Eulerian and Lagrangian measurements of water flow and residence time on a fringing reef flat embayment, American Samoa

by

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Abstract

Hydrodynamic processes on coral reefs are important for nutrient cycling, larval dispersal, temperature variability, and understanding the impacts on coral reef ecosystems from terrestrial sediment, nutrients, and contaminants discharged from adjacent, disturbed watersheds. A combination of Eulerian and Lagrangian measurements were used to characterize spatially distributed water flow and residence times in relation to endmember forcing conditions in the fringing coral reef flat-lined embayment of Faga'alu, on the island of Tutuila in American Samoa. Thirty Lagrangian drifter deployments collected spatially distributed flow data and Eulerian current profilers were installed at fixed locations for nine days to collect long-term flow data in relation to forcing conditions. Mean current speeds (residence times) over the reef flat varied from 1-37 cm s-1 (2.78-0.08 hr), 1-36 cm s-1 (2.78-0.08 hr), and 5-64 cm s-1 (0.56-0.04 hr) under tidal, wind, and wave forcing, respectively. The highest flow speeds were observed over the southern reef near the reef crest and during large waves, suggesting the strong influence of wave forcing. The lowest flow speeds and highest residence times were consistently observed over the northern reef and in the northwest corner of the bay, particularly when wave-driven flow was low or when winds were onshore. Flow directions during tidal forcing were the most variable, with instances of transport from the reef flat to the forereef. During onshore wind forcing flow directions were mostly towards the northwest corner of the bay. During wave forcing flows followed a clockwise pattern over the southern reef onto the northern reef, and out to sea through the channel. Lagrangian estimates of mean flow speeds were 57-78% higher than Eulerian estimates, either due to the spatial heterogeneity in observed flows or the influence of Stokes drift on the surface drifters. These results demonstrate the applicability of a hybrid Lagrangian-Eulerian measurement scheme to understand spatially distributed and temporally extensive flow patterns and thus residence time in geomorphically-complex embayments that characterize many reef-lined coasts.

Keywords:

coral reefs, drifters, Water circulation, Residence time

Introduction

Hydrodynamic conditions like circulation and residence time of reef waters 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 the water quality (Falter et al. 2004; Wyatt et al. 2012). 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 reef embayments (Hoitink and Hoekstra 2003; Storlazzi et al. 2004; Presto et al. 2006; Draut et al. 2009; Hoeke et al. 2013). Spatially distributed flow patterns under variable forcing conditions are logistically difficult to quantify, so conservation planning and remediation studies are often done with coarse estimations of pollutant discharge and distance-based plume models (Klein et al. 2012). Since hydrodynamic conditions can exacerbate or limit the impacts of terrestrial sediment from disturbed watersheds (Hoitink and Hoekstra 2003), an improved understanding of the actual spatial patterns and temporal variability in flows and residence times of water over corals is needed for understanding sedimentation patterns and impacts to coral health.

Studies in various coral reef environments adjacent high islands have shown current speeds, directions, and residence times over reef flats are controlled by wave, wind, and tidal forcing, depending on the orientation and shape of the reef, relative to the prevailing wave, wind, and tidal climates (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 the reef crest depth and wave energy propagation onto the reef flat (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 forereef (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, 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 record wave height and period, current speed and direction, and/or tidal elevation (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. Remote sensing approaches are infeasible where the study area is small in scale and experiences frequent cloudy conditions. Hydrodynamic computer models can predict spatially distributed flow (Hoeke et al. 2011), but typically require accurate bathymetry, detailed forcing data, and significant modeling expertise (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, compare to 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 have shown the ability to capture synoptic measurements of small-scale flow structures and patterns by deploying large numbers of GPS-logging drifters to collect high-density observations of flow velocities (Johnson et al. 2003; MacMahan et al. 2010). Although high frequency deployments of a fleet of GPS-logging drifters has yielded synoptic measurements of water movement in surf zones near linear, sandy beaches, it has been limited in shallow reef environments (Falter et al. 2008; Wyatt et al. 2010).

Lagrangian measurements can provide spatially extensive data on the flow field, but 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.

In August 2012, Faga'alu on the island of Tutuila in American Samoa, was chosen by the US Coral Reef Task Force (USCRTF) as a priority watershed site for the Watershed Partnership Initiative (WPI). The WPI is an active effort of the USCRTF to reduce land-based sources of pollution by facilitating and enhancing coordination, partnerships, and contributions of US Federal agency resources and expertise to implement geographically specific integrated activities to reduce pollutant loads to coral reef ecosystems. Efforts are underway to reduce sediment loading from the anthropogenically-disturbed areas to Faga'alu Bay, and other studies monitoring sediment loading from Faga'alu Stream (Messina and Biggs, in review) and sediment accumulation on the reef are underway (Holst-Rice et al. 2015). The results from this paper will help interpret the spatial and temporal patterns of sediment accumulation measurements on the reef by illustrating the spatial pattern of currents that distribute sediment over the reef in relation to seasonally varying hydrodynamic forcing conditions.

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. Our goal in this study was to apply both Eulerian and Lagrangian methods to understand the spatial flow patterns and residence time that determine the dispersal of terrestrial sediment discharged to a bathymetrically complex coral reef-lined embayment, in relation to different ‘end-member’ forcing conditions.

Materials and Methods

Study Area

Faga'alu Bay, on the island of Tutuila, American Samoa (14.290 S, 170.677 W) is a V-shaped, coral reef-fringed embayment at the mouth of a small (2.48 km2), steep-sided watershed (Figure 1). The bathymetrically complex reef is characterized by a shallow reef flat extending from just off the shore to the reef crest, where it then descends nearly vertically to the deep (>20 m) waters of Pago Pago Bay. 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 (1-5m) sediment-floored pools with coral bommies. An anthropogenically altered, vertical-walled, 5-15 m deep paleo-stream channel ('ava') extends from the mouth of Faga'alu Stream eastward to Pago Pago Bay; this ava channel divides the reef into a larger southern and a smaller northern section. NOAA's National Centers for Coastal Ocean Science (2005) surveys describe coral coverage varies from less than 10% on the degraded northern reef, to more than 50% on the more intact southern reef.

Faga'alu Bay is situated on the western side of Pago Pago Bay where the surrounding high topography blocks wet-season northerly winds from October-April, but the Bay is exposed to dry-season southeasterly tradewinds 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 (<0 m MSL; Vetter (2013)). Faga'alu Bay is only open to a narrow window (south-southeast) of 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 (2013) 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. Destructive tropical cyclones typically occur in the South Pacific from November-April (Militello et al. 2003), impacting American Samoa every 1-13 years recently (1981-present) (Craig 2009). The only available data on water current circulation around Tutuila was found in 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).

Methods

Lagrangian Measurements

Given the relatively small area of Faga'alu Bay (0.25 km2), high spatial density drifter 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 (PVC pipe and plastic sheeting), 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 and compensate for the buoyancy of the pipe. The GPS logger was installed in a PVC housing at the top. The drifters were transported to the launch zones and retrieved using a stand-up paddle board.

Five drifters were released from five launch zones (Figure 1) within a 10 min time frame at the beginning of each deployment. Drifter position data was recorded by the GPS logger at 5 s intervals and resampled 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 ava channel to Pago Pago Bay, but tracks were limited to 1 h for comparisons with ADCP data.

Eulerian Measurements

Three Nortek Aquadopp 2-MHz acoustic 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 profilers were deployed on sand or rubble patches amongst the corals, as deep as possible to maintain adequate water levels over the profiler during low tide (Figure 2c-d). The profilers collected 580 current samples at 2 Hz every 10 min and 2,048 wave samples at 2 Hz every 60 min.

Ancillary Data

The instrument deployments were timed to capture end-member hydrodynamic forcing conditions that characterize the study area (Yamano et al. 1998). The 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 for the recorded data (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 on a pole mounted to a building (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.

Analytical Methods

Simultaneous data from the drifters and ADCPs were subset by end-member forcing, and two techniques were used to compare the drifter results with the ADCP results: progressive vectors of cumulative flow and 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. The progressive vectors, EOFs and mean flow velocities from binned 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

Oceanographic and Meteorological Forcing

A large range of tide, wind, and wave conditions was sampled during the 8 day period of overlapping ADCP and intensive drifter deployments, 2014 Year Day (YD) 47-55 (15-23 February 2014) (Figure 3). Three distinct periods were observed: (1) a strong onshore wind event with small waves; (2) a large southeast swell with weak winds; and (3) weak winds from variable directions and small waves, where tidal forcing was dominant. Three end-member forcings were defined: 1) Small waves and strong onshore winds ('WIND') during 2014 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 characterize the dominant wind conditions experienced in Faga’alu Bay. During TIDE, wind speeds were low to moderate (1.5-3.4 m s-1) and wind directions were variable, 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 2013).

Eulerian Measurements

On the northern reef flat (AS3; Figure 1), the water level dropped below the minimum blanking distance of the ADCP at low tides (Figure 4d), and flow was assumed to be nearly zero during these times given the relatively 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 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 velocity flow was observed over the southernmost part of the reef (AS1) in a northwesterly direction, 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, though direction was more variable under tidal forcing, with some cross-reef flow to the northeast (Figure 4c). Flow speed at AS2 was responsive to high winds and but highest during high waves (Figure 4e). At AS3, flow directions and speeds were highly variable under all forcing conditions, and 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, and to a lesser degree during wind forcing, flow velocity was highest during high tide and decreased significantly as the tide stage falls. This was most evident at AS1, but was also observed at AS2, during YD 53-55. This effect was noticeably absent or significantly reduced during wind forcing on YD 47-49, and tidal forcing on YD 51-52.

Lagrangian Measurements

Thirty drifter deployments were conducted from 19 January 2014 to 23 February 2014, with 22 of those deployments coinciding with the ADCP deployments during 2014 YD 47-55 (15-23 February 2014; Appendix Table A1). Drifter tracks from all deployments covered nearly the entire reef flat and ava channel (Figure 5), showing three general spatial patterns: 1) Faster flow speeds over the southern reef flat; 2) slower, more variable currents over the deeper pools of the southern back-reef, northern reef, and ava channel near the stream mouth; and 3) faster current speeds exiting the east end of the ava channel. Instances of off-reef transport over the reef crest were observed, mainly exiting through a small channel in the southern reef crest at high tide under calm wave and wind conditions; most of these continued moving out to sea and some were quickly re-entrained in the surf zone and traveled landward over the reef flat. Other anomalous drifter tracks show where drifters were entrained in the surf zone at the reef crest and quickly exited back out to sea in the far northeast portion of the study area.

Progressive Vectors

Progressive vectors from ADCP data indicated the flow velocity at AS1 and AS2 was 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 along-shore towards the ava channel, the progressive vectors over the southern reef showed little variation in flow direction, going ashore in some cases. In general, the lengths of progressive vectors were similar to the actual tracks of the drifters, indicating similar flow speeds, albeit sometimes different directions. The exception was over the northern reef, where drifters quickly moved into the ava channel and were influenced by very different currents than the ADCP at AS3. The progressive vectors over the 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 flow velocities.

During tidal forcing the drifters traveled in erratic directions and traveled farther than the progressive vectors from ADCPs (Figure 6a-b). Drifter tracks and progressive vectors compared poorly in speed and direction at AS3 on the northern reef, slightly better at AS2, though progressive vectors are still shorter and do not vary direction, and fairly well at AS1 on the southern reef. Under the low wave conditions at high tide, some drifters were observed to flow seaward over the reef crest near AS2, but progressive vectors were exclusively shoreward. Some drifters were also observed moving from the northern reef onto the southern reef during light and variable winds; during large waves, some drifters moved from the southern to the northern reef.

During wind forcing, the drifter tracks showed flow directions were mainly towards the northwest corner of the bay, and suggest flow out of the ava channel (at least at the surface) was suppressed under strong onshore (easterly) winds. Progressive vectors and drifter tracks were shorter than during tide and wave forcing, indicating flow speeds were slower (Figure 6c-d). Progressive vectors compared well with drifter tracks in speed and direction for all locations, though the progressive vector at AS3 is still short in comparison to the drifter tracks near the same location. Though moderate to strong easterly winds are most prevalent throughout the year due to the trade winds, fewer observations were made under wind forcing than tidal or wave forcing so there is less certainty in the observed flow patterns. Also, a drifter deployed at the northeast reef was lost during the WIND period, so no drifter tracks were available from that location.

During wave forcing, longer progressive vectors at all locations, including the northern reef, indicate significantly faster flow speeds than during wind and tidal forcing (Figure 6e-f). The progressive vectors on the southern reef show exclusively onshore flow, even going ashore in some instances. The drifter tracks clearly indicate a coherent pattern of clockwise flow over the southern reef, through back-reef pools and near the stream mouth, and then seaward over the northern reef and out the ava channel. Despite waves breaking on the northern reef crest, it appears the flow across the southern reef and into the ava channel influences an overall eastward flow over the northern reef and out to sea. 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 that traveled through each grid cell differed due to the spatial position of the grid cell relative to the flow pattern. Grid cells in the middle parts of the bay and ava channel had more drifter tracks than grid cells in the outer bay and near the shore. More observations suggest more certainty, whereas some of the outlying grid cells with a small number of observations may have been influenced by an anomalous drifter track or a small range of forcing conditions.

Overall, variance ellipses from drifters and ADCPs were more circular at AS3 and on the northern reef, and more ellipsoid at AS1 and AS2 and on the southern reef. These results suggest current directions are more variable over the northern reef, and more consistent on the southern reef, under all forcing conditions. Finer-resolution drifter data resolved the general clockwise flow from the southern reef, over the northern reef, and out to sea, and also illustrated the decreased flow velocities close to shore and in the southern back-reef pools. ADCP data showed mean flow directions were similar during different end-member forcing conditions, but mean flow speed varied at each location. Mean velocities calculated from ADCP data for AS1, AS2, and AS3 during tide forcing were 14.6 cm s-1, 5.3 cm s-1, and 0.9 cm s-1; during wind forcing were 11.6 cm s-1, 3.9 cm s-1, and 1.5 cm s-1; during wave forcing were 18.1 cm s-1, 10.9 cm s-1, and 1.21 cm s-1, respectively (Table 2). Over the area covered by drifter tracks, mean flow velocities from drifters varied from 1-37 cm s-1, 1-36 cm s-1, and 5-64 cm s-1 under tidal, wind, and wave forcing, respectively.

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 shoreward flow, but the variance ellipses and mean velocities from drifters showed clockwise flow across the southern reef and seaward out the ava channel. Variance ellipses from drifters were more ellipsoid and mean velocities were higher near the reef crest and on the southern reef, compared to the northern reef and southern back-reef pools. Though flow directions were more variable, mean velocities 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 ellipsoid than under tide forcing, indicating flow directions were more consistent during strong onshore winds. Similar to tide and wave forcing, the overall flow pattern from the drifters was more variable ellipses and higher velocities over the southern reef, and more circular variance ellipses and slower velocities in the back-reef pools, ava channel, and northern reef.

Wave forcing showed the highest mean flow speeds and most ellipsoid variance ellipses, indicating high waves are a strong control on flow velocities in the bay. While flow speeds at AS1 were consistently influenced by even small breaking waves, as wave height increased, breaking waves were observed further north along the reef crest, particularly near the ava channel, increasing flow speeds over the reef flat near AS2. The increased flow near AS2 increased flow speeds near the ava channel and the southern back-reef pools. The variance ellipses at AS3 indicated variable flow directions, but the magnitude of the major and minor flow axes were larger than tide and wind forcings, indicating flow speeds were higher during wave forcing. The drifters showed a clear pattern of faster, more unidirectional flows near the reef crest on the southern reef, transitioning to slower, more variable flow over the back-reef pools, and finally turning eastward over the northern reef and seaward out of the ava channel. Similar to the results during tidal forcing, mean velocities increased moving seaward through the ava channel, but due to the low data density outside the reef crest it is unclear whether the flow continues eastward to Pago Pago Harbor or swirls around and is re-entrained in the surf zone on the southern reef.

Residence Time

Water residence time over the reef flat was computed from mean drifter velocities under different forcing conditions (Figure 8). Residence times 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. Contrary to results at AS1 and AS2, at AS3 mean speed was slower and residence time was longer during wave forcing compared to wind forcing. 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.

Comparing Eulerian and Lagrangian results

Mean flow speed and residence time differed between the Eulerian and Lagrangian methods under different forcing conditions (Table 2). 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. The highest percent error for a single location was at AS3 on the northern reef, likely due to the strong heterogeneity in the flow over the spatial bin as the drifters moved into the ava channel. The lowest percent error was at AS1 on the southern reef, where the flow is most homogeneous. The percent error for all locations together was lowest for speed during tide forcing, and lowest for residence time during wind forcing.

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 pattern of mean flow speeds and flow directions showed a predominantly clockwise circulation through the bay under all forcing conditions, with higher flow speeds throughout the bay during wave forcing, compared to tidal and wind forcing. The shortest residence times were measured on the outer 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 northwest corner of the embayment. Given the proximity of the 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 southern reef bordering the ava channel are under greatest threat of land-based sources of pollution. 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 southern reef and the slower, more variable flow over the northern reef under all forcing conditions. The Eulerian method characterized flows adequately near the 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 northern and southern reef flats, and southern back-reef pools. The spatially distributed drifter measurements also illustrated several unique features in the flow pattern, particularly near areas of complex bathymetry like the ava channel. From the orientation of the reef flat and channel, it would seem that flow over the southern reef near the ava channel would flow directly from the reef crest northward into the main channel. However the flow near AS2 is deflected away from the ava channel, shoreward to the west where it flows into the back-reef pools and then enters the ava channel. This deflection is likely caused by wave energy refracting and surging into the ava channel, pushing southward from the main channel onto the southern reef.

The variance ellipses and mean velocities from ADCPs showed exclusively onshore flow under all forcing conditions, whereas the higher resolution drifter data only showed the same pattern under wind forcing. This suggests that strong onshore winds, in the absence of high waves, drives all surface flows into the northwest corner of the bay, with a notable lack of seaward flow out of the ava channel. Data density was lowest during wind forcing and perhaps drifter deployments longer than 1 h would have observed seaward flow.

Observations on the linear reef flat in 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 ava channel. Flow through the ava 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 reef pass were lower and flow could even reverse near the bottom (Hench et al. 2008). The increase in flow speed through the ava 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 (Vetter 2013).

Compared to Eulerian measurements, the Lagrangian measurements recorded higher mean flow speeds (57-78%) at all locations and during all forcings except for one: on the 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. 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 (Figure 2b)), while Eulerian methods make a depth-averaged flow measurement (Falter et al. 2008; Lowe and Falter 2015). 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 m deep reef flat in 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 (Delft 3D) 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. Importantly, while the drifter speeds in Falter et al. (2008) were significantly higher, 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 drifter, however, Falter et al. (2008) concluded the wave-induced deflection was low so while this may explain some of the discrepancy it 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, while Stokes drift may have been important near the reef crest at AS1 and AS2 where wave energy is strongest.

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. Other studies might be more interested in surface transport related to sediment plumes (Warrick et al. 2007), plankton and larvae transport (Siegel et al. 2003) where Lagrangian methods would be more appropriate. Alternatively, marine sediment studies focused on near-bed shear stress and benthic sediment movement (Presto et al. 2006) should use the appropriate 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’s 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 endemember 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

This study investigated water circulation patterns driving sediment dynamics and resulting impacts on coral health at the study site, but water circulation is critical for understanding both the natural ecological processes and the impacts of anthropogenic impacts on all coral reefs. This study showed that flow speeds, flow directions, and water residence times were spatially heterogeneous in fringing-reef environments.

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Tables

Table 1. End member 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 (January to March, 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 AS2

Figure 3. Time series of physical forcing data was used to define end-member 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. 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 5. Map of all drifter tracks during the experiment, colored by speed (m s-1).

Figure 6. 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 7. 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 8. 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. Red numbered deployments coincide with ADCP deployments.