Monitoring the Seafloor Using the
Noninvasive Eddy Correlation Technique:

Integrated Benthic Exchange Dynamics

BY PETER BERG AND MARKUS HUETTEL

BACKGROUND

The eddy correlation technique has been used for 60 years in atmospheric boundary layer research to measure land-air exchanges of different constituents (e.g., Swinbank, 1951). Only recently, the technique has also been applied to the benthic boundary layer by Berg et al. (2003), who determined sediment-water fluxes of dissolved O_2 and validated their findings against in situ chamber measurements. It is technically challenging to measure the key eddy correlation variables at a point near the sediment-water interface and at the high frequency required to fully resolve turbulent eddies. However, if feasible, the reward is high in that major limitations inherently linked to other flux methods, such as lab measurements in sediment cores and deployments of in situ chambers, can be bypassed. Specifically, eddy correlation measurements integrate over a larger area (Berg et al., 2007) and are done under true in situ conditions with no disturbances of sediment, light, and bottom boundary layer flow. The latter is particularly important for permeable sediments, where current and wave-driven porewater flushing can significantly alter biogeochemical cycling (Huettel et al., 1998; Jahnke et al., 2000; Reimers et al., 2004). As methodological bias is minimized, this technique can significantly improve monitoring at the seafloor.

Here, we present our latest progress on the eddy correlation technique within our integrated Benthic Exchange Dynamics (iBED) project. Although eddy correlation is a general flux method, we focus only on O_2, which has been the theme of this project.

BASIC PRINCIPLES AND INSTRUMENTATION

The eddy correlation technique relies on measuring vertical water column velocity and O_2 concentration in a ~ 1 cm^3 volume located 5 to 30 cm above the sediment surface and at a rate of 16 to 64 Hz. With the underlying assumption that all O_2 transported vertically toward or away from the sediment surface is facilitated by turbulent motions, the vertical flux can be derived from these two variables. Specifically, the eddy flux is defined as $\overline{u_z'C'}$ where u_z' is the fluctuating vertical velocity away from the mean, C' is the fluctuating concentration away from the mean, and the bar symbolizes an averaging over time (Berg et al., 2003). Typically, 10 to 15 minutes of continuous data are required to obtain one statistically sound flux estimate. The flux is valid for an oval-shaped sediment surface area, the so-called footprint, located upstream of the measuring point. A typical footprint is 40-m long and 1-m wide, but can vary several fold depending on site-specific parameters (Berg et al., 2007).

The eddy correlation instrument we have developed (Figure 1) consists of an acoustic Doppler velocimeter (ADV), an O_2 microelectrode connected to an amplifier designed specifically for eddy correlation measurements, and a battery container, all mounted on a light frame. In addition to the three velocity components and O_2 concentration, the instrument records time, temperature, water depth, and the measuring volume's position above the sediment surface.

EDDY CORRELATION DATA AND DERIVED O_2 FLUXES FOR A MARINE SEDIMENT

Figure 2 shows an example of typical eddy correlation data and derived O_2 fluxes through 17 h, spanning a period from dusk to the following morning, for a shallow nearshore site with sandy sediment (Apalachicola Bay, Florida, April 2008). The median grain size here is 211 ± 16 µm (SD), the organic content is 0.2%, and the sediment surface is inhabited by a dense population of benthic diatoms. With a permeability of 1.3×10^{-11} m^2, the sediment permits water flow through the pore space. The variation in the three velocity components (Figure 2a) depicts mainly the orbital water motion produced by the wind-driven waves, which reached down through the 1- to 1.5-m water column (Figure 2d). The instrument's measuring volume was located 12 cm above the sediment surface (Figure 2e). Except for the last four fluxes (Figure 2c), the overall pattern of the 15-min fluxes agrees with the day-night light pattern (Figure 2e), with a gradual change from an O_2 release during the last sunlight hours to an uptake during the night and flux reversal at sunrise the next morning. This flux cycle reflects the net result of phototrophic oxygen production and respiration processes and gives a minimum O_2 concentration level right before dawn (Figure 2b). The wave-generated oscillating flow was responsible for most of the vertical O_2 transport as indicated
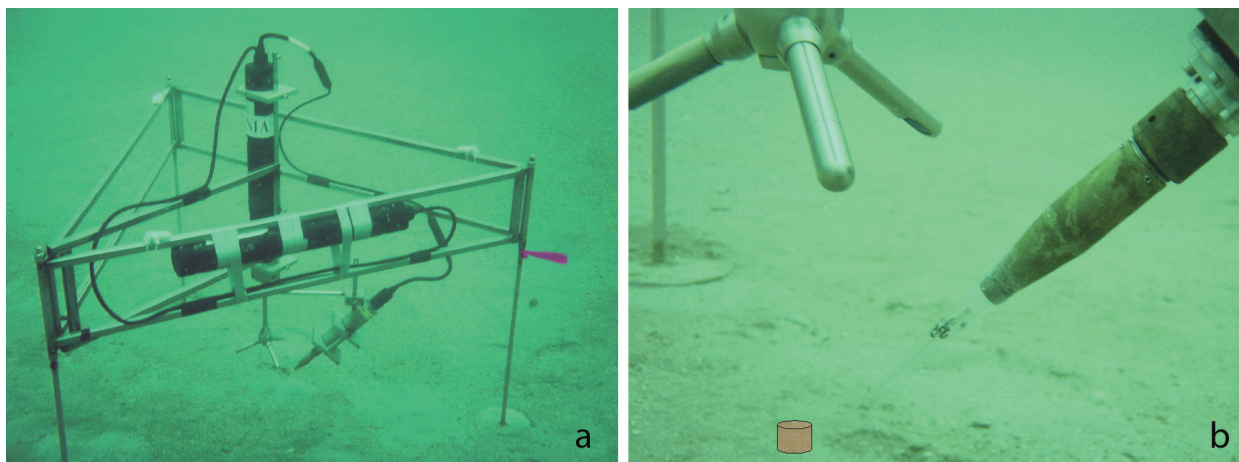

Figure 1. (a) Our eddy correlation instrument at the 27-m-deep "Benthic Observatory and Technology Testbed On the Mid Shelf—Understanding Processes" (BOTTOMS-UP) site in the South Atlantic Bight. The purple streamer on the right leg of the frame reveals current direction. The three white boxes on the upper horizontal bars are compact light and temperature loggers. (b) Close-up of the acoustic Doppler velocimeter (ADV) sensor head (left) and O_2 microelectrode (right). The 10- to 30-µm tip of the microelectrode is not visible, but it is positioned a few millimeters from the ADV's measuring volume, the position and shape of which is marked as a red cylinder.
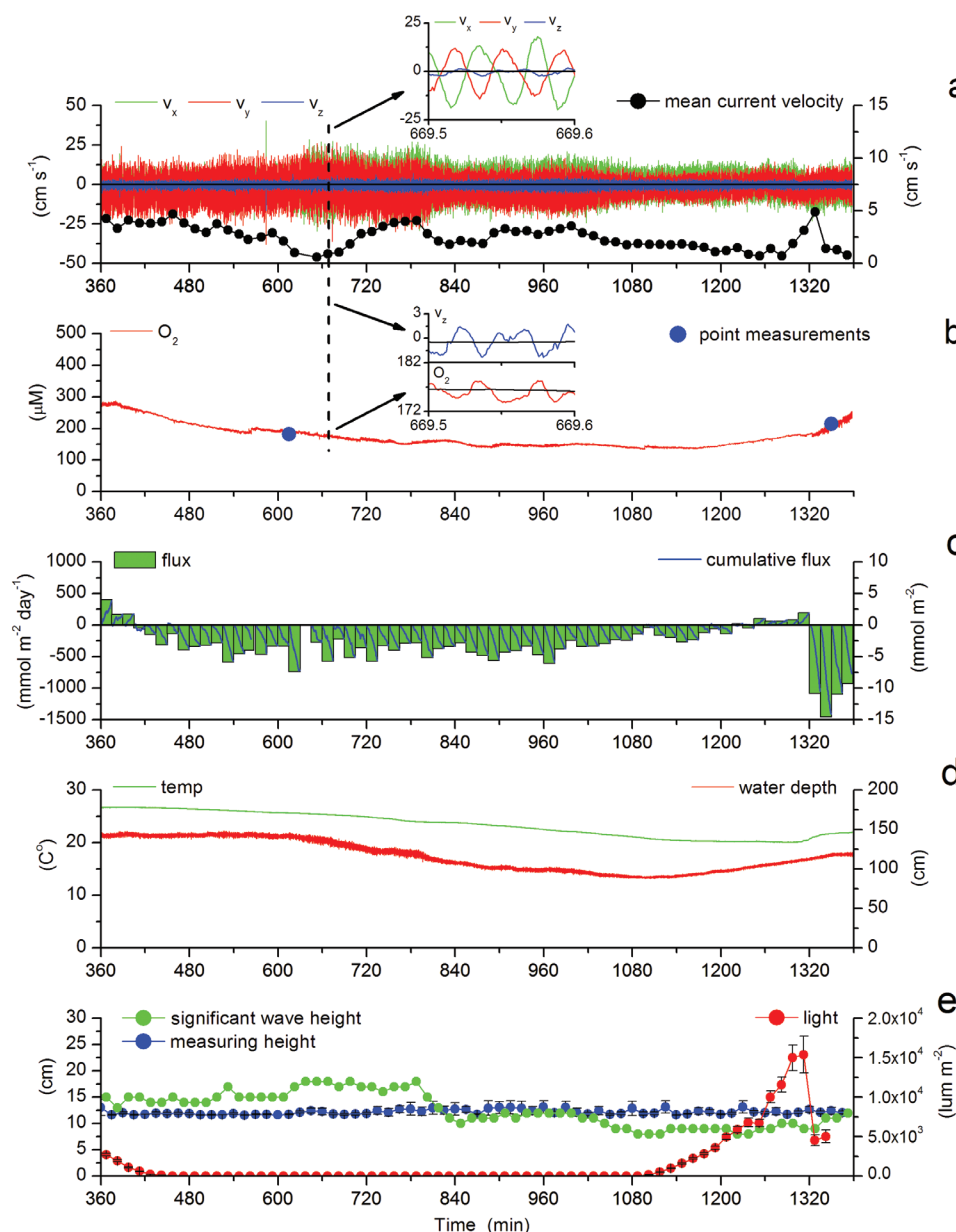
Figure 2. Record of a 17-h eddy correlation deployment at a shallow site in Apalachicola Bay, Florida. (a) The three velocity components (x, y, z, the latter vertical) and derived 15-min mean current velocity. The inset with the magnified 6-s time axis reveals that wave orbitals dominated the flow. (b) The O_2 concentrations. The two point measurements were determined with a handheld YSI DO (dissolved oxygen) meter. The inset with the magnified 6-s time axis shows near-perfect correlation between the vertical wave orbital velocity and the O_2 concentration. (c) Eddy correlation O_2 fluxes derived from 15-min sections of the data and matching cumulative fluxes. (d) Water temperature and water depth. The latter is derived from the ADV's pressure sensor readings. (e) Significant wave height, height of the ADV's measuring volume above the sediment surface, and light at the bottom. All data represent 15-min averages.

between eddy correlation and chamber fluxes in other comparable deployments, and propose that the difference is caused by the wave-generated oscillating flow and pressure at the sediment-water interface (Figure 2a, inset). Existing chamber technology cannot reproduce these rapid oscillations, which may enhance porewater exchange and thus the flux. It should be noted that prior to extracting the eddy flux, the three velocity components were rotated so that the mean vertical velocity equaled zero exactly before the flux was extracted. This step eliminated the potential error that fractions of the larger horizontal wave orbital motions (Figure 2a, inset) are projected into the vertical direction, which could result in an overestimation of the flux. It should further be noted that any other potential errors that we can envision in eddy correlation flux measurements would result in an underestimation of the true flux—not a systematic overestimation. For example, using an O_2 electrode with a response time of several seconds, or an electrode that accidentally was positioned away from where the velocity is measured, would distort or diminish the true eddy correlation signal, and thus lead to an underestimated flux.

Our results suggest that chamber measurements in sediments exposed to even moderate wave action may underestimate the fluxes.

The last four flux estimates, showing extremely high sediment O_2 uptake (Figure 2c; average: 1138 mmol m^{-2} day^{-1}) during daylight hours, were caused by extensive anoxic porewater release, sediment resuspension, and shading (Figure 2e). All of these events resulted from the retrieval of the benthic chambers that were placed upstream from

by the near-perfect correlation between the vertical wave orbital velocity and the O_2 concentration (Figure 2b, inset). At 368 ± 21 mmol m^{-2} day^{-1} (SE, n = 45), the average nighttime O_2 uptake

was a factor of 3.8 higher than the 98 ± 21 mmol m^{-2} day^{-1} (SE, n = 5) that was measured simultaneously with in situ chambers.

We have seen similar divergences

the eddy correlation instrument. These artifacts demonstrate the strength of the eddy correlation technique to show rapid and drastic changes in flux, and show convincingly the magnitude of error that can arise in eddy correlation flux measurements if the footprint area of the technique is disturbed.

FURTHER DEVELOPMENTS OF THE EDDY CORRELATION TECHNIQUE

The intriguing advantages of the eddy correlation technique have prompted the development of eddy instruments in several other labs. For example, Kuwae et al. (2006), McGinnis et al. (2008), and Brand et al. (2008) successfully extracted eddy correlation fluxes from measurements recorded with standard microelectrode amplifiers, showing that good results also can be achieved with less-sophisticated technology. Also, Crusius et al. (2008) equipped an ADV with a fast dual sensor recording temperature and conductivity to measure vertical fluxes of salt and heat over permeable sediments with upward seeping groundwater. These two fluxes were then used to semi-independently estimate groundwater seepage rates with a higher temporal resolution than can be achieved with traditional methods.

So far, all successful eddy correlation measurements of benthic O_2 fluxes have been made with the fast Clark-type microelectrodes (Revsbech, 1989) with 10- to 25-μm-wide glass tips to achieve the required fast response time. The fragility of this thin electrode tip represents a limitation of the technique, in particular for long-term deployments in aquatic observatory systems. A more rugged alternative to the Clark-type microelectrode is the oxygen optode,

and we have developed an eddy correlation instrument using optodes based on fluorescence lifetime measurements (Holst et al., 1995; Glud et al., 1998). The weakness of the system is slower response of the optodes; the advantage is better long-term stability and mechanical strength. Our first comparisons between electrode- and optode-equipped eddy correlation instruments suggest that the optode is a valid alternative to the electrode. However, further research is needed to assess whether the response time and sensitivity are sufficient under all field conditions to allow reliable flux measurements.

To our knowledge, no one has yet focused on developing sensors or modifying existing sensors specifically for aquatic eddy-correlation measurements. Defining the requirements for these sensors is not straightforward—as they vary with conditions at the field site—but as a first-order guideline, sensors should have a ~10-cm-long shaft or longer and a millimeter-sized tip or smaller to minimize flow disturbance, and they should be able to capture 90% of an abrupt concentration change in ~1 s or less. It may be possible to adapt many existing sensors to meet these requirements. We anticipate that the great potential of the eddy correlation technique and its advantages over other flux methods will drive such a development and make it a standard method in benthic research. ▱

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