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Predictions of Turbidity Due to Enhanced Sediment Resuspension Resulting from Sea-Level Rise on a Fringing Coral Reef: Evidence from Molokai, Hawaii

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ABSTRACT

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Accelerating sea-level rise associated with global climate change will affect sedimentary processes on coral reefs and other shoreline environments by increasing energy and sediment resuspension. On reefs, sedimentation is known to increase coral stress and bleaching as particles that settle on coral surfaces interfere with photosynthesis and feeding, and turbidity induced by suspended sediment reduces incident light levels. Using relationships developed from observations of wave orbital velocity, water-surface elevation, and suspended-sediment concentration on a fringing reef flat of Molokai, Hawaii, predictions of the average daily maximum in suspended-sediment concentration increase from ~11 mg/l to ~20 mg/l with 20 cm sea-level rise. The duration of time concentrations exceeds 10 mg/l increases from 9% to 37%. An evaluation of the reduction of wave energy flux through breaking and frictional dissipation across the reef flat shows an increase of ~80% relative to the present will potentially reach the shoreline as sea level increases by 20 cm. Where the shoreline exists on low, flat terrain, the increased energy could cause significant erosion of the shoreline. Considering the sediment budget, the sediment flux is predicted to increase and removal of fine-grained sediment may be expedited on some fringing reefs, and sediment in storage on the inner reef could ultimately be reduced. However, increased shoreline erosion may add sediment and offset removal from the reef flat. The shifts in sediment availability and transport that will occur as result of a modest increase in sea level have wide application to fringing coral reefs elsewhere, as well as other shoreline environments.

ADDITIONAL INDEX WORDS: *Sediment budget, wave dissipation, suspended sediment.*

INTRODUCTION

Discussion about effects of climate change on coral reef health and sustainability has largely focused on the effects of rising sea-surface temperature (*e.g.*, Jokiel and Coles, 1990; Sheppard and Obura, 2005). This is for good reason: bleaching events in 1995, 1998, and 2005 in the Caribbean have been some of the most intense events to ever occur, and each was associated with climate change and global warming that is well documented and ongoing (IPCC, 2007). However, increased sedimentation has also been correlated to coral stress and bleaching (*e.g.*, Meehan and Ostrander, 1997; Riegl and Branch, 1995). The presence of suspended sediment may stress corals by reducing incident light levels (Rogers, 1990), and moreover, particles that settle on coral surfaces interfere with photosynthesis and hinder feeding (Bak, 1978). As part of global warming, sea levels will continue to rise, and the effects of increased water-surface elevation on coral reefs has received little attention in the scientific literature. The impacts can be varied, and include increased circulation due to broader interaction with offshore water and changes in exposure to dissolved and particulate matter. Increased water-surface elevation will also change rates of erosion, resuspension, and transport of terrigenous sediment on fringing reefs, and these impacts on turbidity are explored in this study.

It is generally accepted that one-half or more of the present sea-level rise is a response to warming and expansion of seawater—the steric effect—resulting from an overall climate warming. Additional causes of observed sea-level rise include melting of glaciers and ice sheets, but future projections for those sources are not well constrained (Bindoff, *et al.*, 2007). Also, the rate of rise is not well established for many regions of the ocean because of complications from local tectonics (uplift and subsidence), decadal patterns in winds, pressures at the sea surface, and other factors. Recent analyses indicate that global (*i.e.*, eustatic) sea level has risen at ~2 mm/y for at least the last century or so, and IPCC estimates range between ~1 and 6 mm/y at present for the next century (IPCC, 2007). Global sea level is expected to rise at a much faster rate than at present because of global warming (*e.g.*, Church *et al.*, 1991), and IPCC projections for the later half of the 21st century range between ~1 and 11 mm/y. In this study we will use a moderate estimate of 5 mm/y for future sea-level rise that will result in an increase in the water-surface elevation of 20 cm in the next three to five decades. Although the rate of sea-level rise can be

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debated, here we investigate the impact of 20 cm of rise and assume it is at a rate or under circumstances that reef accretion in Hawaii cannot keep up.

Aside from providing 10s of centimeters of growing space for corals that are at or near sea level, the rise will have an impact on coral reef sustainability in a variety of interrelated ways. Slower-growing coral species may be unable to keep up with sea-level rise (Hoegh-Guldberg, 1999), and when coupled with other stresses related to sea-level rise such as rising temperatures and reduced salinity, reef sustainability could be greatly compromised. In addition, circulation and wave energy across the reef complex will change. For example, reef crests and flats dissipate offshore wave energy (*e.g.*, Wolanski, 1994) and it is hypothesized that with rapid sea-level rise, significantly more wave energy could propagate past the reef crest and onto the reef flat. Change in circulation may create enhanced flushing; the greater seabed shear stresses induced could cause increased sediment resuspension and shoreline erosion (*e.g.*, Buddemeier and Smith, 1994).

Sediment resuspension and transport in reef environments is difficult to predict. Uncertainties are associated with highly variable seabed roughness, settling characteristics of mixed carbonate and siliciclastic sediment, and the changing availability of types of sediment within the seabed. Turbidity on reef flats could increase by two separate processes associated with increased water-surface elevation: increased capacity for resuspension of sediment in shallow reef areas, and increased capacity to erode fine-grained sediment from adjacent coastal plains and deltaic deposits. This study utilizes time-series wave and sediment-transport data on a fringing reef and explores relationships between sediment resuspension and water-level variations due to tides to develop predictions that indicate that rising sea level may increase turbidity on coral reefs. The settling of sediment from suspension subsequently is responsible for short-term deposition rates that have been connected to coral stress (Philipp and Fabricius, 2003). These results imply that fringing reefs will be particularly susceptible to increased impact resulting from sedimentary processes, and they may have application to other shallow coastal habitats.

BACKGROUND

Description of Reef Flat Environment

The data for this study come from detailed investigations of the fringing reef along the south coast of the island of Molokai, Hawaii; general characteristics of the reef morphology and wave climate are summarized in Field *et al.* (2008b). The Molokai reef is the largest continuous fringing reef in the main Hawaiian Islands (Figure 1), extending for >50 km along the south-central coast. The fringing reef consists of a broad, shallow (0–2-m water depth) reef flat that extends nearly 1 km offshore, rising to a reef crest that is partially exposed at low tide, and a fore reef that descends gradually offshore to ~30-m water depth. The morphology of the inner reef flat is similar to other fringing reef flats (*e.g.*, Kennedy and Woodroffe, 2002) and is characterized by a slight depression with an inshore band of fine-grained terrigenous sediment and very little coral coverage (Guilcher, 1988). The mid- to outer reef flat is

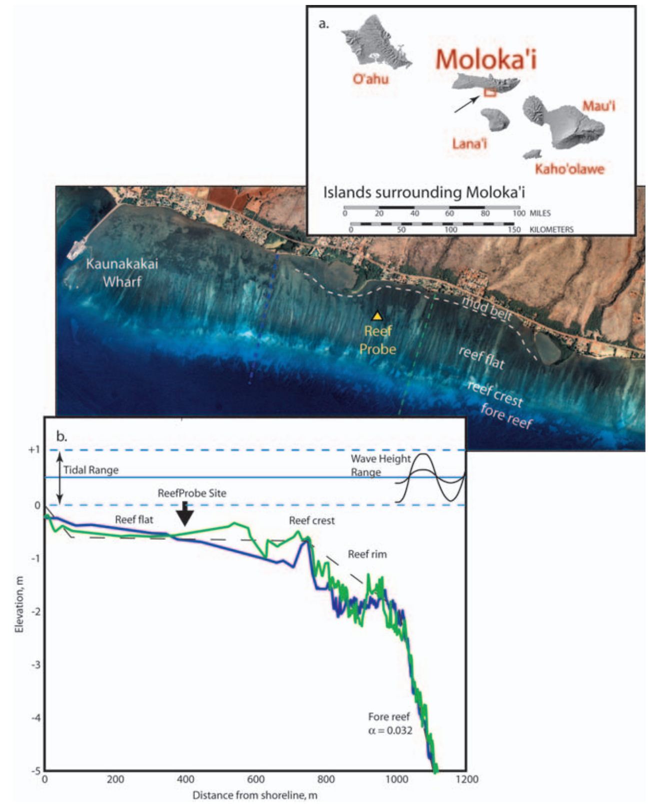

Figure 1. Aerial photograph of the study area on the south-central Molokai reef. The triangular symbol denotes the ReefProbe instrumentation site and dashed lines indicate locations of cross-sections shown in (b). The inset (a) shows selected Hawaiian Islands depicting the location of Molokai within the surrounding islands, and (b) shows two reef cross-sections from the shoreline to the fore reef. The dashed line represents the idealized reef morphology.

cemented with encrusting coralline algae, variable to patchy covering of fine-grained terrigenous sediment, and striations of sand and gravel (Calhoun and Field, 2008; Guilcher, 1988). The nearly continuous reef crest, which is exposed to the majority of wave breaking (Storlazzi *et al.*, 2004), is composed of some robust coral coverage, reef rubble, and mostly sand-sized carbonate sediment. Along most of the coast, the fore reef has extensive live coral coverage, mainly *Porites compressa* and *Montipora* sp., and is dominated by spur and groove morphology (Storlazzi, Logan, and Field, 2003). Very high coral coverage is observed for the extent of the fore reef along the south coast of Molokai, except in the 4-km region east of Kaunakakai Harbor (Jokiel *et al.*, 2008). Net sea-level rise on the island of Molokai can be approximated by the eustatic rate, although subsidence and flexure are active in the region. Subsidence of the islands due to volcanic loading is most rapid at Hawaii and decreases to the northwest. At Kahului, Maui, the subsidence rate is 0.8 mm/y, which adds to eustatic sea-level rise, while at Honolulu, Oahu, the rate is negligible (Jones, 1993). Molokai, located between Oahu and Maui, is close to being tectonically stable (Grigg and Jones, 1997) and thus we will consider only eustatic sea-level rise.

Summary of Results from Prior Studies

The sediment dynamics on the south-central Molokai reef has been the topic of significant study (*e.g.*, Ogston *et al.*, 2004; Presto *et al.*, 2006; Storlazzi *et al.*, 2004). Terrestrial sediment is delivered to the fringing reef from erosion of the south side of the island. Transport of fine-grained terrigenous sediment to the reef increased during the 20th century because of a variety of human-induced changes to the watersheds (Roberts, 2001). Much of the fine sediment delivered to the reef is trapped on the shallow inner reef flat where it is stored in thin deposits (Field *et al.*, 2008a) and trapped by macroalgae (Stamski and Field, 2006). Offshore waves break and much of their energy is dissipated at the reef crest located approximately 0.5–1.0 km from the shoreline (Storlazzi *et al.*, 2004). Previous studies of dynamic sediment-transport processes have shown that maximum turbidity occurs because of combined wave–current interaction stresses (Ogston *et al.*, 2004). The combination of higher-than-average tidal water-surface elevation and strong winds is necessary to resuspend the observed high concentrations of sediment (10–30 mg/l) on the mid-reef flat. This happens almost daily when trade winds blow at moderate to high levels, and is enhanced in the afternoons because of the insolation-generating heating of the Hawaiian Islands. Trade-wind conditions occur ~83% of the time from May to November and 37% of the time from November to May and are the condition driving the dominant net sediment flux along the reef flat in the annual record (Presto *et al.*, 2006). The relative orientation between the wind and shoreline morphology causes retention of much of the terrigenous sediment in a band of 500-m width along the shore.

METHODS

Time-Series Data

A small bottom-boundary-layer tripod, the ReefProbe, was deployed ~500 m from the shoreline on the fringing south-central Molokai reef flat. The mean water depth at this location was approximately 1 m. The instrument monitored water-surface elevation, waves, currents, suspended-sediment concentration, temperature, and salinity for over 2 years of record (January 2000 to May 2002). Data bursts of 256-second duration at 2-Hz sampling rate were collected hourly. Wave orbital velocities were estimated from the root mean square (RMS) fluctuation of velocity magnitude around the hourly burst mean. An anemometer was mounted on the seaward end of the Kaunakakai wharf for the later part of the data record, and provided half-hourly wind speed and direction data. For more details on the data and calibration of optical sensors to suspended-sediment concentration see Ogston *et al.* (2004) and Presto *et al.* (2006).

The optical sensors used to measure the suspended-sediment concentration were treated with an antifouling agent, yet experienced some biofouling at periods in the overall record. For this study we selected a month-long segment of data (August to September, 2001) from sensors that had not succumbed to fouling. This subset of the data captures a spring–neap tidal cycle and contains periods of both strong trade-wind and light variable wind conditions, and thus is representative of the long time series. Seabed grain-size information was obtained from sample collection and analyses as part of a study by Calhoun and Field (2008). The grain size of sediment in suspension was obtained from collection of particles in a settling column placed near the ReefProbe, with opening at ~30 cm above the seabed.

Estimation of Shear Stresses and Model of Suspended-Sediment Concentrations

Shear stresses, τ_b, at the seabed were estimated using a Grant–Madsen wave–current interaction model (Grant and Madsen, 1979), and are characterized by the shear velocity, u_*, where $\tau_b = \rho u_*^2$, and ρ is the fluid density. The model integrates observations of wave orbital velocity and mean currents, and the angle between them. Seabed roughness was estimated to obtain the shear stress, and for this study we estimated the local roughness to be 0.2 cm, which reflects not only grain roughness but also slight biological mounding of the seabed surface. At the ReefProbe site, the seabed consisted of coarse carbonate sediment mixed with finer terrigenous sediment (Ogston *et al.*, 2004) and no nearby coral heads or physical bedforms.

Using a simple one-dimensional (1-D) model, suspended-sediment concentration can be calculated from the observed stresses. This basic 1-D model only evaluates resuspension, diffusion, and settling, and does not take into account advection of sediment from other areas. Thus, it is not meant to simulate physical conditions on the reef flat, but rather is used as a tool with which to predict changes under differing water-surface elevations. At each hourly time interval, sediment resuspension at a reference level very close to the seabed (z_a) was estimated from the relation for the reference concentration (Smith and McLean, 1977):

$$C_a = C_b \frac{\gamma_o S}{1+\gamma_o S} \tag{1}$$

where the concentration at a reference height, C_a, is related to the concentration of sediment in the seabed, C_b, a resuspension parameter, γ_o, and the excess shear stress, S, defined as:

$$S = \frac{\tau_b - \tau_{cr}}{\tau_{cr}} \tag{2}$$

where τ_{cr} is the critical shear stress required for erosion. The concept of a reference level was initially formulated for systems where suspended sediment is shed from an underlying bed load layer, the reference height being the distance from the seabed to the top of the bed load layer. Although there is no bed load layer for muddy sediment, the concept is still used.

The Rouse equation, in its most simplistic form, describes the vertical profile of a specific suspended-sediment size class,

$$C_z = C_a \left({}^{z}/_{z_a}\right)^{-{}^{Ws}/{}_{Ku_*}} \tag{3}$$

where C_z is the concentration at any height, z. The ratio of C_z/C_a is a function of the shear velocity (u_*) and the settling velocity (Ws) for a given size class. K is von Karman's constant (~0.40). In this study, the Rouse equation was used to estimate the concentration of suspended sediment at 20 cm above the

Table 1. *Model input parameters.*

Parameter	Typical Range of Values	Value Used in Model
Settling velocity, W_s	0.001 cm/s to 0.04 cm/s	0.01 cm/s
Concentration in seabed, C_b		0.049 g/cm^3
Resuspension parameter, γ_o	10^{-5} to 10^{-3}	1.7×10^{-4}
Threshold of erosion, u_{*cr}	0.7 cm/s (crushed silicate) to 4.0 cm/s (consolidated mud)	0.95 cm/s

seabed, where suspended-sediment concentrations were measured at the ReefProbe site.

The equations above utilize several parameters that are not well known on the reef flat: C_b, γ_o, Ws, and τ_{cr}. Representative ranges of the values of these parameters from the literature and estimated values from the data are shown in Table 1. Best estimates were made for these parameters, and the value of γ_o was used as a tuning parameter for the model, and checked to ensure that the value used is realistic for the sediment on the reef flat.

Model of Wave-Energy Decay over Fringing Reef

Larger waves break on coral reef crests, where energy is redistributed and dissipated, or propagate onto the reef flat where further frictional dissipation occurs. Wave-generated flows have been the topic of significant study on reefs (*e.g.*, Hearn, 1999; Symonds, Black, and Young, 1995). Here, we do not try to assess the validity of a specific wave model, but rather use the model to illustrate the impacts of changing sea level on the wave energy that propagates across the reef flat to the shoreline. A semiempirical model of wave transformation on coral reefs was developed by Gourlay (1996a,b) and incorporates factors of offshore wave height and period and reef-crest and reef-flat water depth to establish the wave setup, breaking zone width, and to estimate the number of reformed waves after breaking. It assumes that waves break at the reef crest parallel to shore, which causes water surface setup, and that after breaking, the reformed wave heights can only exist at a wave height to water depth (including setup) ratio of 0.4, which was determined from field data both in reef environments (Gourlay, 1997) and sandy coastal zones (*e.g.*, Thornton and Guza, 1983). The reformed waves propagate without refraction across the reef top. Energy is dissipated as waves propagate across the reef flat due to friction/roughness and break parallel to the shoreline behind the reef. The wave energy ($E = 1/8\rho g H^2$) can thus be calculated at any point across the reef top. A simple version of the model was utilized by Sheppard *et al.* (2005) in the Seychelles to evaluate the impacts of coral mortality on shoreline processes. They provide a spreadsheet version of the model (http://www.bio.warwick.ac.uk/res/frame.asp?ID=42).

For the Molokai reef flat, the model was applied in an idealized, simplistic form and the reef flat can be considered as the reef top in the model. We calculate the input wave energy flux for four different wave heights, and compare that with the energy flux at the shoreline. The input wave heights span the range of observations reported in Storlazzi *et al.* (2004). Parameters necessary for the model construct are listed in Table 2. The friction factor used (0.14) is consistent with a smooth coral pavement with partial coral rubble (Sheppard *et al.*, 2005). The setup and breaking condition is dependent upon the seabed slope at the location of breaking. In this case we use the slope just offshore of the reef crest, the reef rim, as shown in Figure 1.

RESULTS

Data Description

A 28-day record from 8 August 2001 to 5 September 2001 of water-surface elevation, wave orbital velocity, currents, and suspended-sediment concentration from the ReefProbe tripod were used in this study. It was selected as a period that covers a lunar cycle of tidal variation when winds were initially strong, sensors were not biofouled, and signals were clear and variable, allowing us to test the sediment resuspension model in a variety of situations.

The wind speed over the reef flat has a clear diurnal cycle (Figure 2a) when the trade-wind pattern is strong with the winds increasing rapidly mid-morning to speeds of ~12 m/s (peak of 15 m/s) and dropping rapidly in the afternoon. This time series includes a period of very regular trade-wind forcing (days 585 to 596) and a period of less regular wind forcing (days 597 to 613). The water-surface elevation (Figure 2b) on the mid-reef flat ranged from 0.38 to 1.35 m in response to the mixed semidiurnal tides. The wave orbital velocity (RMS) ranged from 2 to 12 cm/s (Figure 2c), and was strongly modulated by the water-surface elevation. Currents on the

Table 2. *Parameters needed to evaluate wave dissipation across reef flat.*

Parameter	Source	Values Used in Model
Offshore wave height and period	Range observed in Storlazzi *et al.* (2004)	Variable wave height from 0.2 to 0.8 m (RMS), and 7-s wave period
Angle of reef face	Measured—Figure 1	0.032
Reef flat depth	Measured with tidal variation	Present: varies from 0.5 to 1.5 m with tide. Future: varies from 0.7 to 1.7 m with tide.
Reef width	Measured—Figure 1	1000 m
Frictional coefficient on reef flat	*fw*, Gourley (1997) 0.1–0.2; Sheppard et al. (2005) 0.12	0.14
Reef profile shape factor	*Kp*, comparable with Ala Moana form in Gourlay (1996a)	0.2

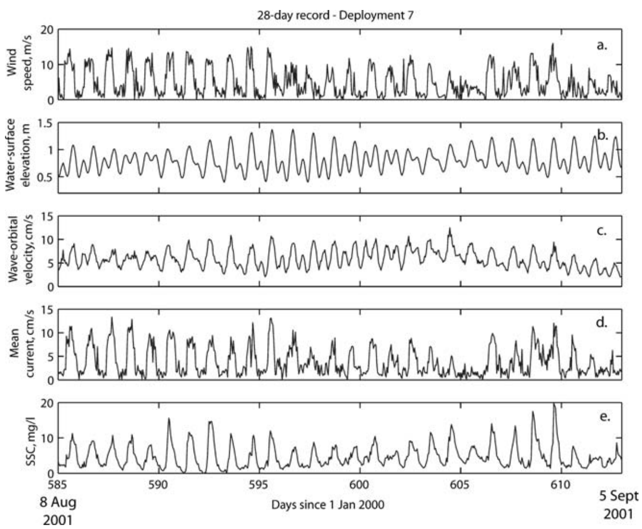

Figure 2. Time-series data over a trade-wind period including spring/neap cycle: (a) wind speed collected from an anemometer located at the end of Kaunakakai Wharf; and hourly averaged data from the ReefProbe site of (b) water-surface elevation, (c) wave orbital velocity, (d) current speed, and (e) suspended-sediment concentration.

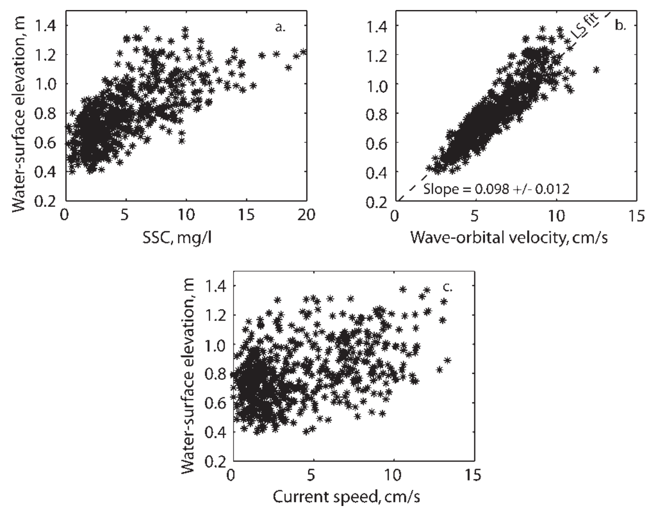

Figure 3. Relationships between: (a) water-surface elevation and suspended-sediment concentration, (b) water-surface elevation and wave orbital velocity showing a least-squares fit, and (c) water-surface elevation and current speed for the 28-day time series shown in Figure 2.

reef flat were dominantly directed along the reef toward the west, and ranged in speed from 0 to 13.2 cm/s (Figure 2d). During times of weak winds (*e.g.*, days 604 to 606), the speeds induced by the neap tides were only 0 to 3.4 cm/s. Other studies have shown that the tidally induced currents are relatively small on the reef flat (Ogston *et al.*, 2004), reaching maximum speeds between 3 and 5 cm/s. The suspended-sediment concentration in the water column varies on a daily basis (Figure 2e), and ranged from 0 to 20 mg/l, with a typical daily peak of 10.8 mg/l.

Data Correlations

To evaluate the forcing for sediment resuspension as a function of the water-surface elevation, the suspended-sediment concentration, wave orbital velocity, and mean currents were correlated to the water-surface elevation. There is a general trend in the relationship between the water-surface elevation and the suspended-sediment concentration with increasing concentrations at higher sea levels, but there is much scatter in the data (Figure 3a). The wave orbital velocity is strongly dependent on water-surface elevation, particularly at the lower levels (Figure 3b). There is more scatter in the relationship at higher water-surface elevations, likely due to the variation in offshore wave energy. Although the relationship between water depth and wave orbital velocity is not linear in shallow water, in this range of water depths the data show that the relationship can be approximated using a linear fit. On the basis of the data, a relationship was created between the change in water-surface elevation on the mid-reef and the wave orbital velocity:

$$\Delta U_{\mathrm{rms}}(\mathrm{cm/s}) \approx 0.1 * \Delta \mathrm{WSL}\ (\mathrm{m}) \tag{4}$$

where ΔU_{rms} represents the change in wave orbital velocity, and ΔWSL represents the change in water-surface elevation. The alongshore current speed shows little dependence on water-surface elevation (Figure 3c). A higher water-surface elevation may be necessary for the strongest current magnitudes, but in general, no clear relationship exists. This is likely due to the dependence of alongshore velocity on the wind speed (Figure 4), with the water-surface elevation acting as a secondary control.

The suspended-sediment concentration is better correlated to the calculated shear velocity at the bed (Figure 5) than to the water-surface elevation. The shear stresses obtained from the wave–current interaction model incorporate both the wave orbital velocity (which is a function of water-surface elevation, Figure 3b) and the mean currents (which is not, Figure 3c). A threshold of sediment motion can be estimated from this relationship at $u_* \sim 0.95$ cm/s. Above threshold, the relationship can be adequately described with an exponential as predicted from theory (see Equations 1–3). The variation of the data above the theoretical relationship is expected, as particles with a slow settling velocity cannot respond instantaneously to reductions in stress, and no account is taken for advection. This relationship suggests that a simple 1-D model between bed shear stresses and suspended-sediment concentration can be developed that will generally describe the conditions of sediment resuspension in the Molokai reef flat, but may not capture all of the details.

Parameters for Prediction of Suspended-Sediment Concentration

The settling velocity, *W*s, of particles depends on their nominal diameter. The grain-size distribution of sediment on the seabed at the mid-reef site consisted of coarser carbonate fragments and a matrix of fine sediment of terrigenous origin

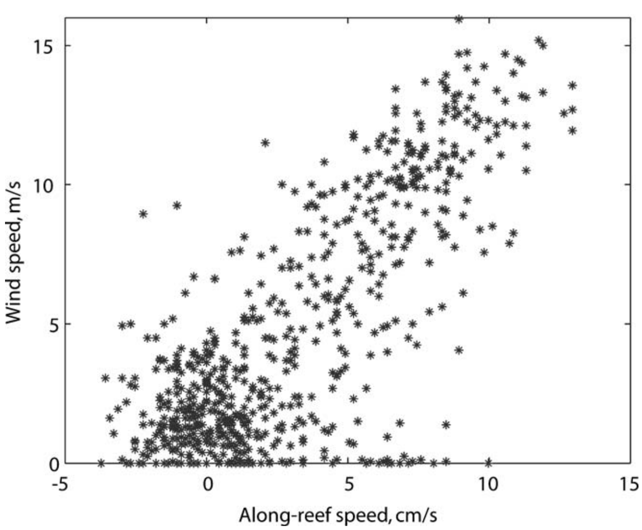

Figure 4. Along-reef component of current speed *vs.* magnitude of wind speed. The alongshore current is more dependent upon wind speed than on water-surface elevation (see relationship in Figure 3).

(Field *et al.*, 2008a). Not all of this sediment is put into suspension under high shear stresses, only the finer material. A simple sediment trap with opening at ~30 cm above the seabed was placed at the site to capture particles over a single daily cycle. The grain size of the sediment captured in the trap had a median diameter of ~8.5 μm (Figure 6) and ranged in size from D_{25} = 4 μm to D_{75} = 25 μm, with corresponding settling velocities of 0.0010 and 0.040 cm/s, respectively,

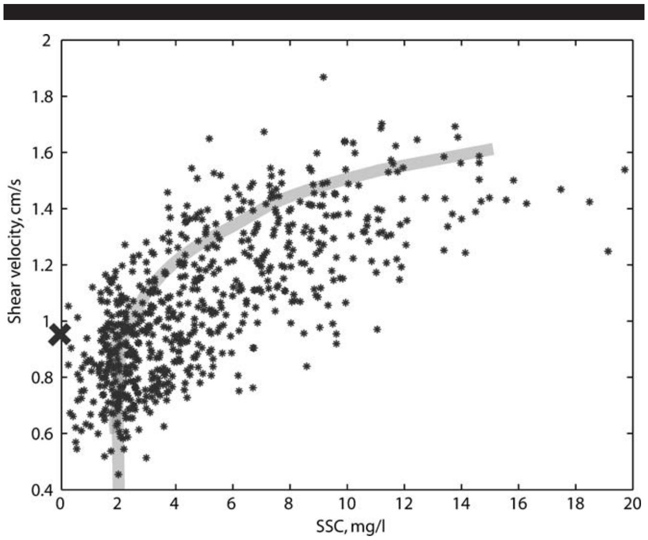

Figure 5. Suspended-sediment concentration *vs.* the shear velocity, u_{*wc}. The stars indicate the data points. The gray line shows an example theoretical relationship that indicates a threshold of grain motion (large "X" at u_{*wc} ~ 0.95 cm/s) below which the suspended-sediment concentration is near zero (but in the natural system reflects a small amount of sediment or organic matter that is continually suspended in the water column), and above which the concentration increases exponentially with the shear stress felt on the seabed.

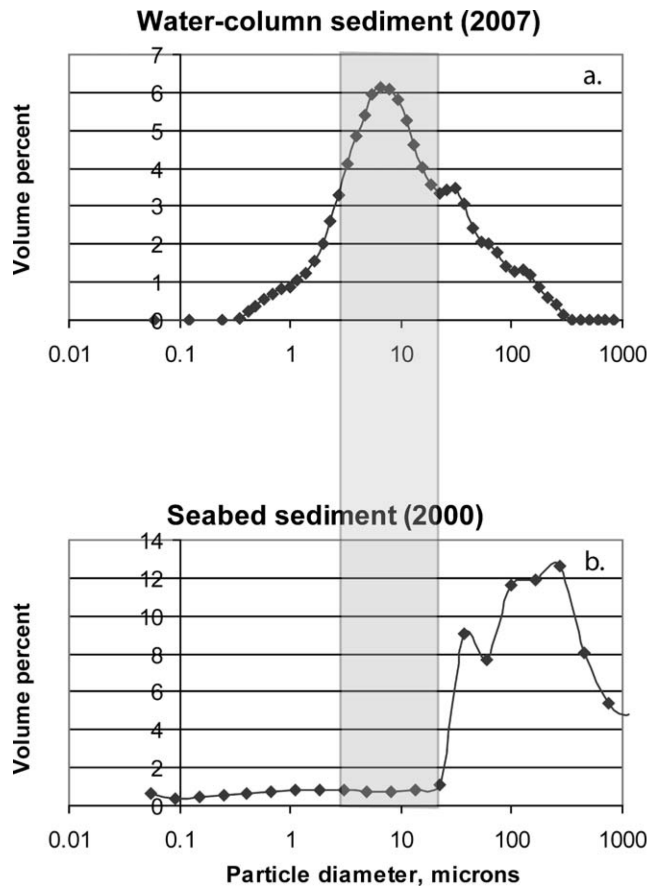

Figure 6. Grain-size data at the Reef Probe instrument site in (a) the water column and (b) the seabed. Bulk grain size was analyzed using both a Coulter Counter for silt and clay and a settling column for sand. Within the silt and clay fractions, the grains are composed of ~90% terrigenous material.

assuming flocculation does not occur. In this study, a single value of settling velocity of 0.01 cm/s is used to represent the assemblage of fine material in suspension.

The concentration of fine-grained sediment within the seabed, C_b, acts to control the reference concentration. To determine an appropriate bed concentration, we evaluated the mass concentration of fine-grained particles that exist in the seabed. Defining the fine-grained fraction 0 to 64 μm, seabed grain-size analysis indicates that 9% of the total sediment mass in the seabed falls within the fine-grained size range. A value for the porosity of the seabed was assumed to be 0.8 on the basis of visual observation of the unconsolidated sediment. Therefore, the concentration of fine-grained sediment in the seabed was estimated to be 0.049 g/cm^3.

The resuspension parameter, γ_o, is an empirical constant that has been used to define the reference concentration of suspended sediment. On the basis of suspended-sediment measurements at 10 cm above the bed in the Columbia River, a value of 1.24×10^{-3} was determined (Smith and McLean, 1977) that has been frequently used for resuspension estimates. Other researchers have found values of γ_o that vary over

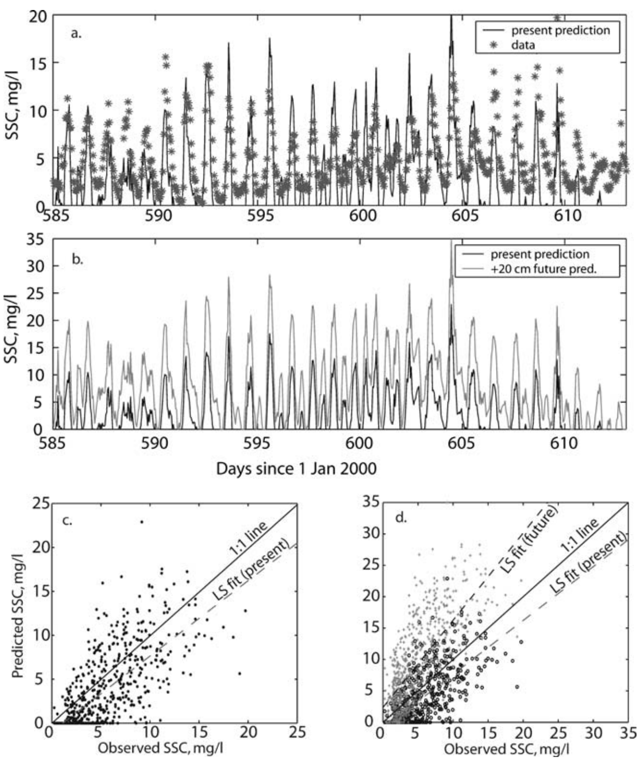

Figure 7. Suspended-sediment concentrations: (a) time series of hourly observed (stars) and predicted (line) using present sea-level elevation, (b) time series of predicted using present sea-level elevation (black line) and predicted with 20-cm sea-level rise (gray line), (c) observed *vs.* predicted showing least-squares fit and the 1 : 1 correlation line, and (d) observed *vs.* predicted using both present (black symbols) water-surface elevations and future (gray symbols) water-surface elevations (present + 20 cm).

two orders of magnitude, ranging from 1.6×10^{-5} to 5.4×10^{-3} (*e.g.*, Kachel and Smith, 1986; Wiberg and Smith, 1983). In fine-grained sediment, it has been suggested that smaller values of γ_o are appropriate. Using the best estimates of the bed concentration and settling velocity on the Molokai reef flat, a value of 1.7×10^{-4} for γ_o yields the best fit of the model to the data, and is a reasonable value according to the literature.

Suspended-Sediment Concentration Predictions

Predictions of suspended-sediment concentrations on the basis of measured mean velocities and wave orbital velocities were made using the parameters discussed above (Table 1). A comparison between the modeled and observed concentrations is shown for the 28-day time period (Figure 7a). The model predicts concentrations that range from 0 to 20 mg/l and the mean difference between the modeled and predicted estimates is 2.8 mg/l. The prediction does a reasonable job of replicating the peak concentrations observed on the mid-reef flat. At low levels of shear stress (below the critical erosion value), the suspended-sediment concentrations dropped to 0 mg/l in the model, whereas a minimal quantity is seen in the data. This is likely due to the small amount of very-fine-grained sediment, or light-scattering organic matter that has an extremely low settling velocity and does not settle out of suspension in the few hours of low tides and slack winds. Although there is significant scatter between the modeled and predicted concentrations at any specific data point (Figure 7c) due to the limitations of the prediction method, the mean of the observed daily peaks (10.8 mg/l) and the predictions (11.1 mg/l) is similar, with a standard deviation of the difference between peaks of ± 2.3 mg/l. It is the peak concentrations that will be compared with the "future" condition. Forcing the model to a least-squares fit with a slope of 1.0 between the predicted and observed concentrations overemphasizes the low-concentration data points, where we cannot predict or observe accurately, and thus overestimates in the future condition.

The model was rerun with 20 cm added to the water level to simulate sea-level rise over the next three to five decades. For this analysis, it was assumed that the only impact on suspended sediment would be the increase in wave orbital velocity felt near the seabed due to increased water-surface elevation. Using Equation (4), sea-level rise of 20 cm was predicted to result in an increase in wave orbital velocity of $\sim$2 cm/s. The shear stresses were recalculated with 2 cm/s added to the wave orbital velocity, and suspended-sediment concentrations were predicted for this future case (Figure 7b). The future model predicts concentrations that range from 0 to 35 mg/l and average 20.3 mg/l (Table 3). Although the timing of peaks in suspended-sediment concentration remains the same, the magnitude of those peaks is significantly greater in the future case with 20-cm rise than in the present case (greater than the prediction uncertainty of ± 2.3 mg/l).

Wave-Energy Dissipation

Wave-energy calculations were performed for varying offshore wave heights and water-surface elevations over a stylized fringing reef. The reef at south Molokai has significant variation (see Figure 1) not captured in the computations and therefore the absolute accuracy of the model is less relevant than the relative changes with water-surface elevation. The friction factor of the reef was used to set the predicted wave height at mid-reef to the observed values. Wave heights calculated from observed U_{rms} values at water elevations of 0.5, 1.0, and 1.5 m were 2.8, 9.1, and 18 cm respectively, and predicted wave heights at the ReefProbe site were 2–3, 9, and 18 cm, respectively. The magnitude of energy flux predicted as the waves approach the shoreline as a function of the various combinations of water-surface elevation and offshore wave heights is shown in Table 4.

In the present condition (sea level not adjusted), it can be seen that significantly more wave energy reaches the shore at high tide than at low tide, regardless of the offshore wave height. This is consistent with an evaluation of wave propagation across the reef crest and flat presented in Storlazzi *et al.* (2004). The amount of wave energy reaching the shoreline is relatively consistent and constrained by the water-surface elevation, not the offshore wave height (*e.g.*, 78 J/m s^{-1} for an 0.8-m wave and 72 J/m s^{-1} for an 0.2-m wave at high tide, Table 4). In all cases, the amount of wave energy is significantly reduced at mid- to low-tide elevations (*e.g.*, 78 J/m s^{-1} at

Table 3. *Model-estimated peak suspended-sediment concentrations (SSC) during strong trade winds with and without sea-level rise incorporated.*

	Mean SSC	Mean Daily Peak in SSC	Maximum Peak in SSC	Percentage of Time Conc. >10 mg/l
Present condition (for trade-wind period, no recent input)	3.1 mg/l	11 mg/l	23 mg/l	76/830 h 9.2%
Future condition with 20 cm sea-level rise (for trade-wind period, no recent input)	8.8 mg/l	20 mg/l	35 mg/l	307/830 h 37%

high tide, 16 J/m s^{-1} at mid-tide, and 1.4 J/m s^{-1} at low tide for the 0.8-m wave height, Table 4).

In the future condition (20 cm added to sea level), the same trends hold as for the present condition, but the amount of energy reaching the shoreline is significantly greater. For example, during high tide and a 0.8-m wave height, 129 J/m s^{-1} reaches the shoreline in the future scenario, a 65% increase over the 78 J/m s^{-1} predicted in the present condition.

DISCUSSION

Higher Water Levels and Increased Resuspension

Peak Concentrations

During the period evaluated in this study, the observed mean daily peak in suspended-sediment concentration was 10.8 mg/l, whereas the predicted peaks for the same time period averaged 11.1 mg/l. Recent studies have shown that frequency and duration of turbidity is critical for determining the stress induced on corals (*e.g.*, Philipp and Fabricius, 2003), but as a general rule of thumb, a concentration of ~10 mg/l or higher is considered to be of concern (Rogers, 1983). In the present situation, turbidity in the water column reaches this level frequently (daily during strong trade winds), but for a relatively short duration. In the future scenario, the peak concentrations were predicted to be significantly greater, averaging 20.3 mg/l. If the model predictions are accurate, this suggests that organisms on the mid-reef flat will have to be capable of dealing with almost twice the level of maximum suspended-sediment concentrations in any given day as sea level increases by 20 cm. Complications to this simple model arise from sediment supply limitations. As increased quantities of sediment are suspended at higher tides and potentially a small fraction removed from the site (rather than being redeposited as bed stresses reduce), the seabed may become depleted of fine-grained sediment or develop coarse-grained armoring if no replacement of fine-grained sediment occurs. Most of the resupply of fine-grained sediment to the seabed surface occurs daily through deposition of sediment as trade winds and waves decrease. In addition, episodic inputs occur through flood delivery from upland sources, shoreline erosion, and extreme setup and wave events that act to mix surface seabed sediment.

Duration of Time above Threshold Increase

During a typical month in the trade-wind season, the mid-flat experiences suspended-sediment concentrations of >10 mg/l approximately 9% of the time (Table 1). On the mid-flat (at ~400 m from shore), very little coral is actively growing, and it is clearly not hospitable to new coral recruitment and growth. Only slightly farther from the shoreline (at ~550 m from shore), individual corals are actively growing and able to propagate. In the future estimate, the duration of time that the flat will be exposed to suspended-sediment concentrations of >10 mg/l is predicted to be 37%, an increase of a factor of four. The increased duration and increased concentrations will cause less light to be available for photosynthesis. Additionally, these increased concentrations tend to occur during the afternoon because of the phasing of tides and trade winds on the Molokai reef flat (Ogston *et al.*, 2004), and produce an increase in the duration of exposure to suspended-sediment concentrations >10 mg/l during daylight hours from ~1.1 h/d to 4.4 h/d. Assuming that the mid- to outer-reef flat is at the

Table 4. *Wave energy flux across reef flat due to breaking and friction. The future estimates assume 0.2 m added to the present water depths.*

Wave Height (H_{rms})	Present Water Depth on Reef Flat (for Future add 0.2 m)	Present Wave Energy Flux Reaching Shoreline (J/m s^{-1})	Future Wave Energy Flux Reaching Shoreline (J/m s^{-1})
0.8 m	1.5 m (high tide)	78	129
	1.0 m (mid-tide)	16	32
	0.5 m (low tide)	1.4	4.2
0.6 m	1.5 m (high tide)	76	126
	1.0 m (mid-tide)	14	29
	0.5 m (low tide)	1.0	3.5
0.4 m	1.5 m (high tide)	73	124
	1.0 m (mid-tide)	14	29
	0.5 m (low tide)	0.8	3.1
0.2 m	1.5 m (high tide)	72	122
	1.0 m (mid-tide)	13	29
	0.5 m (low tide)	0.7	2.9

limit of its ability to handle the light reduction due to the daily suspended terrigenous material, then the impact to the ecosystems that are able to populate this zone on the fringing reef will be vast.

Higher Water Levels and Increase of Available Fines through Wave Attack

It is clear that the reef crest elevation controls the amount of wave energy that propagates onto the reef flat and the amount of attenuation that occurs there (*e.g.*, Hearn, 1999). Increased energy attenuation has been observed at lower water-surface elevations, and larger significant wave heights at higher water levels (Brander, Kench, and Hart, 2004). This was also observed in the Molokai reef-flat data as seen in the tidal variation of wave orbital velocity on the reef flat (Figure 2b) without significant dependence on the offshore wave height (Ogston *et al.*, 2004), and is shown in the present study with the wave energy flux estimates. When the tide is high ($\sim$1.5-m water depth on the reef flat), the energy flux that reaches the shoreline is relatively consistent for any of the tested offshore wave heights. At mid- to low-tide elevations, the wave energy flux contained in the waves as they transit the reef flat is significantly less than at high tide (reduction of a factor of four to five at mid-tide and of $>$50 at low tide).

These calculations lead to our future prediction of greater energy transmission across the reef crest and flat, and thus greater energy available for attack and erosion of shorelines. As a rough estimation of the projected differences in energy flux in a typical day, we assume a mean wave height of 0.4 m, and calculate the energy reaching the shoreline assuming 6 h/d at each of high and low tides, and 12 h/d at mid-tide. In this case, the total energy flux to the shoreline in the present sea-level case is 2.2×10^6 J/m and in the future case, with 0.2-m added sea-level rise, is 4.0×10^6 J/m. This increase of $\sim$80% in energy at the shoreline will be available for shoreline erosion. In areas where the shoreline exists on low, flat, erodible terrain, we would predict significant erosion causing retreat of the shoreline. A limitation to this analysis is that we do not consider the infrequent extreme events that cause greater setup of water on the reef flat and therefore increase wave-energy transmission across the reef crest.

Implications for Sediment Removal (the Budget)

The impacts of sea-level rise on turbidity may increase or decrease different terms in the sediment budget. Increased sediment in suspension on a daily basis could lead to increased sediment flux out of the system. The flux is dependent on both the concentration of sediment in suspension and the velocity of the currents that advect sediment out of the system. In this case, the along-reef velocity carries sediment to sites of storage, or sites of shoreline interruption where constrictions of the reef flat induce slight off-reef currents (Presto *et al.*, 2006). Enhanced suspended-sediment concentrations may act to move more fine-grained sediment from the reef flat and the quantity of sediment in storage on the inner-reef mud belt could be ultimately reduced. Additionally, cross-reef currents associated with the movement of the tidal prism onto and off the reef flat could be enhanced with greater water depths, also increasing the potential for removal of inner-reef mud belt.

Yet there is a greater potential for sediment to be eroded from the shoreline and added to the sediment budget with higher water-surface elevation. In many places along fringing coral reefs in Hawaii and elsewhere (*e.g.*, Palau, Guam, Puerto Rico) the sediment eroded would add fine-grained sediment to the nearshore and may add to suspended-sediment levels, decreasing the number of available recruitment sites for corals (Larcombe, Costen, and Woolfe, 2001). On Molokai, shoreline erosion apparently only adds a small amount of sediment to the reef flat budget at present (Field *et al.*, 2008b), and the dominant sediment input is from infrequent "Kona" storms that occur several times per winter and place sediment in fan deposits near the mouth of drainage gulches (Field *et al.*, 2008b). Increased erosion of coastal plain and fan delta deposits may change this balance, and offset the amount of additional sediment leaving the reef flat through increased resuspension and flux.

The processes that we observe and report here for the Molokai fringing coral reef can be extrapolated for different values of sea-level rise. The changes that we predict—more intense and longer periods of wave resuspension, coupled with increased shoreline erosion—have broad application. Fringing coral reefs are common throughout the Pacific Ocean and Caribbean Sea, and many of them are at risk from terrigenous runoff. Not all fringing coral reefs will experience increased concentrations of suspended sediment due to changes associated with sea-level rise, but it is likely that many will. The effects can be minimized by management activities to decrease sediment input from adjacent watersheds and to limit other stresses to the reef habitat.

CONCLUSIONS

One of the results of 21st- century climate change is rising sea level. Observations of sediment dynamics on a fringing reef in Molokai, Hawaii allow us to evaluate the present transport dynamics and predict changes in response to future sea-level rise. Here we explore the case in which the water-surface elevation over fringing reefs may increase by 20 cm in the next three to five decades and that reef accretion will likely not keep up. Changes in sediment resuspension on the reef due to greater propagation of wave energy across the reef crest will result in higher shear stresses, and changes predicted in the amount of wave energy that reaches the shoreline will act to erode shoreline sediments.

Resuspension of sediment from the seabed presently occurs on a daily basis as shear stresses induced during trade winds at high tidal elevations exceed a critical threshold for sediment motion. Using the observed relationship between wave orbital velocity and water-surface elevation, we predict that the average daily maximum in suspended-sediment concentration will increase on Molokai with sea-level rise from $\sim$11 mg/l to $\sim$20 mg/l. Not only will the maximum concentrations be exceeded, but also the duration of time that concentrations exceed 10 mg/l (a rule of thumb for coral health) will increase from 9% to 37%. On the Molokai reef flat, high tide and strong trade winds generally coincide during daylight hours and thus the reef will experience high levels of turbidity throughout ~4.4 of the daylight hours, potentially affecting the efficiency of photosynthesizing organisms. Our predictions do not include effects of supply limitation, one aspect of which is bed armoring.

The same processes that promote enhanced resuspension from the seabed will allow more energy from offshore waves to propagate over the reef crest and across the reef flat. This energy, expended at the shoreline, is predicted to cause shoreline erosion. An evaluation of the reduction of energy during the breaking process and due to friction across the reef flat shows an increase of ~80% over the present wave energy will be transferred to the shoreline when the water-surface elevation is increased by 20 cm. In areas where the shoreline exists on low, flat, erodible terrain, the increased energy would cause significant erosion and retreat of the shoreline.

The impacts of sea-level rise on turbidity may increase or decrease different terms in the sediment budget. Increased sediment in suspension on a daily basis may remove more fine-grained sediment from the reef flat through enhanced suspension and enhanced off-reef currents, and the quantity of sediment in storage on the inner reef mud belt could be ultimately reduced. However, increased shoreline erosion will add sediment to the mud belt and may offset the amount of additional sediment leaving the reef flat through increased resuspension and flux.

The changes that we predict for the Molokai reef flat with relatively minor sea-level change have broad application to other fringing coral reefs and other shallow coastal habitats. Even small increases in water levels may alter sediment dynamics in ways that affect the host organisms.

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