# THE INFLUENCE OF A CROSS-REEF CHANNEL ON CIRCULATION OVER A FRINGING REEF AT IPAN, GUAM

# A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI'I AT MĀNOA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

# MASTER OF SCIENCE

# IN

# OCEANOGRAPHY

# AUGUST 2013

# By S. Jeanette Clark

Thesis Committee:

Mark Merrifield, Chairperson Margaret A. McManus Geno Pawlak

## Acknowledgements

I would like to thank my committee, Mark Merrifield, Geno Pawlak, and Margaret McManus for their support. Chris Kontoes, Carly Quisenberry, and Derek Young assisted in deployment and recovery of the Ipan, Guam field experiment and in setting up the numerical model. I'd also like to thank Janet Becker for her support. We also received invaluable support from the University of Guam Marine Laboratory during all of our deployments, in particular Jason Miller who assisted in diving operations. This work was supported by the Army Corps of Engineers via a subcontract from the University of California, San Diego (PO 1036151) and by the National Science Foundation (OCE 0927407)

#### Abstract

Forcing mechanisms of water circulation over a shore-attached, 400 m wide, fringing reef at Ipan, Guam with a deep (30 m), narrow (30 m) cross-reef channel are examined using current and bottom pressure measurements and a numerical model. The reef flat is shallow (0.5 m) and mostly exposed at low tide. During a 6-week deployment, the reef experienced moderate onshore winds, with an average magnitude of 2 m/s. The significant wave height measured on the fore reef ranged from 0.5 m to 2.2 m at the peak of a remotely generated wave event. Hourly mean currents on the reef flat during mid and high tides (~0.2 m/s) are directed towards the reef channel in the alongshore direction, independent of wave and wind conditions. Maximum current speeds on the reef flat reach 0.58 m/s during the wave event measured in this study. The channel flow, which is depth intensified, is always directed offshore, reaching a depth-averaged maximum of 0.72 m/s during the peak of the wave event measured in this study. Low frequency modulation of the alongshore current on the reef is significantly correlated with the alongshore sea surface height gradient. The wind stress does not play a significant role in forcing the circulation. Circulation over the reef appears to be primarily forced by wave-driven setup, modulated by the tide, which creates a sea surface height gradient between the reef flat and channel, where waves do not break and setup is low. The presence of the channel affects reef flat circulation as far away as two kilometers, a significant distance given the size of the channel and the fact that this reef lacks a back lagoon.

The numerical model suite Delft3D was used to simulate waves and circulation over the reef for comparison with the field observations. Observed tide, wind, and wave conditions for two weeks surrounding the main wave event are used to specify model boundary conditions. Model runs confirm that wind and tidal forcing results in weak flows that do not reproduce the circulation patterns observed on the reef. Runs that include waves replicate the observations made on the reef relatively well. The low frequency variability caused by changing significant wave height is captured well in the model output. The model does a poorer job replicating high frequency variability caused by tidal modulation, however. Overall, our results from both the model and observations support the hypothesis that the alongshore current on the reef flat is forced primarily by the alongshore-varying wave-driven setup between the reef flat and channel.

# **Table of Contents**

List of figures
List of tables
1. Introduction
2. Methodology
2.1 Study site
2.2 Instrumentation
2.3 Setup calculations
2.4. Numerical model
3. Observations
3.1 Waves, currents, and water level
3.2 Current forcing mechanisms
3.3 Observations discussion
3.3.1 Wave driven currents
3.3.2 Friction on the reef
3.3.3 Water level effects
3.3.4 Channel flow structure
3.3.5 Reef streamlines
4. Numerical model
4.1 Model output results
4.2 Comparison of model output and observations42
4.3 Friction effects

5. Summary		52
Bibliography	/	

# List of figures

# 1. Introduction

1.1 Schematic of hypothesized circulation

# 2. Methodology

- 2.1 Map of study site with sensor locations
- 2.2 Computational grid for numerical model
- 2.3 Boundary conditions for numerical model

## 3. Observations

- 3.1 Deployment conditions
- 3.2 Depth and time averaged velocity vectors
- 3.3 Reef flat and channel velocity profile time-series
- 3.4 Effect of wave height and tide on alongshore sea surface height difference
- 3.5 Regression of pressure gradient and bed stress terms
- 3.6 Comparison of pressure gradient, bed stress, and surface stress time-series
- 3.7 Varying depth intensification of channel current with wave height and temperature
- 3.8 Satellite photos showing reef streamlines

## 4. Numerical model

- 4.1 Eulerian velocity vectors for 3 different friction runs during wave event
- 4.2 Time average Eulerian velocity vectors from model output
- 4.3 Reef water level during wave event
- 4.4 Reef water level alongshore section
- 4.5 Comparison of model output and observations current time-series
- 4.6 Comparison of model output and observations wave setup time-series

# List of tables

Table 1: Instrument setup

Table 2: RMSE and R values between model output and observations for 5 different friction coefficient values

### **1. Introduction**

Fringing and barrier reefs are common morphological features on many tropical coastlines. Typical geometry of these reefs consists of a sloping fore-reef where waves break in a narrow surf zone, which transitions to a shallow reef flat inshore of the surf zone. This reef flat often gives way to a back lagoon, which can vary in size and shape. The lagoon empties into one or more deep channels that cut through the reef flat, allowing water exchange between the lagoon and open ocean. Fringing reef currents are widely recognized to be significant for the transport of sediment, larvae, and nutrients on a variety of spatial scales, all of which can play an important role in the reef ecosystem [*Hearn et al.*, 2001; *Kraines et al.*, 1998; *Presto et al.*, 2006]. The diversity and abundance of coral and fish species make fringing reefs and their lagoons important sites for fisherfolk and tourists alike. Strong currents over the reef and through the channels can be dangerous, however, and in Guam have resulted in a large number of drownings on the fringing reefs there [*Lucas and Lincoln*, 2010].

Reef circulation can be forced by wind [e.g. *Symonds et al.*, 2011], waves, tides [e.g. *Angwenyi and Rydberg*, 2005; *Taebi et al.*, 2011], and buoyancy effects [e.g. *Hench et al.*, 2008]. The relative importance of these forcing mechanisms varies depending on a number of factors, but depth-limited wave breaking is generally recognized as the most important forcing mechanism for fringing reef circulation [*Hench et al.*, 2008; *Lowe et al.*, 2009b; *Monismith*, 2007; *Taebi et al.*, 2011]. The depth-averaged, steady momentum and mass balance in the crossshore (x) direction for wave driven flow over shallow reefs is given by

(1) 
$$gh_r \frac{\partial \eta}{\partial x_j} = -\frac{1}{\rho} \frac{\partial S_{ij}}{\partial x_j} - \tau^B{}_j + \tau^S{}_j$$
(2) 
$$\frac{\partial (h_r u_i)}{\partial x_i} = 0$$

where the total water depth is  $h_r = (h + \eta)$ ,  $\eta$  is the sea surface elevation, h is the mean water depth,  $u_i$  is the water velocity vector, and  $\rho$  is the water density. Advection of momentum and rotation are neglected. The mean (wave-averaged) bed stress and the surface wind stress are represented by  $\tau^B_{j}$  and  $\tau^S_{j}$ , respectively. Invoking a quadratic friction law for the bed stress gives  $\tau^B_{j} = C_r |u|u_j$ , where  $C_r$  is a dimensionless drag coefficient. The value of  $C_r$  is typically determined from observations [*Monismith*, 2007]. The surface wind stress is given by  $\tau_j^S = (\rho_a C_w | u^w | u^w_j) / \rho$ , where  $u^w_j$  is the wind velocity vector, the wind drag coefficient  $C_w = 1.3 \times 10^{-3}$ , and air density  $\rho_a = 1.2 \text{ kg m}^{-3}$ .  $S_{ij}$  is the radiation stress tensor. The cross-shore component of radiation stress,  $S_{11}$  is given by

(3) 
$$S_{ij} = E_w \left[ \frac{2kh}{\sinh(2kh)} + \frac{1}{2} \right]$$

where k is the wavenumber, and the wave energy density,  $E_w = 1/8\rho g H^2$ , is computed from the wave height, H. Strong cross-shore gradients in radiation stress are generated in the surf zone due to the breaking of waves, assuming frictional losses are small. These gradients are balanced by a wave-driven setup, which increases with the incident wave height [*Longuet-Higgins and Stewart*, 1964].

Analytic solutions to these equations using the case of a wide, shallow reef flat with a steep fore-reef have been attempted to examine the cross-shore currents on the reef [*Gourlay and Colleter*, 2005; *Hearn*, 1999; *Symonds et al.*, 1995]. These solutions consider a one-dimensional (1-D) reef flat with a sloping fore-reef that ends in a back lagoon where the mean water level is equal to that of the offshore water level. These solutions demonstrate that, assuming bottom friction and advection in the surf zone are not significant, the cross-shore radiation stress gradient generated by breaking waves creates a sea surface set-up in the surf zone, resulting in a pressure gradient across the reef towards the lagoon, where setup is zero. This pressure gradient between the surf zone and lagoon is balanced by the bottom stress term, resulting in a mean flow across the reef flat into the lagoon. Due to the relationship between H and S<sub>11</sub>, the magnitude of the current over the reef flat therefore varies positively with offshore significant wave height [*Gourlay and Colleter*, 2005; *Hearn*, 1999; *Symonds et al.*, 1995].

By assuming that waves do not break on the reef flat, and that wind stress is small, equation (1), rewritten in vector notation, can be reduced to

(4) 
$$g(h+\eta)\frac{d\eta}{dx} = -C_r|\mathbf{u}|u$$

This balance between the pressure gradient force and friction term describes 1-D cross shore flow over a reef flat into a lagoon quite well, and has been utilized at French Polynesia [*Hench et al.*, 2008], Kaneohe Bay [*Lowe et al.*, 2009b], and Ningaloo, Australia [*Taebi et al.*, 2011]. Changes in the pressure gradient are caused by changes in wave setup, which is positively

correlated with offshore wave height.

Depending on the morphology of the reef, the water depth can affect the current in one of two competing ways. When the total water depth, h<sub>r</sub>, is relatively small, currents over the reef increase as h<sub>r</sub> increases due to the pressure gradient force increasing relative to the frictional force. It follows from this that as h<sub>r</sub> goes to zero, so will the velocity. In contrast, if h<sub>r</sub> is relatively large, an increase in h<sub>r</sub> will cause diminished wave breaking, therefore decreasing the water velocity [Hearn, 1999]. These predictions of varying current speed with local water depth have been observed on several fringing reefs. Kaneohe Bay has a depth-limited breaking condition so that at high tides, waves do not break over the reef and the current speed diminishes [Lowe et al., 2009b]. Ningaloo reef, a much shallower reef flat with a steeper fore-reef than Kaneohe, is in the opposite regime, where the current speed overall increases with local water depth [Taebi et al., 2011]. Typically, a linear relationship between water depth and mean current is observed [Lowe et al., 2009b; Taebi et al., 2011]. However, at Ningaloo, a quadratic relationship between tidal height and current speeds was observed, and is attributed to the competing influences of depth-limited wave breaking and the pressure gradient term [Taebi et al., 2011], a phenomenon which is also predicted in the theory [Hearn, 1999; Symonds et al., 1995]. In most fringing reefs, variation in water level is tidally dominated, so the flow is often highly tidally modulated, with episodic wave events that increase setup, and therefore water level, over the reef, which modulates flow on a lower frequency.

Numerical modeling studies have be made for several fringing reefs, including Kaneohe Bay [*Lowe et al.*, 2009a] and Ningaloo [*Taebi et al.*, 2012; *Van Dongeren et al.*, 2013]. The Kaneohe Bay experiment utilized the Delft3D coupled wave and flow model to set up a 2D simulation of circulation within the bay [*Lowe et al.*, 2009a]. Hindcast results from this experiment showed good agreement between the observations [*Lowe et al.*, 2009b] and model output for both the overall circulation patterns and wave setup on the reef [*Lowe et al.*, 2009a]. The most recent numerical model set up at Ningaloo utilized XBeach for both 1D and 2D simulations for the wave and circulation dynamics on the reef [*Van Dongeren et al.*, 2013], and was able to replicate the observations described by *Taebi et al.* [2011] accurately [*Van Dongeren et al.*, 2013]. The results from *Van Dongeren et al.* [2013] show some alongshore variability, and an alongshore component of the current, which dominates in the lagoon and towards the shoreward side of the reef flat. The primary focus of these two numerical models, however, as in their corresponding observational papers, is the cross-shore balance between gradients in setup and the bed stress.

The numerical and observational studies at French Polynesia, Kaneohe Bay, and Ningaloo reefs illustrate the forcing mechanisms behind wave-driven circulation over fringing reefs. However, each of these study sites has a back lagoon, and focuses primarily on 1D cross-shore dynamics over the shallow reef flat. In this paper, we present a different case where the fringing reef does not have a back lagoon; rather, the reef flat is directly attached to shore. This introduces a second dimension into the problem, so the force balances described previously must be modified. At Pago Bay, just north of the study site presented here, the importance of 2D dynamics is apparent with the measurement of both alongshore and cross-shore flows were measured using dye experiments [*Marsh*, 1982]. Alongshore flows have also been measured using dye at Kapaa reef, on the island of Kaua'i in the Hawaiian Islands, and were hypothesized to be primarily wave driven [*Inman et al.*, 1963; *Kohn and Helfrich*, 1957]. Kapaa reef, like Pago Bay and the Ipan reef discussed here, is a shallow, shore-attached fringing reef with a cross reef channel. Here, we are able to expand on this analysis and look more quantitatively at the forces behind alongshore variability on these reef dynamics.

On a fringing reef with no back lagoon, we hypothesize the setup can vary in the alongshore direction between the reef flat and the channel. This alongshore gradient in sea surface height occurs because the channel mouth is deep enough (~30m) that waves do not break there. The alongshore pressure gradient term is balanced by bottom stress.

(5) 
$$g(h+\eta)\frac{d\eta}{dy} = -C_r |\mathbf{u}|v$$

We hypothesize that this is the primary force balance that drives flow on the reef flat. Because there is no back lagoon, a pressure gradient in the cross-shore direction is not expected to be a major factor in the force balance on the reef. Although cross shore gradients in momentum stress tensor can drive alongshore currents in the surf zone [*Feddersen et al.*, 1998; *Longuet-Higgins*, 1970], here the surf zone is narrow and these gradients are likely not an important part of the force balance on the reef flat. Finally, we will show that the surface wind stress is small, and can be ignored in the momentum balance.

Figure 1 shows a simplified schematic of the hypothesized circulation over a shoreattached fringing reef. Breaking waves over the fore reef create a gradient in cross-shore radiation stress, which is balanced by wave setup that varies little in the cross-shore direction. Instead, the setup varies alongshore towards a deep channel. The balance of the pressure gradient force and bottom stress drives alongshore current over the reef flat and into the channel, where the flux is balanced by a return flow to sea.

In this study, both observational and numerical techniques are utilized to examine the dynamics of the circulation of a shallow reef flat at Ipan, Guam. We first present the study site, and outline the observational techniques that we employed at the site. The numerical model is discussed, including a description of the basic governing equations of the model, in addition to the domain and boundary conditions used. The results section of this paper is divided into two parts-observational experiments and numerical experiments. In the observational experiments results, the current and pressure data in the context of wave driven currents are discussed. The results of numerical simulations are then discussed in a qualitative sense in comparison to observations. Finally, the two portions of the experiment are synthesized in a final summary.



**Figure 1** a) 2-D schematic of shore-attached fringing reef circulation with velocity vectors. b) 1D alongshore section of reef circulation showing alongshore reef flat current (v), offshore channel current (u), setup ( $\eta$ ), and mean reef flat depth (h). Note that the vertical scale is exaggerated.

# 2 Methodology

#### 2.1 Study site

The reef in this study is on the southeast coast of Guam (Figure 2.1a). The northern reef flat (north of the reef channel) is approximately 400 m wide, and spans approximately 2 km from the channel to a small peninsula that separates it from another reef just to the north (Figure 2.1b). To the south of the channel is a reef of roughly the same dimensions. The reef flat is shallow, and has an average depth of approximately 0.5 m, with a tidal amplitude between 0.1 m and 0.25 m. During low tides, much of the reef flat is exposed. The reef flat is relatively smooth, and composed mostly of algae covered coral, which is generally flat and featureless, but does have some coherent ridge-like structures, which are ~25 cm tall. Sandy areas and sea grass beds are interspersed amongst the coral, particularly in areas closer to shore. The reef flat directly attaches to the shoreline, which is mostly rocky with some areas of narrow sandy beach. The fore reef is steep, with a slope of  $\sim 4^{\circ}$ , and is characterized by a rugged spur and groove topography. At the reef rim, in the surf zone, the reef is slightly shallower than the reef flat, about 0.3 m, and is also very rugged, with both protruding rocks and deep holes in the surf zone. The channel is approximately 400 m long, spanning the entire distance between the surf zone and shore. At its deepest point, the channel is 30 m deep. It is roughly wedge shaped, ending in very shallow water near shore. The channel has a sandy bottom and very steep sides, which can overhang and occasionally collapse, resulting in the deposition of scattered large boulders. The channel is a drowned river, and the Togcha River continues to flow into it today. The Togcha river drains a small watershed  $(5.72 \text{ km}^2)$ , and is bordered by a much larger watershed, the Ylig watershed, which drains a large amount of the rainfall in the area [Luo and Khosrowpanah, 2012].

#### 2.2 Instrumentation

Between August 2005 and February 2012, bottom-mounted pressure sensors (Seabird SBE26plus) and acoustic velocimeters with pressure sensors (Nortek Aquadopp and AWAC) were deployed in numerous sampling configurations across the reef flat, fore reef, and in the channel. This study focused on the time period from December 2011 to February 2012, when sensors were deployed in both a cross-shore and alongshore array, including an acoustic velocimeter (Nortek AWAC) in the reef channel. Sampling was conducted in either 1 Hz bursts

over one depth cell, or as 2-minute averages with an average interval of 1 minute over a number of depth cells. Full detail regarding sampling schemes is found in Table 1. The study site and sensor locations are shown in Figure 2.1b.

Velocity on the reef flat was measured using the acoustic velocimeters. Velocity measurements taken when the water level dropped below the blanking distance for the instrument are removed from the dataset according to a pressure threshold and an acoustic backscatter threshold. The pressure threshold was set to when the reef flat water level was less than 0.45 m. Offshore wave height is calculated from bottom pressure measurements at sensor 7 at a depth of 8.3 m, where four times the standard deviation of the bottom pressure over a 3-hour burst with 1 Hz resolution is equal to the significant wave height, H<sub>s</sub>, on the fore reef. Wave breaking inshore of sensor 7 reduces H<sub>s</sub> by an order of magnitude [Vetter et al., 2010], and the location of this wave breaking is consistent except for the largest of wave events occurring during typhoons [Péquignet et al., 2011; Vetter et al., 2010]. Wave direction is calculated from velocity component measurements at this location-again over 3 hour bursts with 1 Hz resolution. To calculate wave period, T, an energy density spectral analysis was done on each 1 Hz pressure burst from sensor 7. The frequency with the maximum energy density was used to calculate the dominant wave period. Local velocity is depth averaged unless otherwise noted, and block averaged over periods of 1 hr. Local water level, h<sub>r</sub>, is calculated from 1 hr block averages of local pressure, and converted to meters. Tidal analysis is done using the t tide toolbox for MATLAB [Pawlowicz et al., 2002]. Meteorological data are taken from the National Oceanographic and Atmospheric Administration (NOAA) weather station at Pago Bay, located approximately 3 km north of the channel. All wind and water velocity data follow the North/East positive convention for the u and v components, respectively. Wave direction is measured with 0° corresponding to waves traveling from the north.

#### 2.3 Setup Calculations

Wave setup,  $\eta$ , is computed by referencing the water level on the reef flat to the water level measured on the fore reef at a depth of 8.5 m (sensor 7, Figure 2.1b). De-trended (overall mean removed) pressure on the fore reef (sensor 7) is subtracted from de-trended pressure on the reef flat, and linearly regressed against the incident wave height so that with no waves, setup equals zero. There is a small amount of set-down (< 0.1 m for waves less than 3 m) on the fore reef [*Vetter et al.*, 2010], which we do not include in our calculations. This will introduce a small

amount of error into calculations of setup on the reef, but since our primary focus in this paper is on alongshore variation in water level, excluding set down from our calculations will not significantly alter the results. Similarly, alongshore sea surface height gradients,  $d\eta/dy$ , are computed by subtracting the de-trended water level closest to the channel (Sensor 5, Figure 2.1b) from the de-trended water level on the northern end of the reef (Sensor 2, Figure 2.1b) and linearly regressing the difference against incident wave height, H. Because both of these sensors are on the reef flat as opposed to the fore-reef, the previous error regarding set down is not a factor here. Clock drift between the two sensors is less than 10 seconds, and is not thought to be a significant source of error in setup calculations.

#### 2.4 Numerical Model

A numerical model of the Ipan, Guam reef area was set up to gain additional insight into the observational results. The model was developed utilizing Delft3D, a finite-difference hydrodynamic model, coupled to SWAN, a third-generation wave model. A similar approach was used by *Lowe et al.* [2009a]. Delft3D FLOW uses the horizontal momentum equations

(6) 
$$\frac{Du}{Dt} - fv = -\frac{1}{\rho}\frac{\partial P}{\partial x} + F_x + \frac{1}{h^2}\frac{\partial}{\partial z}\left(\frac{\partial u}{\partial z}\right) + M_x$$

(7) 
$$\frac{Dv}{Dt} - fu = -\frac{1}{\rho} \frac{\partial P}{\partial y} + F_y + \frac{1}{h^2} \frac{\partial}{\partial z} \left(\frac{\partial v}{\partial z}\right) + M_y$$

where  $F_x$  and  $F_y$  are horizontal Reynold's stresses and  $M_x$  and  $M_y$  are contributions of external sources or sinks of momentum, in this case from wave stresses. A full explanation of the development and validation of the Delft3D model and its equations can be found in *G R Lesser et al.* [2004]. The wave stress is expressed by

(8) 
$$\overrightarrow{M} = \frac{D}{\omega} \overrightarrow{k}$$

This formulation represents wave forcing due to breaking, where M is the forcing due to radiation stress gradients, D is the dissipation due to wave breaking,  $\omega$  is the angular wave frequency, and k is the wavenumber [*G R Lesser et al.*, 2004].

The SWAN model incorporates several different processes, including wave propagation, refraction, wind generation, dissipation, and non-linear wave-wave interactions. The dissipation term consists of contributions from white capping, bottom friction, and depth-induced breaking

[Booij et al., 1999]. The Battjes and Janssen [1978] model is used to express the energy dissipation rate for wave breaking, where

(9) 
$$D_{tot} = -\frac{1}{4} \alpha Q_b \left(\frac{\sigma}{2\pi}\right) H_{max}^2$$

Here,  $Q_b$  is the fraction of wave breaking,  $\sigma$  is the mean frequency,  $\alpha = 1$ , and  $H_{max}$  is the maximum wave height that can exist at a certain depth.  $H_{max} = \gamma h$ , where  $\gamma$  is the breaking parameter and h is the local water depth. Values of the breaking parameter  $\gamma$  have been found to range between 0.55 to 1.33, with higher values corresponding to steep slopes [*Nelson*, 1987; 1994; 1997]. For this experiment, we used a value of  $\gamma = 1.28$ , based on observational data from *Vetter et al.* [2010]. Although this is much higher than the default value of 0.73 used in the model, the fore-reef at Ipan is very steep, so our value of 1.28 is reasonable [*Booij et al.*, 1999; *Nelson*, 1987; 1994; 1997].

The coupled model was developed over a two-dimensional Cartesian grid with a resolution of 25 m. The model domain is shown in Figure 2.2 and covers a spatial extent of approximately 4x3 km. The model domain bathymetry is based on a high-resolution aerial LIDAR survey of the area [*Chamberlin*, 2008]. The bathymetry was adjusted up 0.4 m to match water level observations during the time of the experiment. The model was run using a time step of 1 min over a period of approximately 2 weeks for both the wave and flow modules. The flow module communicated with the wave module every hour, and results were stored every hour. Wave forcing was done using a JONSWAP type spectrum with a peak enhancement factor of 3.3 and a cosine power directional spreading scheme for wave direction.

FLOW and SWAN were computed on the same grid. SWAN utilized the FLOW module output of water level, currents, bathymetry, and wind after each communication between modules. Water level and wave forcing were incorporated into the FLOW and SWAN modules, respectively, along the seaward boundary of the domain. Uniform wind forcing based on observations from the NOAA Pago Bay weather station was also incorporated across the entire domain in the FLOW module. Figure 2.3 shows the detailed forcing conditions. The conditions used in the model replicate conditions experienced during the deployment described in the observations portion of this paper.

To compare our observations with the model output, we select the grid cell in the domain that is closest to the actual location of the sensor in question. More details on the sensor types,

sampling schemes, and locations can be found in the observations methods section of this paper. The model was tested using spatially uniform roughness coefficients,  $C_r$ , ranging from 0.002 to 0.025. To test how well the model replicated observations, the root mean square error (RMSE) was calculated between the model and the observations for the alongshore pressure gradient and the channel velocity. Correlation coefficients were also calculated between the observed and modeled channel velocities and alongshore pressure gradients.







Instrument	Aquadopp		SBE26plus	AWAC
Location (Denth)	1 (0.4m), 3	7 (8.3m)	2(0.5m), 5	6 (19.8 m)
(Depth)	(0.4m), 4 (0.4m)		(0./m)	
Velocity Profile	20 cm blanking	50 cm		40 cm blanking
	distance with 10,	blanking		distance with 20, 1 m
	10 cm cells	distance with		cells
		1, 1 m cell		
Sampling	1 Hz sampling for	1 Hz sampling	1 Hz sampling,	Hz sampling for 60 s
Scheme	60 s every 120 s	for 2.5 hrs	continuous	every 120 s
		every 3 hrs		

**Table 1** Instrument sampling setups for sensors shown in Figure 2.1b.



**Figure 2.2** Computational grid used in the Delft3D model. Depth scaling is cut-off at 50m. White contours are plotted every 50m.



**Figure 2.3** Forcing conditions for the Delft3D model run. From top to bottom, significant wave height (H), wave period (T), wave direction, tidal height, and wind velocity.

#### 3. Observations

#### 3.1 Waves, currents, and water level

General conditions during the deployment were typical for this region and are shown in Figure 3.1. During the deployment, the area experienced moderate, relatively short period (~10 s) swell with an average significant wave height of around 1 m. Around January 7, a moderate swell event began, with the largest significant wave height reaching just over 2 m at its peak on January 11. The wave direction is predominately from the East, owing to the fact that the majority of swell that reaches Guam is trade-wind swell. Moderate and consistent trade winds blew at around 2 m/s from the east/northeast for the entire deployment. A mixed diurnal-semidiurnal tide was observed with a range around 0.5 m, and three spring-neap cycles were captured in the dataset. Satellite altimetry data did not show significant eddy activity in the Guam vicinity during the deployment period. The altimeter products were produced by Ssalto/*Duacs* and distributed by *Aviso*, with support from *Cnes* (http://www.aviso.oceanobs.com/duacs/).

Mean currents over the reef are predominantly south/southwest, towards the reef channel (Figure 3.2). Measurements from the two northern ADCPs (sensors 1 and 3) show a slightly stronger onshore component of the flow, while the flow at sensor 4 is predominately alongshore. Depth and time averaged currents for the length of the deployment (6 weeks) over the reef are  $\sim 0.25$  m/s. At low tides, measurements on the reef flat are not reliable because the sensor head is often in water less than 20 cm, the blanking distance of the instrument. During the early January wave event, water velocity at sensor 4 was consistently around 0.45 m/s, with a maximum value of 0.58 m/s. Velocity profiles of currents over the reef show a roughly uniform flow with depth outside of the sensor blanking distance (Figure 3.3.a). On the fore reef, hourly averaged currents are weak, on the order of 0.01 m/s. The depth averaged, time averaged reef channel current is 0.15 m/s (Figure 3.2), however, velocity in the channel is zero or close to zero at low tides. During mid and high tides, velocities in the channel are around 0.4 m/s. During the wave event, the maximum depth averaged channel velocity was 0.74 m/s. The measured channel velocities are always offshore, and never reverse to an onshore direction. Even during strong wave events, velocity profiles for the reef channel show a bottom-intensified flow (Figure 3.3.b). The difference between the near surface and near bottom flow in the channel ranges from 0 m/s to 0.2 m/s. The depth intensification is consistent with diver observations during deployment and recovery of the channel instrument.

Wave setup at over the reef in the cross-shore direction, measured at sensor 2, is significantly correlated with the offshore significant wave height (r = 0.85) with a regression coefficient of 0.39. These results are comparable to those described in *Vetter et al* [2010], who use similar methods as those described here. *Vetter et al* [2010] found a stronger correlation of setup with incident wave height, but their observation period had larger wave events relative to the observation period in this study. Here, very little change in setup across the reef flat is observed between sensors 1 and 2, which agrees with the *Vetter et al* [2010] analysis of setup difference in a cross-shore line of sensors located near sensor 4.

Although wave-generated setup does not appear to vary in the cross-shore direction, sea surface height decreases in the alongshore direction moving towards the channel. The mean difference in sea level between sensor 2 and the channel is 0.2 m, but during the large wave event this increased to a maximum of 0.71 m. The alongshore sea surface height difference ( $d\eta$ ) between the reef flat and the channel is also positively significantly correlated with wave height (Figure 3.4, r = 0.65). The wave generated cross-shore setup and alongshore  $d\eta$  show a very strong positive correlation (r = 0.93). Alongshore  $d\eta$  is also related to the tidal height, the highest values of  $d\eta$  occur during low tides (Figure 3.4). This result is similar to results from analysis of wave driven setup and significant wave height, and agrees with results that indicate waves on the reef break more efficiently in shallower water [*Vetter et al.*, 2010].

#### 3.2 Current forcing mechanisms

As mentioned previously, reef circulation can be forced by wind [e.g. *Symonds et al.*, 2011], waves [*Hench et al.*, 2008; *Lowe et al.*, 2009b; *Taebi et al.*, 2011], and tides [e.g. *Taebi et al.*, 2011]. The hypothesized primary force balance is that of equation (5). The alongshore pressure gradient term is balanced by the bottom stress term which results in an alongshore current towards the reef channel. To test this hypothesis,  $|\mathbf{u}|v$  at sensors 3 and 4 was plotted against  $g(\eta+h)d\eta/dy$ , where  $\eta + h$  is the local water depth, and  $d\eta/dy$  is estimated by taking the difference between the de-trended pressure data at sensor 2 and sensor 5 divided by 2000 m, or the approximate distance between those two sensors (Figure 3.5). For the reasons discussed in the methods section of this paper, data at low tides (mean water level below 0.45 m) were

removed from the dataset for this analysis. The correlations between the alongshore bed stress and pressure gradient were significant, with  $r_3 = 0.70$  and  $r_4 = 0.79$  (Figure 3.5).

To determine an approximate friction coefficient,  $C_r$ , in this balance, a linear orthogonal regression is used since there is error associated with the variables on both axes. This regression finds the coefficients in the form Y = aX + b so that sum of the squared distances between the line and data points  $[X_i \ Y_i]$  is minimized. Using this model, the slope of the regression line is the friction coefficient. The friction coefficients calculated by this method for these sensors are  $C_{r3} = 0.0035 \pm 0.0002$ ,  $C_{r4} = 0.0054 \pm 0.0002$  (Figure 3.5).

Possible wind forcing of the alongshore current was analyzed by calculating the surface wind stress term as in equation (1), but in the alongshore direction, and compared it to the value of the alongshore bed stress, as in equation (5). Wind velocities during the deployment were typically about 2 m/s from the northeast (Figure 3.1e). Compared to the values of the bed stress and the pressure gradient terms, the surface wind stress is negligible (Figure 3.6).

Tides can influence currents on the reef flat either by generating currents via the ebbflood movement of the tides, or by tidal modulation of the wave-driven currents [*Hearn*, 1999; *Symonds et al.*, 1995; *Taebi et al.*, 2011]. Because these processes occur at similar frequencies, however, it can be difficult to distinguish between the two when performing time series analysis. *Taebi et al* [2011] were able to distinguish these two modes using an EOF analysis. The reef flat at Guam, however, is so shallow that it becomes nearly dry at low tide, resulting in a lack of data on the reef flat during low tides due to instruments being out of the water. Because of this, the effect of the tides on the currents could not be distinguished between a possible ebb-flood forcing mechanism and modulation of the existing currents.

#### **3.3 Observations Discussion**

#### 3.3.1 Wave-driven Currents

During this deployment, winds were moderate and blowing from the northeast (Figure 3.1e), in approximately the same direction as the prevailing currents. Data from previous deployments (not shown) with winds that were either lighter, or from a different direction, still show currents significantly correlated with wave height and primarily in the alongshore direction. Additionally, previous deployments on this reef contain data from sensors placed south of the reef channel. The currents at these sensors are primarily in the alongshore direction, but moving northward towards the channel, and do not reverse. This direction is against that of the

prevailing winds in the area. Based on these two observations, and the analysis of the momentum equation terms for this experiment, it seems unlikely that wind is a major forcing mechanism for the circulation on the reef flat.

At low tides on the reef at Ipan, there is little to no water on the reef, so the data in this experiment does not include dynamics at low tides. Complete analysis on tidal motion, therefore, is impossible. However, the consistency of the direction of the currents, alongshore towards the channel on the reef and seaward in the channel, supports the hypothesis that the flow is likely not generated by the ebb-flood movement of the tides to raise and lower the water level on the reef flat. Although the magnitude of the current changes with the tide, the mean currents are strong, and consistent in their direction (Figure 3.6). Because the amount of water needed to change tidal elevation over the reef is small, since the reef is so shallow, currents generated due to an ebb-flood mechanism are likely also small. The primary influence on the tides for the reef circulation instead probably lies only in the modulation of reef currents.

Alongshore currents can also be driven by cross-shore gradients in the alongshore momentum stress tensor component  $S_{xy}$  [*Feddersen et al.*, 1998; *Longuet-Higgins*, 1970; *Longuet-Higgins and Stewart*, 1964]. At the Ipan reef, the surf zone is very narrow on the edge of the reef flat, and is consistently in the same location [*Péquignet et al.*, 2011]. Since the balance of alongshore currents with gradients in  $S_{xy}$  is generally only relevant in the surf zone [*Feddersen et al.*, 1998; *Longuet-Higgins*, 1970], alongshore momentum stress gradients are likely not important for the overall circulation on the reef, although they could play a small role in driving alongshore currents near and in the surf zone.

The correlations of the reef flat currents with both wave height and the alongshore pressure gradient, combined with our observations regarding the wind, tides, and alongshore momentum stress, support the hypothesis that the circulation on the reef is primarily wave driven and tidally modulated. The force balance on the reef in the alongshore direction is primarily between the alongshore pressure gradient term,  $g(\eta+h)d\eta/dy$ , and the friction term  $C_r|\mathbf{u}|v$ , where  $C_r$  is the quadratic friction coefficient. This alongshore pressure gradient arises from wavegenerated set up on the reef flat. The wave-driven setup is generated by the balance of crossshore gradients in radiation stress in the surf zone. The difference between the setup on the reef flat and the channel, where waves do not break and setup is minimal, creates the alongshore pressure gradient. This alongshore pressure gradient balances the bed stress, thus generating a wave-driven flow in the alongshore direction. Our data support the hypothesis that the dominant balance on the reef flat is between the alongshore bed stress and alongshore pressure gradient (Figure 3.5). The strongest correlation (r = 0.79) between these two terms is at sensor 4, which is closest to the channel and has the strongest alongshore current. Data from the northern reef flat sensor, sensor 1, where the alongshore current is not significantly correlated with the alongshore pressure gradient (r = 0.06), is not shown. Sensor 1 is furthest away from the channel and has a much weaker alongshore component of the current than sensors 3 and 4, which are closer to the channel. This decrease in the alongshore current speed is not surprising. Close to the channel, the transport of a cross-shore section of reef must match the wave-driven transport of water over the length of the surf-zone between that cross-shore section and the northern peninsula, assuming zero seaward transport in the surf zone. A cross-shore section of reef further from the channel is approximately the same area, but its transport must match the wave-driven flux over a smaller length of surf zone. Therefore, the velocity over a given cross-shore width of reef will decrease moving away from the channel. Because of the alongshore momentum balance, the local dη/dy will decrease as well (Figure 1).

Based on this, clearly the most appropriate analysis would be to compare the alongshore currents with the local alongshore pressure gradient, as opposed to the overall alongshore pressure gradient. A brief comparison of the alongshore bed stress at sensor 1 to the alongshore pressure gradient between sensors 1 and 3 (Figure 2.1b) does give a higher correlation coefficient,  $r_1 = 0.32$ , but this is still nowhere near the strength of the correlations that were observed at sensors 3 and 4. Correlating total current magnitude at sensor 1 with the overall alongshore pressure gradient gives a correlation coefficient of  $r_1 = 0.42$ , a marked improvement over the correlation with just the alongshore component of the current ( $r_r = 0.06$ ). This result indicates that at the northern end of the reef, the cross-shore force balance is as or more important than the alongshore force balance. The cross-shore pressure gradient would be expected to vary in a similar manner to the alongshore pressure gradient, explaining why the total magnitude of the current at sensor 1 is significantly correlated with the alongshore pressure gradient.

Unfortunately, this hypothesis cannot be confirmed by the data. A cross-shore pressure gradient was not detected between sensors 1 and 2. Using the balance in equation (4), with a friction coefficient of 0.006 and a cross shore length scale of 350 m, it is possible to estimate the cross-shore sea surface height difference needed to drive a given current speed. To drive a flow

of 0.2 m/s, the sea surface height difference only needs to be 1.7 cm. It is possible, then, that a cross-shore pressure gradient does exist, but is too small for the sensors used in this study to measure accurately. Although this is still a likely explanation for the currents in the cross-shore direction at this location, the alongshore dynamics are still unclear. The currents here are clearly still influenced by the channel, since they are always flowing towards it, but there must be other physics, possibly related to the complicated bathymetry surrounding the peninsula, that affect the flow there.

#### **3.3.2** Friction on the reef

An orthogonal linear regression between the alongshore pressure gradient and the quadratic friction term at sensors 3 and 4 (Figure 3.5) gives an average friction coefficient of 0.0045. This friction coefficient is an order of magnitude lower than the friction coefficient described in Kaneohe Bay,  $C_r = 0.02$  [*Hearn*, 1999; *Lowe et al.*, 2009b], and two orders of magnitude lower than the canonical value for a coral reef of 0.1 [*Hearn*, 1999]. Measurements of  $C_r$  on sandy beaches yield a variety of estimates ranging from 0.018-0.003 [*Apotsos et al.*, 2007; *Feddersen et al.*, 1998; *Garcez Faria et al.*, 1998]. The canonical value of the friction coefficient for a sandy bottom is 0.002 [*Hearn*, 1999]. Our average value of  $C_r$  is 0.0045, clearly falling within the range of values for a sandy beach, as opposed to a coral reef. This is surprising given the coral substrate of our study site.

This low friction coefficient indicates that the reef currents observed here are stronger than what would be expected based on previous studies on wave driven currents on reef-flats [*Hench et al.*, 2008; *Lowe et al.*, 2009b; *Taebi et al.*, 2011]. The most obvious explanation for why the friction coefficient is so much lower on the reef flat in Guam than at other fringing reefs is the difference between reef rugosity at these locations. As noted previously, although the forereef at Guam has live coral with a rugged spur and groove structure, the reef flat is primarily composed of algae covered dead coral. It is relatively flat and featureless, with only small ridges crossing the reef flat. This featureless reef likely reduces the drag coefficient, as coral heads and other coral structure increase friction on reef flats [*Monismith*, 2007]. Another possible explanation for the low friction coefficient is the use of a linear approximation for the alongshore pressure gradient. For the reasons discussed in section 3.2.1, a linear approximation of the overall pressure gradient likely overestimates the local pressure gradient, which is what drives the local currents on the reef. This introduces a possible error into the analysis shown in Figure 3.5 that gives the value of the friction coefficient.

#### 3.3.3 Water Level Effects

The importance of water level on the reef to both velocity and wave-driven setup has already been mentioned, and examined more extensively in previous work at this site [*Vetter et al.*, 2010], but here we examine these water level effects in the context of alongshore variability. Laboratory experiments and field results indicate that as the mean water level over a shallow reef decreases, wave setup will increase due to the relationship of breaking efficiency with depth [*Gourlay*, 1996; *Vetter et al.*, 2010]. Water level on the reef also affects transport, with transport decreasing as water level decreases [*Gourlay*, 1996]. This is especially important on this reef, since at low tides, the water level drops to near zero for most of the reef flat.

During this study, the alongshore sea surface height difference on the reef flat, dn, increases as tidal height decrease and incident wave height increases (Figure 3.4), agreeing with the setup theory of *Vetter et al.* [2010]. At first glance, it would seem that this would predict an increase in velocity on the reef flat at low tides. However, velocities in the channel decrease at low tides (Figure 3.3a), indicating that transport on the reef must be lower at low tides. This decrease in transport can occur either because velocities are weaker, or the water level is lower. Looking at equation (5), although  $d\eta/dy$  and  $\eta$  (setup) increase at low tides due to increased breaking efficiency, the still water depth, h, decreases. At Guam, the reef flat is so shallow that the still water depth on the reef goes to zero at low tides, so even though  $\eta$  and  $d\eta/dy$  increase at low tide, because h drops to zero, the left side of equation (5) decreases, therefore causing the velocity on the reef flat to decrease. So, although the tide can affect the terms of equation (5) in competing ways, the importance of the still water depth, h, dominates, and the reef circulation in general weakens at low tides. Although constraints on the instruments ability to measure in shallow water do not allow us to measure these low tide velocities on the reef flat, the observations from the channel are consistent with this analysis of water level effects. It should also be noted that the reef should never get completely dry unless  $h+\eta$  is zero, and this will only occur when there are no waves at a low tide, or when the water level is so low that no setup can reach the reef flat. Thus although the wave driven circulation slows down at mid and low tides because the water level on the reef is low, in theory it will not completely shut down if there are waves, since there will still be some setup on the reef, unless the tide is extremely low and the

wave setup does not reach the reef flat. This is reflected in the channel velocities, which, although dropping at low tides to between 0.1 and 0.2 m/s, do not go to zero until the significant wave height drops below 0.5 m between 1/17 and 1/22 (Figure 3.3b).

#### **3.3.4 Channel flow structure**

The channel flow is always to the east (offshore), and does not reverse during the deployment. This is not surprising, since reversal in channel flows typically occurs as part of a buoyancy driven water exchange with a back lagoon system [*Hench et al.*, 2008]. This reef system lacks both a lagoon and sufficient freshwater input to cause buoyancy driven exchange, so the constant seaward direction of the current is expected.

One perplexing aspect of the channel velocity is that it is depth intensified. This is clear both from the velocity profile time series (Figure 3.3b) and from diver observations during deployment and recovery of the channel instrument. Frictional bottom stress typically reduces near bed velocities, yet in this case we observe the opposite scenario. The reasons for this are unclear. It is possible that a diurnal cooling cycle of the water on the reef could cause enough of a density difference between the water on the reef and the channel to make the reef water sink as it enters the channel near the shore. Temperature data from the channel sensor, with the seasonal trend and overall mean removed, indicates that there is not a relationship between the strength of the bottom intensification and the temperature of the water (Figure 3.7), which shows that the depth intensification is probably not buoyancy driven. There does appear to be a relationship between the strength of the depth intensification and the significant wave height, however, with the most depth intensified flow occurring when waves are larger (Figure 3.7).

A more plausible explanation for the depth-intensified flow is that convergence of the reef currents on both sides of the channel is strong enough to force into a depth-intensified jet. This depth intensification is probably due to the wedge shaped geometry of the channel, which, combined with a slightly onshore component of the convergence, will constrain the return flow out of the channel to a depth-intensified jet. Without velocity measurements near the channel, however, the onshore component of the convergence in the flow on the reef flat near the channel cannot be confirmed, unfortunately. On-site observations of foam and debris lines along the center of the channel, in addition to our measurements of channel bound currents on both the northern and southern reef flats, indicate that the channel is a site of high convergence, so this mechanism seems to be plausible, assuming that there is an onshore component of the

convergence. The correlation between the strength of the depth intensification of the channel current and significant wave height (Figure 3.7) supports this hypothesis, since currents will be stronger, leading to more intense convergence at the channel, during bigger waves. The details of the convergence and depth-intensification, however, are complex, and beyond the scope of this experiment.

#### 3.3.5 Reef streamlines

Field observations at the study site indicate that ridges of coralline-like material run approximately northeast to southwest on the reef flat, and are roughly 20 cm in height. This directional coral growth is clearly visible in satellite images of the study site from Google Earth (Figure 3.8). These lines in coral growth correspond well with the direction of measured mean velocities on the reef (Figure 3.2). Close to the channel, the coral growth patterns are directed in the alongshore direction, and turn gradually until they are nearly directly across-shore at the end of the reef.

It has been suggested that corals will grow so that most of their surface area is parallel to mean currents, therefore reducing drag on the coral head, while still exposing the coral to currents that can deliver nutrients [*Wainwright and Koehl*, 1976]. Additionally, experiments have shown that morphology can vary within a single coral species depending on flow regimes [*M P Lesser et al.*, 1994]. Although field observations of the coral on the reef flat at Ipan, Guam indicate that the coral is mostly dead and covered in algae, it seems likely that the unique flow environment on the reef flat, with consistent currents in the southwest direction, caused a preferential growth in the coral so that the coral grew parallel to the mean flow direction. It is also possible that the ridge-lines are the result of scouring by the currents in the rubble on the reef flat. With the scant amount of information we have regarding the history of the reef flat and the coral on it, it is difficult to draw a conclusive answer as to the origins of the ridges.

The consistent direction of the coral ridges is a useful observation here because we have the unique opportunity to validate, at several different points, the legitimacy of using the coral ridge lines as a first order approximation for current direction. We do this simply by comparing the direction of the ridges with observed mean current vectors. From the results, the coral growth in satellite images does seem to do a surprisingly good job at predicting current direction. Figures from *Taebi et al.* [2011] that show mean current vectors superimposed on satellite images suggest that coralline ridges at Ningaloo also run in the same direction as the mean

30

current. Of course, this method says nothing about the current speeds, or how various factors such as water level and wave height control current strength. However, simply knowing the direction of the prevailing currents on a reef can be useful. In the future, Google Earth images at other reef flats around the world could be used to determine mean current direction over shallow reef flats by examining coralline streamline patterns.



**Figure 3.1** Deployment conditions, from top to bottom, significant wave height (H), wave period (T), wave direction, tidal height, and wind velocity.



**Figure 3.2** Depth and time averaged velocity vectors and variance ellipses plotted over study site bathymetry (colorbar, m).



**Figure 3.3 a.** North/South velocity (m/s) profile for station 4 (positive North). Y-axis is depth above bottom. White areas are regions of the profile with non-viable data due to the depth cell being out of the water, or low scattering. **b.** East/West velocity (m/s) profile for station 6 (positive East). Y-axis is depth. Average depth at this station is approximately 20m. White areas are non-viable data due to lack of scattering particles.



Figure 3.4 Alongshore sea surface height difference,  $d\eta$ , measured between sensors 2 and 5, plotted against the significant wave height, H, and tidal height.



**Figure 3.5** Linear orthogonal regression of pressure gradient term (y axis) and friction term (x axis), scattered with significant wave height, H. Correlation coefficients and the slope of the regression, or the friction coefficient  $C_r$ , are also shown.



**Figure 3.6** Comparison of momentum equation terms as in equation (5) in the alongshore direction for sensors 3 and 4.



**Figure 3.7** Scatter plot of the difference between the near bottom and near surface channel velocity with significant wave height and de-trended temperature.



**Figure 3.8** Google Earth satellite photos showing reef scouring in approximately the same direction as flow on the reef flat for near the channel (1) and midreef (2).

## 4. Numerical Model

#### 4.1 Model output results

Initial test runs of the Delft3D numerical model were done isolating possible wind forcing and tide forcing. For both cases of tide forcing only and the combined tide and wind forcing, circulation on the reef was sluggish (<0.1 m/s). The currents weakly oscillated in the cross-shore direction, and there was little to no flow in the channel.

In the numerical model experiments, five model runs were done with the friction coefficient varying between 0.002 and 0.025. To validate how well the model predicts the observed reef circulation, the Root Mean Square Error (RMSE) and correlation coefficient (R) was calculated for two key variables, channel velocity and alongshore pressure gradient,  $d\eta$  (Table 2). The lowest RMSE and highest R values, indicating the best fit, are for C<sub>r</sub> values of 0.004 and 0.006. Since there is a considerable amount of missing current data from the reef flat during the observations, a more qualitative comparison between the model output and observations must be made to determine which friction coefficient best replicates the observations made on the reef. The lower friction model run, C<sub>r</sub> = 0.004, shows currents that reverse on nearly every low tide, which, based on observations, likely does not occur on the reef. Based on this, the C<sub>r</sub>=0.006 run was selected as the one which best replicated the observations results. Unless otherwise noted, further discussion will focus on this model run.

The scale of the channel influence and its relation to the friction coefficient was examined in this series of model runs. The scale of influence is the estimated distance between the channel and the point on the reef where the currents on the reef are weak and no longer directed towards the channel. Figure 4.1 shows quiver plots of the depth-averaged Eulerian currents, at high tide and during the wave event, for C<sub>r</sub> values of 0.025, 0.006, and 0.002. The apparent cross-shore divergence in Eulerian velocities at the reef crest is balanced by Lagrangian wave-driven flow, which also drives the onshore flow further inshore. As the friction decreases, the point of the reef where currents appear to not be affected by the channel moves further north, until for C<sub>r</sub> = 0.002 the entire reef circulation is towards the channel.

Depth and time averaged Eulerian currents over the model run using the forcing conditions in Figure 2.3 on the Ipan reef flat are directed predominately in the alongshore direction towards the reef channel on both the northern and southern portions of the reef flat (Figure 4.2). These currents increase in strength with proximity to the channel. The time averaged magnitude of the flow typically ranges from 0.1 m/s to 0.5 m/s, depending on exact

location on the reef. In the channel, currents are directed offshore. The channel is also a site of strong convergence of alongshore currents from the northern and southern portions of the reef flat (Figure 4.2). The very shallow surf zone has a mean Eulerian velocity in the offshore direction that results from some of the water on the reef flat flowing back off the reef due to an offshore gradient in wave setup. The Eulerian flow in the surf zone from the FLOW module is balanced by stokes drift in the surf zone, directed in the onshore direction, which is calculated in the WAVE module. Currents offshore of the surf zone on the fore reef are small in comparison to the reef flat currents.

Although the time-averaged currents are towards the channel, there is a short period of time when alongshore flow for parts of the reef reverses, weakly moving away from the channel at ~0.1 m/s (Figure 4.5). This reversal in flow occurs during low tides during a period of low waves. There is no reversal in the direction of the channel current, which is always directed offshore. Generally, currents on the reef and in the channel decrease to near zero at low tides, and are stronger at high tides.

The model output indicates that tidal height and significant wave height both contribute to the water level on the reef flat. In general, the water level on the reef flat is higher during wave events due to the presence of setup. This wave setup is significantly correlated with wave height (r = 0.80). On the reef flat, there is an alongshore gradient in water level between the northern end of the reef and the channel (Figure 4.3, Figure 4.4). Water level gradients in the cross-shore direction are present in certain places on the reef, but are not as strong as the gradients in the alongshore direction (Figure 4.3). Just offshore of the surf-zone, there is a small region of wave set-down. Figure 4.3 also shows a small amount of numerical noise in the water level offshore of the reef, but it is not thought that this noise affects the overall model results on the reef in an important way. Dissipation output from the model shows highest dissipation on the eastern rim of the reef flat, and very low dissipation between the eastern rim and shore, indicating that all of the wave breaking occurs here, rather than at the shore in the western part of the domain.

Similar to the methods used in the observation section, the force balance between the alongshore pressure gradient and the bed stress in the model output is examined. To do this, the local alongshore pressure gradient is approximated by subtracting the water level from the grid cell below the velocity grid cell in question from the grid cell above it. We use this approximation of the alongshore pressure gradient and examine the force balance between the pressure gradient term and the bed stress as in the observations section of this paper. The

correlation coefficients between the alongshore pressure gradient and alongshore velocities for the three grid cells closest approximating the locations of sensors 1, 3, and 4 are  $r_1 = 0.14$ ,  $r_3 = 0.89$ ,  $r_7 = 0.79$ . These results show a similar pattern to that in the observations section of this paper. The correlations of the two sensors nearer to the channel (sensors 3 and 4) are much stronger than the sensor at the northern end of the reef (sensor 1), which in this case is not even statistically significant.

#### 4.2 Comparison of model output and observations

Qualitatively, the model output represents the major features of the reef circulation nicely. The most obvious feature of the circulation is the direction of the time-averaged reef flat currents. The average currents on the reef flat are directed towards the channel both on the northern reef flat, which the observations section of this paper focuses on, and on the southern reef flat, where we have observed channel bound currents during previous deployments.

The model output also shows a seaward current in the reef channel, similar to what our observations have indicated. There is also a strong convergence in the channel area of currents from the northern and southern reef flat. This convergence was predicted in the observations section of this paper based on our measurements of currents on the northern and southern reef, and based on observations of foam and debris lines in the channel during deployments. This agreement supports the theory that the bottom intensified channel current is caused by this convergence in the channel area. Actual depth intensification of the channel current could not be replicated in the model, however, since the model runs were all done as single layer, depth-averaged runs.

A comparison of the current magnitude time-series from the model output and observations shows that there is relatively good agreement between the two (Figure 4.5). The current time-series in the channel is replicated particularly well (Table 2). The low frequency variability, caused by variation in the significant wave height, which was discussed in the observations portion of this paper, is shown in the model output, with stronger currents occurring during the peak of the wave event. The high frequency variability, dictated largely by tidal elevation, is also reflected nicely in the model output. Channel current velocities drop to near zero at low tides as transport on the reef decreases, and water no longer flows into the channel.

The time-series of currents on the reef flat in the model output are not as similar to the observations as in the channel, but the results are still good overall. The low frequency

variability in the alongshore velocity at sensors 3 and 4 is accurately shown in the model, with stronger currents occurring during the wave event which peaked around January 11, and weaker currents during the period of low waves around January 20 (Figure 4.5).

When the significant wave height and the tide is low, the model output shows a northward alongshore current at sensors 3 and 4. During the deployment, the water was not deep enough to get an accurate measurement of the current velocity, so a comparison cannot be made between the model output and observations. The reversed current in the model output, however, is weak enough and occurs infrequently enough, in both a spatial and temporal sense, that it likely does not represent an important part of the dynamics of the system.

The model output does not agree as well with the reef flat (sensors 3 and 4) observations with respect to high frequency variability. Although it is difficult to get a good sense of the high frequency variability on the reef flat for this time period due to the lack of data at low tides, some observations can be made. In the case of sensor 3, the model shows current speeds that drop at low tide, yet observations, where they exist, seem to show the opposite, with current speeds increasing at low tide. It is possible that sensor 3 happened to be placed in a small divot in the reef, which, when surrounded by drier reef at low tide, could have been the site of a small jet, where water velocities increased as the tide got lower, until that portion of the reef also went dry. The resolution of the model does not allow for such small-scale features to be represented, so this jet is not reflected in the model output. Data at the other reef sensor, sensor 3, is too sparse to gain any information about the high frequency variability.

The model output agreed very well with observations of the alongshore difference,  $d\eta$ , in sea surface height on the reef flat (Table 2). Figure 4.6 shows a comparison of the model output and observations of the alongshore  $d\eta$  measured between sensors 2 and 5. Although the model slightly overestimates the alongshore pressure gradient during the main wave event, overall the magnitude and variability of the alongshore  $d\eta$  due to waves and tidal effects is predicted well in the model. Similarly, the model output agrees well with observations on water depth. The water depth on the reef flat at Guam is dictated by the combined effect of wave setup and tidal height. The model output is able to capture these effects well to give depths that are generally accurate, although small discrepancies in the local mean water depth do exist because of the small scale variability of the reef bathymetry that cannot be captured with this model resolution.

The most informative piece of information from the model output, however, is the alongshore water level variation over the reef. As discussed in the observations section of this

paper, we hypothesized that the alongshore currents on the reef are driven by an alongshore pressure gradient. This is in contrast to previous work on coral reefs where cross-shore pressure gradients drive cross-shore currents. We were able to measure an overall alongshore pressure gradient,  $d\eta/dy$ , and found that it is well correlated with the alongshore currents on the reef. We also predicted that the local  $d\eta/dy$  would be smaller further from the channel, based on constraints due to conservation of mass and the geography of the reef. The model output agrees with this hypothesis. Figure 4.4 clearly shows that the alongshore pressure gradient is the strongest closer to the channel, and further from the channel it is much smaller, leading to an overall alongshore profile of water level that is similar to our schematic in Figure 1. This reduction in  $d\eta/dy$  further from the channel results in weaker currents at the northern end of the reef, which again agrees with the observations section of this paper.

The model output also shows that the water level does not vary much as much in the cross-shore direction as it does in the alongshore direction. In the observations section of this paper, it was noted that there is a cross-shore component of the flow, particularly at the northern end of the reef. The cross-shore flow was hypothesized to be driven by a cross-shore pressure gradient that is too weak to reliably measure with the instruments available. The model data does show a weak cross-shore pressure gradient at the northern end of the reef flat in particular (Figure 4.3), indicating that a cross-shore balance could be important for this part of the reef.

One of the biggest challenges with the analysis of the alongshore frictional force balancing the alongshore pressure gradients in the observations section of this paper was that we had to use the overall pressure gradient on the reef, rather than the local pressure gradient, due to the spatial constraints of our sampling scheme. The model output, however, has no such constraints, so the analysis could focus on the correlation between local pressure gradients and local alongshore currents. The model output results show a similar trend to the observations, with low correlations between the two terms at the north end of the reef flat, and much higher correlation nearer the channel. The observations section of this paper points out that this low correlation in the alongshore direction could be due to the influence of other forcing mechanisms on the currents. A cross-shore balance is probably significant here, and the model output does show a small cross-shore pressure gradient at the northern end of the reef. However, the lack of correlation in the alongshore direction is still unexplained.

#### 4.3 Friction effects

In the observations section of this paper, the friction coefficient was estimated to be 0.0045 using a linear regression between the alongshore pressure gradient and bed stress terms of equation (5). As noted in section 3.3.2, this value of  $C_r$  is surprisingly low for a reef, but possible reasons for the low friction were identified, and included smooth substrate for a reef and the linear approximation of the alongshore pressure gradient. The  $C_r$  value that best replicated observations, however, was 0.006, only slightly larger than the value estimated in the observations section of this paper. Additionally, higher friction coefficient values do a poorer job replicating observations than lower values (Table 2). This validates the estimate of the friction coefficient in the observations section, indicating that the reef is probably smoother than reefs such as Kaneohe Bay, where the friction coefficient was estimated to be 0.02 [*Lowe et al.*, 2009b].

The low friction coefficient on the reef at Guam is of more interest than just indicating that the reef is smoother than expected, however. Figure 4.3 shows that the scale of influence of the channel on the reef flat currents changes with friction. High friction model runs show that the currents on the northern end of the reef flat are weak and variable in direction, even during high tides and waves, when currents on the reef are the strongest (Figure 4.1). As the friction coefficient decreases, the scale of influence increases until currents on the entire reef flat between the channel and the northern peninsula are flowing towards the channel. This observation is key because, as was discussed extensively in the observations section of this paper, the currents on the reef flat, even at the very northern end, consistently flow towards the channel without changing direction. This feature of the circulation is especially important because the influence of the channel is very large, 2 km, compared to the size of the channel. It seems that, based on these observations of friction affecting the scale of channel influence in the model output, that the low friction observed on the reef is responsible for this defining feature of the reef circulation.

	RMSE		r	
Cr	u, channel	dη	u, channel	dη
0.002	0.085	0.058	0.861	0.524
0.004	0.074	0.056	0.867	0.827
0.006	0.080	0.060	0.870	0.830
0.01	0.097	0.077	0.878	0.771
0.025	0.109	0.103	0.859	0.604

**Table 2** Root mean square error (RMSE) and correlation coefficient (r) between model output and observations of cross-shore channel velocity (u, channel) and alongshore pressure gradient measured between sensors 2 and 5 ( $d\eta$ ).



Figure 4.1 Eulerian velocity vectors plotted over depth (colorbar, m) for from left to right,  $C_r = 0.025$ , 0.006, 0.002 model runs.



**Figure 4.2** Time averaged Eulerian velocity vectors plotted over depth (m) for the Ipan reef (left panel) with detail of the mid reef flat (top right) and channel (bottom right).



**Figure 4.3** Water level on the Ipan reef flat during a mid tide and 1.5m incident waves. White portions of the domain are dry points.



**Figure 4.4** Alongshore water level section on the reef flat between the channel and northern peninsula during the 2 m wave event.



**Figure 4.5** Comparison of model output and observed data for currents at the channel sensor 6, sensor 4, and sensor 3. See Figure 2.1b for sensor map. Note that only one component of the current (the dominant component for that location) is plotted in each panel, and that the convention is positive north/east.



Figure 4.6 Comparison of model output and observed data for the alongshore sea surface height difference between sensors 2 and 5,  $d\eta$ , on the reef flat.

#### **5.** Summary

This study focused on a large, shallow reef flat with a deep, narrow sandy channel located on the southeast coast of Guam. These reef flats are common in this part of Guam, and can be found in other parts of the world as well. Although past research on shallow reef flats finds that wave driven currents are predominantly in the cross-shore direction and are driven by cross-shore gradients in wave-driven setup, our study site is unique in that the mean currents are predominantly in the alongshore direction. These alongshore currents are wave driven, rather than being driven by wind or tides. Waves break over the reef flat, but do not break in the channel because the water there is very deep (30 m). Breaking waves over the reef flat create a wave driven setup, which in this case is uniform in the cross-shore direction. The difference in sea surface height between the wave-driven setup on the reef and the channel, where setup is low, is balanced by the bed-stress, or alongshore current.

Analysis of this balance between the sea surface height gradient and bed stress was done according to equation (5) using a quadratic friction law. Linear orthogonal regression analysis of the two terms in the equation gave a friction coefficient,  $C_r$  of approximately 0.0045. While this is an order of magnitude lower than similar studies done on wave driven currents over reefs [*Lowe et al.*, 2009b; *Taebi et al.*, 2011] it compares well with studies of momentum balance on sandy beaches [*Apotsos et al.*, 2007; *Feddersen et al.*, 1998; *Garcez Faria et al.*, 1998] and suggests that the reef at this study site may be smoother than other previously studied reef flats.

Water level effects on both the mean current and setup over the reef are extremely important. At low tides, reef circulation slows down dramatically as the still water level drops to zero, causing the pressure gradient term of equation (5) to decrease, and thus decreasing the velocity on the reef. The decrease in transport over the reef at low tides is also reflected in the channel velocity, which decreases at low tides, even during wave events. The alongshore pressure gradient is also affected by water level, with the highest values occurring during low tides due to more efficient breaking on the fore-reef. These competing water level effects are predicted in analytic studies, and have been validated in other locations as well [*Gourlay*, 1996; *Lowe et al.*, 2009b; *Vetter et al.*, 2010].

In this study an alongshore current is observed that, rather than being forced by alongshore radiation stress or wind, is forced by waves. This current, which is only present because of the deep channel in the reef, is forced at extremely far distances from the channel (up to 2km), which is remarkable given the relatively narrow width of the channel (30m). The dominant alongshore component of the current on the reef is in contrast to wave driven currents on other reefs, which are primarily in the cross-shore direction [*Hench et al.*, 2008; *Lowe et al.*, 2009b; *Taebi et al.*, 2011]. A numerical model does show alongshore currents over the reef flat at Ningaloo [*Van Dongeren et al.*, 2013] but these currents are primarily in the reef lagoon, as opposed to on the reef flat.

The Delft3D numerical model, a coupled WAVE and FLOW simulation, was able to capture the main features of the circulation. The model results showed alongshore currents on the reef flat that increased in strength closer to the channel, and with only a few small exceptions, constantly flowed towards the channel. There was a gradient in water level between the channel and the northern end of the reef flat, with the strength of the gradient being strongest closer to the channel, and weaker further from the channel. These results from the numerical model experiments, combined with our observations data, support the hypotheses regarding both primary force balance on the reef and the shape of the alongshore pressure gradient on the reef.

Comparison of model output of varying friction coefficients to the observations indicated that the estimation of friction in the observations experiment was likely fairly accurate. This shows that the Guam reef is likely simply smoother than other reefs previously studied, and helps explain the relatively high flow speeds observed on the reef. Additionally, based on these model runs, it seems that the friction coefficient may be key to setting the scale of influence of the channel. Model runs with low friction coefficients showed that currents on the reef flat were influenced by the channel as far as 2 km away, large compared to the size of the channel itself. These low friction, large scale of influence runs are consistent with the observations, which indicate that the alongshore current as far as 2.3 km away is effected by the channel, since the flow there is always directed towards the channel, regardless of wave conditions.

The currents on the reef and in the channel at Ipan, Guam are often very strong, and the area is well known to locals to be extremely dangerous to swimmers and fisherfolk. Through this analysis we have identified the two primary conditions for dangerous currents on the reef and in the reef channel: high tides and high waves. We have also shown that it is possible to develop a numerical model to predict relatively accurately the currents on both the reef flat and the channel. Additionally, we have established that in some cases, Google Earth images of fringing reefs show streamlines in the coral parallel to mean flow direction. Hopefully these tools will

help enable shallow reef flats such as the study site at Ipan, Guam to be managed in such a way so as to reduce the dangers of swimming or fishing there.

### Bibliography

Angwenyi, C. M., and L. Rydberg (2005), Wave-driven circulation across the coral reef at Bamburi Lagoon, Kenya, *Estuarine, Coastal and Shelf Science*, *63*(3), 447-454, doi:<u>http://dx.doi.org/10.1016/j.ecss.2004.12.008</u>.

Apotsos, A., B. Raubenheimer, S. Elgar, R. T. Guza, and J. A. Smith (2007), Effects of wave rollers and bottom stress on wave setup, *J. Geophys. Res.*, *112*(C2), C02003, doi:10.1029/2006jc003549.

Battjes, J. A., and J. P. F. M. Janssen (1978), Energy loss and set-up due to breaking of random waves, *Coastal Engineering Proceedings*, *1*(16), doi:10.9753/icce.v16.

Booij, N., R. C. Ris, and L. H. Holthuijsen (1999), A third-generation wave model for coastal regions: 1. Model description and validation, *Journal of Geophysical Research: Oceans*, *104*(C4), 7649-7666, doi:10.1029/98jc02622.

Chamberlin, C. (2008), A digital elevation model of Guam for tsunami inundation modeling, edited, p. 7, NOAA Pacific Marine Environmental Laboratory technical report, Seattle, WA.

Feddersen, F., R. T. Guza, S. Elgar, and T. H. C. Herbers (1998), Alongshore momentum balances in the nearshore, *J. Geophys. Res.*, 103(C8), 15667-15676, doi:10.1029/98jc01270.

Garcez Faria, A. F., E. B. Thornton, T. P. Stanton, C. V. Soares, and T. C. Lippmann (1998), Vertical profiles of longshore currents and related bed shear stress and bottom roughness, *J. Geophys. Res.*, *103*(C2), 3217-3232, doi:10.1029/97jc02265.

Gourlay, M. R. (1996), Wave set-up on coral reefs. 1. Set-up and wave-generated flow on an idealised two dimensional horizontal reef, *Coastal Engineering*, *27*(3–4), 161-193, doi:10.1016/0378-3839(96)00008-7.

Gourlay, M. R., and G. Colleter (2005), Wave-generated flow on coral reefs—an analysis for two-dimensional horizontal reef-tops with steep faces, *Coastal Engineering*, *52*(4), 353-387, doi:10.1016/j.coastaleng.2004.11.007.

Hearn, C. (1999), Wave-breaking hydrodynamics within coral reef systems and the effect of changing relative sea level, *J Geophys Res-Oceans*, *104*(C12), 30007-30019.

Hearn, C., M. Atkinson, and J. Falter (2001), A physical derivation of nutrient-uptake rates in coral reefs: effects of roughness and waves, *Coral Reefs*, *20*(4), 347-356, doi:10.1007/s00338-001-0185-6.

Hench, J. L., J. J. Leichter, and S. G. Monismith (2008), Episodic circulation and exchange in a wave-driven coral reef and lagoon system, *Limnol Oceanogr*, 53(6), 2681-2694.

Inman, D. L., W. R. Gayman, and D. C. Cox (1963), Littoral sedimentary processes on Kauai, a subtropical high island.

Kohn, A. J., and P. Helfrich (1957), Primary organic productivity of a Hawaiian coral reef, *Limnol Oceanogr*, 241-251.

Kraines, S. B., T. Yanagi, M. Isobe, and H. Komiyama (1998), Wind-wave driven circulation on the coral reef at Bora Bay, Miyako Island, *Coral Reefs*, *17*(2), 133-143, doi:10.1007/s003380050107.

Lesser, G. R., J. A. Roelvink, J. A. T. M. van Kester, and G. S. Stelling (2004), Development and validation of a three-dimensional morphological model, *Coastal Engineering*, *51*(8–9), 883-915, doi:<u>http://dx.doi.org/10.1016/j.coastaleng.2004.07.014</u>.

Lesser, M. P., V. M. Weis, M. R. Patterson, and P. L. Jokiel (1994), Effects of morphology and water motion on carbon delivery and productivity in the reef coral, Pocillopora damicornis (Linnaeus): Diffusion barriers, inorganic carbon limitation, and biochemical plasticity, *Journal of Experimental Marine Biology and Ecology*, *178*(2), 153-179, doi:10.1016/0022-0981(94)90034-5.

Longuet-Higgins, M. S. (1970), Longshore Currents Generated by Obliquely Incident Sea Waves, 1, *J. Geophys. Res.*, 75(33), 6778-6789, doi:10.1029/JC075i033p06778.

Longuet-Higgins, M. S., and R. W. Stewart (1964), Radiation stress in water waves, a physical discussion with applications, *Deep Sea Research*, *11*, 529-563, doi:citeulike-article-id:6353848.

Lowe, R. J., J. L. Falter, S. G. Monismith, and M. J. Atkinson (2009a), A numerical study of circulation in a coastal reef-lagoon system, *Journal of Geophysical Research: Oceans*, *114*(C6), n/a-n/a, doi:10.1029/2008jc005081.

Lowe, R. J., J. L. Falter, S. G. Monismith, and M. J. Atkinson (2009b), Wave-Driven Circulation of a Coastal Reef–Lagoon System, *Journal of Physical Oceanography*, *39*(4), 873-893, doi:10.1175/2008jpo3958.1.

Lucas, D. L., and J. M. Lincoln (2010), The Impact of Marine Preserve Areas on the Safety of Fishermen on Guam *Rep.*, Centers for Disease Control & Prevention, National Institute for Occupational Safety & Health, Honolulu, HI.

Luo, Q. C., and S. Khosrowpanah (2012), Continuing calibration and application of LUOM in the southern guam watersheds, Technical Report No. 131, edited, Water and Environmental Research Institute of the Western Pacific, University of Guam.

Marsh, J. A., R.M. Ross and W.J. Zolan (1982), Water circulation on two Guam reef flats, *Proceedings of the 4th Interna. Marine Science Center, Univers. E.D. Gomez, C.E. Birkeland, R. 1*, 355-360.

Monismith, S. (2007), Hydrodynamics of Coral Reefs, *Annu. Rev. Fluid Mech.*, *39*, 37-55, doi:citeulike-article-id:6354730.

Nelson, R. C. (1987), Design wave heights on very mild slopes—an experimental study, *Transactions of the Institution of Engineers, Australia. Civil engineering*, *29*(3), 157-161.

Nelson, R. C. (1994), Depth limited design wave heights in very flat regions, *Coastal Engineering*, 23(1–2), 43-59, doi:<u>http://dx.doi.org/10.1016/0378-3839(94)90014-0</u>.

Nelson, R. C. (1997), Height limits in top down and bottom up wave environments, *Coastal Engineering*, *32*(2–3), 247-254, doi:<u>http://dx.doi.org/10.1016/S0378-3839(97)81752-8</u>.

Pawlowicz, R., B. Beardsley, and S. Lentz (2002), Classical tidal harmonic analysis including error estimates in MATLAB using T\_TIDE, *Comput. Geosci.*, *28*(8), 929-937, doi:10.1016/s0098-3004(02)00013-4.

Péquignet, A. C., J. Becker, M. Merrifield, and S. Boc (2011), The dissipation of wind wave energy across a fringing reef at Ipan, Guam, *Coral Reefs*, *30*(0), 71-82, doi:10.1007/s00338-011-0719-5.

Presto, M. K., A. S. Ogston, C. D. Storlazzi, and M. E. Field (2006), Temporal and spatial variability in the flow and dispersal of suspended-sediment on a fringing reef flat, Molokai, Hawaii, *Estuarine, Coastal and Shelf Science*, *67*(1–2), 67-81, doi:10.1016/j.ecss.2005.10.015.

Symonds, G., K. P. Black, and I. R. Young (1995), Wave-driven flow over shallow reefs, *J. Geophys. Res.*, *100*(C2), 2639-2648, doi:10.1029/94jc02736.

Symonds, G., L. J. Zhong, and N. A. Mortimer (2011), Effects of wave exposure on circulation in a temperate reef environment, *J Geophys Res-Oceans*, *116*, doi:Artn C09010 Doi 10.1029/2010jc006658.

Taebi, S., R. J. Lowe, C. B. Pattiaratchi, G. N. Ivey, and G. Symonds (2012), A numerical study of the dynamics of the wave-driven circulation within a fringing reef system, *Ocean Dynam*, *62*(4), 585-602, doi:10.1007/s10236-011-0514-4.

Taebi, S., R. J. Lowe, C. B. Pattiaratchi, G. N. Ivey, G. Symonds, and R. Brinkman (2011), Nearshore circulation in a tropical fringing reef system, *J. Geophys. Res.*, *116*(C2), C02016, doi:10.1029/2010jc006439.

Van Dongeren, A., R. J. Lowe, A. Pomeroy, D. M. Trang, D. Roelvink, G. Symonds, and R. Ranasinghe (2013), Numerical modeling of low-frequency wave dynamics over a fringing coral reef, *Coastal Engineering*, *73*(0), 178-190, doi:http://dx.doi.org/10.1016/j.coastaleng.2012.11.004.

Vetter, O., J. M. Becker, M. A. Merrifield, A. C. Pequignet, J. Aucan, S. J. Boc, and C. E. Pollock (2010), Wave setup over a Pacific Island fringing reef, *J. Geophys. Res.*, *115*(C12), C12066, doi:10.1029/2010jc006455.

Wainwright, S. A., and M. A. R. Koehl (1976), *The nature of flow and the reaction of benthic cnidaria to it*, Plenum Press, New York.