Ocean storage, including costs and risks

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Abstract

The long-term effectiveness of ocean storage will have to be based on theoretical understanding and models as there is no way to perform experiments on the required time and space scales for outgassing estimation. Based on observations of tracer behavior, the ventilation time of deep water has been revealed. Calibrated and constrained by these results, most of the O-GCMs tell us that CO_2 injected into the thermohaline circulation would not come back to the atmosphere in more than several hundred years.

There are two types of concepts of ocean storage: one is a lake type concept to keep the CO_2 at the ocean floor or a depression site as long as possible, and the other is to inject CO_2 into the deep waters so that it is dispersed as quickly as possible. The technological concepts so far for implementation with minimum environmental impacts are much elaborated based on laboratory and computer experiments incorporating the key understanding of the CO_2 clathrate properties attained in this decade.

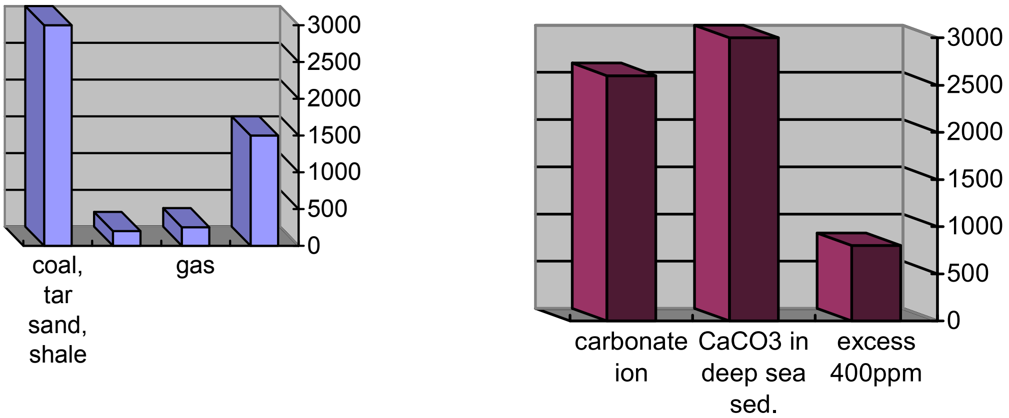
The frequently addressed concern of this technology includes the ecological modification of the ocean system. But even in the business-as-usual release of CO_2 into the atmosphere, some modification might be foreseen in the deep ocean environment and could be inevitable not caused by the climate change but by the direct influence of the increase in the CO_2 concentration in deep waters in future. We cannot stop the CO_2 invasion into the deep ocean due to the existing of the excess CO_2 in the atmosphere. Whichever release method is used, carbon dioxide we are releasing to the atmosphere now will find its way into the deep oceans. Hence, the right scientific question is whether there exist additional risks to the deep-sea environment associated with this technology. If we accept the target of a stabilization level of the atmospheric concentration of CO_2, our generation's commitment to the CO_2 futures anyway extends to the modification of the deep-sea environment induced by the increase in atmospheric CO_2 concentration level.

The environmental impact of the injected CO_2 in near field is manageable, in principle. The field experiment will offer the opportunity to increase and validate our ability to the environmental impact assessment of this technology.

Introduction

In order to understand the future climate for centuries ahead, we need knowledge on CO_2 behavior in the atmosphere, the ocean and the terrestrial biosphere on timescales of years to tens of thousand years. Based on the same knowledge, we can control the CO_2 concentration of the atmosphere by the engineering approach (Marchetti, 1977) for managing the CO_2 emission. The technology of ocean storage of CO_2 offers the means of 'peak-shaving' the time profile of the atmospheric CO_2 concentration before its reaches the long-term equilibrium level (Hoffert et al., 1979). The knowledge of the carbon cycle (Wigley and Schimel, 2000) offers the basis of this future projection of the atmospheric CO_2 concentration.

Figure 1 illustrates the potential carbon sources and sinks compared with the estimates of sizes of the ultimate minable reserve of carbonaceous fossil fuels. With the carbonate alkalinity of seawater to be constant, the increase in CO_2 causes a decrease in $[CO_3^{2-}]$ in seawater. Hence, the bar for the carbonate ion in the Figure shows the primary capacity of the oceanic sink for the purposeful storage of CO_2. The CO_2 ocean storage is thus to be examined in the context of a fossil fuel era (Khesghi, 2002). On the other hand, in the context of CO_2 inventory, one can easily understand that the purposeful injection of CO_2 into the ocean now means a decrease of the future sink capacity of the ocean when a part of the injected CO_2 reached surface waters, in a few centuries later from the present.



The unit is Giga tons Carbon
The last bar shows the amount of extra CO_2 required to raise its content in the atmosphere by 400 ppm.
Source: Broecker (2001)

Figure 1 Potential carbon source and sinks

Compared with the amount of the fossil fuel reserves, the physical ocean capacity is almost infinite, as we will see it later in the discussion on the lake scenario of the storage concept. Figure 2 is an example of the explanation on how large the oceanic capacity is even in the dilution scenario of the ocean injection. The shift of concentration profile of total inorganic carbon contents of the seawater is calculated and added to the observed profiles in the North Pacific and the North Atlantic Oceans, provided that the injected CO_2 is uniformly distributed within the water columns from 1 km depth to 3 km.

The question of when this decrease will be effected or the question on the 'sequestration efficiency' can be examined by the O-GCM model prediction (Orr, 2000). There is little consensus at present particularly about the overall viability of direct injection into the mid-depth range among the efficiency estimation results by three-dimensional ocean models. We infer that the cause of the inconsistency is due to the lack of understanding in ventilation process of the ocean in mid-depth ranges (500-1750m) (Broecker, 2001), or more specifically in the process associated with the Southern Ocean (Mignone et al., 2002).

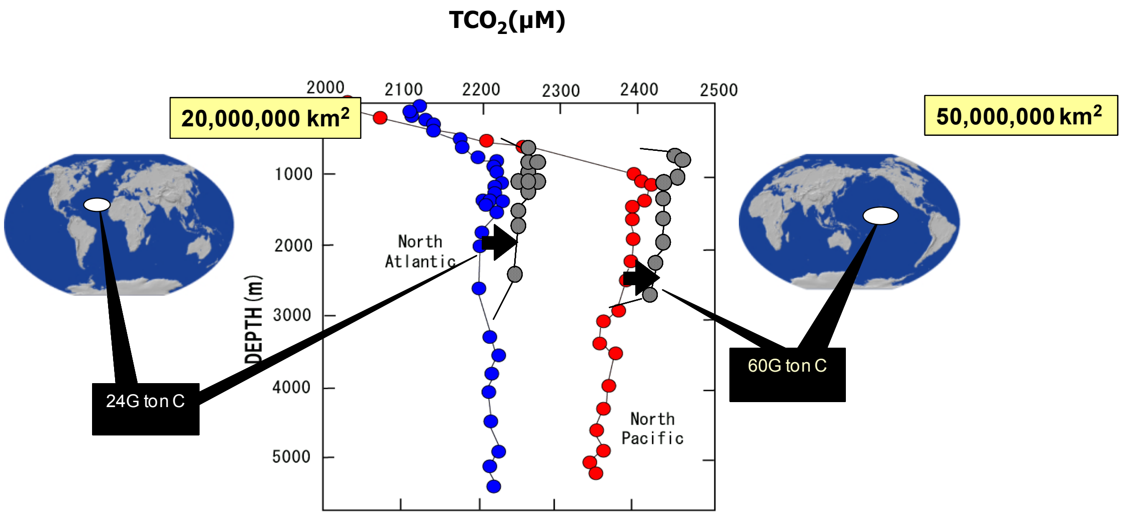


Figure 2 An example of the storage capacity of ocean storage

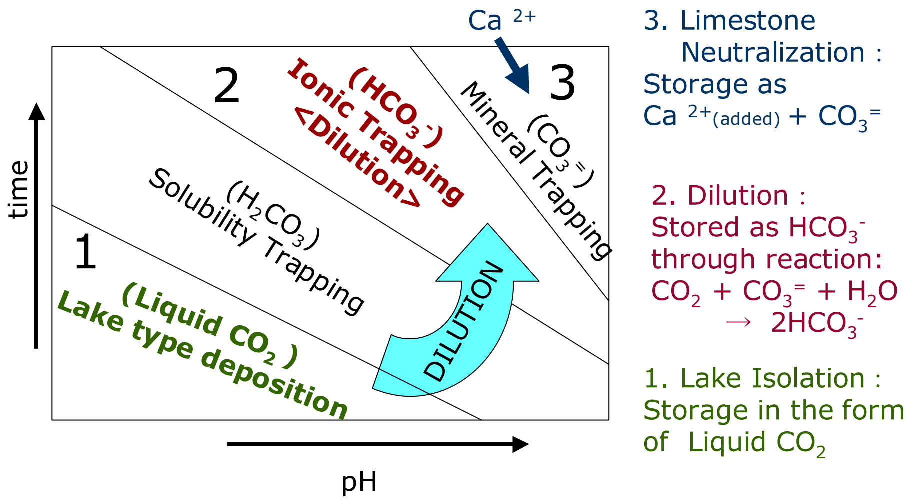


Figure 3. Trapping mechanism of ocean storage schemes as compared with geological options: 1; Lake isolation strategy, 2; Dilution/dispersion strategy, and 3; Neutralization with added limestone

Recently, a third way of ocean storage has been proposed (Caldeira and Rau, 2000). The three types clearly differ in the trapping mechanism of CO_2 in the ocean. As illustrated in Figure 3 for comparison with geological storage options, the pH impact to the ambient environment decreases in this sequence.

Technologies

From the first proposal of this technology (Marchetti, 1977) twenty five years ago to the present day detailed technical examinations, the method of CO_2 injection into the ocean is discussed in both directions: the isolation from water body i.e. typically 'lake scenario' to limit the spatial extent of the impact, and the dispersion/dilution in water body to minimize the degree of impact. For example, the dry-ice (solid CO_2) dropping method which is the simplest but energy intensive and costly implementation of this technology, and was proposed (Steinberg, 1985) and then examined (Nakashiki et al.,1991) in the early days of research work, could be implemented to the either directions by selecting simply the size of dry-ice blocks: a solid CO_2 cube with 3 m inside length would lose half of its initial mass to dissolution at a depth of 3000 m, where the melted liquid CO_2 with the same temperature as of the ambient seawater becomes heavier than the seawater.

Several years ago, a review (Ohsumi, 1995) was made of a wide range of technological studies on the implementation of both concepts of isolation and dispersion. Following this review, there also appear several technological concepts for the implementation of CO_2 ocean storage, most of which eventually aim to minimize the overall environmental impact.

Table 1 Technological Schemes of CO_2 Ocean Storage

Dilution/dispersion strategy:
+ longitudinal dispersion (Ozaki et al., 2001; Tsushima et al., 2002)
+ ascending plume (Crounse et al.,2001; Chen et al., 2001)
+ descending plume (Wannamaker and Adams, 2002; Nihous, 2002)
- by hydrate particles (Takano et al., 2002)
- by droplets containing hydrate (Hirai et al., 1999)
+ isopycnal spreading (Golomb, 2002)
Lake isolation strategy:
+ depositing with vertical short pipe in cooled liquid containing solid (Aya et al., 2002)
Release of calcium and bicarbonate ion to the sea near to the emission site of flue gas (capture and storage combined) (Caldeira and Rau, 2000)

Besides the direct injection of liquid CO_2 or its hydrate to the ocean interior, the novel concept, i.e. the last item in the listing of the Table, was proposed recently to the ocean sequestration strategy; the release of bicarbonate ion resulted by the limestone/water/flue gas reaction at the emission site. Since the neutralization of the CO_2 with calcium carbonate is the geochemical consequence in the ocean environment in time scales of several tens thousand years, the essential feature of this proposal is to avoid the decrease in the oceanic sink that is expected a few centuries after injection.

As seen in the above table summarizing these proposals, a part of this progress is backed by the continued laboratory works or the computer experiments. The research using remotely operated vehicles (ROVs) or submersibles (Shitashima, 1997; Brewer et al., 2002) is also very fruitful, because all the conditions we encounter in deep sea are neither fully understood nor simulated in land-based experiments. Even laser Raman spectroscopy is being used in situ (Brewer et al.,2002).

Lake scenario

The main advantage of 'lake scenario' over the dilution scheme is an additional retardation of CO_2 to reach the surface. The performance (i.e., leakage rate) estimate of the lake-type deposition of CO_2 onto the ocean floor and the topics of CO_2 hydrate properties in relevance to this concept were covered in the previous review paper (Ohsumi, 1995). The recent model study (Fer and Haugan, 2002) shows that the leakage rate of CO_2 as solute into the ambient bottom waters is equivalent to 0.1 m/y expressed as the surface retreat rate of the liquid CO_2 lake, which is one order of magnitude larger than the figure the former estimate (Ohsumi, 1995). As seen in the study on the 'lake type scenario' (Nakashiki, 1997), more research on the actual ocean floor flow regime is needed to estimate the dissolution of such a pool of liquid CO_2 on the ocean floor. In conclusion, this concept was poorly documented in a systematic manner, partly because the nature of the benthic boundary layers and benthic storm phenomena are not well understood.

Plume dynamics study

The ocean has the natural structure of density stratification and the fact that CO_2 hydrate has a greater density than the CO_2 enriched seawater makes it necessary for the modification of a simple plume model. Ascending and descending plume behaviors are modeled so far (Sato and Sato, 2002; Wannamaker and Adams, 2002) and, more importantly, the international project on the ocean field experiment of CO_2 injection into the sea provided the participating modelers from various research institutions the opportunity to undertake the inter-laboratory comparison of their models. The collaboration among the modelers were very effective to make feedbacks to the laboratory physical property studies resulting in the promoted effort of more critical laboratory measurements. The study will provide the basis for the formulation of the efficient scheme of the injection with reduction of the environmental impacts.

Study on phase property

The laboratory studies using a small scale experimental set-up (e.g., Uchida, 1997; Warzinski and Holder, 1999; Yamasaki et al., 1999; Yamane et al., 1999; Uchida et al., 1999) revealed almost all of the important questions in formulating the plume dynamics. The laboratory experiment using high pressure test facilities provided the progress in understanding the processes at the surface of the CO_2 droplet where the CO_2 hydrate membrane occasionally covers and affects the transport phenomena at this interface. The comprehensive study of both concepts of fixed point release of CO_2 and CO_2 lake scenario was conducted in Tokyo Institute of Technology (Hirai et al., 1997a; Hirai et al.,1997b; Hirai et al., 1997c), where the transport property of liquid CO_2 under deep ocean conditions were collected using high pressure apparatus of the appropriate size for such work. Using a larger high pressure tank was also effective and the prediction of ascending phenomena of an independent single droplet of injected CO_2 in deep ocean environment becomes reliable (Ozaki et al., 2001).

Transport

Having identified the CO_2 emission sources, it is then necessary to match these sources with geological reservoirs and/or suitable sites in the ocean. This mapping, on a regional basis, of ocean storage opportunities is not underway. In GOSAC project (Orr, 2001), the following seven sites are selected based on the accessibility to the deep ocean from large emission sources:

Bay of Biscay, off New York, off Tokyo, off San Francisco, off Bombay, off Rio de Janeiro, and off Jakarta. That was the only example to show what one should bear in mind when we consider the problem of transport.

Although the problem the deep-water pipelines even to a depth of 3000 m is tractable according to experts (Palmer, 1997), it is reasonable to conclude that the longer the transport distance, the more economical ship transport becomes. Ship transport was extensively examined in Japan (Ishimaru, 1997).

Costs

In 1996, the cost analysis on ship transport including injection was presented by Mitsubishi Heavy Industry (Fujioka et al., 1997). Pipeline deployment in the US for ocean injection also appeared in the literature (Halmann and Steinberg, 1999). The cost, in general, is comparable with generic estimates in geological storage. Considering the economy of scale, the cost estimate is usually conducted on the several units of a typically 1000MWe – scale fossil fuel fired power plant.

Research on technology described in the previous sections in this paper was targeted at more reliable prediction of the impact in a near field or alternatively they are the challenge for developing of a reasonably attainable dilution method. Therefore, the results of these efforts will not drastically change the economics of ocean storage.

There must be many detailed cost analyses not open to public on the various options of CO_2 injection. The author believes that these efforts show roughly that we need not to pay more than 10USD per ton CO_2 when liquified or pressurized CO_2 is available at the oceanic coast.

Future R&D for the technology

The level of integration as a whole system is the most advanced in the case of 'moving ship' concept (Ozaki et al., 2001) featuring the minimum attainable impact to the immediate ambient water mass at mid-depth range in the ocean, but this example is an only comprehensive feasibility study.

For the industrial background of the actual technology, we have the experience in handling large volumes of CO_2 in the oil industry such as in EOR practices. When the CO_2 behavior in the ocean is well understood in a controllable manner, particularly for any injection method, and the corresponding environmental assessment is established through the elucidation of the phenomena under actual ocean conditions, the lead time of technology development for full scale implementation, such as 100kg CO_2 per second injection rate, is considered to be several years.

Before the R&D for full scale implementation is conducted, the performance of each proposed technology should be tested in the actual ocean on an appropriate scale, particularly for the purpose of establishing environmental assessment methods associated with the technology. In relation to the risks to be discussed below, appropriate risk management systems should be developed in the course of R&D. We are now going to this stage, and therefore the success to make the ocean experiment planned in the International Collaboration on Ocean Sequestration is critical.

A larger scale field experiment (Haugan, 1998) might be also necessary in the development of the technology and should be conducted under international collaboration

Risks

Risk is not treated so far with regard to the future implementation of the technology. Specific risks associated with the implementation of this technology should be scrutinized in the context of our recent history towards the preservation of the ocean environment, i.e. the provisions of the London Dumping Convention and others. The principle discussed in the forum of these international conventions on the ocean environment is that waste originating from land-based human activities should not be transferred to the ocean. However, the CO_2 emitted from human activities already finds its way to the ocean. Therefore, if we make a short-circuit route for CO_2

to the deep ocean by skipping its existing path through the atmosphere and surface ocean, the question is whether there exist the additional risks to the deep ocean environment. The key issue is the unintended consequences. This could lead to an assessment of the environmental vulnerability of the deep ocean compared to the other parts of the environment that are exposed directly to future increase in greenhouse gases.

The risks in the geological long-term were identified as the enhancement of the carbonate sediment dissolution rate. Consequences include destabilization of the continental slope that could cause deep-sea avalanches. This type of geological hazard is difficult to quantify and might not be an additional risk to the business-as-usual emission scenario.

The biological risks are being discussed in more detail and for the long-term ecological risks, in particular, we reached provisional conclusions. In the second workshop organized by IEA Greenhouse Gas R&D programme, the suggestion of four principles on which the management of CO_2 emissions should be based was made. These were:-

- No species should be driven to extinction.
- There must be no significant disruption of ecological processes at basin-scales.
- There should be no increased impact on living resources over and above that which will occur if no mitigation is exercised.
- + Limits must be set to the volumes of oceanic waters and areas of sea-bed within which critical changes in pH and/or CO_2 concentrations are permissible.

It is to be noted that these guidelines came from the definition of 'pollution' adopted in the London Convention and the principles as follows (Angel, 1997):

- Development must be in a manner that avoids prejudicing environmental amenities for future generations.
- Serious and irreversible damage to the environment must be avoided.
- Measures which transfer damage from one environmental compartment to another must be avoided.
- There is a need for concerted international action to achieve environmental protection and preservation.

These principles were also those we have based ourselves on the United Nations Framework Convention on Climate Change (UNFCCC), hence the problem here is the concept of 'pollution' with relation to the risks associated with ocean storage of CO_2.

The above discussion resulted in the guidelines was made in early 1996 and the needs for the biological studies were documented for the first time in accordance with the former discussion on the protection of marine environment on this occasion, by taking into account that if business-as-usual emissions of CO_2 continues, the consequences for global systems, mainly via climatic effects, would be unacceptable under the same criteria.

Recently, new findings on the possible direct, not 'via climate', effect of CO_2 on marine organism were reported (Angel, 1997). It suggests that the CO_2 partial pressure increase in surface oceans with an increment of 200 micro atmospheres could significantly affect the growth rate of some sea urchins. The inferred mechanism is that the induced decrease in $[CO_3^{2-}]$ concentration causes a decrease in the solubility products $[Ca^{2+}][CO_3^{2-}]$, and consequently the organisms need more energy to maintain formation of their carbonate skeleton. Considering that these effects on marine organisms will be exerted directly to the surface fertile domain of the ocean, the revealed facts may lead to a discussion of the optimum redistribution of unequilibrated excess CO_2 between deep oceanic interior and surface ocean environment (+atmosphere) in a protective sense of ocean environment as a whole. The similar discussion (Thornton and Shirayama, 2001) in this course was also presented in terms of pH change in 1995, so the findings are more straight-forward evidence we should take into account when considering the risks associated with the technology on the marine environment.

Short term local impact

Lethal direct impacts of CO_2 to biota are well documented by the effort of the Japanese R&D program from 1997 to 2002. For example, onboard experiment of lethal effects of CO_2 to deep-sea plankton (Watanabe et al., 2002) gave those important inputs to the assessment models such as developed by the MIT group (Auerbach et al., 1997). Hence, the provisional impact assessment can be ready to present,. if site specific data on an ecological structure for the deep sea environment is available.

Conclusions

1) Where the opportunity for geological storage is restricted for geographical or geological reasons, ocean storage could be a major constituent in the mitigation policy package.
2) Before starting the actual technology development for implementation, the knowledge of the CO_2 behavior in the near field region of injection should be confirmed or verified in the actual ocean, trough experiments
3) The ecosystem impact needs to be revealed in more detail for the requirement posed in the context of the assessment of technology relating to the ocean.
4) The site specificity is the key for the implementation of the 'lake type' storage. In this case, detailed ocean surveys including baseline studies are very necessary.
5) The geographical proximity of ocean and geological storage to sources differs. The intrinsic advantage of ocean storage over geological storage is the relative flexibility in the site selection. Furthermore, the generic assessment methodology of ocean storage may be modified to an actual implementation case more easily than in the case of geological storage.

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References

Angel, M.V., 1997: Environmentally focused experiments: Pelagic studies. In Ocean storage of CO_2 - workshop 4 - Practical and experimental approaches pp 59-70, IEA Greenhouse Gas R&D Programme, Cheltenham, UK.

Auerbach, D.I., J.A. Caufield, E.E. Adams and H.J. Herzog, 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.

Aya, I., R Kojima, K. Yamane, P.G. Brewer and E.T. Peltzer, III, 2002: In situ experiments of cold CO_2 release in mid-depth. In Proceedings of the sixth international conference on greenhouse gas control technologies, Kyoto, Japan, 30 September – 4 October.

Brewer, P.G., G. Friederich, E.T. Peltzer and F.M. Orr, Jr., 1999: Direct experiments on the ocean disposal of fossil fuel CO_2, Science 284, 943-945.

Brewer, P.G., J. Pasteris, G. Malby, E. Peltzer, S. White, J. Freeman, B. Wopenka, M. Brown and D. Cline, 2002: Laser Raman spectroscopy used to study the ocean at 3600-m depth, EOS 83, 469-470.

Broecker, W.S., 2001: Carbon Futures. In Geosphere - Biosphere Interactions and Climate, L.O. Bengtsson and C.U. Hammer, eds., pp 66-80, Cambridge Univ. Press.

Caldeira, K. and G.H. Rau, 2000: Accelerating carbonate dissolution to sequester carbon dioxide in the ocean: Geochemical implications, Geophys. Res. Lett. 27, 225-228.

Chen, B., S. Masuda, M. Nishio, S. Someya and M. Akai, 2001: A Numerical prediction on plume structure of LCO_2 in the ocean. – A near field model, In Greenhouse Gas Control Technologies, D.J. Williams, R.A. Durie, P. McMullan, C.A.J. Paulson and A.Y. Smith, eds., pp 417-422, CSIRO, Australia.

Crounse, B.C., E.E. Adams, S.A. Scolofsky and T.H. Harrison, 2001: Application of a double plume model to compute near field mixing for the international field experiment on CO_2 ocean sequestration. In Greenhouse Gas Control Technologies, D.J. Williams, R.A. Durie, P. McMullan, C.A.J. Paulson and A.Y. Smith, eds., pp 411-416, CSIRO, Australia.

Fer, I. and P. M. Haugan, 2002: On the fate of purposefully disposed CO_2 lake in the deep ocean, In Proceedings of the sixth international conference on greenhouse gas control technologies, Kyoto, Japan, 30 September – 4 October.

Fujioka, Y., M. Ozaki, K. Takeuchi, Y. Shindo and H. J. Herzog, 1997: Cost comparison in various CO_2 ocean disposal options, Energy Convers. Mgmt 38, Suppl ppS273 -S277.

Golomb, D. S., 2002; Carbon dioxide/limestone/water emulsion for ocean and geologic sequestration of CO_2. In Proceedings of the sixth international conference on greenhouse gas control technologies, Kyoto, Japan, 30 September – 4 October

Halmann, M.M. and Steinberg, M, 1999: Greenhouse gas carbon dioxide science and technology. Lewis Publishers, Washington DC, p 149.

Haugan, P.M. and Drange, H., 1996: Effects of CO_2 on the ocean environment. Energy Convers. Mgmt 37,1019- 1022.

Haugan, P.M. 1998: Carbon dioxide, Contribution to Environmental risks from large-scale ecological research in the deep sea, H. Thiel, M.V. Angel, E.J.Foell, A.L. Rice and G. Sshrriever pp. 155-166 Official Publications of the European Communities, ISBN 92-828-3517-0.

Hirai, S.. K. Okazaki, Y. Tabe, and K. Hijikata,1997: Mass transport phenomena of liquid CO_2 with hydrate, Waste Management 17, 353-360.

Hirai, S., K. Okazaki, Y. Tabe, K. Hijikata, and Y. Mori, 1997: Dissolution rate of liquid CO_2 in pressurized water flows and effect of clathrate films, Energy International 22(2/3), 285-293

Hirai, S., K. Okazaki, H. Yazawa., Y. Ito, Y. Tabe and K. Hijikata,1997: Measurement of CO_2 dissolution coefficient and application of LIF in pressurized water. Energy International 22(2/3), 363-367.

Hirai, S., Y. Tabe, G. Tanaka and K. Okazaki 1999: Advanced CO_2 ocean dilution technology for longer term sequestration with minimum biological Iimpacts. In Greenhouse Gas Control Technologies, B. Eliasson, P.W. F. Riemer and A. Wokaun eds., pp 317- 322, Elsevier Science Ltd

Hoffert, M.J., Y.-C. Wey, A.J.Callegari, and W.S. Broecker, 1979: Atmospheric response to deep-sea injection of fossil fuel carbon dioxide, Climatic Change 2, 53-68.

Ishimaru, J., 1997. Design of ship/tanker for transportation of CO_2. In Ocean Storage of CO_2 - Workshop 4 - Practical and Experimental Approaches, pp 95–106, IEA Greenhouse Gas R&D Programme, Cheltenham, UK.

Keshgi, H.S. 2002: Evasion of CO_2 injected into the ocean in the context of CO_2 stabilization, In Proceedings of the sixth international conference on greenhouse gas control technologies, Kyoto, Japan, 30 September – 4 October.

Marchetti, C., 1977: On engineering the CO_2 problem, Climate Change 1, 59-68.

Mignone, B.K., J.L. Sarmiento, R.D. Slater and A. Granadesikan, 2002: Sensitivity of sequestration efficiency to mixing processes in the global ocean, In. Proceedings of the sixth international conference on greenhouse gas control technologies, Kyoto, Japan, 30 September – 4 October.

Nakashiki, N. 1997: Lake-type storage concepts for CO_2 disposal option, Waste Management 17, 361-367.

Nakashiki, N., T. Ohsumi, and K. Shitashima, 1991: Sequestering of CO_2 in a deep-ocean – Fall velocity and dissolution rate of solid CO_2 in the ocean. CRIEPI Report (EU91003). Abiko, Chiba, Japan: Central Research Institute of Electric Power Industry.

Nihous, G.C., L. Tang and S.M. Masutani, 2002: A sinking plume model for deep CO_2 discharge, In Proceedings of the sixth international conference on greenhouse gas control technologies, Kyoto, Japan, 30 September – 4 October.

Ohsumi, T., 1995: CO_2 storage options in the deep sea, Marine Technology Society Journal 29(3) 58-66.

Orr, J.C., O. Aumont, A. Yool, K. Plattner, F. Joos, E. Maier-Reimer, M.-F. Weirig, R. Schlitzer, K. Caldeira, M. Wickett, and R. Matear, 2001: Ocean CO_2 sequestration efficiency from a 3-D ocean model comparison, In Greenhouse Gas Control Technologies, D.J. Williams, R.A. Durie, **P. McMullan**, C.A.J. Paulson and A.Y. Smith, eds., pp 469-474, CSIRO, Australia.

Ozaki, M., J. Minamiura, Y. Kitajima, S. Mizokami, K. Takeuchi and K. Hatakenaka, 2001: CO_2 ocean sequestration by moving ships, Journal of Marine Science and Technology 6, 51-58.

Palmer, A. 1997: Pipelines into deep water, In Ocean Storage of CO_2 - Workshop 4 - Practical and Experimental Approaches, pp 77-82, IEA Greenhouse Gas R&D Programme, Cheltenham, UK.

Sato, K. and T. Sato, 2002: Numerical prediction of the dilution process and its biological impacts in CO_2 ocean sequestration, Journal of Marine Science and Technology 6, 169-180.
Shitashima, K., 1997: CO_2 supply from deep-sea hydrothermal systems, Waste Management 17, 385-390.

Steinberg, M., 1985: Recovery, disposal, and reuse of CO_2 for atmospheric control. Environmental Progress 4, 69-77.

Takano, S., A. Yamasaki, K. Ogasawara, F. Kiyono, M. Fujii and Y. Yanagisawa, 2002: Development of a formation process of CO_2 hydrate particles for the ocean disposal of CO_2, In Proceedings of the sixth international conference on greenhouse gas control technologies, Kyoto, Japan, 30 September – 4 October.

Thornton, H. and Shirayama, 2001: CO_2 ocean sequestration and its biological impacts, III-1: Effects of CO_2 on benthic organisms. Nippon Suisan Gakkaishi 67(4), 756-757 (in Japanese).

Tsushima, S., S. Hirai, H. Sanda, and S. Terada, 2002: Experimental studies on liquid CO_2 injection with hydrate film and highly turbulent flows behind the releasing pipe, In Proceedings of the sixth international conference on greenhouse gas control technologies, Kyoto, Japan, 30 September – 4 October.

Uchida, T. 1997: Physical property measurements on CO_2 clathrate hydrates. Review of crystallography, hydration number, and mechanical properties, Waste Management 17, 343-352.
Uchida, T., T. Ebinuma and S. Mae, 1999: Formation rate measurements of CO_2 -hydrate film formed at liquid CO_2 water interface, In Greenhouse Gas Control Technologies, B. Eliasson, P.W. F. Riemer and A. Wokaun eds., pp1073- 1075., Elsevier Science Ltd.

Wannamaker, E.J. and E.E. Adams, 2002: Modeling descending carbon dioxide injections in the ocean. In Proceedings of the sixth international conference on greenhouse gas control technologies, Kyoto, Japan, 30 September – 4 October.

Warzinski, R.P. and G.D. Holder, 1999: Ocean storage of CO_2: Experimental observations of clathrate hydrates in seawater, In Greenhouse Gas Control Technologies, B. Eliasson, P.W. F. Riemer and A. Wokaun eds., pp1061-1063, Elsevier Science Ltd

Watanabe, Y., A, Yamaguchi, H. Ishida, T. Ikeda and J. Ishizaka, 2002: Lethal effect of elevated pCO_2 on planktons collected from deep sea in North Pacific, In Proceedings of the sixth international conference on greenhouse gas control technologies, Kyoto, Japan, 30 September - October.

Wigley, T.M.L and D. S. Schimel, 2000: The Carbon Cycle, Cambridge University Press.

Yamane, K, I. Aya, S. Namie and H. Nariai, 1999: Strength abnormality of CO_2 hydrate membrane just below dissociation temperature, In Greenhouse Gas Control Technologies, B. Eliasson, P.W. F. Riemer and A. Wokaun eds., pp1069- 1071, Elsevier Science Ltd.

Yamasaki, A., M. Wakatsuki, Y. Yanagisawa and K. Yamada, 1999: Formation, coagulation, and sedimentation of CO_2 hydrate particles in a high pressure, low temperature reactor, In Greenhouse Gas Control Technologies, B. Eliasson, P.W. F. Riemer and A. Wokaun eds., pp1065- 1067, Elsevier Science Ltd.