Coral Reefs (2004) 23: 559–569
DOI 10.1007/s00338-004-0415-9

REPORT

A. S. Ogston · C. D. Storlazzi · M. E. Field
M. K. Presto

Sediment resuspension and transport patterns on a fringing reef flat, Molokai, Hawaii

Received: 20 May 2002 / Accepted: 25 September 2003 / Published online: 30 July 2004

Abstract Corals are known to flourish in various turbid environments around the world. The quantitative distinction between clear and turbid water in coral habitats is not well defined nor are the amount of sediment in suspension and rates of sedimentation used to evaluate the condition of reef environments well established. This study of sediment resuspension, transport, and resulting deposition on a fringing reef flat off Molokai, Hawaii, uses a year of time-series data from a small, instrumented tripod. It shows the importance of trade winds and ocean wave heights in controlling the movement of sediment. Sediment is typically resuspended daily and the dominant controls on the magnitude of events (10–25 mg/l) are the trade-wind-generated waves and currents and tidal elevation on the reef flat. The net flux of sediment on this reef is primarily along the reef flat in the direction of the prevailing trade winds (to the west), with a secondary direction of slightly offshore, towards a zone of low coral abundance.

These results have application to reef studies and reef management in other areas in several ways. First, the observed resuspension and turbidity results from fine-grained terrigenous sediment that appears to be trapped and recycled on the reef flat. Thus corals are subjected to light attenuation by the same particles repeatedly, however small the amount. Secondly, the measurements show high temporal variability (from daily to seasonal scales) of sediment resuspension, indicating that single measurements are inadequate to accurately describe conditions on a reef flat.

Communicated by: P.K. Swart

A. S. Ogston (✉) · M. K. Presto
School of Oceanography, University of Washington, Box 357940, Seattle, WA 98195, USA
E-mail: ogston@ocean.washington.edu
Tel.: +1-206-5430768
Fax: +1-206-5436073

C. D. Storlazzi · M. E. Field
U.S. Geological Survey, Pacific Science Center, 1156 High St., Santa Cruz, CA 95064, USA

Keywords Suspended sediment · Turbidity · Coral reefs · Sedimentation · Reef flat

Introduction

Sedimentation and suspended sediment are generally recognized as important factors that can negatively affect coral health (Buddemeier and Hopley 1988; Acevedo et al. 1989; Rogers 1990; Fortes 2000). Conversely, some workers (e.g., Roy and Smith 1971; Tudhoe and Scoffin 1994; Anthony 2000; Larcombe et al. 2001) have shown that coral communities can flourish in turbid environments. Terrestrial sediment delivered to reef waters at minimal levels can provide nutrients to corals and enhances growth (Anthony 2000), while higher levels of suspended sediment may attenuate light, and sediment accumulation can eliminate recruitment sites, physiologically stress individual corals, and even bury coral colonies (e.g., Rogers 1990; Brown 1997). Although there is evidence that increased sediment supply can adversely affect coral reefs (e.g., Cortes et al. 1994; Field et al. 2000; Szmant et al. 2000), the precise meaning of "sediment supply," as Woolfe and Larcombe (1998) point out, is open to a number of interpretations.

A rule-of-thumb in reef environments has been that suspended sediment concentration (SSC) of greater than 10 mg/l may attenuate enough light to adversely affect coral health (Dodge et al. 1974; Dodge and Vaisnys 1977), and that accumulation rates of greater than 10 mg/cm^2/d are associated with fewer coral species, less live coral, and decreased net productivity (Rogers 1990; Te 1992). There is a range of turbid environments in which active coral growth exists. Issues such as the frequency and duration of suspension events and sediment type must also be evaluated in determining impact on reef health.

Sedimentation due to increased sediment runoff from up-slope practices has been identified as a chronic problem affecting reefs throughout the Hawaiian Islands (Gulko et al. 2000), and specifically for areas on Molokai

(Roberts 2001). The fringing reef on the south coast of Molokai, Hawaii (Fig. 1), provides an opportunity to evaluate levels and characteristics of resuspension of fine-grained sediment on a fringing reef. Within this environment, the objectives of this paper are to:

- Describe the SSC on the reef flat, its frequency and duration, and the mechanisms responsible for resuspension and advection of sediment.
- Describe the sediment transport patterns on this reef flat and potential for off-reef transport of the sediment to correlate with the patterns of coral coverage.
- Evaluate the potential for sediment accumulation rates on the reef flat over various time scales and assess the effects these rates may have on coral.

Material and methods

Study area

The southern shore of Molokai has a well-developed, broad fringing reef flat with a well-defined shallow reef crest. The reef flat is protected from much of the annual wave energy by the island of Molokai itself and the other Hawaiian Islands. The reef flat extends 53 km along the south shore and has a maximum width of 1.5 km near the center of the island, pinching out toward the east and west ends (Storlazzi et al. 2004). In cross-section (Fig. 1b), the reef flat in the central one-third of the island (which includes the study area) is very shallow (0- to 2-m water depth) over its entire width. The reef crest (depths of 1–2 m) is composed of large coral heads and mounds of rubble bound by encrusting coral and coralline algae, some of which are subaerially exposed at lower low tide. The fore reef extends from the reef crest to a depth of approximately 30 m.

Distribution of sediment, algae, and coral on the reef flat vary as a function of across-shore location. Near the shoreline, the environment is dominated by alternating bands of silty sand and algal-covered limestone remnant from previous reef growth. In central south Molokai, in particular, the inner reef flat is mantled by sediment varying in thickness from a thin veneer to 10's of cm and having a significant terrestrial sediment component (Calhoun and Field 2001). On the outer half of the reef flat, the surface is dominated by low-relief (< 1 m)

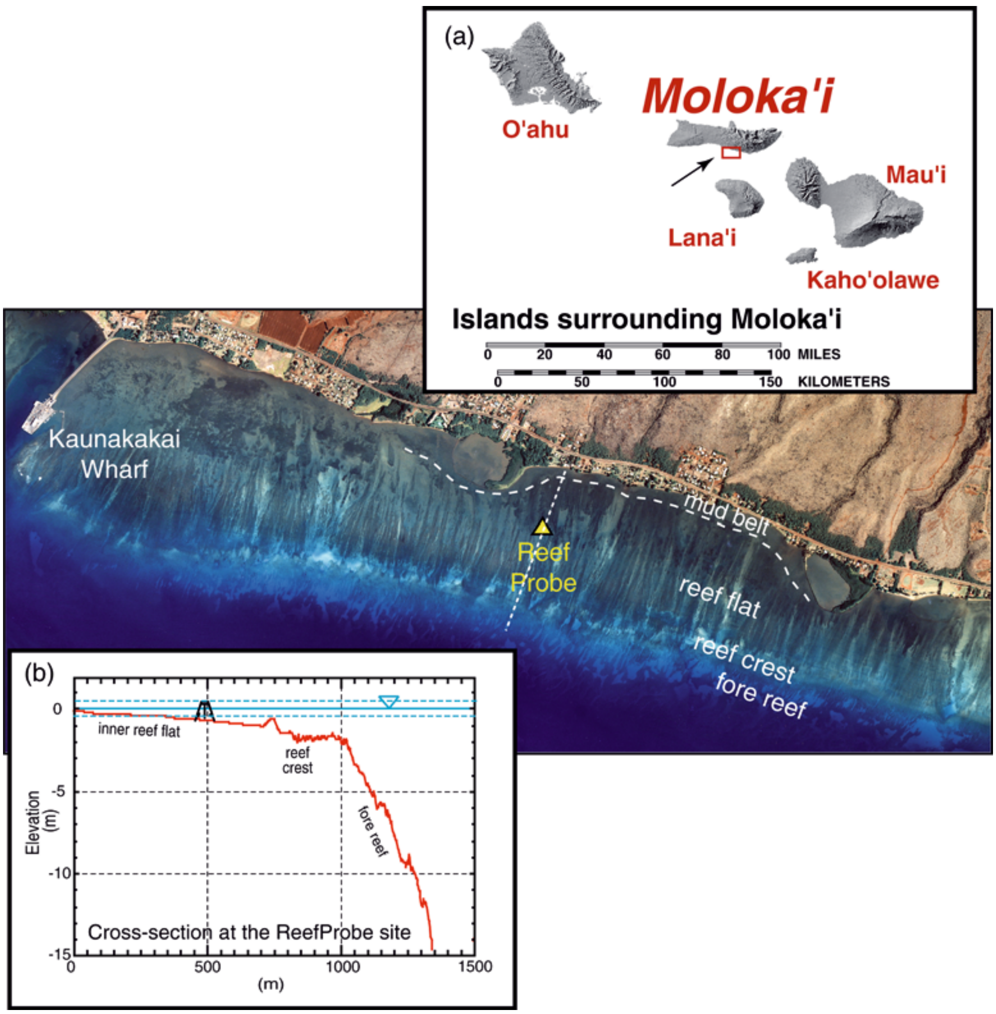

Fig. 1 Aerial photograph of the study area on the south central Molokai reef. The triangular symbol denotes the ReefProbe instrumentation site. The *inset* (*a*) shows selected Hawaiian Islands depicting the location of Molokai within the surrounding islands and the relatively protected south shore, and (*b*) shows the reef cross-section from shoreline to the fore reef

subdued spur-and-groove structures. Coral cover is highly variable but is generally confined to the spurs. Seaward of the reef crest, the fore reef off south Molokai is generally very well developed with a very high percentage (50 to 80%) of live coral. Directly offshore of the study area, the upper fore reef has very low abundances of live coral. Estimates of dominant coral species and coverage along the upper fore reef (~10-m water depth) showed pronounced changes in the abundance of live coral adjacent to the study area (P. Jokiel et al. written communication). Whereas most of the Molokai reef tract has coral coverage on the order of 80–90%, in the 3-km-long zone off the study area, it is less than 10%. Recent detailed studies show that coral abundance in this zone is gradually increasing (Jokiel et al. 2004), but overall is very low.

In general, much of the inner reef flat is characterized by a seaward-thinning lens of muddy sand ranging from 5 to 15 cm in thickness; thick accumulations of 75 cm or more are present locally (Field et al. 2000). The sand fraction is dominantly carbonate fragments (58–65% carbonate on the reef flat and beach); whereas, the silt and clay fraction has a significant (40 to 70%) terrigenous component (Calhoun and Field 2001). The terrigenous silt component of reef flat sediment decreases in the offshore direction, but the inner reef flat acts as a reservoir of fine sediment available for resuspension (Calhoun and Field 2001).

Physical setting: The reef is exposed to a number of different hydrodynamic and meteorologic forces during the course of the year, allowing examination of their different contributions to sediment dynamics on the reef flat environment. Tidal variation around the Hawaiian Islands is a mixed semi-diurnal type with a spring tidal range of approximately 1 m and a mean tidal range of 0.6 m (microtidal). Moberly and Chamberlain (1964; also see Schroeder 1993; and Fletcher et al. 2004) have synthesized the wave and swell patterns for the Hawaiian Islands, and their results are summarized here. Short-period waves formed by the prevailing NE trade winds, long-period south swell, tidal oscillations, and the relative exposure of different parts of the reef to these processes all affect the transport of suspended sediment in this reef environment. The waves affecting the coastal areas of the islands have four main sources: North Pacific swell, NE trade-wind swell, southern swell, and Kona storm swell. North Pacific swell (significant wave height, H, =2.5 to 6 m; wave period, T, =10 to 18 s) is most common in October to May and only affects the northwestern coastlines. Trade-wind waves (H = 1 to 3.5 m; T = 5 to 8 s) occur 70% of the year and is strongest and most persistent (up to 90% of the time) in the period of April to November. Southern swell (H = 0.5 to 1.5 m; T = 14 to 22 s) is strongest April to October. Kona waves (H = 3 to 5 m; T = 8 to 10 s) are formed on an irregular basis by S and SW winds caused by low-pressure systems passing north of the Islands. The Islands' southern shores also infrequently receive wave trains from proximal and distal tropical cyclones.

Northeasterly trade winds dominate the marine climate over the Hawaiian Islands. During the winter, the north Pacific high is centered east-northeast of Hawaii, and the trade winds are weak and inconsistent. Trade winds intensify in the summer months when the high shifts northward. Winds vary locally in response to land influences and topographic steering in the Hawaiian Islands. The south shore of Molokai experiences a diurnal cycle in trade-wind strength (sea/land breeze overprint peaking in the afternoon).

When the northeast trade winds hit the mountainous Hawaiian Islands, moist air below the trade-wind inversion is forced up the hillsides. The windward sides of the islands can receive five to ten times more precipitation in a year than falls over the open ocean, whereas the leeward sides receive less than half the open-ocean amount. Since 1996, rainfall amounts in the Hawaiian Islands have been less than the average of the last 50 years, leading to drought conditions on Molokai (NCDC 2001). Based on historical rain gauging records, the average annual rainfall is 66 cm, with a large proportion of the rainfall occurring in November through February. Over the year of record in the present study, the rainfall was only 33 cm, with the bulk occurring in two rainfall events.

Process study instrumentation and methods

To assess the temporal variation of physical processes, sediment resuspension, and transport, an instrumented tripod (ReefProbe) was placed on the reef flat (Fig. 1) between the zones of active and inactive coral growth at a depth of approximately 1.2 m. The seabed at this site was covered with loose sediment generally biologically roughened (e.g., biogenic mounds and tracks). The system was deployed for 12 months from January 2000, with periodic refurbishment of the instruments approximately every three months; the final deployment for this experiment ended in January 2001. Instrumentation on the tripod included a KVI pressure sensor, Marsh McBirney bi-direction electromagnetic current meter, Wet-Labs transmissometer, D&A Instruments optical backscatter sensor and a SeaBird conductivity/temperature sensor (CT). All instruments (except the CT) logged 2-Hz data in 512-s bursts every hour, while the CT recorded once every 2 min. The current meter and optical sensors were placed at approximately 20 cm above the seabed (cmab), pressure at ~30 cmab, and CT at ~55 cmab. Despite periodic cleaning, biofouling of the optical sensors caused some data to be unusable.

Optical sensors were calibrated in the laboratory by suspending the finer fraction from seabed sediment collected at the instrument site (Fig. 2). Since optical instruments are sensitive to particle characteristics including size and shape (Bunt et al. 1999), an additional check on this calibration was performed by obtaining water column samples near the optical instruments throughout the deployment period (Fig. 2). Although there is a large amount of variability in the data due to

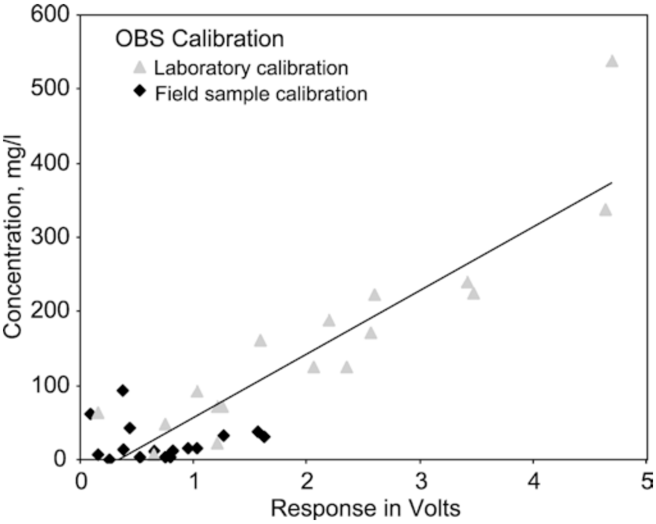

Fig. 2 Calibration of the Optical Backscatter Sensor to the mass concentration of sediment suspended at the instrument site. The *triangle* symbols denote 4-monthly laboratory calibration events, and the *diamond* symbols denote the in situ field calibration samples. No significant deterioration of the sensor appears to have occurred

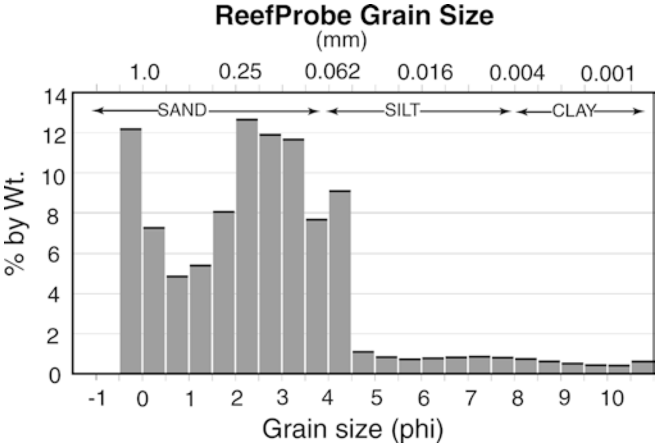

Fig. 3 Seabed grain-size data at the ReefProbe instrumentation site. Bulk grain size was analyzed using both Beckman Coulter Counter (silt and clay) and 2-m settling tubes (sand). Although the grain size histogram is dominated by the sand-sized fraction, there is a significant amount of silt and clay, and within these fractions, the grains are composed of 90% terrigenous material

small-scale patchiness and sampling techniques, the field samples generally fall within the scatter of the laboratory calibrations, and thus the laboratory calibrations were used for determining SSC. Differences between the laboratory calibration and the calibration from water samples is likely due to the resuspension of the in situ porous, platy carbonate particles in addition to the fine terrigenous mud preferentially suspended in the laboratory calibration.

Offshore wind and wave conditions during the time of deployment were obtained from NOAA buoys 51002 and 51003, located roughly 443 km south of the Hawaiian Islands. In the initial part of the study period, wind speed and direction were only available from the offshore wave buoys. As it became clear in the data record that trade-wind activity played a large role in the transport dynamics on the reef flat, a wind station was placed at the end of the Kaunakakai Wharf (Fig. 1). Direct local wind measurements (mean and peak speed and direction) during the final three months of the instrument deployment were made at a 30-min sampling rate. Rainfall data were obtained through the HydroNet rain gauging system (NWS- NOAA). Rain gauge records for the year were made by compositing data from the two gages at Kawela and Kaunakakai, due to incomplete data at both sites.

From the ReefProbe data, hourly averaged velocity (*U*) and suspended-sediment concentrations (*SSC*) were used to calculate the sediment flux (*Flux* = *SSC* * *U*). This value applies only at one point but is interpreted as a typical value for the reef flat cross-section. The major uncertainties on this flux value arise from the uncertainties in the SSC data (calibration effects discussed previously). Removal of biofouling effects on the OBS signal also adds subjectivity to the data, and as a result the SSC values can only be considered approximate.

In order to examine the resuspension potential due to waves and currents acting together on the seabed, the shear stress on the seabed was estimated. Shear stress can be related to the observed velocities on the reef flat in a simplistic form by a total stress formulation,

$$U_* = \frac{f_w}{2}(\overline{U} + Urms) * Urms \quad (1)$$

where U_* is the shear velocity and related to the shear stress on the seabed by $\tau_b = \rho U_*^2$, $\bar{U}$ is the mean current, *Urms* is the rms orbital velocity, and f_w is a friction factor (Swart 1974). In the regions of interest, f_w is mainly a function of the orbital velocity felt at the seabed. The calculated values (Swart 1974) ranged from 0.02 to 0.075 in this study. U_* can be used as representative for the stress on the seabed due the combined effects of waves and mean currents.

Results

Results are based on a year of time-series measurements made on the central reef flat and include sea-level variations, currents, SSC, temperature, and salinity. The instrumented tripod was placed at the edge of an area of relatively thick sediment cover (approximately 5–10 cm thick at the tripod site), where the seabed sediment is dominantly sand-size (62%) with 28% silt and 10% clay (Fig. 3; Calhoun and Field 2001).

Tidal elevation on the reef flat as measured by the ReefProbe pressure sensor varied by approximately 0.8 m (Fig. 4a). A small amount of low-frequency (38-h band pass filter) sea level set-up on the reef flat can be

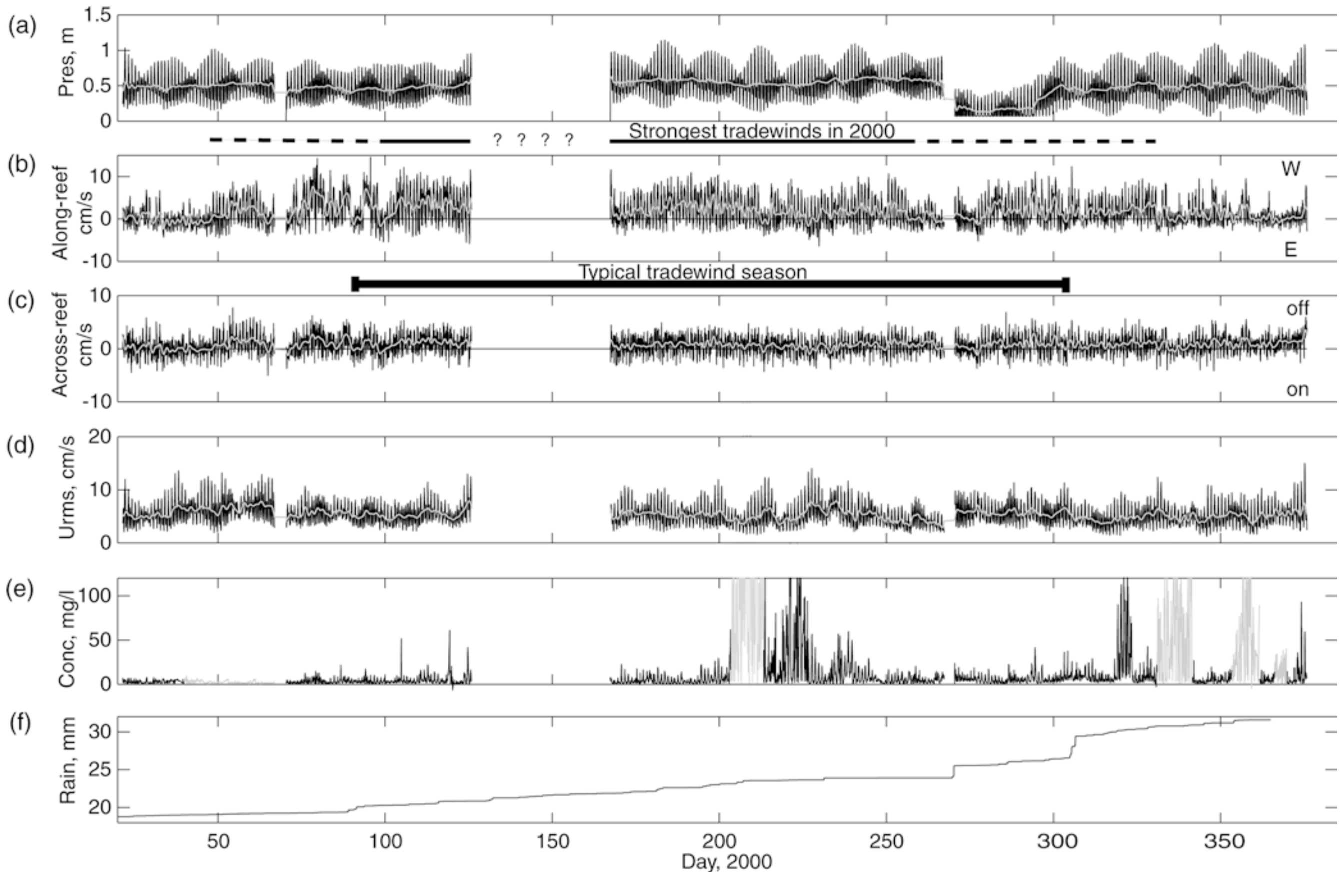

Fig. 4a–f Hourly-averaged, time-series data for the year of record on the reef flat. The data consists of: (**a**) sea-surface elevation; in the last deployment, some sensor drift is evident (days 270–300); (**b**) along-reef current speed; (**c**) across-reef current speed; (**d**) wave-orbital velocity; (**e**) suspended-sediment concentration. The *pale lines* denote questionable data due to bio-fouling of the sensor and; (**f**) Cumulative rainfall from Hydronet onshore gauges. In panels a, b, c, and d, the *dark line* is the hourly averaged data and the *light line* is low-pass filtered data at 38 h (i.e.- tidal and higher frequencies removed)

seen in the low-pass filtered pressure signal (dashed line in Fig. 4a) and was on the order of 0.10 m. The maximum setup occurred midyear (days 170 to 260), a time period typically characterized by combined south swell and persistent trade-wind activity.

Temperature on the reef flat varied between 19.4 and 31.2°C (in January and October, respectively), with variations occurring on a daily basis (typically 3°C diurnal heating and cooling of the shallow reef flat waters), as well as on low-frequency trade-wind and seasonal time scales (moving off-reef water onto the reef flat and changing air temperatures). Salinity typically ranged between 32 and 35 ppt, varying weakly with tidal elevation (maximum of 1 part over a tidal cycle), indicating that the water on the reef flat is stratified (either horizontally or vertically), perhaps due to evaporation effects on the shallow reef flat. Some additional variations may be in response to precipitation events, although a direct correlation is difficult to assess due to the low rainfall throughout this study (33 cm over the year).

Near-bed wave-orbital velocities varied on a daily basis at tidal frequencies (Fig. 4d), with a peak value of approximately 15 cm/s. At low water elevations, the orbital velocity was small while at high elevations the orbital velocity was large and had a larger variation. The high correlation between tidal elevation and orbital velocity ($r^2 = 0.61$) indicates that the orbital velocity felt on the reef flat was strongly controlled by the water depth, either from depth-limited offshore waves whose energy was not completely dissipated by breaking at the reef crest, or by in situ generation of wind waves. The low-pass trend in orbital velocity does not strongly correlate with the along-reef velocity, although the peak orbital velocity did occur at the peak in wind-driven setup.

The hourly averaged SSC (Fig. 4e) over the year ranged between 0 and over 100 mg/l. Sediment was suspended on a daily basis and was highly correlated with the tidal elevation (peak suspension near high tide). Throughout the one-year record of data, the burst-averaged SSC on the reef flat exceeded 10 mg/l in approximately 15% of the hourly measurements, and exceeded 20 mg/l in approximately 6% of the measurements. Seasonally, more sediment is resuspended during the trade-wind period (trade winds are generally persistent April through November and strongest during the summer months), and the SSC on the reef flat exceeded

10 and 20 mg/l in approximately 26 and 12% of the measurements, respectively. In order to examine the impact on light attenuation on the reef flat, the SSC measurements during daylight hours (assumed to be between 6 am and 6 pm local time) were evaluated. During the periods of strong trade winds (indicated in Fig. 4), the SSC exceeded 10 and 20 mg/l, in approximately 30 and 14% of the measurements, respectively. During times of high trade-wind activity, SSC frequently reached 20 to 25 mg/l. Although it is more difficult to assess the data during non-trade-wind periods due to bio-fouling in the record, it appears that periodic increases in SSC (less than approximately 10 mg/l) occurred in the water column during these times. The energy for resuspension is likely provided from offshore wave energy propagation onto the reef flat.

Wind speeds (Fig. 5a) in the final deployment reached 17.6 m/s and at highest speeds were dominantly directed along the reef flat from the east (110°; Fig. 5b). The correlation between wind speed and along-reef currents is high ($r^2 = 0.56$). The diurnal variation in wind speed was strongly pronounced (Fig. 5a). Both tidal currents and wind-driven currents occur on the reef flat and can be seen in the time series data (Fig. 4b and c). It is difficult to extract the tidal currents from the wind-driven currents because of their overlapping frequency bands; therefore the data in the transition between the trade-wind and non-trade-wind periods is expanded in Fig. 5. It appears that tidal currents were generally weak (3 to 5 cm/s; Fig. 5d) on the reef flat, as is evident during days 334 to 339 when the trade-wind energy was low (Fig. 5a). Earlier in the record (Fig. 4, between days 75 and 85), wind-driven current speed reached maximum values of 15 cm/s. Throughout the year, the strongest currents associated with the winds were directed west along the reef flat, with a smaller off-reef component (ranging from 0 to 6 cm/s).

The flux of sediment along and across the reef flat was strongly dependent on both the wave-driven orbital velocities and wind-driven mean currents controlling the amount of sediment that was in suspension and the transport of that sediment. Sediment flux (Fig. 6a) was at a maximum in the peak trade-wind period and was persistently directed to west along the reef and offshore, consistent with the peaks in current speed and direction. The cumulative sediment flux (Fig. 6b) shows the persistent along-reef and offshore flux during the trade-wind period, resulting in a net sediment flux at the instrument site to the west and off reef. When periods during which bio-fouling made the suspended-sediment concentration data uncertain (shaded regions in Fig. 6b) were eliminated, contributions to the net flux were fairly consistent over time during the trade-wind period. During times of weaker trade winds, the slope of the cumulative flux curve tended to be flatter although there was limited data indicating less net sediment flux.

Over a typical day in the trade-wind period, the progressive vector diagram of sediment flux shows the approximate path that particles took once in suspension. In the example 24-h progressive vector diagram shown in Fig. 7, a small amount of transport occurs prior to initiation of the wind-driven circulation (points “a” to “b”). These particles follow the tidal currents, which were weakly onshore and to the east during the rising tide.

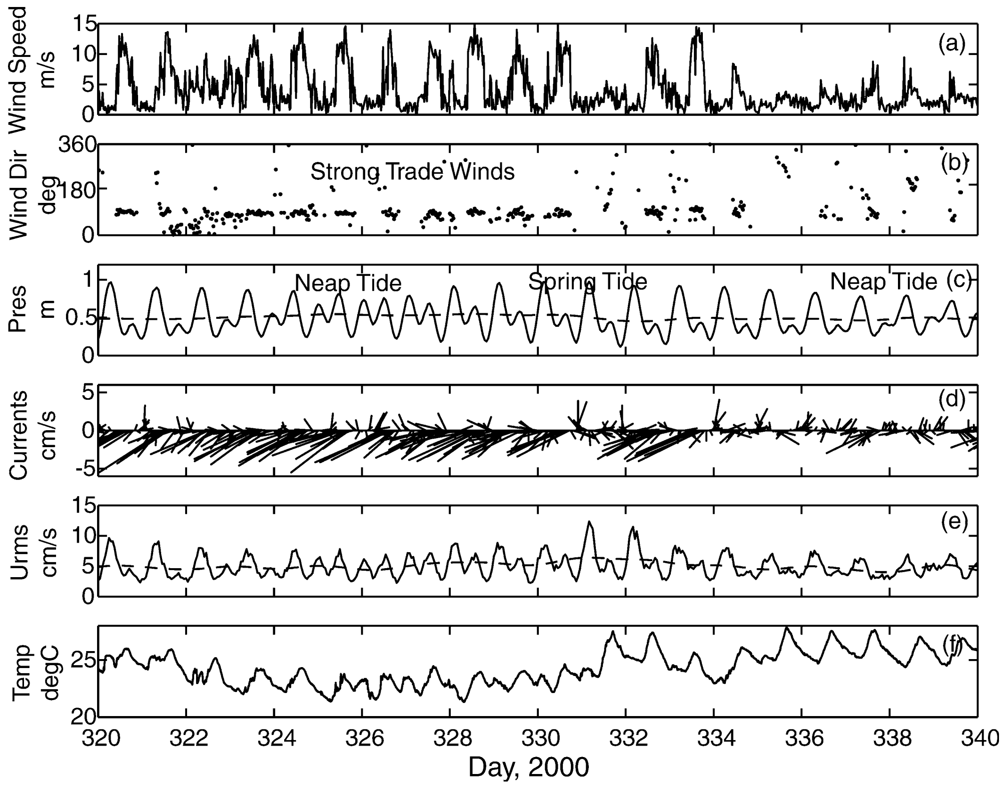

Fig. 5a–f Expansion of the time-series data shown in Fig. 4: (**a**) wind speed; (**b**) wind direction; (**c**) sea-surface elevation; (**d**) vectors of currents (up and to right are onshore and east, respectively); (**e**) wave-orbital velocity; and (**f**) water temperature. Note the differences between the three different regimes depicted: strong winds/spring tides, strong winds/neap tides, and weak winds/tide varying from spring to neap

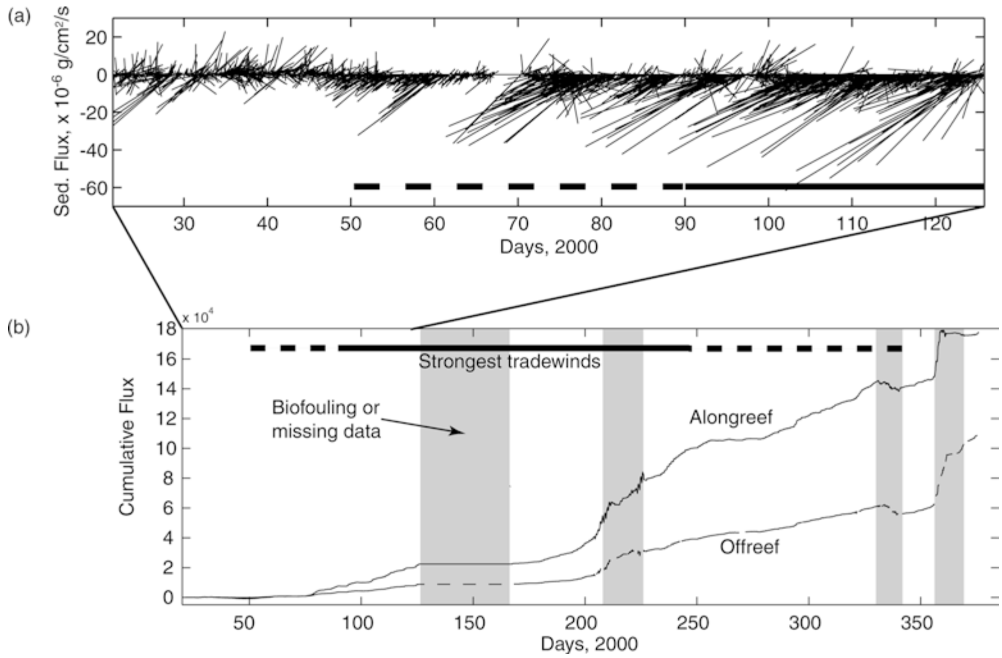

Fig. 6a, b Direction, magnitude, and cumulative suspended-sediment flux over the study period. (**a**) Sediment flux vectors for the first two periods of the year-long deployment. (**b**) Cumulative sediment flux over the record, showing the net sediment flux was to the west and off reef. The *shaded bands* denote data gaps or periods where the sediment concentration data was subject to bio-fouling

When the wind-driven circulation started, there were greater speeds and larger amounts of sediment in suspension (due to combined shear stresses) and the particles were transported to the west and offshore (points "b" to "c"). As the wind-driven currents dropped, both the amount of sediment and the speed with which it was being advected decreased and the remainder of the particles in suspension again moved with the tidal currents (points "c" to "d"). On average, during the periods of higher suspension, the particles will move 61 and 43 m/h in the along-reef and off-reef directions, respectively, assuming that the currents at the measurement site are relatively typical of the currents on the reef flat. At an average duration of suspension of approximately 4 h, the particles can be considered to have moved 240 m to the west and 170 m off reef. This is a crude estimate, particularly in the off-reef direction, where currents will change significantly with water depth. Overall, the cumulative sediment flux diagram (Fig. 6b) indicates that circulation on the reef flat at the measurement location was generally off reef and to the west.

Discussion

Mechanisms of sediment resuspension on the reef flat

Suspended sediment in the water column can be caused by resuspension due to shear stresses induced by wave-orbital velocities and/or mean currents, advection from another area, or any combination of these processes. As a rough estimate, unidirectional current speeds observed on the reef flat were insufficient to resuspend even the finest sediment from the seabed (~20 cm/s; Hjulstrom 1955). Wave-orbital velocities observed on the reef flat in the absence of currents were also generally insufficient to resuspend the finest sediment (~15 cm/s; Komar and Miller 1973). Thus the resuspension observed on the reef flat on a daily basis must have been generated by wave-current interaction, and this interaction must be considered when formulating the stresses on the seabed. As can be seen in Fig. 8, the peaks in SSC are highly correlated with the peaks in the calculated representative stress (correlation coefficient of 0.73 during non-advective times), indicating that the sediment was actively being resuspended from the seabed at the ReefProbe site by combined wave-current stresses on a daily basis.

The largest seasonal variations observed in the year of data presented here were between the trade-wind and non-trade-wind periods. The strongest along-reef current speeds in the present data set (indicative of along-reef wind forcing) occurred throughout the months of March to November (shown with bars in Fig. 4b), with the strongest persistent trade-wind activity occurring between mid-March and mid-August (dark bars in Fig. 4b), consistent with historical records. Not only is the resuspension capability enhanced during the trades, but the net flux also increases because the net velocity during resuspension times is much higher, leading to transport to the west and off the reef flat.

Interaction between wind and tide height and resuspension potential

The mean currents generated on the reef flat occurred dominantly in response to the diurnal wind, which typically moves towards the west (from 102°deg True) along the reef flat, whereas the tidal currents were weak (3 to

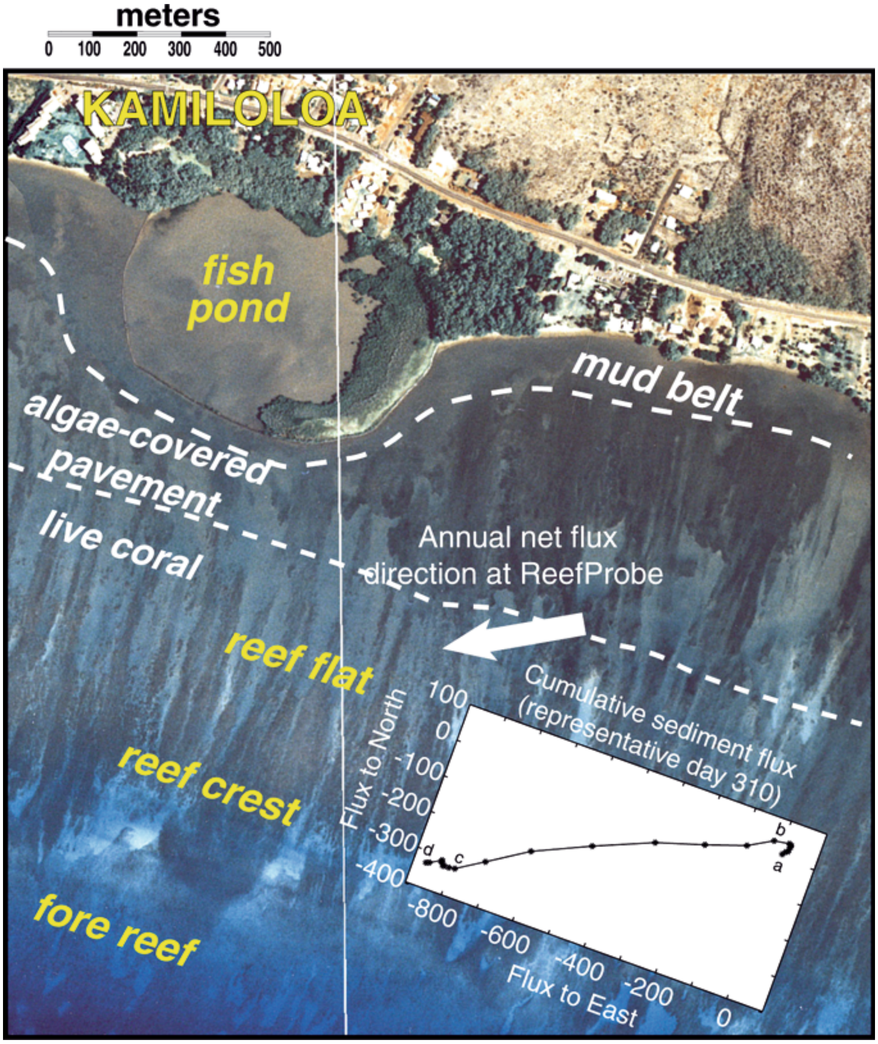

Fig. 7 Direction of net suspended-sediment flux on the reef flat over the year of record is denoted by a *white arrow* over the triangle on the site map that marks the instrument site. The net flux is directed along the reef flat toward the west and off reef. The *inset* shows a single day progressive vector diagram of sediment flux (*stars* mark each hour). During a single, relatively typical day, sediment moves with tidal currents prior to the onset of the trade winds (points "a" to "b"). When the trade winds develop, the flux is distinctly off reef and to the west, in this case for a period of 4 to 5 h (points "b" to "c"). When the winds settle again, the flux of sediment is again small and variable with the weak tidal currents (points "c" to "d")

5 cm/s). The wave-orbital velocity is a function of the daily fluctuations in tidal elevation due to the ability to generate larger trade-wind driven waves in deeper water as well as increased energy dissipation of offshore waves at lower tides. As indicated above, both increased mean currents and increased wave-orbital velocities are necessary to provide the stresses necessary to resuspend sediment on the reef flat. This suggests that the greatest amount of resuspension occurs when the trade winds are strong and the tide is high, creating the most intense nearbed currents. The effects of the highest tides occurring during the strongest winds can be seen in Fig. 8 (days 295 to 297 and 310 to 312, for example). The juxtaposition of the semidiurnal tidal frequencies (12.4 h) and the diurnal wind frequency (24 h) causes a subtle wave-wave interaction or "beating" in the suspended sediment signal with a frequency of approximately 16 days.

Net flux of sediment and coral coverage

The net flux of sediment at the measurement site over the year of data is approximately 3 metric tons/m-length in the off-reef direction and 5 metric tons/m-width in the along-reef direction as depicted in Fig. 7. According to Calhoun and Field (2001), the bulk of the silt and clay fraction on the reef flat is of terrigenous origin. Most of the material in suspension is silt and clay, hence much of the calculated sediment flux is of terrigenous origin.

This pattern of sediment flux differs from one inferred from the concept of reef circulation in systems with a more developed lagoon of onshore flow over the reef crest, and offshore flow in channels (Wiens 1962; Cacchione 1998). This fringing reef flat does not exhibit a high number of channels, and therefore the circulation on the reef flat must have a more three-dimensional nature, either in the vertical or horizontal plane. As waves break on the fore-reef, a net flux of water onshore must be balanced by either a return flow in the lower water column or into focused zones of offshore flow in horizontal circulation cells. Presently, we are unable to determine the three-dimensional flow structure but the broad shallow reef flat suggests that horizontal circulation is more likely. It is probable that man-made structures (e.g., fish ponds,

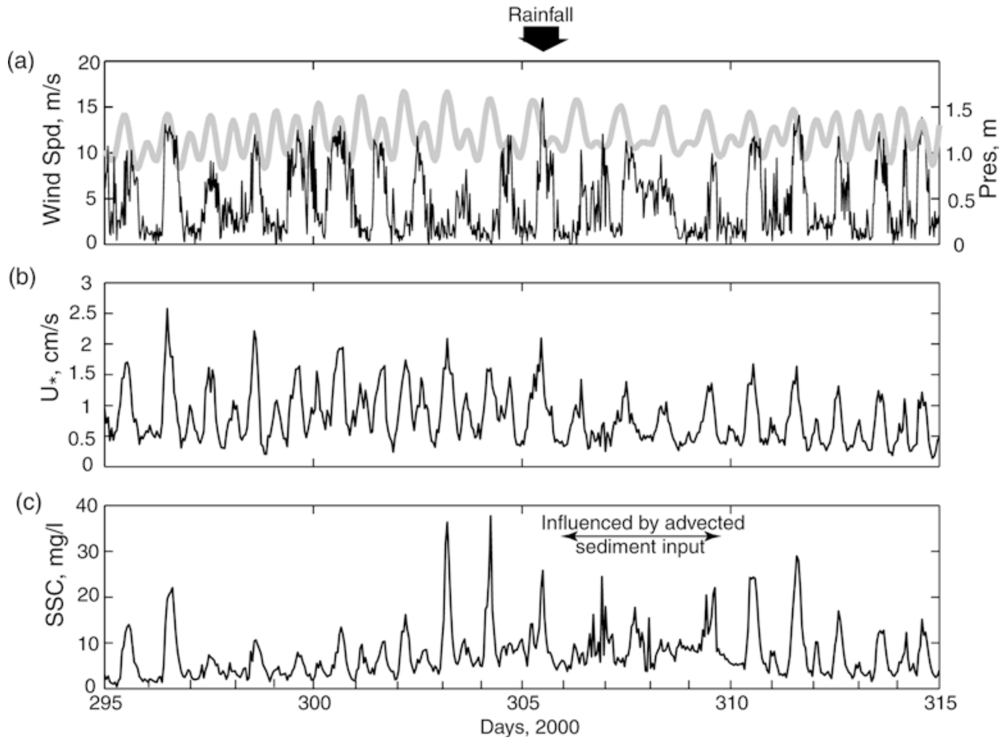

Fig. 8a–c Time-series data displaying the influence of winds and waves on suspended sediment concentrations on the reef flat. (**a**) Wind speed (*thin black line*) and tidal elevation (*thick gray line*). Note that with the close periodicity of the two signals, the signals are coherent only sometimes. (**b**) Shear velocity, U_*, based on a wave friction factor and the combined wave-current velocity. (**c**) Suspended-sediment concentration showing the daily resuspension peak, the magnitude of which depends on both the tidal elevation and trade-wind magnitude. Note also the response on days 306 to 310, presumably in response to advected suspended sediment from up-coast river discharge

impervious wharf) could influence the circulation on the inner reef flat and may determine the location of offshore flow zones.

The data point to the potential for advection of terrestrial sediment (supplied both by rainfall and the inner reef mud belt). Significant rainfall events in this record were limited to one in late September (day 270) and another in early November (day 305; Fig. 4f). The suspended sediment data for these two events show only small direct influence from the plume of freshwater and sediment (see Fig. 8, days 305 to 310). Because of the dominant westerly flux direction, this suspended sediment must have been discharged from the drainage basins to the east. The limited magnitude of the signal in the present data indicates that the precipitation was not severe enough to mobilize large amounts of sediment in the drainage basins or the energetics on the reef flat were insufficient to transport the sediment to the instrument site. It is expected that in non-drought periods, rainfall events provide the major input or supply of sediment to the reef flat.

Mapping of coral cover and diversity along the inner fore reef (~10 m water depth) showed pronounced changes in percentage of live coral cover adjacent to the area of the tripod measurements (Jokiel et al., 2004). In the 3-km stretch east from Kaunakakai Harbor, coral abundance decreases drastically from the reef average of 90% to values as low as 10%. The cause of the decrease has not been determined, but the role of sediment suspended on the reef flat study area and its seaward advection is one possible factor.

Potential for impacts on coral growth

During the trade-wind season (roughly April through November), resuspension events occur on this reef flat on a daily basis. Most of the sediment in the water column falls out of suspension when the winds reduce, usually in the late afternoon. A sedimentation rate can be estimated over a 24-h period to simulate the amount of sediment that would be deposited in a sediment trap or protected crevice (and therefore unavailable for resuspension). Using an average daily suspension of 20 mg/l, a deposition rate can be estimated by assuming that all of the sediment in suspension falls out of the water column between suspension events and that there is no variation in forcing along the transport pathway. Over the spatial scales (approximately 240 m in the alongshore direction and 170 m in the across-shore direction) that sediment moves in a daily cycle, this is a reasonable assumption. The mean daily deposition rate on the reef flat therefore is estimated at 2 mg/cm^2/day. It must be realized that as the sediment may get resuspended in the next daily cycle, it thus cannot be viewed as a long-term accumulation rate that would result in burial or smothering of individual corals. Presumably, a portion of that amount could get trapped in selected areas, resulting in net accumulation on the reef flat through time. Using maximum observed concentrations of 100 mg/l, the deposition rate is estimated at 10 mg/cm^2/day, which approaches the limit of acceptable rates for coral growth, as defined by Rogers (1990). The same sediment is typically resuspended and re-deposited in the next daily cycle. This analysis also highlights the difficulty in interpretation of sediment trap data because a daily clearing of the water column will contribute to sediment trap fluxes and cause an accumulation of sediment in the trap, yet may not contribute to accumulation rates on the seabed where sediment is resuspended in the next daily cycle.

Light attenuation due to increased water turbidity can affect primary productivity and coral growth on reefs (Dodge et al. 1974; Dodge and Vaisnys 1977; Hubbard and Scature 1985; Edmunds and Spencer-Davies 1989). Although the south Molokai reef flat is extremely shallow, particulate matter will absorb and/or scatter light during times of resuspension, thus limiting light availability to coral. Limited data utilizing a photosynthetically available radiation sensor (PAR) on Molokai indicates that levels of SSC approaching 10 mg/l can attenuate approximately 15% of the available radiation (K. Yates, written communication) on the 1.2-m deep reef flat. The southern Molokai reef flat is subjected to these and higher levels of SSC frequently (approximately 30% of the daylight hours during the trade-wind months), as well as short periods of significantly higher SSC with duration of days of exposure, impacting light levels significantly. The persistent reduction of light on the seabed may contribute in part to the limited coral coverage and low diversity observed on the reef flat, especially in the areas closer to the shore. Overall, the very shallow nature of the reef flat appears to allow sufficient light penetration for adequate primary productivity and reef growth on the outer half of the reef flat (Yates and Halley 2000). The highest concentrations observed on this reef flat (up to 100 mg/l) occur episodically and may influence light levels for short periods of time. This may explain lack of coral coverage inshore of the instrument site where the mean SSC are higher.

Conclusions

Our studies of currents, winds, and tides from a single, long-term (one year) deployment of an instrumented tripod on a fringing coral reef have provided the following insights about processes on reef flats.

- Trade winds, which are relatively strong and blow nearly parallel to the south Molokai fringing coral reef throughout much of the year, are capable of resuspending bottom sediment through the combined effect of wind-driven currents and wave-orbital velocities. The strength of both of these is dependent upon the water depth, and therefore is modulated by the tidal elevation. Higher wave-orbital velocities due to propagation of offshore energy onto the reef flat also occur at higher tidal elevations.
- Resuspended sediment may travel approximately 300 m before redeposition because of the relatively short period of time in suspension. The average daily deposition rate is approximately 2 $mg/cm^2/day$, and maximum rates may approach the upper limit of acceptable deposition rates for coral growth.
- The net flux of sediment is along reef to the west and off reef to the south. Although the along-reef flux is consistent with the trade-wind direction, the off-reef flux may be due to local effects of the horizontal circulation on the reef flat or vertical current structure. The off-reef flux corresponds to an anomalous 7-km-wide zone of low coral cover, but a definitive link between the low coral cover and high turbidity is still unresolved.
- Rainfall appears to bring highly mobile fine terrestrial sediment into the system. The discharge-related signal was weak during the period of study, but evidence indicates that during times of normal to high precipitation, episodic stream discharge replaces the sediment that moves off reef into deeper waters in the sediment budget.

Rogers (1983, 1990) demonstrated that suspended sediment of varying concentrations affects coral growth and health. Our study adds to that understanding by documenting that suspended sediment is not uniform and single measurements or estimates are inadequate to describe conditions on a reef flat where seasonally varying wind and waves suspend sediments on a daily basis. Our study also shows that discharge of even minor amounts of sediment, if trapped on the reef flat, may have a significant effect since this sediment can be resuspended many times before leaving the reef flat environment.

Acknowledgements The authors would like to thank Lyndon Dela Cruz for monitoring the instrument package used in this study, and Josh Logan and Susie Cochran for help in the field and with GIS work. The comments of the reviewers were extremely helpful in revising this manuscript.

References

Acevedo RJ, Morelock J, Olivieri RA (1989) Modification of coral reef zonation by terrigenous sediment stress. Palaios 4:92–100

Anthony KRN (2000) Enhanced particle-feeding capacity of corals on turbid reefs (Great Barrier Reef, Australia). Coral Reefs 19:59–67

Brown BE (1997) Disturbances to reefs in recent times. In: Birkeland C (ed) Life and Death of Coral Reefs. Chapman and Hall, London, 536 pp

Buddemeier RW, Hopley D (1998) Turn-ons and turn-offs: causes and mechanisms of the initiation and termination of coral reef growth. Proc 6th Int Coral Reef Congr, Townsville, AU, 253–261 pp

Bunt JAC, Larcombe P, Jago CF (1999) Quantifying the response of optical backscatter devices and transmissometers to variations in suspended particulate matter. Cont Shelf Res 19:1199–1220

Cacchione DA (1998) Bottom currents, waves, and sand transport in a reef channel off Kailua, Hawaii. 1st Reg Conf on Coastal Erosion Management in Hawaii and other Pacific Islands. Wailea, Maui, 1–3 April

Calhoun RS, Field ME (2001) Beach and reef-flat sediments along the south shore of Moloka'i, Hawai'i. Proc Carbonate Beaches 2000, Am Soc Civ Eng, 163–171 pp

Cortes J, Macintyre IG, Glynn PW (1994) Holocene growth history of an eastern Pacific fringing reef, Punta Islotes, Costa Rica. Coral Reefs 13:65–73

Dodge RE, Aller RC, Thompson J (1974) Coral growth related to suspension of bottom sediments. Nature 247:574–577

Dodge RE, Vaisnys JR (1977) Coral populations and growth pattern: Responses to sedimentation and turbidity associated with dredging. J Mar Res 35:715–730

Edmunds PJ, Spencer-Davies P (1989) An energy budget for *Porites porites* (Scleractinia), growing in a stressed environment. Coral Reefs 8:37–43

Field ME, Bothner M, Jokiel PL, Ogston AS (2000) Response of a reef to sediment overload: Moloka'i, Hawai'i. Abstract volume, 9th Int Coral Reef Sym, 61 pp

Fletcher CH, Richmond BM, Grossman EE, Gibbs AE (2004) Atlas of Natural Hazards in the Hawaiian Coastal Zone. USGS Geologic Investigations Series 1–2716, 186 pp (in press)

Fortes M (2000) The Effects of Siltation on Tropical Coastal Ecosystems. In: Wolanski E (ed) Oceanographic Processes of Coral Reefs. CRC Press, Boca Raton, pp 93–112

Gulko D, Maragos J, Friedlander A, Hunter C, Brainard R (2000) Status of coral reefs in the Hawaiian Archipelago. In: Wilkinson C (ed) Status of Coral Reefs of the World: 2000. Australian Institute of Marine Science

Hubbard DK, Scature D (1985) Growth rates of seven species of scleractinian corals from Cane Bay and Salt River, St. Croix, USVI. Bull Mar Sci 32:890–908

Hjulstrom F (1955) Transportation of detritus by moving water. In: Trask PD (ed) Recent Marine Sediments, a symposium, SEPM, Spec Pub 4, pp 5–31

Jokiel P, Brown E, Field ME (2004) Distribution of coral along the 10-m isobath, South Moloka'i, Hawai'i. US Geological Survey Open File Report (in press)

Jokiel P, Brown E, Friedlander A, Rodgers SK, Smith WR (2004) Hawai'i coral reef assessment and monitoring program: Spatial patterns and temporal dynamics in reef communities. Pac Sci (in press)

Komar PD, Miller MC (1973) The threshold of sediment movement under oscillatory water waves. J Sed Pet 43:1101–1110

Larcombe P, Costen A, Woolfe K (2001) The hydrodynamic and sedimentary setting of nearshore coral reefs, central Great Barrier Reef shelf, Australia: Paluma Shoals, a case study. Sedimentology 48:1–25

Moberly RM, Chamberlain T (1964) Hawaiian Beach Systems. University of Hawai'i, 95 pp

National Climate Data Center (2001) Electronic data http://www.ncdc.noaa.gov/ol/climate/climateresources.html

Roberts LM (2001) Historical Land Use, Coastal Change, and Sedimentation on South Moloka'i. In: Saxena N (ed) Recent Advances in Marine Science and Technology, 2000, PACON International, pp 167–176

Rogers CS (1983) Sublethal and lethal effects of sediments applied to common Caribbean reef corals in the field. Mar Poll Bull 14:378–382

Rogers CS (1990) Responses of coral reefs and reef organisms to sedimentation. Mar Ecol Progr Ser 62:185–202

Roy KJ, Smith SV (1971) Sedimentation and coral reef development in turbid water: Fanning Lagoon. Pac Sci 25:234–248

Schroeder TA (1993) Climate Controls. In: Sanderson M (ed) Prevailing Trade Winds. University of Hawai'i Press, Honolulu, 126 pp

Storlazzi CD, Logan JB, Field ME (2004) Quantitative morphology of a fringing reef from high-resolution laser bathymetry: Southern Moloka'i, Hawai'i, GSA Bulletin (in press)

Swart DH (1974) Offshore sediment transport and equilibrium beach profiles. Delft Hydraulic Lab Publication, No. 131

Szmant AM, Yeung C, Cohen K (2000) Turbidity and sedimentation as stressor to Florida reef corals. Abstract volume, 9th Int Coral Reef Sym, 63 pp

Te FT (1992) Response to higher sediment loads by *Pocillopora damicornis* planulae. Coral Reefs 11:131–134

Tudhoe AW, Scoffin TP (1994) Growth and structure of fringing reefs in a muddy environment, south Thailand. J Sed Res A64:752–764

Wiens HJ (1962) Atoll Environment and Ecology. Yale University Press, New Haven, 532 pp

Woolfe KJ, Larcombe P (1998) Terrigenous sedimentation and coral reef growth: a conceptual framework. Mar Geol 155:331–345

Yates K, Halley RH (2000) Reef production in a shallow, turbid environment. Abstract volume, 9th Int Coral Reef Sym, 66 pp