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Measuring pore water oxygen of a high-energy beach using buried probes

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ABSTRACT

We conducted six field campaigns to investigate the spatial and temporal evolution of pore water oxygen content on a high-energy sandy beach aquifer during several tidal cycles at different seasons. We buried autonomous probes in intertidal sands to record dissolved oxygen saturation, salinity, temperature and water head at a 2–10 min frequency. Oxygen concentrations display significant changes both with time (tide and seasons) and space (cross-shore and vertical variations). Seawater circulation in tidal sands forms a saline pore water circulation cell with oxygen-saturated pore water in the zone of seawater recharge. Oxygen-depleted pore water in the lower beach is the result of in situ respiration processes that occur during seawater circulation. Oxygen depletion varies throughout the year and anoxic conditions are reached at the end of spring, as planktonic organic matter becomes abundant in seawater and more organic matter is therefore supplied to pore water. On a shorter time scale (weeks to minutes), oxygen variations are driven directly by physical forcing. Tidal amplitude affects the extent of the saltwater circulation cell and the associated location of the recharging and discharging zones of the beach. The evolution of the water table level during the tidal cycle influences the circulation of pore water in the sand and ultimately, the timing of oxygen variations during flood and ebb. This first in situ study in a high-energy sandy beach shows that the dynamics of pore water oxygen are governed by biogeochemical processes at the seasonal scale and by physical forcing at the time scale of minutes to a few days.

1. Introduction

Permeable sandy sediments cover a large part of continental shelves and are common along the shorelines of coastal plains (Emery, 1968). Biogeochemistry of permeable sediments was ignored until recently because of the low organic matter content in such sediments (Boudreau et al., 2001; Huettel et al., 2014), but we now know that the low levels of organic matter are in part due to the efficient mineralization of organic carbon in permeable sediments (Huettel et al., 2003; Jahnke et al., 2005; Rocha, 2008), which may therefore contribute significantly to the oceanic carbon cycle (Shum and Sundby, 1996; Chipman et al., 2012; Cyronak et al., 2013).

Intertidal sands play an important role in the biogeochemical cycles of carbon, nitrogen and phosphorus (Rusch et al., 2000; De Beer et al., 2005; Grunwald et al., 2010). Anschutz et al. (2009) showed that reflective sandy beaches can be thought of as a bioreactor in which organic matter is degraded via bacterial respiration. This results in recycled nutrients being returned to the coastal ocean. Sandy beaches are influenced by tide and waves, which promote circulation of seawater within the beach and between the beach and the coastal ocean (Robinson et al., 2007; Xin et al., 2010; Abarca et al., 2013). Sandy beaches also receive discharges of fresh continental groundwater, which adds complexity to the physical and biogeochemical processes in beaches that influence elemental cycles (Moore, 1999; Slomp and Van Cappellen, 2004; Charette and Sholkovitz, 2006, Fig. 1).

Advection is the main mode of solute transport in permeable sediments: pore water flows are driven by pressure gradients induced by bottom currents (Forster et al., 1996) and tides and waves (Huettel and Webster, 2001). Advective transport exceeds diffusive transport in porous media by orders of magnitude (Boudreau et al., 2001; Precht and Huettel, 2004) and promotes transport of both oxygen (Booij et al., 1991; Forster et al., 1996; Ziebis et al., 1996) and organic matter into the sediment (Huettel and Rusch, 2000; Rusch et al., 2001; Ehrenhauss et al., 2004). Aerobic respiration, which represents 25%–50% of carbon

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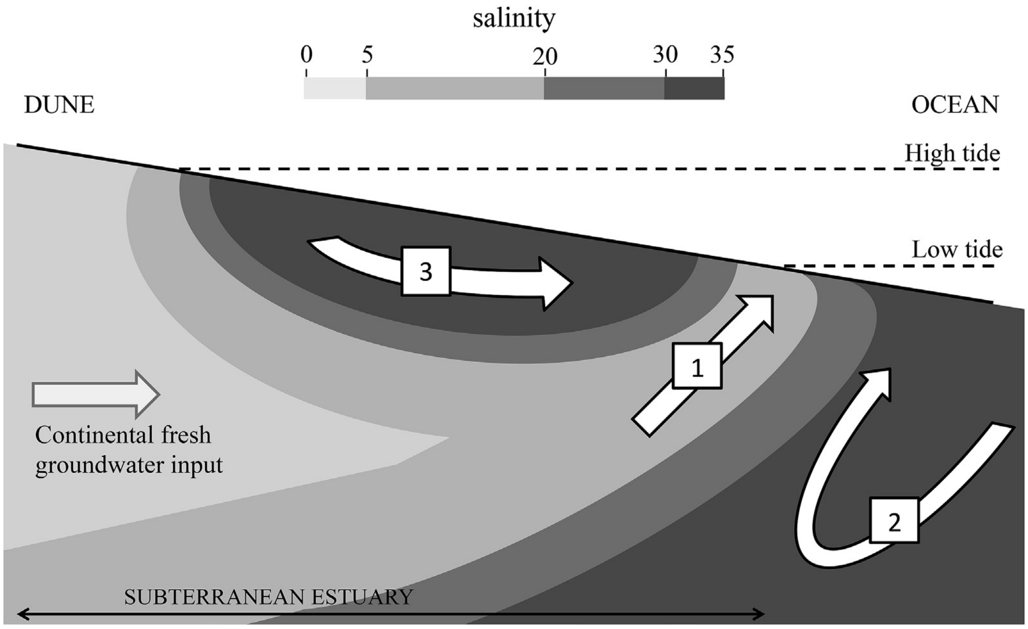

Fig. 1. Conceptual diagram of subterranean estuary in an exposed beach, including major nearshore flow processes: (1) freshwater discharge, (2) density-driven circulation and (3) seawater circulation induced by wave set-up, tide and wave-bed form interactions (inspired from Robinson et al., 2007 and Abarca et al., 2013). In situ probes were positioned in the seawater circulation area.

mineralization in coastal sediments (Polerecky et al., 2005), is enhanced by advection in permeable sediments (Zetsche et al., 2012).

In exposed beaches, the pore water is regularly flushed by oxygen-rich seawater. The transport of fresh marine organic matter and oxygen into the sand by tidal pumping and wave run-up (Riedl and Machan, 1972; McLachlan, 1990) contribute material for remineralization, which can lead to oxygen depletion and release of nutrients. Aerobic respiration being the principal pathway of organic matter mineralization in these environments (Anschutz et al., 2009; Charbonnier et al., 2013), supply and consumption of oxygen can be used to characterize biogeochemical processes in permeable sediments (D'Andrea et al., 2002; Polerecky et al., 2005; Cook et al., 2007).

The multiple forces, such as tides, waves, currents, air exposure and/or topographic changes that act on the oxygen regime in the pore water of wave-dominated and high-energy tidal beaches, as well as the difficult access during part of the tidal cycle and during storms challenge our ability to observe and describe the biogeochemical system of beaches. Nevertheless, oxygen in sandy sediments has been measured both in the field and in the laboratory using benthic chambers and core incubations (D'Andrea et al., 2002; Jahnke et al., 2005; Zetsche et al., 2012) or in flumes (Huettel and Gust, 1992; Ziebis et al., 1996; Precht et al., 2004). A few in situ studies have been made in permeable sediments using microsensors (Werner et al., 2006; Delgard et al., 2012), benthic chambers (Malan and McLachlan, 1991; Janssen et al., 2005), planar optodes, or a combination of these methods (De Beer et al., 2005; Cook et al., 2007). These instruments cannot be deployed on exposed tidal beaches, where conditions can be extreme with several meters high waves and a wide swash zone.

To explore benthic oxygen dynamics in such environments, we have used a different approach, which is based on burying autonomous probes below the sediment surface of a sandy beach (Truc Vert, SW France). We deployed in situ probes during several days in the permanently water-saturated sediment layer, which allowed us to record continuously the time variability of dissolved oxygen, salinity, temperature and pressure during several tidal cycles. The probes could not be left in place during a full year, because of the high probability of loss due to the shifting of sands caused by the swell, the tidal regime, and the weather. At a given position, we could observe accretion or erosion of more than 1 m of sand within a few days. Instead, we deployed our probes on six different occasions over two years. A long-term monitoring being impossible in such a harsh environment, our repeated short-term experiments appeared to be the best way to assess oxygen variability at the different time scales affecting the system (minutes, days, seasons). The aim of this study was to determine how the concentration of dissolved oxygen in pore water of a reflective sandy beach varies over time and how this fluctuation might be linked to biogeochemical processes and physical forcing.

2. Materials and methods

2.1. Study area

The southwest coast of France between the Gironde and the Adour estuaries is a 240-km-long straight sandy shore bordered by high aeolian sand dunes. The beaches on this coast display a double bar system created by strong hydrodynamic forces (Castelle et al., 2007). The Truc Vert beach used for this study is representative of this coast, but is not exposed directly to human activity. The beach is located north of the Cap Ferret sand spit (Fig. 2).

The sediment consists of medium sized quartz sand with a mean grain size of 435 μm. The mean $CaCO_3$ content is 1.2 wt%, and the mean organic carbon concentration is only 280 ppm. The porosity is 0.38–0.42 (Charbonnier et al., 2013). The meso-macro type tide has an average tidal range of 3.2 m, extending to 5 m during spring tides. The mean wave amplitude is 1.5 m, but waves can reach 10 m during winter storms. The Truc Vert beach has a ridge and runnel morphology that evolves with weather conditions (Castelle et al., 2007, 2014).