Wave Control on Reef Morphology and Coral Distribution: Molokai, Hawaii

by

Curt D. Storlazzi[1], Michael E. Field[2], James D. Dykes[3], Paul L. Jokiel[4], and Eric Brown[5]

1 Research Scientist, U.S. Geological Survey Pacific Science Center, University of California, 1156 High Street, Santa Cruz, CA 95064, manta@es.ucsc.edu
2 Senior Research Scientist, U.S. Geological Survey Pacific Science Center, University of California, 1156 High Street, Santa Cruz, CA 95064, mfield@usgs.gov
3 Physical Scientist, Oceanography Department, Naval Oceanographic Office, 1002 Balch Blvd, Stennis Space Center, Mississippi 39522, dykesj@navo.navy.mil
4 Senior Research Scientist, Hawai'i Institute of Marine Biology, University of Hawaii at Manoa, P.O. Box 1346, Kaneohe, Hawai'i 96744, jokiel@hawaii.edu
5 Research Scientist, Hawai'i Institute of Marine Biology, University of Hawaii at Manoa, P.O. Box 1346, Kaneohe, Hawai'i 96744, pavona@aol.com

ABSTRACT

A multi-disciplinary project lead by the U.S. Geological Survey is currently studying the fringing reef off southern Molokai, Hawaii, in an effort to characterize the biological structure and geologic variability of coral reef systems. Wave modeling and field observations were utilized to help understand the physical controls on reef morphology and the distribution of coral species. The morphology of the reef crest, which extends roughly 50 km from east to west and up to 1500 m offshore, appears to be primarily controlled by the amount of wave energy impinging on the coastline. Extratropical cyclones and inter-anticyclonic systems crossing the North Pacific during the winter months generate the wave energy regime that appears to dominate the reef. This North Pacific swell generates near-bed orbital velocities greater than 3.0 m/sec and shear stresses greater than 2.5 N/m^2 that inhibit substantial coral development in shallow water (<10 m). The reef is sheltered from these waves by the island of Molokai; however, refraction around the east and west ends of the island cause the reef crest to pinch out roughly 5 km from each end of the island. Where the reef crest merges into the shoreline, more robust high-energy corals and low coral cover typify the fore reef. In contrast, more delicate branching corals characterize the central portion of the reef, which is sheltered from the large North Pacific swell, and up to 80% live coral cover.

KEYWORDS: coral reef, Hawaiian Islands, reef morphology, wave modeling, wave forces

INTRODUCTION

It has been know for some time that there are strong qualitative correlations between wave energy and coral speciation and reef morphology (Dollar, 1982; Done and Massel, 1993; Rogers, 1993; Blanchon and Jones, 1997). Recently, Grigg (1998) discussed the interplay between wave energy and reef properties in the Hawaiian Islands, but as in many previous studies, he only classified wave energy in terms of the loosely divided categories of "low", "medium", or "high" wave energy regimes. There has yet to be a large-scale quantitative investigation into these relationships that compares the energy exerted by waves to the reef morphology and coral species distribution.

The primary forces acting on a coral are drag, lift, weight, and inertia. Weight and inertia are a function of coral colony morphology and these forces act to counter the forces of lift and drag, which act to dislodge the coral from the substrate. Since both the lift and drag forces are a function of the horizontal components of wave orbital velocity, it appears that wave height and period data can provide a first order approximation of the forces impinging upon a coral reef. Our goal here is to utilize newly acquired high-resolution and spatially extensive quantitative data on coral species distribution and reef morphology off southern Molokai, Hawaii, in conjunction with wave model data, to quantify the interplay between these variables.

STUDY AREA

The island of Molokai is located roughly 21°N, 157°W in the Northern-central Pacific between the islands of Oahu and Maui in the Hawaiian Archipelago (Figure 1). The island is 62 km long east-west and on average 13 km wide north-south. A 53 km long fringing coral reef lies off the south shore of the island between Molokai, Lanai, and Maui. The reef crest is on average roughly 1 km wide and has a maximum width of over 1.5 km. The reef pinches out roughly 7 km from the western end of the island and 3 km from the eastern end of the island. The reef flat is shallow, attaining a maximum depth of roughly 2 m except in certain locations where 'blue holes' with vertical walls can extend to depths as great as 10 m. The reef crest is in a nominal depth of 1-2 m, and the fore reef extends from the reef crest to a depth of roughly 30 m.

The wave climate off Molokai is dominated by four end-members: the North Pacific swell, Northeast Tradewind waves, Southern Ocean swell, and Kona storm waves (Moberly and Chaimberlin, 1964). The North Pacific winter swell has on average significant wave heights (H_s) on the order of 3-8 m and peak periods (T_p) of 10-20 sec. The Northeast trade wind waves occur throughout the year but are largest from April through November when the trade winds blow the strongest; these waves have H_s of 1-4 m and T_p between 5-8 sec. The Southern swell occurs during the Southern Hemisphere winter and has H_s on the order of 1-2 m and T_p of 14-25 sec. Kona storm

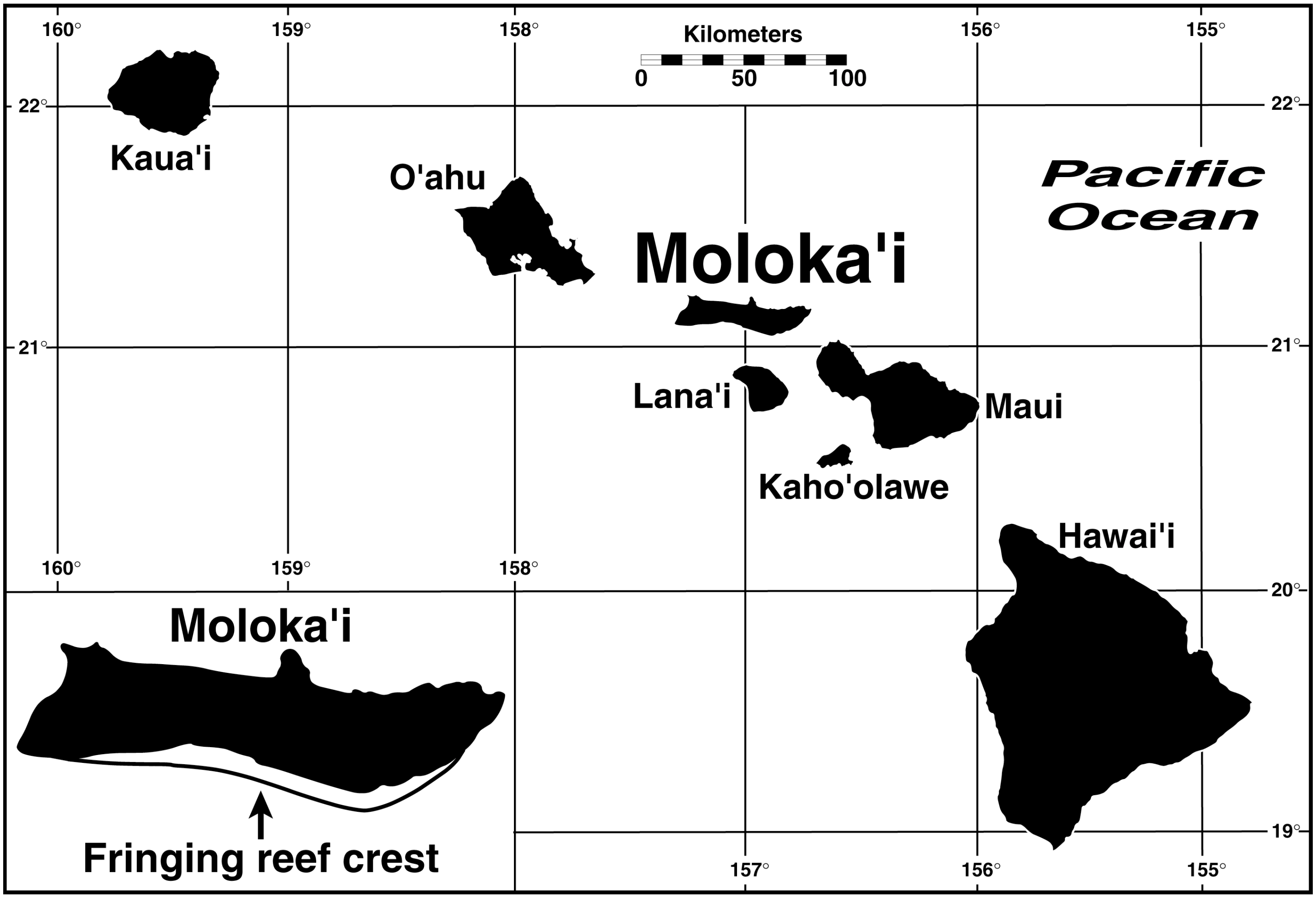

Fig. 1 Location of the study area

waves are neither frequent nor consistent in their occurrence and typically have H_s of 3-5 m and T_p between 8-12 sec.

METHODS

The reef morphology surface was computed from a combination of bathymetric data using ARC/INFO geographic information system (GIS). These data included both high-resolution Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) data collected by the U.S. Army Corps of Engineers (USACE) for the U.S. Geological Survey (USGS) in 1999 and previously collected U.S. National Ocean Service (NOS) depth soundings. The SHOALS system collected a 2 m footprint every 4 m from the shoreline out to more than 35 m water depth, for a total of over 2,000,000 depth soundings. These data were merged with over 100,000 NOS depth soundings. ARC/INFO was then used to compute 8 cross-sectional profiles of the reef to a depth of 30 m evenly spaced from one end of the island to the other.

Data on coral coverage were collected during dedicated surveys in February 2000. Observations of coral coverage along the 10 m isobath were conducted at 7 locations (every 1.6km) stretching 11 km from the west end of the island east to Punakou using *in-situ* visual estimates of the substrate. The dominant species recorded were the delicate finger coral *Porites compressa*, a low energy species; and numerous *Montipora* species (‘rice’ coral), which is a medium energy, coral; and *Pocillopora meandrina* (‘cauliflower’ coral) and *Porites lobata*, which are high energy branching and encrusting species.

In order to provide accurate wave data for locations along the south shore of Molokai, the Wave Model (WAM) was run at the U.S. Naval Oceanographic Office to generate a gridded field of wave height, period, and direction for an analysis. Over the area of interest a high-resolution WAM domain at 1.6 km by 1.6 km was nested within a 1 degree by 1 degree global WAM. WAM requires surface wind forcing, which was provided by NOGAPS, a global spectral model run at the U.S. Fleet Numerical Meteorology and Oceanography Center. Since the WAM product is wind generated, once inside the (approximate) 10 m isobath shallow water interactions are not indicated in the model product. This depth, therefore, was the minimum depth for all subsequent calculations.

The H_s and T_p for the grid cells closest to the south shore of Moloka’i output by the WAM were used to calculate the dominant wave horizontal orbital velocity, u, and amplitude excursion, A_e, from linear wave theory. These data were then used to calculate both the wave friction factor, f_w (Nielsen, 1992):

$$f_w = 0.04\left[\left(\frac{A_e}{0.0025}\right)^{-0.25}\right] \tag{1}$$

and the peak bed shear stress under oscillatory flow, $\hat{\tau}_b$ (Jonsson, 1966):

$$\hat{\tau}_b = \frac{1}{2}\rho_f f_w (A_e\omega)^2 \tag{2}$$

where: ρ_f = density of the fluid (~ 1026 kg/m^3) and $\omega = 2\pi/T_p$, radian wave frequency (1/sec). These values were then compared to observations of coral coverage and species distribution. Finally, the relationship between wave-induced near-bed stresses and reef width were examined using regression analysis.

RESULTS

Reef Morphology

The coral reef off southern Molokai can be subdivided into three general parts (reef flat, reef crest, and fore reef). The reef flat, a roughly horizontal surface with relatively low coral cover and shore-normal 'ridge-and-runnel' structures (Blanchon and Jones, 1997), typically extends from the shoreline out some distance to the reef crest. The reef crest, which is poorly defined off southern Molokai, is characterized by more irregular morphology dominated by robust coral heads and is the location where most deepwater waves break. Along Molokai's fringing reef, the reef crest is typically observed in water depths of 2-4 m. Offshore of the reef crest to depths of roughly 30 m is the fore reef, which is the zone of highest coral cover and is generally characterized by shore-normal 'spur-and-groove' structures. Eight shore-normal transects were computed from the shoreline out to the base of the present reef along the 30 m isobath off the south shore of Molokai (Fig. 2); the cross-

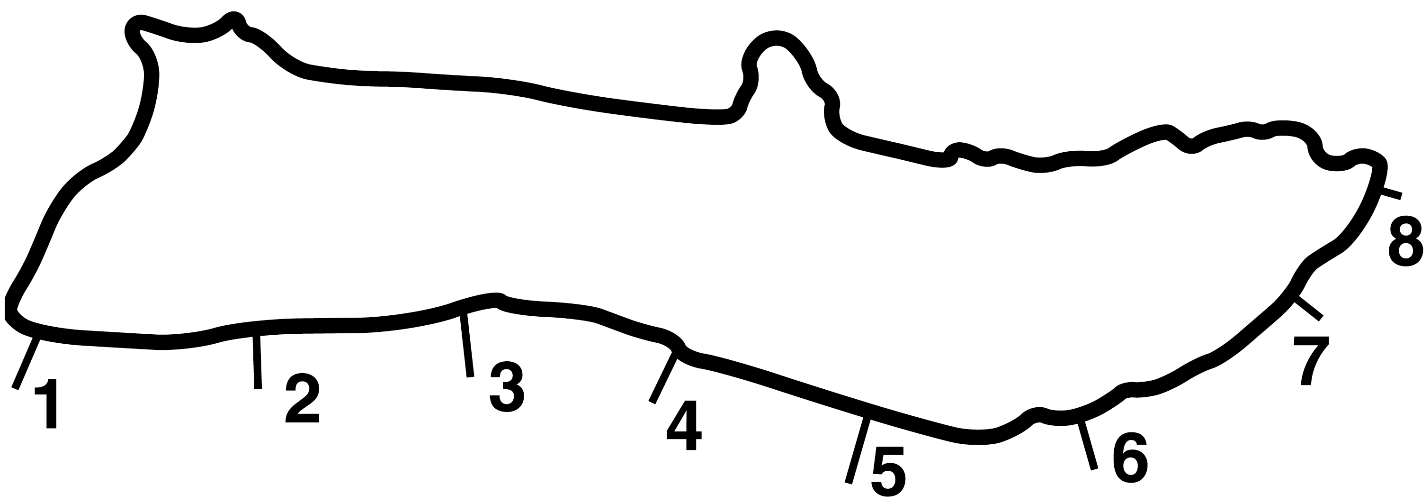

Fig. 2 Location of reef profiles

sectional profiles of the reef along these transects are shown in Figure 3. Profiles #1 and #8 clearly demonstrate that no shallow reef flat is present at the ends of the island and suggest that these profiles are good examples of the island where no well-defined reef exists. Profiles #3 through #6 display a well-defined reef flat that extends over 1500 m offshore. These profiles also show a steeper slope from greater than 20 m to the 30 m isobath, which corresponds to the toe of the present-day reef observed during scuba transects. Profiles #2 and #7 show the transition from no clearly defined reef at the ends of the island to the well-defined reef shown off the central portion of the island (Profiles #3-6). These Profiles (#2 and #7) display a reef flat on average 500 m wide and a less

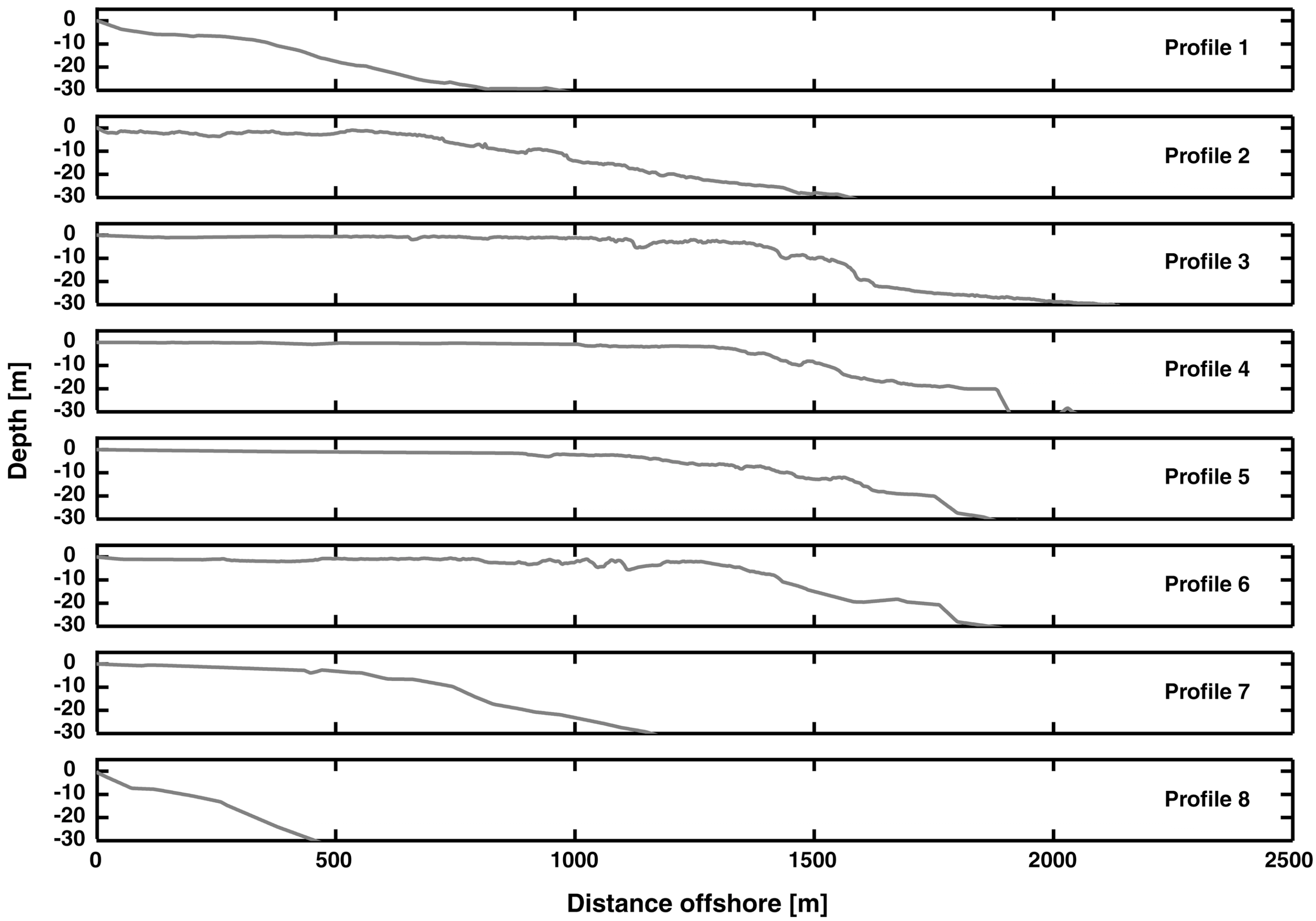

Fig. 3 Cross-sectional profiles of the fringing reef off southern Molokai

steeply sloping fore reef that lacks the abrupt increase in slope between 20 m and 30 m seen in Profiles #3 through #6.

Coral Distribution

Total coral coverage was extremely high, typically greater than 90% except near the western end of the island, where the total coral cover drops sharply. *Porites compressa* dominates most of the central portion of the reef, with individual percentages often exceeding 80% of the total species observed; it too, however, decreases with increasing proximity to the island's west end. *Porites lobata*, a more robust, encrusting member of the *Porites* genus, is typically observed to comprise only 5% of the total coral cover. However, within 8 km of the west end of Moloka'i, it reaches a maximum of 30% of the total species observed before decreasing to only 10% at the western-most mapping station. *Montipora* species, which commonly comprise less than 20% of the total species, increase up to 60% of the total species 9.5 km from the island's west end but virtually disappear at the west end of the island. *Pocillopora meandrina* is also found at very low levels (~ 3%) along most of the reef, except in the western-most stations where it makes-up between 10% and 20% of the total species observed.

Wave Modeling

The WAM was run for the four main wave regimes for the Hawaiian Islands and a commonly observed combination of a North Pacific swell and trade wind waves (Table 1). The WAM North

Table 1. SWAPS WAM modeling conditions*

Wave Regime	Date, mm/dd/yyyy	Hs, m	Tp, sec	Wave Direction†, deg	Uwind, m/sec
North Pacific swell	01/28/1998	8.4	20	320	6.1
Kona storm waves	08/16/1998	2.8	9	170	7.2
Southern Ocean swell	06/08/2000	2.5	20	180	6.2
Tradewind waves	06/23/1998	3.2	8	50	13.8
Tradewind waves & North Pacific swell	11/30/1998	4.6	8 (Tradewind) 16 (N. Pacific)	50 (Tradewind) 350 (N. Pacific)	12.5

* Data from NOAA buoys #51001 and #51002

† Direction from true north the waves are coming from

Pacific swell run displayed a strong effect on the northern, eastern, and western sides of the island, which were exposed to the brunt of this large swell with a high horizontal orbital velocity (u > 1.5 m/sec). In contrast, the area off the southern shore where the large fringing reef has developed is in a significant shadow zone characterized by a low horizontal orbital velocity (u < 0.2 m/sec). Along the majority of the fringing reef, bed shear stresses are less than 0.2 N/m^2 in 10 m of water. At both the east and west ends of the island where the reef starts to narrow and finally disappear (Fig. 2), the shear stresses rapidly increase five-fold to greater than 1 N/m^2. The northern coast of Lanai and the western coast of Maui, both of which exhibit substantial reefs, also are in Molokai's wave shadow.

The Kona storm waves, which were modeled to see how the south shore of Molokai would be impacted by an unrefracted swell, did not generate high orbital wave velocities (mean = 0.19 m/sec) anywhere along the island, likely due to their relatively short period. The Southern Ocean swell, on the other hand, produced intermediate stresses (~0.3 N/m^2) along almost the entire length of Molokai's fringing reef. These waves also directly impact the southwestern shore of Maui, which do not exhibit similar reef development even though these reefs are protected from North Pacific swell by the island of Molokai. The modeled trade wind waves appear to primarily impact the eastern and southeastern coast of the island. Due to their short period and intermediate height, these waves produce rather low orbital velocities, on the order of 0.3 m/sec. In combination with a typical North Pacific swell, however, the model suggests that much higher orbital velocities impact the eastern and southeastern shore of Molokai, on the order of 0.8-0.9 m/sec along the areas where the reef starts to pinch out.

DISCUSSION

In general, a reef's optimum growth typically exists between 10 m and 20 m, reflecting the trade-off between reduced wave-induced stress at depth with decreased light available for photosynthesis. This suggests that in high-energy environments the reef should be less well defined, and display both lower coral cover and more wave-resistant species. Conversely, a more developed reef with both higher total coral cover and more delicate coral species should be present in lower energy regimes. Figure 4a displays the relationship between wave-induced near-bed shear stress calculated using the data from the WAM North Pacific winter swell run and coral observations along the 10 m isobath. *Porites compressa*, a delicate finger-like coral that covers the majority of the central portion of the reef, rapidly disappears toward the ends of the reef where the modeled shear stresses increase above 0.45 N/m^2. As *P. compressa* starts to disappear, we see an increase in the more resistant, plate/encrusting *Montipora* species at shear stresses between 0.44 N/m^2 and 0.47 N/m^2. These species appear to be able to thrive where the *P. compressa*, which dominates at lower shear stresses, cannot. As the modeled shear stresses exceed 0.47 N/m^2, the *Montipora* species start to disappear and are replaced by the very robust *Porites lobata*, at to a lesser extent, branching *Pocillopora meandrina* up to 0.51 N/m^2, above which both species decline to very low numbers. Total cover starts to rapidly drop from an average of 90% along most of the central portion of the fore reef,to 20% when the modeled shear stresses typically exceed 0.5 N/m^2. Thus, the zones where each of the coral species dominates appear to be able to be defined by near-bed shear stresses.

A strong inverse, linear, relationship exists between the modeled shear stresses and the reef flat width (estimated as the 0-5 m isobath distance, r^2=0.83) and the total reef width (estimated as the 0-30 m isobath distance, r^2=0.90) as shown in Figure 4b. Both of these correlations exceed the 0.1% significance level for $n = 8$. The central portion of the reef off southern-central Molokai is protected from direct wave impact and thus the reef framework would be able to develop into an extensive shallow reef flat and broad fore reef. The east and west ends of the island are exposed to larger, longer period waves that generate high orbital wave velocities and thus strong near-bed shear stresses. This appears to limit substantial reef development due to physical breakage of the coral and high abrasion by both bedload and suspended sediment.

The relationships between wave-induced forces and the distribution patterns of various coral species provide some insight into the controls on coral species distribution and, on a larger scale, into

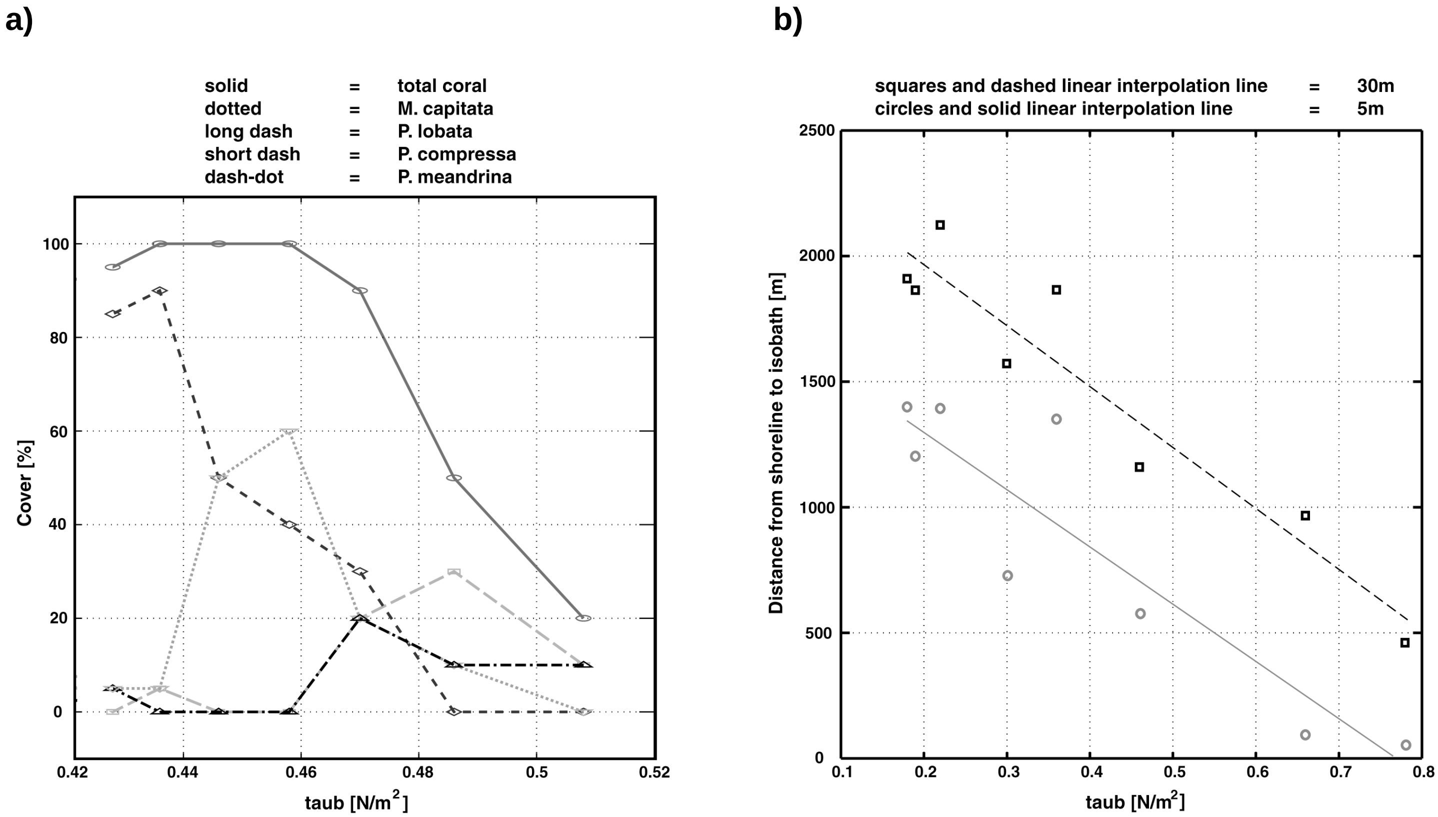

Fig. 4 Plots showing the relationships between modeled wave-induced bed shear stresses and (a) coral cover, (b) reef width

the development of reefs as three-dimensional structures. Further studies running high-resolution shallow-water wave models using the SHOALS bathymetric data for specific locations will allow us to better constrain these relationships. This information will hopefully allow us to better understand the importance of how other factors, such as anthropogenic eutrophication and increased sedimentation, influence coral species distribution.

CONCLUSIONS

Wave modeling was used, in conjunction with bathymetric and coral species distribution data, to better understand the influence of wave-induced forces on coral reefs. It was shown that reef flat width, total reef width, and total coral cover decrease with increasing wave-induced near-bed shear stresses. As near-bed shear stress increases, the dominant species *Porites compressa* decreases rapidly and is replaced with more hearty *Montipora* species. At even higher shear stresses, *Montipora* species are replaced by the very robust *Porites lobata*, at to a lesser extent, *Pocillopora meandrina*. , Less than 20% total coral cover and little to no well-defined reef structure was observed when modeled near-bed shear stresses exceeded 0.51 N/m^2.

ACKNOWLEDGEMENTS

This work was carried out as part of the USGS's Coral Reef Project as part of an effort in the U.S. and its trust territories to better understand the health and geologic variability of coral reef systems. Paul Jokiel and Eric Brown contributed as part of the ongoing USGS/University of Hawaii Cooperative Studies Program. We would especially like to thank Josh Logan (USGS), our project's GIS specialist, who graciously provided hours of processing to help us visualize and analyze the SHOALS and NOS bathymetric data to constrain the reef's morphology. We would also like to thank Joe Reich, the captain of the *R/V Alyce C.*, who piloted and navigated during the coral coverage surveys and during our numerous dive transects and instrument deployments.

REFERENCES

Blanchon, P. and Jones, B., 1997. Hurricane Control on Shelf-edge-reef Architecture Around Grand Cayman. *Sedimentology*, 44, 479-506.

Dollar, S. J. (1982). Wave stress and coral community structure in Hawaii. Coral Reefs 1:71-81.

Done, T.J. and Massel. S.R.. (1993). Effects of cyclone waves on massive coral assemblages on the Great Barrier Reef: meterology, hydrodynamics and demography. Coral Reefs 12:153-166.

Grigg, R.W., 1998. Holocene Coral Reef Accretion in Hawaii: A function of wave exposure and sea level history. *Coral Reefs*, 17, 263-272.

Jonsson, I.G., 1966. Wave Boundary Layers and Friction Factors. *Proceedings of the 10th International Conference on Coastal Engineering*, 127-148.

Moberly, R.M., and Chaimberlin, T., 1964. *Hawaiian Beach Systems*, University of Hawaii, 95p.

Nielsen, P., 1992. *Coastal Bottom Boundary Layers and Sediment Transport*, World Scientific, 324 p.

Rogers, C.S., 1993. Hurricanes and Coral Reefs: The Intermediate Disturbance Hypothesis Revisited. *Coral Reefs*, 12, 127-138.