Available online at www.sciencedirect.com
SCIENCE DIRECT®

Continental Shelf Research 26 (2006) 401–421

CONTINENTAL SHELF RESEARCH

www.elsevier.com/locate/csr

# Cross-shore velocity shear, eddies and heterogeneity in water column properties over fringing coral reefs: West Maui, Hawaii

C.D. Storlazzi[a,*], M.A. McManus[b], J.B. Logan[a], B.E. McLaughlin[b]

[a]US Geological Survey, Pacific Science Center, Santa Cruz, CA 95064, USA
[b]Oceanography Department, University of Hawaii at Manoa, Honolulu, HI 96822, USA

Received 2 December 2004; received in revised form 21 September 2005; accepted 15 December 2005
Available online 21 February 2006

**Abstract**

A multi-day hydrographic survey cruise was conducted to acquire spatially extensive, but temporally limited, high-resolution, three-dimensional measurements of currents, temperature, salinity and turbidity off West Maui in the summer of 2003 to better understand coastal dynamics along a complex island shoreline with coral reefs. These data complement long-term, high-resolution tide, wave, current, temperature, salinity and turbidity measurements made at a number of fixed locations in the study area starting in 2001. Analyses of these hydrographic data, in conjunction with numerous field observations, evoke the following conceptual model of water and turbidity flux along West Maui. Wave- and wind-driven flows appear to be the primary control on flow over shallower portions of the reefs while tidal and subtidal currents dominate flow over the outer portions of the reefs and insular shelf. When the direction of these flows counter one another, which is quite common, they cause a zone of cross-shore horizontal shear and often form a front, with turbid, lower-salinity water inshore of the front and clear, higher-salinity water offshore of the front. It is not clear whether these zones of high shear and fronts are the cause or the result of the location of the fore reef, but they appear to be correlated alongshore over relatively large horizontal distances (orders of kilometers). When two flows converge or when a single flow is bathymetrically steered, eddies can be generated that, in the absence of large ocean surface waves, tend to accumulate material. Areas of higher turbidity and lower salinity tend to correlate with regions of poor coral health or the absence of well-developed reefs, suggesting that the oceanographic processes that concentrate and/or transport nutrients, contaminants, low-salinity water or suspended sediment might strongly influence coral reef ecosystem health and sustainability.
Published by Elsevier Ltd.

*Keywords:* Currents; Turbidity; Temperature; Salinity; Coral reefs; Shear; Eddies; Fronts

## 1. Introduction

Coral reefs typically grow in relatively clear, oligotrophic waters. Sewage injection, terrestrial runoff and groundwater percolation through the shoreface can introduce nutrients to the coastal zone (Coles and Ruddy, 1995; McKenna et al., 2001; Umezawa et al., 2002; Garrison et al., 2003).

*Corresponding author. Tel.: +1 831 427 4721; fax: +1 831 427 4748.
*E-mail addresses:* cstorlazzi@usgs.gov (C.D. Storlazzi), mamc@hawaii.edu (M.A. McManus), jlogan@usgs.gov (J.B. Logan), bem@soest.hawaii.edu (B.E. McLaughlin).

0278-4343/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.csr.2005.12.006

These processes can modify coral-zooxanthellae population dynamics (Heikoop et al., 2000; Harrison and Ward, 2001), and increase macroalgal growth and subsequently produce overgrowth and death of corals (Szmant, 2002). Land use practices such as overgrazing and coastal development can increase the supply of terrestrial sediment to the nearshore. Lower than normal salinities due to freshwater discharge from streams or submarine groundwater discharge have been shown to reduce coral growth rates (Guzman and Tudhope, 1998), or at very low levels, kill corals (Jokiel et al., 1993). Fine-grained terrestrial sediment can smother corals and increase turbidity, which in turn, decreases light available for photosynthesis and can create physiological stress or even coral mortality (Acevedo et al., 1989; Fortes, 2000; Rogers, 1990; Buddemeir and Hopley, 1988). Toxic substances and heavy metals often adhere to fine-grained sediment, which become their transport mechanism into the nearshore reef ecosystem (Dickson et al., 1987; Saouter et al., 1993; Bastidas et al., 1999; Gee and Bruland, 2002).

West Maui, Hawaii, USA is characterized by a series of fringing reefs separated by sandy beaches and shorefaces. Over the past two decades, a number of factors have affected the quality of the nearshore waters off West Maui. Coastal development and agriculture has increased runoff and the supply of sediment to West Maui's coastal waters while terrestrial wastewater injection has increased the volume of nutrients percolating out of the shoreface via submarine groundwater discharge (Soicher and Peterson, 1996; West Maui Watershed Management Project, 1996; Dollar and Andrews, 1997). Using field data and a numerical groundwater model, Soicher and Peterson (1996) found that while groundwater sources provide a gradual, steady supply of nutrients to the coastal waters, ephemeral stream flow (generally during the winter months) at discrete locations discharges high levels of nitrogen, phosphorus and fine-grained terrestrial sediment into the nearshore region.

While a number of investigations have focused on wave-, wind- or tidally driven flow and transport along or across a specific reef (e.g. Roberts et al., 1977, 1980; Kraines et al., 1998; Lugo-Fernandez et al., 1998; Tartinville and Rancher, 2000; Storlazzi et al., 2004a), there have been limited investigations, however, of these physical processes on and between fringing reefs along an irregular volcanic island's shoreline. The goal of this study is to understand the spatial variability in flow patterns, water column properties and the processes governing the transport of larvae, fine-grained sediment, nutrient, contaminant and other particulate matter along a complex inner shelf with coral reefs. The observations described here, in conjunction with data from long-term, fixed oceanographic packages (Storlazzi and Jaffe, 2003; Storlazzi et al., 2003, 2004b), elucidate the complex interactions between the wind, waves, tides, and lower-frequency currents that drive hydrographic variability off West Maui. We hypothesize that these processes influence the development and present health of the reefs in the study area.

## 2. Study area

### 2.1. Geology

The island of Maui is located at 20.8°N, 156.5°W in the North-central Pacific between the islands of Molokai, Lanai and Hawaii ('the Big Island') in the Hawaiian Archipelago (Fig. 1). The island comprises two large basaltic shield volcanoes that formed in the last 2 million years (Clague and Dalrymple, 1989) that are separated by a flat isthmus. West Maui is roughly 30 km long in the north–south direction and on average 20 km wide in the east–west direction. Land use in the study area was historically dominated by pineapple and sugarcane cultivation; more recently, however, urbanization and development along the shoreline have increased substantially (M&E Pacific, 1991).

The shoreline in the study area is characterized by low basaltic seacliffs and carbonate sand beaches. The geomorphology of the inner shelf (<40 m depth) off West Maui in the Pailolo and Auau Channels between the islands of Maui, Lanai and Molokai is highly variable and includes boulders, small patches of sand, extensive sand fields and a number of patch and small fringing coral reefs with various exposures (Fig. 2a) as discussed by Gibbs et al. (2005). In areas exposed to large waves there is only a thin veneer of coral overlying a basaltic substrate, while in more protected areas live corals are growing on top of a relict reef structure. Reefs extend from the shoreline out to 1 km offshore in water depths of 30 m; the majority of the reefs are situated in water depths between 3 and 20 m. Coral coverage is very discontinuous in the study area, varying between 0% and 80% (Jokiel et al., 2001) even though there is adequate hard substrate