Field observations of wave-driven circulation over spur and groove formations on a coral reef

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Abstract Spur and groove (SAG) formations are found on the forereefs of many coral reefs worldwide. Modeling results have shown that SAG formations together with shoaling waves induce a nearshore Lagrangian circulation pattern of counter-rotating circulation cells, but these have never been observed in the field. We present results from two separate field studies of SAG formations on Palmyra Atoll which show their effect on waves to be small, but reveal a persistent order 1 cm/s depth-averaged Lagrangian offshore flow over the spur and onshore flow over the grooves. This circulation was stronger for larger, directly incident waves and low alongshore flow conditions, consistent with predictions from modeling. Favorable forcing conditions must be maintained on the order of 1 h to accelerate and develop the SAG circulation cells. The primary cross and alongshore depth-averaged momentum balances were between the pressure gradient, radiation stress gradient, and nonlinear convective terms, and the bottom drag was similar to values found on other reefs. The vertical structure of these circulation cells was previously unknown and the results show a complex horizontal offshore Lagrangian flow over the spurs near the surface driven by alongshore variability in radiation stress gradients. Vertical flow was downward over the spur and upward over the groove, likely driven by alongshore differences in bottom stress and not by vortex forcing.

1. Introduction

One of the most prominent features of coral reefs worldwide are elevated periodic shore-normal ridges of coral ("spurs") separated by shore-normal patches of sediment ("grooves"), generally located on the forereef offshore of the surf zone [Storlazzi et al., 2003]. These features, termed “spur and groove” (SAG) formations, have been observed on fringing reefs, barrier reefs, and atolls, and vary in their size and shape [Rogers et al., 2013].

Hydrodynamic processes influence coral growth in several ways [Chappell, 1980]. First, waves and mean flows can suspend and transport sediments and reef debris. Suspended sediment is generally recognized as an important factor that can negatively affect coral health [Buddemeier and Hopley, 1988; Acevedo et al., 1989; Rogers, 1990; Fortes, 2000; Fabricius, 2005]. Second, forces imposed by waves can subject corals to breakage, resulting in trimming or reconfiguration of the reef [Maselink and Hughes, 2003; Storlazzi et al., 2005]. Third, the rates of nutrient uptake on coral reefs [Atkinson and Bilger, 1992; Thomas and Atkinson, 1997; Atkinson et al., 2001], photosynthetic production, and calcification by coral [Dennison and Barnes, 1988] and particulate capture by reef organisms [Genin et al., 2009] increase with increasing water motion.

Although the geometric properties of SAG formations are well documented [Munk and Sargent, 1954; Roberts, 1974; Blanchon and Jones, 1997; Storlazzi et al., 2003], analysis of their hydrodynamic function has been limited [Rogers et al., 2013]. Using a depth-averaged, phase-resolving model (funwaveC), Rogers et al. [2013] showed that SAG formations together with shoaling waves induce a nearshore Lagrangian circulation pattern of counter-rotating circulation cells, confirming suggestions from the geologic literature [Munk and Sargent, 1954; Roberts et al., 1977; Storlazzi et al., 2003]. This model also revealed that this type of circulation is enhanced by spur-normal waves, increased wave height, weak alongshore currents, increased spur height, and decreased bottom drag.

The classical dynamical basis by which waves drive flow is through changes to the waves from physical processes such as shoaling, refraction, dissipation, etc., which create spatial gradients in radiation stresses and impart a force in the momentum equation [Longoet-Higgins and Stewart, 1964]. Specifically for SAG
formations, the mechanism for circulation is an imbalance between the cross-shore radiation stress gradient and cross-shore pressure gradient terms in the depth-averaged momentum equations [Rogers et al., 2013]. The alongshore variation in radiation stress gradient is primarily due to the local cross-shore slope, whereas the alongshore variation in mean pressure gradient is primarily due to the local depth; the residual forcing from this imbalance accelerates the flow until the bottom stress or nonlinear convection is large enough to balance it, resulting in alongshore variable flow and the counter-rotating circulation cells [Rogers et al., 2013].

The radiation stress gradient can be recast as a vortex force in the full three-dimensional momentum equations, first proposed by Craik and Leibovich [1976], and refined by others including Kumar et al. [2012]. The vortex force is the interaction of the Stokes drift with flow vorticity, and is essential in the mechanism for Langmuir circulation. For SAG formations, the three-dimensional velocity structure is unknown but it is hypothesized that due to the coincident Stokes drift and horizontal vorticity in the mean flow, the vortex force may be important in driving secondary flow.

Another important mechanism capable of creating secondary flow is from lateral (normal to the main flow direction) periodic variations of bottom stress first proposed by Townsend [1976]. The mechanism of instability is the induction by the normal Reynolds stresses of a pattern of secondary flow, directed from regions of large stress to ones of small stress; this also induces, by continuity, downward flow over the regions of high stress and upward flow over those of small stress [Townsend, 1976]. It is hypothesized this may be an important mechanism influencing the secondary flow circulation on SAG formations due to the periodic large alongshore differences in bottom roughness between the spur and groove.

Roberts et al. [1977] present, to our knowledge, the only known field measurements of currents on SAG bathymetry based on a single dye release in strong alongshore flow conditions at Grand Cayman, (Cayman Islands). They measured 31 cm/s onshore near-bed velocity in the groove which carried the dye plume onshore and up and over the spur before being advected alongshore. Beyond the limited data in Roberts et al. [1977] which did not resolve the three-dimensional velocity structure, the wave-induced circulation cells predicted by Rogers et al. [2013] have never been observed in the field.

Here we present field observations of wave-induced circulation cells over SAG formations, including their vertical structure, and discuss several mechanisms consistent with the observed circulation. Based on the near-bed observations, we discuss why coral growth and development may be enhanced on the spur. To address these questions, two separate field studies were conducted on Palmyra Atoll in the Central Pacific (section 2.1) and data were processed per accepted methods (section 2.2). Results show wave-induced circulation and their vertical velocity profiles (section 3.1), momentum balances (section 3.2), bottom roughness characteristics (section 3.3), and near-bed velocity and bottom stress (section 3.4). A discussion on waves and circulation (section 4.1), mechanism for circulation (section 4.2), implications for coral health (section 4.3), and conclusions (section 5) follow.

2. Methods

2.1. Field Experiment

Palmyra Atoll (5°52′N, 162°05′W) is part of the Northern Line Islands of the central equatorial Pacific (Figure 1a) and largely because of the absence of acute anthropogenic stress on the ecosystems, its reefs contain abundant calcifiers, namely hard corals and crustose coralline algae [Williams et al., 2013] and high growth rates [Koweek et al., 2014]. Two separate field experiments were conducted on the atoll to characterize SAG circulation cells (Figure 1b). The first experiment, hereafter referred to as SFR12, was conducted from 16 to 26 September 2012, on the south forereef in approximately 8–10 m depth (Figures 1b and 1d). The SAG formations at SFR12 had approximately 1.8 m high spurs, 15 m average wavelength, 2 m wide grooves, and the spurs were oriented with an approximately 175° heading offshore, approximately parallel to the larger scale reef slope, which was approximately 15% (Figure 1d). The second experiment, hereafter referred to as NRF13, was conducted from 4 to 9 September 2013, on the northwest corner of the atoll in approximately 8–11 m depth (Figures 1b and 1c). The SAG formations at NRF13 had approximately 1.9 m high spurs, 14 m average wavelength, 1.4 m wide grooves, and the spurs were oriented with an approximately 0° heading offshore, approximately parallel to the larger scale reef slope, which was approximately 7% (Figure 1c). Live coral and coralline algae cover was high on the spurs (Figures 2a and 2d), whereas the bottom of the grooves were typically covered with reef debris, sediment, and fewer live coral colonies (Figures 2b and 2e).
The NFR13 instrument array consisted of two cross-shore transects of instrumentation covering two spurs and two grooves (Figure 1c). Transect A consisted of four sites (A1–A4) measuring velocity and pressure, and Transect B consisted of four sites (B1–B4) measuring pressure located approximately 15 m offshore from Transect A (Table 1). A deep forereef mooring, Site C1, measuring velocity and pressure was located approximately 115 m downslope from transect A in approximately 20 m water depth. The SFR12 instrument array consisted of one cross-shore transect (Transect M) covering one spur and one groove (Figure 1d), consisting of two sites (M1 and M2) measuring velocity and pressure (Table 1). A weather station was located on the atoll which measured wind speed and direction (RM Young 3002 sensor), and other meteorological variables (Figure 1b).

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2.2. Data Analysis

Instantaneous measured velocity data $\mathbf{u}(u,v,w)$ were rotated to local bathymetry coordinates of cross-shore ($x$) and alongshore ($y$) directions based on the orientation of spurs. The cross-shore coordinate at NFR13 corresponded to a $0^\circ$ compass heading, directed offshore (Figure 1c), and cross-shore coordinate at SFR12 corresponded to a $175^\circ$ compass heading, directed offshore (Figure 1d). The vertical ($z$) coordinate is taken as upward from mean sea level (MSL). Time averaging (---) was computed over 15 min intervals for mean velocity $\bar{u}$, average free surface deviation from MSL, $\bar{\zeta}$, and wave statistics. Only velocity data from the ADCP/APDs between selected depth ranges were used for analysis (Table 1). The ADV data were combined with the ADCP data at sites A2 and A3 to create velocity profiles.
Table 1. Experiment Instrumentation for NFR13 and SFR12 Experiments, Sites, Depth, Instrumentation and Sampling Rates

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth h (m)</th>
<th>Instrumentation, Sample Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFR13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1 (Groove)</td>
<td>10.31</td>
<td>1 MHz Nortek Aquadopp 0.5 m bins, 4.0–8.0 MAB, 1 Hz</td>
</tr>
<tr>
<td>A2 (Spur)</td>
<td>8.59</td>
<td>600 kHz RDI ADCP 0.4 m bins, 5.3–7.3 MAB, 2 Hz</td>
</tr>
<tr>
<td>A3 (Groove)</td>
<td>10.88</td>
<td>1200 kHz RDI ADCP 0.4 m bins, 2.3–9.7 MAB, 2 Hz</td>
</tr>
<tr>
<td>A4 (Spur)</td>
<td>9.10</td>
<td>2 MHz Nortek Aquadopp 0.5 m bins, 0.75–7.5 MAB, 1 Hz</td>
</tr>
<tr>
<td>B1 (Groove)</td>
<td>10.59</td>
<td>RBR 1050, 1 Hz</td>
</tr>
<tr>
<td>B2 (Spur)</td>
<td>10.22</td>
<td>RBR 1050, 1 Hz</td>
</tr>
<tr>
<td>B3 (Groove)</td>
<td>10.69</td>
<td>RBR 1050, 1 Hz</td>
</tr>
<tr>
<td>B4 (Spur)</td>
<td>10.33</td>
<td>RBR 1050, 1 Hz</td>
</tr>
<tr>
<td>C1 (Deep Forereef)</td>
<td>19.02</td>
<td>1200 kHz RDI ADCP 0.75 m bins, 3.5–17.0 MAB, 2 Hz</td>
</tr>
<tr>
<td>SFR12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1 (Spur)</td>
<td>8.72</td>
<td>1200 kHz RDI ADCP, 0.5 m bins, 2.1–7.5 MAB, 0.67 Hz</td>
</tr>
<tr>
<td>M2 (Groove)</td>
<td>10.53</td>
<td>1200 kHz RDI ADCP, 0.5 m bins, 2.1–9.1 MAB, 0.67 Hz</td>
</tr>
</tbody>
</table>

Figure 2. Field experiment images and spur and groove bathymetry, for NFR13 experiment (a–c), and SFR12 experiment (d–f). (a) Typical spur and Station A2 (center) with divers for scale looking onshore, (b) typical groove and Station A3 (center) showing reef debris looking onshore, and (c) NFR13 spur and groove bathymetry in alongshore direction (Stations A1–A4) showing instrument placement (red squares), (d) Station M1 showing spur looking alongshore from M2, (e) Station M2 showing groove and reef debris looking alongshore from M1, and (f) SFR12 spur and groove bathymetry in alongshore direction (Stations M1–M2) showing instrument placement (red squares).
Linear wave theory has been shown to be accurate on rough reefs with steep and complex geometry, and large wave amplitudes nearly equal to the mean depth [Monismith et al., 2013]. The use of spectral wave definitions (i.e., the superposition many sine waves over many frequencies) is common practice, which does not assume a constant wave form and there is some flexibility to include nonlinear wave forms in the formulation [Dean and Dalrymple, 1991; Sheremet et al., 2011]. Wave analysis was conducted on pressure p and velocity data by dividing each 15 min segment into 33 sections of equal length, each with 75% overlap, applying a Hanning window to the segments and computing the spectral S(f) of frequency f. The rms wave height H_{rms} was calculated by \[ H_{rms} = \sum_{f} S_{f}^{1/2} \] , where \( S_{f} \) is the power spectral density of the free surface \( z \), calculated from, \( S_{f} = S_{pp} \left( \cosh k h / (\mu g \cosh h) \right)^{-2} \), and \( S_{pp} \) is the power spectral density of p. \( \mu \) is density, g is gravitational constant, h is depth of the bottom below MSL, \( h_{0} \) is the height of the pressure gauge above the bottom, and wave number \( k \) is related by the dispersion relation \( \sigma^{2} = g k \tan h, \) and radial frequency \( \sigma = 2 \pi f = 2 \pi / T \) [Dean and Dalrymple, 1991]. Mean wave period, \( T_{m} \) was calculated based on the first spectral moment of \( S_{f} \). Mean wave direction \( \theta_{m} \) was computed from the first spectral moment of \( \theta(f) \) calculated by, \( \tan 2 \theta(f) = S_{uv}(f)/S_{uu}(f) - S_{uv}(f) \), where \( S_{uu} \) and \( S_{uv} \) are the autospectra and cross spectrum of u and v from the ADVs and near-bed ADCP/ADPs bins [Herbers et al., 1999]. The mean Lagrangian velocity \( \mathbf{UL} \) was calculated by [Andrews and McIntyre, 1978], \[ \mathbf{UL} = \mathbf{UE} + \mathbf{UL} \] , where \( \mathbf{UE} = \overline{\mathbf{U}} \) is the mean measured Eulerian velocity and Stokes drift,

\[ \mathbf{UL} = \frac{\sigma H_{rms} \cosh 2k(h+z)}{8 \sinh 2kh} \mathbf{k}, \]  

(1)

was computed spectrally and integrated from 1/5 to 1/25 Hz, and \( k \) is the magnitude of wave number \( \mathbf{k} \) [Dean and Dalrymple, 1991]. The Lagrangian depth-averaged mean velocity \( \mathbf{UL}(U_{L}, V_{L}, W_{L}) \) was calculated by combining available data at a given location (ADV/ADCP/ADP), assuming \( \mathbf{UE} = 0 \) at the bottom, linearly interpolating in \( z \) and taking the average. To quantify the strength of circulation, we define a cross-shore circulation velocity \( U_{c} \) as [Rogers et al., 2013],

\[ U_{c} = \langle U_{L} \rangle \cos \varphi, \]  

(2)

where \( \langle U_{L} \rangle \) denotes a spatial average in the alongshore direction to remove the average cross-shore reef flow, and \( \varphi \) is the angle between \( x \) and \( y \) components of \( \mathbf{U}_{L} \). In the presence of strong alongshore current (\( \varphi \approx \pi / 2 \)) \( U_{c} \) will approach zero; while in the presence of strong cross-shore current (\( \varphi \approx 0 \)) \( U_{c} \) will approach \( \Upsilon_{L} - \langle U_{L} \rangle \).

Error in the velocity measurements was taken as the measured error from the redundant beam of the ADCPs, 1% of the measurement \( \pm 0.5 \) cm/s for the ADPs, and 0.5% of the measurement \( \pm 0.1 \) cm/s for the ADVs. The error was propagated through the calculations per standard error analysis methods [e.g., Emery and Thomson, 2004].

The approximate depth integrated momentum equations for horizontal flow are given by [e.g., Mei et al., 2005],

\[ \frac{\partial \mathbf{U}_{L}}{\partial t} + \mathbf{U}_{L} \cdot \nabla \mathbf{U}_{L} = -g \nabla \zeta - \frac{1}{\rho_{e} (\sigma + \delta h)} \left[ \nabla \cdot \mathbf{S} + \mathbf{r}_{b} - \mathbf{r}_{s} \right], \]  

(3)

where \( \mathbf{S} \) is the radiation stress tensor, \( \mathbf{r}_{b} \) is the mean bottom stress, and \( \mathbf{r}_{s} \) is the mean surface stress. The terms in equation (3) will be referred to from left to right as unsteady (US), convective nonlinear (NL), mean pressure gradient (PG), radiation stress gradient (RS), bottom stress (BT), and surface stress (ST). Equation (3) was evaluated for the NFR13 experiment in the alongshore direction at the midpoint between stations A1–A2 and A2–A3, but was not evaluated between A3 and A4 due to variable local bathymetry and larger distance between sites. Time derivatives were taken using the leapfrog method, while alongshore spatial derivatives used a central difference scheme, and cross-shore spatial derivatives used a forward Euler scheme. A leapfrog scheme was used to compute the alongshore PG due to lack of highly accurate p (RBR) at A2.

For linear waves \( S_{yy} = S_{z} \left[ n (\sin^{2} \theta + 1) - \frac{1}{2} \right] \) and \( S_{yy} = S_{xx} = \frac{1}{2} S_{z} n \sin 2 \theta \), were computed spectrally and integrated over 1/5 to 1/25 Hz, where \( n = C_{p} / C \), with group velocity \( C_{p} \) and phase speed \( C \) [Longuet-Higgins and Stewart, 1964]. To evaluate \( \partial S_{yy} / \partial x, \theta_{m} \) at the B stations was assumed equal to the corresponding A station.

The measured velocity can be expressed as \( \mathbf{u} = \overline{\mathbf{u}} + \mathbf{u}' + \mathbf{u}'' \), where \( \mathbf{u}' \) is the turbulent velocity and \( \mathbf{u}'' \) is the wave-induced velocity. Assuming motions that are correlated with the free surface are due to waves, and
those that do not are due to turbulence, $S_{uv} = S_{uv}^{sp}/S_{w}^{sp}$, and $S_{uv} = S_{uv} - S_{uv}^{sp}$, and $\overline{u w} = \int S_{uv}^{sp} df$ [Benilov and Filyushkin, 1970; Benilov et al., 1973]. The process is similar for the other components of the Reynolds stress tensor (e.g., $\overline{u u}$) and wave motions (i.e., $\overline{uu}$). The total kinetic energy due to turbulence (TKE) is $TKE = \frac{1}{2} \left( \overline{u^2} + \overline{v^2} + \overline{w^2} \right)$. 

Mean bottom stress, $\tau_b$, was computed from the turbulent Reynolds stress, which are assumed constant within the inertial sublayer, [e.g., Reidenbach et al., 2006],

$$\tau_b = -\rho \overline{uw}$$

using the measured turbulent velocities ($\overline{u}$) from the ADVs. $\tau_b$ used in equation (3) at the midpoint between A1 and A2 was assumed equal to the measured $\tau_b$ at A2, and at the midpoint A2 and A3 was taken as the average of $\tau_b$ at A2 and A3. The surface stress was approximated by a typical quadratic drag law,

$$\tau_s = \rho_0 C_{D0} \overline{u_0} |\overline{u_0}|,$$

where air density $\rho_0 = 1$ kg m$^{-3}$, wind drag coefficient $C_{D0} = 0.0015$, and wind velocity $\overline{u_0}$ [Smith, 1988].

A common bottom stress parameterization is given by [e.g., Grant and Madsen, 1979; Feddersen et al., 2000],

$$\tau_b = \rho C_D \overline{|u|},$$

where $\overline{u}$ is evaluated near the bed but above the bottom boundary layer, and $C_D$ is a nondimensional drag coefficient which may depend on the flow environment, height above the bed and bottom roughness. Combining equations (4) and (5) gives,

$$C_D = \frac{-\overline{uw}}{\overline{|u|}}$$

where in environments with low wave and turbulence energy, the denominator is often simplified to $\overline{uw}$, and $\overline{u}$ is either the depth-averaged or near-bed velocity, see Rosman and Hench [2011] for a complete discussion.

3. Results

During the NFR13 experiment, the tidal elevation $\overline{\zeta}$ varied by 0.8 m (Figure 3a). Wave energy was characterized by two main events, the first on 4–5 September with wide frequency spread, and average $H_{rms}$ of 0.6 m at 9 s period, and the second on 8 September with narrower frequency spread and average $H_{rms}$ of 0.5 m at 11 s period (Figures 3b–3d). $H_{rms}$ was slightly higher at deep forereef station C1, but showed only very slight difference between all stations at A and B (Figure 3c). $T_m$ increased with propagation onshore (from C1 to A), but showed very little alongshore variation (Figure 3d). Shorter period waves were directed on average at $-\theta$, while the longer period swell were directed at $+\theta$ (Figure 3e), and average wave direction was nearly incident for the 4–5 September wave event, while angled at about 20° on 8 September. $\theta_m$ was directed more normally incident with onshore propagation consistent with Snell’s law, and $\theta_m$ varied by approximately 10° within sites A1–A4 (Figure 3f), essentially the accuracy of the instrument reference frame. The wind speed was directed generally in the positive x and y directions (approximately to the NW) and its magnitude varied from 0 to 8 m/s (Figure 3g).

During the SFR12 experiment $\overline{\zeta}$ varied by 0.8 m, (Figure 4a). The waves were characterized by $H_{rms}$ between 0.6 and 1.3 m (Figure 4b), $T_m$ of 8–13 s (Figure 4c), and $\theta_m$ of about zero (incident to cross-shore coordinate x) (Figure 4d). Site M1 (spur) had slightly higher $H_{rms}$, and lower $T_m$ compared to Site M2 (groove), but $\theta_m$ was nearly the same.

3.1. Circulation and Vertical Structure

For the NFR13 experiment, the cross-shore depth-averaged Lagrangian velocity $U_t$, varied from $-12$ to 12 cm/s and was generally directed offshore (+) with velocities on the deep forereef (C1) showing similar trends (Figure 5a). $U_t$ was generally more positive at A2 (spur) than at A3 (groove) especially on 4, 5, and 7 September. The deep forereef (C1) $V_t$ varied from $-50$ to 30 cm/s and was generally positive (to the west) (Figure 5b). At the SAG site A1–A4, $V_t$ was smaller in magnitude but followed a similar trend. Two larger scale anomalous flow events occurred on 5 and 8 September with strong flow at C1 directed onshore and negative alongshore (southwest). $W_t$ varied from $-4$ to 2 cm/s and was generally negative (down) at A2 and
A4 (spurs) and A1 (groove), and positive at A3 (grooves) (Figure 5c).

Uc varied from 2 to 6 cm/s and was nearly always positive at A2 and A4 (spurs) and negative at A1 and A3 (grooves), and was strongest on 4 and 5 September (Figure 5d). The horizontal Stokes drift was O(0.1 cm/s) over the experiment duration, and was thus a small O(10%) fraction of the Lagrangian velocity.

During the SFR12 experiment, UL varied between 26 and 12 cm/s but was generally directed onshore (Figure 4e), VL varied between 226 and 28 cm/s (Figure 4f), and the circulation Uc varied from 21.2 to 1.2 cm/s, and was generally directed offshore at M1 (spur) and onshore at M2 (groove) (Figure 4g). The horizontal Stokes drift was O(1 cm/s) over the experiment duration, and was thus a significant fraction of the cross-shore Lagrangian velocity.

A snapshot of the Lagrangian velocity field interpolated in the alongshore direction (NFR13 A stations) at a time of weak alongshore flow and strong Uc, shows characteristic offshore flow cells centered over the spurs and weak onshore flow over the groove and at depth (Figure 6). The alongshore and vertical velocities show a strong counterclockwise rotation on the side of the spur (y = 12 m, h = 5 m), and there is a suggestion of clockwise rotation on the opposite side of the spur (y = 2 m, h = 6 m; and y = 24 m, h = 5 m).

The characteristic circulation cells shown Figure 6 were present under different flow conditions with strong Uc, including weak Vl and weak Ul (Figure 7a), strong Vl and weak Ul (Figure 7b), weak Vl and strong offshore Ul (Figure 7c), strong Vl and strong offshore Ul (Figure 7d). However, for periods of weak Uc, these characteristic circulation cells are not present for different flow conditions including weak Vl and weak Ul (Figure 7e), strong Vl and weak Ul (Figure 7f), weak Vl and strong Ul (Figure 7g), strong Vl and strong offshore Ul (Figure 7h). Where weak and strong refer to below and above the mean, and Vl and Ul are taken as the average of stations A1–A4, and Ul is taken as the average of the magnitude from stations A2 and A3.

In the cross-shore direction, the profile of the rms of the Eulerian velocity (Uc) is a complex shape, with NFR13 of larger magnitude than during the SFR12 experiment (Figure 8a). The profile of Stokes velocity (Uc) is similar for all NFR13 profiles and very small compared to the Eulerian velocities, while during the SFR12 experiment, Stokes drift is higher over the spur than the groove and of a similar magnitude to the Eulerian velocity (Figure 8b). The Lagrangian velocity (Uc) profile shape is different...
between periods of weak and strong $U_c$ for all sites (Figure 8c). For periods of strong $U_c$, during the NFR13 experiment $u_L$ rms was much stronger on the spurs about 3 m below the surface (A2, A4), while during the SFR12 experiment the trend is similar but weaker.

Figure 4. Physical forcing of tide, waves, depth-averaged mean Lagrangian velocity $U_L$, results and circulation velocity $U_c$ during SFR12 experiment duration, (a) mean free surface $\zeta$, (b) rms wave height $H_{rms}$, (c) mean wave period $T_m$, (d) mean wave direction $h_m$, (e) cross-shore $U_L$, (f) alongshore $V_L$, and (g) circulation $U_c$. Blue is M1 (spur) and red is M2 (groove). Solid lines (-) are mean values, dotted lines (..) are mean ± the 95% confidence limit are only shown for (e–g).

Figure 5. Depth-averaged mean Lagrangian velocity $U_L$, results and circulation velocity $U_c$ over NFR13 experiment duration, (a) $U_L$, (b) $V_L$, (c) $W_L$, and (d) $U_c$. Colors are green, blue, red, black, and cyan for A1 (groove), A2 (spur), A3 (groove), A4 (spur), C1 (deep forereef) [not shown for (c) and (d)], respectively. Solid lines (-) are mean values, dotted lines (..) are mean ± the 95% confidence limit.
In the alongshore direction, the profile of \( v_E^{\text{rms}} \) for the bottom half of the water column is similar to a log-layer shape on the spurs, while on the grooves the shape is also like a log-layer but with an offset of about the spur height (Figure 8d). The profiles are similar higher in the water column. The profile of \( v_S^{\text{rms}} \) (from equation (1)) is similar for all profiles and very small compared to the Eulerian velocities (Figure 8e). For both experiments, the profile of \( v_L^{\text{rms}} \) had a similar log-layer-like shape for both strong and weak \( U_c \) conditions, but strong \( U_c \) conditions had a larger magnitude (Figure 8f).

### 3.2. Momentum Balance

The significant terms in the depth-averaged cross-shore momentum balance (equation (3)), were of \( O(10^{-4} \text{m/s}^2) \) between nonlinear convective, mean pressure gradient, and radiation stress gradient (\( \text{RS}_{xy} \)) terms (Table 2) i.e.,

\[
V_y \frac{\partial U_c}{\partial y} = -g \frac{\partial \zeta}{\partial x} - \frac{1}{\rho (\zeta + h)} \frac{\partial S_{xy}}{\partial y},
\]

while the unsteady, second nonlinear convective (\( U_c \partial U_c / \partial x \)), radiation stress gradient (\( \text{RS}_{xy} \)), and bottom stress terms were of secondary importance \( O(10^{-5} \text{m/s}^2) \). The significant terms in the depth-averaged alongshore momentum balance (equation (3)), were of \( O(10^{-4} \text{m/s}^2) \) between nonlinear convective, mean pressure gradient, and radiation stress gradient (\( \text{RS}_{yy} \)) terms (Table 2) i.e.,

\[
V_x \frac{\partial V_c}{\partial y} = -g \frac{\partial \zeta}{\partial y} - \frac{1}{\rho (\zeta + h)} \frac{\partial S_{xy}}{\partial y},
\]

while the unsteady second nonlinear convective (\( U_c \partial V_c / \partial x \)), bottom stress, and radiation stress gradient (\( \text{RS}_{yy} \)) terms were of secondary importance \( O(10^{-5} \text{m/s}^2) \). Surface stress from wind forcing was insignificant at both sites \( O(10^{-6} \text{m/s}^2) \) (Table 2). Because the relative difference in elevation between pressure gauges is not known, there may be net bias in the calculated pressure gradient, which is constant in time. It is assumed to first order this bias is zero. This assumption is reasonable to first order because the change in wave direction (Figure 3), and the periodic reversal of \( U_c \) and \( V_c \) (Figure 5) suggests the temporal mean of the mean pressure gradient over the entire measurement period should be near zero. Second, the mean pressure gradient arises as a response to the other forcing terms and is expected to be of the same order as the other major terms [Rogers et al., 2013], which is the result in Table 2.
3.3. Bottom Roughness

The bottom coefficient $C_D$ was computed at A2 and A3 using the Reynolds stress using equation (6) from the ADVs (Table 3). The $C_D$ was similar $O(0.01)$ at both sites in the cross-shore direction and in the alongshore direction over the spur (A3), while it was much larger $O(0.1)$ in the alongshore direction over the groove (A2). Fits to logarithmic profiles were performed for the alongshore Eulerian velocity profiles, [e.g., Reidenbach et al., 2006] but the results for bottom roughness scale $z_0$ (A3: 0.009 ± 0.023 m, A4: 0.008 ± 0.016 m, C1: 0.02 ± 0.04 m) and offset height d (A3: 0.62 ± 0.12 m, A4: 0.51 ± 0.33 m, C1: 0.57 ± 1.36) had very large scatter. Use of Grant and Madsen [1979] to remove the effect of waves and predict a physical roughness scale $k_N$ (A3: 0.06 ± 0.03 m, A4: 0.05 ± 0.04 m, C1: 0.12 ± 0.12 m) also had very high scatter.

3.4. Near-Bed Results

During the NFR13 experiment, the near-bed average cross-shore Lagrangian velocity $\bar{\omega}$ measured by the ADVs was slightly higher in magnitude over the spur (A2) compared to the groove (A3) (Figure 9a), while $\bar{\omega}$ was significantly higher in magnitude over the spur (Figure 9b). $\bar{\omega}$ was similar in magnitude at the two sites but was variable over the groove but generally negative (down) over the spur (Figure 9c). The rms of the near-bed cross-shore wave velocity $(\bar{\omega})_{rms}$ was similar over the spur and the groove for periods of stronger,
directly incident wave forcing (5 September), but larger in the groove for weaker wave forcing (Figure 9d). The measured wave velocity was smaller at both locations than what would be predicted by linear wave theory (based on the mean $H_{rms}$, $T_m$, and $h_m$). This difference was most pronounced over the spur. The $u_0$, TKE, and $j_{sb}$ computed from the wave-separated Reynolds stress, were significantly higher over the spur than over the groove by up to a factor of four (Figures 9e–9g).

4. Discussion

4.1. Waves and Circulation

The effect of SAG’s on waves appears to be minimal. The NFR13 results show only very small alongshore differences in wave properties $H_{rms}$, $T_m$, and $h_m$ (Figures 3c, 3d, and 3f). For higher wave forcing during the SFR12 experiment, $H_{rms}$ was slightly higher over the spur (Figure 4b). At both field sites, the alongshore SAG wavelength $O(10 \text{ m})$ is much smaller than the surface wavelength $O(100 \text{ m})$. As shown by Rogers et al. [2013], for small SAG wavelengths, the effects of diffraction are likely strong, and alongshore differences in wave parameters are therefore minimal. Linear wave theory predicts larger horizontal wave motions over the spur, but the measured wave velocities were very similar for strong normally incident waves, and smaller over the spur for weaker incident waves (Figure 9d). Thus, the SAG formations appear to be slowing the horizontal wave motion over the spur more than what would be predicted by linear wave theory.

For both experiments, the results show the presence of persistent $O(1 \text{ cm/s})$ cross-shore circulation velocity $U_c$, directed offshore over the spurs and onshore over the grooves (Figures 4g and 5d) as predicted by the modeling results of Rogers et al. [2013]. The period of strongest measured $U_c$ is on 4 September (NFR13), which for that experiment is also the period of highest $H_{rms}$ nearly incident waves, and relatively small alongshore flow $V_s$. Periods of weaker $H_{rms}$ but directly incident waves (6 September) or high $H_{rms}$ but angled waves (8 September) show weaker $U_c$. This is consistent with the modeling results of Rogers et al. [2013], which predicted stronger $U_c$ with high $H_{rms}$ directly incident waves ($\theta_m = 0$), and weak alongshore flow ($V_s$). The SFR12 experiment had smaller $U_c$ than the NFR13 experiment likely because while $H_{rms}$ was higher, the SAG formations were smaller, less well defined (Figure 2), and the alongshore $V_s$ was stronger.
ear convection is large enough to balance it, resulting in alongshore variable direction. The mean pressure gradient arises as a response to wave forcing. The residual forcing from the waves are most affected by the local bathymetric slope (near the deeper offshore slope). The radiation stress gradient term is the direct result of the shoaling momentum balance obtained by Rogers et al. [2013] for the same relative position on the SAG formations (near the deeper offshore slope). The radiation stress gradient term is the direct result of the shoaling waves, are most affected by the local bathymetric slope [Rogers et al., 2013], which varies in the alongshore direction. The mean pressure gradient arises as a response to wave forcing. The residual forcing from the imbalance between the pressure gradient and radiation stress gradient accelerates the flow until the nonlinear convection is large enough to balance it, resulting in alongshore variable $U_c$ flow and the counter-rotating circulation cells (Figures 5a and 6) consistent with modeling results of Rogers et al. [2013].

The cross-shore Lagrangian flow shows a significant difference in shape in the mean rms profile between periods of strong and weak $U_c$, i.e., the circulation cells appear to be modifying the velocity profile shape in the cross-shore direction (Figure 8c). This effect was most pronounced during the NFR13 experiment but was also observed in the SFR12 experiment. This is in contrast to the alongshore direction which shows a log-layer like flow profile for both strong and weak $U_c$, but simply of different magnitudes (Figure 8f). The profile shape is similar to a log-layer shape on the spurs, while on the grooves the shape is also like a log-layer but with an offset of about the spur height (Figure 8d). We emphasize that because both field site locations were near the deeper end of the spurs, the direction of cross-shore flow was offshore over the spur and onshore over the groove. However, as predicted by Rogers et al. [2013] this is likely reversed at shallower depths, but was not investigated in this study.

### 4.2. Mechanism for Circulation

The cross-shore momentum balance indicates the primary terms were nonlinear convective, mean pressure gradient (RS$_y$), and radiation stress gradient of $O(10^{-4}$ m/s$^2$). This was the same primary cross-shore momentum balance obtained by Rogers et al. [2013] for the same relative position on the SAG formations (near the deeper offshore slope). The radiation stress gradient term is the direct result of the shoaling waves, are most affected by the local bathymetric slope [Rogers et al., 2013], which varies in the alongshore direction. The mean pressure gradient arises as a response to wave forcing. The residual forcing from the imbalance between the pressure gradient and radiation stress gradient accelerates the flow until the nonlinear convection is large enough to balance it, resulting in alongshore variable $U_c$ flow and the counter-rotating circulation cells (Figures 5a and 6) consistent with modeling results of Rogers et al. [2013].

The alongshore momentum balance indicates the primary terms were nonlinear convective, mean pressure gradient and radiation stress gradient (RS$_x$) of $O(10^{-3}$ m/s$^2$). Changes to the waves propagating in the alongshore direction from refraction, bathymetric changes or bottom dissipation create a radiation stress gradient (RS$_y$). As in the cross-shore direction, the pressure gradient arises in response to the forcing and the imbalance between the mean pressure gradient and radiation stress gradient accelerates the flow until the nonlinear convection is enough to balance it, driving an alongshore $V_x$ flow (Figures 5b and 7).

### Table 2. Order of Terms in Depth-Averaged Momentum Equations (Equation (3i)) From NFR13 Experiment in the Cross-Shore (x) and Alongshore (y) Directions

<table>
<thead>
<tr>
<th>Term</th>
<th>Cross-Shore (x)</th>
<th>Alongshore (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\partial \xi / \partial t$</td>
<td>$1 \times 10^{-5}$</td>
<td>$2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$U_c \partial \xi / \partial x$</td>
<td>$1 \times 10^{-5}$</td>
<td>$2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$V_c \partial \xi / \partial y$</td>
<td>$1 \times 10^{-5}$</td>
<td>$2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\frac{g H^2}{\Delta} \partial \xi / \partial x$</td>
<td>$2 \times 10^{-4}$</td>
<td>$6 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\frac{g H^2}{\Delta} \partial \xi / \partial y$</td>
<td>$2 \times 10^{-4}$</td>
<td>$6 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\frac{\beta UL}{\alpha} \frac{\partial U}{\partial x}$</td>
<td>$4 \times 10^{-5}$</td>
<td>$6 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\frac{\beta UL}{\alpha} \frac{\partial V}{\partial y}$</td>
<td>$4 \times 10^{-5}$</td>
<td>$6 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\frac{\beta UL}{\alpha} \frac{\partial U}{\partial y}$</td>
<td>$4 \times 10^{-5}$</td>
<td>$6 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\frac{\beta UL}{\alpha} \frac{\partial V}{\partial x}$</td>
<td>$4 \times 10^{-5}$</td>
<td>$6 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Note: $\beta = 1 / [\rho (\zeta + h)]$. Order O is the average of the absolute value of the term over the experiment duration.

### Table 3. Bottom Drag Coefficient $C_D$ Results From NFR13 Experiment From Near-Bed ADV Measurements in Cross-Shore (x) and Alongshore (y) Directions

<table>
<thead>
<tr>
<th>$C_D(x)$</th>
<th>$C_D(y)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.015 ± 0.001</td>
<td>0.011 ± 0.001</td>
</tr>
<tr>
<td>0.0072 ± 0.0007</td>
<td>0.10 ± 0.007</td>
</tr>
</tbody>
</table>

*Note: Reference height $z_{sw} = 0.7$ m, confidence intervals are 1 standard deviation.*
For both cross and alongshore directions, the nonlinear convective terms are important at this site due to the large variability in bathymetry from the SAG formations and rough reef. The largest errors in the momentum balance are likely from the pressure gradient terms due to instrument accuracy in $p$ measurement and the unknown net constant bias between gauges (assumed to be zero). The second largest errors in the momentum balance are likely the smaller nonlinear convective terms (cross-shore $\nabla U/\partial x$, alongshore $\nabla V/\partial x$), which were likely larger than the calculated value due to the approximation of $\partial U/\partial x$ between Transect A and C.

The characteristic shape of the flow field appears analogous to Langmuir circulation cells but of opposite rotation in the $yz$ plane (Figure 6). Since the vertical vorticity $\omega_z$ at $h = 4 \text{ m}$, $y = 11 \text{ m}$ is negative, the horizontal vortex force, $u_S \times \omega_z$ [Craig and Leibovich, 1976] is directed toward positive $y$, contrary to the observed circulation in the $yz$ plane. For waves and currents opposed, the vortex force is stabilizing [Leibovich, 1983], and thus it appears unlikely the vortex force is the mechanism for the observed rotation in the $yz$ plane. However, only limited studies have been conducted on Langmuir circulation with opposing waves and currents and to our knowledge no studies have been conducted on alongshore periodic bathymetry [Thorpe, 2004]. Additionally, further onshore where waves and currents are aligned [Rogers et al., 2013], the vortex force would be destabilizing [Leibovich, 1983]. Thus, further study seems warranted.

The computed bottom drag coefficient values, $C_D$, were similar to values computed for other reefs [Rosman and Hench, 2011]. $C_D$ on the spur in both directions and over the groove in the cross-shore direction are of

Figure 9. Near-bed mean Lagrangian velocity and bottom stress results from ADVs ($h = 0.7 \text{ m}$) during NFR13 experiment duration, (a) cross-shore $\nabla U$ (cm/s), (b) alongshore $\nabla V$ (cm/s), (c) vertical $\nabla W$ (cm/s), (d) cross-shore $\sqrt{\langle u^2 \rangle}$ (cm/s), (e) cross-shore Reynolds stress $\overline{uw}$ ($\text{m}^2/\text{s}^2$), (f) turbulent kinetic energy TKE ($\text{m}^2/\text{s}^2$), and (g) bottom shear magnitude $\overline{\tau}$ (Pa). Colors are blue and red for A2 (spur) and A3 (groove), respectively. For (d), result from linear wave theory is cyan and magenta for A2 (spur) and A3 (groove), respectively.
similar magnitude, while over the groove in the alongshore direction is an order of magnitude larger. The larger \( C_D \) is likely the result of the SAG morphology affecting the flow profile over the groove in the alongshore direction. This effect is seen in the alongshore Eulerian velocity profile which shows low velocity water over the grooves near the bed, while higher up in the water column the profiles are similar over both the spur and grooves (Figure 8d). These results suggest that the form drag from the SAG morphology in the alongshore direction may be dominant over differences in the frictional drag from benthic cover (i.e., coral versus debris/sand). These results for \( C_D \) are local measurements, but the net average \( C_D \) over the larger scale SAG morphology \( O(100 \text{ m}) \) requires further study.

4.3. Implications for Coral Health

The near-bed velocity, turbulence, and bottom shear stress are of particular interest because they directly affect organisms on the bed. Differences in these parameters between the spur and groove may illuminate why corals thrive on the spurs and not in the grooves, beyond the influence of light levels that are generally higher on the spur. While the cross-shore near-bed velocity was slightly higher on the spur (Figure 9a), the alongshore near-bed velocity was much higher (Figure 9b) during the NFR13 experiment. The vertical velocity was also directed down over the spur, while directed up over the groove (Figures 6 and 9c). There was also increased turbulence kinetic energy over the spur (Figure 9f). Corals subjected to stronger water motion have greater mass transfer, including increased nutrient uptake rates [Atkinson and Bilger, 1992; Thomas and Atkinson, 1997; Atkinson et al., 2001], photosynthetic production and calcification [Dennison and Barnes, 1988], and particle capture [Genin et al., 2009]. Since corals living on the spurs are the recipients of much higher alongshore flows and variable vertical flow from the surface providing increased “food” supply, and increased turbulent motions providing increased contact, they may have a net advantage to corals living in the grooves.

The bottom shear stress was also significantly higher and more variable on the spur than the groove with an average of \( 0.37 \pm 0.21 \) and \( 0.17 \pm 0.07 \) Pa, respectively, during the NFR13 experiment (Figure 9g). Assuming incipient motion based on the shields parameter [e.g., Julien, 2010], this would correspond to flow capable of suspending sediments smaller than very fine gravel on the spur and coarse sand on the groove during the relatively small wave conditions observed during the NFR13 experiment. During higher wave events, bottom stress would be much higher. Since the spur has much higher mean flows primarily in the alongshore direction, and bottom slope is toward the grooves, sediment suspended by the bottom stress would be shed from the spurs toward the grooves where it could accumulate. This sediment and debris accumulation was present at the study sites (Figures 2b and 2e), and has been observed as a primary feature of SAG formations around the world [Rogers et al., 2013]. Over time, the sediment in the grooves is carried downslope [Storlazzi et al., 2003]. Lower debris and sediment accumulation on the spurs relative to the grooves would be a significant advantage for recruitment and coral growth [Buddemeier and Hopley, 1988; Acevedo et al., 1989; Rogers, 1990; Fortes 2000; Fabricius, 2005]. During large wave events, the bottom stress would likely be much greater than what was observed during the NFR13 study period (such as during SFR12 experiment); potentially subjecting the coral on the spur to proportionally higher bottom shear stress and perhaps breakage. However, the magnitude of this effect remains unclear and requires further study.

5. Conclusions

The results from two separate field studies of SAG formations on Palmyra Atoll show the effect of SAG formations on waves was small, and there was a persistent \( O(1 \text{ cm/s}) \) depth-averaged Lagrangian circulation \( (U_c) \) of offshore flow over the spurs and onshore flow over the grooves. This circulation was stronger for larger, directly incident waves and low alongshore flow conditions. There also appeared to be a spin-up time for the observed \( U_c \) on the order of 1 h for which favorable forcing conditions must be maintained to accelerate and develop the SAG circulation cells. These are the first field observations of SAG hydrodynamics and confirm the modeling results from Rogers et al. [2013]. The primary cross and alongshore momentum balances were between the pressure gradient, radiation stress gradient and nonlinear convective terms. The vertical structure of these circulation cells was previously unknown and the results show a complex horizontal offshore Lagrangian flow over the spurs near the surface driven by alongshore variability in radiation stress gradients consistent with Rogers et al. [2013]. Vertical flow was downward over the spur and upward over the groove, likely driven by alongshore differences in bottom stress [Townsend, 1976] and not by vortex forcing [Craik and Leibovich, 1976]. The bottom drag coefficients were similar to values found on
other reefs; and were enhanced over the groove in the alongshore direction. Beyond the influence of light levels that are generally higher on the spur, we suggest that the conditions for coral recruitment and growth appear to be more favorable on the spur than the groove due to (1) higher “food” supply from higher mean alongshore velocity, downward vertical velocity, and higher turbulence, and (2) lower sediment accumulation due to higher and more variable bottom shear stress.

The present study was conducted near the deeper end of the SAG formations. At shallower depths, the direction of the depth-averaged cross-shore circulation ($U_z$) is likely reversed [Rogers et al., 2013], but this effect and the three-dimensional Lagrangian velocity structure at these shallower depths remains unknown and requires further study. The observed similarity to Langmuir circulation but with opposite rotation, and the possible importance of the vortex force and lateral variation of stress mechanism would warrant further analytical or modeling work. Additionally, SAG hydrodynamics under large wave conditions, as well as investigation into the sediment transport through the grooves, also warrants further inquiry.

Acknowledgments
Data from this study has been deposited at the NOAA National Oceanographic Data Center and can be obtained there (accession O123612). This project was funded by the Gordon and Betty Moore Foundation, and supported with an NDSEG Fellowship to JSR (U.S. Department of Defense, Office of Naval Research, 32 CFR 168a), and an NSF Graduate Research Fellowship to JSR (U.S. Department of Education, Office of Educational Research and Improvement, 32 CFR 168a). This project was funded by NSF Grant, 0123612. This project was funded by the Gordon and Betty Moore Foundation. Data from this study has been submitted to the COAWST database. A data set of SAG flow and wave data is available at the following web site: http://www.soest.hawaii.edu/coawst/.

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