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Modelling impacts and recovery in benthic communities exposed to localised high CO_2

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ABSTRACT

Regulations pertaining to carbon dioxide capture with offshore storage (CCS) require an understanding of the potential localised environmental impacts and demonstrably suitable monitoring practices. This study uses a marine ecosystem model to examine a comprehensive range of hypothetical CO_2 leakage scenarios, quantifying both impact and recovery time within the benthic system. Whilst significant mortalities and long recovery times were projected for the larger and longer term scenarios, shorter-term or low level exposures lead to reduced projected impacts. This suggests that efficient monitoring and leak mitigation strategies, coupled with appropriate selection of storage sites can effectively limit concerns regarding localised environmental impacts from CCS. The feedbacks and interactions between physiological and ecological responses simulated reveal that benthic responses to CO_2 leakage could be complex. This type of modelling investigation can aid the understanding of impact potential, the role of benthic community recovery and inform the design of baseline and monitoring surveys.

1. Introduction

Carbon dioxide capture and storage (CCS) provides a credible option for the removal of a significant proportion of carbon dioxide (CO_2), primarily from point source fossil fuel and industrial emissions, thereby reducing the environmental and economic effects of climate change (Fuss et al., 2014; IPCC, 2005). Although the likelihood of CO_2 leakage from CCS is thought to be small (IPCC, 2005) both environmental legislation (e.g. EC, 2009; OSPAR, 2007; Dixon et al., 2015) and public interest, require operators to assess the potential environmental risks associated with CCS and to employ appropriate monitoring and mitigation strategies to detect leakage and reduce the potential for environmental damage. Fundamental to achieving these requirements is to understand the possible impacts of CO_2 leakage on local organisms and ecosystems and the potential for their recovery once any leak has ceased (Widdicombe et al., 2013).

In many parts of the world, deep geological storage reservoirs are situated offshore (Nakanishi et al., 2009; Senior, 2010). Consequently, benthic faunal communities are expected to be the most likely to be exposed to elevated levels of CO_2 should point-source leakage occur at the sea floor. Given that many of these species are also sessile or have limited mobility and dispersal potential (i.e. no planktonic stage) and that some species have relatively slow generation times, benthic communities are more likely to be affected by CCS leakage. Whilst pelagic biota may also be affected, as the plume of CO_2 disperses up through the water column, the impacts on planktonic communities will likely be less than those for the benthos. This is primarily because planktonic organisms are generally highly dynamic both spatially and temporally and have fast generation times. In addition, the lateral advection of replacement populations, are likely to negate the impact and hasten the recovery for planktonic species, while larger, actively mobile pelagic species, such as fish, may be able to detect and avoid impacted regions altogether. Consequently, most recent CCS environmental impact studies have concentrated on the response of benthic communities and this also forms the focus of the current paper.

Carbon dioxide is naturally found in sea water and in sediment pore water, providing the substrate for photosynthesis and being the product of respiration. However, excess CO_2, beyond natural variability, causes significant changes to sea water chemistry, including increased acidity (reduced pH) and reduced carbonate content, all of which can impact the health, function and survival of marine organisms (Gattuso and Hansson, 2011; Widdicombe and Spicer, 2008). To fully appreciate the environmental risks associated with a CO_2 leak requires several variables to be quantified: the probability that leakage will occur, the degree of chemical perturbation that would result from the leak, the spatial extent over which potentially harmful perturbations would occur and the length of time this perturbation would persist. Using model simulations, this study focuses on describing how the chemical nature of a CO_2 leak, specifically the severity and longevity of any chemical perturbation, will impact upon a representative benthic community, including an estimation of recovery potential.

The impacts of high CO_2 on marine systems have been studied using different approaches, each of which has specific strengths and weaknesses (Jones et al., 2015). Manipulative experiments conducted in

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laboratories or mesocosms allow for controlled, short term exposure experiments on single species or simplified communities (e.g. Kita et al., 2013; Widdicombe et al., 2013). Natural CO_2 release sites (also known as natural analogues) can be studied to investigate ecosystem-level responses or those of particular species or features in a natural setting (e.g. Calosi et al., 2013; Hall-Spencer et al., 2008), but are often geographically limited, sometimes confounded by other environmental factors such as temperature and often ecologically and physio-chemically distinct from CCS storage sites and possible leakage signals. Controlled leakage experiments performed in the field offer a method of conducting more ecologically realistic exposure experiments in conditions relevant to real-life CCS activities and with opportunities to assess natural processes such as recovery (Blackford et al., 2014; Taylor et al., 2015b). However, these studies can be expensive, lack repeatability as well as being restricted to a limited number of exposure scenarios. Models, such as that used here, can be used to integrate knowledge and explore a wide range of scenarios including processes of recovery, albeit within simplified, idealised ecosystems.

Several modelling studies have been used to explore the spatial and temporal distribution of chemical changes in seawater resulting from a wide range of seabed CO_2 leakage scenarios. For example, Dewar et al. (2013) detailed the fine scale dynamics of bubble plumes arising from smaller scale leak events; Blackford et al. (2013) examined mid-scale leaks within tidal regimes; Blackford et al. (2008) and Phelps et al. (2015) described larger hypothetical leakage events. Whilst the degree of perturbation tends to scale with leak rate, these studies projected considerable variability in individual leak characteristics, suggesting that potential leakage events cannot be simplistically generalised. The magnitude and spatial extent of chemical perturbation in the surface sediments and overlying water during a leak depends on many factors, including the nature of the leakage pathway, the rate of leakage (Paulley et al., 2013), its duration, the physio-chemical composition of the overburden including shallow sediments (Blackford et al., 2014; Queirós et al., 2015c), the properties of any bubble plumes (Dewar et al., 2013) and the degree of hydrodynamic mixing at the leakage site. The latter is driven by tidal mixing, currents, thermal stratification and weather, resulting in temporally and spatially complex plumes of high CO_2 water (Blackford et al., 2013; Phelps et al., 2015). Despite all this variability, modelling studies do uniformly suggest that once leakage ceases, chemical recovery in seawater is very rapid, driven by hydrodynamic mixing, dilution and outgassing (Blackford et al., 2013; Phelps et al., 2015). Furthermore, a CO_2 release experiment conducted in the field also showed fast chemical recovery in seawater and surface sediments (Blackford et al., 2014).

To date, no modelling studies have incorporated representations of benthic biota within a physically and chemically realistic simulation of leakage, although some model studies have investigated biological impacts of ocean acidification on pelagic processes (e.g. Artioli et al., 2014; Dutkiewicz et al., 2015; Tagliabue et al., 2011). These studies have shown significant interactions and feedbacks between ecosystem components arising from relatively simple impact mechanisms, suggesting that such modelling at least has a role in developing hypothesis, even if parameterisations and the resulting projections remain uncertain, due to our limited spread of observations to date.

Despite the fact that each individual leak is likely to be unique in the precise nature of its formation, development, size and duration, it is possible to generalise that all leaks will produce a gradient of chemical change in water and sediments with maximum perturbation occurring at the epicentre reducing to zero at some distance from the source of the leak. From a biological point of view the degree of perturbation or distance from leakage is the key determinant of impact (Barry et al., 2013; Widdicombe et al., 2015).

In this study we have utilised a comprehensive ensemble of model scenarios that span the expected range of chemical perturbations and event durations (exposure scenarios) with an aim to investigate the physiological and ecosystem response of zoobenthic communities exposed to low pH due to CO_2 leaks and the subsequent potential for recovery. We have applied these scenarios to a 1D (vertical) setup of an established marine ecosystem model ERSEM (Blackford et al., 2004; Butenschön et al., 2016), rather than attempt a more realistic implementation of a limited number of scenarios in a computationally demanding 3D model. We have incorporated a parameterisation of benthic fauna response to decrease in pH based on published impact responses, as detailed in the following section.

2. Methodology

2.1. Description and setup of the model

A coupled 1D water column model GOTM-ERSEM (e.g. Allen and Clarke, 2007) was implemented to study the impact of CO_2 leakage on zoobenthic communities. ERSEM is a well-tested marine ecosystem model (Fig. 1) configured for temperate shelf seas and can be coupled to a range of hydrodynamic host models representing either 1D (water column) or fully 3D marine systems (Butenschön et al., 2016). ERSEM includes a sub-model of the benthic environment capable of reproducing sediment and pore-water biogeochemical processes, biological interactions and the resulting benthic-pelagic exchange in an active sediment layer of 0.3 m depth (Butenschön et al., 2016; Ebenhöh et al., 1995). The model splits zoobenthos into three functional groups, based on their feeding sources: suspension feeders, feeding mainly on particulate organic matter (POM) at or immediately above the sea floor; deposit feeders, which feed on material within sediments, and smaller organisms within the sediment structure, termed meiobenthos (Table 1). The functional type approach enables a reasonable formulation of the physical impacts that zoobenthos exert on sediment structure and chemistry due to bioirrigation, which enhances diffusivity of solutes in the sediments, and bioturbation, which affects the vertical redistribution of POM. Benthic alkalinity and concentrations of DIC in sediment pore water are both used to define the typical sediment pH profile. For the present study, the existing ERSEM model formulation of pelagic carbonate chemistry (Artioli et al., 2012) has been extended to account for fluxes of benthic alkalinity, thereby enabling the calculation of mean (depth-averaged) benthic pH alongside the existing calculation of pelagic pH. Sources and sinks of benthic alkalinity include contributions from bacterial and zoobenthic exudation of ammonium and phosphate, nitrification and denitrification (Fig. 2). Alkalinity and DIC fluxes across benthic-pelagic interface are calculated using equilibrium profile assumptions. A detailed description of the implementation of benthic-pelagic fluxes in ERSEM is given in Butenschön et al. (2016).

For the present study, the General Ocean Turbulence Model – GOTM (www.gotm.net, Burchard et al., 1999, 2006) was used to represent a seasonally stratified water column of 69 m depth in the central North Sea (56°N, 3°E). The model was forced using climatological atmospheric data derived from 20 years (1980–2000) of ECMWF-ERA40 reanalysis data (Uppala et al., 2005). In order to realistically simulate the onset and the duration of stratification in such a dynamic environment as the North Sea using a simple 1D model, the simulated vertical profiles of temperature and salinity were relaxed to their climatology retrieved for the study location from a 3D model covering the same period of time and forced with the same atmospheric conditions (Holt et al., 2012). ERSEM biogeochemical variables were initialized applying values typical for the study area. Results of a spin-up simulation of 5 years were sufficient to achieve a steady annual cycle, and these were used as initial condition for all exposure scenarios.

2.2. Parameterization of zoobenthic response to lowering pH

The response of individuals and species to lowering pH is complex. However, much information can be derived from more than a decade of dedicated ocean acidification and CCS impact research. This work suggests that the impacts of lowered pH induced by acute hypercapnia are highly species- and context-specific (Christen et al., 2012), depending