# TITLE:

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

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scripted terms: a, b, km2

## ABSTRACT

Hydrodynamic processes on coral reefs are important for nutrient cycling, larval dispersal, temperature variability, and understanding the impacts of terrestrial sediment, nutrients, and contaminants from adjacent impaired watersheds on coral reef ecosystems. In order to understand the spatial and temporal variability in flow velocities and the resulting residence time of water in the fringing coral reef flat-lined embayment of Faga'alu, on the island of Tutuila in American Samoa, data from acoustic current profilers and ocean surface current drifter deployments were combined with meteorologic data and numerical wave model results. These data and model results, collected over nine days, made it possible to evaluate the relative contribution of tidal, wind, and wave forcing on the flow patterns and resulting residence times of water masses over the reef. Mean residence times varied from 2.78-0.08 hr, 2.78-0.08 hr, and 0.55-0.04 hr under tidal, wind, and wave forcing, respectively; the lowest residence times were 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 embayment. These results demonstrate the applicability of a hybrid Lagrangian-Eulerian measurement scheme to understand 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, including the residence time of waters over the reef flat, are a primary control on sediment dynamics in fringing reef embayments (Draut et al., 2009; Storlazzi et al., 2009 ), and are important for other biologically important processes like nutrient cycling, larval dispersal, and temperature regimes (Falter et al., 2004; Wyatt et al., 2012). Current conservation planning is done with coarse estimations of pollutant discharge and distance-based plume models (Klein et al., 2012), but understanding the spatial and temporal variability in current speeds, flow directions, and residence time of water over corals is critical for understanding sedimentation patterns and impacts to coral health. However, spatially distributed flows under variable forcing conditions are logistically difficult to quantify.

Hydrodynamic conditions control sediment accumulation in two ways: by limiting primary deposition, and by resuspending and advecting previously deposited sediment. Following large or intense storm events, sediment-rich freshwater is discharged into reef-fringed bays and advected seaward over the reef by momentum in a thin surface layer. This sediment-rich layer significantly attenuates photosynthetically active radiation and transports fine sediment over the reef where it can settle out of the water column and damage corals. Although the hypopycnal surface plume is able to move counter to prevailing ocean currents (upcurrent) by sliding over denser seawater, as sediment particles settle they are entrained in the prevailing current and transported accordingly (Wolanski et al., 2003). As flow velocities increase, residence time of the plume over the reef flat is decreased, limiting time for small particles to settle out of the water column. In reef environments where shallow reef crests limit the propagation of incoming surface wave energy, wave action alone may be insufficient to resuspend and disperse sediment, but in combination with wave- or wind-driven currents, orbital velocities may reach critical shear stress for sediment resuspension and dispersal (Ogston et al., 2004; Hoeke et al., 2013). By influencing orbital velocities, bed shear stress, and suspended sediment transport, current circulation is a strong control on the spatial distribution of deposition, resuspension, and dispersal of terrigenous sediment discharged to reefs (Hoitink and Hoekstra, 2003; Storlazzi et al., 2004; Presto et al., 2006; Hoeke et al., 2013).

Studies in various coral reef environments adjacent high islands showed 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 (Hench et al., 2008; Hoeke et al., 2011; Presto et al., 2006; Storlazzi and Field, 2008; Storlazzi et al., 2004). Variations in reef morphology relative to the orientation of the dominant meteorological and oceanographic forcing can generate heterogeneous waves and currents over relatively small (hundreds of meters) spatial scales, unlike those observed along relatively linear sandy shorelines (Storlazzi et al., 2009; Hoeke et al., 2011, 2013). Buoyancy forcing from hypopycnal river floods is generally ignored or considered inconsequential due to their rarity and short duration relative to other forcings (Hench et al., 2008; Hoeke et al., 2011). Current speeds and patterns over reefs exposed to remotely-generated groundswells are generally dominated by wave forcing (Hench et al., 2008; Hoeke et al., 2011; Vetter et al., 2010), whereas wind forcing is dominant for reefs protected from groundswells (Presto et al., 2006). Tidal elevation modulates both wave-driven currents by controlling the reef crest depth and subsequent wave energy propagation into the reef flat, and wind-driven currents by regulating water depth for wind-driven surface wave development (Presto et al., 2006). Reef flat currents in wave-driven environments 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 an individual fluid parcel as it moves through space and time, 2) the Eulerian perspective focuses on specific locations, observing the fluid flow past that location over time. Eulerian methods characterize water circulation on the reef 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). Eulerian methods are well-suited to characterizing flows over long periods and a large range of forcing conditions. However, collecting high spatial resolution data of hydrodynamic processes using strictly Eulerian methods is expensive and logistically difficult (Curt D. Storlazzi et al., 2006; Storlazzi et al., 2004). Spatially distributed current speeds and directions can be predicted by hydrodynamic computer models (Hoeke et al., 2011), but models typically require accurate bathymetry, detailed forcing data, and significant modeling expertise (Hoeke, 2010; King et al., 2012; Wolanski et al., 2009). While imagery-based remote sensing is useful to map the temporal and spatial distribution of flood plume boundaries (Klemas, 2012; Warrick et al., 2007), even high resolution imagery may not quantify the underlying current circulation, which is a strong control on sediment transport. Instead, Lagrangian methods including the use of GPS-tracking drifters have been used to map flow patterns in coastal areas, compare to Eulerian descriptions of flow speeds (C. D. Storlazzi et al., 2006; Storlazzi et al., 2004; 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). While deploying a fleet of GPS-logging drifters has yielded synoptic measurements of water movement in surf zones near linear, sandy beaches, it has not been attempted in a shallow reef environment.

While Lagrangian measurements provide spatially explicit data on the flow field, 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 (C. D. Storlazzi et al., 2006; Wyatt et al., 2010). Storlazzi et al., (2006) successfully combined Eulerian and Lagrangian methods 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. This approach yields spatially distributed flow data from the Lagrangian drifters, within the context of the longer time series of flow forcing from the Eulerian methods.

Since water residence time is critical to sediment dynamics and coral heath, what is the water residence time over the Faga'alu reef flat and how does it change under wave, wind and tidal forcing? To address this main research question we compared the spatially extensive Lagrangian measurements with the longer term Eulerian measurements to calculate spatially distributed water residence time under different 'end-member' forcing conditions: tide, wind, wave.

## STUDY AREA

Insert Figure 1 here

Figure 1. Data collection locations in Faga'alu Bay. Wind speed and direction were recorded at the weather station (WxStation), a Dobie wave gauge recorded wave height and period (Wave Gauge), three ADCP's were deployed for one week to measure current speed and direction, and five GPS-logging drifters were deployed from the same five launch zones (DrifterLaunch) for thirty separate deployments (January to March, 2014).

Faga'alu Bay, on the island of Tutuila, American Samoa (14.290 S, 170.677 W) is a V-shaped, reef-fringed embayment at the mouth of a small (2.48 km2), steep-sided watershed (Figure 1). The 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 waters of Pago Pago Bay. Wave breaking is constrained to the shallow reef crests, the transitions between the steeply-sloping fore reef and the roughly horizontal reef flats. Near the reef crest, the reef flat is cemented reef pavement, but near the shore in the southern backreef there are areas of deeper (1-5m) pools. An anthropogenically altered, vertical-walled, 5-10 m deep paleo-stream channel (ava) extends from the mouth of Faga'alu Stream eastward to Pago Pago Bay; this ava divides the reef into a larger southern and a smaller northern section . NOAA surveys found coral coverage varies from <10% on the degraded northern reef, to >50% on the more intact southern reef. Following large or intense storm events, suspended sediment is discharged from Faga'alu Stream in the northwest corner of the Bay, and advected seaward over the reef by momentum in a thin surface layer of freshwater. Suspended sediment concentrations (SSC) in this layer often exceed 500mg/l which significantly attenuates photosynthetically active radiation and transports fine sediment over the reef where it can settle out of the water column and onto coral reef organisms. Although the hypopycnal surface plume is able to move counter to prevailing currents (upcurrent) by sliding over denser seawater, as sediment particles settle they are entrained in the prevailing current and transported accordingly (Wolanski et al., 2003). As flow velocities increase, residence time of the plume over the reef flat decreases, limiting time for small particles to settle out of the water column and controlling the sedimentation rate, even for the same concentration and magnitude of different plumes.

Insert Figure 2 here

Figure 2. A) Image of the embayment on a typical, rain-free day. The darker areas of the bay are live coral, and the light areas are deeper pools with carbonate sand bottom. B) Image of a flood plume (2/21/14) in the northern portion of the bay following a heavy precipitation event. Plumes usually persist for several hours, and rarely are seen after 24h due to the flushing of water through the deep channel and out to sea.

Faga'alu Bay is situated on the western side of Pago Pago Harbor 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. Faga'alu 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). Given that the reef crest is exposed at low tide, cross-reef transfer of wave energy and water flow is strongly dependent on the tidal stage and wave setup. Faga'alu 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.

Little data on current circulation around Tutuila is available, and almost no data on circulation over the reef flat has been collected (CH2M HILL, 1984; Jacob et al., 2012; Wiles et al., 2012). Militello et al. (2003) modeled wave-induced setup on reef flats and developed stage-frequency relationships for large tropical storms and hurricanes in American Samoa. Thompson and Demirbilek (2002) characterized offshore wave climate from data collected near Western Samoa (1985-1990), and used numerical modeling to simulate wave propagation dynamics in Pago Pago Harbor. Vetter et al (2013) deployed wave/tide gauges in Faga'alu Bay on the southern forereef and reef flat, and an ADCP in the ava , for one year (2012-2013). Vetter (2013) concluded flow dynamics in the bay were predominantly forced by waves breaking over the southern reef crest, and the wave influence increased linearly with tide height. Using an estimate of total lagoon volume, Vetter (2013) calculated flushing time varied from thirty-three hours during low wave height, to less than two hours during conditions when peak significant wave height was 1.6 m, and mean current speed out of the main channel was 0.14 m/s.

## METHODS

To characterize the spatial pattern of flows and determine the relationship between forcing conditions and residence time of water over the reef flat in Faga'alu Bay, a combination of Eulerian and Lagrangian measurements was used. Lagrangian drifters were used to collect spatially distributed data on flow velocities, in conjunction with Eulerian current profilers at fixed locations to collect long-term data in relation to forcing conditions.

### Eulerian Measurements

Three Nortek Aquadopp 2-MHz acoustic current profilers recorded tide, wave, and current data at three locations on the reef flat in Faga'alu for one week (Figure 1). The profilers were attached to cinder block anchors and placed on sand or rubble patches amongst the corals, as deep as possible to maintain adequate water levels over the profiler during low tide (Figure 3). The profilers collected 580 current samples at 2 Hz every 10 min and 2048 wave samples at 2 Hz every 60 min. On the northern reef, the water level dropped below the minimum blanking distance of the current profilers at low tides, and flow was assumed to be nearly zero during these times given the relatively low water depth relative to the height of the corals.

Insert Figure 3 here

Figure 3. Five GPS-logging drifters and three acoustic current profilers were deployed on the reef flat in Faga'alu. TOP: Images of the shallow-water drifters on land, and deployed in the field. BOTTOM: Images of the acoustic current profilers deployed on the southern reef flat (AS1).

### Lagrangian Measurements

Drifters for shallow coral reef environments need to be shallow enough to avoid interaction with corals, deep enough to not be affected by the surface movements, extend high enough to be visible but not high enough to be affected by winds, and finally, rugged enough to sustain the impact of a breaking wave onto the reef in the event it is entrained in the surf zone. Due to Faga'alu Bay's relatively small area (0.25 km2), high-density drifter data could be collected with a small number of drifters (n = 5) and field personnel (n = 1). Five drifters were designed and constructed with materials available on-island, from PVC tubing and plastic sheeting, with a small waterproof housing for a HOLUX M1000 GPS recorder, and a float collar to maintain upright orientation (Figure 4). The fins of the drifters were roughly 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 housed in a PVC housing. The drifters were transported to the launch zones and retrieved using a stand-up paddle board.

Five drifters were released from the same five launch zones within a 10-m time frame at the beginning of each deployment, and allowed to drift until they exited the offshore end of the ava channel at Pago Pago Harbor. Drifter position data was recorded by the GPS logger at 5 s intervals and resampled to 1 min intervals to reduce signal noise. Drifters were allowed to drift until they exited the ava channel, but tracks were limited to 1 hr for analysis. Drifter speed and direction were calculated using a forward difference scheme on the drifter locations (Davis, 1991; MacMahan et al., 2010) and gridded in 100 m x 100 m bins for analyses.

### Ancillary Data

The instrument deployments were timed to capture end-member forcing conditions that characterize the study area. The end member conditions time ranges 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 WaveWatchIII (WW3; REFERENCE) modeled data on swell height and direction for the recorded data (Hoeke et al., 2011). WW3 model data, calibrated to wave data recorded in situ by the DOBIE wave/tide gauge, were used to define forcing during the ADCP and drifter deployments.

Wind speed, wind direction, barometric pressure, and precipitation 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). Meteorological and tide data were also recorded at NOAA's National Data Buoy Center's NSTP6 station (REFERENCE) located approximately 1.8 km north of Faga'alu. Wind speed, wind direction, barometric pressure, and tidal elevation data were ralso ecorded at NSTP6 at 6 min intervals. For this study, wind conditions are sufficiently described qualitatively so the topographic effects on wind speed and direction recorded at the stations are considered inconsequential.

### Analytical Methods

Data from the drifters and current profilers was subset by end-member forcing condition, and two techniques were used to compare the drifter results with the profiler results: Empirical orthogonal functions (EOF) and progressive vectors of cumulative flow. Spatially distributed water residence times were calculated for end-member conditions from drifter data only.

Progressive vectors, which are cumulative summations of flow assuming spatial homogeneity, were generated for the profiler data following the methodology used by Storlazzi et al. (2006) and were compared to simultaneous 1 hr tracks of drifter data. A series of 1-h progressive vector diagrams of projected cumulative flow were computed from ADCP data collected during each end member condition period, and compared to drifter tracks to demonstrate the usefulness of drifters for illustrating spatially variable flows compared to fixed current profilers. The progressive vectors from the current profilers illustrate the flow variability at those fixed points during the 1 hr drift duration. However, progressive vectors are calculated assuming spatial homogeneity of the flow, causing them to move onshore in some instances.

EOF principal axes, variance ellipses, and mean flow vectors were calculated for spatially binned drifter data (100 m x 100 m) (MacMahan et al., 2010) and profiler data. Where drifters did not travel through a spatial bin, no EOF or residence time could be calculated .EOF's and mean vectors from drifters and profilers were compared to determine if the short-term observations from the drifters adequately described the flow characterized by the long-term current profilers, and characterize the spatial variability of flow over the reef flat. Mean flow vectors were used to calculate water residence time over the reef under different forcing conditions. Mean flow vectors from the current profilers and driftes were compared to assess whether the short term drifter deployments agreed with estimates from the long-term current profilers.

## RESULTS

### Oceanographic and Meteorologic Forcing

Insert Figure 4 here

Figure 4. Time series of physical forcing data was used to define end-member periods for analysis. Forcing data included: a) Tide stage, b) wind speed, c) wind direction from NDBC station NSTP6, d) wave height, e) wave period, and f) wave direction from NOAA WW3. Day 47=16 Feb 2014, Day 54=23 Feb 2014. Forcing

During the period of overlapping ADCP and intensive drifter deployments, 2014 Year Day (YD) 47-55 (15-23 February 2014), a large range of tide, wind, and wave conditions was sampled (Figure 4). Three distinct periods were observed including a strong onshore wind event, a high southeast groundswell, and weak winds from variable directions where tidal forcing was dominant . Three end-member forcings were defined: 1) Small waves and strong onshore winds ('WIND') during 2014 Year Day (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, average wind speed reached a maximum of 9.7 m/s with maximum gusts of 28 m/s from the northeast to southeast on YD 48. These wind conditions are typical of average wind conditions observed during the winter tradewind season. During TIDE, wind speeds were low to moderate (3-6 m/s) 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 (O. Vetter, unpublished data).

\*\*Note: Local time is UTC-11 so local dates are actually one day earlier (e.g. Tide=2/18-2/19 Local time)

### Eulerian Measurements

Current profilers at three locations on the reef flat recorded water flow for one week during YD 47-55. On the northern reef flat (AS3) the water level dropped below the minimum blanking distance of the ADCP at low tides (Figure 5 d), and flow was assumed to be nearly zero during these times given the relatively low water depth. The short data gap at AS1 on YD 50 was due to the ADCP being disturbed, likely by fishermen looking for octopus.

In general, tidal forcing showed slower flow speeds and more variable directions, wind forcing showed medium flow speeds and less variable directions, and wave forcing showed the fastest flow speeds and more consistent flow directions. The highest velocity flow was observed over the southernmost part of the reef (AS1) and was oriented predominantly in a northwesterly direction, indicating the strong influence of even small breaking waves over the reef crest. Flow direction at AS2 was consistently to the southwest, though variable under tidal forcing, even exhibiting some cross-reef flow to the northeast. Flow speed at AS2 was responsive to high winds and high waves, and highest during high waves. At AS3, flow direction and speed were highly variable under all conditions, and exhibited the lowest flow speeds of the three ADCP's.

Flow speeds at AS1 and AS2 illustrated the modulating effects of tidal stage on wave-forced flow (Figure 5 e). During wave forcing, and to a lesser degree during wind forcing, flow velocity is highest during high tide and decreases significantly as the tide stage falls. This is most evident at AS1, but is also observed at AS2, during YD 53-55. This effect is noticeably absent or significantly reduced during wind forcing on YD 47-49, and tidal forcing on YD 51-52.

Insert Figure 5 here

Figure 5. Current profilers at three locations on the reef flat recorded water flow for one week. Time series of tide (a) and water flow measured by the acoustic current profilers at the southernmost point, AS1 (b), the central part of the reef, AS2 (c), and northern reef, AS3 (d). At AS3 (d), water depths at low tide were too shallow to measure flow data. Note the variations in current speeds both in space and time due to the different forcing conditions.

### Lagrangian Measurements

Thirty drifter deployments were conducted from January to February 2014, with 22 of those deployments coinciding with the ADCP deployments during YD 47-55 (February 15-23; Append Table 1). Drifter tracks from all deployments covered nearly the entire reef flat and ava channel (Figure 6), showing three gneral spatial patterns: 1) Faster flow speeds over the southern reef flat, 2) slower, more variable currents over the deeper pools of the southern backreef, northern reef, and ava channel near the stream mouth, and 3) Faster current speeds exiting the east end of the ava. Several examples of cross-reef transport were observed, mainly exiting through a subtle depression in the southern reef crest at high tide under calm wave and wind conditions. Some continued moving out to sea and some were quickly re-entrained in the surf zone and traveled 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.

Insert Figure 6 here

Figure 6. Map of all drifter tracks, colored by speed, recorded during the experiment.

### Progressive Vectors

Progressive vectors were calculated from ADCP data for each forcing end-member and compared to drifter tracks under the same forcing conditions (Figure 7). While the drifter tracks changed direction from onshore to cross-shore towards the ava channel, the progressive vectors over the southern reef showed little variation in flow direction, going ashore in some cases, indicating the flow velocity was relatively consistent at AS1 and AS2. The progressive vectors over the northern reef were much more erratic, and traveled much shorter distances due to the lower flow speeds observed at AS3. In general the lengths of progressive vectors were similar to the actual tracks of the drifters, except over the northern reef where drifters quickly moved into the ava channel and were influenced by very different currents than the ADCP at AS3.

Insert Figure 7 here

Figure 7. Progressive vectors calculated from ADCP data, compared to actual Lagrangian drifter tracks under different forcing conditions.

Under tidal forcing the drifters showed highly erratic flow paths and in some instances were observed to move from the northern onto the southern reef, and seaward over the reef crest (Figure 7 a and b). Compared to the consistent progressive vectors, the drifters traveled in erratic directions and traveled farther than predicted by ADCP's at fixed points, indicating higher travel speeds. 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 wind forcing, progressive vectors and drifter tracks were shorter than tide and wave forcing, indicating flow speeds were slower (Figure 7 c and d). 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 for WIND forcing. 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. The drifter tracks show a general trend of flow towards the northwest corner of the bay, and suggest flow out of the ava channel (at least at the surface) may be suppressed under strong onshore (easterly) winds.

Under wave forcing, longer progressive vectors at all locations, including the northern reef, indicate significantly faster flow speeds (Figure 7e). The progressive vectors on the southern reef mainly indicate onshore flow, even going ashore in some instances. Despite waves breaking on the the northern reef crest, it appears the flow across the southern reef and into the main channel influences an overall eastward flow over the northern reef and out the main channel. The drifter tracks clearly indicate a coherent pattern of clockwise flow over the the southern reef, through the backreef pools and near the stream mouth, and then seaward over the northern reef and out the ava channel. All drifters exited the channel during the 1 hr drift, suggesting under high waves the flushing time of the whole bay is under 1 hr.

#### Empirical Orthogonal Functions (EOF)

EOF's and mean flow velocity were calculated from ADCP and spatially binned drifter data collected during each end member forcing period (Figure 8). Due to their spatial position relative to the flow pattern, some grid cells contained a much higher number of observations, especially those grid cells in the middle parts of the bay. More observations suggests more certainty in observed patterns, while some of the outlying grid cells with a small number of observations may have been influenced by an anomalous drifter track.

The overall pattern of EOF's and mean flow velocities from drifters are similar to the corresponding results from ADCP's. Variance ellipses from both data sources are more ellipsoid on the southern reef at AS1 and AS2, and more circular at AS3, under all forcing conditions. Over the whole bay, mean flow velocity varied from 1-37 cm/s, 1-36 cm/s, and 5-64 cm/s under tidal, wind, and wave forcing, respectively. Mean velocities calculated from ADCP data showed similar directions but varied in speed during different forcings, showing the highest mean flow speed under high waves. Finer resolution drifter data resolved the general clockwise flow from the southern reef, over the northern reef and out to sea. The drifter data also illustrates the decreased flow velocity near shore and in the backref pools on the southern reef flat.

Insert Figure 8 here

Figure 8. EOF's calculated from ADCP data, compared to EOF's calculated from spatially binned (100m x 100m grid cell) Lagrangian drifter data under different forcing conditions. Drifter EOF's are colored by number of observations to illustrate varying data density depending on grid cell.

Compared to wind and wave forcing, tide forcing showed the most circular EOF's from ADCP and drifter data, indicating flow directions were more variable under light, variable winds and low waves. Though flow directions were more variable, mean velocities indicated flow speeds were higher under tidal forcing than wind forcing, but still lower than under wave forcing. While EOFs and mean vectors from ADCP's showed exclusively shoreward flow, EOF's and mean vectors from drifters showed clockwise flow across the southern reef and seaward out the ava channel. EOF's from drifters were more ellipsoid and mean velocities were higher near the reef crest and on the southern reef. EOF's were more circular and mean velocities slower near the backreef pools and northern reef.

Wind forcing showed the lowest mean velocities from ADCP and drifter data, though the EOF's were more ellipsoid than under tide forcing, indicating flow directions were more consistent during strong onshore winds. While EOF's and mean velocities from ADCP's showed exclusively onshore flow under all conditions, under wind forcing the higher resolution drifter data also shows this pattern, with a notable lack of seaward flow out of the ava channel. Though data density was low during wind forcing and perhaps longer drifter deployments would have observed seaward flow, this may also suggest strong onshore winds in the absence of high waves drives all surface flows in the northwest corner of the bay. The overall observed pattern of EOF's from the drifters was more ellipsoid, higher velocity flow over the southern reef, with drecreasing speeds and more circular EOF's in the backreef pools, ava channel, and northern reef.

Wave forcing showed the highest mean flow speeds and largest EOF's compared to tide and wind forcing, for both the ADCP and drfiter data, indicating high waves are a strong control on flow speeds in the bay. While flow speeds at AS1 are consistently influenced by even small breaking waves, as wave height increases, breaking waves are observed further north along the reef crest, particularly near the ava channel, increasing flow speeds over the reef flat near AS2. This increased flow near AS2 increases flow speeds near the ava channel and the deeper, backreef pools of the sourthern reef. While the EOF at AS3 was still circular, indicating variable flow directions, the magnitude of the major and minor axes of flow were larger than other forcings, indicating flow speeds were higher. 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 backreef pools, and finally turning eastward over the northern reef and seaward out of the ava channel. Mean velocities increased moving seaward through the ava channel, similar to the results under tidal forcing, 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 Times from drifter observations

Residence time of water at each ADCP was calculated from the mean flow under each forcing condition. Residence times were X, X, and X, for tide, wind and wave forcing, respectively.

/Spatially distributed residence time of water over the reef flat was computed from the mean flow speeds calculated from drifter data under different forcing conditions (Figure 9). Residence times varied from 2.78-0.08 hr, 2.78-0.08 hr, and 0.56-0.04 hr under tidal, wind, and wave forcing, respectively. The shortest residence times were measured near the southern reef crest, and under high wave conditions in general. 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.

Insert Figure 9 here

Figure 9. Residence time calculated from mean velocity of drifters under endmember conditions

## Discussion

The bay-wide mean current speeds (residence times) varied from 1-37 cm/s (2.78-0.08 hr), 1-36 cm/s (2.78-0.08 hr), and 5-64 cm/s (0.56-0.04 hr) under tidal, wind, and wave forcing, respectively. The highest flow speeds were consistently observed at AS1 and over the southern reef near the reef crest, suggesting the strong influence of breaking waves, even when the waves were relatively small. Over the northern reef, mean flow directions were more variable, reversing and flowing towards the river mouth under strong onshore winds and sometimes during tidal forcing with variable winds. The lowest flow speeds and highest residence times were consistently observed in the northwest corner of the bay, when wave-driven flow was low or when winds were onshore.

Both the Eulerian and Lagrangian methods characterized the main difference between the faster, less variable flow over the southern reef and the slower, more variable flow over the northern reef under all forcing conditions. However, where the Eulerian method characterized flows adequately over the southern reef flat where bathymetry and wave forcing were fairly simple, the spatially distributed Lagrangian method more accurately characterized spatially complex flows resulting from complex bathymetry.

Mean flow directions at the ADCP's were exclusively onshore, but the higher resolution drifter measurements resolved the general flow pattern of clockwise flow over the southern reef and out to sea over the northern reef and through the ava channel. 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. Hoowever the flow near AS2 is deflected away from the ava channel, shoreward to the west where it flows into the backreef 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.

Observations on the reef flat in Molokai, Hawaii, showed current speeds were faster where the reef is deeper and narrower (Curt D Storlazzi et al., 2006) but the EOF's and progressive vectors in Figures 7 and 8 suggest the opposite: current speeds are rapid over the shallow reef crest, slowing significantly and becoming more variable when reaching deeper pools and the ava channel.

Flow through the ava channel, however, is not spatially constant. Under both wave and tide forcing, the flow speed through the ava channel steadily increases moving seaward, reaching a maximum at the reef crest. The same pattern is 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. Hench (2008) vertically binned ADCP data in a similar reef in Moorea showed that under low wave forcing surface currents were lower in the reef pass and could reverse near the bottom. 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 it's implications for placing a Eulerian ADCP at a fixed point in the channel, and using data from that one point to define flow for Faga'alu Bay, like in O. Vetter (unpublished).

Drifter observations in the gridcell corresponding to Vetter's (unpublished) ADCP location showed flow speeds of 1-30 cm/s wtih a mean of 8 cm/s, for all forcing conditions. Vetter's (unpublished) ADCP time series shows lower flow speeds in the channel Jan-April than during the more active tradewind season June-October so it is likely that the drifter deployments included more quiescent distribution of days than occur during the whole year. While one large swell event was sampled during the drifter deployments, these conditions appear to be more common during the year than were observed during the one intensive week of drifter deployments. Also, Vetter's (unpublished) ADCP data sampled the full depth of the water column, as opposed to just the surface current that could be affected by winds, especially when strong east winds blow into the bay. This suggests that perhaps Eulerian and Lagrangian methods are more comparable in shallow depths, where the drifter is influenced by a relatively larger portion of the water column.

The overrall 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 occurrence of floods under typically low wave conditions in the wet season, or 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 polluiont. The spatial flow pattern and longer residence times result in greater exposure (=intensity x duration) of the corals in these areas to sediment stress and likely causes the reduced coral health in these locations.

## Acknowledgements

This work was carried out in collaboration between San Diego State University and the US Geological Survey's Coral Reef Project. Funding was provided by a grant by the NOAA Coral Reef Conservation Program. A significant contribution of equipment and expertise was provided by the USGS Pacific Coastal and Marine Science Center. We would like to thank Dr. Michael Favazza for providing logistical support in the field.

# References

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## Table Titles

Table 1. End member periods

## Figure Captions

Figure 1. Data collection locations in Faga'alu Bay. Wind speed and direction were recorded at the weather station (WxStation), a Dobie wave gauge recorded wave height and period (Wave Gauge), three ADCP's were deployed for one week to measure current speed and direction, and five GPS-logging drifters were deployed from the same five launch zones (DrifterLaunch) for thirty separate deployments (January to March, 2014).

Figure 2. A) Image of the embayment on a typical, rain-free day. The darker areas of the bay are live coral, and the light areas are deeper pools with carbonate sand bottom. B) Image of a flood plume (2/21/14) in the northern portion of the bay following a heavy precipitation event. Plumes usually persist for several hours, and rarely are seen after 24h due to the flushing of water through the deep channel and out to sea.

Figure 3. Five GPS-logging drifters and three acoustic current profilers were deployed on the reef flat in Faga'alu. TOP: Images of the shallow-water drifters on land, and deployed in the field. BOTTOM: Images of the acoustic current profilers deployed on the southern reef flat (AS1).

Figure 4. Time series of physical forcing data was used to define end-member periods for analysis. Forcing data included: a) Tide stage, b) wind speed, c) wind direction from NDBC station NSTP6, d) wave height, e) wave period, and f) wave direction from NOAA WW3. Day 47=16 Feb 2014, Day 54=23 Feb 2014. Forcing

Figure 5. Current profilers at three locations on the reef flat recorded water flow for one week. Time series of tide (a) and water flow measured by the acoustic current profilers at the southernmost point, AS1 (b), the central part of the reef, AS2 (c), and northern reef, AS3 (d). At AS3 (d), water depths at low tide were too shallow to measure flow data. Note the variations in current speeds both in space and time due to the different forcing conditions.

Figure 6. Map of all drifter tracks, colored by speed, recorded during the experiment.

Figure 7. Progressive vectors calculated from ADCP data, compared to actual Lagrangian drifter tracks under different forcing conditions.

Figure 8. EOF's calculated from ADCP data, compared to EOF's calculated from spatially binned (100m x 100m grid cell) Lagrangian drifter data under different forcing conditions. Drifter EOF's are colored by number of observations to illustrate varying data density depending on grid cell.

Figure 9. Residence time calculated from mean velocity of drifters under endmember conditions

## APPENDIX