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 1-37 cm s-1 (0.1-2.8 hr), 1-36 cm s-1 (0.1-2.8 hr), and 5-64 cm s-1 (0.04-0.6 hr) under tidal, strong wind, and large wave forcing, respectively. Flow speeds were highest and residence times shortest over the exposed southern reef near the reef crest. The lowest 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 instances of 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 70-139% 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). Since 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 coral reef environments 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), and wind-driven currents by regulating water depth for wind-driven surface wave development (Presto et al. 2006). Flows in wave-driven environments 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. 2009; 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).

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). Collecting high spatial resolution data on hydrodynamic processes using Eulerian methods is logistically difficult (Storlazzi et al. 2004, 2006b), so other methods including hydrodynamic models, remote sensing, and Lagrangian methods have been used. Satellite optical remote sensing approaches are infeasible where the study area is small (e.g. < 1km2) and experiences frequent cloudy conditions. Hydrodynamic computer models typically require accurate bathymetry and detailed forcing data that may not be available (Wolanski et al. 2009; Hoeke 2010; King et al. 2012). Lagrangian methods such as GPS-tracking drifters have been used to map flow patterns in coastal areas, to compare with Eulerian flow descriptions (Storlazzi et al. 2006a; Wyatt et al. 2012), or validate hydrodynamic computer models (Ouillon et al. 2010). Research on rip currents in beach surf zones has 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) but this approach has not been widely used in shallow reef environments (Falter et al. 2008; Wyatt et al. 2010).

Lagrangian drifter studies in nearshore environments are typically 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 time, 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 are: How do flow speeds and residence times vary spatially on the reef flat? How are flow speeds and residence times influenced by high waves, high winds, or calm conditions?

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). Faga'alu Bay is characterized by a semi-diurnal, microtidal regime where parts of the shallow reef crest and reef flat are exposed at extreme low tides. Faga'alu Bay is only open to south-southeast swell directions, and swells approaching from a southerly angle must refract to the west, reducing their energy. Offshore significant wave heights (*Hs*) from southerly and southeasterly directions 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 peak significant wave heights on the fore reef in Faga'alu up to 1.7 m, but wave heights 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, coral reef-fringed embayment adjacent a small (2.48 km2), steep-sided watershed. The bathymetrically complex 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 the 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 extends from the mouth of Faga'alu Stream eastward to Pago Pago Bay (“Channel” in Figure 1); this channel divides the reef into a larger, more exposed southern and a smaller, more sheltered northern section. 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” (Figure 1) (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.

A total of 30 drifter deployments were conducted over a 2 month period (January 19-February 24), with 20 of those deployments during a one-week period (February 16-24). 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 to Pago Pago Bay, 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). The ADCPs collected 580 current samples at 2 Hz every 10 min. Depth of deployment was 0.9 m (AS1), xx m (AS2),…

Ancillary Data

The instrument deployments were timed to capture end-member hydrodynamic forcing conditions that characterize the study area (Yamano et al. 1998). End member conditions 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 (Figure 1). 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 used to define forcing end-members during the ADCP and drifter deployments.

Wind speed and wind direction were recorded at 15 min intervals using a Davis VantagePro weather station installed near the stream mouth, approximately 5 m above sea level (Figure 1). Wind and tide data were also recorded at 6 min intervals at NOAA National Data Buoy Center (2014) station NSTP6, located approximately 1.8 km north of Faga'alu. 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 two techniques were used to compare the results from drifters and ADCPs: 1) progressive vectors of cumulative flow and 2) empirical orthogonal functions (EOF). 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). EOF principal axes, variance ellipses, mean flow velocities, 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). Where drifters did not travel through a specific spatial bin, no EOF or residence time could be calculated. Progressive vectors, EOFs, and mean flow velocities from drifter and ADCP data were compared to demonstrate the usefulness of Lagrangian methods for describing spatial flow patterns compared to projected flow from Eulerian methods, and to determine if the short-term observations as the drifters moved through the spatial bin were similar to the long-term ADCP observations over the duration of the 1h drift.

Results

*Meteorological and Oceanographic Forcing*

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: 1) a strong onshore wind event with small waves; 2) weak winds from variable directions and small waves, where tidal forcing was dominant; and 3) a large southeast swell with weak winds. Three end-member forcings were defined: 1) Small waves and strong onshore winds ('WIND') during YD 47-49; 2) Small waves and weak winds ('TIDE') during YD 50-51; and 3) Large waves and weak winds ('WAVE') during YD 52-55 (Table 1). During WIND, 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. 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).

*Eulerian Measurements*

The water level at low tide dropped below the blanking distance of the ADCP at AS3 on the northern reef (Figure 4d), and 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. The short data gap at AS1 on YD 50 was due to human disturbance.

In general, tidal forcing was characterized by slow flow speeds over the reef flat and more variable directions, wind forcing by slow flow speeds and less variable directions, and wave forcing by the fastest flow speeds and most consistent flow directions. The highest flow speeds were observed over the exposed southernmost part of the reef (AS1) in a northwesterly direction from the reef crest into the embayment, indicating the strong influence of even small breaking waves over the reef crest (Figure 4b, e). Flow direction at AS2 was consistently to the southwest from the reef crest into the embayment, though direction was more variable under tidal forcing, with some off-reef flow to the northeast (Figure 4c). Flow speeds at AS2 were correlated with strong winds and large waves (Figure 4e). 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). During wave forcing, flow velocity was highest during high tide and decreased significantly as the tide fell. This was most evident during YD 53-55 at AS1, but was also observed at AS2. This effect was absent or significantly reduced during wind forcing on YD 47-49, and tidal forcing on YD 51-52.

Mean Velocities during end member conditions: TIDE, WIND, WAVE

Mean velocities calculated from ADCP data for AS1, AS2, and AS3 during TIDE were 14.6 cm s-1, 5.3 cm s-1, and 0.9 cm s-1; during WIND were 11.6 cm s-1, 3.9 cm s-1, and 1.5 cm s-1; during WAVE were 18.1 cm s-1, 10.9 cm s-1, and 1.2 cm s-1, respectively (Table 1). Mean flow velocities from drifters varied from 1-37 cm s-1, 1-36 cm s-1, and 5-64 cm s-1 during TIDE, WIND, and WAVE, respectively. Drifters mean speeds (standard deviation) for TIDE, WIND, WAVE were 8.7 (6.0), 6.9 (5.4), 12.9 (7.2) cm s-1, respectively (Table 1). Probability plots and histograms showed that the distributions of drifter speeds were normal only during WAVE; distributions were non-normal during TIDE and WIND (Figure 4 b). 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 TIDE, WIND, and WAVE.

*Lagrangian Measurements*

The fleet of drifters was deployed 30 times from 19 January 2014 to 23 February 2014, with 22 of those deployments coinciding with the ADCP deployment (Appendix Table A1). Drifter tracks from all deployments covered nearly the entire reef and channel (Figure 5), showing three general spatial patterns: 1) Faster flow speeds over the exposed southern reef flat; 2) slower, more variable currents over the deeper pools of the southern inshore back-reef, sheltered northern reef, and near the stream mouth deep in the embayment; and 3) faster offshore current speeds exiting the seaward end of the channel. Instances of offshore transport over the reef crest were observed, generally exiting through small channels in the reef crest at high tide under calm wave and wind conditions; most of these were quickly re-entrained in the surf zone, and traveled landward over the reef crest and onto the reef flat.

*Progressive Vectors*

Progressive vectors from ADCP data indicated flow speeds at AS1 and AS2 were relatively consistent but did not describe the heterogeneous flow directions over the reef flat. (Figure 6). Whereas the drifters tracked currents moving from cross-shore near the reef crest to alongshore towards the channel, the progressive vectors over the exposed southern reef showed little variation in flow direction, going ashore in some cases. In general, the lengths of progressive vectors were similar to the tracks of the drifters, indicating similar 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. The progressive vectors over the sheltered northern reef were erratic and much shorter than the drifter tracks due to the lower flow speeds observed at AS3. The progressive vectors from the ADCPs illustrate the temporal flow variability at those fixed points during the 1 h drift duration, but progressive vectors are calculated assuming spatial homogeneity of the flow and failed to capture the spatially heterogeneous currents.

During tidal forcing the drifters moved in erratic directions and traveled farther than the progressive vectors (Figure 6a-b). Drifter tracks and progressive vectors compared poorly in speed and direction at AS3 on the northern reef. The comparison was slightly better at AS2, though progressive vectors are still shorter and do not vary direction, and fairly well at AS1 on the exposed southern reef. Under the low wave conditions at high 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 more exposed southern reef during light and variable winds; during large waves, some drifters were driven from the exposed southern to the sheltered northern reef.

During wind forcing, 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. Progressive vectors and drifter tracks were shorter than during tide and wave forcing, indicating slower flow speeds (Figure 6c-d). Progressive vectors compared well with drifter tracks in speed and direction for all locations, though the progressive vectors at AS3 are still short in comparison to the drifter tracks near the same location. Though moderate to strong easterly tradewinds are most prevalent throughout the year, there is less certainty in the wind-driven flow pattern since fewer observations were made during wind forcing windwind.

During wave forcing, longer progressive vectors characterized all locations, indicating faster current speeds than during wind and tidal forcing (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, and then seaward over the sheltered northern reef and out the channel. 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. All drifters exited the channel during the 1 h period, suggesting under high waves the flushing time of the whole bay is under 1 h.

*Empirical Orthogonal Functions (EOF)*

Variance ellipses and mean flow velocities were calculated from simultaneous ADCP and spatially-binned drifter data collected during end member forcing conditions (Figure 7). The number of drifter tracks in 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 in the outer bay 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 forcing conditions variance ellipses from drifter and ADCP data were more circular on the sheltered northern reef, suggesting more variable current directions, and were more oblong on the exposed southern reef suggesting more consistent current directions 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 forcing conditions.

Tide forcing showed the most circular variance ellipses from both ADCP and drifter data, indicating flow directions were most variable under light, variable winds and low waves. 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 ellipsoid and mean velocities were higher near the reef crest and on the exposed southern reef, compared to the sheltered northern reef and southern back-reef pools. Though flow directions were more variable, mean speeds were higher during tidal forcing than wind forcing, but still lower than wave forcing.

Wind forcing showed the lowest mean flow velocities from both ADCPs and drifters, but the variance ellipses were more oblong than under tide forcing, indicating flow directions were more consistent during strong onshore winds. Similar to tide and wave forcing, more oblong 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.

Wave forcing showed the highest mean flow speeds and most oblong variance ellipses, indicating high waves are a strong control on flow 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. Although flow speeds at AS1 were influenced by even small breaking waves, as wave height increased, breaking waves were observed further north along the reef crest, particularly near the channel, increasing flow speeds over the reef flat near AS2 and the back-reef pools. The circular variance ellipses at AS3 indicated variable flow directions, but flow speeds were highest during wave forcing. Similar to the observations during tidal forcing, 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 Harbor or is re-entrained onto the exposed southern reef.

*Residence Time*

Water residence time was computed from mean drifter velocities under different forcing conditions (Figure 8). Residence times in grid cells varied from 2.78-0.08 hr, 2.78-0.08 hr, and 0.56-0.04 h under tidal, wind, and wave forcing, respectively. The shortest residence times were measured near the southern reef crest, and under high wave conditions. The longest residence times were observed over the inner reef flat close to shore and in the northwest corner of the embayment, under tidal and wind forcing. Water residence times computed from mean flow velocities at AS1 were 0.34 h, 0.23 h, and 0.16 h, for tide, wind and wave forcing, respectively. Residence times at AS2 were 0.60 h, 0.52 h, and 0.28 h, for tide, wind and wave forcing, respectively. Residence times at AS3 were 1.45 h and 2.72 h, for wind and wave forcing, respectively. Unfortunately, no data was recorded by the ADCP at AS3 simultaneously with drifters during tide forcing due to the low water level during drifter deployments. Contrary to results at AS1 and AS2, mean speed at AS3 was slower and residence time was longer during wave forcing compared to wind forcing, indicating the northern reef may be more influenced by winds than waves.

*Comparing Eulerian and Lagrangian results*

Mean velocities from the ADCPs were lower than mean velocities from drifters in all cases except for on the southern reef under wind forcing. The RMSE and percent error (RMSE/mean) were computed for all locations during each forcing condition, and for each location under all forcing conditions. For each ADCP location, under all forcing conditions, mean flow speed calculated from Eulerian and Lagrangian methods differed by 70-139%, and residence times differed by 58-136% (Table 2). For each forcing condition, at all ADCP locations, mean flow speed calculated from Eulerian and Lagrangian methods differed by 43-79%, and residence times differed by 27-153%. The percent error for a single location was highest at AS3 (139%) where flow was most spatially heterogeneous, and lowest at AS1 (70%) where the flow is most homogeneous. The percent error for all locations together was lowest during tide forcing (43%) and highest during wave forcing (79%).

Discussion

The high number of drifter deployments provided an unprecedented data set for a reef flat area, with high data density, extensive spatial coverage, and wide range of sampled 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 outer exposed reef flat closest to where waves were breaking on the reef crest, and were longest over the inner reef flat close to shore and deep in the sheltered northwest corner of the embayment. Given the proximity of the sheltered northern reef to the stream mouth and the frequent occurrence of floods under typically low wave conditions in the wet season and moderate easterly winds during the dry season, this suggests the northern reef and areas of the shoreward northern end of the southern reef bordering the channel are likely most exposed to the freshwater and sediment discharging from Faga'alu Stream. The spatial flow pattern and longer residence times result in greater exposure (= intensity x duration) of the corals in these areas to stress from terrestrial pollution, and likely causes the reduced coral health in these locations.

Both the Eulerian and Lagrangian methods characterized the main difference between faster, less variable flow over the exposed southern reef and the slower, more variable flow over the sheltered northern reef under all forcing conditions. The Eulerian method characterized flows adequately near the exposed southern reef crest where bathymetry and wave forcing were fairly simple, but the spatially distributed Lagrangian method more accurately characterized spatially complex flows over the sheltered northern reef and southern back-reef pools deep in the embayment. The drifters also 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 near the channel flows directly from the reef crest northward into the channel. The flow near AS2, however, is deflected away from the channel, likely due to wave refraction, 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 variance ellipses and progressive vectors presented here (Figures 6-7) suggest the opposite for surface drifters in this reef-lined embayment. Current speeds were rapid over the shallow reef crest, 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 forcing. The same pattern was not evident under wind forcing, possibly due to wind driven flow being forced 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 implications on placing a single, fixed ADCP in the channel to define water residence or flushing time.

Compared to Eulerian measurements, the Lagrangian measurements consistently recorded higher mean flow speeds except for one location and condition: on the exposed southern reef during wind forcing (Table 2). Three factors can explain the discrepancy between the ADCP and the drifter speeds. One potential source of disagreement is the heterogeneity of flow speeds within the 100m 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. A second potential source of disagreement is the comparison of surface and depth-averaged measurements. Lagrangian measurements are more influenced by processes at the surface (drifters were ~0-30 cm into the water column; see Figure 2b), whereas Eulerian methods make a depth-averaged flow measurement (Falter et al. 2008; Lowe and Falter 2015) over the depth range of the sampling bin. Surface flows can be faster due to the logarithmic decrease in flow speed observed near the bottom, particularly over rough benthic surfaces on coral reefs. A third source of disagreement between the Eulerian and Lagrangian methods is the potential importance of Stokes drift caused by wind or gravity waves (Stokes 1847; Kenyon 1969). 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. 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. Although the drifter speeds reported in Falter et al. (2008) were significantly higher than those presented here, they did not differ from Eulerian measurements in current direction. The ratio of Stokes transport to total transport decreased with increasing wave-driven currents, but the results presented here show that the difference between Lagrangian and Eulerian measurements (not including Stokes drift) increased with wave-driven current speed (Table 2). Another potential error is surfing of the drifters; however, Falter et al. (2008) concluded the wave-induced deflection was low, so although this may explain some of the discrepancy, it likely was not the dominant process. It is likely that all of these potential sources of disagreement are operating at the same or different times, but the discrepancy between Eulerian and Lagrangian flow speeds at AS3 was likely due to strong heterogeneity in flow, whereas Stokes drift may have been important near the reef crest at AS1 and AS2 where wave energy is highest.

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 an overestimation of nutrient uptake on the reef of 30-100% corresponding to the error in Lagrangian estimates. Falter et al. (2008) and others are interested in water properties that are evenly distributed through the water column. Lagrangian methods would be more appropriate for studies more interested in surface transport related to sediment plumes (Warrick et al. 2007) or plankton and larvae transport (Siegel et al. 2003). Alternatively, marine sediment studies focused on near-bed shear stress and benthic sediment movement (Presto et al. 2006) would likely benefit from Eulerian methods.

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. Like the atmospheric climate, regional-scale forcing controls large-scale biophysical patterns such as nutrient and heat distributions. However, whereas atmospheric climate and global ocean circulation have benefitted from remote-sensing methods, water circulation over small-scale reef ecosystems are 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 or rely on only a few fixed instrument locations. 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. 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. It is important to note that the spatially-distributed residence times calculated from Lagrangian drifters likely represent an underestimation compared to Eulerian methods, and further application of the residence times must be appropriate to the research question.

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 used in the study. 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 are from NOAA WW3.

Figure 4. a) Boxplots and b) histograms of all drifter speeds (cm s-1) during end member periods TIDE, WIND, and WAVE. 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 5. Time series of acoustic current profilers 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 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.

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

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