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Temporal and spatial variability in the flow and dispersal of suspended-sediment on a fringing reef flat, Molokai, Hawaii

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Abstract

A multi-year study was conducted on a shallow fringing reef flat on Molokai, Hawaii to determine the temporal and spatial dispersal patterns of terrigenous suspended sediment. During this study, trade-wind conditions existed for the majority of the year on the reef flat. The trade-wind conditions produced strong currents and resuspended moderate amounts of sediment on the reef flat on a daily basis during the year of study, resulting in an overwhelming contribution to the total sediment flux. The magnitude and direction of the trade winds relative to the orientation of the coastline, the shallow-relief and broad morphology, and tidal elevation, provided the primary control of the physical processes that resuspended and transported sediment on the reef flat over the period of record.

Spatial data indicate that much of the terrigenous sediment resuspended on the reef flat is transported predominantly alongshore and is confined to the inner- to mid-reef flat. Evidence for the limited across-shore mixing and transport is provided by the dominantly alongshore wind-driven currents during trade-wind conditions and the well-defined across-shore gradient in percentage calcium carbonate of the suspended sediment. Regions of slightly offshore suspended-sediment transport along the reef flat can be attributed to the circulation pattern set up by the interaction between the trade winds, coastal morphology, and anthropogenic coastal structures (i.e., fish ponds and wharf). The regions in which sediment were seen to move offshore provide the strongest link between the sediment dynamics on reef flat and fore reef, and qualitatively appears to be correlated with low coral coverage on the fore reef.

Keywords: sediment transport; turbidity; terrigenous sediments; trade winds; coral reefs; Hawaii

1. Introduction

Studies of terrigenous sediment dispersal in coral reef settings are few despite the potential for severe environmental impacts to the ecosystems. The consequences of large amounts of terrigenous sediment input onto coral reefs include the decrease of photosynthetically available radiation (PAR), abrasion by sediment, loss of hard substrate, and direct burial (Grigg and Dollar, 1990; Rogers, 1990; Fabricus and Wolanski, 2000; Dollar and Grigg, 2004). Although some corals thrive and do not appear to be affected by moderate inputs of terrigenous sedimentation (Yonge and Nicholls, 1931; Te, 1992; Anthony, 2000), most are impacted by significant amounts of sediment (Rogers, 1983, 1990; Szmant et al., 2000). Because of these recognized impacts, more information on sediment dynamics in reef environments is needed to understand the controls, concentrations and durations of sediment in the water column, as well as dispersal mechanisms. For instance, reefs exposed to strong currents, waves, and/or tides may be less affected by large sediment loads because of the high rates of removal (Larcombe et al., 1995; Larcombe and Woolfe, 1999; Dollar and Grigg, 2004). Additionally, the orientation of the coastline in relation to prevailing environmental factors, such as winds and waves, is an important factor in controlling whether sediment is trapped on the reef flat or efficiently removed (Woolfe and Larcombe, 1998; Golbuu et al., 2003). In these complex environments, temporal and

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spatial observations on the transport, mixing, and fate of sediment and water are essential for understanding the impact that terrigenous sediment may have on the systems (Dodge and Vaisnys, 1977).

This paper describes the results of a study conducted on the fringing reef on the south coast of Molokai, Hawaii, by the United States Geological Survey that examined the processes and consequences of land-derived sediment on Hawaiian coral reefs. The objectives of this paper are to: (1) identify and quantify the resuspension and advection processes that transport sediment on the reef flat due to seasonally varying environmental forcings; (2) examine the relationship between the shallow, broad reef flat and the wind-driven processes to address the residence time of water and sediment on different regions of the reef flat; and (3) investigate the link between reef-flat sediment-transport processes and impacts on the fore reef and areas of active coral growth. This research aids in the evaluation of fringing reef systems by identifying the active forcing mechanisms for sediment delivery on reef flats and their temporal and spatial implications.

2. Background

2.1. Physical characteristics

The island of Molokai (21°N–157°W) is the fifth largest of the Hawaiian Islands, approximately 60 km long (E–W) and 10 km wide (N–S) (Fig. 1). Molokai is made up of two extinct shield volcanoes, the eastern volcano rising 1515 m and the western volcano only 400 m. The eastern volcano traps northeast trade-wind moisture by orographic uplift, resulting in an average rainfall of 500 cm/year on the eastern (windward) and northern flanks of Molokai. Only the very eastern portion of the southern slope of the island is heavily vegetated and deeply incised by persistent runoff and perennial streams. The western (leeward) side of the island is relatively arid, with scrub vegetation and exposed volcanic soil. The watersheds on the south and leeward coast of Molokai receive less than 25 cm/year of rainfall generated from episodic Kona storms and infrequent, but strong trade-wind systems. The southwestern side of Molokai is predominantly a barren tableland, relatively flat in comparison to the eastern and northern sides of the island.

The south coast of Molokai has the most extensive fringing reefs (>50 km long) in the eight main Hawaiian Islands. The fringing reef consists of a broad, shallow (0.5–3 m) reef flat that extends more than 1 km offshore, rising to a reef crest that is partially exposed at low tide, and a fore reef that descends gradually offshore to about 30 m water depth (Storlazzi et al., 2003). The morphology of the inner-reef flat is similar to other reef flats, characterized by a slight depression with an inshore band of fine-grained terrigenous sediment and very little coral coverage (Guilcher, 1988; Ogston et al., 2004). The mid- to outer-reef flat is cemented with encrusting coralline algae, variable to patchy covering of fine-grained terrigenous sediment, and striations of sand and gravel (Guilcher, 1988; Calhoun and Field, 2002). The nearly continuous reef crest, which causes the majority of wave breaking (Storlazzi et al., 2002), is composed of robust coral coverage, reef rubble, and predominantly 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. The highest coral cover in Hawaii is observed on the extent of the fore reef along the south coast of Molokai, except in the region 4 km east of Kaunakakai Harbor, where the coral cover is the lowest in the state (Jokiel et al., submitted for publication).

The coastline of southern Molokai has been modified by the construction of ancient fish ponds (Fig. 1) built on the inner-reef flat during the 13th and 14th centuries (Roberts, 2001). Most of the fish ponds are now obsolete, and many are partially filled with sediment and overgrown with vegetation. In addition, the construction of the Kaunakakai wharf (Fig. 1) in the late 1930s created an impermeable fixed structure extending 580 m offshore across the reef flat. As seen on other reef flats (Stoddart, 1969), the structure likely affects the circulation of the shallow waters, possibly modifying flushing, sedimentation, and temperature.

The study area was located off the south-central coast near the towns of Kamiloloa and Kaunakakai, east of Kaunakakai wharf (Fig. 1). The study area extends 5 km alongshore and approximately 1 km offshore and contains two ancient fish ponds. It is downwind of the discharge points of three ephemeral streams. The study section of reef flat is onshore of a region of low coral cover on the fore reef.

2.2. Meteorological and environmental forcings

Trade winds historically occur 90% of the time in the months of April through November and 50% of the time the rest of the year in the Hawaiian Islands (Moberly and Chaimberlain, 1964). Trade winds are generated by a semi-permanent high-pressure system (EASTPAC) located to the north of the Hawaiian Islands that result in strong winds out of the northeast for much of the year. Trade winds on the south coast of Molokai are diurnal, with the strongest winds in the afternoon (>7 m/s) due to the insolation-generated heating and night time cooling of the Hawaiian Islands similar to a "sea breeze". The winds are topographically steered by the rugged island terrain resulting in a dominant wind direction from the east to slightly southeast direction (~80–100° true) along the southern Molokai shoreline, with a slight onshore component.

Wave energy affecting the Hawaiian Islands originates from four dominant directions, three of which directly impact the south coast of Molokai (Fig. 1). Trade winds generate offshore wave heights of 1–3 m with periods of 5–8 s. The general direction of trade-wind waves is from 45° (NE) but can range from 0° to 90° due to orographic steering around the islands. Kona storms generate wave heights of 3–5 m with periods of 8–10 s arriving from the southwest. Storms in the Indian and Southern Oceans generate swells that reach the Hawaiian Islands in the summer months with wave heights of 1–3 m and periods of 10–20 s. The island of Lanai provides some

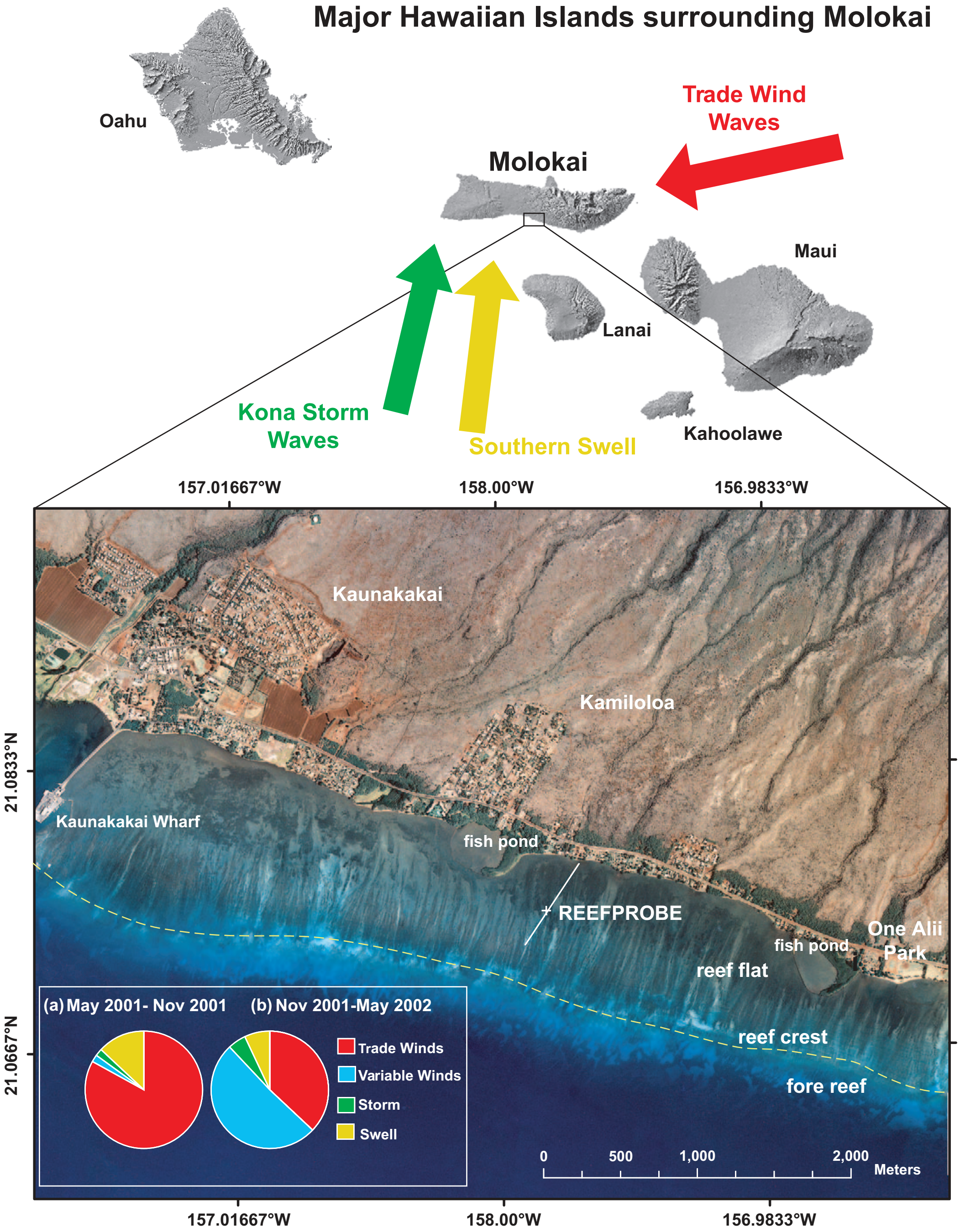


Fig. 1. Location of the study area off the south-central coast of Molokai, Hawaii. Time-series data were collected using a bottom mounted tripod (Reefprobe, +) located approximately 500 m offshore on the reef flat. The spatial data were collected inshore of the reef crest from Kaunakakai wharf east 5 km to One Alii Park. The white line marks where samples were taken to measure calcium carbonate percentages. Inset shows the percentage of time trade-wind conditions, storm conditions, swell conditions, and variable-wind conditions occurred at the Reefprobe (a) May 2001–November 2001, (b) November 2001–May 2002. Note that seasonal conditions were determined from wind speed, wind direction, and wind duration measured on the reef flat.

protection from the south swell, resulting in limited wave action along sections of Molokai's south shore. Winter storms in the North Pacific generate very large swell (3–10 m wave heights and 10–20 s periods) that affect the northern coasts of the Hawaiian Islands, but have little impact on the south coast of Molokai (Moberly and Chaimberlain, 1964).

Tides on the reef flat are mixed, semi-diurnal, and microtidal (<2 m) with a spring tidal range of 1 m and a mean range of 0.6 m (Ogston et al., 2004; Storlazzi et al., 2004). However, this small tidal exchange of water across the reef flat is important for sediment resuspension and transport. The effects of storm, swell, and trade-wind generated waves are enhanced on the reef flat during high tide when the potential exists for more offshore wave energy to propagate over the reef crest and the greater water depth allows for larger in situ wave formation (Ogston et al., 2004; Storlazzi et al., 2004).

3. Methods

3.1. Time-series data

A small bottom-boundary-layer tripod (Reefprobe) was deployed 500 m from the shoreline in approximately 1-m water depth on the reef flat to monitor waves, currents (along and across-shore), tides, suspended-sediment concentration (SSC), salinity and temperature (Fig. 1). The Reefprobe was located (21.0745°N–156.9972°W) at the landward edge of active coral growth in an area dominated by coralline algae, reef rubble, and fine terrigenous sediment with a mean grain size of 0.025 cm (2.0 phi) (Ogston et al., 2004; Storlazzi et al., 2004). The Reefprobe was deployed consecutively in three-month intervals throughout the period from January 2000 until May 2002. Instrumentation on the Reefprobe consisted of an electromagnetic current meter 20 cm above the bed, a pressure sensor 30 cm above the bed, an optical backscatter sensor (OBS) 20 cm above the bed and a conductivity and temperature sensor (CT) approximately 50 cm above the bed. The OBS experienced some biofouling, which was mitigated by anti-fouling agents, and the remaining drift was removed as much as possible in the data analysis. The instruments recorded data at 2 Hz for 512-s bursts every hour, and the CT recorded every 2 min over the duration of the experiment (Ogston et al., 2004). An anemometer was mounted on the seaward end (580 m offshore) of Kaunakakai wharf approximately 5 m above the sea surface to measure wind speed and direction for the latter part of the study. For the purposes of this study, the data collected in the second year (May 2001–May 2002) best illustrate the seasonal variations in sediment-transport dynamics and are discussed in this paper.

3.2. Spatial survey data

The area spanning from Kaunakakai wharf (Fig. 1) 5 km eastward to One Alii Park and from the shoreline to the reef crest (~1 km offshore) was sampled for the spatial sediment dynamics study during May 16–19, 2002, and August 18–22, 2002. A mobile bottom-boundary-layer instrumentation package (Backpack) was used to study the spatial distribution of the processes measured by the Reefprobe. The sensors were mounted on a pole and consisted of an electromagnetic current meter (20 cm above the bed), two optical backscatter sensors (OBS, 20 and 50 cm above the bed), pressure sensor (52 cm above the bed), and a transmissometer (70 cm above the bed). The instruments' sensors were switched on and off at each sampling location and recorded data at a rate of 5 Hz for approximately 90 s at each location. Wind speed was measured at every location with a handheld anemometer. Water samples were taken with Niskin bottles to measure SSC for calibration of the transmissometer and OBS, percentage carbonate of the suspended sediment, and salinity for the May 2002, survey. A CT sensor was used to measure salinity and temperature during the August 2002 survey. The surveys were conducted using a small, flat-bottom skiff to transit between the sampling locations (~50 m spaced) and the transects (~500 m spaced) to gather the most synoptic data possible. The low and high tide surveys were conducted daily during the afternoons in May and August 2002, respectively, when winds are historically persistent and strong (>7 m/s). The duration of each survey lasted 3–5 h during peak winds surrounding the low tide (0.08 m) in May and high tide (0.71 m) in August. To cover the study area, 3–4 daily sampling periods were needed to complete the survey. The measured winds showed that the trade winds were persistently strong throughout the surveys. Although the sampling occurred at similar tidal and wind conditions, some variations in the data resulted from slight changes in environmental conditions over the survey.

3.3. Sensor calibration

The optical sensors for the temporal and spatial studies were calibrated both in the laboratory using seabed sediment from the Reefprobe site and in the field using water-column samples in order to minimize the errors associated with both techniques (Bunt et al., 1999). For the OBS-3 at the Reefprobe, the linear regression of the calibration data from the bottom sediment and water samples show a correlation coefficient of $r = 0.84$ ($n = 24$) for the second year of record. There was a slight drift in the sensor over the 2-year experiment, and this was accounted for by calibrating before each deployment (Ogston et al., 2004). The optical sensors (OBS and transmissometer) for the spatial studies in May and August were calibrated in the laboratory using bottom sediment from the Reefprobe site as well as from water samples collected at the height of the OBS (20 cmab) from multiple locations on the reef flat. Both the field and laboratory calibrations for OBS from the two spatial studies show a similar gain response with high correlation, $r = 0.98$ (field, $n = 78$) and $r = 0.89$ (lab, $n = 10$).

3.4. Calcium carbonate content

The calcium carbonate content by weight of the suspended sediment in the water samples was measured to identify the amount of sediment derived from island erosion (terrigenous) versus that produced on the reef (calcium carbonate). An array of alongshore and across-shore samples was chosen to characterize the study area. Each filtered sample was measured for mass inorganic carbon using UIC Coulometer and the associated technique (Engleman et al., 1985). The percentage by weight of calcium carbonate was calculated assuming all of the inorganic carbon in the samples was calcium carbonate (Glenn et al., 1995).

3.5. Suspended-sediment flux and shear stress calculations

Suspended-sediment fluxes (UC) at the Reefprobe site were calculated using the hourly burst mean SSC (C) and near-bed current velocity (U). The suspended-sediment flux evaluates the correlated suspended sediment and the mean near-bed currents on the reef flat, assuming the flux, but not resuspension, due to waves ($\overline{U'C'} = 0$) is negligible, as confirmed with data from individual bursts. Total suspended-sediment flux ($\overline{UC}$) was calculated for different environmental conditions by summing over the duration of occurrence on the reef flat,

$$\overline{UC} = \sum \overline{U}_1\overline{C}_1 3600s + \overline{U}_2\overline{C}_2 3600s + \cdots + \overline{U}_n\overline{C}_n 3600s.$$

The flux was determined in the alongshore and across-shore direction for different conditions on the reef flat and was used to determine the primary forcing for sediment-transport dynamics.

Bed shear stresses, τ_b, were estimated using the Grant–Madsen wave–current interaction model (Grant and Madsen, 1979), and are characterized by the shear velocity, $u{*}_r$, where $\tau_\mathrm{b} = (1/2)\rho u{*}_r^2$, and ρ is the fluid density. The model uses the wave-orbital velocity, near-bed current velocity, the angle between the two, and bed roughness to calculate the shear stress from the hourly averaged data collected at the Reefprobe. The angle of the wave-orbital velocities was based on visual observation. Most waves on the reef flat during trade-wind conditions propagate in the wind direction (100° true). The waves on the reef flat during storm and swell propagate perpendicular to the shoreline (190–220° true), as most of these deep-water waves were refracted in these shallow depths. The characteristic bed roughness on the reef flat was difficult to estimate due to reef rubble, coral heads, and algal mats. The mean grain size of the sediment at the Reefprobe site is fine-medium sand (0.025 cm), and is smaller than the observed roughness elements (coral fragments, algae mats, etc.) at the experiment site. The extreme roughness associated with the bed variability of reef flats has been shown to yield drag coefficients of two orders of magnitude greater than particle sizes (Roberts et al., 1992; Nelson, 1994, 1996; Thomas and Atkinson, 1997; Lugo-Fernandez et al., 1998; Hearn et al., 2001). To account for the complex roughness at the study site, a roughness scale of 2.5 cm, two orders of magnitude greater than the mean grain size, was used in the calculations. Without further evaluation of the bed roughness, the shear velocities should be recognized as estimates.

4. Results

4.1. Seasonal variation in transport conditions

Two distinct seasons have been identified in the Hawaiian Islands for this study, the trade-wind (May–November 2001, Fig. 1a) and non-trade-wind (November 2001–May 2002, Fig. 1b) seasons. Four general types of transport conditions were observed on the reef flat during the two seasons: trade winds, variable winds, storms, and swell. The variation in meteorological conditions observed on the reef flat within the two seasons is relatively consistent with historical records (Moberly and Chaimberlain, 1964).

Trade-wind conditions within the trade-wind season dominated the time-series data (83%), and were less prevalent during the non-trade-wind season (37%). During trade-wind conditions (Fig. 2a), near-bed currents were influenced by trade-wind magnitude and duration, resulting in a dominant (>10 cm/s) westerly alongshore component and a slight (~2 cm/s) offshore (south) component on the reef flat regardless of tidal cycle. The SSC increased from <1 mg/l to 10–20 mg/l diurnally as the trade-wind speed increased in the afternoon and remained high until the wind speeds decreased in the late afternoon/early evening. The tidal elevation and wind-driven waves on the reef flat modulated the wave-orbital velocities, which ranged from 5 to 10 cm/s. The variation in salinity on the reef flat during trade winds ranged approximately 1 ppt and varied with the ebb and flood tides, while the temperature increased in the afternoon typically from 25 to 27 °C from insolation, similar to observations by Ogston et al. (2004) and Storlazzi et al. (2004).

Variable-wind conditions were rarely present (2%) during the first half of the record, but dominated the record during the non-trade-wind season (51%). During variable-wind conditions (Fig. 2b), very small alongshore and across-shore currents of 1–3 cm/s were observed, which corresponded with the tidal cycle and are assumed to be tidal currents. The low SSC (<5 mg/l) during these periods was controlled primarily by the wave-orbital velocities (<7 cm/s) which was modulated by the tidal elevation. The salinity ranged between 34 and 35 ppt as the tide ebbed and flooded, respectively, while the temperature varied generally between 25 and 29 °C, with solar heating and weak water exchange during the day.

Storm conditions (5% of the time) were more prevalent during the non-trade-wind season than the trade-wind season (2%), with a large Kona storm impacting the island in November 2001, and smaller storms occurring in December 2001 and January 2002. Storm conditions (Fig. 2c), while infrequent, were associated with high wave-orbital velocities, strong winds from various directions, and elevated rainfall (Fig. 2c, shaded regions). The 7.5 cm of rainfall on November 26–27, 2001, resulted in large amounts of sediment runoff delivered to the coastline and reef flat (Field et al., 2004). This November 2001 Kona storm (Fig. 2c, first shaded region) was associated with SSC greater than 50 mg/l and wave-orbital velocities greater than 10 cm/s from the concurrence of large storm generated waves and high tide. The winds varied in magnitude and direction, resulting in a relatively minor net current in the alongshore and across-shore direction. Although bursts of high SSC appeared on the days following the storm, the greatest values occurred during December 2–4, 2001 (Fig. 2c, second shaded region) when the trade winds were more intense. The lowest water temperatures (24–27 °C) and salinity values (28–35 ppt) were observed during storms due to the input of fresh water to the reef flat and more energetic mixing with offshore waters.

Swell conditions contributed 13% of the record during the trade-wind season, although this may be a minimal estimate (50% historically during trade-wind season Moberly and Chaimberlain, 1964) due to difficulty in discerning these conditions if concurrent with trade winds (Andrews and Pickard, 1990). Sheltering of the south-central coast by other islands

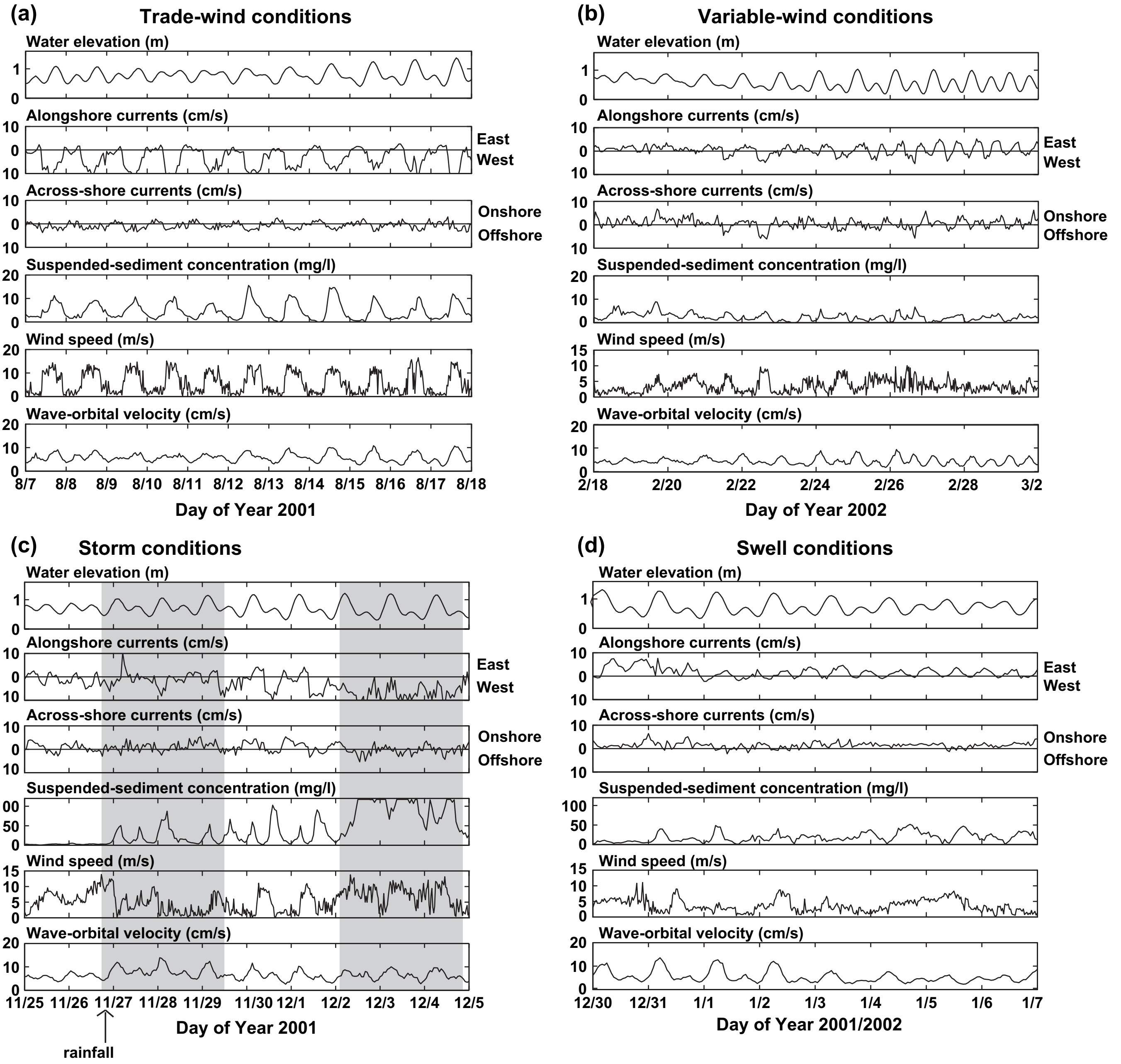
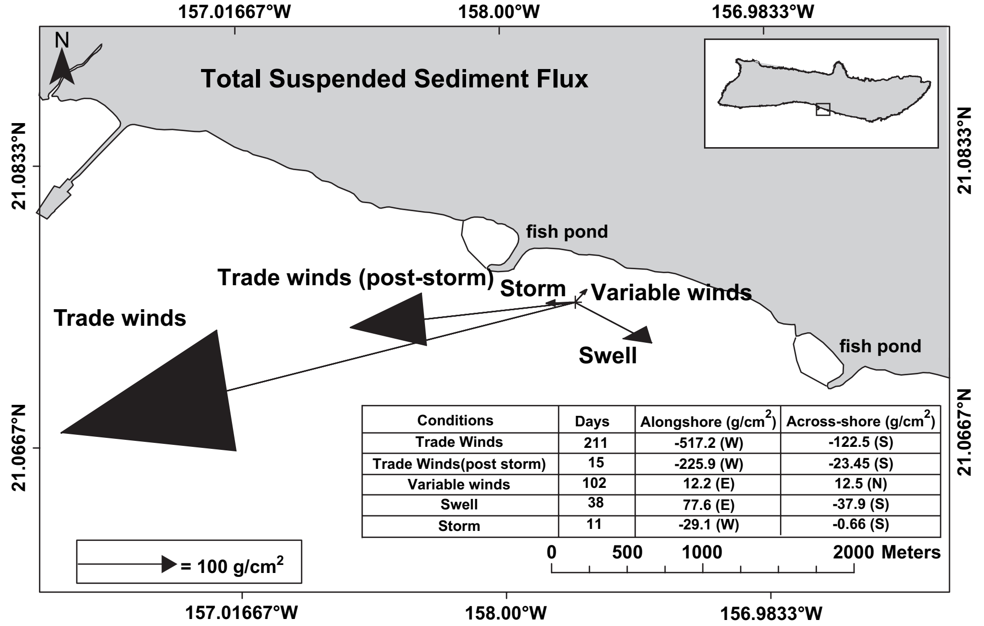


Fig. 2. Time-series data of water elevation, alongshore currents, across-shore currents, suspended-sediment concentration (SSC), wind speed, and wave-orbital velocity during (a) trade-wind conditions, (b) variable-wind conditions, (c) storm conditions and (d) swell conditions. Each set of subplots is representative of the specific seasonal conditions determined from wind direction, magnitude, and duration.

(W. Maui and Lanai) also accounts for the limited observed contribution. Swell conditions not associated with trade winds (Fig. 2d) were characterized by an increase in wave-orbital velocity to greater than 10 cm/s, which was enhanced during high tide, due to less wave dampening. The associated wave-orbital velocities correlated with peaks in SSC, as high as 50 mg/l. The near-bed currents during swell periods, without the presence of trade winds, were small and dictated primarily by the tides (<5 cm/s), with slightly dominant east and onshore components. The temperature and salinity ranges were similar to trade-wind conditions, with solar heating during the afternoons and small tidal variations.

4.2. Suspended-sediment fluxes

The total alongshore and across-shore suspended-sediment flux summed over the duration of each seasonal condition (Fig. 2a–d) are shown in Fig. 3. In this analysis, the trade-wind condition is further dissected into two parts, typical trade winds as described above and trade winds following a Kona storm. Trade-wind conditions in the year-long record contributed to the majority of the total flux due to strong westerly currents, enhanced wave-orbital velocities during high tides, and moderate, but consistent SSC over a period of 211 days (517.2 g/cm^2 of sediment alongshore to the west and



Conditions	Days	Alongshore (g/cm^2)	Across-shore (g/cm^2)
Trade Winds	211	-517.2 (W)	-122.5 (S)
Trade Winds(post storm)	15	-225.9 (W)	-23.45 (S)
Variable winds	102	12.2 (E)	12.5 (N)
Swell	38	77.6 (E)	-37.9 (S)
Storm	11	-29.1 (W)	-0.66 (S)

Fig. 3. The total sediment flux represented by vectors scaled to the alongshore and across-shore components for the different seasonal conditions from the May 2001–May 2002 data set. The trade-wind sediment flux was further divided to show the flux following a large Kona storm. The dominant sediment-transport direction is to the southwest by trade-wind conditions.

122.5 g/cm^2 offshore). The flux associated with storm conditions (29.1 g/cm^2 alongshore to the west and 0.66 g/cm^2 offshore) is relatively small due to indistinct current direction and infrequent occurrence (11 days). Although the storm flux is small, the trade-wind conditions following the November 2001 Kona storm and subsequent sediment input events (15 days), transported the second largest amount of sediment (225.9 g/cm^2 to the west and 23.45 g/cm^2 offshore), due to extremely high SSC (>50 mg/l) and strong currents. Swell conditions, with moderate SSC, transported a minor amount of sediment in comparison to the trade winds due to inconsistent currents and the limited duration of these conditions (38 days) observed in this record. Variable-wind conditions, though frequent (102 days) on the reef flat, result in low total sediment flux due to small values of SSC and weak near-bed currents.

4.3. Resuspension and advection events

Shear velocities from the interaction of waves and currents ($u*_r$) on the reef flat ranged from 0.6 to 2.6 cm/s for all seasonal conditions. The critical shear velocity for resuspension at the instrument site is estimated to be 0.82 cm/s. Resuspension of sediment by trade-wind generated waves and currents on the reef flat during trade-wind conditions (Fig. 2a) shows a clear relationship of increasing SSC with increasing shear velocity (Fig. 4a, $r = 0.83$). Conversely, during the time period directly after the November 2001 Kona storm (Fig. 2c, second shaded region), when winds were very strong and terrestrial sediment input had been previously high, the relationship between SSC and shear velocity is indistinct (Fig. 4b, $r = 0.21$). This period is identified as advection of sediment by mean currents from another area on the reef flat as the high SSC does not correspond to shear velocities indicative of resuspension at the instrument site.

An example of resuspension and advection events in the same period occurred during consistent trade-wind conditions approximately three weeks after the November 2001 storm (Fig. 5a, shaded regions, December 16–19, 2001). The high wave-orbital velocities that coincided with high tide during the onset of trade winds generated greater shear velocities at the bed, resulting in SSC of 50–90 mg/l. The increasing SSC with increasing shear velocity indicates resuspension at the bed on the reef flat near the Reefprobe site (Fig. 5b, $r = 0.69$). As the trade winds continued, a second set of high SSC (50–100 mg/l) events were observed on the reef flat at the Reefprobe site. The strong alongshore currents to the west associated with the strong winds coincide with the secondary peaks of SSC. The shear velocity during this period decreased while the SSC increased, indicating resuspension at the instrument site was not the physical process responsible for the elevated SSC. There is no clear relationship between the shear velocities and SSC for this period (Fig. 5b, $r = 0.32$) which is consistent with other observed advection events.

4.4. Spatial variations in reef-flat processes

The May 2002 survey characterized processes during low tides under trade-wind conditions on the reef flat. The SSC measured on the reef flat during these conditions (Fig. 6a) ranged from less than 5 mg/l to more than 70 mg/l, with the SSC generally decreasing offshore. The highest SSC was focused nearshore and east (upwind) of the fish ponds and Kaunakakai wharf. The near-bed currents on the reef flat (Fig. 7a)

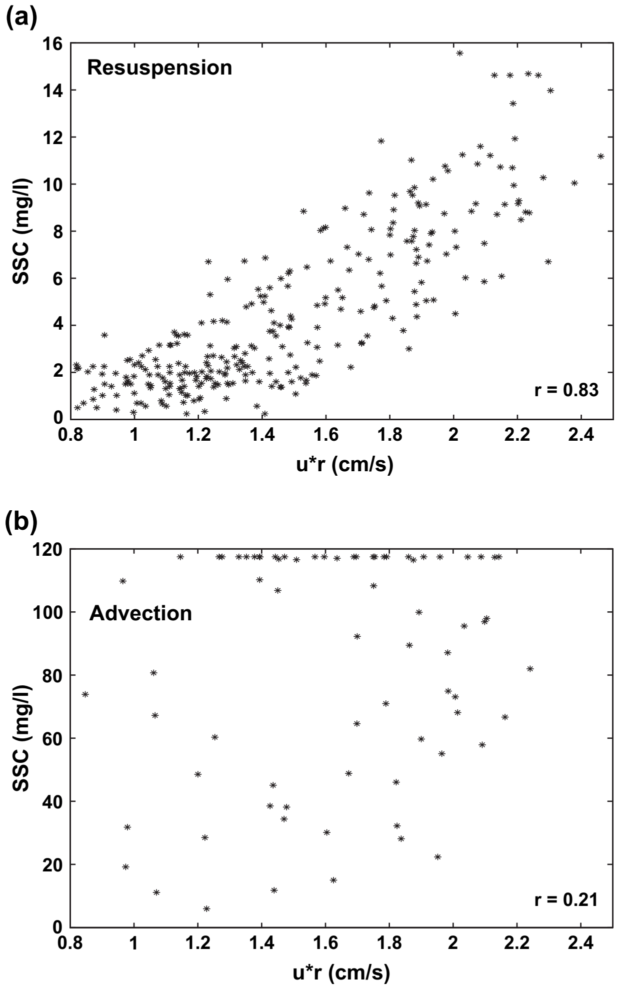


Fig. 4. Relationship between calculated wave–current shear velocities (u^*_r) and SSC. (a) Trade-wind conditions (Fig. 2a). The high correlation between shear velocity and SSC indicates that the SSC is controlled by local resuspension during trade-wind conditions. (b) Post-storm period (December 2–5, 2001, second shaded region in Fig. 2c). The low correlation between shear velocity and SSC indicates the sediment in the water column after the storm event did not originate from local resuspension of seabed sediment, but rather was advected to the study area from a region nearby.

ranged from 1 to 25 cm/s and were predominantly alongshore. The across-shore component was minor with greater offshore flow on the east (upwind) side of the fish ponds and wharf and greater onshore flow on the west (downwind) side of the fish ponds. Some of the velocity measurements, particularly in deeper water, were affected by shore-normal coral ridges on the outer-reef flat, which were more prominent during low tide.

The August 2002 survey examined processes during high tides under trade-wind conditions on the reef flat. The SSC ranged from less than 5 mg/l in the offshore regions to more than 130 mg/l nearshore. Maximum SSC was east (upwind) of the fish ponds and wharf (Fig. 6b), as observed in the low tide survey. The SSC was higher and extended further offshore during the August high tide survey than the May low tide survey on the reef flat, although the limited data over the reef crest suggest low SSC in this area during both tidal stages. The currents ranged from 1 to 25 cm/s and showed a pattern similar to the May low tide study, but with stronger currents (Fig. 7b). The alongshore component again dominated at all the measurement sites on the reef flat with only minor across-shore components around the fish ponds and wharf. The magnitude of the currents increased where the reef flat is narrow and deep, and decreased in the broader and shallower parts of the reef flat (Fig. 7b). Where the Kaunakakai wharf obstructs the alongshore flow, the currents are significantly slower and have a greater offshore component, implying stagnation of water at the wharf.

Currents measured during the August high tide survey allow an approximation of a flow transport rate for different sections of the reef flat during trade winds. Following a trajectory at mid-reef flat, assuming an average current speed of 10 cm/s from the spatial current data, a water parcel is transported the distance of 4.6 km in 12.8 h (0.35 km/h), assuming high tide and high wind conditions persist for the entire duration. Typical trade-wind conditions existed for an average of 6 h each day, thus a parcel of water flowing on the mid-reef flat would take roughly 2 days to travel ~5 km, the length of the study area. On the inner-reef flat the flow transport rate, assuming an average current speed of 6 cm/s from the spatial current data, during high tide and trade-wind conditions is roughly twice as long as the mid-reef flat taking 23.4 h to travel ~5 km (0.23 km/h), resulting in over 4 days to travel the study area. A flow rate for the low tide survey was not evaluated as the current data were not as complete as in the high tide survey, but would presumably be slightly less in value, resulting in a longer travel time.

Water samples collected during the August high tide survey showed an inverse correlation ($r = -0.87$) between weight percentage of calcium carbonate and SSC in the across-shore direction (Fig. 8). As the SSC decreases offshore on the reef flat, there is a corresponding increase in the carbonate material in the suspended sediment, from approximately 10% nearshore (25 m from shore) to greater than 60% near the reef crest (800 m from shore). The greatest increase in carbonate content occurred on the mid- to outer-reef flat (~550–800 m from shore). In the alongshore direction, the carbonate content (30–40%) was relatively constant along a mid-reef transect approximately 500 m offshore, except for a sharp decrease to 18% near the wharf.

5. Discussion

5.1. Reef flat sediment transport in response to trade winds

For the majority of the year, trade winds impact the study area and are the principal controlling factor for the sediment-transport processes on the reef flat. This has been previously shown for the reef flat off south-central Molokai and in other shallow reef-flat environments where tidal currents and wave energy are small (Pickard, 1986; Andrews and Pickard, 1990; Ogston et al., 2004). Although SCC magnitude during trade-wind conditions is low to moderate in comparison to

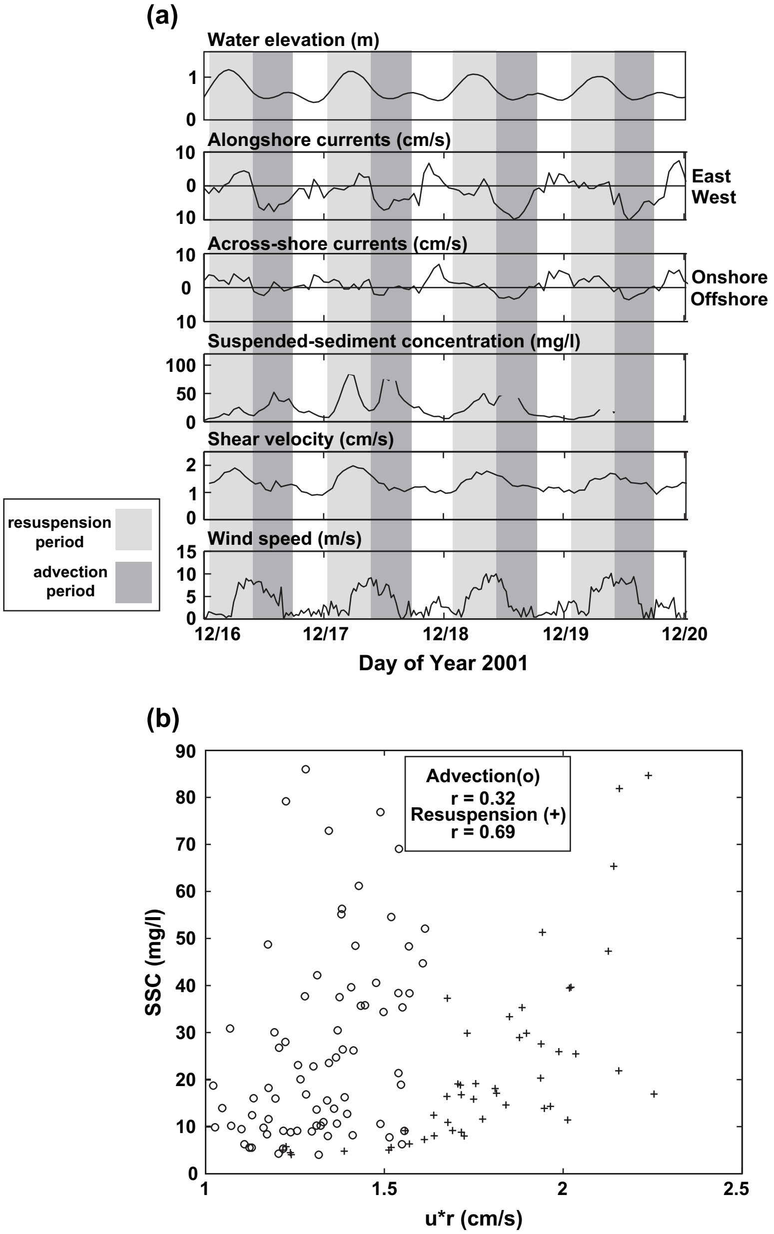


Fig. 5. (a) Post-storm (December 16–19, 2002) time-series data of water elevation, across-shore and alongshore currents, SSC, shear velocity, and wind speed during trade-wind conditions. The pattern of double peaks in the SSC occurs over a daily cycle with the first peak associated with high shear velocity while the second does not. This suggests that two separate processes are causing high SSC signals during this period of time, the first being local resuspension, and the second by advection from another area. (b) Relationship between calculated wave–current shear velocity and SSC from the peaks of SSC during the post-storm period (December 16–19, 2002). The data fall into two groups that are similar to the resuspension and advection relationships shown in Fig. 4.

other seasonal conditions, the trade winds induce relatively strong currents on a persistent daily basis over a long seasonal duration (Fig. 1a,b). This results in the trade-wind period contributing to the largest total flux of sediment of all the transport conditions presented along and across the reef flat for the year of record (Fig. 3).

While the time-series record reveals the dominance of trade winds on the net annual flux at one location on the reef flat, the spatial surveys demonstrate the variations within the trade-wind condition as a result of tidal stage and reef-flat morphology. Tidal stage controls the ability of trade-wind induced waves and currents to resuspend and transport sediment. During low tide, parts of the reef crest were exposed, dissipating more offshore wave energy, and the lower water elevation inhibited the in situ development of trade-wind-driven waves. This decrease in wave energy and wave-orbital velocity results in lower SSC on the reef flat at low tide (Fig. 6a). At high tide, the greater water depth allows deep-water wave energy propagation and in situ wind–wave development to create conditions for greater amounts of sediment resuspension and transport over a larger area on the reef flat (Fig. 6b). Thus, the substantial amount of SSC observed spatially on the reef flat is due to the concurrence of high tide, trade-wind generated currents and waves, and the propagation of offshore deep-water

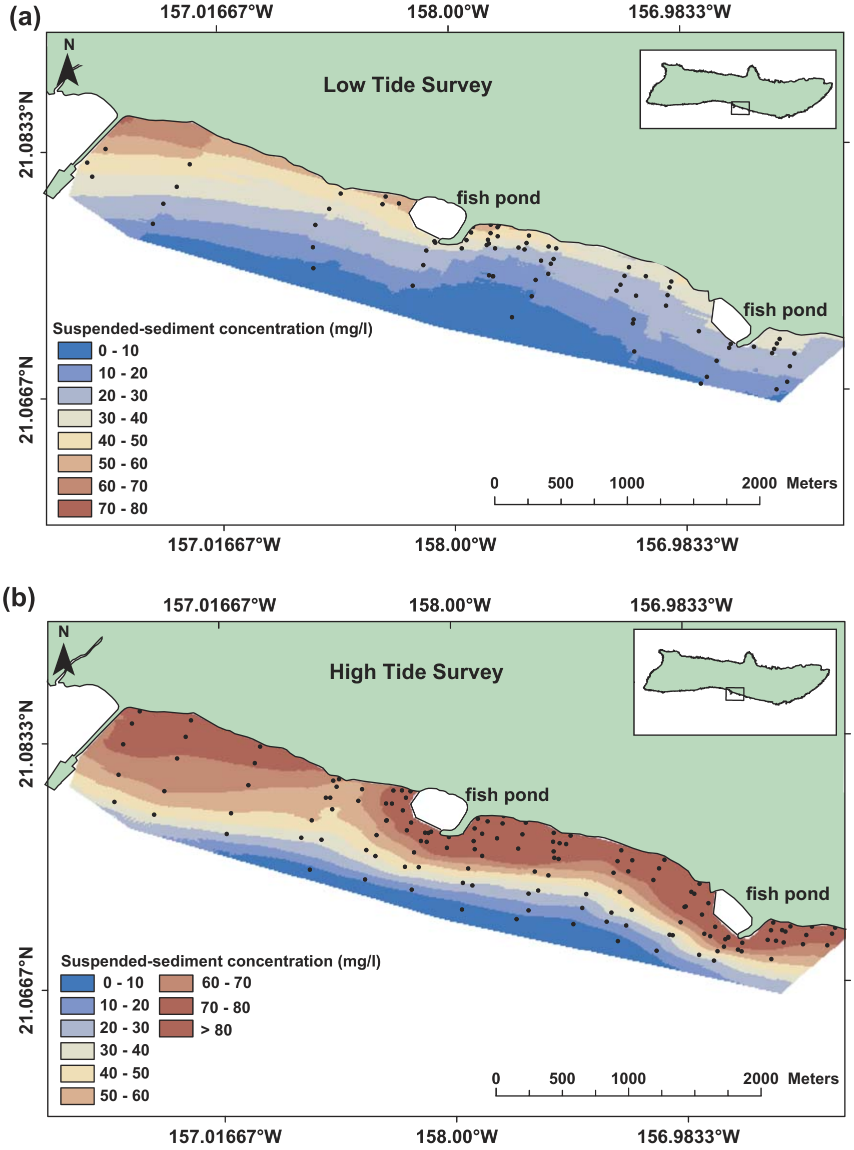


Fig. 6. Contour plots of SSC for the spatial surveys during trade-wind conditions on the reef flat. (a) SSC from the low tide survey. The highest SSC (60–70 mg/l) were located in a nearshore band, and east of the fish ponds and Kaunakakai wharf. (b) SSC from the high tide surveys. SSC in excess of 80 mg/l are seen in a nearshore band and east of the fish ponds and wharf. The SSC rapidly decreases with distance offshore from 130 mg/l to <5 mg/l, exhibiting the constraint of SSC to the inner-reef flat.

wave energy as shown temporally by Ogston et al. (2004) and Storlazzi et al. (2004).

5.2. Constraint of alongshore sediment flux on the reef flat

Sediment flux on the reef flat is predominantly confined to the inner 600 m of the reef flat as a consequence of the alongshore wind-driven currents and the shallow-relief, broad, morphology of the reef flat. The westward alongshore flow on the reef flat during all tidal stages are a response to two factors: (1) the direction of trade winds (~80–120°) that are topographically steered in relation to the orientation of the shoreline (110°); and (2) the dominance of wind-driven currents over tidal currents. The reason for the slight offshore component of the trade-wind-driven flow during all tidal stages is somewhat ambiguous, but is likely in response to the fixed coastline structures and coastline orientation, as observed from the May and August 2002 surveys. Those measurements showed that during periods of high and low tide and strong trade winds the flow decreased and was steered offshore at the fish pond walls along the coastline and the impervious wharf (Fig. 7a,b). In non-modified coastline areas, the relationship of the wind direction and coastline orientation may also control the offshore component of the near-bed flow as a balance to the slight onshore wind-driven surface flow. The direction of currents at the mid- to outer-reef flat is less influenced by the coastal structures and coastline and flow was predominantly alongshore.

The morphology of the reef flat inhibits the transfer of sediment across-shore due to limited energy propagation

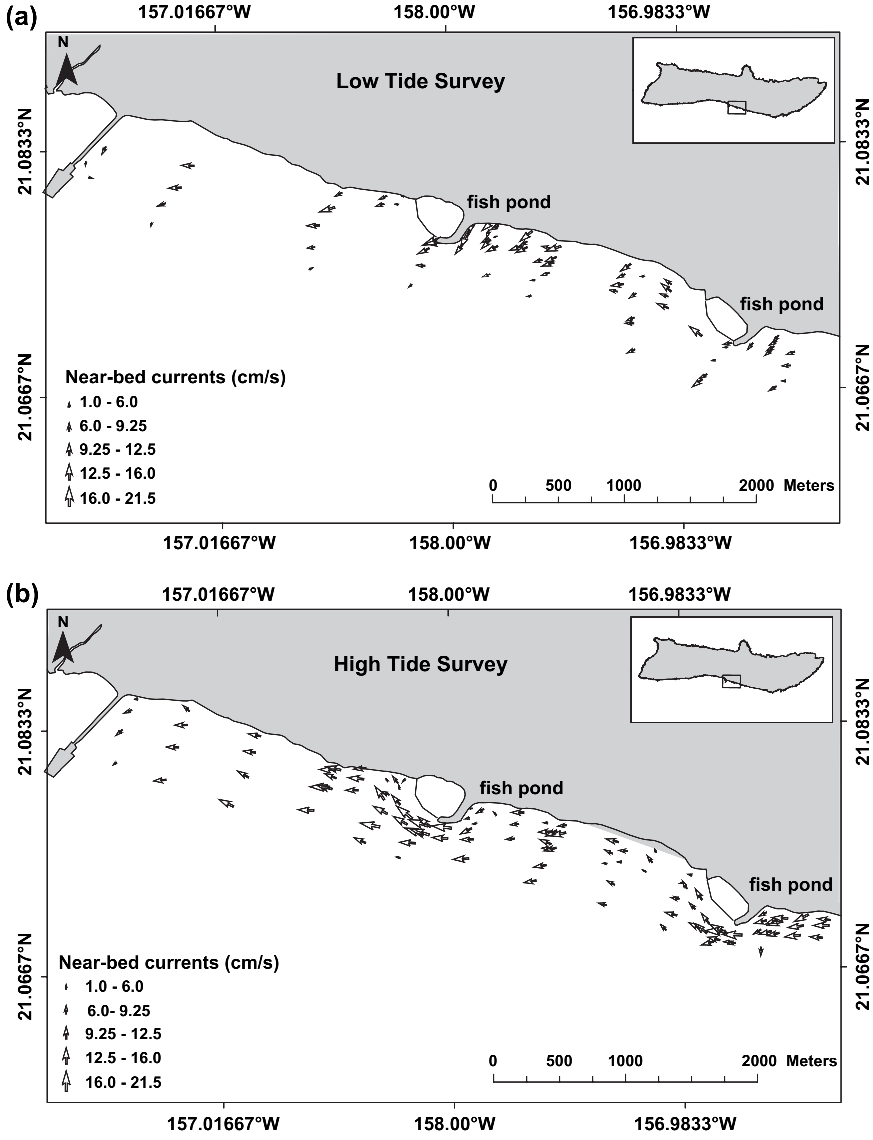


Fig. 7. Near-bed mean current velocities on the reef flat during trade-wind conditions. (a) Low tide survey (May 2002), (b) high tide survey (August 2002). The dominant current direction is alongshore to the west for most points on the reef flat with slight offshore flow on the east (upwind) side of the fish ponds and onshore flow on the west (downwind) side for both surveys.

past the reef crest and horizontal across-reef flat mixing. This is observed in the gradient of decreasing SSC in the offshore direction observed during the spatial surveys (Fig. 6a,b). The concentrations decreased from greater than 80 mg/l nearshore to less than 5 mg/l at the farthest offshore reef-flat sampling locations, indicating that only minor amounts of sediment were transported to the offshore waters along the length of the survey area. The highest SSC occurred within 400 m of the shore (Fig. 6b) and the only area on the reef flat in this study where high SSC persisted farther offshore was located just east (upwind) of the wharf, resulting from offshore-oriented currents and sediment fluxes in this area.

The carbonate content of the suspended sediment (Fig. 8) further indicates that the band of terrigenous sediment is confined to the inner- and mid-reef flat and is transported primarily alongshore. The lowest carbonate content (<20%) is correlated with the highest SSC on the reef flat and the suspended-carbonate percentages increase in the offshore direction as SSC decreases, indicating a smaller contribution of terrigenous material rather than an increase in calcium carbonate inputs. The similar patterns of seabed-carbonate content (Calhoun and Field, 2002) and suspended-carbonate content imply that the primarily fine, terrigenous material resuspended on the inner- to mid-reef is not being advected or rapidly diffused towards the outer-reef flat. Thus, the terrigenous sediment appears to move alongshore in a discrete inner- to mid-reef band with little across-shore mixing.

5.3. Residence time of water and transport rates

The residence time of water on the reef flat is a function of the strength of circulation mechanisms to flush material from the system by tidal flow, wind-driven flow, flow induced

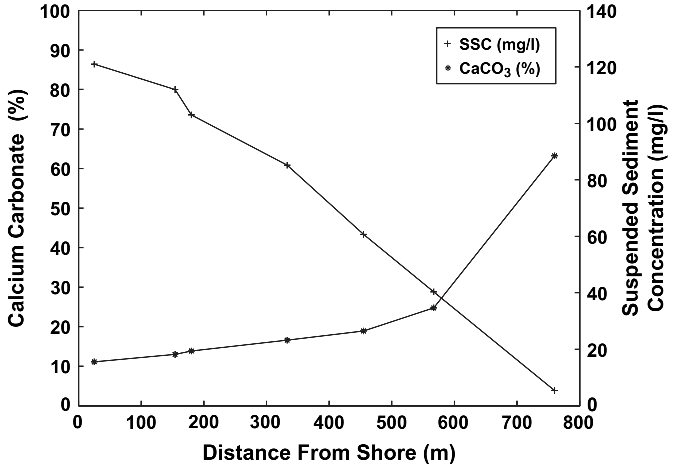


Fig. 8. Percentages of calcium carbonate in the suspended-sediment samples and the corresponding SSC at an across-shore transect located through the Reefprobe site (Fig. 1). The relationship between SSC and calcium carbonate percentage varies inversely. The carbonate percentages are lowest where SSC is highest. The greatest increase in percentage of calcium carbonate occurs between approximately 550 and 800 m offshore, and correlates with the decrease in SSC.

by breaking of wind-driven waves on the reef flat, and offshore wave energy (Hearn and Parker, 1988; Symonds et al., 1995). The south-central fringing reef off Molokai experiences small tidal currents, relatively minor amount of deep-water swell, and its broad, shallow, morphology limits the ability for these mechanisms to flush material from the reef flat. In comparison, trade-wind-driven processes are an almost daily condition on the reef flat and drive the strongest currents, therefore making it the dominant mechanism that impacts the residence time of water as well as sediment transport.

On the inner-reef flat, the shallow depths as well as the flow interference from coastal structures limit the trade-wind-driven current speeds, resulting in a relatively long time (~4 days) for water to transit through the study area (~5 km). The currents on the outer-reef flat are not altered by local coastal structures (fish ponds) and show accelerated speeds at the apex of these structures where the reef flat is deeper, and along with the shorter pathway through the study area result in a shorter time (~2 days) for water to transit the length of the study area (~5 km). The currents on the mid-reef flat are relatively consistent alongshore, except near the Kaunakakai wharf where an abrupt decrease in speed and offshore veering occurs. Additionally, in the areas upwind (east) of all the coastal structures, the residence time may be considerably longer as the currents are drastically slowed and the only circulation mechanism is the tides.

In this system, the residence time of water and sediment varies with across-reef location, as the along-reef transport dominates. In steeper, narrower reef systems that allow significant offshore waves and currents to propagate into the shore, the across-shelf mixing will likely be the dominant control of residence time. The physical characteristics of the reef flat (width, depth, orientation, tidal range, etc.) will determine the dynamics of sediment removal or storage, and must be considered when evaluating circulation patterns and expected flushing times of the different types of reef morphology.

5.4. Replenishment and removal of sediment on the reef flat

Over time, the alongshore transport of sediment via the trade-wind-driven currents, as well as small offshore transport caused by the deflection of currents by permanent structures, and from tides, creates the potential for much of the terrigenous sediment to be removed from the finite-length reef flat. Therefore, there would appear to be a discrepancy between the daily transport and removal of sediment from the reef flat and the substantial and seemingly persistent deposits of terrigenous sediment. Consequently, new sediment must be supplied to the reef flat and advected into the study area to create the apparent balance of sediment on the reef flat.

Two types of SSC events, resuspension and advection, were identified in the data record by examining the relationship between shear velocity and SSC (Fig. 4). For example, prior to the November 2001 Kona storm, resuspension events of relatively low to moderate SSC dominantly occurred under trade-wind conditions (Fig. 4a). Following this storm, advection and resuspension events of high SSC were observed during trade-wind conditions (duration of ~6 h) for a period of a few days to weeks after the rainfall/flood event (Fig. 5a). This transport of sediment at the mid-reef flat indicates that alongshore currents from the east deliver the freshly supplied fine-grained suspended sediment to the study area via advection events. In addition, the high SSC events that occurred daily after the storm were likely the result of resuspension of easily re-mobilized sediment that was discharged onto the reef flat. The episodic input of terrigenous sediment from storms and the subsequent daily resuspension and alongshore transport results in a temporally continuous system of sediment advection to the west via the trade-wind-driven currents. Without the input of sediment during rainfall runoff events, which occur seasonally but also respond to decadal cycles, the trade-wind conditions and other natural forcing would eventually remove the majority of the terrigenous sediment from the finite system over time, except where trapped by the coastal structures.

In the absence of input from terrestrial sources, a simplified mass balance can be formulated to approximate the time required to remove all the existing terrigenous sediment from an inner-reef-flat band throughout the study area: $C_2V = C_1V - C_1A\mathrm{Vel}\,\Delta t$, where C_2 and C_1 are the concentrations of sediment at times 2 and 1, respectively, V is the volume of the study area, A is the cross-sectional area where sediment moves out of the volume, Vel is the velocity of sediment moving out of the volume, and Δt is the span of time. Assuming no gradients over the plan view area in Δt, this becomes: $C_2h = C_1h - C_1h/l\,\mathrm{Vel}\,\Delta t$, where h is the height of the study area volume and l is the length. Therefore, using an average daily suspended-sediment concentration value of 20 mg/l per resuspension cycle (1 per day) in a 1-m water column, and an average velocity (Vel) of $l/4$ days, the removal term becomes 0.5 mg/cm^2. The amount of fine-grained sediment in a 10-cm depth of seabed is approximately 5 g/cm^2, assuming a porosity of 0.8, and a sediment density of 2.65 g/cm^3. Thus, it would take approximately 10,000 cycles (or 10,000 days) to remove all of the seabed sediment from the study area if no input from the east or adjacent watersheds were to occur. Assuming the removal happens throughout the year, this corresponds to roughly 30 years for complete removal to occur. This is a minimum estimate as there would be sediment supplied from existing deposits to the east and armoring of the seabed by the larger carbonate fragments which would protect the fine-grained terrigenous particles in the seabed over time. Meteorological data indicate the incidence of large storms that include heavy rainfall and large swell is more frequent than the approximate amount of time needed to remove sediment from the reef flat as calculated, with significant precipitation occurring on an annual basis during wet years (National Weather Service Hydronet System) and less frequently during dry years. Although the removal time estimates are crude, this analysis provides a baseline for evaluating the sediment budget on the reef flat and a preliminary understanding of why the terrigenous deposits remain even though persistent, daily sediment resuspension and transport are observed.

5.5. Link between the reef flat and the fore reef processes

The minimal amount of across-shore mixing as a result of trade-wind-driven circulation suggests that the delivery of sediment suspended on the reef flat to the fore reef is generally small. The variability of near-bed currents along and across the reef flat is influenced by shoreline structures, creating along-reef variations in the magnitude of off-reef suspended-sediment flux off the reef. The suspended-sediment flux decreases in regions with low current velocities, such as upwind of the fish ponds and wharf. Although the suspended-sediment flux is of lower magnitude at the structures, it is significant for the delivery of sediment offshore.

The offshore flux at the wharf and fish ponds provides one of the strongest links between the processes on the reef flat and the decrease in coral coverage offshore of the study site on the fore reef. In general, during trade-wind conditions the offshore flux of sediment is small, yet these conditions are persistent over a large part of the year. The sediment that is transported by the trade winds to the area of the wharf and the fish ponds is mainly fine-grained terrigenous sediment, which is easily re-mobilized after settling out following the previous high tide/trade-wind cycle. This daily resuspension of sediment in the area of the wharf and fish ponds results in a net transport of sediment towards the fore reef and areas of observed low coral coverage (Jokiel et al., submitted for publication). The transport of terrigenous sediment into the fore reef environment may have been a factor in causing low coral coverage by blocking crucial sunlight for active coral growth, increasing deposition to regions of minimal resuspension, and potentially degrading the coral in these areas (Grigg and Dollar, 1990; Rogers, 1990).

Fringing reefs are attached to land masses, and inherently sediment that is eroded from land either by anthropogenic or by natural causes will be transported to the reef-flat environment. As discussed previously, the morphology, wave climate, tides, and wind-driven processes are important factors for assessing sediment-transport dynamics of reef-flat systems. The geologic development of the shallow reef crest limits the impact of deep-water wave energy on the shallow reef flat and increases the importance of trade-wind waves and currents and tides. This indicates that the minor processes occurring on a daily basis may have greater influence on the physical environment than the large episodic events. In addition, alterations to the reef-flat environments by man-made structures also affect the physical dynamics and the transport of sediment. As observed in this study, structures that extend onto the reef flat can cause local areas of flow stagnation and sediment trapping, as well as zones of slightly enhanced off-reef sediment flux. Thus, it appears that increasing terrestrial sediment to inner-reef-flat environments may have great impact, as the minimal across-reef mixing is controlled by the morphology and limited wave energy in micro-tidal environments, resulting in long retention times.

6. Conclusions

From the above results the following conclusions are presented:

- Trade-wind-driven processes are the dominant control for circulation and sediment dispersal on the shallow, broad reef flat off of southern Molokai, Hawaii. Sediment resuspension and transport occur on a daily basis throughout much of the year and has a great impact on the sedimentary environment of the reef flat. The input of terrigenous sediment on the reef flat is due primarily to infrequent large storms that generate heavy precipitation that delivers sediment to the coast.
- The magnitude of suspended-sediment concentration on the reef flat is controlled by the concurrence of trade winds, high tide, and available sediment. Periods of enhanced suspended-sediment concentration on the reef flat were attributed not only to local resuspension, but also to advection from other areas on the reef flat following storms, as shown by the relationship between suspended-sediment concentration and shear velocity at the Reefprobe.
- The persistence of terrigenous sediment on the reef flat is explained by the duration and recurrence of processes impacting the reef flat. The amount of time to remove sediment from the reef flat by daily sediment resuspension and transport is greater than the frequency of storms with large precipitation to deliver sediment from the upland watershed. This indicates that the daily processes occurring on the reef flat may be more influential for sediment redistribution than storm events.

- The confinement of the majority of terrigenous sediment to the inner- and mid-reef flat is due to the predominant current direction, the broad and shallow reef-flat morphology, and the orientation of the coastline to the prevailing trade winds. This is shown by the increase in calcium carbonate percentage of the suspended sediment with increasing distance offshore, as well as the circulation pattern on the reef flat. The slight offshore sediment transport at the fish ponds and wharf towards the area of low coral coverage suggests a link between the reef flat and fore reef sediment dynamics.

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