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Regional scale impacts of distinct CO_2 additions in the North Sea

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ABSTRACT

A marine system model applied to the North West European shelf seas is used to simulate the consequences of distinct CO_2 additions such as those that could arise from a failure of geological sequestration schemes. The choice of leak scenario is guided by only a small number of available observations and requires several assumptions; hence the simulations reported on are engineered to be worse case scenarios. The simulations indicate that only the most extreme scenarios are capable of producing perturbations that are likely to have environmental consequences beyond the locality of a leak event. Tidally driven mixing rather than air–sea exchange is identified as the primary mechanism for dispersal of added CO_2. We show that, given the available evidence, the environmental impact of a sequestration leak is likely to be insignificant when compared to the expected impact from continued non-mitigated atmospheric CO_2 emissions and the subsequent acidification of the marine system. We also conclude that more research, including both leak simulations and assessment of ecological impacts is necessary to fully understand the impact of CO_2 additions to the marine system.

1. Introduction

Emission of anthropogenically derived CO_2 to the atmosphere and the subsequent uptake by the oceans, leading to climate change and ocean acidification, respectively, are both predicted to cause severe environmental, ecological and resource impacts (IPCC, 2001; Stern, 2006; Raven et al., 2005). Consequently there is much interest in developing methods for reducing carbon emissions, including carbon capture (from power stations) and its subsequent storage in geological formations. An active sequestration programme has been in operation at the Sleipner field in the North Sea since 1996 run by the Norwegian company Statoil. Here carbon dioxide is striped from natural gas by solvents and disposed of in a saline formation with approximately one million tonnes of CO_2 sequestered each year. Further projects are planned for the North Sea, exploiting the large volumes of geological reservoirs in the region. Injection of carbon dioxide under high pressure into depleted reservoirs is also of financial interest as it may lead to enhanced oil recovery.

The delivery and geological storage of large volumes of highly pressurised CO_2 raises the concern of leakage and its potential environmental consequences to the marine system. A number of mechanisms of leakage are possible, fast flow events such as a pipeline failure, faulty injection well casings and transmissive faults or fractures in the cap rock; and slow flow phenomena such as seepage through porous geological structures. Research is scarce but suggests that in the long-term only a small fraction of sequestered CO_2 might escape (DTI, 2003 and references therein). However, given the possibility of leakage, it is prudent to assess the potential for causing environmental impacts and to compare this with the predicted environmental impacts of ocean acidification.

2. Methodology

A marine system model (POLCOMS-ERSEM-HALTAFALL), describing the North West European continental shelf, is used to simulate the dynamics of added CO_2 and it's consequences in terms of the resulting perturbation in pH. The model system is as described in Blackford and Gilbert (2007) except for the extension to cover the whole of the North Western Shelf; salient details are briefly reviewed here.

The hydrodynamic model POLCOMS is a three-dimensional baroclinic system described by Holt and James (2001) and Proctor and James (1996). It is a primitive equation finite difference model; solving for velocity, surface elevation, potential temperature, salinity and turbulent kinetic energy using spherical polar coordinates in the horizontal and *s*-coordinates (Song and Haidvogel, 1994) in the vertical. It employs a sophisticated advection scheme (the “Piecewise Parabolic Method”; James, 1996) to minimize numerical diffusion and ensure the preservation of features even on coarse grids under oscillatory flows. Turbulent viscosities and diffusivities are calculated using a Mellor–Yamada level 2.5 turbulence closure, but with an algebraically specified mixing length. The model is applied to the Northwest European shelf on an approximately 7 km grid

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with 18 *s*-levels giving a vertical resolution between 0.5 and 15 m depending on water depth. Holt et al. (2005) describes the detailed evaluation of the model against observations concluding that the model, with some exceptions, generally accurately describes the spatial and temporal variability in dynamic features of the region.

ERSEM is a complex functional type ecosystem model describing carbon and nutrient flows through both pelagic and benthic lower trophic ecosystems (Blackford et al., 2004; Baretta et al., 1995). However the ERSEM model dynamics do not impact on the results presented here as there is no feedback between the altered CO_2, pH and the ecosystem processes included in the model at this stage (see Section 3).

HALTAFALL (Ingri et al., 1967) is an iterative chemical speciation model which, as applied here, uses calculated dissolved inorganic carbon (DIC, the sum of the chemical species resulting when CO_2 dissolves in water) and parameterized total alkalinity (TA) to derive pH and the partial pressure of CO_2 in the water. The latter is required to drive the air–sea flux calculation of CO_2 which uses the parameterization of Nightingale et al. (2000). Sensitivity to air–sea flux parameterizations is discussed below. The model is forced by an assumed invariant atmospheric CO_2 concentration of 375 ppm, riverine DIC inputs derived from Pätsch and Lenhart (2004) and Thomas et al. (2005) and an assumption of zero flux divergence for DIC at the lateral boundaries.

We choose to investigate three modes of CO_2 release, relating to the possible mechanisms of leakage. Parameterising the rate and duration of a leak event is obviously speculative; apart from the stochastic nature of such an event there is little information available to guide us towards realistic scenarios. We use two sources to guide our choice of leak scenario. Klusman (2003a, b) reports preliminary estimates of seepage from a terrestrial EOR – sequestration project in Colorado, USA of <3800 tonnes $CO_2\,a^{-1}$ over an area of 78 km^2 with ^{14}C measurements indicating rates of <170 tonnes $CO_2\,a^{-1}$. These estimates equate to 0.14–3.0 $mmol\,m^{-2}\,d^{-1}$ which are the unit relevant to the model system. The Colorado site has accepted 23×10^6 tonnes of CO_2 since 1986. Secondly, we use the typical capacity of the pipelines used to deliver CO_2 to well systems, 100–250 mscfd (million standard cubic feet per day). This equates to $1.34–3.15 \times 10^{11}\,mmol\,d^{-1}$ or $1.60 \times 10^3–3.75 \times 10^3$ tonnes $C\,d^{-1}$.

An important consideration, principally relating to fast-rate leak events is the behaviour of the resulting high pressure CO_2 plume; it's rate of travel to the sea surface and the balance between direct gassing to the atmosphere and solution in the water column. There is evidence from natural shallow (<20 m) high pressure gas seeps that the majority of CO_2 in bubble plumes can transfer to the water column (Leifer et al., 2006). Hence we assume for simplicity all CO_2 from a leak is dissolved. For low pressure seepages we assume all gas is dissolved in the bottom layer, for high pressure leaks we assume an equal distribution of CO_2 input through out the water column.

Consequently, and after some sensitivity analysis we elected to report on the following scenarios, summarised in Table 1.

i Long-term diffuse seepage: We assume a constant low level seepage of CO_2, spread homogeneously across the area of one model box (49 km^2), representing a movement of CO_2 through permeable geological formations. We employ two seepage rates, $3.85 \times 10^0\,mmol\,m^{-2}\,d^{-1}$ similar to the upper end of the Colorado observations (Klusman, 2003a, 2003b) and a ×100 treatment of $3.85 \times 10^2\,mmol\,m^{-2}\,d^{-1}$, giving a total input over one year of 3.02×10^3 and 3.02×10^5 tonnes CO_2, respectively.

ii Short-term leak: Analogous to a fracture in a pipeline that persists for one day. We use two inputs, 6.93×10^3 and $6.93 \times 10^4\,mmol\,m^{-2}\,d^{-1}$ giving total inputs of 1.49×10^4 and 1.49×10^5 tonnes CO_2, respectively, about 5 and 50 times a typical pipeline capacity.

iii Long-term leak: Analogous to say, an immitigable fault in the well casing, we assume a catastrophic out-gassing of $6.93 \times 10^3\,mmol\,m^{-2}\,d^{-1}$ or 5.43×10^6 tonnes CO_2 over one year, five times the input rate at Sleipner, or 5 years worth of sequestered CO_2.

Our final assumption is that the point source leaks (ii and iii) disperse instantaneously into a single 7 × 7 km model box. Clearly this is a weakness although the tidally driven horizontal mixing processes in the region are strong (Holt et al., 2001) and would be capable of achieving this mixing within a few days.

All modes of release were simulated at two sites, North (57.75N, 1.00E), approximating to the Forties oil field – and South (54N, 1E), representative of the Viking group of oilfields. The former site is characterised by a water column depth of 138 m which is strongly stratified during the summer. The latter site has a depth of 28.5 m and is generally mixed throughout the year. The short-term leaks (ii) were simulated at four times during the seasonal cycle on Julian days 11, 101, 191 and 281, respectively, 11th January, 10th April, 8th July and 8th October.

The scenarios used a four year spin-up simulation with annually repeating forcing conditions (weather and boundary forcing and atmospheric CO_2 values fixed at 375 ppm approximating the

Table 1
Simulated scenarios

Scenario	Site	Input duration days	Depth (m)	Input concentration ($mmol\,m^{-3}\,d^{-1}$)	Daily input per metre square			Daily input to model environment		Total input	
					CO_2 ($mmol\,m^{-2}\,d^{-1}$)	Carbon ($g\,m^{-2}\,d^{-1}$)	CO_2 ($g\,m^{-2}\,d^{-1}$)	Carbon (tonnes $box^{-1}\,d^{-1}$)	CO_2 (tonnes $box^{-1}\,d^{-1}$)	Carbon (tonnes)	CO_2 (tonnes)
Seepage-low	North	365	7.7	0.5×10^0	3.85×10^0	4.60×10^{-2}	1.68×10^{-1}	2.25×10^0	8.23×10^0	8.23×10^2	3.02×10^3
	South	365	1.6	2.42×10^0							
Seepage-high	North	365	7.7	5.0×10^1	3.85×10^2	4.60×10^0	1.68×10^1	2.25×10^2	8.23×10^2	8.23×10^4	3.02×10^5
	South	365	1.6	2.42×10^2							
Short-term leak-low	North	1	138.0	5.0×10^1	6.93×10^3	8.28×10^1	3.04×10^2	4.06×10^3	1.49×10^4	4.06×10^3	1.49×10^4
	South	1	28.5	2.42×10^2							
Short-term leak-high	North	1	138.0	5.0×10^2	6.93×10^4	8.28×10^2	3.04×10^3	4.06×10^3	1.49×10^5	4.06×10^4	1.49×10^5
	South	1	28.5	2.42×10^3							
Long-term leak	North	365	138.0	5.0×10^1	6.93×10^3	8.28×10^1	3.04×10^2	4.06×10^2	1.49×10^4	1.48×10^6	5.43×10^6
	South	365	28.5	2.42×10^2							

Columns as follows: (3) the duration of the simulated input; (4) the water column depth receiving the added CO_2 (for the seepage simulations the specified depths represent the bottom layer of the model); (5) the input concentration per cubic metre; (6–8) the daily input per metre squared (column 4 multiplied by column 5); (9 and 10) the daily input to the model environment (columns 7 and 8 multiplied by the area of input, $49.0 \times 10^6\,m^2$); (11 and 12) the total input to the simulation (columns 9 and 10 multiplied by the input duration in column 3).