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 near-shore ecosystems, and interacts with terrestrially-derived sediment, nutrients, and contaminants to determine watershed impacts on coral reef ecosystems. We characterize water circulation patterns and residence times in relation to end-member forcing conditions using a rapid field technique 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. Eulerian current profilers installed at fixed locations collected continuous flow data during different forcing conditions. Current velocities were binned to a 100 x 100 m grid and analyzed with empirical orthogonal functions. Mean current speeds (residence times) over the grid cells 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 channel. 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 on the drifters, or a combination of all of these. The results demonstrate a hybrid and rapid 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 to fringing reefs (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 loading and the duration of time the corals are exposed to sediment (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 the dominant 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). Current speeds and patterns 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 surface 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 from the reef flat to the fore reef (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 deeper in the embayment 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 one or more fixed locations over time. Eulerian methods are well-suited to characterizing flows over long periods and 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 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. 2006a; 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 flow speeds and residence times influenced by high waves, high winds, or calm conditions? How do flow speeds, flow directions, 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 swells 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). Available data on water circulation around Tutuila were limited to government and consultant reports, and no data on circulation over the reef flat has been collected (CH2M HILL 1984; Wiles et al. 2010; Jacob et al. 2012).

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. The bathymetrically complex, fringing reef is characterized by a shallow reef flat extending from just offshore 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 (“Backreef Pools” in Figure 1). An anthropogenically-altered, vertical-walled, 5-15 m deep paleostream channel (“Channel” in 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 (“South Reef” in Figure 1), and a smaller, more sheltered northern section (“North Reef” in Figure 1). See Cochran et al. (2016) for a detailed description of the bathymetry. Surveys in 2005 found coral coverage varied from less than 10% on the degraded North Reef, to more than 50% on the more intact South Reef (National Centers for Coastal Ocean Science 2005).

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 with materials available on-island, 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 fleet of five drifters was deployed 30 times over a two month period, from 19 January 2014 to 23 February 2014, with 22 of those deployments coinciding with the 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 in Faga'alu 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. These velocity profiles were 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 512s 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, calibrated to DOBIE wave 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 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 compare the results from drifters and ADCPs: 1) progressive vectors of cumulative flow, 2) mean flow velocities and variance ellipses, and 3) and residence times. Progressive vectors, mean flow velocities, and residence times from simultaneous drifter and ADCP data were 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.

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 to be 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

*Defining End Members from meteorological and oceanographic forcing data*

A large range of tide, wind, and wave conditions was sampled during the 8 day 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 winter tradewind season 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 over the reef flat and more variable directions, WIND by slow flow speeds and less variable, 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). Histograms showed that the distributions of drifter speeds were normal only during WAVE; distributions were non-normal during TIDE and WIND (Figure 4). 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 small relative increase in speeds during WAVE, indicating the strong influence of even small breaking waves over the South Reef crest (Figure 4b, e). At AS1, flow directions were very consistent, 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 under all forcing conditions, and AS3 exhibited the lowest flow speeds of the three ADCPs (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 6), showing three general spatial patterns: 1) Faster flow speeds over the exposed South Reef; 2) slower, more variable currents over the Backreef Pools, sheltered North Reef, and deep in the embayment, near the stream mouth; and 3) faster offshore current speeds exiting the seaward end of the Channel.

Progressive vectors from ADCP data indicated the general difference in flow speeds over the North and South reefs, and that flow speeds and directions 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 7). In general, the lengths of progressive vectors were similar to the tracks of the drifters, indicating some consistency in flow speeds over the reef flat, 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 7a-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 North Reef onto the exposed South Reef during light and variable winds.

During WIND, the drifter tracks were mainly towards the northwest corner in 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, and one drifter deployed on the North Reef was lost.

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 South Reef, through the Backreef Pools and near the stream mouth, and then seaward over the sheltered North Reef and out the Channel. Despite some wave breaking on the more sheltered North Reef crest, it appears the flow across the exposed South Reef and into the Channel influences an overall seaward flow over the North Reef. 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 than grid cells on the reef crest and close to shore. More observations suggest more certainty, whereas grid cells with a small number of observations may have been influenced by an anomalous drifter track or a small range of forcing conditions.

Under all forcings, variance ellipses from drifter and ADCP data were more circular on the sheltered North Reef, suggesting more variable flow directions. Variance ellipses were more eccentric on the exposed South Reef suggesting more consistent directions. Variance ellipses and mean flow velocities from drifter data resolved the general clockwise onshore flow from the exposed South Reef, over the sheltered North Reef, and out to sea. Drifter data also illustrated the low current speeds near shore and in Backreef 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. Variance ellipses from drifters were more eccentric and mean velocities were higher near the reef crest and on the exposed South Reef, compared to the sheltered North Reef and Backreef Pools.

During WIND, velocities were similar but the variance ellipses were more eccentric than during TIDE, indicating flow directions were more consistent during strong onshore winds. Similar to TIDE and WAVE, more eccentric variance ellipses and higher speeds were observed over the exposed South Reef, and more circular ellipses and slower speeds in the Backreef Pools, Channel, and sheltered North 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 South Reef, transitioning to slower, more variable flow over the Backreef Pools, and finally turning seaward over the sheltered North 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 South 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 Backreef 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 exposed South 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 South Reef crest during WAVE. The longest residence times were observed close to shore, in the Channel and North Reef in the northwest corner of the embayment 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 was 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 South Reef (AS1) during WIND (Table 2). The Root Mean Square Difference (RMSD) and percent difference (RMSD/mean) were computed for all locations during each end member forcing, and for each location under all forcing conditions. 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 is 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

General and anomalous flow patterns-comparisons to other reefs

The high number of drifter deployments provided an unprecedented data set for a reef flat area, with high data density, extensive spatial coverage, and covering a wide range of expected forcing conditions at the study site. The overall flow pattern under all forcing conditions is predominantly clockwise circulation over the exposed South Reef and Backreef 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 South 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 South 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 Backreef 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 6 and 8) 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 Backreef 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.

Relating flows to sediment stress on the North Reef

Floods occur year-round, 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 North Reef and areas of the South Reef bordering the channel are most exposed to the freshwater and sediment discharging from Faga'alu Stream. The spatial flow pattern and longer residence times in these areas result in greater terrestrial sediment stress (= intensity x duration) from particle settling and light reduction, likely reducing coral health (Erftemeijer et al. 2012).

Sediment Settling

Sediment settling velocity is strongly dependent on particle size, water salinity, and water temperature, which vary over small spatiotemporal scales in stormwater plumes. Hydrodynamic conditions interacting with benthic topography can alter 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 North and South Reefs suggest coarse to medium silt could settle on the reef, but these particles may also settle out of suspension before they can reach these areas.

Sediment Light Attenuation

The spatial flow pattern suggests that the sediment plume is deflected away from the South Reef towards the North Reef, reducing light for photosynthesis and stressing corals. Field observations showed sediment plumes during storms extended from the stream to seaward of the North Reef and Channel, and persisted for several hours to days. While particle settling blocks all light for photosynthesis, recent work by 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. In addition to overall light reduction, suspended sediment strongly reduces blue and red wavelengths that are most effective at driving photosynthesis (Jones et al. 2015).

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 South Reef during WIND (Table 2). Several factors can explain the difference between the ADCP and drifter speed including 1) the issues of comparing point and areal measurements, 2) the difference between depth-averaged and surface current measurements, 3) the influence of Stoke’s drift on Lagrangian drifters, and 4) methodological error in sampling and analysis. It is unlikely that the difference is explained by drifters and ADCPs experiencing different forcing conditions, given the consistent differences over space and time.

Point and areal comparisons

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).

Surface and depth-integrated comparisons

The second potential source of disagreement is comparison of surface and depth-averaged measurements. Lagrangian measurements are more influenced by processes and faster flows at the surface (drifters were ~0-30 cm into the water column; see Figure 2b), whereas Eulerian methods make a depth-averaged flow measurement which is typically lower than surface flow speed (Falter et al. 2008; Lowe and Falter 2015). Surface flows are faster 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).

Importance of Stoke’s drift and infragravity waves

A third source of disagreement between the Eulerian and Lagrangian methods is the potential importance of Stokes drift caused by wind, gravity, or infragravity waves (Cheriton et al., In Review; Stokes 1847; Kenyon 1969; Pomeroy et al. 2012). Maximum wave height measured on the reef flat in 2013 was 0.25 m, corresponding to an offshore wave height of 1.7 m (Vetter, unpublished data). For the expected range of wave heights (0-0.25 m), wave period (4-12 s), and water depths (0.4-1.3 m) at the ADCPs, predicted Stoke’s drift velocity from gravity waves (UStoke)is 0-37 cm s-1. UStoke was highly sensitive to water depth, especially for larger wave heights and lower wave periods (Figure 1). While the magnitudes of UStoke calculated for the full range of conditions could explain the 0.1-14.2 cm s-1 differences between drifters and ADCPs, magnitudes of UStoke > ~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 UStoke influencing the drifters is actually more on the order of 0.1-3 cm s-1. Stoke’s 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 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.; Pomeroy et al. 2012).

Possible sampling errors

The fourth possible source of discrepancy between Eulerian and Lagrangian estimates is methodological error in sampling and analysis. 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 are operating in combination or over different locations and times. The highest discrepancy between Eulerian and Lagrangian flow speeds observed on the North Reef (AS3) was likely due to strong heterogeneity in flow. Over the South Reef (AS1 and AS2) where wave energy is highest, Stokes drift from gravity and infragravity waves was likely the most important source of the 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% on average, similar to the results presented here. A numerical simulation of a water-column profile predicted drifter speeds at the surface 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, compared with the depth-averaged Stokes transport.

It is important to note that the spatially-distributed residence times calculated from Lagrangian drifters likely represent an underestimation since the mean flow speed from drifters was consistently higher than Eulerian methods. Further application of the residence times presented here must be appropriate to the research question, whether the interest is in residence time of near-surface water or total volumetric flux.

Applying Eulerian or Lagrangian model results

While the combination of Eulerian and Lagrangian methods is advantageous for interpreting spatially distributed velocities in relation to long-term forcing, in some cases, a single estimate of transport is needed, and the decision to use the Eulerian or Lagrangian estimates depends on the application. Falter et al. (2008) concluded that relying on solely Lagrangian estimates of water transport would have caused a 30-100% overestimation of nutrient uptake on the reef, corresponding to the error in Lagrangian flow estimates. Lagrangian methods would be more appropriate for studies interested in near-surface processes such as sediment plumes (Warrick et al. 2007) or plankton and larvae transport (Siegel et al. 2003), while Eulerian methods would be more appropriate for studies where near-bed or volumetric flux is important, such as temperature regimes (Herdman et al. 2015), nutrient uptake (Falter et al. 2008), or benthic sediment movement (Presto et al. 2006).

Nutrient uptake on coral reefs is considered to be limited primarily by the flow of water over the benthic surface (Bilger and Atkinson 1992; Falter et al. 2004), and our results show that flow speeds can be highly variable over small scales on the reef. Nutrient uptake and other water quality parameters can be influenced by the depth and metabolic activity of the benthic surface contacted by a traveling water parcel, so the particular flow path and residence times of water over various benthic surfaces are important. Lowe and Falter (2015) argue that nutrient uptake mass-transfer models should be refined for smaller scale flows and tested in actual reef sites, but critical water circulation measurements to parameterize these models will require a combination of Eulerian and Lagrangian measurements similar to the methodology presented in this study.

Future applications of this method

Coral reefs are physically and biologically heterogeneous environments, but ecologically-important flow speeds and spatial patterns have been difficult to measure in relation to the long-term forcing conditions (Monsen et al. 2002). Like the atmospheric climate, regional-scale forcing controls large-scale biophysical patterns such as nutrient and heat distributions. Whereas global climate and ocean circulation research have benefitted from remote-sensing methods, water circulation over small-scale reef ecosystems 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 presented here provides insight on the spatial patterns of flow 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, annual, or longer 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 reef flat circulation from future climate scenarios with changing storm frequencies and characteristics. For instance, a predicted increase in the strength and frequency of Southern Ocean storms (Hemer et al. 2013) could be extended to predict changing sediment dynamics, temperature regimes and nutrient cycling at the study site (Lowe and Falter 2015). The end-member forcing conditions could also be further refined to describe wave heights and wind speeds of varying magnitude, or combined with an empirical relationship accounting for varying tide stage for finer-resolution predictive models of current speeds.

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 forcing conditions.

Figure Captions

Figure 1. Maps of the study area and locations of instrumentation in Faga'alu Bay. Wind speed and direction were recorded at the weather station (Weather Station), acoustic current profilers were deployed at three locations (ADCP) 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) The acoustic current profiler at location AS1. d) The acoustic current profiler deployed at location AS1.

Figure 3. Time series of physical forcing data was used to define end-member forcing periods 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 speed and direction at AS1. c) Current speed and direction at AS2. d) Current speed and direction at AS3. d) Current speeds at all three locations. Vectors denote direction "to". AS3, water depths at low tide were too shallow to measure currents. Note the variations in current speeds both in space and time due to the different forcing conditions shown in Figure 3.

Figure 5. Histograms of all drifter speeds (cm s-1) during end member periods TIDE, WIND, and WAVE. Mean (solid vertical line) and median (dotted vertical line) are drifter speed (cm s-1) for each end member. Both parametric pair-wise t-tests and non-parametric pair-wise Mann-Whitney u-tests supported the conclusion that mean speeds for each end member period are significantly different than each other (p<0.001).

Figure 6. Map of all drifter tracks during the experiment, colored by speed (m s-1).

Figure 7. Progressive vectors calculated from acoustic current profiler (ADCP) data, compared to drifter tracks under end-member forcing conditions: 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, corresponding with Figure 1.

Figure 8. Variance ellipses and mean current vectors for the ADCP data and spatially binned drifter data under different end member forcing conditions. 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 9. 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 deployments.