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Dynamics of the benthic boundary layer and seafloor contributions to oxygen depletion on the Oregon inner shelf

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ABSTRACT

Measurement of in situ O_2 consumption and production within permeable sediments, such as those found over the Oregon–Washington inner shelf, has traditionally been done using methods that isolate the sediments from the dynamic influences of currents and wave motions. Modified from atmospheric research, the non-invasive eddy correlation technique can be used to characterize benthic boundary layer dynamics and measure O_2 flux across the sediment–water interface without excluding the natural hydrodynamic flow. In 2009, eddy correlation measurements were made in 5 discrete months with varying conditions at a 30 m site off Yaquina Head, Newport, OR. The O_2 flux was found to be primarily into the bed (-18 ± 3 mmol m^{-2} d^{-1}; mean ± SE, $n = 137$ 15-min bursts) but was sensitive to non-steady state changes in O_2 concentrations caused by the differential advection of water masses with variable mean O_2 concentrations. Important contributions to O_2 eddy fluxes at surface wave frequencies were seen in eddy correlation cospectra and these are interpreted as being indicative of consumption enhanced by advective transport of O_2 into the bed. The sediments were deposits of fine sand with permeabilities of $1.3–4.7 \times 10^{-11}$ m^2 and wave-generated ripples. Sediment pigment and organic carbon concentrations were low (chlorophyll-α: 0.02–0.45 μg g^{-1}, phaeophytin-α: 0.38–1.38 μg g^{-1} and organic carbon: 0.05–0.39% dry wt in discrete depth intervals from cores collected between March and October), but it was evident that during the summer fresh pigments were trapped in the sand and rapidly mixed over the uppermost 0–13 cm. From these results it is inferred that physical forcing associated largely with waves and currents may accentuate the role of sediment-covered inner shelf habitats as a regional O_2 sink compared to the middle shelf. In effect, the action of waves and currents in the benthic boundary layer enables aerobic respiration that counterbalances the oxygenation of the water column by primary production and mixing in the surface layer.

1. Introduction

The Oregon inner continental shelf is a highly dynamic coastal environment on the edge of the California Current System. The benthic boundary layer (BBL) of the inner shelf is especially complex because of differential influences from many scales of physical and biogeochemical processes (Connolly et al., 2010; Huettel and Webster, 2001; Kirincich and Barth, 2009; Kirincich et al., 2009). Most notably, during the summer northerly winds tend to dominate, bringing pulses of relatively cold, high salinity, nutrient-rich and O_2-depleted bottom water onto the shelf as a result of Ekman transport (Kirincich et al., 2005; Perlin et al., 2005). These periods of upwelling produce stratification that accentuates the impacts of local water column respiration and benthic organic matter remineralization. Shelf hypoxia (defined as when bottom waters have dissolved O_2 concentrations < 63 μM) occurs intermittently during summer months (Adams et al., 2013; Chan et al., 2008; Grantham et al., 2004; Peterson et al., 2013). At other times, the entire water column is nearly saturated with respect to atmospheric O_2 due to the intense turbulent mixing of long period Pacific storm waves which may suspend sediment and generate a rippled seabed (Komar et al., 1972).

On the Oregon shelf and in other similar environments, BBL water properties and exchange with the overlying water and sediments may also be affected by surface wave-driven return flows (Lentz et al., 2008), intermittent non-linear internal waves (Nash et al., 2012a, 2012b), particle sinking, benthic primary production and bioturbation (Reimers et al., 2004a). This research investigates the dynamics generated by such inconstant but co-occurring processes through short-term Eddy Correlation (EC) measurements of dissolved O_2 fluxes made in five successive months within a single Oregon shelf study area centered at 30 m depth.

The EC method is a non-invasive technique adapted from atmospheric boundary layer research and developed for BBL studies by Berg

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et al. (2003). Basically, O_2 fluxes are determined from simultaneous time-series measurements of the fluctuating components of vertical velocity and O_2 concentrations. Ideally, these flux derivations represent repetitive measurements of total benthic O_2 exchange at high temporal resolution under in situ conditions with minimal, if any, disturbance of the sediment or hydrodynamic flow (Berg et al., 2007). EC O_2 flux determinations also have the advantage that they can effectively integrate heterogeneity caused by benthic organism and physical exchange processes acting over seafloor areas of tens of square-meters (Berg et al., 2013, 2007; Lorrai et al., 2010; McGinnis et al., 2008; Reimers et al., 2012; Rheuban and Berg, 2013).

Despite the advantages of the EC method, fundamental assumptions regarding steady state conditions and nondivergent horizontal turbulent transport also need to be met in order to derive fluxes that represent only the seafloor source or sink for O_2 in the environment (Berg et al., 2003; Brand et al., 2008; Reimers et al., 2012). Holtappels et al. (2013) illustrate non-steady state cases that produce erroneous representations of benthic sources or sinks, and recommend careful consideration of derived EC fluxes in light of the coincident hydrodynamic conditions in dynamic coastal environments. Furthermore, methods used for detrending the data and coordinate rotation of velocities must be carefully considered (Lorke et al., 2012). Detrending distinguishes between low-frequency components that contribute to the flux and those that are thought to bias flux calculations (Finnigan et al., 2003). At wave-dominated sites, velocities must be oriented to avoid mapping horizontal motions of surface waves onto the vertical velocities, while still preserving the wave contribution to the flux (Reimers et al., 2012). The range, response time and calibration stability of the O_2 sensor, as well as the amplifier used, can further affect the flux determination (McGinnis et al., 2011).

In this work we present EC measurements made with microelectrodes and a sensitive commercial amplifier, and we evaluate the EC method for assessing the temporal variability of water to sediment O_2 fluxes and their controlling factors on the Oregon inner shelf with its complex hydrodynamics. In particular, the effects of waves and currents, and bottom layer O_2 concentrations are examined in distinct <20 h data sets retrieved throughout an upwelling season. As supporting information, we use hydrographic data, in situ microprofiles of pore-water O_2 concentration, and the physical, chemical and biological properties of sediment cores collected from within the study area.

2. Material and methods

2.1. Study site

Sampling for this study was conducted at discrete times between March and October 2009 on the Oregon shelf at approximately 44.7°N 124.1°W (Fig. 1). The study site is adjacent to the Newport Hydrographic line, one of few transects off the central Oregon Coast with long-term O_2 records (Pierce et al., 2012), as well as being the present site of the U.S. Ocean Observatories Initiative, Oregon Endurance Array for observing cross-shelf and along-shelf variability. The area is heavily fished for Dungeness crab and is under consideration for the installation of anchored wave energy extraction devices (Boehlert and Gill, 2010). Lander deployments and sediment and water column collections were executed from OSU research vessels *Wecoma* and *Elakha* and positioning was often influenced by the location of crab pot lines in the area. The coordinates of individual benthic collections are available as on-line Supplementary material.

2.2. Instrumentation

The BOXER (Benthic Oxygen Exchange Rate) lander, specifically designed and built for benthic EC studies in high energy marine environments, was the primary instrument used in this study (Reimers et al., 2012). The main EC system mounted on the lander

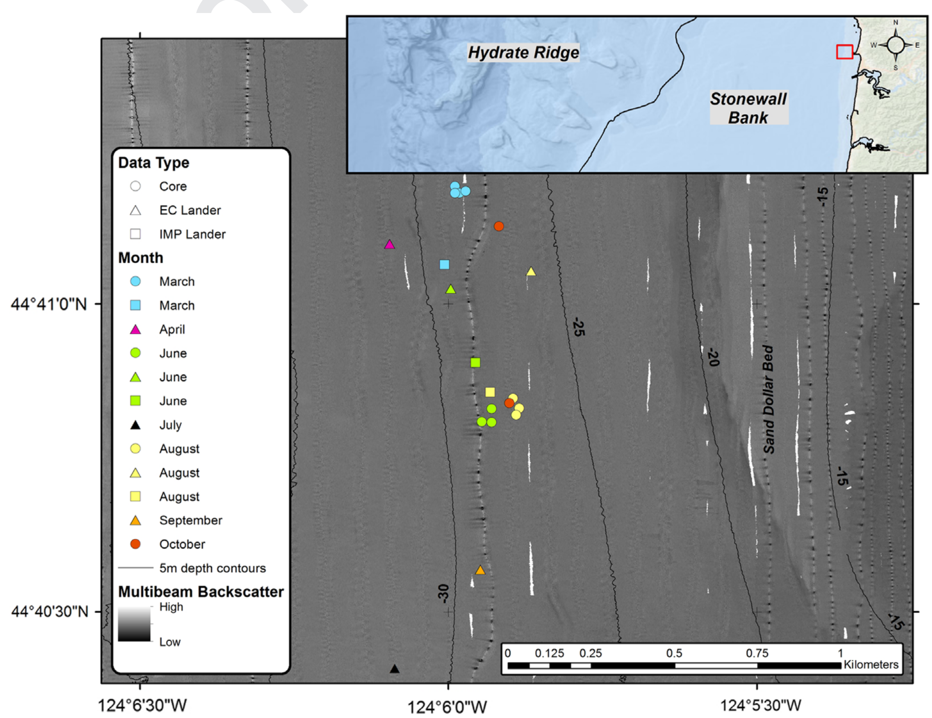

Fig. 1. Bathymetric and multibeam backscatter map of study site (prepared by C. Romsos, Active Tectonics and Seafloor Mapping Laboratory, OSU). Symbols indicate locations for the lander deployments and core samples (with coordinates listed within Supplementary material). Inset map shows location in relation to the continental margin bathymetry offshore of Yaquina Head, Newport, Oregon. The black line in the inset marks the shelf break.

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