# Ocean Sequestration of Carbon Dioxide

E. Eric Adams (eeadams@mit.edu; 617-253-6595)
Department of Civil and Environmental Engineering
Massachusetts Institute of Technology
Room 48-325
77 Massachusetts Avenue
Cambridge, MA 02139

Elisabeth M. Drake (edrake@mit.edu; 617-253-5325)
Howard J. Herzog (hjherzog@mit.edu; 617-253-0688)
Energy Laboratory
Room E40-455
Massachusetts Institute of Technology,
Cambridge, MA 02139

## Abstract

The sequestration of $CO_2$ in the deep ocean has been proposed as one way to help mitigate potential global climate change. In the past few years many laboratory and modeling studies have been performed on ocean disposal of $CO_2$ including the assessment of its environmental impact. However, these studies must be validated/complemented with field studies. As a first step in this direction, a pilot scale field experiment will be conducted off the west coast of the big island of Hawaii during the summer of 2000. The focus will be on the various physical-chemical interactions that occur between seawater and $CO_2$ discharged as a buoyant liquid at a depth of about 1000 m. In this paper we discuss key issues involved with the design, ocean engineering, measurements, siting, and costs of this experiment. The project is being conducted the Climate Technology Initiative of the Framework Convention of Climate Change and involves participation and sponsorship from Japan, the US, Norway, Canada, and Switzerland.

## Background and Motivation

### *Introduction*

One potential option to mitigate atmospheric $CO_2$ levels is to capture and sequester power plant $CO_2$. Commercial $CO_2$ capture technology, though expensive, exists today. However, the ability to sequester large quantities of $CO_2$ is uncertain. The deep ocean is one of only a few possible $CO_2$ disposal options (others include depleted oil and gas wells, coal beds, or deep saline aquifers), so it is important that we understand as much as possible about this strategy.

As indicated by recent international conferences on the subject (e.g., Handa and Ohsumi, 1995; Herzog, 1996; Ormerod 1997), much has been learned about ocean $CO_2$ sequestration in the past half-dozen years. Of necessity, however, most of our knowledge has resulted from theoretical or laboratory studies. As we learn more, these studies must be validated and complemented with field studies.

In December 1997 an agreement was signed authorizing the first step in this direction: an international, pilot scale, field experiment scheduled to take place off of Hawaii during the summer of the year 2000. The agreement was signed by Japan, Norway and the US under the auspices of the Climate Technology Initiative; Canada and Switzerland have recently joined as sponsors.

The objectives of this field experiment are to learn more about the physical-chemical process which occur between seawater and $CO_2$ discharged as a buoyant liquid at ocean depths of order 1000 m. We see this as the first step in a progression of field experiments which will ultimately lead to a full scale field test. Participants from the four countries are currently planning this experiment. In this paper we outline our plans based on initial scoping and site selection reports (Adams and Herzog, 1997, 1998).

### *Choice of disposal options*

Five major ocean disposal options have been considered to-date (Herzog *et al.*, 1996):

- dry ice released at the ocean surface from a ship.
- liquid $CO_2$ injected at a depth of about 1000 m from a pipe towed by a moving ship and forming a rising droplet plume.
- liquid $CO_2$ injected at a depth of about 1000 m from a manifold lying on the ocean bottom and forming a rising droplet plume.
- a dense $CO_2$-seawater mixture created at a depth of between 500 and 1000 m forming a sinking bottom gravity current.
- liquid $CO_2$ introduced to a sea floor depression forming a stable "deep lake" at a depth of about 4000 m.

Considering issues of required development time, cost, environmental impact, and sequestration efficiency (avoidance of $CO_2$ leakage back to the atmosphere), a consensus is developing that the best ocean disposal options, at least initially, are the discharge of $CO_2$ as a buoyant liquid at a depth of 1000 m or greater, either through a pipe towed from a moving ship or from a bottom mounted pipe. Note that, although the means of delivery would be quite different (i.e., ship vs. pipe), the plumes resulting from the two options would be quite similar.

### *Types of field experiments*

Although our collective understanding of the behavior of these two options exceeds that of the other options, there are still some technical uncertainties which should be studied in the field. Ultimately, we envision a series of three types of field experiments at which these uncertainties are studied at increasing larger scales. This paper focuses on the first type of experiment designed to test technical feasibility.

- ***Pilot scale tests of technical feasibility.*** The first type of experiment tests the technical feasibility of disposing of liquid $CO_2$ by focusing on the various physical-chemical interactions that occur between seawater and $CO_2$. A number of tests will be performed at an open ocean site, over a relatively short duration (one month), and at a significantly reduced scale (e.g., with a $CO_2$ loading of 0.1 to 1 kg/s.

- ***Longer term tests of environmental impact.*** The second type of experiment would focus on environmental impacts--both acute and chronic, including those expected in the water column and the seafloor--associated with the $CO_2$ discharge. In order to constrain the spatial dimensions of the experiment, tests could be conducted in a semi-enclosed body such as a fjord, as long as the hydrographic conditions were sufficiently similar to those of potential open ocean sites. However, the tests would need to be conducted over a sufficient time frame to be consistent with the lifetimes of impacted organisms (e.g., at least a year for many pelagic species). Extensive measurements would need to be taken before and after the release, as well as during the $CO_2$ release, in order to assess both change and recovery.
- ***Full scale tests.*** Before $CO_2$ ocean disposal can be accepted as a commercial technology, field tests will need to be conducted at full scale. Because of the substantial costs involved in producing large quantities of $CO_2$, a logical step in this direction would be to conduct an open ocean experiment using a "free" source of $CO_2$. Possible sites include the North Sea of the Gulf of Mexico where $CO_2$ produced with natural gas is routinely vented to the atmosphere.

## Experimental Objectives

The major objectives of our pilot scale field experiment are to:

- better understand the physical-chemical processes affecting the transport and fate of $CO_2$ released as buoyant liquid droplets at water depths of order 1000 m.
- provide proof of concept.
- allow development and validation of near field models of transport and fate, which in turn could be used to more reliably predict environmental impact.
- help establish $CO_2$ delivery techniques and field monitoring methodologies that will help in future experiments.

The physical-chemical interactions which need study are described below as a function of the scale of interaction. See also Figure 1.

### ***$CO_2$ injection and droplet formation***

The $CO_2$ will be injected through one or more nozzles and will form droplets upon its release. Important issues for nozzle design are the distribution of droplet sizes, interactions among droplets near the nozzle (e.g., aggregation/breakup), and the possibility of hydrate clogging at the nozzle. These characteristics will clearly be functions of the nozzle design and, in particular, whether the design results in a jetting or atomization mode of droplet formation. Laboratory research on this topic is underway at the $CO_2$ Ocean Disposal Simulator (CODS) at the Hawaii Natural Energy Institute, but must be supplemented by field observations to provide proof of concept.

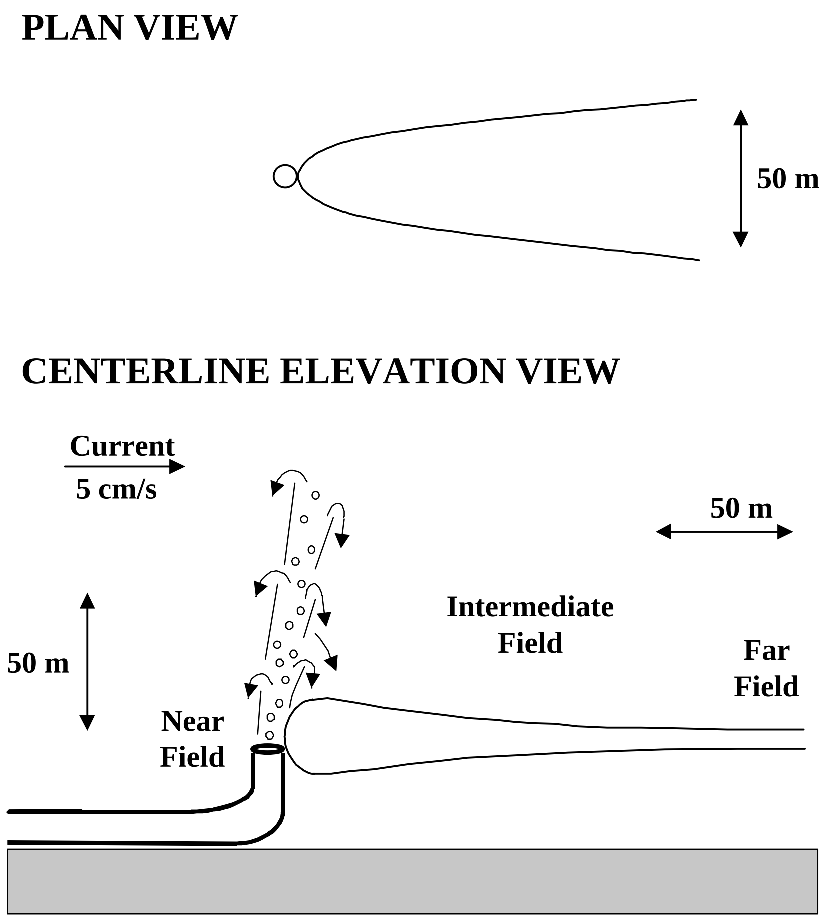


**Figure 1:** Views of a $CO_2$ plume from a pilot scale release using modeling approach of Caulfield *et al*. (1997b). The modeling assumes a concentrated release of $CO_2$ at a rate of 1 kg/s from a single jet at a depth of about 1000 m in a stratified ambient ocean with uniform current speed of 5 cm/s. The initial droplet radius is 0.7 cm, and no account has been taken of reduced mass transfer due to possible hydrate formation. The near field, intermediate field, and far field regions proposed for experimental study are identified in the Centerline Elevation view.

### *Droplet dynamics*

Perhaps the most important technical uncertainty with the droplet plume option is whether or not hydrates will form on the rising droplets of a turbulent droplet plume. Hydrate "skins" will affect the rate of $CO_2$ dissolution and droplet rise velocity. The combined effects will influence the elevation within the water column at which the $CO_2$ ultimately comes to rest, and hence the efficiency of sequestration. Some experimental work on hydrate formation for individual, stationary, droplets in a moving flow field has been conducted recently (e.g., Hirai *et al.*, 1996), and further laboratory experiments are planned for the CODS facility, but conditions may be different for a collection of free droplets in a highly turbulent plume. Field measurements to test the influence of hydrate formation will include direct observations of liquid $CO_2$ droplets at different elevations within the plume, and indirect measurements based on the vertical extent of pH perturbations and the concentration of tracers (e.g., fluorescent dye) injected with the $CO_2$.

### *Droplet/plume interaction*

The behavior of a droplet plume in a stratified ambient is complicated by the fact that the core of the plume is positively buoyant, while the edge is negatively buoyant because the plume has entrained ambient water from lower depths and because a solution of $CO_2$ in seawater is denser than ambient water. The heavier solution tends to peel off as the plume rises. The location and magnitude of the peeling affects the ultimate level and thickness of the $CO_2$ plume. This effect needs rigorous study, especially in the presence of ambient currents. The level and thickness of the $CO_2$ plume are of primary importance in determining whether or not the plume will impact the bottom (Caulfield *et al.,* 1997b). Some understanding can be gleaned from experiments conducted in atmospheric pressure tanks (e.g., using air bubbles in salinity-stratified tanks), but a more complete confirmation requires field testing where the physical-chemical properties of $CO_2$ can be simulated at realistic pressures. Field tests will consist of observations of the plume flow field using video cameras, as well as 3-D velocity measurements. Additional measurements may be taken inside and outside the plume of other properties such as pH and the concentration of injected tracers (e.g., fluorescent dye).

### *Intrusion dynamics*

Once $CO_2$-enriched water peels from the plume, it will sink while intruding into the stratified ocean. Because of ambient density stratification, the $CO_2$-enriched seawater collapses vertically and spreads horizontally as it is advected by ocean currents. The intrusion is complicated by multiple peelings from the same plume, and multiple plumes from a multi-port injection. Theoretical and experimental data are available to describe gravitational intrusion under idealized conditions (e.g., mass injected at a point in a linearly stratified, or a two-layer ambient; Akar and Jirka, 1994, 1995) but field validation is necessary. Properties to be measured include the width and thickness of the intrusion layer as a function of distance from the injection. These properties will be determined by measuring pH and the concentration of an injected tracer. Vertical profiles of velocity at various positions will also help establish the lateral extent of the intruded plume.

### *Ambient diffusion*

At some distance from the point of injection, gravitational spreading will effectively cease, but the $CO_2$-enriched seawater will continue to spread due to passive ocean turbulence. Although much slower than plume-induced mixing near the point of injection, ambient diffusion is important for diluting plume contaminants and hence determining the distances required for plume concentrations and pH to return to background levels. Indeed our model sensitivity studies suggest that ambient diffusion is one of the most important variables affecting the mortality of zooplankton passing through a $CO_2$-enriched plume (Auerbach *et al.*, 1997, Caulfield *et al.*, 1997a; Adams *et al* 1997.).

Many field experiments have been conducted to measure horizontal and vertical diffusion in near surface waters (e.g., Okubo, 1971) but fewer data are available to describe such mixing at greater depths. Of particular importance would be measurements near the sea floor, where ambient turbulence (particularly in the vertical) may be considerably enhanced due to the proximity of the bottom boundary layer (Thorpe, *et al*. 1990). Several recent experiments with $SF_6$ have shown an influence of boundary mixing (Ledwell and Hickey, 1995; Ledwell and Bratkovich, 1995), and a recent near bottom tracer experiment relating directly to the "deep lake" $CO_2$ injection scenario has shown enhanced vertical mixing in very deep waters off the coast of Japan (T. Ohsumi, CRIEPI, personal communication). However, additional measurements conducted near the bottom of the thermocline relating more closely to the droplet plume and towed pipe scenarios would be helpful.

## Experimental Design

Below we discuss some of the issues concerning our pilot scale field experiment.

### *Scale of the experiment*

The scale of the experiment refers to the duration of tests and the magnitude of the $CO_2$ loading. We envision a series of 10-20 tests, each lasting from several hours to a day, performed over a period of several weeks. In addition, one or more tracer tests of longer duration are proposed.

The $CO_2$ loading should be sufficient for full scale simulation of a single nozzle and, as such, $CO_2$ loadings in the range of 0.1 to 1.0 kg/s are contemplated. The loading from a 500 $MW_e$ coal-fired power plant is about 130 kg/s (Herzog *et al*., 1996), so these tests will simulation the behavior from one nozzle out of an array of 100 to 1000 nozzles serving a large power plant.

$CO_2$ will be released from sufficient depth that liquid $CO_2$ droplets will dissolve before they reach an elevation where they flash into vapor (approximately 500 m). To allow for the study of relatively large droplets with possible hydrate skins, a discharge depth of 700-1000 m is envisioned. It is desirable to discharge the $CO_2$ from at least two elevations above the ocean floor in order to observe the influence of the bottom boundary layer on plume transport and mixing.

While the $CO_2$ injection, droplet formation, and droplet dynamics will be simulated at full scale, processes at the remaining three scales (droplet/plume interaction, intrusion dynamics and ambient diffusion) will clearly be reduced in scale. The choice of scale (i.e., $CO_2$ loading) reflects a trade-off between measurement resolution (i.e., the ability to detect the $CO_2$ at various distances from the injection) and the cost of supplying $CO_2$. The cost of $CO_2$, including transportation and storage, could be as high as $500 per tonne. At a loading of 1 kg/s, ten experiments, each lasting eight hours, would require about 300 tonnes of $CO_2$.

### *$CO_2$ Delivery*

We considered the following options for discharging $CO_2$ at a depth of 1000 m.

- from a pipe constructed along the ocean bottom.
- from a vertical pipe attached to an oil platform.
- from a pipe towed by a ship or barge.
- from a submerged tank.

After due consideration a bottom pipeline was selected. This was considered the easiest option because the $CO_2$ would be handled on shore, and any troubleshooting of the delivery system could be conducted before the start of an experiment, minimizing interruptions to researchers and research vessels on site. In addition, the pipe will be semi-permanent, allowing follow-on tests to be conducted if desired. Cables harnessed to the pipe will bring electricity to the terminus, and allow monitoring of the plume from shore.

The distance from shore to the pipe terminus at the Hawaiian site is about 3 km. (The exact terminus has not yet been identified.) A pipe designed to deliver $CO_2$ at a rate of 1 kg/s over this distance requires a diameter of about 3 cm and, in order to avoid phase changes, must withstand pressures as high as 170 bar. Steel pipe of the appropriate strength and flexibility is available commercially in lengths up to 10 km, coiled on large diameter reels. The typical cost of such a pipe is about $10,000 per km, but the larger cost comes in pipe deployment which requires the support of a pipe laying ship or barge and possibly a submersible to help anchor the pipe, attach risers, etc. Traditional pipe laying involves attaching straight pipe sections, but because of the small pipe diameter, the coiled pipe will simply be unreeled. We are currently comparing the various options which include:

- reel fixed on shore; vessel moves offshore,
- reel fixed on vessel; vessel moves offshore,
- reel fixed on vessel; vessel moves onshore.

In order to test the performance of different nozzles, and the effect of discharge at different heights above the bottom boundary layer, a riser system will be attached to the end of the pipe. A manifold will allow the nozzles to branch from the riser and be controlled remotely by solenoid valves. Anti-back flow valves installed near the nozzles and an "electric blanket" will be included to prevent seawater from intruding into the risers and potentially clogging the pipe with hydrates.

***Measurements***

Below we subdivide our experiments on technical feasibility into three sub-sets encompassing the near, intermediate and far fields. See Figure 1 for approximate dimensions for a pilot scale experiment. While these experiments address the objectives of a "first experiment", we remain open to participation by other researchers who may avail themselves of the basic set-up to perform complementary studies.

- ***Near field experiments*** would be designed to test nozzle designs and observe droplet behavior. Observations will be made with a system of lights and tilt/pan video camera mounted on the seafloor near the diffuser section.
- ***Intermediate field tests*** will study droplet/plume interaction and intrusion dynamics at distances of order 100 m downstream from the discharge point. Measurements will include three-dimensional distributions of salinity, temperature, concentrations of fluorescent dye, velocity and pH. The principal measurement platform will be a remotely operated vehicle (ROV) which can maneuver precisely along a three-dimensional survey path. We will also collect discrete water samples which will be analyzed for carbon chemistry aboard a supporting research vessel. Vertical arrays of pH sensors and an acoustic doppler current profiler will document ambient conditions.
- Although currently beyond the budgetary limits of our study, we hope to conduct ***far field experiments*** to measure ambient diffusivity. For the range of experimental release rates being considered, excess $CO_2$ concentrations, and hence perturbations in pH, will be too small to detect after several days. Hence an artificial tracer, such as fluorescein or $SF_6$, would be injected. The former is a fluorescent tracer, which is relatively easy to measure

*in situ*, while the latter affords greater measurement sensitivity, but must be analyzed from discrete samples brought aboard ship.

## Site Selection

A number of factors were considered in selecting a site. The four most important were:

- ***Proximity to deep water***. The site needs to be in relatively deep water in order to minimize the costs of transporting $CO_2$ from shore.
- ***Representing hydrography***. The vertical profile of temperature and density gradient should be representative of ocean sites where a “real” $CO_2$ injection might someday occur.
- ***Shoreline support facilities***. The site should have the infrastructure to handle large $CO_2$ tanks, be near transportation facilities for emergency supplies, be able to house researchers, support the experiment with trained personnel, etc.
- ***Licensing considerations***. Although the environmental impacts of an initial $CO_2$ experiment will be minimal, permission to conduct the experiment must be obtained from appropriate jurisdictions.

We reviewed several sites adjacent to deep water which have been considered previously in connection with Ocean Thermal Energy Conversion (OTEC) plants (e.g., Frye *et al*., 1981). These sites, and the approximate distance from shore to water of a depth of 1000 m, included: the Kona coast of the big island of Hawaii (3 km); Punta Tuna in southeastern Puerto Rico (4 km), the north shore of St. Croix, US Virgin Islands (3 km), the west coast of Mexico (5 km), the west coast of Luzon, Philippine Islands (6 km) and Guam (7 km). Waters off the northeast coast of Bermuda were also strongly considered; although 1000 m is not reached until a distance of about 12 km, the Bermuda Biological Station for Research (BBSR) could supply excellent shoreline support. We ultimately chose the Hawaiian site, in large part because of the strong local support from the University of Hawaii, the Natural Energy Laboratory of Hawaii Authority, and the Pacific International Center for High Technology Research.

We also looked into oil rigs in the Gulf of Mexico, some in water depths approaching 1000 m. Some of the shallower rigs are abandoned and are currently being used for marine research. However, oil companies were reluctant to give us permission to share any of the active rigs which were located in deeper water.

Finally, we considered conducting our experiments in a fjord, where water depths tend to drop off rapidly. A survey of Norwegian fjords, compiled by Haugan (1996), indicates that several fjords have sufficient depth. Another advantage of fjords is that they tend to be much calmer than the open ocean. However, these were not pursued in great detail because of the possible delay in obtaining required environmental permits.

## Schedule

Our project began in December 1997 and will formally last for four and half years. A nine-member technical subcommittee comprised of members of the participating countries meets twice a year and reports once a year to a project steering committee representing the project’s sponsors.

Our first task was site selection, which was completed early this year. Background surveying of bathymetry and currents could start as early as late 1998. Design of all measurement systems will be completed in 1999, and the actual experiments will be conducted in the summer of the year 2000.

## Acknowledgement

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## References

Adams, E. and Herzog, H., 1997, "Scoping and site selection study for an ocean $CO_2$ disposal field experiment," MIT Energy Laboratory report, June 1997.

Adams, E. and Herzog, H., 1998, "Site selection study for an ocean $CO_2$ disposal field experiment," MIT Energy Laboratory report, February, 1998.

Adams, E., Caulfield, J., Herzog, H., and Auerbach, D., 1997, "Impacts of reduced pH from ocean $CO_2$ disposal: sensitivity of zooplankton mortality to model parameters". *Waste Management* 17(5/6):375-380.

Akar, P.J. and Jirka, G. H., 1994, "Buoyant spreading processes in pollutant transport and mixing, 1: lateral spreading with ambient advection", *J. Hydraulic Research*, 32(6): 815-831.

Akar, P.J. and Jirka, G.H., 1995, "Buoyant spreading processes in pollutant transport and mixing, 2: upstream spreading in weak ambient current", *J. Hydraulic Research*, 33(1): 87-100.

Auerbach, D., Caulfield, J., Adams, E. and Herzog, H., 1997, "Impacts of ocean $CO_2$ disposal on marine life: I. A toxicological assessment integrating constant-concentration laboratory assay data with variable-concentration field exposure", *Environmental modeling and assessment* 2:333-343.

Caulfield, J , Adams, E., Auerbach, D., and Herzog, H., 1997a, "Impacts of ocean $CO_2$ disposal on marine life: II. Probabilistic plume exposure model used with a time-varying dose-response analysis", *Environmental modeling and assessment* 2:344-353.

Caulfield, J., Auerbach, D., Adams, E., and Herzog, H., 1997b, "Near field impacts of reduced pH from ocean $CO_2$ disposal," *Energy Convers. Mgmt.*, 38S:343-348.

Frye, D., Davison, A., and Leavitt K., 1981, "Physical oceanographic data from the OTEC Punta Tuna, Puerto Rico site, Sept. 1979-June 1980," Report LBL-12327, Lawrence Berkeley Laboratory, Univ. of California.

Handa, N. and Ohsumi, T. (eds), 1995, *Direct ocean disposal of carbon dioxide.* Terrapub, Tokyo.

Haugan, P.M., 1996, "Norwegian fjords as potential sites for $CO_2$ experiments", Technical note, Geophysical Institute, Univ. of Bergen.

Herzog, H. (ed.), 1996, *Proceedings of the 3rd International Conference on Carbon Dioxide Removal*, Cambridge, MA, September, 1996.

Herzog, H., Drake E., and Adams E., 1996, "$CO_2$ capture, reuse and storage technologies for mitigating climate change," White paper prepared for US Dept. of Energy, DE-AF22-96PC01257.

Hirai, S., Okazaki, K., Araki, N., Yazawa, H., Ito H., and Hijikata, K., 1996, "Transport phenomena of liquid $CO_2$ water flow with clathrate-hydrate at the interface," *Energy Convers. Mgmt.*, Vol. 37, pp. 1073-1078.

Ledwell, J.R., and Bratkovich, A., 1995, "A tracer study of mixing in the Santa Cruz Basin," *J. Geophys. Res*., Vol. 100(C10), pp. 20,681-20,704.

Ledwell, J.R. and Hickey, B.M., 1995, "Evidence for enhanced boundary mixing in the Santa Monica Basin," *J. Geophys. Res*., Vol. 100(C10), pp. 20,665-20,679.

Okubo, A., 1971, "Oceanic diffusion diagrams," *Deep-Sea Research*, Vol. 18, pp. 789-802.

Ormerod, B., 1997, "Ocean storage of carbon dioxide" proceedings of four workshops sponsored in 1996 and 1997 by IEA Greenhouse Gas R&D Programme, Cheltenham, UK.

Thorpe, S.A., Hall, P., and White, M., 1990, "The variability of mixing at the continental slope", *Phil. Trans. R. Soc. Lond.* A, Vol. 331 pp. 183-194.