef into a larger, more exposed southern section (“southern reef” in Figure 1), and a smaller, more sheltered northern section (“northern reef” in Figure 1). See Cochran et al. (2016) for a detailed description of the bathymetry. Surveys in 2015 found coral coverage varied from less than 10% on the degraded northern reef, to more than 50% on the more intact southern reef (Cochran et al. 2016).

Lagrangian Measurements

Given the relatively small area of Faga'alu Bay (0.25 km2), high spatial density data could be collected with a small number of drifters (*n* = 5) with rapid turn-around. Five cruciform drifters were constructed, adapted from the design of Austin and Atkinson (2004), with a small waterproof housing for a HOLUX M1000 GPS recorder and a float collar to maintain upright orientation (Figure 2a-b). The fins of the drifters were approximately 30 cm wide and 18 cm in height, constructed of 1.3 cm diameter PVC with holes drilled to flood the piping. The GPS logger was installed in 5 cm dia. PVC housing at the top, extending 7 cm above the fins, though when deployed it only rose ~3 cm above the water surface (Figure 2b).

The five drifters were deployed 30 times from 19 January 2014 to 23 February 2014 (2014 Year Day [YD] 19-54), with 22 of those deployments coinciding with acoustic doppler current profilers (ADCP) deployment (February 16-24) (Appendix Table A1). Drifters were released from five separate launch zones (Figure 1) within a 10 minute period at the beginning of each deployment. Drifter position was recorded by the GPS logger at 5 s intervals and averaged to 1 min intervals to increase signal-to-noise ratios; speed and direction were calculated using a forward difference scheme on the drifter locations (Davis 1991; MacMahan et al. 2010). Drifters were generally allowed to drift until they exited the channel, but tracks were limited to 1 h for comparisons with simultaneous ADCP data.

Eulerian Measurements

Three Nortek Aquadopp 2-MHz acoustic doppler current profilers (ADCP) recorded current data at three locations on the reef flat for one week (YD 47-55, 2014) (Figure 1). The ADCPs were deployed on sand or rubble patches among the corals, as deep as possible to maintain adequate water levels over the ADCP during low tide (Figure 2c-d). Deployment depths were 0.97 m (AS1), 1.30 m (AS2), and 0.34 m (AS3). ADCPs collected a vertical profile of current velocity every 10 min, averaged from 580 samples collected at 2 Hz. Each vertical profile is composed of eight 0.2-m bins starting from 0.35 m above the seabed, using a blanking distance of 0.1 m. Measurements with a signal strength (amplitude) of ≤ 20 counts were removed, and the top 10% (from the water surface level) of each profile was removed as well. Occasionally during low tides AS3 was emergent and thus no usable data were available during these time periods. Flow was assumed to be nearly zero during these times given the low water depth relative to the height of the corals, many of which were above the water surface. Human disturbance caused a short data gap at AS1 on YD 50.

Ancillary Data

The instrument deployments were timed to capture “end-member” hydrodynamic forcing conditions that characterize the study area, such as high winds, high waves, or calm conditions (Yamano et al. 1998). This approach isolates the influence of wind-driven and wave-driven forcing to determine the dominant flow patterns caused by these forcings. End-member periods were defined post-deployment using modeled and in situ wave, wind, and tide data following the methodology described by Presto et al. (2006). Incident wave conditions were recorded by a NIWA Dobie-A wave/tide gauge (DOBIE) deployed on the southern reef slope at a depth of 10 m. The DOBIE sampled a 512-s burst at 2 Hz every hour. The DOBIE malfunctioned and recorded no data coinciding with the ADCP deployment, but compared well (not shown) with NOAA/NCEP Wave Watch III (WW3; Tolman, 2009) modeled data on swell height and direction (Hoeke et al. 2011). WW3 model data were sufficient to define forcing end-members during the ADCP and drifter deployments.

Wind and tide data were recorded at 6-min intervals at NOAA National Data Buoy Center (2014) station NSTP6, located approximately 1.8 km north of Faga'alu (Figure 1 inset). For this study, wind conditions to define end members are sufficiently described qualitatively so the topographic effects on wind speed and direction recorded at the stations are assumed to be inconsequential for the analysis.

Analytical Methods

Simultaneous data from the drifters and ADCPs were grouped by end-member forcing, and three techniques were used to compared to determine if the short-term observations as the drifters moved through the spatial bin were similar to the ADCP observations during the 1-h drift.: 1) progressive vectors of cumulative flow, 2) mean flow velocities and variance ellipses, and 3) and residence times.

A series of 1-h progressive vector diagrams of cumulative flow were computed from ADCP data following the methodology used by Siegel et al. (2003) and Storlazzi et al. 2006a). Mean and principal flow axes, velocity variance ellipses, and residence times were calculated from simultaneous ADCP data and spatially binned drifter data (100 m x 100 m) following the methodology of MacMahan et al. (2010). Spatial bins were sized to include sufficient drifter tracks while resolving spatial flow variability. Where drifters did not travel through a specific spatial bin, no analyses could be made. “Residence Time” in a lagoon is typically defined as the time it takes for a water parcel to exit the lagoon to the ocean (Tartinville et al. 1997) but can be determined for any spatial domain (Monsen et al. 2002). For this analysis, residence time was calculated as the time it would take a water parcel to cross a 100-m grid cell, traveling at the mean speed calculated from instantaneous drifter or ADCP speeds.

Results

*Meteorological and oceanographic forcing*

A large range of tide, wind, and wave conditions was sampled during the 8-d period of overlapping ADCP and drifter deployments, 2014 YD 47-55 (Figure 3). Three distinct periods were observed, and defined as end-member forcings: 1) a strong onshore wind event with small waves ('WIND') during YD 47-50; 2) weak winds from variable directions and small waves, where tidal forcing was dominant ('TIDE') during YD 50-52; and 3) a large southeast swell with weak winds ('WAVE') during YD 52-54 (Table 1). During WIND, gusty northeast to southeast winds were observed, with average speeds of 2.6-4.9 m s-1 and maximum gusts of 14.5 m s-1 on YD 48 (Figure 3). These wind conditions are typical during the dry-season trade winds and represent the dominant wind conditions experienced in Faga’alu Bay. During TIDE, wind directions were variable and speeds were low to moderate (1.5-3.4 m s-1), which is typical during the summer wet season. During WAVE, maximum wave height reached 1.3 m on YD 52, which is near the annual maximum height expected for this location (Vetter, unpublished data). Large waves predicted by WW3 during WIND and TIDE were from a northerly direction that is blocked by the island and wave-breaking was not observed at the study site; on YD 52 the swell direction moved to the southeast causing large breaking waves on the reef crest.

*Flow variability during TIDE, WIND, WAVE forcing*

In general, TIDE was characterized by slow flow speeds and variable directions, WIND by slow flow speeds and mostly onshore directions, and WAVE by the fastest flow speeds and most consistent directions. Mean (±STD) flow velocities of all ADCP data during WIND, TIDE and WAVE were 7.4±7.3 cm s-1, 5.6±6.1 cm s-1, and 11.2±10.1 cm s-1, respectively. Similar to the long-term ADCP results, mean drifter speeds (±STD) during WIND, TIDE, WAVE were 8 ±6.5 cm s-1, 7.1 ±5.8 cm s-1, and 12.3±8.1 cm s-1, respectively (Table 1). The results of both parametric pair-wise Student’s *t*-test and non-parametric pair-wise Mann-Whitney *u*-test supported the conclusion that drifter speeds were significantly different during WIND, TIDE, and WAVE.

Flow speeds at AS1 were fairly consistent during WIND, TIDE and WAVE, with only a relatively small increase in speeds during WAVE, indicating the strong influence of even small breaking waves over the southern reef crest (Figure 4b, e). At AS1, flow directions were consistently in a northeast direction into the embayment during all end members. Flow direction at AS2 was consistently to the southwest into the embayment during WIND and WAVE, though direction was more variable during TIDE, with some off-reef flow to the northeast (Figure 4c). Flow speeds at AS2 increased with strong winds (WIND) and large waves (WAVE) (Figure 4c, e). At AS3, flow directions and speeds were highly variable, and AS3 exhibited the lowest flow speeds (Figure 4d-e).

Flow speeds at AS1 and AS2 illustrated the modulating effects of tidal stage on wave-forced flow (Figure 4e), which is common on fringing reefs (Costa et al. 2016). During WAVE, flow velocity was highest during high tide and decreased significantly as the tide fell. This was most evident at AS1, but was also observed at AS2 during YD 52-54. This effect was absent or significantly reduced during WIND, and TIDE.

*Spatial variability of flow trajectories*

Drifter tracks from all deployments covered nearly the entire reef flat (Figure 5), showing three general spatial patterns: 1) Faster flow speeds over the exposed southern reef; 2) slower, more variable currents over the back-reef pools, sheltered northern reef, and deep in the embayment, near the stream mouth; and 3) faster current speeds exiting the seaward end of the channel.

Progressive vectors from ADCP data indicated the general difference in flow speeds over the northern and southern reefs, and that flows at AS1 and AS2 were relatively consistent. Progressive vectors did not describe the heterogeneous flow directions over the reef flat, but this is unsurprising given the complex bathymetry and coastline variability (Figure 6). In general, the lengths of progressive vectors were similar to the tracks of the drifters, indicating some consistency in flow speeds, albeit sometimes different directions. The exception was over the sheltered northern reef, where drifters quickly moved into the channel and were influenced by very different currents than the ADCP at AS3.

During TIDE, the drifters moved in erratic directions and traveled much farther than the progressive vectors from AS2 and AS3 (Figure 6a-b). Under low wave conditions and at high tide during TIDE, some drifters moved seaward across the reef crest near AS2, but progressive vectors were exclusively shoreward. Some drifters traveled from the sheltered northern reef onto the exposed southern reef during light and variable winds.

During WIND, the drifter tracks were mainly towards the northwest corner of the bay, suggesting seaward flow (at least at the surface) was suppressed under strong onshore winds (Figure 6d). Though moderate to strong easterly trade winds are most prevalent throughout the year, there is less certainty in the wind-driven flow pattern since fewer observations were made during WIND.

During WAVE, longer progressive vectors and drifter tracks characterized all locations, indicating faster current speeds than during WIND and TIDE (Figure 6e-f). The drifter tracks clearly indicate a coherent pattern of clockwise flow over the exposed southern reef, through the back-reef pools and near the stream mouth. Despite some wave breaking on the more sheltered northern reef crest, it appears the flow across the exposed southern reef and into the channel influences an overall seaward flow over the northern reef and out to sea. This pattern was not evident in the progressive vectors. All drifters exited the channel during the 1-h period, suggesting during WAVE the flushing time of the whole bay was under 1-h.

*Spatial structure of mean flows*

Variance ellipses and mean flow velocities were calculated from simultaneous ADCP and spatially-binned drifter data (Figure 8). The number of drifter tracks through each grid cell differed due to the position of the grid cell relative to the flow pattern. Grid cells in the middle of the bay and channel had more drifter tracks, and hence more certainty, than grid cells on the reef crest and close to shore that may have been influenced by an anomalous drifter track or a small range of forcing conditions.

In general, more circular variance ellipses were observed on the sheltered northern reef, suggesting more variable flow directions. More eccentric variance ellipses were observed on the exposed southern reef, suggesting more consistent directions. Variance ellipses and mean flow velocities from drifter data resolved the general clockwise onshore flow from the exposed southern reef, over the sheltered northern reef, and out to sea. Drifter data also illustrated the low current speeds near shore and in back-reef pools. ADCP data showed mean flow directions were consistent, but mean flow speeds differed among WIND, TIDE, and WAVE.

During TIDE, the most circular variance ellipses were observed in both ADCP and drifter data, indicating flow directions were most variable under light, variable winds and low waves (Figure 8a-b). Variance ellipses and mean velocities from ADCPs showed exclusively onshore flow, but the results from drifters showed clockwise flow across the exposed southern reef and seaward out the channel.

During WIND, velocities were similar to during TIDE but the variance ellipses were more eccentric, indicating more consistent flow directions during strong onshore winds. Similar to TIDE and WAVE, more eccentric variance ellipses and higher speeds were observed over the exposed southern reef, and more circular ellipses and slower speeds in the back-reef pools, channel, and sheltered northern reef.

During WAVE, the highest mean flow speeds and most eccentric variance ellipses were observed, indicating high waves are a strong control on flows in the bay. The drifters showed a clear pattern of faster, more unidirectional flows near the reef crest on the exposed southern reef, transitioning to slower, more variable flow over the back-reef pools, and finally turning seaward over the sheltered northern reef and out the channel.

Wave breaking was observed on the reef crest near AS1 during even the smallest wave conditions, driving flow speeds on the far southern reef flat. As wave height increased, breaking waves were observed further north along the reef crest, near AS2 and the channel, increasing flow speeds over the reef flat near AS2 and the back-reef pools. Similar to during TIDE, mean speeds increased seaward through the channel, but due to the low data density outside the reef crest, it is unclear whether the flow continues seaward to Pago Pago Bay or is re-entrained onto the reef.

*Spatial structure of residence times*

Water residence time was computed from the mean velocity of drifters in each grid cell during end member forcings (Figure 9). Residence times in grid cells varied from 2.8-0.14 h, 2.8-0.15 h, and 2.8-0.08 h during WIND, TIDE, WAVE, respectively. The shortest residence times were measured near the southern reef crest during WAVE. The longest residence times were observed close to shore, in the channel, and over the northern reef during TIDE and WIND.

*Comparing Eulerian and Lagrangian flow speeds and residence times*

To compare Eulerian and Lagrangian flow measurements, mean velocity and estimated water residence time from simultaneous ADCP data were compared with drifters in the corresponding grid cell (Table 2). Mean velocities from the ADCPs were lower than mean velocities from drifters in all cases except for the southern reef (AS1) during WIND (Table 2). The Root Mean Square Difference (RMSD) and percent difference (RMSD/mean) showed mean flow speed calculated from Eulerian and Lagrangian methods differed by 51-195%, and residence times differed by 48-201% among ADCPs (Table 2, bottom row). Mean flow speed calculated from Eulerian and Lagrangian methods differed by 53-79%, and residence times differed by 119-151% among end member forcings (Table 2, right column). The percent difference in mean flow speeds, among locations, was highest at AS3 (195%) where flow was most spatially heterogeneous, and lowest at AS1 (51%) where the flow was most homogeneous. The percent difference in mean speeds, among end members, was lowest during TIDE (53%), when flow speeds were lowest, and highest during WAVE (79%).

Discussion

The high number of drifter deployments provided an unprecedented data set in a fringing-reef setting, with high data density, extensive spatial coverage, and a wide range of characteristic forcing conditions. The overall flow pattern under all forcing conditions is predominantly clockwise circulation over the exposed southern reef and back-reef pools and seaward through the channel, with higher speeds during wave forcing than tidal and wind forcing. The shortest residence times were measured on the exposed southern reef flat near breaking waves on the reef crest, and were longest over the reef flat close to shore and deep in the sheltered northwest corner of the embayment, which is consistent with studies in other fringing reefs (Lowe et al. 2009b; Ouillon et al. 2010).

The drifters illustrated several unique flow features, particularly near areas of complex bathymetry like the channel. From the orientation of the reef flat and channel, it appears that flow over the exposed southern reef should enter directly into the channel and out to sea (Taebi et al. 2011). Instead, wave refraction into the channel deflects the flow near AS2 away from the channel, shoreward into the embayment where it flows into the back-reef pools and into the shoreward end of the channel.

Observations on the linear reef flat off Molokai, Hawaii (Presto et al. 2006), showed near-bed current speeds were faster where the reef is deeper and narrower but the observations presented here (Figures 5 and 7) suggest the opposite for surface drifters on this fringing reef. Current speeds were rapid over the shallow reef flat, slowing significantly and becoming more variable when reaching deeper back-reef pools and the channel.

Flow through the channel was not spatially constant, showing steadily increased speed moving seaward, reaching a maximum at the reef crest, during both WAVE and TIDE. The same pattern was not evident during WIND, possibly due to wind driven flow into the bay at the surface, but the data density is too low to be certain. In a similarly configured reef in Moorea, French Polynesia, vertically binned ADCP data showed that under low wave forcing, surface currents in the channel were lower and flow could even reverse near the bottom (Hench et al. 2008). The increase in flow speed through the channel at the study site is either caused by the increasing volume of water contributed by the reef flats on either side or a narrowing of the channel cross-section. Either way, the increase is notable for illustrating the inadequacy of using a single current meter in the channel to estimate water residence or flushing time from the bay.

Differences between Eulerian and Lagrangian flows

Lagrangian results showed consistently higher mean flow speeds than Eulerian results, except for one location and condition: on the exposed southern reef during WIND (Table 2). Several factors can explain this difference: 1) comparing point and areal measurements, 2) comparing depth-averaged and surface current measurements, 3) the influence of Stokes’ drift on Lagrangian drifters, and 4) sampling and analytical errors. It is unlikely that the difference is explained by drifters and ADCPs experiencing different forcing conditions, given the consistent differences over space and time.

The first potential source of disagreement is the heterogeneity of flow speeds within the 100 m spatial bin sampled by the drifters, compared to the point measurement from the ADCP, especially in the more bathymetrically complex areas like near AS3 where the disagreement was highest (Lowe et al. 2009b).

The second potential source of disagreement is comparing surface and depth-averaged measurements. Lagrangian measurements are more influenced by surface processes and faster flows (drifters were ~0-20 cm into the water column; see Figure 2b), whereas Eulerian methods average over depth ranges which include slower flow speeds due to the logarithmic decrease in flow speed observed near the bottom, particularly at the study site where coral structures can cover more than half of the water depth even at high tide (Figure 2c-d)(Falter et al. 2008; Lowe and Falter 2015). In this study, the ADCPs top measurement bin averaged the near-surface higher speed flows with the very slow speeds below the top of the coral canopies, resulting in a slower speed than would be measured by the drifters.

A third source of disagreement between the Eulerian and Lagrangian methods is Stokes’ drift caused by wind, gravity, or infragravity waves (Stokes 1847; Kenyon 1969; Pomeroy et al. 2012; Cheriton et al. 2016). For the expected range of wave height (0-0.25 m) (Vetter, unpublished data), wave period (4-12 s), and water depth (0.4-1.3 m) at the ADCPs, predicted Stokes’ drift velocities from incident waves (*UStokes*)is 0-37 cm s-1. *UStokes*is highly sensitive to water depth, especially for larger wave heights and lower wave periods. Although the magnitudes of *UStokes*calculated for the full range of conditions could explain the 0.1-14.2 cm s-1 differences between drifters and ADCPs, *UStokes*> ~5 cm s-1 should be considered extreme values. Since the combination of high wave height and low wave period is unlikely, especially at low water depth when wave-propagation is limited, a more likely range of *UStokes* influencing the drifters is more on the order of 0.1-3 cm s-1. Stokes’ drift is a likely cause of the higher speeds observed by drifters, but not the only cause. There is also evidence that infragravity waves (25-1000 s period) caused by high incident waves and long periods undergo little energy dissipation and increase in skewness and asymmetry while propagating over fringing reef flats. Infragravity waves can be highly energetic and play an important role in driving flow over fringing reefs and transporting reef material (Cheriton et al. 2016; Pomeroy et al. 2012).

The fourth possible source of discrepancy between Eulerian and Lagrangian estimates is sampling and analytical error. Sampling errors from drifters can be “surfing” on waves, wind slip, or interaction with the bottom. Wind slip of tall-masted, finless drifters can be up to 1 cm s-1 per m s-1 of wind (0-8 cm s-1 for the sampled conditions) (MacMahan et al. 2010), but given the low windage on the drifters used here and the large fins, it is unlikely wind slip was important (Figure 2b). Sampling error from the ADCPs could be from reverberation, side-lobe interference, bias near the limit of the blanking distance, or inability to sample flows near the surface (Mueller et al. 2007).

It is likely that all of these potential sources of disagreement occurred in combination or at different locations and times. The highest differnce, observed on the northern reef (AS3), was likely due to strong heterogeneity in flow. Over the southern reef (AS1 and AS2) where wave energy is highest, Stokes drift from gravity and infragravity waves was likely the most important source of difference.

On a 1.5-2.0 m deep reef flat off Oahu, Hawaii, Falter et al. (2008) found that cruciform drifter speeds exceeded both Lagrangian dye and Eulerian depth-averaged current speeds (which included depth-averaged Stokes’ transport computed from wave gauge data) by 30-100%, similar to the results presented here. A numerical simulation predicted surface drifter speeds should exceed the depth-averaged current speed plus Stokes’ drift by 30%, so Falter et al. (2008) attributed the discrepancy to higher Stokes’ transport near the surface.

Applications of this Hybrid Eulerian-Lagrangian Method

Coral reefs are physically and biologically heterogeneous environments, but ecologically-important flow speeds and trajectories have been difficult to measure in relation to long-term forcing conditions (Monsen et al. 2002). Like the atmospheric climate, regional-scale oceanic forcing controls large-scale biophysical patterns such as nutrient and heat distributions. Whereas global climate and ocean circulation research have benefitted from satellite remote-sensing, water circulation over individual reefs is more similar to atmospheric micro-climates, and the long-term, synoptic observations of remote sensing have not been possible. Many water circulation studies significantly simplify the study site for modeling purposes (Lowe et al. 2010) or rely on only a few fixed instrument locations (Hench et al. 2008). The combination of spatially extensive Lagrangian drifters and temporally extensive Eulerian current meters provides insight on the spatial flow patterns within the context of variable circulation-forcing conditions.

Quantifying residence time and flow patterns in relation to end-member forcing conditions can be used to extrapolate the findings from a targeted study period to seasonal or annual time scale by determining the proportion of days that are dominated by tidal, wind, or wave forcing. A similar approach could be used to extrapolate the effects on changing sediment dynamics, temperature regimes and nutrient cycling at the study site (Lowe and Falter 2015) from future climate scenarios and predicted increase in the strength and frequency of Southern Ocean storms (Hemer et al. 2013).The end-members could also be further refined to describe waves and winds of varying magnitude, or combined with varying tide stage for finer-resolution predictive models of current speeds (Storlazzi et al. 2011).

Implications of Circulation Patterns on Reef Health

The spatial flow pattern illustrated by the drifters suggests that the sediment plume is deflected away from the southern reef towards the northern reef. This was confirmed by field observations where sediment plumes during storms extended from the stream to seaward of the northern reef and channel, and persisted for several hours to days. Sediment settling velocity is dependent on particle size, particle density, and water density, which vary over small spatiotemporal scales in stormwater plumes. Hydrodynamic conditions interacting with benthic topography can offset settling velocities or cause resuspension, making it difficult to predict sediment settling and accumulation on the reef. Assuming settling velocity of silt in seawater (35% salinity, 29 C) varies from 4 x 10-4 to 0.4 cm/s, settling time varies from ~4 min/m for coarse silt (~0.063 mm) to ~70 hr/m for fine silt (~0.002 mm). The observed residence times over both the northern and southern reefs suggest coarse to medium silt could settle on the reef, provided these particles do not settle out of suspension before they reach the reef.

Floods occur year-round at the study site, and coincide with typically low wave conditions in the wet season and moderate to strong easterly winds in the dry season. Given the observed flow patterns, this suggests the northern reef and areas of the southern reef bordering the channel are most exposed to sediment discharge from Faga'alu Stream, resulting in greater terrestrial sediment stress (= intensity x duration) and reduced coral health from particle settling and light reduction (Erftemeijer et al. 2012; Storlazzi et al. 2015). Although particle settling blocks all light for photosynthesis, Storlazzi et al. (2015) showed even low concentration of fine-grain sediment in the water column (10 mg L-1) reduced photosynthetically active radiation by ~80% at depths of only 0.2-0.4 m.

Water circulation is critical for understanding both the natural ecological processes and the impacts of anthropogenic activities on coral reefs. This study showed that flow speeds, flow directions, and water residence times can be spatially- and temporally-heterogeneous in fringing reef-lined environments, resulting in heterogeneous physical, chemical, and biological environments.

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Tables

Table 1. Time frames defining the end-member meteorologic and oceanographic forcing periods.

Table 2. Mean flow speed and residence time computed from the ADCPs and corresponding spatially-binned drifter data for different forcings.

Figure Captions

Figure 1. Maps of the study area and instrumentation in Faga'alu Bay. Wind speed and direction were recorded at NDBC station NSTP6 (inset). Acoustic current profilers (ADCP) were deployed at three locations for one week to measure current speed and direction, and GPS-logging drifters were deployed thirty times (19 January to 23 February 2014) from five launch zones (Drifter Launch).

Figure 2. Images of the oceanographic instrumentation at high tide. a) Shallow-water drifters on land with ruler for scale. b) Shallow-water drifter deployed in the field over the southern reef flat. c-d) The ADCP at location AS1.

Figure 3. Time series of physical forcing data used to define end-member forcings for analysis. a) Tidal stage. b) Wind speed. c) Wind speed and direction. d) Wave height. e) Wave period. f) Wave height and direction. Vectors denote direction "to". Wind data are from NDBC station NSTP6; wave model data (significant wave height, average wave period, peak wave direction) are from NOAA WW3.

Figure 4. Time series of acoustic current profiler data on the reef flats a) Tide level at location AS1. b) Current vectors at AS1. c) Current vectors at AS2. d) Current vectors at AS3 (water depths at low tide were too shallow to measure currents). d) Current speeds at all three locations. Vectors denote direction "to". Note the variations in current speeds both in space and time due to the different forcing conditions shown in Figure 3.

Figure 5. Map of all drifter tracks during the experiment, colored by speed (m s-1).

Figure 6. Progressive vectors calculated from ADCP data, compared to drifter tracks under end-member forcings: a) ADCP data under tidal forcing. b) Drifter data under tidal forcing. c) ADCP data during strong winds. d) Drifter data during strong winds. d) ADCP data during large waves. f) Drifter data during large waves. Black dots indicate the location of the ADCP, start of the progressive vector. White circles indicate drifter deployment zones.

Figure 7. Variance ellipses and mean currents for the ADCP data and spatially-binned drifter data under end-member forcings. a) ADCP data under tidal forcing. b) Drifter data under tidal forcing. c) ADCP data during strong winds. d) Drifter data during strong winds. d) ADCP data during large waves. f) Drifter data during large waves. Drifter data are colored by number of observations to illustrate the varying data density.

Figure 8. Residence time calculated from mean velocity of drifters under endmember conditions. a) Tidal forcing. b) Strong winds. c) Large waves.

Appendix A

Table A.1. Drifter deployment dates and conditions. Deployments #9-30 coincide with ADCP deployment.