Deep-Sea Research II 92 (2013) 249–260

Contents lists available at SciVerse ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

The response of abyssal organisms to low pH conditions during a series of CO_2-release experiments simulating deep-sea carbon sequestration

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ARTICLE INFO

Available online 20 March 2013

Keywords:
Ocean acidification
Deep sea
Carbon storage
Environmental hypercapnia
High-CO_2 ocean
CO_2-release experiment

ABSTRACT

The effects of low-pH, high-pCO_2 conditions on deep-sea organisms were examined during four deep-sea CO_2 release experiments simulating deep-ocean C sequestration by the direct injection of CO_2 into the deep sea. We examined the survival of common deep-sea, benthic organisms (microbes; macrofauna, dominated by Polychaeta, Nematoda, Crustacea, Mollusca; megafauna, Echinodermata, Mollusca, Pisces) exposed to low-pH waters emanating as a dissolution plume from pools of liquid carbon dioxide released on the seabed during four abyssal CO_2-release experiments. Microbial abundance in deep-sea sediments was unchanged in one experiment, but increased under environmental hypercapnia during another, where the microbial assemblage may have benefited indirectly from the negative impact of low-pH conditions on other taxa. Lower abyssal metazoans exhibited low survival rates near CO_2 pools. No urchins or holothurians survived during 30–42 days of exposure to episodic, but severe environmental hypercapnia during one experiment (E1; pH reduced by as much as ca. 1.4 units). These large pH reductions also caused 75% mortality for the deep-sea amphipod, *Haploops lodo*, near CO_2 pools. Survival under smaller pH reductions ($\Delta pH < 0.4$ units) in other experiments (E2, E3, E5) was higher for all taxa, including echinoderms. Gastropods, cephalopods, and fish were more tolerant than most other taxa. The gastropod *Retimohnia* sp. and octopus *Benthoctopus* sp. survived exposure to pH reductions that episodically reached −0.3 pH units. Ninety percent of abyssal zoarcids (*Pachycara bulbiceps*) survived exposure to pH changes reaching ca. −0.3 pH units during 30–42 day-long experiments.

1. Introduction

Although it is widely accepted that reducing greenhouse gas emissions is a key for avoiding dangerous climate warming and associated consequences, international efforts to curtail emissions have been largely unsuccessful. Some progress has been made, with 19 of 37 signatory nations to the Kyoto Protocol having met their emission reduction targets (IEA, 2011), but global emissions rose nonetheless from 21 to 29 Mt CO_2 y^{-1} (+38%) between 1990 and 2009. An effective emissions reduction program will require broad application of a portfolio of carbon-free energy alternatives, methods for increased energy efficiency, and carbon storage strategies (Pacala and Socolow, 2004). Development of carbon capture and storage methods have focused on C storage in the biosphere and in suitable geologic strata such as deep aquifers, depleted oil and gas wells, or deep ocean sediments and porous subseabed formations (Anderson and Newell, 2004; Yang et al., 2008; Herzog, 2011). Carbon storage by direct injection of waste CO_2 into the deep ocean (e.g. Marchetti, 1977) has been considered, but avoided owing to concern for environmental damage (Tamburri et al., 2000; Herzog, 2001; Seibel and Walsh, 2001). Deep-sea C storage is also thought to be possible through iron fertilization of ocean surface waters (Buesseler et al., 2008; Vaughan and Lenton, 2011), but has unknown efficiency and is also expected to alter environmental conditions and ecosystem function in the deep-sea.

The urgency for climate stabilization is likely to increase as atmospheric CO_2 levels and related climate consequences rise through this century. If so, concern for the impacts of global warming on terrestrial and upper ocean systems may eventually outweigh consideration of the potential impacts of ocean C storage for deep-sea ecosystems. Society may then decide to ‘pull out all the stops’ to avoid runaway climate change, and expand the use of deep ocean carbon storage and other methods that are currently avoided due to cost or environmental concerns.

Biological communities in the deep-sea are threatened by elevated environmental CO_2 levels (environmental hypercapnia)

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0967-0645/$ - see front matter
http://dx.doi.org/10.1016/j.dsr2.2013.03.037

caused by the direct injection of waste carbon dioxide, or through the leakage of CO_2 from subseabed C storage sites. Carbon dioxide released at or near the seabed reacts with seawater to form carbonic acid, and can produce large and highly variable changes in ocean pH and carbonate saturation, particularly near release sites. Small scale experiments releasing liquid CO_2 in the deep-sea have measured pH levels less than 4.0 near pools of liquid CO_2 (Brewer et al., 2005). Models of boundary layer turbulence near CO_2 pools in the deep ocean indicate similar near-field and variable pH in the dissolution plume emanating from deep-sea lakes of sequestered CO_2 (Herzog et al., 2001; Fer and Haugan, 2003). The spatial extent and severity of pH perturbations near injection sites will depend upon the method of CO_2 injection, time-scale and rate of release, and local hydrography (Caldeira et al., 2005).

Deep-sea animals are expected to be highly sensitive to high-CO_2, low-pH dissolution plumes near deep-sea CO_2 injection or storage sites. The ability of animals to tolerate environmental change is based on physiological repertoires that have evolved over thousands of generations, and taxa inhabiting the typically stable conditions in deep-ocean waters are generally more sensitive to environmental perturbations of any sort than related shallow-water taxa (Seibel and Walsh, 2003). Most deep-sea taxa have lower metabolic rates (largely due to reduced temperature) and reduced enzyme function – both key factors for coping with physiological stress – compared to their shallow water counterparts (Seibel and Walsh, 2003). Energy limitation in the deep-sea may also constrain the ability of animals to increase energy allocation toward acid–base regulation and other physiological processes used to cope with physiological challenges associated with environmental hypercapnia.

Few studies have examined the sensitivity of deep-sea animals to variable, low-pH conditions near deep-sea CO_2 storage sites. Low tolerance of key community taxa to high ocean pCO_2 levels caused by ocean carbon storage could disrupt the function of deep-sea food webs, leading to reduced biodiversity, shifts in community structure, and reduced community production. A series of experiments used to evaluate the potential impacts of a large scale deep-sea carbon dioxide storage program on benthic deep-sea communities were performed by releasing small pools of liquid CO_2 on the seabed off Central California (Barry et al., 2005). Reports from these experiments found that meiofauna, including harpacticoid copepods, euglenoids, and foraminifera experienced elevated mortality after exposure to episodic pH changes of ca. −0.2 units (Barry et al., 2004; Carman et al., 2004; Thistle et al., 2005, 2006, 2007). In this paper, we report the response of various taxa to episodic exposure to low-pH dissolution plumes near pools of liquid CO_2 released on the seabed at abyssal depths, including changes in abundance and biodiversity.

2. Methods

2.1. Study area

Four carbon-dioxide release experiments (CO_2—1, 2, 3, 5; hereafter E1, E2, E3, E5) were performed at two abyssal sites near the base of the continental rise off the central California coast. Site A (3600 m, E1, E3, E5) and Site B (3320 m, E2) were both characterized by a flat, soft-sediment environment (Fig. 1). Bottom water temperatures were near 1.5 °C, with oxygen levels of ca. 125 μmol kg^{-1} and ambient pH of ~7.78 (SWS). Currents were generally sluggish (<5 cm s^{-1}) and oscillated in direction over the dominant semidiurnal tidal period near 12 h (Barry et al., 2005).

The sediment-dwelling macrofauna at Site A were dominated by a dense assemblage of *Haploops lodo*, a tube-dwelling ampeliscid amphipod, but also included numerous other Crustacea, Polychaeta, Mollusca, and Cnidaria. The macrofaunal assemblage at Site B was very similar to Site A, with much lower densities of *H. lodo*. Meiofauna

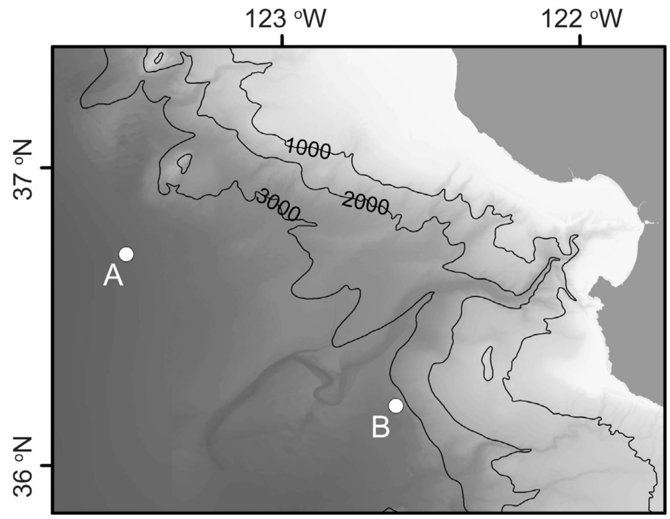

Fig. 1. Map of study sites on the continental slope off central California. Site A (3600 m) was used for E1, E2, and E5. Site B (3310 m) was used for E2. Depth contours in meters.

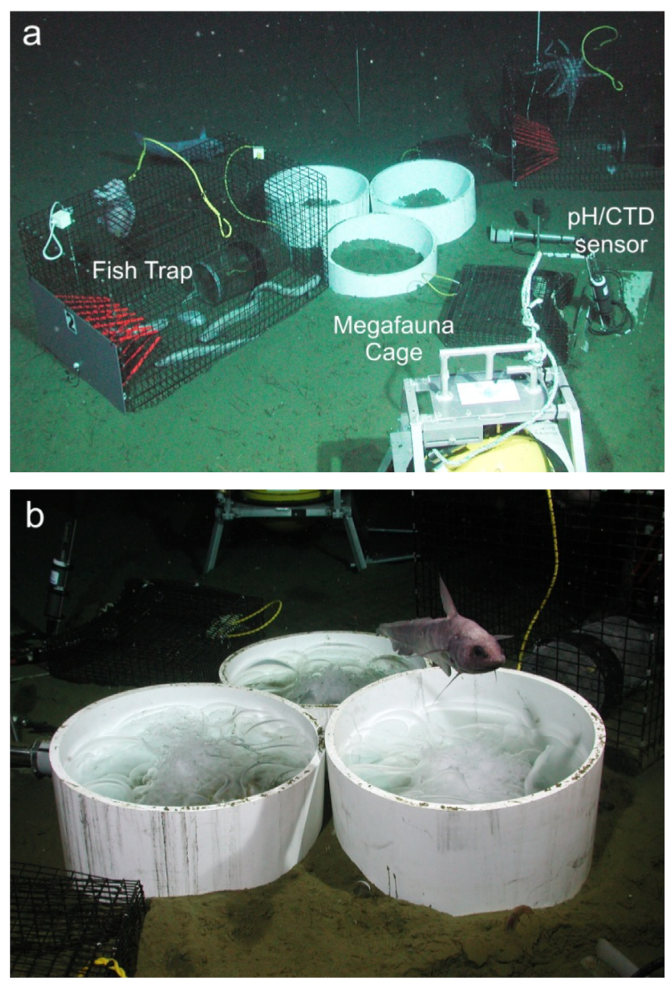

Fig. 2. Photographs of CO_2 release experiment E2. (a) Overview of E2 showing fish traps with zoarcids (*P. bulbiceps*) and octopus (*Benthoctopus* sp.), smaller megafaunal cages, and sensors. CO_2 containers (center) are mostly empty because the image was taken at end of experiment. (b) Close-up of CO_2 containers at start of E2, showing liquid CO_2 (~100 l) and a macrourid fish (*C. armatus*) swimming above the containers.