FIELD OBSERVATIONS OF SETUP OVER TWO FRINGING REEFS:

IPAN REEF, GUAM AND MOKULE'IA REEF, HAWAI'I

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This work is dedicated to Ida, who made Dad.
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Abstract

Wave and water level observations from Ipan, Guam (July 2006) and Mokule’ia, Hawai’i (April 2004) are used to examine wave-driven setup over fringing reef systems. The Ipan reef is a wide (530 m), shallow (0.5 m) fringing reef with a flat, relatively smooth (<0.1 roughness scale) and featureless platform and an almost vertical reef face. In comparison, the Mokule’ia reef is narrower (~100 m), rougher (vertical scales ~0.5 m), and deeper (1.2 m) than Ipan, with a gently sloping (0.88°) reef face consisting of rugged spur and groove topography. Observed incident swell peaked at 2.5 m significant wave height at Ipan, and 4 m at Mokule’ia. Wave breaking occurs at the reef edge at Ipan, and over a broader surf zone Mokuleia. Wave breaking and bottom friction result in negligible swell amplitudes at the shoreline (<90% of offshore levels). Average (15 minute mean) water levels on both reefs are highly correlated (>0.96) with offshore $H_{sig}$. Setup at Ipan is uniform across the reef, and scales as $\sim 0.38 H_{sig}$, approximately twice as high as reported over sand bottom beaches and other reefs. Setup at Mokule’ia is roughly three times ($\sim 0.11 H_{sig}$) lower than Ipan for a given incident wave height. The dynamics of setup are well described by the traditional balance of the radiation stress gradient and the cross-shore pressure gradient observed on sand beaches. Because wave breaking occurs almost exclusively at the reef edge, and because the reef platform is smooth, friction appears to play a negligible role in the setup balance at Ipan. Bottom friction can also be neglected in the setup balance at Mokuleia; however, frictional dissipation is not entirely discounted given the weak setup amplitudes. Changes in tidal height over the reefs of 0.5 – 1 m result in weak (5%) modulations of the nearshore setup.
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1. Introduction

The coastal regions of Pacific Islands are particularly vulnerable during storm events. Shoreline sea level rise, due to offshore wave inundation, increases this vulnerability and many coastal communities are subject to regular flooding, causing hazardous conditions for island communities and shoreline infrastructure. Hazard scenarios for continental coastlines have been widely studied and refined; however, these are often inapplicable to island systems [Garcia 2003]. For example, evacuation to higher ground may not be an option for island inhabitants due to the lack of infrastructure and/or geographical limitations. In addition, the applicability of wave-driven inundation models developed for wide sand beaches has not been well-established for steep island coasts. The Pacific Islands Land-Ocean Typhoon Experiment (PILOT), sponsored by the US Army Corps of Engineers, was designed to develop and refine predictive models of coastal flooding along island shorelines due to storm waves and elevated sea levels associated with typhoons. Because many of these coastlines include shallow fringing reefs, an understanding of large wave transformation over this substrate is fundamental for the development of predictive models.

An important component of a runup inundation model is the wave-driven water level change at the shoreline, or, wave setup. Early reports of wave setup were made by Munk and Sargent [1948] based on visual observations at a Bikini Atoll reef. Longuet-Higgins and Stewart [1962, 1963, 1964] theorized that cross-shore slopes in the mean water level through the surf zone balance the cross-shore gradient of the wave momentum flux, or, radiation stress. Measurements over a variety of sand beaches have validated the dominant balance; however, few direct observations of setup are available over fringing reef environments.
This work investigates wave-driven setup at two fringing reefs as part of the PILOT experiment. The study sites are Ipan reef on the east coast of Guam, and Mokule‘ia reef on the north shore of Oahu, Hawai‘i. The two field studies provide an opportunity to test setup theory for reefs with significantly different geomorphologies and roughness scales. In addition, we examine whether setup over these reef platforms differs from setup observed over sand beach environments. We analyze one month of data collected from Ipan Reef in July 2006 when an incident swell event of 2.5 m significant wave height \( (H_{\text{sig}}) \) occurred, and a two-week deployment from Mokule‘ia Reef in March and April 2004, which included a 4 m \( H_{\text{sig}} \) event.

Our findings from both reefs show that setup is highly correlated with offshore wave height; setup over the Ipan reef is approximately twice as high for given offshore \( H_{\text{sig}} \) compared to results obtained for gently sloping sand beaches [Guza and Thornton 1981]. Setup at Ipan reef is uniform across the width if the reef due to wave breaking occurring primarily at the reef edge with wave bore energy decaying within 40 m landward of the break point. The Longuet-Higgins and Stewart [1962] setup balance appears to account for the observed setup without the need for friction terms; and strong wave driven onshore flows on the reef appear to have little influence on the observed setup.

Setup elevation at Mokule‘ia is approximately half the magnitude of that found at Ipan for similar incident wave energy; however the radiation stress balance over the reef at Mokule‘ia is also well modeled using Longuet-Higgins and Stewart’s [1962] balance without the use of frictional dissipation. This is done using a reduced
breaking coefficient $H_{bg}/d = 0.45$, [Raubenhemier 2001]. We present a hypothesis to explain this phenomenon using the theory of undertow [Apostos et al. 2005]. The more gradual reef slope at Mokule'ia causes a significant cross-shore variation in break point, dependent on wave height; analysis of various linear wave models highlights the physical differences between these two reefs.

The paper is organized as follows. In section 2, previous studies of wave-driven setup are summarized, beginning with the basic wave setup balance that was developed for two-dimensional, sand bottom beaches. This is followed by a review of wave and setup studies made over reefs. The Ipan experiment is described and observed and predicted setup, based on the setup equation of Longuet-Higgins and Stewart, are compared in section 3. Wave-driven currents on and off Ipan Reef are also examined. In section 4, the Mokule'ia experiment is described, and observed and predicted setup are evaluated. Setup over the two reefs are compared in section 5, including a discussion of the relative importance of friction in the momentum balance. A summary follows in section 6.
2. Background

2.1. Setup: Theory and Observations

The theoretical framework for wave setup was established by Longuet-Higgins and Stewart [1962] who examined the steady cross-shore momentum balance over a two-dimensional planar beach. Neglecting flow accelerations, alongshore pressure gradients, and surface and bottom stresses, a steady balance is reached between the cross-shore pressure gradient and the cross-shore gradient of the radiation stress, $S_{xx}$.

\[
\frac{\partial \eta}{\partial x} = -\frac{1}{\rho g (\eta + h)} \frac{\partial S_{xx}}{\partial x} \tag{2.1}
\]

where $\eta$ is the time-averaged sea surface elevation anomaly, $h$ is the water depth, and $x$ is the cross-shore coordinate. The radiation stress is the depth-integrated, time-averaged, cross-shore component of the horizontal momentum flux associated with the waves [Longuet-Higgins and Stewart, 1962]. $S_{xx}$ is related to the wave energy density ($E$) by

\[
S_{xx} = E \left( \frac{2kh}{\sinh 2kh} + \frac{1}{2} \right) \tag{2.2}
\]

where $k$ is the dominant wavenumber, and $E$ is given by

\[
E = \frac{1}{8} \rho g H_{rms}^2 \tag{2.3}
\]
where \( \rho \) is the water density and \( H_{rms} \) is the root mean squared wave height \([\text{Longuet-Higgins and Stewart 1964}]\). The radiation stress is the wave equivalent of the Reynolds stress that is used to describe the momentum transfer between turbulent motions and lower frequency flows. Integrating equation (2.1) across shore gives the sea level relative to an offshore level \( \bar{\eta}_s \)

\[
\bar{\eta}_e - \bar{\eta}_s = \int_{x_0}^{x} \frac{1}{\rho g (\bar{\eta} + h)} \frac{\partial S_{xx}}{\partial x'} dx'
\]  

(2.4)

In practice, the solution of equation (2.4) requires a specification of \( H_{rms} \) as a function of \( x \), or \( h \) for monotonic beach slopes. \textit{Longuet-Higgins and Stewart} [1962] suggested a wave energy saturation approach in the surf zone whereby the wave height (\( H \)) is limited by the water depth,

\[
H = \gamma h
\]

(2.5)

where \( \gamma \) is referred to as a similarity parameter.

\textit{Bowen et al.} [1968] examined changes in \( S_{xx} \) across the outer and inner surf zone regions, separated by the wave break point. In the outer region, wave energy flux, \( EC_g \) is conserved. As the group velocity, \( C_g \) decreases as the waves shoal prior to breaking, the radiation stress increases leading to negative setup (set-down) of the water. In the inner region, radiation stress gradients are at a maximum as wave energy decreases due to breaking, resulting in positive sea surface gradients toward
shore and setup. Bowen et al. [1968] verified the presence of the setup and setdown regions using laboratory experiments. Bowen et al. [1968] found equation (2.5) to agree with laboratory experiments, and the similarity approach has been used in a number of studies based on field observations [e.g., Bowen et al., 1968; Thornton and Guza, 1981; Nielsen, 1988].

Hansen [1978] used field measurements from a German beach in the North Sea to highlight the significance of wave setup in the design of coastal structures. Hansen found that wave setup is dependent on significant wave height \( (H_{sk}) \) and local water depth and, in agreement with Bowen et al. [1968], noted that the slope of setup increases with increasing bottom slope. He observed that setup can reach values up to 30% of the offshore wave height.

Guza and Thornton [1981] evaluated equation (2.1) using field measurements on a gently sloping sandy beach at Torrey Pines, CA. The mean water level was measured using dual resistance nichrome wire at the shoreline and pressure sensors offshore, with atmospheric pressure removed using barometer readings. Inside the surf zone, they observed that setup is related to offshore wave height, with a regression of \( \bar{y} = 0.17 H_{sk} \). They found that constant setup slope through the surf zone was consistent with equation (2.1), but not a slope increase at the shoreline. A similar setup increase at the shoreline was observed in the laboratory experiments of Bowen et al. [1968].

Thornton and Guza [1983] modeled the transformation of a distribution of wave heights, and showed that the Rayleigh distribution is a good model for observed wave
heights in the surf zone. To calculate wave breaking dissipation, they concluded that the distribution of breaking waves is expressed by a weighting $W(H)$ of the Rayleigh distribution of all waves, including a skewing factor that preferentially dissipates the larger waves in the distribution. For straight, parallel wave contours they proposed an energy balance given by

$$\frac{\partial EC_s}{\partial x} = -(\varepsilon_j + \varepsilon_b) \tag{2.6}$$

where $\varepsilon_j$ is the energy dissipation due to bottom friction given by

$$\varepsilon_j = \frac{1}{16\sqrt{\pi}} \rho c_f \left( \frac{2\pi \bar{f} H_{rms}}{\sinh(\bar{h}k)} \right)^3 \tag{2.7}$$

where $c_f$ is the bed friction coefficient and $\bar{f}$ is the peak spectral frequency. The dissipation due to wave breaking, $\varepsilon_b$, is given by,

$$\varepsilon_b = \frac{3}{16} \sqrt{\pi \rho g B^3 \bar{f}^2 H_{rms}^2} \left( 1 - \frac{1}{\left(1 - (H_{rms} / \bar{h})^2 \right)^{2.5}} \right) \tag{2.8}$$

where $B$ is an empirically determined breaker coefficient that represents the portion of wave face that has broken giving a value for the intensity of wave breaking. With bottom friction shown to be unimportant, $B$ was the only adjustable parameter in the model. Best agreement with the observations was found using a $B$ value substantially larger than the empirical value.
Dally et al. [1985] used linear wave theory to develop analytical setup solutions for various beach profiles and compared these with laboratory data from Horikawa and Kuo [1966] and Bowen et al [1968]. Dally et al [1985] modeled the setup across the surf zone using equation (2.1) under the assumption that the rate of wave energy dissipation is given by the difference between a local and a “stable” energy flux to which the broken waves evolve. They found good agreement between predicted and observed wave decay, and poor agreement in setup distribution across the shore. Dally et al [1985] observed that bottom friction was insignificant over steep beach slopes and hence equation (2.5) was a valid assumption; over mild slopes or over rough topography equation (2.5) was not consistent with the measurements, presumably due to the neglect of bottom friction.

Holman and Sallenger [1985] examined setup from laboratory tests and a field experiment at Duck, NC. Runup data were obtained using digitized time-lapse photography. They separated their results into low, mid and high tidal stages. They proposed that the shoreline setup $\eta_{\text{shore}}$ increased with increasing Irribarren number $\xi_0$, given by

$$
\xi_0 = \beta \sqrt{H_{\text{sig},0}/L_o} \quad (2.9)
$$

where $\beta$ is the beach slope, $L_o$ is the offshore wavelength, and $H_{\text{sig},0}$ is the offshore significant wave height. No single value of $\beta$ accounted for setup under all incident wave conditions. The foreshore $\beta$ was found to give the best fit to runup data under
most conditions, but during low tide, the slope of an offshore sand bar gave a better fit than the foreshore slope.

*Holland et al.* [1995] used video imaging, resistance wires from five locations and pressure sensors in the inner surf zone to study the runup on a natural beach at La Jolla, CA. *Holland et al.* [1995] observed that runup was dominated by energy in the infragravity band (defined as $f < 0.05 \, \text{Hz}$) due to the dissipation of incident swell. Infragravity standing wave patterns were evident.

*Raubenheimer et al.* [2001] used a 3-month dataset from 12 buried pressure sensors between the shoreline and 5m depth to observe setup and setdown at a Duck, NC barred beach as part of the Sandy-Duck experiment. *Raubenheimer et al.* [2001] solved equation (2.5) iteratively taking into account the effects of total water depth on group velocity. They found that the relationship between $\eta_{\text{shore}}$ and $H_{\text{offshore}}$ to be significantly scattered, with a least squares fit regression of $a = 0.2 - 0.3$, concluding that realistic topography is needed to model setup across a natural beach. Predicted and observed setup/setdown agreed well in the outer and middle surf zone, but predicted setup under-estimated the observations in the inner surf zone near the shore. Setup was found to be particularly sensitive to tidal fluctuations. *Raubenheimer et al.* [2001] developed an empirical formula for the shoreline setup on nonplanar beaches that incorporates the dependence of the beach slope. She found that setup increases with decreasing surf-zone averaged beach slope, $\beta_{av} = h_{av}/\Delta x$. A new empirical formula was proposed that includes setup dependence on $\beta_{av}$ as

$$\frac{\eta_{\text{shore}}}{H_{s,0}} = 0.019 + 0.003\beta_{av}^{-1}$$  \hspace{1cm} (2.10)
where $\bar{\eta}_{\text{shore}}/H_{s,0}$ is the ratio of setup at the shoreline to offshore significant wave height.

*Ruggiero et al.* [2004] used pressure sensors and video imaging techniques to measure setup and the vertical excursion about this setup (runup or swash) on a dissipative beach in Oregon. They observed the importance of the infragravity band ($f < 0.05$ Hz) to runup on strongly dissipative beaches as well as the dependence of runup on beach slope. The infragravity band was on average responsible for 96% of the runup elevation.

*Stockdon* [2006] examined wave and water level data from 10 experiments from California, Oregon, North Carolina and the Netherlands. The relationship

$$\bar{\eta}_{\text{shore}} = aH_{\text{sig}}$$

does not agree well with the combined dataset (correlation squared $r^2 = 0.3$). They proposed a linear relationship that includes bottom slope

$$\bar{\eta}_{\text{shore}} = 0.35\beta(H_0L_0)^{1/2}$$  \hspace{1cm} (2.11)

where $H_0$ and $L_0$ are deepwater wave height and wavelength, respectively. The correlation squared between equation (2.11) and observed $\bar{\eta}$ was low at lower tidal heights ($r^2 = 0.29$), and higher at mid and high tides ($r^2 = 0.52$).

*Garcez-Faria et al.* [2000] included wave rollers (the turbulent, shoreward propagating broken wave) and undertow in equation (2.1)
\[
\frac{\partial \eta}{\partial x} = -\frac{1}{\rho g (\eta + h)} \left( \frac{\partial S_{ax}}{\partial x} + \frac{\partial S_{ay}}{\partial y} + \frac{\partial M_c}{\partial x} + \frac{\partial \rho U_r^2 (\eta + h)}{\partial x} \right) \quad (2.12)
\]

where \( M_c = cq \) is the momentum flux associated with wave rollers and
\( \frac{\partial \rho U_r^2 (\eta + h)}{\partial x} \) is the momentum flux of the depth-averaged current, including the undertow \( U_r \). The addition of the roller parameter redistributes the momentum, shifting the transition point from setdown to setup further offshore. They found that using nonlinear theory to calculate radiation stress, rather than linear theory, had no significant effect on the cross-shore setup profile.

\textit{Apostos et al.} [2006] used observations from a field experiment in Duck NC to assess the importance of bottom friction and undertow in predicting setup over a barred beach. They found that equation (2.1), without the inclusion of bottom stress, underestimated the observed setup at all water depths, particularly at the shoreline. Including the roller model does not account for the underestimate of setup. \textit{Apostos et al.} (2006) extended equation (2.12) to

\[
\frac{\partial \eta}{\partial x} = -\frac{1}{\rho g (\eta + h)} \left( \frac{\partial S_{ax}}{\partial x} + \frac{\partial S_{ay}}{\partial y} + \tau_x + \tau_y + \frac{\partial \rho U_r^2 (\eta + h)}{\partial x} - \frac{\partial \rho U_r^2 (\eta + h)}{\partial y} \right) \quad (2.13)
\]

where the added terms are \( S_{ax} \) the alongshore radiation stress, \( \tau_b \) the bottom stress, \( \tau_w \) the wind stress, and \( fU \) the Coriolis acceleration. Equation (2.13) yielded a better agreement between the predicted and observed setup because of the inclusion of the \( \tau_b \) term. As found previously, rollers have little effect on the estimate. The other
12

terms were also estimated to play a small roll in the overall balance.

2.2 Reef Studies

Munk and Sargent [1948] reported a super-elevated mean sea level over a reef flat, based on an aerial survey of Bikini Atoll. They noticed that the mean water level just inside the surf zone was ~ 0.5 m higher than the still water level inside the lagoon. They concluded that not all wave energy was dissipated by friction and wave breaking, and estimated that 5% of the wave energy is converted into potential energy to account for the local rise in mean sea level. Munk and Sargent observed that the spacing of the spur and groove morphology of the outer reef had the same wavelength as the dominant, wind-driven waves of frequency 0.125 Hz. These grooves and ‘buttresses’ were distributed around the island in a way that conforms to the local wave activity, acting as a natural breakwater from the heavy sea conditions.

Motivated by these observations, Tait [1972] examined an experimental reef system to compare to Munk and Sargent’s setup observations at Bikini Atoll. He also examined the wave induced flushing of a lagoon fronted by a fringing reef on Kauai, HI. He obtained predictions of $\eta_{\text{shore}} = 0.2H_{\text{offshore}}$ based on the equations derived by Bowen’s [1968] laboratory experiments. Tait integrated from deep water to the top of the reef face using the integrated solution

$$\eta_b = \frac{1}{8} \frac{\gamma^2 h_b^3 k}{\sinh(2kh_b)}$$

(2.14)

where $\eta_b$ is the setup/down at the point of breaking and $h_b$ denotes the depth where
waves first begin to break.

Roberts, Murray and Suhayda [1975] used data collected from a fringing reef on the Grand Cayman Island. The field experiment included a dense instrument array with deep water drogues, wave sensors, current meters, an anemometer, and a tide gauge. Bottom roughness scales were assumed to be approximately 10 times that of a sandy bottom. Wave heights decreased by 75% from the fore reef into the lagoon. Lagoon flushing and cross-reef flow were reported to be driven by wave breaking and setup, although there were no direct measurements of setup mentioned. The spur and groove morphology of the reef had a significant effect on the current and wave field, with high bottom roughness causing significant current attenuation on the reef (50% decrease). Using a variance spectrum of the bathymetry to measure bottom roughness, they concluded that higher (lower) energy wave regions had developed longer (shorter) wavelength spur and groove.

Kono and Tsukayama [1980] conducted field measurements in the Okinawa Islands using four surface-tracing wave meters. Predictions based on an experimental laboratory model were compared to field observations. The bottom friction coefficient was estimated to be two orders of magnitude higher than laminar flow theory. Bottom friction appeared to be more effective in damping wave heights at low tide than at higher tides.

Gerritsen [1981] conducted a study of breaking waves, energy dissipation and wave setup across coral reefs. He included a field experiment at the 200 m wide fringing reef at Ala Moana, Oahu, HI. Waves were measured at seven stations across the reef.
using capacitance wave recorders. Wave setup was recorded from the mean value of the time series from manometer readings. Radiation stress was calculated from linear theory and the differential equation (2.1) was integrated between the edge reef station and the most nearshore station (where energy was assumed zero). Using the maximum mean wave height from the reef edge sensor, wave height was assumed to be related to water depth by $H_m = 0.8 h_b$. The maximum observed rms wave height was 0.69 and the setup was ~ 0.037 m. Maximum observed setup was 0.107 m. Runup was found to be of similar magnitude to the setup in this area. These values were spot samples throughout the day rather than averages; however, it was noted that the measured setup values showed only small variations over a tidal cycle.

Gourlay [1993] observed that setup over a reef, on the Great Barrier Reef (GBR), occurs regardless of the presence of a beach. Symonds et al. [1995] examined this effect by adding bottom friction to the cross-shore momentum balance,

$$\frac{\partial \eta}{\partial x} = \frac{1}{\rho g (\eta + h)} \left( \frac{\partial S_{xx}}{\partial x} - r U \right)$$  \hspace{1cm} (2.15)

where $r$ is a friction constant, and $U$ is the depth-averaged velocity Symonds et al. [1995] noted that over a shallow, flat, offshore reef (John Brewer reef, GBR) there is no current forcing due to wave breaking and current is forced by the pressure gradient caused by the setup gradient. Their solutions converged to a plane beach [Longuet-Higgins and Stewart 1964], with maximum setup when the depth on the reef and the cross-reef transport are zero.

Hardy and Young [1996] conducted a field experiment at John Brewer Reef, GBR,
AUS. They observed that significant wave height on the reef was limited by water depth \( H_{sig} < 0.4 h \). Their study showed significant change in the wave spectra with attenuation over the reef, with significant losses in the peak swell band due to wave breaking and bottom friction.

*Lugo-Fernandez et al.* [1998] conducted three experiments at a ‘fringing-barrier’ coral reef in the Caribbean. Tidal height significantly affected the wave energy reduction, with 15% greater dissipation at low tide than high tide. Both wave breaking and wave dissipation by bottom friction were considered important factors in the modeling of wave height through the surf zone. Wave heights were low \( H_{sig} < 0.41 \text{ m} \) throughout this experiment. The wave transmission coefficient \( K_T \) [*Nelson and Lesleigher 1985*] was defined as the ratio of the significant wave height at the backreef \( H_L \) and forereef \( H_F \):

\[
K_T = \frac{H_L}{H_F} \tag{2.16}
\]

*Lugo-Fernandez et al.* [1998] showed that \( K_T \) is tidally modulated even with small tidal ranges and wave heights. Wave height attenuation was predicted using the model of Thornton and Guza [1983] and the steady wave equation (2.9). The model estimated that wave breaking \( (\epsilon_b) \) was the dominant wave dissipation process within 30m landward of the reef crest; bottom friction \( (\epsilon_f) \) dominated outside of this region. Their model estimates of wave height agreed with observations to within 20%.

*Massel and Gourlay* [2000] evaluated an extended refraction/diffraction equation to predict wave-breaking and setup on various two-dimensional reef topographies, and
in particular considered a fringing reef in Guam, although it wasn't clear which reef on Guam was considered. Their model used an offshore wave height of 5m and a period of 10 seconds and found that setup rises rapidly in front of the reef crest to \( \bar{\eta}_{\text{shore}} = 0.64 \) m and does not appreciably change over their idealized lagoon until wave breaking at the shoreline increases the value to a maximum of \(-0.7\).

**Lowe et al. [2005]** performed a field study of wave breaking and attenuation on a fringing reef with mild fore reef slope at Kaneohe, Hawai‘i. They concluded, similar to **Lugo-Fernandez et al. [1998]**, that bottom friction is the primary dissipation process on a fringing reef under relatively small wave conditions. Using a similar model to that of **Thornton and Guza [1983]**, they estimated that 80% and 20% of the observed dissipation are due to bottom friction and wave breaking, respectively, for small wave conditions \((H_{\text{rms}} = 0.6 \text{ m})\), 60% / 40% for average conditions \((H_{\text{rms}} = 0.95 \text{ m})\), and 30/70% for large wave conditions \((H_{\text{rms}} > 1.6 \text{ m})\). **Lowe et al** suggested that under large wave conditions there is a regime change in the wave dissipation mechanism and wave breaking becomes the dominant process.
Table 1. Summary of reef field studies that have included an evaluation of wave transformation.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Instruments</th>
<th>Study Area</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Munk and Sargent [1948]</td>
<td>Aerial photographs</td>
<td>Bikini Atoll</td>
<td>Increase in sea level on the reef of 0.4-0.6 m</td>
</tr>
<tr>
<td>Roberts et al. [1975]</td>
<td>Pressure sensors, wave drogues</td>
<td>Caribbean</td>
<td>75% decrease in wave energy and 50% decrease in current flow due to enhanced bottom roughness</td>
</tr>
<tr>
<td>Koso and Tsukayama [1980]</td>
<td>Surface tracing wave meters</td>
<td>Busena Coast, Okinawa</td>
<td>Bottom friction important, and increases at low tide.</td>
</tr>
<tr>
<td>Gerritsen [1981]</td>
<td>Capacitance gauges and tide recorders</td>
<td>Ala Moana, Hawai'i</td>
<td>Linear theory agrees with observed setup.</td>
</tr>
<tr>
<td>Young [1989]</td>
<td>Pressure sensors</td>
<td>Yonge Reef, GBR, AUS</td>
<td>Agreement with Gerritsen: $dF/dx=-(ef+e_b)$</td>
</tr>
<tr>
<td>Hardy and Young [1996]</td>
<td>Wave staffs</td>
<td>John Brewer Reef, GBR, AUS</td>
<td>Significant loss of swell energy over the reef. Wave height on the reef is limited to 0.4 times h.</td>
</tr>
<tr>
<td>Lugo-Fernandez et al. [1998]</td>
<td></td>
<td>Caribbean Islands</td>
<td>Wave breaking dominant 30 m from reef face, dissipation dominant thereafter.</td>
</tr>
<tr>
<td>Lowe et al. [2005]</td>
<td>Pressure sensors</td>
<td>Kaneohe, HI</td>
<td>Frictional dissipation important for small to medium size waves, wave breaking dominant for large waves</td>
</tr>
</tbody>
</table>
3. The Ipan Reef Experiment

3.1 The Study Site

The region of interest is Ipan Reef on the east side of Guam, the southern most Marianas Island in the western Pacific (Figure 3.1). A cross-shore instrument array was deployed (Figures 3.1 and 3.2) and a Datawell directional waverider buoy was deployed approximately 1.2 km southeast of our instrument transect by the California Data Information Program (CDIP) (Figure 3.1).

Figure 3.1. Location of the Marianas chain and map of Guam showing PILOT transect site and CDIP Directional Waverider Buoy.
South of the instrument transect the reef top slopes downward slightly and widens cross-shore by ~100 m. Approximately 800 m south of the transect is a deep, cross-shore gully formed by riverine outflow (Figure 3.3). A strong southward alongshore flow, toward this gully, was observed on the reef during the instrument deployments suggesting the gully has a significant effect on the water-mass movement over the reef flat. The reef pavement is smooth with roughness scale of order 0.1 m (Figure 3.4). The mean water depth over the reef is ~ 0.5 m. The reef top is completely exposed at the lowest excursion of spring tides (Figure 3.4). This low tide period is particularly well-suited for instrument deployments and recoveries. There is little loose coral, rubble and few significant roughness features on the reef flat. There are sporadic single boulders (~ 1 m³, Figure 3.4) that showed no evidence of movement over the course of the study. The macrofauna is primarily low-lying algae, adapted for high-energy environments near the reef edge.
Figure 3.3. Satellite image of Guam overlain on the Shoals bathymetry

Figure 3.4. Ipan Reef substrate at low tide alongshore (a), view of entire reef width, showing sporadic rocks (b) and reef edge exposure and roughness (c).

The cross-shore instrument transect (Figure 3.3) is fronted by a steep reef face, which drops approximately 5m, before deepening more gradually offshore with a bottom slope of $\sim 1/20$. Roughness scales increase significantly just offshore of the reef face (Figure 3.5). The offshore substrate consists of vertical coral walls and steep spur and groove topography with $\sim 5$ m vertical scales. Large (0.5 - 2 m) calcium carbonate boulders lie within the grooves (Figure 3.5). The offshore reef is biologically diverse with densely populated, low-lying corals, indicative of a high wave-energy
environment. Within 500 m to the south of the instrument transect there is a large semi-circular offshore shoal 200 m in diameter, rising from 20 m depth to the reef face (5 m) (Figure 3.6)

Although the reef face is steep, incident wave reflections were not observed visually during the weak to moderate wave conditions. Instead, visual observations at the site revealed a large number of fissures, caves, and holes that allowed wave energy to pass into and ‘under’ the reef platform for approximately 30 m landward of the reef edge. Wave-forced bursts of water through the fissures in the top of the reef were observed (Figure 3.7). The percolation effect is thought to contribute to the wave dissipation at the reef edge.

Figure 3.5. Offshore roughness scales are evident, with divers swimming over a typically sized boulders within the spur and groove bathymetry. The photo was taken from a fissure under the reef flat, looking seaward.
Figure 3.6. A perspective view of the Ipan Reef bathymetry that emphasizes the widening of the reef face topography just south of the instrument transect. Figure courtesy of Tyson Hilmer using Shoals Bathymetry data.

Figure 3.7. As small waves break at the reef edge, water is forced into the porous reef substrate and upward through fissures on the reef flat. These fissures were widespread on the reef platform within 30m of the reef edge.

3.2 Methods

The measurements used in this study were collected in July 2006. This period was chosen because two moderately high wave events occurred during July, and the sensor sampling was nearly continuous during this deployment. Offshore wave conditions were measured in 200 m water depth with a Datawell directional wave buoy. The Datawell directional wave buoy, 1200 m east of the array in 200 m water depth, sampled at 1 Hz and recorded 30 minute averages of deepwater wave height
and direction.

A mile south of the instrument array, a video camera captured images across the reef at 1 Hz [Hilmer, 2006]. The camera station was at a seaside resort where power and a high mount for the camera were available (no coastal structures exist at the instrument array). Although the camera did not sample the conditions at the instrument array, the two sites have similar topographies and reef flat water depths. We treat the video measurements as being representative of breaking wave conditions at the study site.

The cross-shore instrument array consisted of Seabird pressure sensors (SBE 26+ wave and tide recorders) and Aquadopp current profilers (AQD) (Figure 3.2). Seven pressure sensors and current profilers were attached to the reef flat, a current meter and pressure sensor were placed offshore in mean depths of 6 m and 8 m, respectively, and a pressure sensor was buried at the crest of the beach to capture extreme run-up events. The mean depth of each sensor during the July 2006 study period is listed in Table 2.
Table 2. The position and depth of sensors at Ipan Reef, Guam. D signifies the 4th of 5 deployments at Ipan.

<table>
<thead>
<tr>
<th>Location, sensor</th>
<th>Distance from shore (m)</th>
<th>Mean Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1 Buried SBE 26+</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>D2 Inner SBE 26+ (no data)</td>
<td>30</td>
<td>0.35</td>
</tr>
<tr>
<td>D5 Mid AQD</td>
<td>360</td>
<td>0.63</td>
</tr>
<tr>
<td>D6 Outer SBE 26+</td>
<td>390</td>
<td>0.57</td>
</tr>
<tr>
<td>D7 Outer AQD</td>
<td>420</td>
<td>0.24</td>
</tr>
<tr>
<td>D8 Edge SBE 26+</td>
<td>430</td>
<td>0.14</td>
</tr>
<tr>
<td>D9 Offshore AQD</td>
<td>500</td>
<td>5.73</td>
</tr>
<tr>
<td>D10 Offshore SBE 26+</td>
<td>560</td>
<td>7.80</td>
</tr>
</tbody>
</table>

Reef and offshore sensors were placed in custom brackets that held both types of sensors horizontal to the reef (Figure 3.8). These were held in place by threaded rods fixed by marine epoxy in drilled holes in the reef, onto which the brackets were double-bolted for security and strength. Electronic connector sheaths, and the pressure sensors were positioned facing away from incident wave energy so as to minimize risk of damage during wave breaking. The mounting technique has held all the rods and sensors firm for over a year without any need for additional drilling or
reapplication of marine epoxy.

Figure 3.8. Deployed Aquadopp D7, view looking shoreward over the transect region.

The Seabird 26 plus wave and tide recorders were programmed to measure 43,197 samples at 1 Hz every 43,200 seconds, which leaves only 3 seconds of missing data over 12 hour bursts. The Aquadopp current meters sampled at 0.5 Hz continuously throughout the deployment. They were programmed to have a single measurement cell of between 0.1-0.2 m, depending on the depth of the instrument.

The pressure data were corrected to sea surface elevation using linear wave theory. Because of noise contamination in the correction for the deep 6m sensor, a high-pass filter was applied to all time series to remove energy above 0.2 Hz.

Mean water levels were computed as averages over 15 minute intervals to filter out infragravity band fluctuations \( f = 0.02-0.003 \text{ Hz} \) while trying to keep swell band wave conditions somewhat stationary over the averaging period. Swell wave conditions over the same 15 minute intervals were computed from the surface
The significant wave height was computed by

\[ H_{m0} = \sqrt{\int_{f}^{g} S_\eta(f) df} \]  

(3.1)

The significant wave height was computed by \( H_{\text{sig}} = 1.35H_{m0} \).

We computed the wave setup contribution to water level in two ways. First we performed a multiple regression of the form

\[ h_{\text{sensor}} = aH_{\text{sig}} + bh_{D9} + ct + d \]  

(3.2)

where the inputs are offshore \( H_{\text{sig}} \) at D9, offshore water level at D9 \( (h_{D9}) \), a linear trend term \( t \), and a constant offset. The offshore water level exhibited little evidence of wave setup, although some setdown is expected to have occurred prior to the break zone at the reef edge. The offshore water level was included so that tidal and non-wave related sea level changes from the inshore water levels could be removed.

Wave setup at an inshore sensor \( \eta_{\text{sensor}} \) was then estimated relative to the offshore sensor by

\[ \eta_{\text{sensor}} = h_{\text{sensor}} - (bh_{D9} + ct + d) \]  

(3.3a)

Because wave energy on the reef exhibits tidal modulations due to the changing water depths, it is expected that a portion of the setup on the reef occurs at tidal frequencies.

By computing the regression from equation (3.2), we effectively removed this...
component of the setup. The water level time series are too short to accurately predict and remove the tidal heights. Therefore, we also computed setup by simply subtracting the offshore sea level from the reef sea levels and removing the mean and trend of the difference.

\[
\bar{\eta}_{\text{sensor}} = h_{\text{sensor}} - (h_{Dg} + c't + d')
\] (3.3b)

The two estimates of setup yield similar results as discussed in section 4. Equation 3.3a emphasizes the relationship with offshore wave height, equation 3.3b captures the tidal variation of setup due to slight changes in wave dissipation at high and low tides.

3.3 Results

3.3.1 Incident Wave Conditions

Two moderate wave events occurred at Ipan Reef during July 2006. The first, referred to as Event 1, occurred from July 7-10; the second, Event 2, occurred from July 16-19 (Figure 3.9). Event 1 was more energetic with 0.10-0.16 Hz waves arriving from the southeast. Event 2 started with 0.12-0.16 Hz waves incident from the east for a day, followed by 3 days of weaker wave energy centered at 0.1 Hz. The peak offshore \(H_{\text{sig}}\) during Event 1 reached 4.2 m with 9 second peak period; during Event 2 the peak height and period were 2 m and 8-10 second, respectively (Figure 3.10).
Figure 3.9. Vector plot of wave energy density (vector length) and wave propagation direction (vector direction) from the Datawell Waverider buoy, Ipan Reef, Guam. Figure courtesy of CDIP.

Figure 3.10. (a) Significant wave height (m), (b) Peak period (seconds) and (c) Direction from the
offshore wave buoy (Degrees from north).

Video acquisition allowed the real-time monitoring of wave breaking in the vicinity of Ipan Reef. Using a time-stack method [Hilmer 2005] to represent this data, the nature of wave breaking near Ipan Reef was observed over long time scale (Figure 3.11). The majority of waves were observed to break at the reef edge, with little evidence of turbulent surf energy > 30 m seaward of the reef edge even during the largest swells. There was very little penetration of white broken wave bores on the reef flat throughout the period of deployment (Figure 3.11).

Figure 3.11. A typical example of video acquisition data: A 300 second time-stack using a 2 Hz sampling rate during July 2006.

3.3.2 Waves and Water Level on the Reef

Water depth over the reef at Ipan is dominated by tidal frequencies with maximum elevation changes of ± 0.5 m during the study (Figure 3.12). The reef edge sensors (D7 and D8, Figure 3.12 b) are exposed during low tide, consistent with these sensors being ~ 0.3 m higher than the mid-reef. The mid to inner reef sensors (D2, D5, D6) are exposed during spring low tides. Non-tidal changes in water level on the inner
and mid reef are evident in early July during Event 1 (July 8-9, 2006, Figure 3.12 b-d), indicative of wave setup. Offshore water levels do not show a similar anomalous rise during this period (Figure 3.12 a).

![Figure 3.12](image)

**Figure 3.12.** 15-minute averages of water level (month-long mean removed) for (a) offshore, (b) outer-reef, (c) mid-reef, and (d) inner-reef sensors deployed at Ipan during July 2006. Non-tidal changes in reef water levels are evident during July 7-9. All sensors on the reef are exposed during low tides except the mid-reef sensors (c).

Significant wave height amplitudes are similar at the offshore sensors (D9 and D10), and both are up to a factor of two smaller than measured at the CDIP buoy (Figure 3.14). SWAN simulations run by CDIP that account for wave refraction and diffraction indicate a ~20% decrease in wave height at the offshore pressure sensors compared to the deep buoy (Figure 3.13). We speculate that the spur and groove topography leads to strong dissipation leading up to the D9 and D10 sensors.
Figure 3.13. The refraction/diffraction wave transformation model simulations provided by CDIP indicate a 20% decrease in wave heights from deep water to the reef face just off the instrument transect.

Figure 3.14. $H_{1/3}$ values are 2 times higher at the CDIP directional buoy compared to off-reef sensors D9 and D10.

Incident wave heights reduce significantly on the reef (Figure 3.15). For example on 8 July 2006, roughly 2 m offshore wave heights dropped by more than a factor of four at the reef edge (D7) compared to the sensors just off the reef (D9, D10). Wave heights continued to diminish to the mid-reef with little visible swell energy at D2, roughly 400 m from the reef edge (Figure 3.15 c). Video observations from the nearby station depict wave breaking at the outer reef between the D9 and D8 sensors,
with onshore propagation of turbulent bores (evidenced by surface white water) progressing ~30 m onshore from D8. Broken wave bores reached D6 only during higher wave conditions. At the inner reef (D2), the only noticeable oscillations were low amplitude solitary bores that reflect at the shore without breaking.

Figure 3.15. A 500-second wave burst during the peak of Event 1 for (a) offshore, (b) outer-reef, and (c) mid-reef sensors. Waves attenuate almost completely over the 400 m distance separating D9 and D2.

Offshore $H_{ss}$ (at D9) peaks at 2.2 m during Event 1, and at 1 m during Event 2 (Figure 3.16). At the reef edge (D7), $H_{ss}$ amplitudes are 75 % smaller than offshore, and the heights are strongly modulated by tidal elevation over the reef, with weak wave energy during low tides (Figure 3.16 b). Further inshore on the reef flat (D2, Figure 3.16 e), there is an order of magnitude reduction in the wave height compared to offshore, with a peak $H_{ss}$ of 0.1 m.
To further illustrate of the modulation of wave heights on the reef with tidal height, we examine the cross-shore profile of $H_{sG}$ during high tide and low tide (Figure 3.17).

The extent to which waves are depth limited over the reef is further examined with a linear regression of $H_{sG}$ and water depth ($h$) at the reef sensors, yielding the similarity parameter, $\gamma$ (Equation 2.5). $\gamma$ varies across the reef (Figure 3.17 a-d). Waves are weaker for a given water level at the inner-reef sensor ($\gamma = 0.23$) compared to the mid-reef ($\gamma = 0.44$). The outer reef shows a nonlinear relationship between $H_{sG}$ and $d$, which may be due to wave shoaling and breaking at the shallow reef edge, with less influence from the local water depth. On the mid to inner reef, the decrease in $\gamma$ toward shore is presumably due to the effect of bottom friction, which leads to wave dissipation above a depth-limited breaking condition (Figure 3.18).
Figure 3.17. $H_{ag}$ vs. water depth at reef sensors. High tide (HT) observations are shown in black, and low tide (LT) in red. (a) Nearshore (D2), (b) and (c) at reef-flat sensors.

The tidal effect is small compared to the strong dissipation at the reef edge due to wave breaking; however, wave heights are up to 10 times higher at high tide than low tide (Figure 3.18).
Figure 3.18. Bathymetry and sensor position on the reef (a) and $H_{sig}$ at high and low tide during Event 1 (b)

### 3.3.3 Surface Elevation Spectra

Auto- and cross-spectra of the surface elevation on (D5) and off (D9) the reef are compared. The spectra were computed from the entire month-long, continuous time series collected at each sensor. Brief periods when D5 was exposed during low tides are included in the analysis; however, similar results are obtained if a continuous subsection of the time series is used during Event 1. We elected to use the entire series so as to examine energy content from the tides to high wave frequencies. Variable band averaging with frequency was used, resulting in 95% significance levels that vary with frequency.

The auto-spectra show the peak in swell energies offshore at 0.12 Hz (Figure 3.19 a). On the reef, the swell energy is nearly completely dissipated with energy densities several orders of magnitude lower than offshore. In the infragravity ($3 \times 10^{-3} < f < $
$4 \times 10^{-2}$ Hz) and sub-infragravity ($1 \times 10^{-4} < f < 3 \times 10^{-3}$ Hz) frequency bands, the energy level peaks offshore at 0.01 Hz with spectral gaps separating the swell band and the tidal and super-tidal bands ($f < 1 \times 10^{-4}$ Hz). The reef sensor D5 shows higher energy levels than the offshore sensor D9 over the entire infragravity/sub-infragravity bands. We attribute the differences in the observed spectra to a predominantly bound wave energy offshore dictated by the swell spectral content [Okihiro and Guza, 1995] and a wave-driven surf-beat onshore that has a broader frequency content than offshore. By using a 15 minute averaging period to compute and analyze setup, we encompass the frequencies of the bound wave peak offshore. The spectra are similar in the tidal and super-tidal bands, with more sub-tidal energy on the reef than off the reef. We attribute this difference in energy levels at sub-tidal and sub-infragravity bands as being related to the wave-driven setup.

In the swell bands, coherence squared between on and off the reef is near zero, consistent with the nearly total dissipation of swell energy at D5 (Figure 3.19 b). Infragravity band coherences are significant, indicating that ~40% of the energy in this band is related at the two sensors. Coherences fall in the sub-infragravity band, before rising to high levels in the tidal band. There are too few degrees of freedom in the sub-tidal band to draw conclusions about covariability.

Phases show linear variations with frequency in the swell band and at frequencies just below this band, suggestive of non-dispersive, shoreward propagation in shallow water (Figure 3.19 c). In the infragravity band the phase is close to 180°, indicating that water levels rise/fall on the reef as the offshore levels fall/rise. One possible explanation for this behavior is that as wave groups propagate to shore, they are
accompanied by a bound wave that is low under the group; however, when the group of waves break on the reef, they create a rise in water level as the wave energy dissipates (i.e., peak of a surfbeat signal). Phases are near zero at tidal frequencies as expected. There is some indication for a return to a 180° shift at sub-tidal frequencies although coherences are insignificant in this band.

Figure 3.19. (a) Auto-spectra of surface elevation at D5 and D9 spanning swell (0.3 Hz -0.04 Hz), infragravity (0.003 Hz -0.04 Hz), sub-infragravity (0.0001 Hz -0.003 Hz), tide and sub-tidal (< 0.0001 Hz) frequency bands. 95% confidence intervals are depicted. (b) The coherence spectrum for D5 and D9. The dashed line is the 95% significance level. (c) The phase spectrum for D5 and D9.

The temporal variability of spectral energy is compared on and off the reef by computing spectra over 15 minute records for each day of July (Figure 3.20). The resulting spectrograms clearly show the energetic swell energy offshore (Figure 3.20 a) that is absent on the reef platform (Figure 3.20 b). The regular drop-outs in the D9 record occur at low tides when the sensor was exposed for a portion of the sample window. Energy levels in the infragravity band clearly correlate in time with the
swell band energies.

Figure 3.20. Surface elevation spectra versus time off the reef (a, D9) and on the reef (b, D5). Swell band energy is dissipated effectively after breaking at the reef edge. Infragravity band energy levels are similar on and off the reef. Bursts of infragravity energy occur during the two main swell events.

3.3.4 Wave Setup

Water levels are averaged over 15 minute intervals at each sensor and the offshore water level is subtracted either with a least squares fit determined scaling factor (equation 3.3a) or with no scaling factor applied (equation 3.2b). Gaps in the time series correspond to when the sensors were exposed at low tide.

The correlation between water levels on the reef, $\bar{H}$ and offshore $H_{\text{sig}}$ is high ($\sim 0.96$) for all sensors (Figure 3.17), indicating that $\bar{H}$ variations are due to wave-driven setup. Setup is uniform in amplitude across the reef; the regression coefficients
obtained from the least squares fit (equation 3.3a) relating $\bar{\eta}$ and offshore $H_{\text{sig}}$ are 0.36 at D2, 0.40 at D5, and 0.36 at D6. The regression coefficients are higher than previous estimates obtained from sandy beaches, which typically range from 0.2-0.3 [Hansen 1978, Guza and Thornton 1981, Nielsen 1988].

Figure 3.21. Time-averaged water level on the reef, minus the offshore water level at D9 ($\bar{\eta}$, equation 3.3a) is highly correlated with offshore $H_{\text{sig}}$ (plotted here scaled by the regression coefficient, a, in equation 3.3a). Comparisons are shown for (a) D2, (b) D5, and (c) D6.

3.3.5 The Cross-shore Momentum Balance

We next examine the steady, cross-shore momentum balance (equation 2.1) relating the gradients of radiation stress $S_{\text{sh}}$ and sea surface elevation $\eta$ [Longuet-Higgins and Stewart, 1962]. The integration of equation (2.1) requires a methodology for interpolating $H_{\text{rms}}$ observations between the sensors. We evaluate four different ways to model the cross-shore $H_{\text{rms}}$ profile. Each model uses a 1 m grid step between
sensors D9 (offshore) and D2 (nearshore) with water depth specified from the SHOALS Lidar data. The cross-shore profiles of $H_{rms}$, $S_{xx}$ equation (2.1), and $\eta$ equation (3.3) are illustrated for each model using observed $H_{rms}$ values during the peak of Event 1 (Figure 3.22 & 3.23). The predicted setup is compared to the computed $\overline{\eta}$ from equation 3.3a (Figure 3.22).

Model 1 uses a linear interpolation of observed $H_{rms}$ between sensors (Figure 3.23 b, c) to evaluate the setup. The resulting predicted setup is uniform over the reef as observed; however, the model underpredicts the observed setup amplitude during Event 1 (Figure 3.23 d). We attribute this to the model wave attenuation occurring in too deep water depths.

Model 2 assumes that $H_{rms}$ is constant off the reef, consistent with the similar $H_{rms}$ amplitudes observed at D9 and D10. At the reef edge sensor D7 (Figure 3.23 c), the waves are assumed to break. Model 2 setup amplitudes are consistent with the observed setup amplitudes during Event 1 (Figure 3.23 d).

Model 3 assumes constant wave height outside the break point (i.e., no shoaling). Initiation of breaking is determined by the breaking criterion $H_{rms} = 0.44 h$ (Figure 3.23 g). Shoreward of this break point, the model linearly interpolates $H_{rms}$ between sensors on the reef. The model underpredicts setup during Event 1 (Figure 3.23 g).

Model 4 is similar to model 3, but includes a shoaling term for wave heights outside the break point. The shoaling term increases wave heights, and initiates breaking further from the reef edge than the other models. The model 4 assumption of wave
heights increasing significantly near the break point is not consistent with the wave observations between sensors D9 and D10. Model 4 does a good job in estimating the setup values during the peak of Event 1. (Figure 3.23 g)

Figure 3.22. Predicted and observed setup at D2 from Model 1(a) Model 2(b) Model 3 (c) and Model 4 (d).
Figure 3.23. The depth of each sensor (a), and observed (triangle) and predicted (Models 1 and 2) (b) Hrms, (c) Sxx, and (d) setup. The next 3 (e-g) panels show the same comparisons for Models 3 and 4.

Over the entire time series, predicted and observed setup generally agree well for all models, with correlations ranging from 0.88 for model 4 to 0.95 for model 2 (Figure 3.23). As noted, model 1 underpredicts the observed setup (Figure 3.22 a). Model 4 overpredicts setup for low wave conditions when observed setup values are less than 0.4 m, but the model and observed amplitudes are similar for larger offshore wave
heights (Figure 3.23 g & Figure 3.22 d). Models 2 and 3 give similar results. Both assume that waves break very near the reef edge, either at a fixed depth at the D7 sensor (model 2), or at the prescribed breakpoint when \( H_{rm} = 0.44 \, h \). Model 2 gives the best overall prediction of setup compared with the observed values with good agreement throughout all wave energy ranges (Figure 3.24). The assumption that all waves break at the reef edge is consistent with the video observations.

![Setup Model 2](image)

**Figure 3.24.** Time series of Model 2 setup with the observed setup.

We find surprisingly good agreement with estimates based on equation (2.1) and the observations of setup given the roughness of the bathymetry at Ipan, and the neglect of friction terms such as proposed by Apostos *et al.* [2006] and Symonds *et al.* [1995]. The apparent lack of importance of friction is also surprising given the strong wave-driven flows observed on the reef (D5) and on the reef face (D9) (Figure 3.25 &
3.26. Cross-shore currents are well correlated \( r = 0.65 \) with offshore \( H_{rms} \), with shoreward current at D5 during wave events, and offshore flow at D9. The flow amplitudes are stronger at D5 \( \overline{U}/H_{rms} = 0.09 \) (Figure 3.25 d) than at D9 \( \overline{U}/H_{rms} = 0.05 \) (Figure 3.25 c). There is a mean southward current at D5 that is not observed at D9 (Figure 3.26) and dominant southerly flow on the reef reverses to northerly flow during large wave events. The nature of this current has not yet been determined.

![Figure 3.25. Time-series of east to west currents throughout the period. West is positive. (a) \( H_{ds} \) offshore. (b) Tidal excursion. (c) East-west current offshore at sensor D9. (d) East-west current on the reef at sensor D5.](image-url)
Figure 3.26. Time-series of north to south currents throughout the period. South is positive. (a) North-south current offshore at sensor D9. (b) North-south current on the reef at sensor D5.

To assess the contribution of friction to the momentum balance, we estimate the bottom stress, $\tau_B$, following Longuet-Higgins (2005)

$$
\frac{\partial \bar{H}}{\partial x} = -\frac{1}{\rho g (\bar{H} + h)} \left( \frac{\partial S_{xx}}{\partial x} + \tau_B \right) \tag{3.4}
$$

$$
\tau_B = \frac{1}{4} \rho \cdot f_w \cdot U_{br} \cdot U_b^2 \tag{3.5}
$$

where $\rho$ is the density of seawater, $f_w$ is the wave friction coefficient, and $U_b$ is the mean cross-shore velocity component. Using a cross-shore flow of $U_b \sim 0.2 \text{ ms}^{-1}$ based on the observations during a large wave event, and a typical mid-range friction factor for the smooth reef flat ($f_w = 0.1$ [Nielsen 1992]), the bottom stress would be $\tau_B \sim 0.2 \text{ ms}^{-1}$. This value is an order of magnitude smaller than the other terms in
equation (3.4). We conclude that friction has a negligible effect on the setup balance at Ipan Reef.

4. The Mokule'ia Reef Experiment

4.1 The Study Site

Additional PILOT field observations were made at Mokule'ia Reef on the North Shore of Oahu, Hawai'i (Figure 4.1). The reef fronts a steep (~8° slope) coarse sand beach that is 20m wide from the shoreline to the foot of residential beach property. Once below water, the bathymetry transitions from a narrow patch of sand to the rough reef bathymetry depicted in Figure 4.3. Here the reef is made up of predominantly dead coral, much of which has deteriorated into rubble, making the reef flat uneven and brittle. The reef roughness scale is ~ 0.5 m based on diver surveys. Although quite rough, the overall slope of the reef is near zero for ~100m until reaching a shallow (1 m) berm followed by another steeper section that we refer to as the reef face. The berm is partially exposed during spring tide minima. Beyond the reef face, the bathymetric slope reduces to 0.88 ° from horizontal out to at last 700m from shore. The reef roughness in this region is dominated by spur and groove features with ~10 m amplitudes and ~ 100 m length scales.
Figure 4.1. Position of April 2004, Mokule'ia transect and CDIP directional waverider buoy outside Waimea Bay with respect to Oahu, in the Hawai'ian Island chain.

Figure 4.2. Cross-section of bathymetry at Mokule'ia reef, from SHOALS data, including sensor positions during the deployment in April 2004.
Figure 4.3. Typical topography found nearshore at Mokule‘ia reef. The white pressure sensor casing is 0.1 m in diameter.

4.2 Methods

Data were collected during a two-week deployment from March 28 until April 11, 2004. Three Seabird 26 wave and tide recorders were placed across the Mokuleia reef at 1, 5, and 10 m depth (Figure 4.2). The M1 recorder was placed on the reef platform in 1.2 m water depth approximately 30 m from the reef edge. This sensor was within the surf zone for most wave conditions. The M2 recorder was in 5 m depth in the rough spur and groove region of the reef slope. The sensor was assumed to be outside of the break zone, although this was difficult to assess during the largest wave event. The deep M3 record was in 10 m depth well outside the break zone observed for all conditions. Current measurements were not made at Mokuleia.

Each wave and tide recorder was attached to 100 lbs (dry) of anchor chain and placed in gullies or reef indents to reduce vibration or movement. The rough nature of the reef at all locations deterred use of the fixed mounting brackets employed at Ipan. The Seabird 26 plus pressure sensors recorded almost continuously at 1 Hz frequency, with 3568 samples every 3600 seconds.

In addition to the three pressure sensors, a Datawell directional waverider buoy
similar to that deployed in Guam, is positioned in deep water (200 m) 12 km northeast of the instrument transect (Figure 4.1). The buoy transmits spectral estimates every half-hour over the frequency range 0.03 - 0.3 Hz, with the data downloaded and processed by CDIP. A permanent water level recorder, maintained by the Pacific Tsunami Warning Center, is located 6 km east of Mokuleia at Hale‘iwa Harbor. The sensor records a spot sample of water level every two minutes. Water level heights are referenced to the measured mean lower low water.

4.3 Results

4.3.1 Incident wave condition

Three wave events occurred in the study period of March 28 - April 9 2004 during a two-month period of energetic northwest swell (Figure 4.4). The first event, from March 29 - 31, was the weakest of the three with $H_{sig}$ reaching 2.5 m and a peak wave period of 14 seconds from the north-northeast (Figure 4.5). The second event occurred during April 2 - 5 had $H_{sig}$ up to 3 m and a peak period of 15 seconds. The third event occurred from April 7 - 9. This was the most energetic event during the deployment during which $H_{sig}$ reached 4 m and peak period was 18 seconds (Figure 4.5).
Figure 4.4. Vector plot of wave energy density (vector length) and wave propagation direction (vector direction) for (a) March 2004 and (b) April 2004 from the Datawell waverider buoy, Waimea Bay.

Figure courtesy of CDIP.

Figure 4.5. Offshore conditions from CDIP directional buoy at Waimea Bay, Oahu, Hawai‘i, (a)
Significant wave height, (b) period and (c) direction

4.3.2 Waves and Water Level on the Reef

Tides around the islands are a mix of semidiurnal and diurnal oscillations. During the experiment, tidal elevation changes of ±0.5 m were observed at all reef sensors. The tidal fluctuations are correlated on the reef, and the reef oscillations are similar to those observed in Hale'iwa Harbor. All the Mokule'ia sensors remained submerged for the entire deployment. Non-tidal changes in water level are most evident at the 1m sensor during the largest wave event (April 7 2004, Figure 4.6 c). The Hale'iwa Harbor water levels are noisy during the main wave events, indicating that wave energy enters the harbor, either as swell or infragravity waves (Figure 32 d).

![Graphs showing water level changes](image)

**Figure 4.6.** Mean water depth at Mokule'ia 2004. Each pressure sensor at (a) M3 (10m), (b) M2 (5m) and (c) M1 (1 m) and (d) the Hale'iwa Harbor sea level data.

Wave height amplitudes are similar at the Datawell wave buoy and the deep (10 m) pressure sensor at Mokule'ia (Figure 4.7 a). Wave heights decreased considerably
after propagation over the reef (1m sensor, Figure 4.6 d). Similar to Ipan, tidal modulations of $H_{\text{sig}}$ are evident at the shallow M1 sensor, but not at the deeper sensors (M2 and M3). The tidal variation of $H_{\text{sig}}$ is, however, secondary to the strong dissipation due to wave breaking, which occurs between sensors M2 and M1 (Figure 4.6).

![Graphs showing wave height variations over time for M3, M2, and M1 sensors.]

**Figure 4.7.** Significant wave heights from (a) M3, (b) M2 and (c) M1 sensors for the entire deployment 2004.

The character of the wave signal changes considerably across the reef. During the peak of the April 7 wave event, the offshore waves at M3 reached 4m with irregular wave group modulations (Figure 4.8 a). The M2 sensor in 5m depth is more skewed than the M3 with higher amplitudes during wave peaks than troughs (Figure 4.8 b). The M2 waves are weaker than at M3 and there is less groupiness. We interpret this as an indication that M2 is in the surf zone for the largest waves (breaking has occurred to limit wave height), and just outside the surf zone for smaller waves (some
shoaling has occurred). The shallow M1 sensor shows negligible swell band energy due to nearly complete dissipation through the surf zone and over the rough reef bathymetry.

![Figure 4.8](image)

Figure 4.8. A 3568-second wave burst during the peak of the largest observed wave event for (a) M3 (b) M2, and (c) M1 sensors.

The assumption that wave heights scale with water depth, as in equation (2.5), is examined using scatter plots of depth, including water level fluctuations, and $H_{sig}$ at each sensor (Figure 4.9). There is little obvious relationship between the two variables at the mid (M2) and outer (M3) sensor (Figure 4.9 c), consistent with these sensors being offshore or just in the surf zone. In contrast, waves at M1 are depth limited, with a similarity parameter of $\gamma = 0.16$ ($\gamma = 0.35$ if a mean is included in the regression) at a correlation of $c = 0.95$. This value of $\gamma$ is significantly lower to that observed in shallow water at Ipan (D2) (Figure 3.17 a), such a low value compared to mid- and outer reef sensors was attributed to enhanced bottom friction over the reef
4.3.3 Surface Elevation Spectra

The Mokule‘ia surface elevation auto-spectra are computed for a 6 hour window during the peak of the largest wave event (April 7-9), and for the entire 11.6 day record (Figure 4.10 a-c). The M3 and M2 spectra have similar energy distributions with peak swell frequencies at 0.06 Hz. Secondary (~0.12 Hz) and tertiary (~0.17 Hz) at M3 occur at harmonics of the swell peak. The M1 spectra show significantly less energy at all sea and swell frequencies, with typically an order of magnitude reduction compared to offshore. Nearshore infragravity energy is higher at all sensors during the wave event compared to the average spectra. At M1, a broad peak at 0.03 Hz falls near the subharmonic of the 0.06 Hz swell peak. The M1 infragravity band energy is comparable, if not larger, than offshore (Figure 4.10 c).
4.3.4 Wave setup

We compute mean water level anomalies and $H_{slg}$ at Mokule'ia using 15 minute intervals, following the methods used for Ipan Reef (section 3). Mean setup ($\eta$) at M1 is highly correlated ($r = 0.96$) with offshore $H_{slg}$ at M3 (Figure 4.11). The regression coefficient, $r = 0.11$, is smaller than observed at Ipan (0.36-0.39), and is lower than constants derived over sandy beaches [r ~ 0.2, Raubenhemier 1996, Hansen 1976]. Two plausible explanations are that bottom friction over the reef, or wave reflections at the reef face, contribute to the relatively weak setup at Mokule'ia for a given offshore $H_{slg}$; however, we show below that setup is modeled satisfactorily without invoking either process (Section 4.3.6).

Figure 4.10. Surface elevation auto-spectra during the peak of the April 7-9 wave (black line), and for the entire deployment (red line) for (a) M3 (10 m), (b) M2 (5 m) and (c) M1 (1 m).
During the largest wave event (April 7, 2004, Figure 4.7 c), setup estimated from $H_{sig}$ underestimates the observed setup by $\sim 5\%$ at the nearshore (M1) sensor and by $\sim 50\%$ at the mid-reef (M2) sensor (Figure 4.9 b). This discrepancy translates to a 0.02-0.03 m level shift for $H_{sig} > 4$ m offshore.

![Figure 4.11](image.png)

**Figure 4.11.** Observed setup (equation 3.3 a) compared to offshore $H_{sig}$ scaled by the regression coefficient (c) from equation (3.3 b) for (a) M1 and, (b) M2 sensor.

### 4.3.5 The Cross-shore Momentum Balance

To evaluate the cross-shore momentum balance (equation 2.1) for Mokule‘ia Reef, we use the same models for interpolating $H_{rms}$ between sensors as the Japan analysis (section 3.3.6). Model 1 uses linear interpolation of $H_{rms}$ between sensors, Model 2 utilizes a step function for the wave breaking applied 50 m seaward of the reef edge, and Model 3 and 4 assume waves break in a manner that satisfies equation (2.5), with
\( \gamma = 0.45 \) following Raubenheimer [2001]. Model 3 does not include a shoaling term whereas Model 4 does.

Models 1, 2 and 3 all under-predict the observed setup at Mokule'a (Figure 4.12). In each case, the model waves are too small, resulting in weak setup. The Model 4 results agree quite well with the observations, with a correlation of 0.98. Model 4 includes a shoaling term, which increases the wave heights relative to the other models (Figure 4.13 and 4.14). The same affect could have been achieved by increasing \( \gamma \); however, there is little indication in the observed \( H_{rms} \) vs. \( d \) comparison (Figure 4.9) to support such an increase. In fact, smaller values of \( \gamma \) than 0.45 are indicated. Given that smaller \( \gamma \)'s would result in even smaller
predicted setup amplitudes, we do not believe the small values reflect saturation due to wave breaking; instead the values are likely small because of bottom friction dissipation over the shallow reef.

Figure 4.13. Cross-shore variations in (a) depth (b) modeled and observed $H_{sw}$ and (c) modeled and observed setup.
Figure 4.14. Time-series of observed and model 4 setup at Mokule'ia in April 2004, using breaking parameter ($\gamma = 0.45$).

Our evaluation of cross-shore momentum has not included a frictional term, such as that associated with undertow (Apostos et al. 2006). We do not have current observations to evaluate this term; however, we note that Apostos et al. (2006) find that added friction can increase the set-up compared to the inviscid case. Hence, better agreement between Models 1-3 could be obtained by invoking a friction component. Although we do not have in situ current measurements, we can estimate how large of a current is needed to significantly affect the cross-shore momentum balance. To do so, we use the results of Falter [2004] to specify a friction factor of $f_w = 0.22$ for the rough reef topography. Assuming a mean cross-shore flow of 0.2 $\text{m/s}$ during large wave events, similar to that observed at Ipan, we obtain a bottom stress amplitude of $\tau_y \sim 0.4$. In comparison, the pressure gradient and radiation stress terms in equation 3.4 are 10-20 times larger, hence friction appears to be unimportant. Non-negligible friction could occur for a flow speed twice as large, and the estimated setup would likewise increase if this flow were directed offshore over the reef (an onshore flow, as observed at Ipan, would reduce setup). In situ observations are needed to determine if such a flow occurs, but our preliminary assessment is that friction plays a secondary role in the momentum balance (equation 3.4).

5. Summary and Discussion

5.1 Summary: Ipan Reef

The Ipan Reef morphology has evolved into a highly effective system for reducing the energy of incoming swell. Much of the reef is exposed at low tide, particularly at the
reef edge where the majority of wave dissipation occurs. The steep reef face and shallow reef flat cause wave energy to reduce by 94% within 40 m of the reef edge for observed wave heights as large as 2.5 m. Almost zero incident swell energy is propagated to the nearshore D2. The small fraction of incident wave energy that is observed at the outer reef shows a distinct tidal variation, with approximately 50% higher wave heights at high than low tide.

As a result of the efficient wave energy loss over a short cross-shore distance, radiation stress gradients show a sharp gradient at the reef edge, which in turn leads to uniform setup across the reef flat. Setup is highly correlated with the incident significant wave height (0.97), and setup amplitudes scale at 0.35-0.39 times $H_{s18}$ measured off the reef in 10m depth. In addition, setup is well modeled by solving the steady cross-shore momentum balance proposed by Longuet-Higgins and Stewart [1962]. The integration of the cross-shore balance is sensitive to how wave breaking is estimated. At Ipan’s steep reef face, models that force wave breaking on, or close to, the reef face yield the best results, which is consistent with visual observations made on the reef. We estimate that bottom stress plays a lesser role in the cross-shore momentum balance, particularly over the relatively smooth topography of the reef platform. Further observations are needed to assess frictional effects over the rough topography of the reef face. For example, the reduction in wave height at 10m depth on the reef face relative to the deep water wave buoy may be due to dissipation over the spur and groove topography.

Comparisons between surface elevation spectra from on (D5) and off (D9) the reef show an increase in the infragravity to sub-infragravity band ($1 \times 10^{-4} < f < 1 \times 10^{-2}$
Hz) energy. The increase of infragravity and the absence of swell-band energy on the reef during offshore swell-wave events, suggest that infragravity energy is generated on the reef in a similar manner to lower frequency setup. The infragravity and sub-infragravity energy appears to be bound to the incoming swell groups; however, fluctuations in this band are $180^\circ$ out of phase with those on the reef. Further analysis of the infragravity band is needed, however, we believe that the offshore energy is bound to incident wave groups (low during sets), and that the energy on the reef is driven by the breaking waves (high during sets) in addition to any offshore bound energy that shoals on to the reef.

5.2 Summary: Mokule'ia Reef

The fringing reef at Mokule'ia also provides an effective wave dampening, with offshore waves as large as 4m reduced to negligible amplitudes at after crossing the rough reef topography. Variations in tidal height over the reef resulted in weak wave height modulations (0.01 m) near the shore. Although some swell energy is propagated to the nearshore, the energy spectra from Mokule'ia show there is still strong attenuation of the swell frequencies after breaking and that the infragravity energy dominates the wave field nearshore.

The observed setup is highly correlated (0.96) with offshore significant wave height for waves as large as 4m. Setup near the shore (1m depth) scales as 0.11 times the offshore $H_{\text{sig}}$, weaker than reported values over sand beaches or than we observe at Ipan Reef.
Evaluation of cross-shore momentum equation indicates that a balance between radiation stress gradients and the cross-shore pressure gradient holds for the conditions at Mokule'ia. Setup across the reef is well modeled using a simple wave shoaling model with a wave breaking parameter that limits wave heights to just under half of the local water depth ($\gamma = 0.45$). Friction is estimated to be of secondary importance in the momentum balance; however, further current observations over the reef are needed to conclusively evaluate the effect of friction.

5.3 Discussion

The dynamics of wave setup over a fringing reef appear to be similar to that over a sand beach; wave dissipation in the surf zone causes a radiation stress gradient that is balanced by a cross-shore pressure gradient. Bottom friction, which has been found to be increase setup amplitudes over sand beaches (Apostos et al., 2006), is not of first order importance at Ipan because of the reef morphology. Most of the incident wave energy is dissipated at the shallow reef edge due to wave breaking, and the reef platform itself is not particularly rough. If friction is important, it would be at the reef face, over the rugged spur and groove topography. Wave amplitudes at 6m and 10m depth are similar, with no indication of an amplitude increase due to shoaling. We also note that the onshore current at D5 during wave events results in a friction force that would serve to diminish setup, yet the setup is already observed to be quite large. We did not observe much evidence for an offshore directed undertow except perhaps on the reef face (D9). In any case, the good predictive skill of equation (2.1) suggests that friction is not an important process at Ipan Reef in terms of altering setup height. We conclude that the volume added to the reef caused by the shoreward currents must be balanced by a reduction in volume associated with offshore flows.
The importance of bottom stress at Mokule'ia Reef is less certain. We did not have the density of instruments across the reef at Mokule'ia as at Ipan Reef to evaluate the wave transformation, nor were we able to collect current measurements over the rough terrain. Wave breaking at Mokule'ia occurred over a large cross-shore range due to the gradual reef-face slope, and therefore there is some uncertainty as to how to specify the breaking condition. We also did not have a video system place to verify the location of wave breaking. Hence the results are less conclusive than at Ipan. For example, we could have decreased the breaking parameter, \( \gamma \), resulting in wave breaking in deeper water and thus weakening the radiation stress gradient. This could be compensated by a frictional offshore flow, which would increase the setup at the shore in the manner described by Apostos et al. (2006). We are not able to distinguish between these scenarios, except to note that the observed ratio of \( H_{sig} \) to \( d \) supports a deeper break point, and by inference the need for stronger bottom stress. Current observations over the reef and some indication of the actual breaking zone will help resolve this issue.

The greater setup at Ipan than at Mokule'ia for a given offshore wave height (regression with \( H_{sig} = 0.38 \) at Ipan, 0.11 at Mokuleia) is surprising given that equation 2.1 does so well at predicting setup at both locations. We attribute this difference to the steeper reef face bathymetry at Ipan than at Mokuleia. Incoming waves at Ipan likely do not shoal in the usual sense given the steep reef face bathymetry. Waves that would ordinarily increase in amplitude and break in deeper water may not do so until reaching the shallow reef flat at the reef edge. The radiation stress gradient would therefore be larger than would occur if the waves broke in deeper water, resulting in anomalously large setup amplitudes. The gently sloping
reef face at Mokule‘ia allows waves to shoal and break, resulting in a wider surf zone with larger waves breaking outside the reef edge. A wave-induced current experiment is currently underway at Mokule‘ia to test this hypothesis and increase understanding of the momentum balance in this area.

An overarching goal of this study is to develop an algorithm for predicting Pacific island shoreline inundation during storm conditions. In particular, as a local storm increases sea level due to surge and inverse barometric conditions, how will this impact wave-driven coastal inundation? Because the tides are weak at both locations, we did not observe a significant change in setup for the range of water levels sampled during the deployment. Given the strong linear relationship between wave heights and setup, we do not expect that the dynamics of wave-driven setup will be strongly affected by changing sea levels. The basic balance between radiation stress and pressure gradients is still dominant, although the breaking depths are likely to shift onshore for a gently sloping reef face such as at Mokuleia. Although mean setup may not be strongly affected, it is likely that swell energy will penetrate further across the reef as water levels increase.
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