

# Kilo Nalu

## PHYSICAL/BIOGEOCHEMICAL DYNAMICS ABOVE AND WITHIN PERMEABLE SEDIMENTS

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The Kilo Nalu Nearshore Reef Observatory is a cabled physical-biogeochemical ocean observing system along the south coast of Oahu, Hawaii. Real-time observations began with the deployment of a range of instrument packages in March 2007, followed in July 2007 with an autonomous profiler, a moored instrument array, and event-focused shipboard and autonomous underwater vehicle (AUV) surveys. The tropical reef seabed at this site consists of live coral, a fossil limestone reef, and carbonate sands. The slope of the seafloor is 1:30 from the shore to 40-m water depth, 1:2 from 40–100-m depth, and 1:1 from 100–250-m depth. The latter depth is located ~ 2 km offshore, reflecting the extremely narrow coastal shelf at this site.

The goals of the Kilo Nalu Coastal Benthic Exchange Dynamics (CBED) project are to significantly advance our ability to measure the transport of solutes into and out of permeable sediments, to examine the seafloor's response to a wide range of physical forcing (such as surface waves, barotropic and baroclinic tides, currents, and near-bottom turbulence), and to determine the pelagic ecosystem's response to these processes. Here, we provide a brief description of new measurement capabilities already realized at the observatory and highlight a few recent results that demonstrate their importance.

## OBSERVATORY DESCRIPTION

Kilo Nalu supplies shore-based, cabled 24/48V DC power, 100 Mbps Ethernet, and full-bandwidth video capability to distribution nodes at 10-m and 20-m water depth. Baseline instrumentation currently installed consists of a 1200-kHz acoustic Doppler current profiler (ADCP), a thermistor chain, a Seabird-37 conductivity-temperature-depth (CTD) sensor, and an ECO-FLNTU turbidity/fluorescence sensor, all at the 10-m node; and a 1200-kHz ADCP and a thermistor chain at the 20-m node. Baseline observations include significant wave height and directional wave spectra, currents, temperature, salinity, acoustic backscatter, turbidity, and chlorophyll fluorescence. Near-real-time data can be viewed at the Kilo Nalu Web site ([www.soest.hawaii.edu/OE/KiloNalu](http://www.soest.hawaii.edu/OE/KiloNalu)).

To examine the detailed turbulent structure over coral beds, an automated vertical profiler was deployed at Kilo Nalu over a two-month period beginning in October 2007. The profiler moves an instrument package vertically over roughly 50 cm, with a vertical spacing of 2.5 cm, sampling between 10 and 30 minutes at each height. The instrument package includes a downward-looking acoustic Doppler velocimeter (ADV) and a dissolved oxygen (DO) optode. The profiler frame also includes an upward-looking ADV, fixed at approximately 2 m above the bed, to allow separation of wave motion from turbulence.

A suite of instruments has also been developed to provide detailed measurements of the hydrodynamic structure of the bottom boundary layer at the base of the water column. The bistatic coherent Doppler velocity and sediment profiler

(BCDVSP; Figure 1a) measures velocity and sediment-load profiles spanning 1 m immediately above the bed, with 1-cm high x 2.5-cm diameter sample volumes, sampled at 32 Hz. This instrument resolves turbulent motions, wave-induced motions, and low-frequency currents spanning the mean-current boundary layer, as well as the thin oscillatory wave boundary layer that extends 5–10 cm above rippled beds. A nearby ADV provides a reference velocity for

making Reynolds stress measurements above the wave boundary layer.

A remotely programmable scanned laser mounted parallel to the BCDVSP, coupled with a side-looking digital Ethernet camera, operates in three modes to study the seabed: (1) During night hours, the scanned laser imaging system uses a raster scan mode to map the seafloor once every hour, with 2-mm vertical and horizontal resolution (Figure 1b), to determine the position

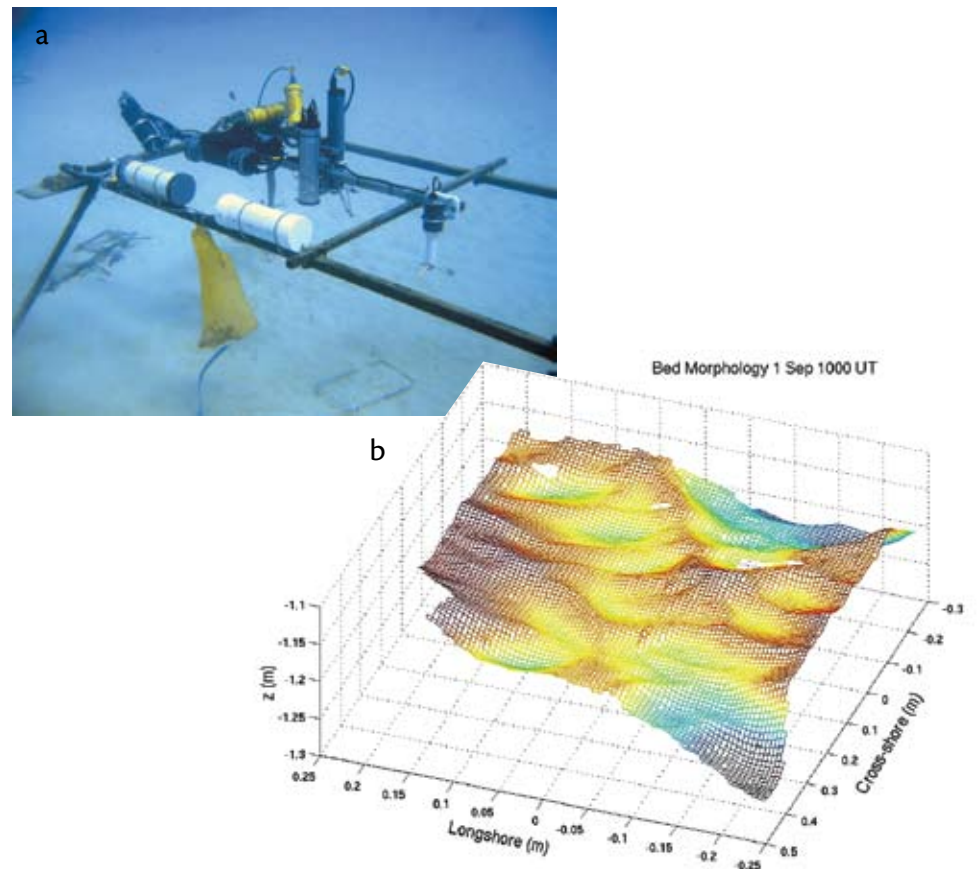


Figure 1. (a) Seabed boundary layer instruments during installation. On the center beam, from left: the digital camera; a power/Ethernet infrastructure package; the stainless steel scanned laser housing and, behind it, the BCDVSP; and a commercial velocimeter used in turbulent flux calculations. The near beam of the frame supports the remote-controlled dye pump and dye reservoir. The dye injection rake can be seen on the seabed prior to burial 10 cm below the sand surface. (b) Seabed morphology measured remotely by the scanned laser system at 2-mm resolution within a 0.5 x 0.5-m square at the Kilo Nalu 10-m sand site. Short-crested, cross-shore ripples are superimposed on a larger-scale feature in this example. The structure of these ripples has a dominating effect on the wave boundary layer structure and the transport of tracers out of the top few centimeters of the bed in response to wave forcing.

of the BCDVSP profiles relative to the migrating ripple crests and troughs. (2) Every two hours, the laser/imager illuminates a cross-shore vertical slice of the water column to 20 cm above the bed for three minutes to show the cross-shore structure of sediment-suspension events in response to the wave forcing over several wave group cycles. These suspension patterns are compared with the sediment concentration and hydrodynamic measurements made by the BCDVSP. (3) At dawn and dusk, remotely controlled rhodamine dye injections from a cross-shore line source buried at 10-cm depth (Figure 1a) within the sandy bed are observed with the laser/imager in raster scan mode to measure the paths followed by the tracer in the sand through the ripple field. These dye injections are used to estimate near-bed diffusivity rates resolved at wave-cycle scales. During daylight hours, the seabed is imaged every hour.

The response of sandy sediment porewater motion to hydrodynamic forcing is also monitored using a remotely operated dye-tracer injection and fiber-optic monitoring system (based on a prototype described in Hebert et al., 2007). This system uses five visible-light spectrometers and an array of fiber-optic probes to track the porewater movement of injected fluorescein dye in a vertical two-dimensional plane in real time. A large dye reservoir and remotely controlled sampling and injection permit direct monitoring of responses to forcing events.

We have also installed a submersible microprofiler equipped with voltammetric microelectrodes (Glazer et al., 2004; Luther et al., 2008) for simultaneously collecting high-resolution profiles

of dissolved redox chemical species ( $O_2$ ,  $H_2O_2$ ,  $Fe^{2+}$ ,  $HS^-$ ,  $S_x^{2-}$ ,  $S^0$ ,  $S_2O_3^{2-}$ ,  $S_4O_6^{2-}$ ,  $Mn^{2+}$ ,  $FeS_{aq}$ , and  $Fe^{3+}_{aq}$ ) across the sediment-water interface. Until recently, power consumption and onboard data storage capacity have limited in situ voltammetric field deployments to days to weeks. However, the power supply and data stream capabilities of Kilo Nalu now allow us to test the feasibility of long-term voltammetric field studies, and to provide high-resolution, near-bed redox gradient profiling at spatial and temporal scales relevant for coupling biogeochemical data to physical data.

Additional monitoring of the environment employs a combination of shipboard and AUV surveys. For example, shipboard continuous profiling experiments have used a slightly negatively buoyant instrument package (Figure 2a) that freefalls from an anchored boat at about  $15\text{ cm s}^{-1}$ , achieving a vertical resolution of 2 cm. Temperature, conductivity, pressure, DO, chlorophyll

fluorescence, light transmittance, and photosynthetically active radiation are measured from the surface to the bottom of the water column, once every 1.5 min. Data from a 24-hour water-column experiment show an intrusion of cold, high salinity bottom water at  $\sim 2100\text{ h}$  (Figure 2b).

## ADVANCING OBSERVATORY CAPABILITIES

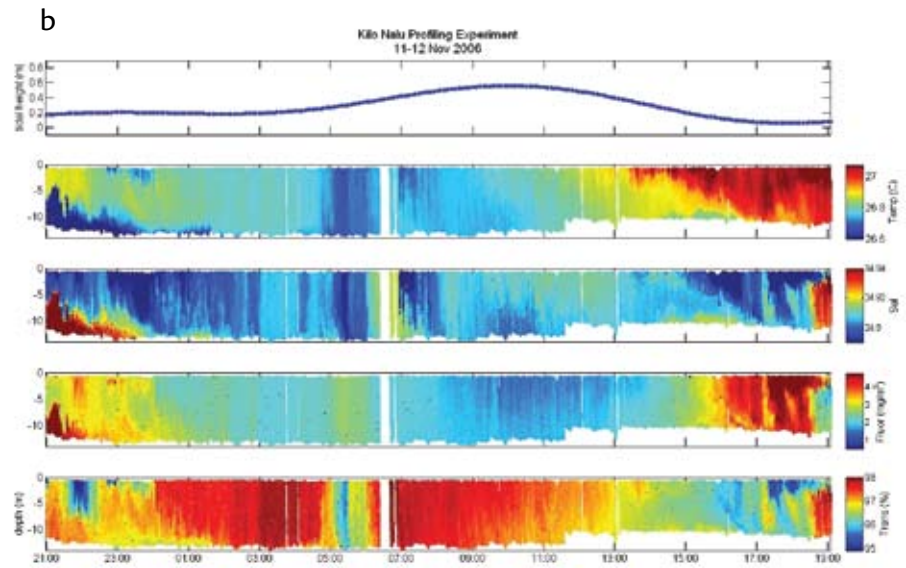
Wave- and current-generated turbulence over reef and sandy bottoms determines the rate of near-bed exchange for momentum and mass. The flow over the very rough beds characteristic of coral reefs poses a challenge to model, however, due to the broad range of roughness scales (Nunes and Pawlak, 2008). Our measured profiles of the near-bed flow indicate highly energetic wave-driven turbulent mixing (Figure 3a). Turbulent energy dissipation rates within this boundary layer, which provide a measure of the strength of the turbulence

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Figure 2. (a) Profiler package and (b) results from a 24-h water-column profiling experiment, November 11–12, 2006. The tidal amplitude during the experiment is shown in the top panel of (b). Lower panels show the depth distributions of seawater temperature, salinity, chlorophyll fluorescence, and light transmittance.



and, indirectly, mixing, are determined at each profiler position following Feddersen and Williams (2007). The thickness of this energetic layer, given by the height over which the vertically integrated dissipation equals the average value, is consistent ( $\sim 40$  cm) across a range of wave conditions. This relationship suggests that the layer thickness for this very rough region is set by the local roughness scale, and indicates that turbulence and thus the benthic mass flux is driven by large-scale flow separation around reef roughness elements. The normalized dissipation also gives a measure of wave energy dissipation. The observed wave dissipation factors ( $\sim 0.03$ – $0.04$ ) are somewhat lower than values from large-scale observations ( $\sim 0.2$ ) over reefs (Falter et al., 2004; Lowe et al., 2005); however, the results are comparable, given that the earlier

observations were in shallower water and that the profiler observations represent a single location.

Although there are numerous mathematical treatments of wave-driven solute exchange between permeable sediment porewater and the overlying seawater, there have been only a few attempts to measure this exchange in the field (e.g., Webb and Theodor, 1968; Falter and Sansone, 2000; Precht and Huettel, 2004; Reimers et al., 2004). Hydrodynamic processes, including oscillating flows from passing surface waves and advection due to the interaction of sand ripples and bottom currents, significantly enhance porewater transport in Kilo Nalu sands. We have found that porewater mixing at 10-m water depth and up to 15-cm sediment depth is enhanced over molecular diffusion by three to four orders of magnitude, with enhanced diffusivities

positively correlated with wave height (Hebert et al., 2007).

We are testing the use of commercial optodes to measure DO concentrations within the benthic boundary layer at Kilo Nalu. Our goal is to use these rugged, stable devices to measure near-bed chemical concentrations, which, in combination with near-bed turbulence measurements, allow estimation of the sediment-seawater DO fluxes. DO was measured within the 50-cm layer above a 10-m-deep reef bed with an optode mounted on the vertical profiler described earlier (one sample every four seconds, 10–30 minutes per position), providing a measurement of the vertical DO gradient. The use of a single optode to determine the gradient assumes that temporal variations are small over profiling times. Although this condition is violated for some profiles,



introducing some scatter in the gradient observations, it is mitigated by ensemble averaging (Figure 3b; discussed below). Preliminary experiments indicate that we are able to adequately resolve the DO and diffusivity profiles to enable flux calculations. Further experiments, using multiple optodes, are ongoing.

The DO vertical gradient was obtained from the profiling optode observations after filtering the data over 4-h windows. The near-bed gradient showed a high degree of variability, although the general pattern has low DO near the bed (negative gradient), with a diurnal component that has a stronger negative gradient (lower near-bed DO) in the early morning hours and weaker gradients during daylight. A strong response was observed to be associated with a November 4–8, 2007, swell event. To highlight the shifts in diurnal patterns, gradient observations were ensemble averaged in 30-min windows by hour of day, for four time periods. Figure 3b shows the daily patterns for each time period, along with the average

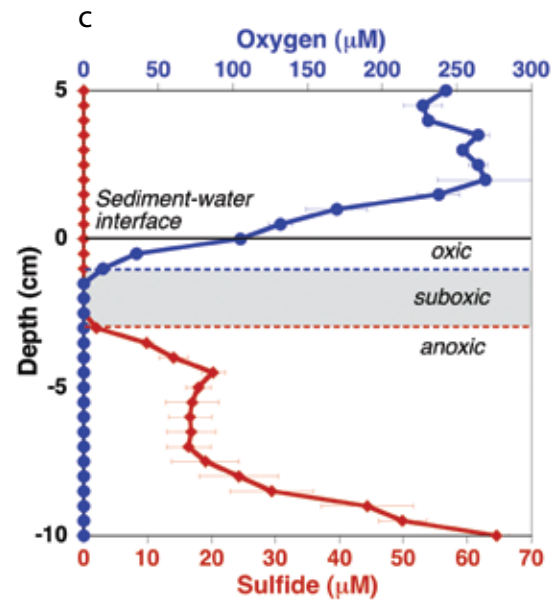
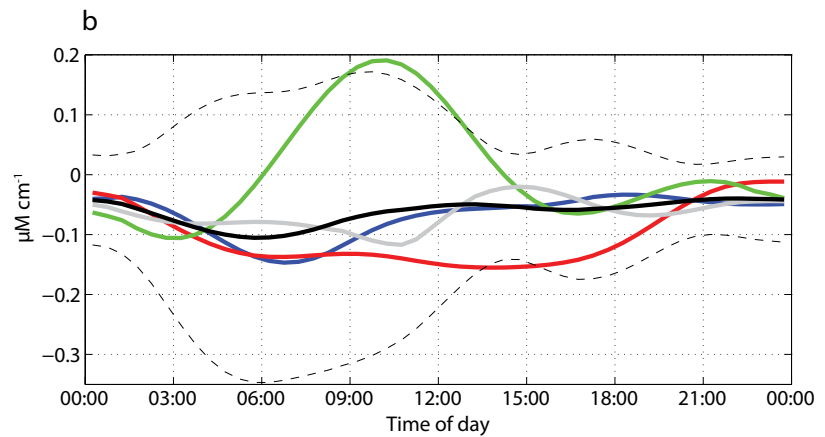
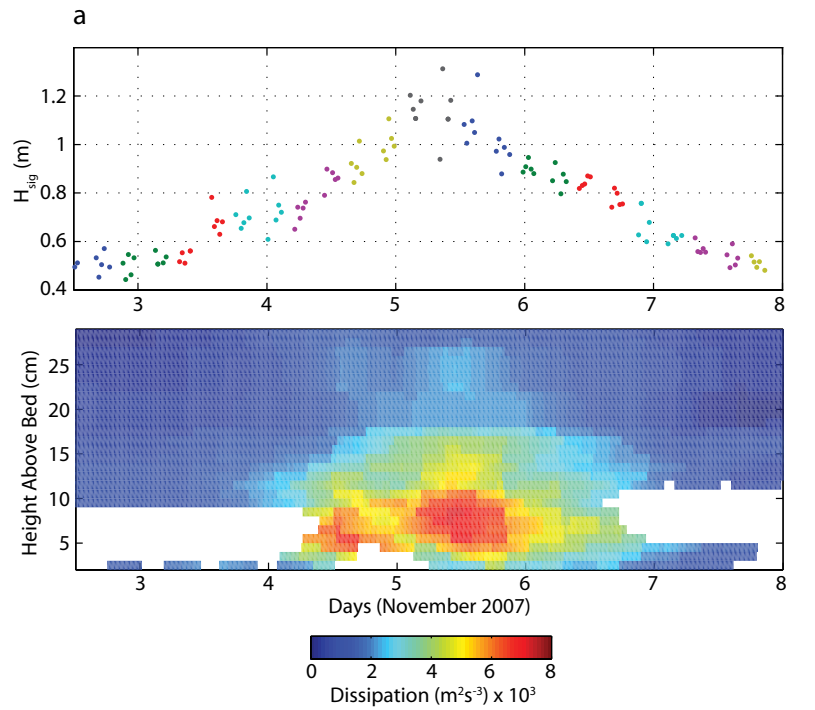



Figure 3. (a) Profiler observations of near-bed turbulent energy dissipation. Upper panel: Wave height versus time; each dot represents an individual data point, with complete vertical profiles grouped by color. Lower panel: Dissipation and height vs time over the course of a swell, highlighting wave-enhanced turbulence; blank regions indicate low backscatter periods in which near-bed effects impaired measurements. Data collected from the 10-m-depth reef site. (b) Ensemble-averaged near-bed DO gradients from profiler data for October 20–November 20, 2007 (all data, black), October 20–November 4 (before swell, blue), November 4–November 8 (during swell, red), November 8–12 (after swell, green), November 12–20 (long after swell, gray). Dashed lines indicate one standard deviation in gradient observations over the entire period. Data collected from the 10-m-depth reef site. (c) Remotely acquired voltammetric microelectrode profile from the Kilo Nalu 10-m-depth sand site. Sediment-water interface is located at depth = 0. Error bars represent  $\pm 1$  standard deviation of the mean.

for full deployment. The “before swell” and “long after swell” windows followed the overall average pattern fairly well. During the swell, however, the negative gradient strengthened relative to the mean. We interpret this as a wave-driven increased flux of DO from the water column down into the sediments. Immediately after the swell, the gradient reversed sharply, indicating a flux of DO upward from the sediments. This shift subsequently relaxed back to the pre-swell “background” diurnal pattern. Further observations are being used to examine these regime shifts more quantitatively.

Initial voltammetric microelectrode results (Figure 3c) illustrate the biogeochemical conditions that drive benthic DO fluxes such as those discussed above: (1) steep oxygen and sulfide gradients exist within centimeters of the sediment-water interface, suggesting intense microbial respiration occurs, and (2) oxygen and sulfide do not coexist in the shallow sediments, suggesting that nitrogen, manganese, and/or iron redox chemistry may play an important role in organic carbon cycling in the upper layers of such porous sandy coastal sediments. Further studies to elucidate the extent to which advective transport impacts redox transformations are underway. This research ultimately aims to enable the collection of long-term data sets of biogeochemical profiles across the sediment-water interface, and to enable determination of redox-active fluxes through the application of eddy correlation (Berg and Huettel, this issue) and near-bed profiling techniques.

The cold, high-salinity water pulses seen at Kilo Nalu (e.g., Figure 2b), most likely associated with shoaling internal

tidal energy, are characterized by high chlorophyll fluorescence and decreased transmittance, and may indicate the connection between variations in water properties and water-column biological activity. In addition, increases in stratification associated with variations in temperature and salinity can affect seawater-benthic exchange by reducing near-bed turbulent mixing. Although such linkages can be expected intuitively, details of the relationships are complex, and quantitative effects on fluxes are unknown. These issues are the focus of the work underway at Kilo Nalu. 

## REFERENCES

- Falter, J.L., and F.J. Sansone. 2000. Hydraulic control of pore water geochemistry within the oxic-suboxic zone of a permeable sediment. *Limnology and Oceanography* 45:550–557.
- Falter, J.L., M.J. Atkinson, and M.A. Merrifield. 2004. Mass transfer limitation of nutrient uptake by a wave-dominated reef flat community. *Limnology and Oceanography* 49:1,820–1,831.
- Feddersen, F., and J. Williams. 2007. Direct estimation of the Reynolds stress vertical structure in the nearshore. *Journal of Atmospheric and Oceanic Technology* 24:102–116.
- Glazer, B.T., A.G. Marsh, K. Stierhoff, and G.W. Luther. 2004. The dynamic response of optical oxygen sensors and voltammetric electrodes to temporal changes in dissolved oxygen concentrations. *Analytica Chimica Acta* 518:93–100.
- Hebert, A.B., F.J. Sansone, and G.R. Pawlak. 2007. Tracer dispersal in sandy sediment porewater under enhanced physical forcing. *Continental Shelf Research* 27:2,278–2,287.
- Lowe, R.J., J. Falter, M. Bandet, G. Pawlak, M. Atkinson, S. Monismith, and J. Koseff. 2005. Spectral wave dissipation over a barrier reef. *Journal of Geophysical Research* 110(C04001), doi:10.1029/2004JC002711.
- Luther, G.W. III, B.T. Glazer, S.F. Ma, R.E. Trouwborst, T.S. Moore, E. Metzger, C. Kraiyya, T.J. Waite, G. Druschel, B. Sundby, M. Taillefert, D.B. Nuzzio, T.M. Shank, B.L. Lewis, and P.J. Brendel. 2008. Use of voltammetric solid-state (micro)electrodes for studying biogeochemical processes: From laboratory measurements to real time measurements with an in situ electrochemical analyzer (ISEA). *Marine Chemistry* 108:221–235.
- Nunes, V., and G. Pawlak. 2008. Observations of physical roughness over a coral reef. *Journal of Coastal Research* 24:39–50.
- Precht E., and M. Huettel. 2004. Rapid wave-driven advective pore water exchange in a permeable coastal sediment. *Journal of Sea Research* 51:93–107.
- Reimers C.E., H.A. Stecher III, G.L. Taghon, C.M. Fuller, M. Huettel, A. Rusch, N. Ryckelynck, and C. Wild. 2004. In situ measurements of advective solute transport in permeable shelf sands. *Continental Shelf Research* 24:183–201.
- Webb, J.E., and J. Theodor. 1968. Irrigation of submerged marine sands through wave action. *Nature* 220:682–683.