

## Ocean release of fossil fuel CO<sub>2</sub>: A case study

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**Abstract.** The natural ocean uptake of the greenhouse gas CO<sub>2</sub> can be accelerated by collecting and liquefying the gas from point sources, and by pumping it into the ocean at appropriate locations and at sufficient depths. Results from a numerical modelling system indicate that injection sites located at about 1,000 m depth in the eastern Norwegian Sea lead to efficient and long term sequestration in the abyss Atlantic. For a release rate corresponding to the CO<sub>2</sub> emissions from a 220 MW gas power plant, it is found that the volume of the near-source water with a pH-reduction  $\geq 0.1$  is  $\sim 0.5$  km<sup>3</sup>. These findings, together with available technology and feasible economics, indicate that the Norwegian Sea represents a possible location for large scale demonstration of operational ocean release of CO<sub>2</sub>.

Steadily increasing demands for energy caused by a growing human population and an increasing standard of living have motivated multidisciplinary research on possible CO<sub>2</sub> mitigation strategies [Eliasson *et al.*, 1999]. Of the different strategies, injection of CO<sub>2</sub> into continental reservoirs or in the ocean have been identified as possible large scale options [Marchetti, 1977; Herzog *et al.*, 1991; Haugan and Drange, 1992; Eliasson *et al.*, 1999; Broecker, 1997]. This paper addresses the latter option.

The world ocean waters and calcareous ocean sediments are able to absorb all but a few per cent of the carbon stored in the known, recoverable fossil fuel reservoirs [Broecker and Peng, 1982]. The huge chemical absorption capacity of the marine environment is, however, rate limited by the slow ( $\sim 1,000$  years) physical mixing time between the ocean surface and sub-surface to bottom waters [Broecker and Peng, 1982]. Purposeful ocean storage of CO<sub>2</sub> can therefore be viewed as acceleration of a natural process [Marchetti, 1977]. Irrespective of mitigation strategy, the option is only successful if the major part of the released CO<sub>2</sub> remains away from the atmosphere for centuries or more, if negative effects on the environment are negligible, if the energy requirements are small, and if the option is technically robust and economically feasible.

Oil and gas fields are known, or are likely to be found, on the shelf and along the continental slope along the north European continent. Some of these fields are located in vicinity of the particularly dense intermediate and bottom waters of the Nordic Seas [Hansen and Østerhus, 2000]. Here we use a numerical model system to perform a case study of the behaviour of CO<sub>2</sub> released at Haltenbanken, a continental

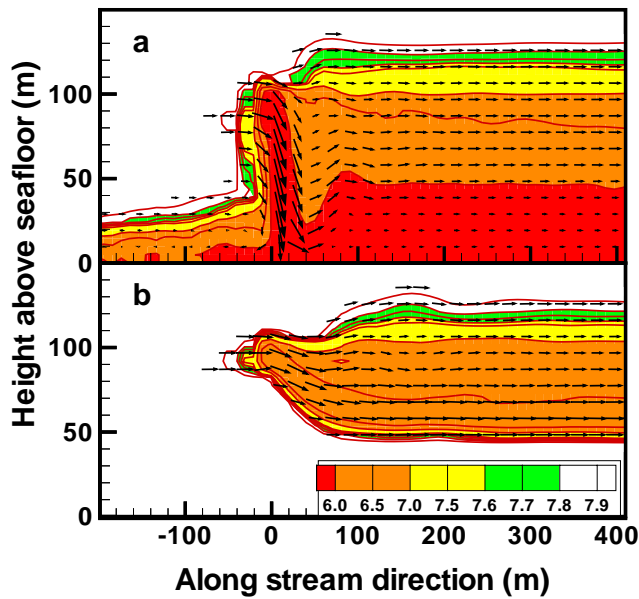
shelf region located off the coast of Norway at 65°N (see Fig. 3). The CO<sub>2</sub> source can be deep water installations on the shelf or point sources on land [Eliasson *et al.*, 1999; Broecker, 1997]. In both cases liquid CO<sub>2</sub> can be piped or shipped to the release site.

The numerical model system consists of the four interfaced components (with resolved horizontal scales indicated): A near-source plume model ( $<10$  m) [Liro *et al.*, 1992; Drange *et al.*, 1998], a local 3-dimensional large eddy simulation (LES) code ( $<1$  km) [Thorkildsen and Alendal, 1997], an intermediate scale 3-dimensional Eulerian advection-diffusion model ( $\sim 10$  km), and a basin scale ocean general circulation model (OGCM; 100-1,000 km) [Bleck *et al.*, 1992]. Annual sequestration rates considered here are 200, 400 and 800 Gg-CO<sub>2</sub>, corresponding to CO<sub>2</sub> emissions from conventional 55-220 MW gas power plants. Release depths range from 350 to 950 m, and it is assumed that the plant is operative for 10 years. The system is run with results from the smaller scale model as input (initialization and source terms) to the next level in the model hierarchy.

Since liquid and gaseous CO<sub>2</sub> are less dense than ambient sea water at the depths considered here [Liro *et al.*, 1992], rising CO<sub>2</sub> bubble or droplet (hereafter particle) clouds will be formed at the outlet nozzle [Herzog *et al.*, 1991; Haugan and Drange, 1992; Liro *et al.*, 1992]. During the ascent, the large CO<sub>2</sub> concentration difference between the surface of the particles and ambient water forces the particles to dissolve [Calderbank *et al.*, 1970]. The dissolution kinetics and near field dynamics of the ascending particles and the subsequent peeling of the dense, CO<sub>2</sub>-enriched plume water have been simulated by extending the dissolution model of Haugan and Drange [1992] to an arbitrary number of particles, coupled to a buoyancy driven plume model [McDougall, 1978; Lemckert and Imberger, 1993] consisting of conservation equations for mass, heat, salt, total dissolved inorganic carbon, and momentum.

For the injection rates and ocean depths given above, it is found that the plume will rise at most 100 m if the initial particle size is 4 mm or less, and that a typical radial distance of the plume is 5 m. In these calculations, possible formation of CO<sub>2</sub> hydrate [Brewer *et al.*, 1999] has been neglected. If massive CO<sub>2</sub> hydrate films form on the particles, the dissolution rate will decrease and the rising height increase. If so, smaller particles with a larger surface to volume ratio [Alendal and Drange, 2001] may counteract the reduced dissolution rate, and this can be accomplished by increasing the pressure drop over the nozzle [Clift *et al.*, 1978]. Controlled experimental studies with single liquid CO<sub>2</sub> droplets have been carried out [Peltzer *et al.*, 2000; Brewer *et al.*, 1999; Warzinski and Holder, 1999], but the effect of the size of the particles, or of turbulence and jet dynamics on the dissolution rate of a cloud of hydrate covered CO<sub>2</sub> particles, are still unknown. Field experiments, like the planned CO<sub>2</sub>

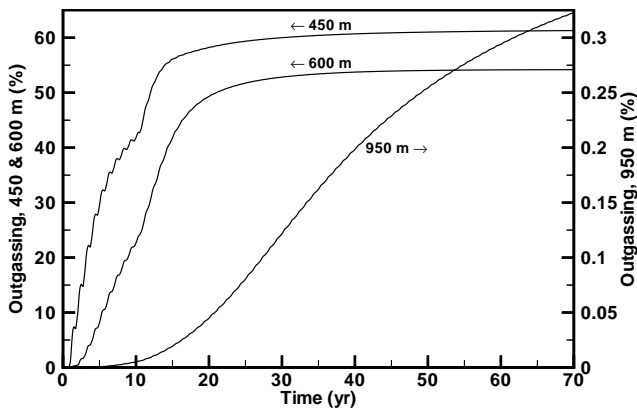
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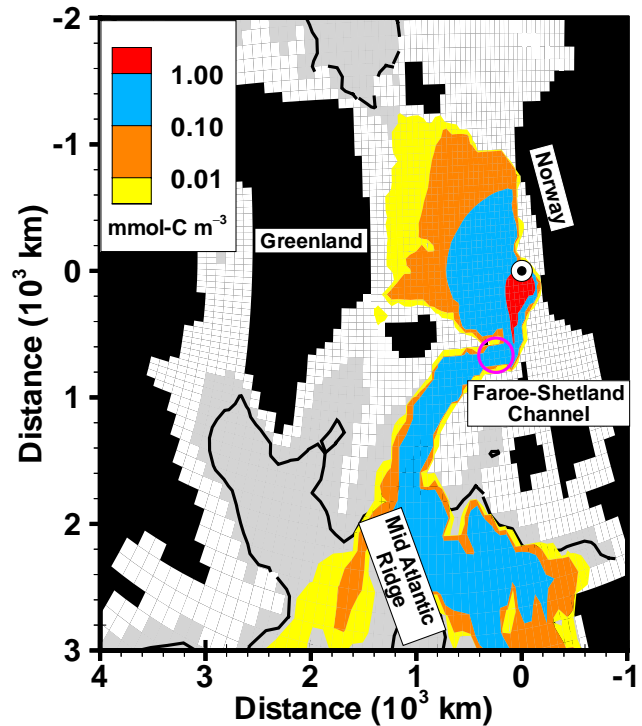
**Figure 1.** *pH*-contour lines and every second velocity vectors simulated by the LES code are displayed for an injection rate of 200 Gg-CO<sub>2</sub> yr<sup>-1</sup>, and with a background current of 0.05 m s<sup>-1</sup> through (a) one port and (b) five ports. The vertical velocity profile, caused by the no-slip boundary condition at the bottom, increases the mixing close to the bottom, hence the upstream transport. The *pH*-value has been computed with *pH*-value of the ambient water  $\sim 7.98$ . The model consist of a 640m (along stream), 320m (span-wise) and 150m (vertical) grid with an uniform 10 m resolution.

sequestration experiment off Hawaii in autumn 2001 (see <http://www.co2experiment.org>), are required to clarify the effect of hydrate on the dissolution kinetics.

The CO<sub>2</sub>-enriched plume water is dense due to the order of magnitude increase in the concentration of dissolved CO<sub>2</sub> in the water [Haugan and Drange, 1992]. Therefore, once CO<sub>2</sub> is dissolved, the plume water tends to sink in the water column, or to spread out on the ocean floor with potential impact on benthic organisms. To simulate this stage, the LES code has been forced with CO<sub>2</sub> concentra-



**Figure 2.** Outgassing for a 10 years CO<sub>2</sub> source located on the continental slope off Haltenbanken at depths of 350 and 600 m (left y-axis) and 950 m (right y-axis). Release rate is 800 Gg-CO<sub>2</sub> yr<sup>-1</sup>, and outgassing is relative to the accumulated amount of injected carbon.



**Figure 3.** Horizontal distribution of the most heavily exposed water masses at the end of year 10 for the 800 Gg-CO<sub>2</sub> yr<sup>-1</sup> case. The contouring give concentration of total dissolved inorganic carbon in mmol-C m<sup>-3</sup> (background concentration is  $\sim 2$  mol-C m<sup>-3</sup>). Maximum concentration at the injection site is  $\sim 2.3$  mmol-C m<sup>-3</sup>. Grey mask (black line) indicates the 2,000 m (3,000 m) depth horizon, and the axes show the geographical distance from the Haltenbanken site (filled circle). The purple circle indicates the location of the Faroe-Shetland Channel. For the OGCM, the horizontal resolution is approx. 50 km in the Nordic seas, there are 23 layers in the vertical, and the diapycnal mixing is set to  $1 \times 10^{-7}/N$ , where  $N$  s<sup>-1</sup> is the Brunt-Väisälä frequency Gargett, [1984]; Ledwell et al. [1993].

tion and buoyancy fields from the plume model. A vertical cross-section through the centre of the CO<sub>2</sub>-enriched water is seen in Fig. 1a in the case of an 200 Gg-CO<sub>2</sub> yr<sup>-1</sup> injection rate. For a constant background current of 0.05 m s<sup>-1</sup>, the dense plume water reaches to the sea floor before the major part of the water is transported in the direction of the background current.

It is well known that the concentration of carbonate (CO<sub>3</sub><sup>2-</sup>) ions decrease, whereas the concentration of dissolved CO<sub>2</sub>, bicarbonate (HCO<sub>3</sub><sup>-</sup>) and hydrogen (H<sup>+</sup>) ions increase as CO<sub>2</sub> is dissolved in sea water [Stumm and Morgan, 1981]. The acidity of CO<sub>2</sub>-enriched sea water, in combination with exposure time, may effect marine life as the major part of marine organisms live in a relatively constant chemical environment. In fact, a lowering of the acidity of sea water with 0.5 *pH*-units may have sub-lethal effects on marine organisms [Auerbach et al., 1997].

In Fig. 1a, water with *pH* < 6 is in contact with the ocean floor. The acidification of the sea floor and of the exposed water masses can be reduced by diverting the injected CO<sub>2</sub> through an array of ports located in the cross-stream direction. If the ports are located 5–10 m apart, the plumes will not interact or only weakly interact, and the density effect and acidification will be reduced (Fig. 1b). The acidification

**Table 1.** Computed reduction in pH from the adv.-diff. model. The volumes are mean values from simulations with a vertical diffusion coefficient of  $5 \times 10^{-5}$  and  $5 \times 10^{-4}$  m<sup>2</sup> s<sup>-1</sup>.

Inject. rate (Gg-CO <sub>2</sub> /yr)	Velocity (m/s)	Reduced pH-Value			
		0.1	0.2	0.5	1.0
		<i>One port</i>			
200	0.02	0.730	0.124	0.013	0.004
	0.05	0.198	0.046	0.004	0.001
	0.10	0.042	0.006	0	0
400	0.05	0.501	0.151	0.020	0.005
	0.10	0.218	0.077	0.009	0.001
800	0.05	0.425	0.153	0.026	0.011
		<i>Five ports</i>			
200	0.02	0.266	0.059	0.004	0.001
	0.05	0.130	0.021	0.001	0
	0.10	0.089	0.014	0.001	0
400	0.05	0.380	0.076	0.006	0.001
	0.10	0.260	0.046	0.003	0
800	0.05	0.551	0.143	0.019	0.004

will also be reduced in the presence of a strong background current. Therefore, injection sites characterised by prevailing current systems are preferable.

As ambient water dilutes the CO<sub>2</sub>-enriched water by mixing, the density difference disappears, and the injected CO<sub>2</sub> follows the ocean dynamics as a passive tracer. This stage has been simulated by the Eulerian advection-diffusion solver. The model is discretized on a 351×101 horizontal grid mesh with 100 m resolution, and on 32 levels in the vertical with 4.8 m resolution. In this model, the horizontal diffusion coefficient is given by the empirical expression  $2.70 \times 10^{-7} t^{1.34}$ , where  $t$  (s) is the time since the carbon release [Okubo, 1971]. Based on the hydrography of the Haltenbanken region, we have estimated the vertical diffusion coefficient to be bracketed by  $5 \times 10^{-5}$  and  $5 \times 10^{-4}$  m<sup>2</sup> s<sup>-1</sup> [Drange et al., 1998].

The obtained volumes and horizontal areas with a drop in the pH-value between 0.1 and 1.0 are given in Table 1 for one and five ports, and for background currents between 0.02 and 0.1 m s<sup>-1</sup>. The environmental impact volume, defined as the volume of water with a reduced pH of >0.1 is  $\sim 0.5$  km<sup>3</sup> for a 800 Gg-CO<sub>2</sub> yr<sup>-1</sup> source. The corresponding horizontal area is  $\sim 18$  km<sup>2</sup>. These figures are scaleable with the injection rate as long as the number of ports are scaled accordingly.

Finally, the basin scale mixing, transport, and subsequent outgassing of the released carbon has been simulated by a North Atlantic-Arctic version of a primitive equation, density-coordinate [Bleck et al., 1992] OGCM. The carbon distribution from the advection-diffusion model has been integrated with a tracer module on-line coupled to the OGCM [Drange, 1996], with a perturbation approach adopted for the computation of the change in the surface water concentration of CO<sub>2</sub> [Joos et al., 1996].

The accumulated outgassing for a 10 years source of 800 Gg-CO<sub>2</sub> yr<sup>-1</sup> is given in Fig. 2. For injection depths between 350 and 600 m, the accumulated outgassing exceeds 50% after 50 years, whereas the outgassing for the 950 m case is less than 0.4% after 70 years (the outgassing figures for

the 200 and 400 Gg-CO<sub>2</sub> yr<sup>-1</sup> cases are similar). Figure 2 clearly indicates that CO<sub>2</sub> should be released at depths greater than 600 m, possibly at depths greater than 800 m, in order to avoid rapid outgassing of the injected CO<sub>2</sub>.

The difference in outgassing is caused by the oceanographic conditions in the region: If CO<sub>2</sub> is released in the upper  $\sim 600$  m of the water column, parts of the carbon is mixed into the surface layer in winter, leading to partly outgassing in the subsequent seasons. This is the reason for the zigzag pattern seen in Fig. 2 for the 350 m and 600 m cases for the first 20 years of the integration.

For the 950 m case, the CO<sub>2</sub>-enriched water remains well below the upper ocean mixed layer throughout the year, yielding almost no outgassing. In fact, the carbon injected at 950 m follows the intermediate water masses in the Norwegian Sea, and the major part flows into the Atlantic Ocean through the Faroe-Shetland Channel [Hansen and Østerhus, 2000], before it enters the northern part of the Atlantic Ocean as bottom water (Fig. 3). The overflow water will take part in the basin to global scale thermohaline circulation [Broecker, 1991] with characteristic time scales of centuries to a millennium. This means that the CO<sub>2</sub>-enriched water masses in the abyss Atlantic will remain isolated from the atmosphere for centuries, at least for the present day ocean circulation regime [Broecker, 1997]. If ocean storage of CO<sub>2</sub> becomes operational, possible changes in the ocean circulation need to be taken into account.

The drop in pH on the spatial scales resolved by the basin scale model and for the given sequestration rates is very small, typically  $10^{-2}$  to  $10^{-4}$  pH units, indicating no biological effects. However, in the case of large release rates and several injection sites, basin scale effects on the marine biota cannot be excluded.

For a 80 km pipeline from e.g. a production installation on Haltenbanken, and for an injection rate of 400 Gg-CO<sub>2</sub> yr<sup>-1</sup>, the cost of investment and operation for liquid CO<sub>2</sub> injection, excluding the separation expenses, is expected to be  $\sim \$13$  per tonne CO<sub>2</sub> [Drange et al., 1998]. Presently, the separation expenses for exhaust gas or for CO<sub>2</sub> containing natural gas are more than 2 times higher [Herzog, 1999] than the investment and operation expenses for transport and release of liquid CO<sub>2</sub>. However, new separation techniques are being developed and tested with a potential cost saving of >50% [Herzog, 1999]. This means that the total expenses may become comparable to or even less than the present tax of NOK300 ( $\sim \$32$ ) paid per tonne CO<sub>2</sub> emitted from offshore installations in Norway. Technology for ocean storage of CO<sub>2</sub> at the depths, distances and amounts considered here is commercially available.

Before purposefully ocean release and storage of fossil fuel CO<sub>2</sub> can be made operational, theoretical results like the one presented here require field verifications for both a single source, and for the cumulative effect of many sources, including hydrate formation. Furthermore, it is of utmost importance that environmental issues including direct and indirect effects on the marine biota [Auerbach et al., 1997] and possible dissolution of calcareous sediments [Broecker and Peng, 1982] are assessed. These effects should also be viewed in the light of ongoing and future acidification of the world ocean surface waters [Haugan and Drange, 1996] due to the natural ocean uptake of atmospheric CO<sub>2</sub>. Since ocean storage will complicate quantification of the natural ocean sink of human generated CO<sub>2</sub>, and consequently

the global carbon budget, a global ocean storage monitoring program is needed. Finally, this study represents one realisation of the mean advective spreading and dispersive mixing of CO<sub>2</sub> released off the coast of mid Norway. Small scale variability and unresolved processes in the ocean environment will generate variability on shorter and smaller scales. To examine this behaviour, a high-resolution (eddy-resolving) OGCM, driven by synoptic atmospheric forcing fields, is needed.

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