

Wave Boundary Layer Processes Over an Irregular Bottom

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LONG-TERM GOALS

The broad long-term goal of this research is to extend understanding of wave processes over a very rough boundary, specifically that presented by a coral reef. From this understanding we aim to develop models that account for the effects of roughness on wave dissipation, sediment transport and biophysical interactions.

OBJECTIVES

The objective of this project is to relate measurements of roughness over a highly irregular bottom to observations of the wave flow at various scales, with the goal of developing a relation between roughness and wave energy dissipation and shear stress. The specific objectives include three elements: 1) observations of the small-scale turbulent processes over a wave orbital excursion; 2) a broad scale characterization of the wave field and its response to roughness; 3) high-resolution spatial surveys of the roughness over the study region. These observations will be further extended using a numerical model of the wave field in the nearshore region. Concurrent observations of sediment load and optical properties will explore the connection between shear stress and sediment suspension and transport over the complex reef topology.

APPROACH

A series of field observations are being carried out to address the objectives outlined above. Measurements of the wave and current field over a broad region of a coral reef are used to determine energy dissipation in an integral sense. Near-bed observations at smaller scales using acoustic profilers deployed on the Rough Boundary Profiler (RBP) then characterize the spatial structure of the boundary flow over a wave orbital excursion. The RBP moves an instrument package along a horizontal track over a distance of up to 3 meters (see figure 1), collecting data over a set time period at each location (typically 0.5 – 2 hours) thus allowing a spatial view of the near-bed flow. The 3 m track can be oriented in the swell direction within a window of +/- 10 degrees.

In parallel to the wave dissipation and boundary layer observations we are carrying out high-resolution roughness surveys over the observational domain. Boat-based surveys examine the roughness at scales down to around half a meter and diver-based surveys determine variability at higher wavenumbers.

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The resulting roughness maps are intended to provide important information on small scales of reef roughness necessary for nearshore wave modeling.

A numerical wave model (COULWAVE, Lynett et al, 2002) is used first to estimate dissipation levels using existing boundary layer models assuming homogeneous roughness and to compare with field dissipation measurements. The model is subsequently modified to examine spatially variable roughness fields obtained from the field surveys in order to explore potential roughness parameterization schemes. The surveys and modeling efforts combined with the measurements of wave dissipation and shear stress will thus enable analysis of the relation between roughness spectra and wave boundary layer turbulence.

Analysis of the boundary layer data is being carried out by PhD student Marion Bandet, with roughness field analysis being done by MS student Vasco Nunes. RBP design and electronics design is carried out by UH marine research engineers Kimball Milliken and Derek Young, respectively.

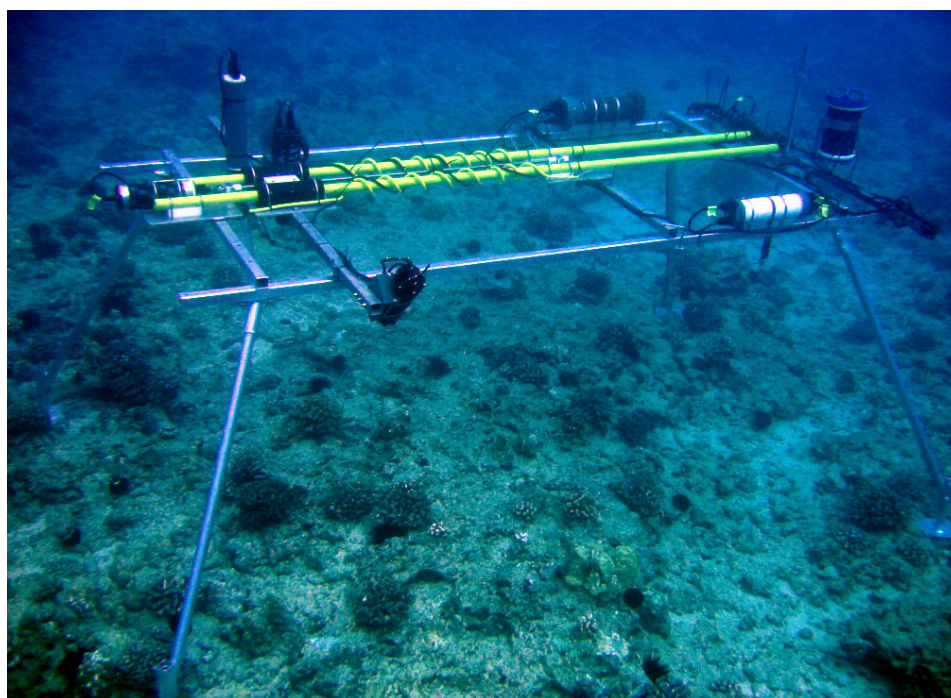


Figure 1: Rough Boundary Profiler (RBP). The automated profiler moves instrument packages along a 3 m track (yellow bars) allowing resolution of the near-bed spatial structure. A shore cable connection provides real-time data and power. The instrument array pictured includes BCDV and scanned laser altimetry system (Stanton, NPS) along with ADV and upward looking ADCP.

WORK COMPLETED

An array of wave gauges, current meters and current profilers was deployed on a reef on the south shore of Oahu (figure 2) for a two-week period in July, 2004 as part of a dye dispersal experiment carried out in collaboration with Stephen Monismith and Derek Fong (Stanford Univ.) (see Related Projects). Deployment of the instrument array, which aimed at characterizing the variations in currents and wave energy over a large area of the reef, coincided with two significant low frequency swell events. The array data is presently being analyzed to determine cross-shore wave field dissipation. In

addition, profiler data will be examined to determine current friction velocities and friction factors as a function of wave forcing. Using wave-current boundary layer theory (i.e. Grant and Madsen, 1979), this data will be used to determine wave friction factors for selected regions of the reef.

In August and September of 2004, the RBP was deployed at the study site with the goal of characterizing the boundary flow at smaller scales extending over the wave orbital amplitude. The August RBP deployment, carried out in collaboration with Tim Stanton (NPS), included use of a bi-static current Doppler velocimeter (BCDV) to obtain high resolution vertical profiles of the 3D near-bed velocities along the RBP axis, along with a scanned laser altimeter which mapped out the bed morphology. The September deployment used a downward-looking ADCP to obtain the phase-averaged flow field along the profiler axis. Each component of the velocity field is sampled separately along individual ADCP beams at each profiler position. The 2D flow field is then reconstructed as a function of wave phase using data from all instrument positions. Data sets from each deployment are being analyzed to yield wave and current boundary layer characteristics spatially integrated over the variable roughness bed.

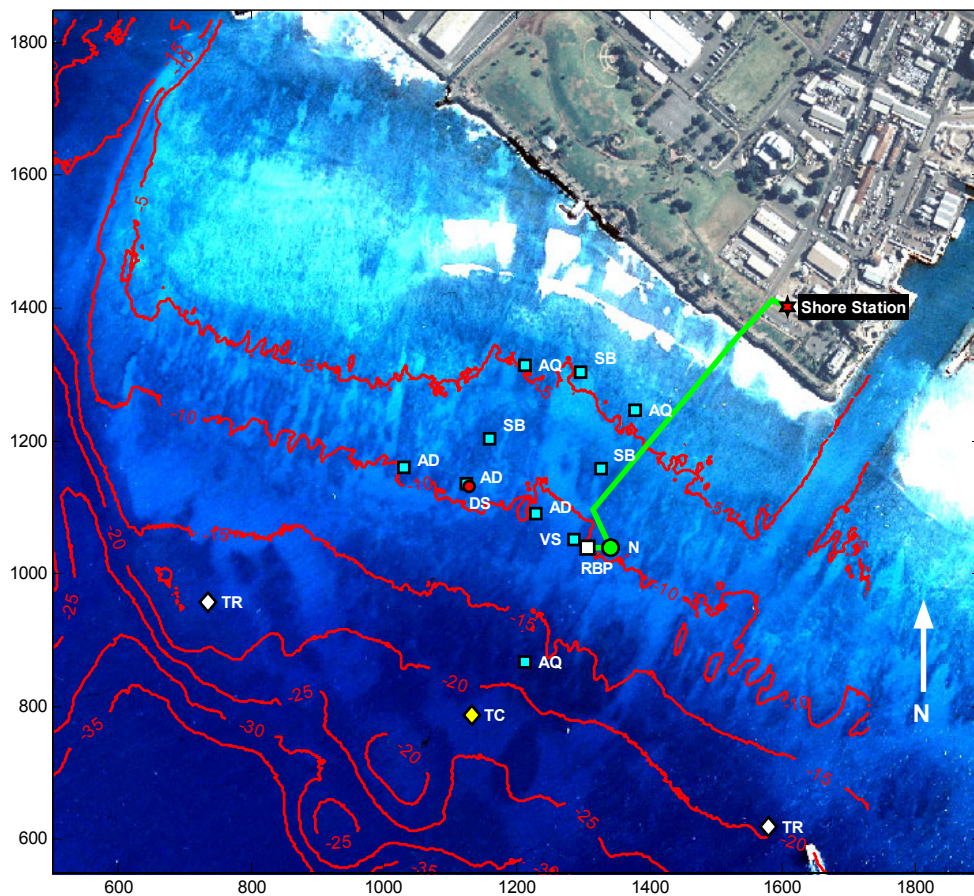


Figure 2: Field observational array, July/Aug. 2004. Aerial view of Kakaako Waterfront Park and offshore reef region with SHOALS bathymetry overlaid (contours at 5m intervals). Instrument array for dye dispersal experiment includes: AD = ADCP (3), AQ = Aquadopp(3), VS = Vector (ADV)/SCUFA frame (1), SB = SBE 26 (3), DS = dye source (1), TC = thermistor chain (1), TR = REMUS acoustic transponder (2). Kilo Nalu cabled observational array is shown, including the RBP profiling platform (RBP, white square) and central node (N, green circle), shore cable connection (green line) and shore station (red star).

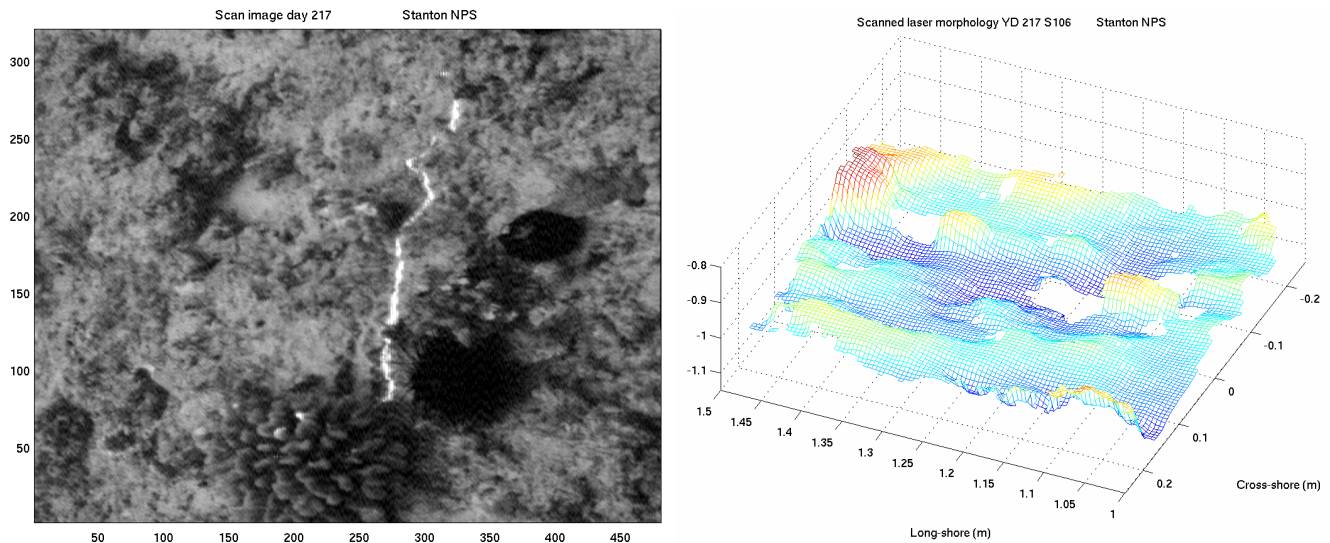


Figure 3: Left: scanned laser altimetry image (T. Stanton, NPS) of 1 m x 0.8 m area of reef surface under RBP showing single scan of the 2 axis system. Right: a single objectively analyzed image of the bed from NPS laser altimetry system at one RBP cross-shore position.

In support of the RBP deployments, a powered fiber optic cable and offshore node was deployed allowing real-time data access and extended deployments (see cable layout in figure 2). The cabled node has formed the foundation for the Kilo Nalu observatory that provides access to the nearshore reef environment for ongoing and future experiments. The node provides ethernet and power via underwater connections for up to four subnode packages. A shore station provides direct access to the connections and remote access is available via wireless ethernet connection. An autonomous offshore wave gauge has been maintained at 20 m depth to characterize the long-term wave climate at the observatory site. We are presently developing a web interface to provide data products in real-time.

Boat-mounted acoustic altimetry measurements of roughness have been carried out over a portion the study area yielding roughness at scales on the order of 50 cm. Roughness at smaller scales is being resolved statistically using 60+ diver-based surveys. The dive-based surveys obtain 3 m transects of the bottom profile using digital images of a system of vertical bars attached to a horizontal bar. Survey data is being examined using a number of statistical estimators, including RMS, standard deviation and consecutive angle difference values as potential candidates for parameterization schemes. Roughness spectral characteristics are also being considered in order to describe bed morphology. The analysis is directed towards merging the various roughness parameters with wave field observations and numerical wave model output, to produce a roughness map that establishes a link between the physical roughness measurements and hydrodynamic wave friction at the study area.

Data analysis of pilot RBP deployments in 2003 at the south shore site and in Kaneohe Bay is continuing, with the aim of establishing measurement accuracy in the spatial profiling and fine tuning data quality routines.

RESULTS

Scanned laser altimetry data from the August RBP deployment, analyzed at NPS, has produced high-resolution map of bed morphology under the RBP track (figure 3). The NPS laser system uses 200

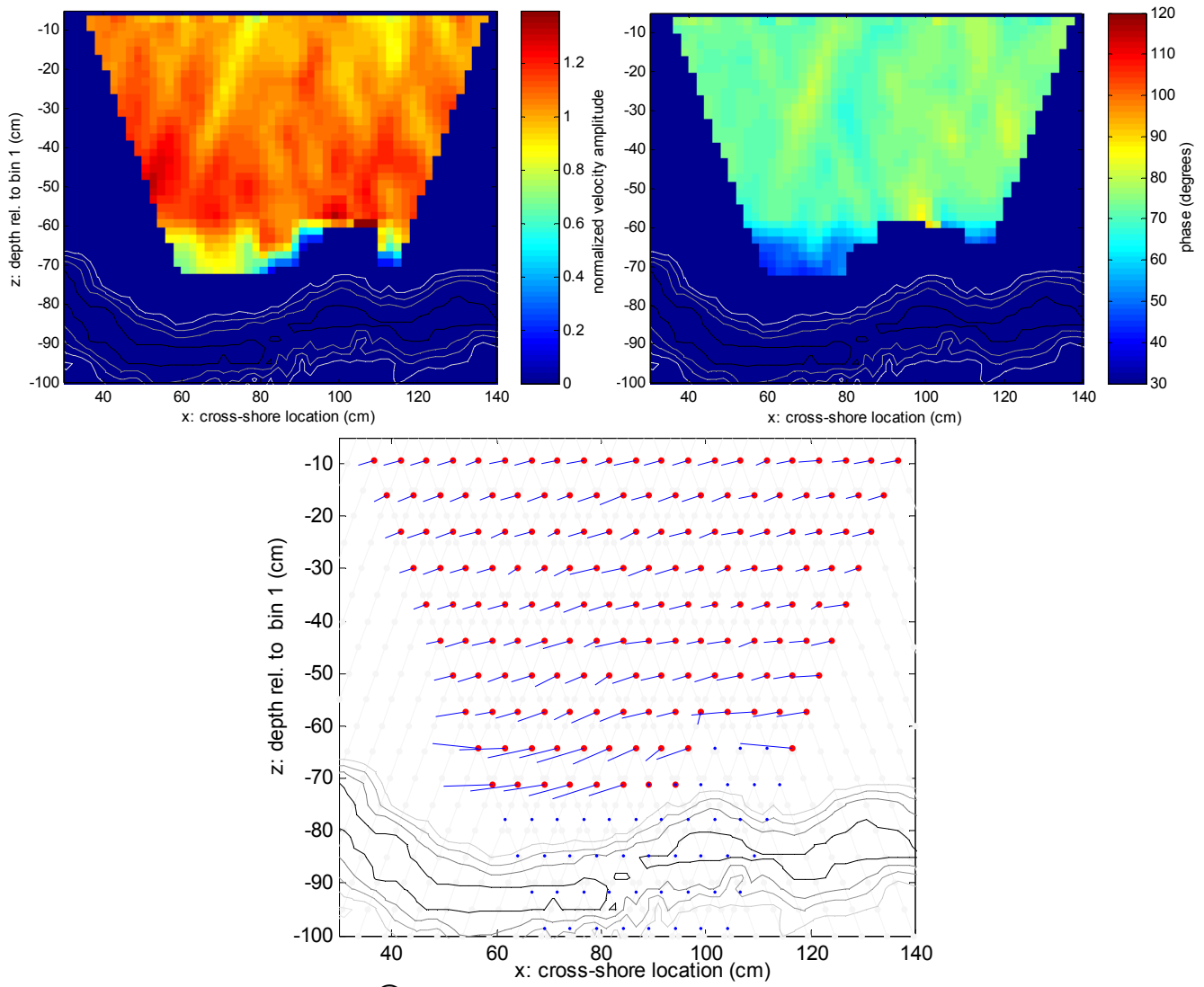


Figure 4: Preliminary phase averaged velocity field data from September, 2004 RBP deployment. a) Phase averaged velocity amplitude, normalized by linear wave velocity. Contours indicate ADCP correlation magnitude highlighting the bottom location. b) Phase angle for semimajor ellipse highlighting phase lead near the bed. c) Phase averaged velocity field for zero downcrossing again highlighting phase lead along with flow turning in near-bed flow.

scan lines to measure morphology within a 0.5 m square. Overlapping squares are then obtained at 5 cm RBP increments providing a robust measurement of the 3D structure of the irregular bottom under the profiler.

Preliminary phase averaged velocity field data from the September deployment reveals spatially variable boundary layer thicknesses between 20 and 30 cm as determined from phase and amplitude profiles (figure 4a,b). Data in the figure represents along-beam ADCP data collected over a 3-day swell period and averaged together by wave phase for wave events matching narrow period and amplitude criteria. The phase plot in figure 4a indicates the wave phase at which the local velocity vector is aligned with the semi-major ellipse axis and highlights the phase shift near the bed.

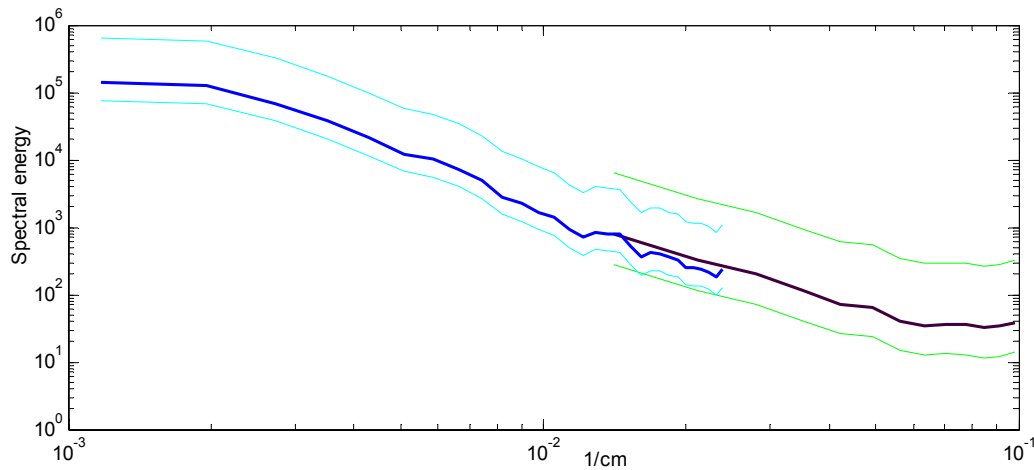


Figure 5: Roughness spectra from boat-based altimetry surveys (blue) and diver-based bar surveys (black) with 95% confidence intervals. Boat data represents a 150 m long transect while the bar data is obtained from 38 transects (3 m each) in the vicinity of the boat transect.

Additional data quality filtering will be necessary to improve the phase averaged picture, as evident by the variations outside the boundary layer in both the phase and amplitude plots. Velocity amplitude (figure 4b) shows spatially variable amplification outside the near bed region characterized by a sharp decay in magnitude. The bottom is represented by contours of ADCP correlation magnitude which increases sharply at the bed. Further analysis will be carried out to corroborate and calibrate the bottom measurements with those obtained by the NPS altimetry system in August.

Figure 4c shows a snapshot of the phase-averaged velocity field coincident with the zero-downcrossing, highlighting the phase shift near the bed along with the flow turning around individual roughness elements. These data will be further examined to obtain spatially averaged wave and current profiles enabling calculation of average friction velocities and friction factors. Further deployments are planned to obtain a broader cross-shore extent of up to 3 meters. Ongoing analysis of BCDV data from the August deployment is expected to yield information on near-bed turbulence.

Roughness data are also being analyzed to characterize variability in the reef morphology. Roughness spectra have been calculated using boat-mounted altimetry data at low wavenumbers and diver-based surveys at higher wavenumbers. Comparisons from data over a set region show good agreement between the methods (figure 5). The spectra indicate that while there are identifiable dominant scales over small regions of the reef, the spectral shape associated with the bottom roughness is generally consistent over larger areas. This suggests that integral measures of spectral energy such as spectral moments or RMS values may be most useful in characterizing variations in hydrodynamic roughness. Further surveys combined with numerical modeling is planned to examine this further.

IMPACT/APPLICATIONS

Our observations of the interactions between waves and the rough boundary over a coral reef will lead to more accurate parameterizations of bed shear stress and wave dissipation as a function of roughness that can be applied in wave and sediment transport modeling over irregular boundaries. Nearshore numerical wave models typically use roughness parameterizations based on uniform roughness, which is only loosely related to the actual roughness over a reef. Illuminating the turbulent processes over a

rough boundary will have further benefits to understanding oscillating flows over irregular boundaries in general with applications to flow around support structures, buried objects and pipelines and cables, as well as to larger scale oceanographic boundary flows.

An additional benefit of the work underway has been the establishment of the Kilo Nalu cabled nearshore reef observatory. This has enabled real-time access to data, facilitating deployment of instruments that would otherwise be limited to short-term deployments.

RELATED PROJECTS

We have been working closely with researchers from UH (Marlin Atkinson, Jim Falter) and Stanford University (Stephen Monismith, Jeff Koseff). Their studies, funded by NSF, aim to relate wave boundary layer processes to nutrient uptake by coral communities. They have constructed an oscillating flume to examine the chemical aspects of the flow and have carried out field observations exploring the dissipation of waves over a reef flat in Kaneohe Bay. We participated in observations in August, 2003 where the pilot version of the RBP was deployed. This data set has thus far yielded one publication (Lowe et al, 2004, submitted) with further data analysis underway.

In addition, we have carried out a dye dispersal study at the reef observatory site in July of 2004, in collaboration with Stephen Monismith and Derek Fong along with Stanford graduate researchers Ryan Lowe and Nicole Jones. This pilot experiment included deployment of a wave/current measurement array that will provide data for the wave boundary layer study (discussed above). The purpose of the dye study is to examine wave-current interactions over the rough reef boundary through its effect on dispersal mechanisms. The study further aimed to examine Lagrangian transport mechanisms in the nearshore reef environment. Dye was released at approximately 10 m depth using an automated source, with varying current and wave forcing. The dye cloud was then tracked using a REMUS autonomous underwater vehicle equipped with a fluorometer.

The Kilo Nalu observatory is also being utilized by a number of other projects. A UH Sea Grant funded study to monitor nearshore water quality (PIs: G. Pawlak and E. H. De Carlo) includes deployment of real-time chemical sampling instrumentation along with tide, current and wave measurements. An NSF funded project to examine sediment porewater-seawater exchange (PIs: F. Sansone, M. Merrifield, G. Pawlak) will also make use of the observatory to carry out field observations.

This research program is expected to benefit considerably from the acquisition of a REMUS AUV as part of an ONR DURIP (PIs: R. Wilkens, G. Pawlak, C. Fletcher), as evidenced by the successful use of the Stanford REMUS in the July dye release experiment.

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