Ocean Disposal/Sequestration of Carbon Dioxide from Fossil Fuel Production and Use: An Overview of Rationale, Techniques and Implications

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Greenpeace Research Laboratories
Technical Note 01/99
March 4th 1999

ISBN: 90 73361 48 6
Printed by Greenpeace International, Amsterdam

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Introduction

In 1992 167 nations signed the United Nations Framework Convention on Climate Change. The Convention includes the objective to achieve "*stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with the climate system*". The Kyoto Protocol to this Convention, adopted in 1997, sets legally binding commitments to reductions in emissions of greenhouse gases. Although many gases arising from anthropogenic activity contribute to climate forcing, carbon dioxide (CO_2) is quantitatively by far the greatest contributor (64%).

A key intention of the Kyoto Protocol was to achieve emissions reductions at source. Despite this, a number of proposed approaches to climate change mitigation rely instead on the development of technical mechanisms for the "management" of anthropogenic CO_2 in the environment. In broad terms, such approaches endeavour to limit the magnitude of atmospheric increases in CO_2 concentration through attempts either to influence the partitioning of carbon between different environmental compartments or to isolate generated CO_2 from the atmosphere over long time-scales. Proposed strategies include direct disposal of liquid or solid CO_2 at sea (both above and beneath the seabed) and the enhancement of uptake of CO_2 by natural biological processes in the oceans. In each case, the techniques involve a high degree of intervention with ecosystems and the global carbon cycle, involving manipulations on the scale of "planetary engineering".

At best these proposals are subject to enormous uncertainties, regarding both their likely effectiveness and the potential for adverse impacts at local, regional and global level. At worst they are increasingly portrayed not merely as measures to mitigate climate change to which we are already committed but also as mechanisms which will permit continued exploration and exploitation of fossil fuel reserves. This document examines a range of proposed carbon management options, some of which are currently under development, with a particular focus on issues of technical feasibility, environmental impact and legality under existing international law.

Understanding the global carbon cycle

Understanding of the global carbon cycle remains limited, both in terms of the role of biological processes and the physics of, for example, ocean circulation and gas exchange, however it is known with certainty that human activities are significantly perturbing the global carbon cycle. This has resulted in a substantial increase in atmospheric CO_2 and an observed flux of anthropogrenic CO_2 into the world's oceans.

The oceans represent the largest global reservoir of carbon, present primarily in the inorganic form bicarbonate. On a global, decadal scale, and without anthropogenic influence, the atmosphere and the oceans may be seen to be in equilibrium with respect to carbon exchange. On a seasonal and regional scale, however, substantial net fluxes of carbon occur, resulting from both physical and biological processes. Although the main driving forces are understood, the magnitude of reservoirs and fluxes of carbon remain relatively poorly quantified. Knowledge of interactions between physical, chemical and biological processes is also limited.

At present, quantitative understanding of the sinks for all of the anthropogenic carbon added from fossil fuel burning, land use change and cement production is incomplete. Nevertheless it is possible, based on current understanding, to confidently predict that continued anthropogenic emissions of CO_2 to the atmosphere will result in substantial increases in atmospheric CO_2. A substantial fraction of anthropegenic emissions will be taken up by the oceans and stored in the terrestrial biosphere. It is also clear that CO_2 sequestered or disposed into seawater will not be isolated from the atmosphere indefinitely. Moreover, the potential exists for continued climate change to impact directly on ocean circulation patterns and marine biological activity and, as a consequence, affect the global carbon cycle, significantly affecting the fraction of anthropogenic emissions which remain in the atmosphere. Despite this, development of oceanic CO_2 sequestration and disposal strategies continues.

Ocean fertilisation

A number of measures designed to increase draw-down of CO_2 to the oceans through enhanced biological fixation have been proposed, based on widespread fertilisation of ocean areas with nutrients (e.g. nitrogen, iron) which otherwise limit primary productivity. Although these techniques have not to date been portrayed as climate manipulation strategies, but rather as programmes for the research of biogeochemical processes or for the enhancement of fisheries productivity, their potential as techniques for the management of carbon has not gone unnoticed.

i) iron fertilisation:

It is predicted that substantial increases in the productivity of the Southern Ocean and, consequently, sequestration of atmospheric CO_2, could be achieved through iron fertilisation. Addition of approximately 470 000 tonnes of iron per year, spread over as much as 25% of the ocean surface and repeated for an indefinite period, would be necessary for this strategy to be effective. In addition to the fact that this does not, in itself, represent a sustainable option, it may also lead to substantial deoxygenation of the water column and/or ocean floor over a wide area, and fundamental changes in planktonic community structure with consequences for whole ecosystem function. Enhanced biogenic production of nitrous oxide (N_2O), itself a greenhouse gas, could offset almost entirely any mitigating effects of enhanced CO_2 draw-down. Moreover, if enhanced productivity manifested as an increase in calcified planktonic species, the partitioning of CO_2 to the atmosphere could increase rather than decrease as a result of disproportionate impacts on bicarbonate equilibrium.

ii) fertilisation with macronutrients (e.g. nitrogen):

These proposals raise similar fundamental concerns regarding effectiveness, sustainability and potential environmental impacts. Programmes such as MARICULT, conducted under the Norwegian agency NIVA, are being developed primarily to enhance fisheries production, a goal which would seem to be in conflict with objectives to enhance the sequestration and long-term isolation of CO_2 in the deeper oceans. Furthermore, the extraction and/or manufacture of bulk quantities of the nutrients required for fertilisation could have enormous penalties, not only in financial terms but also through increased generation of CO_2.

The IPCC Second Assessment Report on climate science found that fertilisation of the Southern Ocean was not viable, essentially for the reasons cited above. In short, although the overall viability of these options would, therefore, appear to be very low, research and development nevertheless continues.

Direct disposal of CO_2 to seawater

The approaches to carbon management which are currently receiving the greatest focus involve the direct disposal of CO_2 to the oceans, either to seawater (via pipeline or through dumping from ships) or to geological formations beneath the seabed. These proposed strategies raise substantial technical, ecological and legal concerns. Moreover, the disposal of CO_2 requires its initial capture from facilities generating the gas, followed by compression, transport and final disposal, processes which represent substantial energy and CO_2 penalties in themselves.

i) energy penalties

Capture of CO_2 alone could account for up to 30% of the overall fuel used in a typical coal-fired power station. Even with improvements expected in fuel efficiency, further energy will be required for compression of the CO_2 to liquid or solid form. For a 500 MW power station, total energy penalties of between 25-45% may be expected, with consequent increases in CO_2 generation. As a result, even for stabilised energy use patterns, pursuit of the ocean disposal option would inevitably increase the total quantity of CO_2 to be disposed and, therefore, equilibrium concentrations of CO_2 in the atmosphere. Rather than preventing dangerous interference with the climate system, as is required under Article 2 of the Climate Convention, such processes may ultimately accentuate irreversibly the magnitude of the problem bequeathed to future generations. In other words, any benefits obtained in terms of avoided climate change arising from CO_2 disposal, would come at the certain cost of irreversibly higher atmospheric CO_2 levels in the future than would otherwise have been the case.

ii) disposal of liquid CO_2

Further problems relate to the specific disposal strategies proposed. The disposal of blocks of frozen CO_2 from ships would clearly draw very high energy penalties. Although this option has yet to be ruled out, attention has focused on the introduction of liquid CO_2 from ships or pipelines. CO_2 disposed at depths greater than 3000m is expected to sink and form a "lake" on the seabed which, unless constrained by seabed topography, might spread out and impact on benthic organisms over very wide areas. Furthermore, assumptions that disposal in this manner would lead to effective isolation of CO_2 from the atmosphere over very long time-scales may be flawed. In the North Pacific, for example, turnover of the water column, which may bring CO_2 back to the surface, may occur in a fraction of the time previously assumed *i.e.* on the scale of hundreds rather than thousands of years. Turbulence and local mixing regimes may lead to even more rapid injection of liquid CO_2 to overlying waters and circulation patterns in a largely unpredictable manner. Equally, the potential impacts of climate and weather pattern changes on circulation patterns and the isolation of disposed CO_2 have received little consideration to date.

Even if CO_2 "lakes" remain *in situ*, impacts on benthic communities may be expected, either through asphyxiation or as a result of suppression of pH values. Modelling studies predict that pH could be reduced below 7 over tens of kilometres from a point discharge of CO_2 to the deep ocean, with suppression below the normal pH of seawater detectable over a far wider field. Although physical turbulence may be a common characteristic of many deep sea environments, the chemical composition of deep sea waters and sediments may be expected to be relatively stable. Species occupying such environments are likely to be particularly sensitive even to small perturbations in pH or other chemical parameters. In common with other stresses, prediction of impacts on deep-sea benthic communities may be limited by lack of data and understanding of the lifecycles and sensitivities of these organisms.

Despite the fact that the prediction of the nature and scale of impacts is likely to remain extremely difficult, if not impossible, several "proof of concept" studies are under development. An experiment to be conducted in the year 2000, funded jointly by USA, Japan and Norway, will study the physics of dispersal of a plume of CO_2 to be introduced by pipeline at a depth of 1000m in seawater off the Kona Coast of Hawaii. Unlike the fertilisation studies outlined above, the underlying objectives of such studies are explicitly the validation of CO_2 disposal technologies.

Injection of CO_2 to sub-seabed formations

Much attention has also focussed on the potential for disposal of CO_2 in geological formations beneath the seabed. Although standard practice for enhanced oil recovery within the offshore industry, proposals to use sub-seabed injection as a major sink for the disposal of anthropogenic CO_2, primarily to address emissions from power generation facilities, are relatively recent.

Injection as a CO_2 disposal, rather than oil recovery, technique has been practised by the Norwegian state oil company Statoil in the North Sea Sleipner field since 1996. Approximately 1 million tonnes of CO_2 derived from the gas field are injected annually into a porous sandstone aquifer located beneath an impermeable shale. A similar, but much larger, programme is planned for the Natuna gas field in the South China Sea. Estimates indicate that substantial capacity exists for CO_2 disposal in this manner.

However, relatively little consideration appears to have been given to the long-term effectiveness and impacts of such practices. Although seemingly confining CO_2 to containment over geological time-scales, again substantial uncertainties exist. Direct physicochemical impacts of the introduction of high pressure CO_2 on formation chemistry and physical integrity remain to a large degree unknown, although considerable dissolution of some rock types may be expected. While some formations may chemically sequester CO_2, the potential for complex and poorly predictable interactions is clear. In addition, the very fact that formations have to be drilled at one or more locations in order to permit disposal threatens to connect otherwise isolated formations with contemporary time-scales.

Legal considerations

One aspect which has received perhaps the least consideration to date is the interpretation and acceptability of ocean disposal of CO_2 under existing international legal conventions. CO_2 derived from power generation and other industrial activities would clearly fall under the definition of industrial waste. As such, disposal of CO_2 at sea, including below the seabed, from ships, platforms and other man-made structures would violate international law, both under the London Convention and, more widely, the United Nations Convention on Law of the Sea (UNCLOS), as well as under some regional conventions. The illegality of such practices was most recently highlighted by the United Nations Group of Experts on Scientific Aspects of Marine Environmental Protection (GESAMP), which stressed that changes to international law would be required before such practices could be pursued.

Some aspects of the proposed CO_2 disposal/sequestration strategies for climate mitigation may also be inconsistent with the provisions of the Kyoto Protocol, an issue which demands further consideration. The Independent World Commission on the Oceans (IWCO) concluded recently that "*The Framework Convention on Climate Change and its Kyoto Protocol do not provide for Parties to dump or store CO_2 in international waters and thereby to offset their emissions.*"

Prospects for the future

More fundamentally the IWCO stressed the essential need for states "*to exploit as a first priority the manifold opportunities that exist for reducing carbon emissions*". This implies the necessity for measures to address emissions at source, a necessity which is inconsistent with continued reliance on, and expansion of the use of, fossil fuels. The "Carbon Logic" approach, developed by Hare (1997), stresses that combustion of all identified fossil fuel reserves is an unsustainable option in climatic terms. Based on estimates of climate sensitivity and the scale of climate change and concomitant effects to which the majority of ecosystem components may be able to adapt, the approach calculates a theoretical maximum quantity of fossil fuel combustion which cannot be surpassed, representing only a fraction of known reserves.

Environmentally effective implementation of the Kyoto Protocol would maintain industrialised country emissions at approximately 1995 levels in the period 2008-2012. Globally, however emissions would continue to grow over this period. Further measures, including greater emission reductions for the industrialised countries, which achieve much deeper and long-lasting cuts in emissions are essential. Ongoing development of unsustainable disposal/sequestration strategies will continue to draw vital resources away from the research, development and implementation of energy efficiency programmes and renewable energy alternatives.

The 1992 Rio Declaration on Environment and Development enshrined the principle that "*the right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations*". The potential for unpredicted, and possibly serious or even irreversible, effects on current or future generations resulting from the various carbon management strategies outlined above is indisputable and threatens to violate this principle of sustainability. At the same time, the assumption that ocean sequestration or disposal of CO_2 will be effective in mitigating committed climate change remains very much open to debate. Moreover, the use of such strategies to meet the provisions of the Kyoto Protocol and to justify continued reliance on fossil fuel reserves into the future clearly represents an abdication of transgenerational responsibility.

March 1999

Introduction

The main focus of domestic international efforts to regulate the release of CO_2 and other greenhouse gases has been on reducing emissions at source (see *e.g.* IPCC, 1996b). Recently, however, there has been an increased emphasis placed upon two broad areas of research. One of these involves sequestration of carbon dioxide in terrestrial or marine ecosystems after it has been released into the atmosphere, essentially using biological processes. In marine ecosystems, such proposals are designed to exploit the potential for living organisms to utilise CO_2 and enhance the so-called marine biological carbon pump. A second option under investigation is the capture of CO_2 from combustion gases followed by disposal on or under the sea bed, or directly into marine waters. The focus of this paper is on the issues that arise in relation to such schemes involving ocean environments. Some of the issues raised, however, are also relevant to other proposed CO_2 disposal techniques involving former oil and gas reservoirs and other terrestrial geological formations.

Investigation into marine sequestration and CO_2 disposal and/or storage technologies has largely been the preserve of the various engineering disciplines. Characteristically the technologies proposed involve very large scale projects designed either to prevent carbon dioxide reaching the atmosphere (CO_2 disposal and or storage) or to sequester carbon from the atmosphere. Specifically the proposals to be examined here fall into three distinct categories:

- The fertilisation of open waters to increase primary production and hence to absorb more carbon in fixed form which will eventually be incorporated into the ocean sediments
- Disposal of captured carbon dioxide directly into oceanic waters.
- Injection of captured CO_2 into sub-seabed geological formations.

All of these technologies can be regarded broadly as exercises in “planetary engineering”. They need to be implemented on a global scale to achieve their designed effect on the working of the planet as whole (Marland, 1996) and are designed to modify, by human intervention, the operation of global scale biogeochemical cycles, in this case the carbon cycle. A useful, informative review of many planetary engineering options designed to mitigate anthropogenic climate change is given by Matthews (1996), from which Figure 1 is reproduced. Clearly, a great deal of ingenuity has been exercised in the development of these schemata, ranging from cloud seeding to “terraforming” of the planet Mars.

Proposals for introducing either nutrients or carbon dioxide on a wide scale into the oceans are predicated on the basis that the environmental damage caused in the oceans or the long term risk posed to future generations, would be offset against the damage avoided in terrestrial systems as a result of the reduced temperature rise over the next century or so (See: Herzog, 1998; Herzog *et al.*, 1997). Indeed, in support of schemes involving the ocean it is often rationalised that equilibration of CO_2 with the ocean takes place naturally, and, hence, that anthropogenic CO_2 will naturally equilibrate with the ocean over time. By “short circuiting” this natural process, and increasing the rate at which CO_2 is taken up, through injection or fertilisation it is argued that the natural equilibration process will be accelerated (see: GESAMP, 1997). It will also, therefore, avoid the “transient” high peak of atmospheric CO_2 predicted for the next few centuries arising from projected future emissions (IPCC, 1996a). Ultimately, the equilibrium reached with the atmosphere (over many centuries), it is argued, would be about the same as that which would have occurred without intervention. In other words, proponents of such strategies consider that a strategy of ocean disposal or ocean fertilisation would not affect the final stabilisation value for CO_2 on millennial time scales, for a given quantity of fossil carbon mobilised into the environment as carbon dioxide.

The above rationale, however, is somewhat simplistic. Carbon dioxide which is released to the environment by combustion of fossil fuels extracted from fossil reservoirs (which are effectively isolated from the environment on geological timescales) becomes incorporated into the contemporary, dynamic carbon cycle more or less permanently (Tans, 1997). Hence, the fact that carbon dioxide sequestered or disposed of in this way may not re-appear in the atmosphere for centuries or possibly millennia does not actually address the overall problem. Instead, the problem is simply deferred, to become an unavoidable problem for future generations. Indeed, many of the problems inherent in these ideas are common to options proposed for terrestrial systems (see *e.g.* WBGU, 1998). The proposed strategies have been collectively termed “Carbon Management (CM)”. It has been observed that technical progress in carbon management is outpacing consideration of its limitations and potential risks. Large scale adoption of such strategies would constitute a major technological and societal choice that would be difficult to reverse. There is a strong risk that this choice will be made without adequate reflection upon its implications (Parson & Keith, 1998) given the current slow political progress on genuine abatement through *inter alia* the development of renewable energy resources.

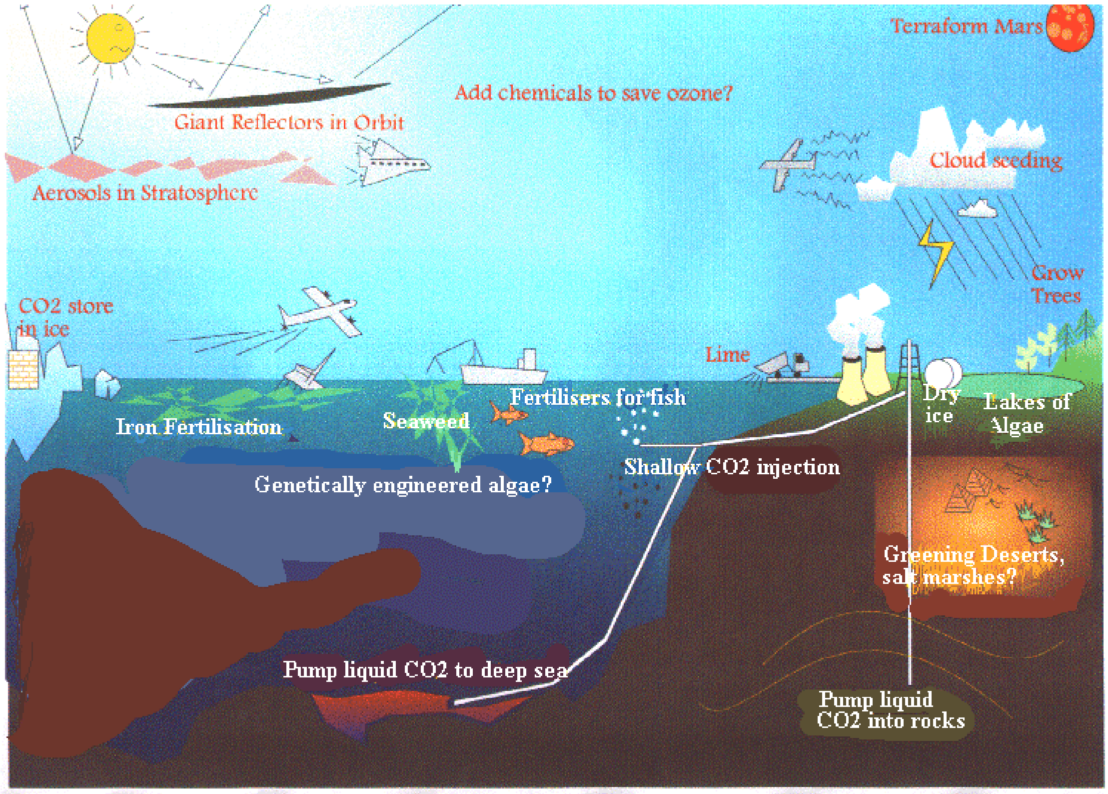


Figure 1: Schematic representation of various proposals which have been made to mitigate anthropogenic climate change through planetary engineering projects. Source: Matthews (1996), reproduced by permission.

In turn, this suggests the potential for a serious conflict within corporations and governments regarding allocation of resources for onward investment in energy technologies. There are finite resources available in the corporate and public domains to direct at development of sustainable (renewable) energy technologies and the associated infrastructure. Carbon management strategies designed to maintain fossil fuel consumption and use into the future are diametrically opposed in philosophy and intent to the development of renewable energy resources and of highly efficient technologies and transport systems. Given that a highly significant component of investment in renewable energy development is being made by multinational oil companies, there is the very real prospect that such investment will be held hostage to the development of expensive carbon management technologies. There also appears to be a presumption in the energy industry that the relatively low cost “least regrets” options which include improvements to energy supply, end-use efficiency, substitution with less carbon intense fuels and inexpensive renewables will not solve the medium to long term problem. Accordingly, it has been argued that technologies to capture and remove CO_2 could have a central role to play in the future. Crucially, they are seen by some in the energy industries as a long term option which allows for continued large scale use of fossil energy resources (Herzog *et al.*, 1997).

This document seeks to examine some of the issues arising from proposals to dispose of CO_2 from fossil fuel combustion into the world’s oceans. Specifically, three techniques of concern are discussed:- i) ocean fertilisation, ii) direct disposal of CO_2 into oceanic waters and iii) disposal of CO_2 below the seabed.

CO_2 fertilisation seeks to enhance the “biological pump” thereby increasing the rate of removal of carbon to the deep oceans. CO_2 disposal into the sea seeks to avoid the initial air-sea equilibration process and store the carbon directly into the oceans. Nevertheless, it will still be subject to the longer timescales which will result at some point in the injected CO_2 in the sea equilibrating with the atmosphere. CO_2 storage under the sea bed in aquifers seeks to isolate the carbon from both the ocean and the atmosphere. In order to be effective in preventing climate change, such a strategy would need to achieve secure containment over geological timescales, rather than just centuries or even several thousand years.

These proposals are examined with a consideration of aspects of the global carbon cycle and in the context of policies relevant to the stabilisation of carbon dioxide and other greenhouse gases.

Climate, energy use and carbon dioxide emissions.

The carbon cycle

An understanding of the role of the oceans in the carbon cycle is central to any evaluation of the likely impacts of ocean disposal of CO_2 and associated storage techniques. The oceans play a large part in the global carbon cycle and this is being substantially changed by the release of fossil fuel derived carbon dioxide. In simple terms, it is the equilibrium which exists between ocean carbon dioxide concentrations and those in the atmosphere, and the way in which this equilibrium is driven, that governs atmospheric carbon dioxide concentrations in the long term.

The ocean environment is the largest global “reservoir” of carbon and contains around 40,000 Gt of carbon in inorganic and organic form. This compares with around 750 Gt present in the atmosphere. Excluding carbon present in soils, the terrestrial biosphere is estimated as containing 610 Gt of carbon. The naturally large exchanges of carbon which take place between the atmosphere and the oceanic and terrestrial compartments do not, in themselves, lead to significant changes in atmospheric CO_2 concentrations and in a pre-industrial context could be regarded as broadly in equilibrium. Carbon dioxide which is introduced into the atmosphere from the combustion of fossil fuels and from deforestation and other land-use changes leads, however, to an increase in the atmospheric loading of carbon and the global carbon reservoirs are now in a state of disequilibrium. Some of this anthropogenic carbon dioxide will be fixed in the terrestrial biosphere, with a larger fraction being taken up by the oceans in a slow equilibration process. At present this involves the uptake of around 2 Gt of carbon *per annum*. This, however, is considerably lower than current anthropogenic emission rates.

Atmospheric carbon dioxide is transferred rapidly into seawater at the air-sea interface, particularly when strong winds cause breaking waves and entrainment of bubbles. As a result of the chemical equilibrium between molecular carbon dioxide and the bicarbonate and carbonate ion present in seawater, only around 1% of the CO_2 remains in dissolved molecular form with the rest being converted to bicarbonate ion. Once the carbon dioxide has become dissolved into the surface waters it enters the marine carbon cycle and may ultimately be transported into deep waters by two major processes. The first of these is known as the “solubility pump” and this depends upon the fact that CO_2 is highly soluble in the cold dense water present in high latitudes and which sinks to deep water as part of the thermohaline circulation.

The entrained CO_2 is partly released to the atmosphere when these waters are warmed by turbulent mixing and resurface in the Indian and Equatorial Pacific Oceans estimated to be around 1000 years later (Wong & Hirai, 1997). In contrast, other areas of ocean where water temperature differentials exist, such as the subtropical gyre of the North Atlantic, may play an important role in the subduction of carbon to deeper waters (Follows *et al.*, 1996). The rate of transport of dissolved CO_2 from the surface to the deeper ocean is limited by the rate at which surface water is transported to, or is mixed with, deeper ocean waters. Hence, on short timescales the oceanic uptake of CO_2 is not as great as is implied by the total volume of the ocean relative to that of the atmosphere (IPCC, 1995)

The dynamics of atmosphere/ocean equilibration of CO_2 do not follow a linear pattern with time. A detailed ocean circulation and carbon cycling model developed by Archer *et al.* (1998) indicates that equilibration of future predicted fossil fuel derived CO_2 releases to atmosphere and ocean will be strongly time dependent. Even once equilibrium with oceanic calcium carbonate reserves is reached, it is likely that 7-8% of the excess CO_2 in the atmosphere will remain, to be neutralised by the silicate rock cycle over a timescale of hundreds of thousands of years.

The second major process which operates to transfer carbon to deep waters is the "biological pump". Planktonic marine primary producers utilise carbon dioxide and bicarbonate ion dissolved in the upper layers of the ocean and fix it in organic form through photosynthetic activity. The phytoplanktonic organisms are then grazed by zooplanktonic animals which in turn are utilised as food by higher marine organisms. A significant but variable fraction of carbon fixed by phytoplankton is secreted or lost from cells, entering the microbial food web directly. Around 70%-90% of the carbon is recycled in the surface waters while the balance is exported to deeper water by the sedimentation of particulate organic matter. This exported fraction is mostly remineralised by bacteria to form CO_2 which is eventually returned to surface waters after an estimated 1000 years or so (Wong & Hirai, 1997).

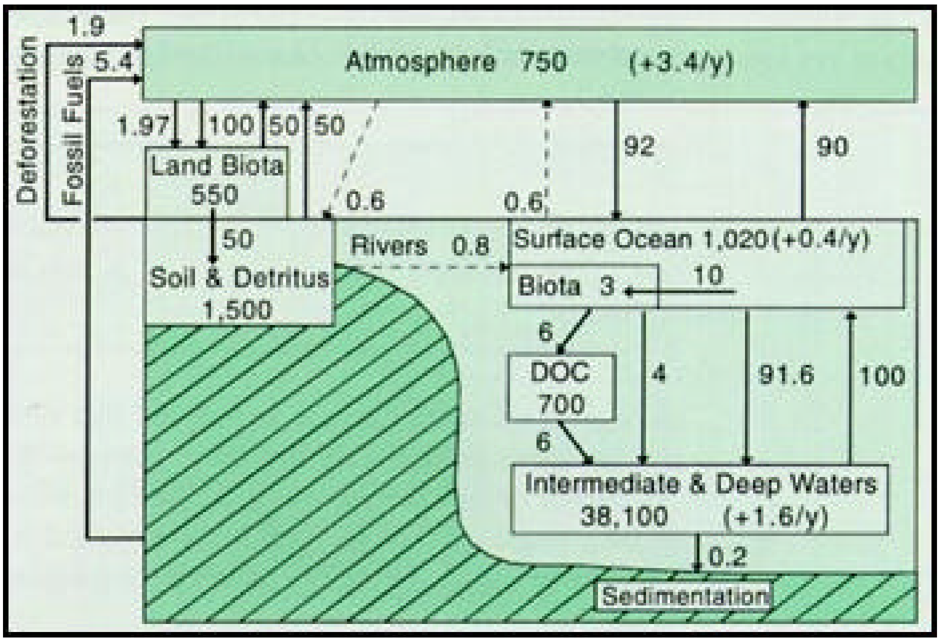


Figure 2 Schematic representation of the global carbon cycle for post industrial times. Fluxes are given in GT y^{-1}, reservoirs in Gt. The figures in parentheses indicate the increase in given compartments of carbon on an annual basis due to anthropogenic carbon dioxide emissions. See also legend to Table 1 and body of text. Source: IEA (1998c)

The biological pump serves to remove only about 10% of the carbon returning to the ocean surface through the upwelling of deep water, as a result of photosynthesis and subsequent sedimentation of detritus. Atmospheric CO_2 is sensitive to the partial pressure of CO_2 in equilibrium with seawater, however, and not on the total content of inorganic carbon, as predicted by the carbonate/bicarbonate equilibrium and the associated buffer factors. Hence, a 1% fall in concentrations of total dissolved inorganic carbon in the seawater will be amplified into an approximately 10% change in partial pressure of CO_2 (Watson & Liss, 1998). Marine organisms present in the surface layers of the sea, consequently, are thought to be responsible for maintaining about three quarters of the vertical gradient in dissolved inorganic carbon between the surface and deep waters. (IPCC, 1995). The biological fixation of carbon therefore exerts a considerable influence upon atmospheric concentrations of carbon dioxide. In the absence of biological processes sequestering carbon into the oceans, it has been estimated that the atmospheric concentration of CO_2 in pre-industrial times would have been around 450 ppmv rather than the 280 ppmv known to have prevailed then (Denman *et al.*, 1996).

Overall, oceanic carbon cycling is a highly complex process, and understanding of it is based largely upon mathematical models supplemented with sparse data obtained from direct oceanic measurements. The major fluxes and reservoirs are poorly quantified. Nevertheless, it has been estimated that if the cycling processes and the resultant vertical carbon gradient did not exist then the surface water carbon concentration would be about 15% higher than at present, leading to a current equilibrium atmospheric concentration of 700 ppmv of carbon dioxide (Bolin, 1986). While warm surface waters are saturated with CO_2 in dissolved form, the deeper colder waters are unsaturated. The observation (IEA, 1999) that the solubility of carbon dioxide in deeper waters is twice that in surface waters, (although actual deep water concentrations of dissolved inorganic carbon are only about 12% higher) has been used as another, albeit specious, rationale for the disposal of CO_2 into deep ocean waters.

Even with the current uncertainties which exist in relation to the size of carbon reservoirs and fluxes, simple calculations based upon the actual concentration of CO_2 and the theoretical saturation achievable in deep ocean waters indicate a notional capacity for several million Gt of CO_2. In practical terms, this is constrained by the amount of carbonate ion available to neutralise the carbonic acid formed by dissolved carbon dioxide if large excursions in overall oceanic pH values are to be avoided. Estimates for carbonate available in deep ocean sediments range between only 1,600 Gt and 4,920 Gt. Dissolved carbonate ion in ocean waters deeper than 500m have been estimated at 1,320 Gt. It must be stressed that these values are highly speculative due to the paucity of empirical data (see: Wong & Hirai, 1997). Nevertheless they have spurred much research into how CO_2 might be injected into deep ocean waters and stored there.

The carbon cycle in the ocean is based upon interactions between physical, chemical and biological processes. These processes are understood in individual terms to varying extents, but the interactive aspects are subject to extremely large uncertainties. In large part this is due to poor spatial and temporal resolution of understanding of these processes in the ocean despite the data generated by large ocean research programmes on this topic and to the resultant inadequacies of the mathematical models applied to such studies (Follows *et al.*, 1996; Ormerod, 1996a). CO_2 uptake from the oceans has largely been inferred from calculations based upon sparse total inorganic carbon measurements. Improving the precision of these estimates by suitably intense sampling programmes is likely to be some decades into the future (Goyet *et al.*, 1997). Hence, current published notional annual uptake estimates for CO_2 range between 1.5 and 3.1 Gt. The question of how and where anthropogenic CO_2 penetrates into the ocean will remain unanswered until additional field measurements are available covering all areas of ocean within the depth of the winter mixed layer at an appropriate spatial resolution. In many respects this question is allied to the questions concerning the likely retention time of carbon dioxide disposed into the ocean. Atmosphere-ocean equilibrium is determined by total ocean circulation processes and physico-chemical properties of the water.

Once again, the predictions of the fate of anthropogenic CO_2 in relation to the oceans are predicated upon the generalised assumptions that the major ocean processes will remain unchanged under conditions of climate change. As noted below, this cannot be relied upon.

Anthropogenic influence on the climate

The World Meteorological Organisation, in its annual statement on the Global Climate has recently reported that the global surface temperature of the earth was the highest since 1860 (WMO, 1998). In addition to stating that 1998 was the 20th consecutive year with above normal temperatures, the statement also notes that the ten warmest years have all occurred since 1983. Seven of these years occurred after 1990, and new monthly temperature records were set in each of the eighteen months preceding October 1998. Currently, average global surface temperatures are some 0.7°C above those recorded at the end of the 19th Century.

These observations, together with documented climate and weather anomalies across the world accord with predictions made by climate models. Moreover, the Intergovernmental Panel on Climate Change (IPCC, 1996a) has projected that by the year 2100 global average surface air temperatures will have increased by between 1° and 3.5°C, relative to 1990. This would constitute a larger increase than any following the emergence of the earth from the last ice-age 10,000 years before present (BP).

The uncertainty of the precise rise likely to occur results from several factors. Different assumptions made about population and economic growth and about the chosen energy supply affect projected future emissions of greenhouse gases. Uncertainty as to the sensitivity of the climate (defined as the temperature rise associated with a doubling of atmospheric CO_2 concentrations or its equivalent in terms of other greenhouse gases) and over the role of atmospheric aerosols affect substantially the climatic effect of any given trajectory of greenhouse gas emissions.

While the evolution of climate has been, and will continue to be, influenced in the shorter term by other sources of cyclic climatic variation, the IPCC concluded nonetheless that “climate has changed over the last century” and that “the balance of evidence suggests a discernible human influence on global climate” (IPCC, 1996a). Work published since the IPCC Second Assessment concluded in 1995 has reinforced this finding. A recent retrospective analysis of extended data sets of climatic indices over the past six centuries (Mann *et al.*, 1998) led to the conclusion that “it is reasonable to infer that greenhouse-gas forcing is now the dominant external forcing of the climate system.” Work in progress at NOAA indicates that 1998 may well be the warmest year in 1200 years.

The “human influence” on climate through the production and release of carbon dioxide was predicted as early as the turn of the century by Svante Arrhenius (see: Arrhenius, 1997). Reflecting the cultural optimism of the time, he suggested that warming of the earth, caused by the greater retention of heat energy emitted from the surface by water vapour and increased atmospheric carbon dioxide concentrations, would be generally beneficial. This view was based upon the critical role of the greenhouse effect in the emergence and support of life on the planet. This optimistic view has subsequently been considerably modified in recent times.

The greenhouse gases

The rise in carbon dioxide concentration in the atmosphere since the onset of industrialisation has been substantial. CO_2 concentration has increased from around 280 ppmv in the 18th century to over 360 ppmv by 1997, with half this increase having occurred since the mid 1960's. The CO_2 concentration is increasing at about 1.5 ppmv (or 0.4%) per year at present. In terms of carbon loading, in pre-industrial times the atmosphere contained about 590 billion tonnes of this gas (calculated as carbon). Between 1765 and 1991 this rose to 755 billion tonnes (Moore & Braswell, 1994). Over this period an estimated 220 GtC was emitted from fossil fuel burning and about 130 GtC was taken up by the oceans. Table 1 shows the estimated 1980s carbon budget for the atmosphere-ocean system. Annual emissions in the 1980s were around 7.1 billion tonnes of carbon, 5.5 billion tonnes of which is from fossil fuels and 1.6 GtC from tropical deforestation. About 3.3 billion tonnes remains in the atmosphere and about 2 billion tonnes is transferred to the oceans. It is inferred that the remainder is stored in the terrestrial biosphere (IPCC, 1996a).

In addition to carbon dioxide, various other gases have been recognised as important in relation to climate change. There is now a broad scientific consensus as to the many potential negative consequences of increasing the atmospheric concentrations of these gases (IPCC, 1996b). Other greenhouse gases include methane, nitrous oxide, chloro- and hydrochlorofluorocarbons (CFCs and HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6) and the perfluorocarbons (PFCs). Concentrations of all have risen steadily in the atmosphere as compared to pre-industrial times. Some of these gases (methane, nitrous oxide) are produced in significant quantities by natural sources . It is, however, the anthropogenic component of emissions of these gases that is leading to their increase in atmospheric concentration. Most of the halogenated compounds (SF_6, CFCs, HCFCs HFCs and PFCs) are either not produced naturally or produced in insignificant amounts relative to releases from anthropogenic sources (see: *e.g.* Stringer & Johnston, 1995).

The CFCs and HCFCs are being phased out under the terms of the Montreal Protocol due to their ozone depleting properties. They are also, however, important greenhouse gases and can significantly modify the radiative forcing of the climate system. In addition they also act indirectly by depleting stratospheric ozone, particularly in the lower-stratosphere. This results in a net negative radiative forcing of the climate system and this offsets (on a globally averaged basis) some of the overall positive forcing due to the direct effects of these gases (IPCC, 1996a).

As temperatures rise in response to increasing concentrations of atmospheric greenhouse gases, a variety of potential impacts have been identified and discussed in the literature. Sea level rise, resulting in the inundation of large tracts of coastal land is perhaps the most obvious (20-86 cm by 2100). In addition, however, wide ranging impacts upon the earth’s major biomes, disruption of hydrological cycles and serious disruptive impacts upon agricultural production and human health have all been predicted as likely effects (DETR, 1998; WRI, 1998). For example, weakening or disruption of the North Atlantic thermohaline circulation mechanism has been predicted as a result of global temperature rise (DETR, 1998). This would have

profound implications for the climatic regime in Northern Europe and hence for the human population and the ecosystems of the region.

IPCC 1995 Global Carbon Budget for the 1980s

Emissions	**PgC/yr**
Fossil Fuels	5.5±.5
Tropical Deforestation	1.6 ± 1.0
Uptake	PgC/yr
Atmospheric Buildup	3.3
Ocean Uptake	2.0 ± 0.8
Forest Regrowth (NH)	0.5 ± 0.5
Land Sink (by difference)	1.3 ± 1.5

Source: IPCC, 1996a.

Table 1: Global carbon budget for post industrial times showing major emission sources and uptakes in $PgCy^{-1}$ (Gt). Discrepancies between the figures cited in this table and those cited in Figure 2 and in the text arise from the considerable uncertainties attached to estimates of carbon fluxes and reservoirs.

Irrespective of virtually any future successful limitations of greenhouse gases, the globe is already committed to an increase in temperature and hence of sea level, as a result of historical emissions and the large degree of inertia in the climatic system (DETR, 1997). To halt temperature increase within four to five decades, for example, would require cessation of all anthropogenic emissions within just a few decades. Even if these emissions could all be stopped within this time frame, sea level would continue to rise over many more decades. This rise would be sufficient to cause damage to vulnerable coasts and small islands. The issue, therefore, is not one of how to stop human induced climate change *per se,* but how to restrict the likely changes to dimensions which can possibly be accommodated by natural ecosystems and human society.

Of the six major greenhouse-gases which are not controlled under the Montreal Protocol, carbon dioxide is quantitatively the most important, accounting for 64% of the total additional direct radiative forcing. Nevertheless the others are also of considerable significance. Methane (CH_4) contributes 19% to the direct radiative forcing and nitrous oxide (N_20) around 6%. The various halocarbons controlled under the Montreal Protocol contribute a sum total of 11% of the direct radiative forcing (IPCC, 1996a).

The relative proportions will obviously change as regulation of, for example, the halocarbons becomes effective. Other contributors may grow in relative and absolute importance in the future. Unless controlled, emissions of HFCs, PFCs and SF_6 are projected to be of the order of 5% of 1990 CO_2 emissions by 2005 and 13% by 2010 (Kroeze, 1995). Some of the PFCs have extremely long lifetimes (of the order of 10,000 years) and very high greenhouse warming potentials (GWPs) earning them the title of “eternal fluorocarbons”. Sulphur hexafluoride (SF_6) used in the electrical and metal smelting industries is emerging as a gas of great significance in relation to climate change with its long atmospheric lifetime of 3200 years and high greenhouse warming potential (Maiss & Brenninkmeijer, 1998).

Future energy use and carbon emissions

The scope for increasing the concentration of CO_2 still further is substantial. Estimates of fossil fuels which could ultimately be recovered vary, but between 4,000 and 4,500 Gt can be considered a reasonable estimate (WEC,1993; Rogner,1997). Against this background of recoverable reserves is a strong trend of increasing energy generation and consumption with much of this reliant upon fossil fuels. World Resources Institute figures (WRI, 1998) state that global energy use has risen by almost 70% since 1971, driven by economic expansion and development. Demand has increased by around 2% per year for the last quarter of a century and will continue this increase over the next 15 years if current energy use patterns are maintained.

By the year 2010, taking into account the Kyoto Protocol, the International Energy Agency (IEA, 1998b) has predicted that energy related annual CO_2 emissions will have risen by over 30% compared to 1990 figures (without the Kyoto Protocol emissions are projected to increase by over 45% by 2010)). Although according to IEA projections, even with the Kyoto Protocol, industrialised country emissions would still exceed those of the developing world in 2010, a significant proportion of the increase in energy demand is projected to be attributable to infrastructural and industrial expansion in developing nations. Their share of global energy consumption is projected to increase from around 30% to reach 40% by the year 2010. Future energy demand and generation is projected to be particularly high in China and South Asia, where coal (a highly carbon intensive fuel) is used to generate some 60-70% of the electricity used.

Even if emissions were to be held at current levels, atmospheric CO_2 would continue to rise for several centuries, doubling pre-industrial concentrations by the middle of 22nd century (IPCC, 1996a). However emissions are continuing to increase. Four of the six IPCC scenarios for future emissions of greenhouse gases project a doubling of CO_2 before 2070. When the effect of other greenhouse gases is taken into account equivalent doubling of CO_2 (due to the combined increase of all the greenhouse gases - CO_2, methane, nitrous oxides, HFCs, PFCs and SF_6) is likely by 2030-2040.

The 1992 Framework Convention on Climate Change and The 1997 Kyoto Protocol

The emerging scientific consensus on the scale and scope of the possible impacts of anthropogenic climate change eventually launched the issue in the political arena. In 1992, at the Rio Earth Summit, 167 nations signed the United Nations Framework Convention on Climate Change (UNFCCC). The ultimate objective of the Convention is to achieve the *"stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with the climate system"* . The aim is to achieve this within a timeframe that allows ecosystems to adapt, does not threaten food production and one that provides for sustainable development. In terms of specific emission commitments the Convention has the "aim" for industrialised countries to reduce carbon dioxide and other greenhouse gas emissions to 1990 levels. This specific obligation in the convention, however, is legally weak and ambiguous and most countries have not adhered to it.

Moreover, the first review of the adequacy of emission commitments at the First Conference of Parties (COP1) in 1995 led to an agreement that the stabilisation of emissions by developed nations at 1990 levels was inadequate for achieving the ultimate objective of the UNFCCC. As a consequence, COP1 agreed to negotiate a protocol (or another legal instrument to the convention) for agreement at COP3. Mid-way through this process, at COP2, the USA declared that any new emission obligations should be legally binding, thereby crystallising a consensus that the Kyoto Protocol (as it would be called) had to contain precise and binding emission obligations. After lengthy negotiation, the Kyoto Protocol to the Convention in was adopted at COP3 in December 1997. Essentially, the Protocol set an average global emission reduction target for the industrialised world of combined greenhouse-gases of 5.1% by 2008-2012 and within this framework each industrialised country has a specific, agreed obligation. In addition countries with legally binding emission commitments are expected to show "demonstrable progress" towards fulfilling their obligations under the Protocol by the year 2005.

The Kyoto Protocol is widely seen as a significant step forward in reducing CO_2 emissions on a global basis. Insofar as the Protocol was forged in the face of diverse economic issues and in the face of different priorities *vis-à-vis* industrialised and developing nations this is undoubtedly true. Nevertheless, the Protocol is also acknowledged as not being adequate in terms of achieving the ultimate objective of the Convention (see: WRI, 1998). Fundamentally, the agreed provisions fall far short of the measures which are known to be necessary to stabilise atmospheric CO_2 at any level. The Protocol, even if it proves effective, is only a first step. Much larger and faster reductions will be required in the second commitment period (2013-2017).

Carbon-Logic

The First and Second Assessment Reports of the IPCC represent the mainstream scientific acceptance that anthropogenic climate change is a real phenomenon requiring protective measures. The Kyoto Protocol is evidence of some tentative political translation of these concerns into legally binding obligations. A clear consensus has yet to emerge, however, concerning the climate goals or greenhouse gas stabilisation targets necessary to prevent “dangerous anthropogenic interference with the climate system”. A default metric of the doubling of CO_2 is often referred to particularly in economic circles. At a political level the European Union has called for global climate policy to limit the temperature increase to a maximum of 2ºC above pre-industrial temperatures. The Alliance of Small Island States has called for a target of a maximum sea-level rise of 20 cm above 1990 levels.

Emissions scenarios can be devised according to a variety of concentration and possible impact constraints imposed upon predictive models. An example of such an approach is the use of the IMAGE model developed in the Netherlands in the so-called "safe emissions corridor approach" (Alcamo & Kreileman, 1996). Nevertheless, restricting CO_2 to any given level would not guarantee that dramatic and unmanageable changes would not occur. Indeed, no concentration target is proof against such uncertainties, but it is assumed that, in general, lowered concentrations result in lowered impact. Central to this assumption is the hypothesis that climate will respond in a linear manner to an increased global temperature regime and that no rate-thresholds of change exist. The validity of these assumptions is far from certain (IPCC, 1998)

If it is accepted that uncertainties are engendered by an incomplete understanding of climatic and ecological systems, then it is possible to develop the concept of precautionary limiting of the rate of change taking place in these systems. Equilibrium concentration values of greenhouse gases to constrain change within the set limits can then be estimated. Subsequently, this can be used to estimate the quantities of fossil fuel which can be used without exceeding these “ecological limits”. This approach has been taken by Hare (1997) and has been termed the “Carbon Logic”.

Essentially, this approach assumes that protection of the majority of ecosystems could be achieved by limiting sea level rise to a rate of 20 mm per decade and a maximum 20 cm increase above 1990 levels. Global temperature rise should be limited to a maximum rate of 0.1°C per decade as quickly as possible with a maximum rise of 1.0°C over the pre-industrial average. These values (see: Rijsberman & Swart, 1990) were derived by the United Nations Advisory Group on Greenhouse Gases (UNAGGG).

The EC proposed limit of 2.0°C requires that equivalent CO_2 be below 485 ppmv, for the IPCC best estimate of climate sensitivity of 2.5°C, or below 415 ppmv, for a sensitivity of 3.5 °C. The actual CO_2 concentration stabilisation levels (assuming that the forcing of other gases is equivalent to around 23 per cent of the effect of the CO_2 increase alone) are around 435 ppmv and 380 ppmv respectively. A 1.0 °C limit, however, requires in the long term that equivalent CO_2 be below 370 ppmv for the IPCC ‘best-estimate’ of climate sensitivity and below 340 ppmv for a sensitivity of 3.5 °C. The actual CO_2 concentration (assuming that the forcing of other gases is as above) would be below 350 ppmv and 330 ppmv respectively. Such levels could be only be reached in the 22nd century, and only as consequence of policies adopted early in the 21st century.

In turn, the calculated CO_2 levels can be used as a basis for calculating the quantities of fossil fuel (as carbon) which can actually be emitted to the atmosphere in this form as a result of energy generation if this stabilisation target is to be met. For a 1° C limit and climate sensitivity of 3.5° C the figure arrived at is 225 Gt of carbon and this assumes major initiatives to preserve and regenerate forests globally. If these initiatives are not embarked upon then the carbon budget figure falls to 145 Gt. Optimistically assuming that the 225 Gt budget can be applied, this equates to around 40 years of consumable fossil resources at current rates of energy consumption. Assuming an increase in energy demand of 2% *per annum* then 225 Gt would provide fuel for some 30 years. This equates to 75% of the known economically extractable reserves of oil alone.

Clearly, this estimate, like all others, is held hostage to the accuracy of the values used to derive it. If it subsequently becomes obvious that the defined ecological limits are insufficient, knowledge of the carbon cycle improves, other greenhouse gases are found to play a smaller or larger role or the climate sensitivity value becomes known with more precision then the approach will require fine tuning. By assuming conservative values to accommodate some of the uncertainty at the outset, then a degree of precaution is built into the approach. Given that policies have to deal retrospectively with an existing commitment to some degree of climate change, this represents, perhaps, the most precautionary approach to date.

The carbon budget approach to "allowable" emissions of greenhouse gases provides an alternative perspective on the core issues relating to climate policy which flow from the related concepts of trans-generational responsibility and of equity across the extant groupings of developed and developing nations (see: Cairns, 1997) In practical terms, it more easily allows the scale of the problem bequeathed to these future generations to be held within the defined “ecological” constraints. In addition it furnishes a metric against which continued development of the fossil fuel industry can be regulated with these “ecological targets” and future generations in mind.

Ocean Fertilisation

Fertilisation with iron

Iron is a limiting micro-nutrient for algal growth in some large areas of the worlds oceans. Ocean fertilisation with iron has been theoretically and to an extent, practically explored. The Ironex series of experiments conducted in the Equatorial Pacific Ocean were conducted to assess the scope for increase in primary production of algae by supplying the limiting nutrient over an area of 64 km^{-2}. In response to a single introduction of the metal to these high nitrate/low chlorophyll waters a biological response was observed. A second experiment in which multiple iron additions were made showed that both particulate and dissolved organic carbon increased as did oxygen concentrations. CO_2 concentrations in the water decreased. Significantly, the researchers stated that the experiments were “not intended as preliminary steps to climate manipulation”. Inevitably, however, these studies have been discussed in relation to their applicability to climate change mitigation (Ormerod & Angel , 1998) and modelling studies have been carried out based upon the concept.

Models have shown (see: Ormerod & Angel, 1998) that the largest effect of iron fertilisation would be in the Southern Ocean, where a doubling of primary production could take place. This, however, could be offset by productivity falls in other ocean areas but could still lead after 100 years to atmospheric CO_2 levels 72 ppmv lower than without iron fertilisation. Predicted concentrations under the IPCC business as usual scenario are around 785 ppmv. The model assumes that Southern Ocean waters would be completely depleted of the macro-nutrients through adding iron. The model also suggested that the optimal effect would take place over some 18% of the Southern Ocean area where convective plumes exist. The draw down of atmospheric carbon dioxide would be less than that implied by the amount of new primary production generated since some of the carbon dioxide would be supplied by changes in the seawater bicarbonate equilibrium

There are, however, some considerable problems associated with this approach. A major drawback is the fact that the practical investigations have shown the effect of the iron to be fairly short-lived. A week after additions were stopped, phytoplankton production had returned to pre-fertilisation levels. Hence, for iron fertilisation to have any significant impact upon atmospheric CO_2 it would need to be maintained over extremely long time frames, in excess of one hundred years (see: Ormerod & Angel, 1998). The amount of carbon which would be sequestered would amount to 0.5 Gt *per annum* given that 2700 ships or 200 aircraft were available to treat 1.7×10^7

km^{-2} of sea surface with around 470,000 tonnes of iron per year (Sarmiento & Orr, 1991) on a continuous basis. In addition to these logistic requirements there would be an energy penalty resulting from the extraction and production of the iron used although this is likely to be minor given current production of the world steel industry at around 700 million tons annually (Nagasawa, 1995). The attached time frame carries with it considerable trans-generational responsibilities to continue the process. Models have shown that if the exercise is stopped after 50 years, a significant proportion of the carbon fixed in this way would return to the atmosphere as CO_2 over the subsequent half century (Ormerod & Angel, 1998).

It is also possible that the increased primary production could result in significant oxygen depletion of oceanic waters due to the activities of microbes in response to increases in dissolved organic carbon. Modelling exercises suggest that widespread deoxygenation of 10-25% could take place over the whole of the Southern Ocean if macro-nutrients were fully depleted by iron addition. This is more serious than it might seem at first sight since the depletion of oxygen would not be consistent. The model predicts anoxic water spreading at mid-depths in the Indian Ocean within 100 years. There is the possibility too of productivity being reduced in areas outside the Southern Ocean as a result.

Another area of concern relates to emissions of the chemical dimethyl-sulphide (DMS). In the Ironex II experiments the increased algal growth resulted in a threefold increase in DMS emissions (Turner *et al.*, 1996). While DMS can exert a cooling effect through the formation of sulphate aerosols and by affecting cloud density the addition of this effect could be counter productive in the long term. Increased cloud cover could act to limit the amount of light available for primary production and hence sequestration of carbon. Furthermore, once iron additions ceased, then DMS evolution would be reduced, potentially allowing temperatures once again to increase. Increased primary production, accompanied by anoxic conditions, could also result in the increased production of the other greenhouse gases N_2O and CH_4. It has been calculated that N_2O production would double and that this could completely offset the net gain from reducing atmospheric CO_2 concentrations (Fuhrman & Capone, 1991, cited by Ormerod & Angel, 1998). Conversely, it has also been postulated that runaway mobilisation of inactive iron already present in seawater could take place as a result of chemical and ecosystem changes in turn resulting in uncontrollable cooling. This possibility arises from the fact phytoplankton blooms may affect the biogeochemical cycling of iron in a number of ways. These include adsorption on the cells as well as intracellular uptake of dissolved Fe, the mechanisms and dynamics of which remain under investigation (*e.g.* Xue *et al.*, 1998, Weger, 1999). Precipitation and accumulation of Fe may take place at the surface or within phytoplankton oxidising micro-environments such as large diatoms, algal aggregates or colonies of algae (Schoemann *et al.*, 1998). This latter is a key area of uncertainty which needs to be resolved before addition of iron on a large scale to the oceans could be seriously contemplated but is one which is likely to prove intractable to prospective analysis.

The potential for changes in whole ocean ecosystems as a consequence of iron fertilisation is suggested by the changes in ecosystem community structure observed in the Ironex II experiment (Martin *et al.*, 1994). The differential response of the various planktonic organisms resulted in an altered community structure (Coale *et al.*, 1996; Martin *et al*, 1994). In particular the explosive growth of algae caused the balance between primary and secondary producers to be lost. Over a longer period of time it is likely that ecosystem changes could be very extensive, with unanticipated effects at all levels of the food web including the appearance of nuisance species. In fact, while ecosystems may be resilient, fundamental changes are often not detected until suitably sophisticated analysis of population and community data is carried out. This applies both to relatively small areas of impact (see: *e.g.* Olsgard & Gray, 1995) and to whole ocean basin systems subject to anthropogenic pressures such as fishing (Pauly *et al.*, 1998).

The precise species of phytoplanktonic and zooplanktonic organisms likely to be favoured in an open ocean environment fertilised with iron, particularly in the long term, is an issue of some importance. Some organisms fix calcium carbonate in the form of calcareous plates, shells or tests. A shift towards dominance of organisms possessing carbonate structures would reduce the total dissolved inorganic carbon in the surface layer. Nevertheless, the calcification reaction would cause an increase in the partial pressure of carbon dioxide in surface waters and a net efflux of CO_2 from the ocean to the atmosphere (see; *e.g.* Crawford & Purdie, 1997). The potential significance of this process in the wider context of the carbon cycle is not known (IPCC, 1996a). Other recent research has thrown into doubt the accepted wisdom that photosynthetic activity exclusively fixes and sequesters carbon dioxide. Major marine photosynthetic organisms have been shown in experimental cultures to act as a source of $CO_{2,}$ rather than a sink. The significance of this, once again, in natural systems where cell densities are very much lower is unknown, but clearly has implications for carbon sequestration strategies involving ocean fertilisation (Tchernov *et al*,. 1998).

The source of the iron used in such activities is also an issue of some importance. It is possible that this requirement could be met through the use of scrap iron and iron rich industrial wastes (see: Johnston *et al.*, 1998). This is turn could cause the introduction of environmentally dangerous substances on a large scale as well as reducing the energy saved globally by recycling steel (see: Nagasawa, 1995). There is every reason, therefore, to expect far reaching negative ecosystem and other changes as a result of fertilising ocean waters with iron for planetary engineering purposes.

The shipboard experiments investigating iron fertilisation are due to continue during 1998. As such they will undoubtedly provide much useful information on the role of iron in the global ice ages, as is the declared intent. In terms of larger application of the idea for climate change mitigation, the Southern Ocean is protected under International Treaty from exploitation in this way. It has been pointed out that until more is learned about the possible ecological impacts of ocean fertilisation it should be considered a highly speculative longer term CO_2 abatement option (Herzog *et al.*, 1997). In this context it should be noted that the IPCC Second Assessment Report, in reviewing research in this area, concluded that the intentional fertilisation of the Southern Ocean to promote growth and hence the drawdown of atmospheric CO_2 appeared not to be viable for two main reasons. Firstly, it would require fertilisation of 25% of the world ocean continuously and indefinitely. Secondly if it worked perfectly, it would only reduce the increase in atmospheric CO_2 concentration over the next century by about 50 ppmv (Denman *et al.*, 1996).

Fertilisation with macro-nutrients

Addition of the macro-nutrients, nitrate and phosphate to seawater has also been proposed. The concept is under investigation in practical terms through the Norwegian MARICULT project which is geared to the investigation of aquacultural possibilities for increasing supplies of food and natural raw materials (Ormerod & Angel, 1998). Nonetheless, the idea that this might increase oceanic uptake of CO_2 is recognised. Most of the potential impacts of this strategy are common to the iron fertilisation concept. In the case of macro-nutrients, however, many of these impacts have been observed in natural systems impacted by nutrients introduced *via* sewage or agricultural sources. Ecosystem changes, anoxic waters and the appearance of nuisance species have all been documented in coastal waters subject to enhanced macro-nutrient loading (see: Johnston *et al*., 1998).

Whether this is achieved by the addition of chemical fertiliser or through the generation of ammonia from natural gas and atmospheric nitrogen (Jones & Cappelen-Smith, 1998), the capital costs are likely to be high. Some schemes envisage the addition of up to 150 million tonnes of nitrogen *per annum* by the year 2100 in order to sequester 150 Gt of carbon over the century. (Jones, 1996). It is estimated (see: Ormerod & Angel, 1998) that a pilot scheme designed to run over three years would require 0.12 Mt N y^{-1} to sequester 0.5 Mt C y^{-1} taking account of CO_2 emissions from manufacture of the nitrogen fertiliser. The costs of the fertiliser would also be extremely high compared to iron, and would generate CO_2 emissions during their manufacture which would offset a large fraction of that drawn down from atmosphere. It has been estimated (Jones, 1996) that typically, around 25% of the carbon taken up by photosynthesis in any given macro-nutrient fertilisation scenario is offset by CO_2 emissions from the fertiliser manufacture. If the manufacture involves the production of nitrates *via* nitric acid, then substantial emissions of nitrous oxide, a powerful greenhouse gas, could also be expected. This is not accounted for in most analyses, since these assume the use of ammonium fertiliser.

In addition, it is possible that only 44% of the carbon dioxide used in the new production would be derived from atmosphere. Modelling exercises (see: Ormerod & Angel, 1998) have suggested that the larger part of the CO_2 would be taken from the seawater due to shifts in the carbonate/bicarbonate equilibrium and changes in oceanic exchange processes. This would effectively double the costs of sequestration. Finally, it is recognised that increasing fish production, a declared aim of macro-nutrient fertilisation proposals which effectively keeps carbon materials in circulation in the upper ocean, is not really compatible with removing CO_2 from the atmosphere to deep oceanic water.

There are also commercial aspects which could provoke changes in international law of wide ranging significance to developing countries. It is argued that some of the costs of macronutriemt fertiliser schemes could be offset against improved fish harvests. This assumes that the species which emerge under this artificial ecological regime are of commercial value. It has been noted also that benefits of such activities will not flow exclusively to those making the investments. Jones (1996) suggested the need for a system of UN ownership of the “additional fish stocks” such that “UN issued fishing licences could regulate the distribution of costs and benefits”.

In conclusion, ocean fertilisation is an extremely high risk strategy for the mitigation of climate change. Interference with biological systems on this scale is unlikely to produce predictable results. The rationale is grounded in the *de facto* wide scale disturbance of marine ecosystems. There is, therefore, the possibility of regime shifts taking place in the impacted ecosystems. Most analyses of the potential for ecosystem disruption have tended to be somewhat simplistic due to the paucity of data. All imply the use of substantial resources either in logistics or materials required or both. There is a need to examine this issue in a more holistic fashion, shifting the focus away from engineering feasibility towards consideration of the full environmental impacts.

One key area that ocean fertilisation proposals do not appear to have factored into the analyses conducted to date are changes which could take place in ocean circulation patterns which might, of themselves, significantly affect primary production. It is unlikely that all the uncertainties can be fully resolved and commitment to the option in practical terms will of necessity be long term. Under these circumstances it is difficult to envisage how such a strategy represents either a precautionary or a sustainable approach to the climate change problem.

Disposal of CO_2 into ocean waters

Energy Penalties

The disposal of carbon dioxide into deep ocean waters has been widely researched on a theoretical basis (Wong & Hirai, 1997; Ormerod, 1996 a & b; Ormerod, 1997; Ormerod & Angel, 1996). Such proposals are specifically predicated upon the basis that it will be possible to capture the carbon dioxide emitted from the majority of the world’s power stations and transport it for disposal into deep water. This strategy carries with it a significant energy penalty from the outset. A typical capture scheme involves absorbing CO_2 into a solvent from the flue gases. Disposal of the complete flue gas is unlikely to be viable since the carbon dioxide content ranges from about 3% in the case of gas turbine plant (Langeland & Wilhelmsen, 1993), similar to a natural gas combined cycle plant (3.6%), to flue gas concentrations of around 14% for a coal fired power plant. In the case of some specialised petrochemical processes this may be as high as 80% (see: Bailey & McDonald, 1993) while coal based plant with oxygen fuel and CO_2 recycle could reach 92%.

Processes for the capture of carbon dioxide have evolved from original interest in enhanced oil recovery and the first capture plants were constructed in the late 1970’s and 1980’s. The process is in use commercially for the carbonation of brine in industrial processes in the US and, while most of the original plants in the US have been closed, a second generation of facilities was constructed in response to qualifying conditions under the US Public Utility Regulatory Policies Act of 1978 (PURPA) (Herzog *et al.*, 1997). The commercially available systems are based upon the use of amine solvents, principally monoethanolamine (MEA), developed originally to treat sour gas containing hydrogen sulphide. The MEA contacts the flue gas in an absorber and takes up the CO_2. This is subsequently steam-stripped to release relatively pure carbon dioxide.

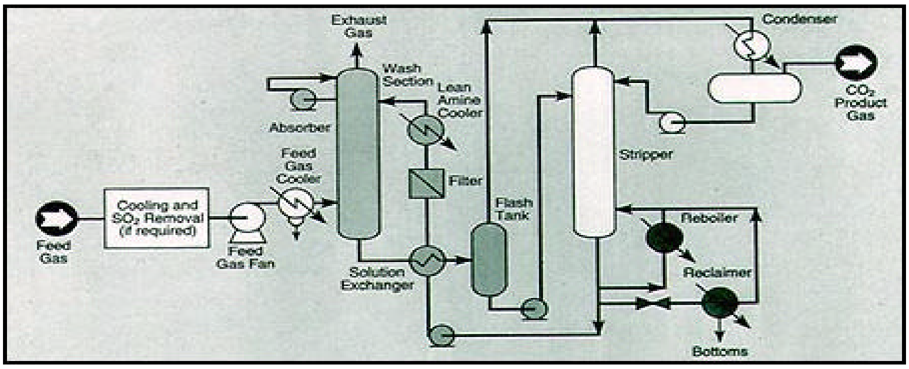


Figure 3: Schematic diagram for a process for the capture of carbon dioxide from power station/industrial process flue gases. This indicates the energy demanding components of the process and the waste streams generated as a result.

Current energy penalties, in other words the reduction in utility output as a result of using the process, range from between 15 and 24% for gas fired plant to between 27-37% for conventional coal fired plant. Advanced coal plant attracts an energy penalty of 13-17% (Herzog *et al.*, 1997). These figures do not include liquefaction and disposal penalties. These estimates are broadly supported by other estimates (Leci, 1996) suggesting absolute reductions in efficiency of up to 35%. Effectively, capture alone would reduced the thermal efficiency of a typical power plant from around 35% to 25% (GESAMP, 1997) accounting for around 30% of the total energy content of the coal used as fuel. Some improvements envisaged for the future suggest penalties could be brought down to between 9% and 15%. This energy penalty effectively results in a reduced efficiency of the plant.

A further 10% of the fuel value of the coal would be required to liquefy and compress the carbon dioxide to a pressure enabling deep-water discharge (150 Atm) (Golomb, 1993). Other estimates (Haugen & Eide, 1996) include liquefaction and disposal penalties with those from capture. These suggest that for a 500MW power station the electricity consumption for the MEA process amounts to between 18 and 24MW. In addition the steam requirement for stripping the solvent equates to between 70 and 140 MW and is smallest for gas fired power stations. In order to prepare the stripped CO_2 for disposal it must be liquefied, pressurised and purified. Assuming injection into an aquifer, this will require an additional 55-60MW for a coal fired plant and about 30-40MW for a gas fired plant. Transport of CO_2 from a pulverised coal plant over 100 km would require a further 3MW and, if the full capacity of a large diameter pipe were used, the total energy required for this phase would be 12-14MW.

Accordingly, the total electricity loss from a 500MW facility capturing and disposing of CO_2 can be expected to amount to at least 80MW (16%) while heat losses due to steam consumption account for at least 70MW. A total penalty of 25%-45% can, therefore, be expected on the basis of current technology. This will inevitably result in greater quantities of carbon dioxide being generated for a given unit of energy produced.

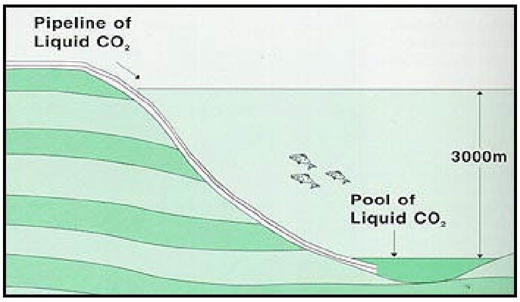
This reduction in efficiency has considerable long term implications for the concept of ocean dumping of carbon dioxide. As noted above, a dumping strategy essentially would influence the near term transient peak of CO_2 (over the next several centuries) but results in the same long term stabilisation level in the atmosphere after several centuries. If the energy used in the capture and disposal processes is taken into account, the long term stabilisation value could then be significantly higher than under a "business as usual" scenario, depending upon the precise mix of fossil fuels used in energy generation and their relative carbon intensities. Hence, the assertion (Herzog *et al.*, 1997) that ocean disposal represents simply a short circuit of natural processes is somewhat disingenuous since it does not appear to accommodate the fact that adoption of the strategy will lead in the longer term to higher CO_2 concentrations than would otherwise have been the case. This has been recognised in modelling exercises which have shown that, where marine disposal systems are used, the long term atmospheric concentrations ultimately exceed those from systems without controls using disposal to ocean (Flannery *et al.*, 1993).

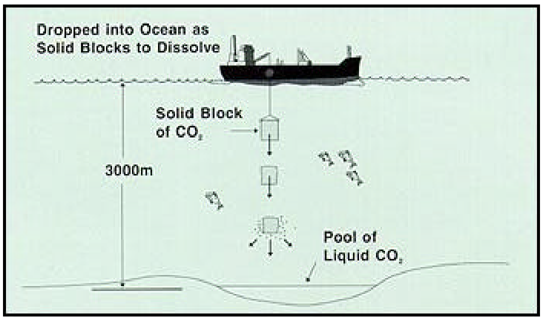
Technical approaches to deep sea disposal

Notwithstanding the basic paradox that in the long term ocean disposal is likely to worsen equilibrium concentrations of atmospheric carbon dioxide, considerable theoretical and practical research has been directed at refining the concept. These activities are culminating in various "proof of concept" experiments. Thus far, proposals for ocean disposal of carbon dioxide involve one of three methods of introduction:

- Introduction by pipeline into deepwater followed by dissolution
- Dispersion following discharge of dry-ice blocks or liquid CO_2 from a ship
- Formation of a lake of liquid CO_2 in the deep ocean

These concepts are illustrated in Figure 4a-c below:





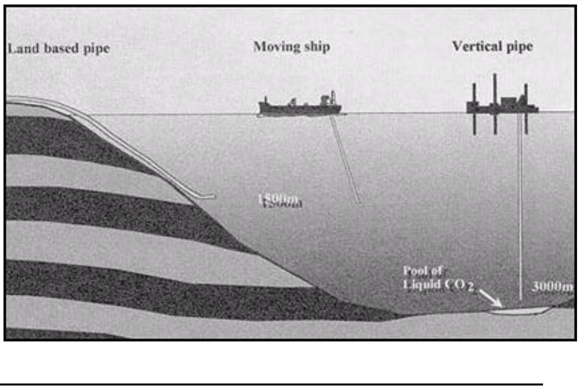


Figure 4 a-c: Concepts for the deep sea disposal of carbon dioxide captured from power and industrial plant. These involve the discharge of liquid carbon dioxide from land based pipelines in to deep water (Figure 4a) or the disposal of blocks of dry ice directly from vessels (Figure 4b). Figure 4c shows the proposed disposal of liquid carbon dioxide from a towed pipeline into mid ocean waters and the discharge of liquid carbon dioxide onto the seabed from a fixed platform.

In practice, the discharge of dry-ice blocks is likely to prove much more expensive than production of liquid carbon dioxide. It costs around twice as much to produce solid as opposed to liquid CO_2 (Golomb, 1993). The solid material would tend to sink; it has been calculated that cubes of 3-4m dimension would sink below 3000m before 50% of the CO_2 dissolved. One idea which has grown from this is to use shaped part solid / part liquid penetrators, 4-5m in diameter and 20-40m in length which sink and embed themselves in the sea-floor (Guevel *et al.*, 1996). Once again, the energy penalty is likely to be high and a large infrastructural cost is implied given that capacity will need to exist to handle the approximately 500 tonnes of CO_2 produced by a 500MW coal fired power plant each hour.

Most research effort has focused on the introduction of CO_2 by pipeline. At depths of less than 500m, introduction of CO_2 will create bubble plumes since, at ambient pressures and temperatures, carbon dioxide exists as a gas. These bubbles will dissolve in the seawater and, it is suggested, become trapped below the ocean thermocline. Although in engineering terms this is a relatively simple option, the retention time of the gas would be relatively short (around 50 years).

At prevailing temperatures and pressures between 500m and 3000m, carbon dioxide exists as a positively buoyant liquid. Hence, it will form a droplet plume, perhaps with the droplets covered in film of hydrate which could inhibit dissolution. Below 3000m, it is anticipated that CO_2 will form a negatively buoyant, sinking, liquid plume which could ultimately form a lake of liquid CO_2 on the sea bottom (Adams *et al.*, 1995) with a clathrate surface. Retention times in these cases should be much greater since deep water exchanges with surface water at a much lower rate than surface water interacts with the atmosphere in the upper mixed layer of the sea. Calculations have suggested that a lake of CO_2 on the deep ocean floor derived from 1GW of coal fired power plant over ten years of operation could cover 654,500m^2 of sea floor to a depth of 80.9m and contain 58 million tonnes of the liquefied gas (Wong & Hirai, 1997). The assumption that the pool would remain 80.9m in depth is merely a hypothetical construct to operate the mathematical model. Unless constrained by local topography, it seems reasonable to assume that, in practice, the liquid CO_2 would spread out to form a thinner layer over a much wider area, with the consequence of more widespread impacts.

Ocean circulation

Broadly speaking, the retention time for CO_2 disposed of to the ocean is regarded as a function of the depth at which it is discharged (Wong & Matear, 1993; GESAMP, 1997). In general, it has been considered that the greater the depth of emplacement, the longer the residence time. There are considerable regional variations in likely residence which have been demonstrated by using models (Bacastow *et al.*, 1993; Ormerod, 1996a). These are related to ocean circulation patterns. The models used, like all models, depend upon the data used to tune them and upon the accuracy of constant factors describing physico-chemical phenomena. The question of retention time is central to the viability of the CO_2 ocean disposal schemata. Time scales of 500-1000 years are necessary for the strategy of ocean disposal to be of effective, ignoring longer term considerations.

The disposal of liquid CO_2 in the water column is subject to ocean circulation processes to a far greater extent than that deposited on the sea floor in solid or liquid form. Eventually, however, ocean processes will dissolve all forms of dumped CO_2 and transport it towards the surface. It has been estimated that at a depth of >3000m a pool of CO_2 containing 58.4 Mt would dissolve into the deep water over approximately 240 years. Various values for the dissolution and movement of CO_2 in the deep sea have been derived through the use of observations and models but the models have acknowledged limitations (Ormerod, 1996a) and hence these predictions are subject to a high degree of uncertainty.

There have also been recent developments in understanding of ocean circulation processes in the North Pacific which necessitate revision of some key assumptions concerning circulation processes. It was assumed that, for example, the age of the water in some deep ocean basins was in excess of 1000 years. Recently the use of passive tracers such as chlorofluorocarbons, tritium and radiocarbon suggests that some of these previous estimates may be grossly inaccurate. The turnover time for deep water in the basins around the margins of the North Pacific (the Okhotsk, Japan and Bering Seas) is now estimated at 100 years or less as opposed to the previously accepted values of up to 1300 years. The basins of the Arctic Ocean which were thought to have a turnover time of 1000 years may actually ventilate in around 75-300 years (see: Wong & Matear, 1996). This obviously throws into serious question the presumed utility of these basins for CO_2 disposal which had previously been assumed to be possible.

Other work in the Pacific Ocean has resulted in conceptual changes around the functioning of the Global Conveyor which suggest that North Pacific bottom water actually turns over more slowly than previously thought, taking an additional 500-1000 years to reach the surface and being diluted by greater volumes of deep and intermediate water. While this may appear favourable to the idea of ocean disposal, the precise movements of water through the oceans are obviously only partially understood. In addition, there appears to be extreme uncertainty about how rapidly vertical mixing takes place, with widely divergent values cited in the literature (Wong & Matear, 1996). No deep measurements are available for the crucial parameter (diffusivity) which may, in any case, vary according to ocean floor topography on a site specific basis. Areas with steep structures on the ocean floor have diffusivities much higher than accepted “background” values, lending weight to the hypothesis that tidal mixing is predominantly responsible for deep ocean mixing (Munk & Wunsch, 1998), perhaps through turbulence created by topographical features (see *e.g.* Chiswell & Sutton, 1998). Wind driving is also considered to be highly important (Wunsch, 1998). The rate of vertical mixing of deep Pacific water is, accordingly, a subject of debate. Based upon ^{13}C and ^{14}C tracer studies, a mixing rate of 30 m y^{-1} has been inferred, implying that dumped CO_2 could reach surface waters in 140-200 years instead of the 1000-1500 years suggested in earlier literature. Overall, a great deal of uncertainty exists concerning the mechanisms of ocean circulation and heat exchange. Mixing is unlikely to be uniform, but may take place at localised active regions, such as well stirred bottom slopes (see: Killworth, 1999).

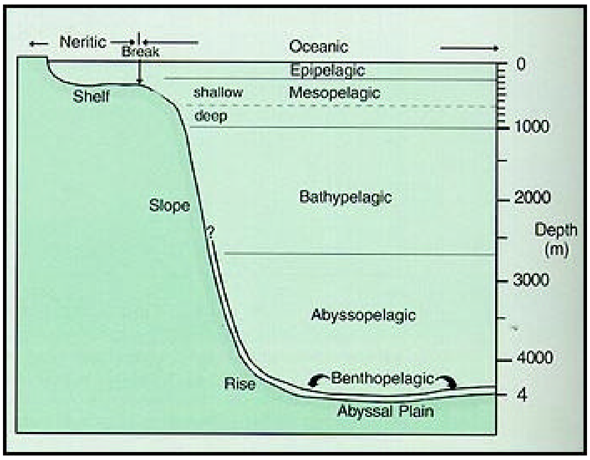


Figure 5: Diagrammatic representation of the major oceanic domains characterised by depth of water. Source: IEA (1998c).

Significantly, all of the analyses of residence times and ventilation times applied in CO_2 disposal studies have assumed that the current pattern of ocean circulation (insofar as it is precisely known) will be maintained into the future. It appears to date that none of the analyses of the fate of the CO_2 have considered the fact that the ocean circulation patterns could change either as a result of natural variability or as a result of climate change. Indeed, it has been suggested (Sarmiento *et al.*, 1998) that ocean circulation changes modelled under a global warming scenario could have very significant implications for oceanic CO_2 uptake in the future. As one possible example, while the basic phenomena associated with the El-Niño-Southern Oscillation are known, the deep oceanic changes associated with it are much more poorly understood. Moreover, complex land-ocean interactions in carbon budgets which occur during ENSO events are only now beginning to be documented. For example, the Amazon Basin, which normally acts as a substantial sink of carbon, may, in ENSO years, act as a significant carbon source (Tian *et al.*, 1998). Despite poor understanding of the mechanistics, however, ENSO events can be traced through changes in atmospheric variables recorded across the whole Pacific Basin (Tourre & White, 1997) and also appear to be correlated with interannual variability in tropical CO_2 sources, including changes in oceanic fluxes. This may be due to suppression of upwelling in the Eastern Pacific (Rayner *et al.*, 1999). What effect these cyclic changes might have on overall deep and bottom water circulation is simply unknown.

Similarly, the modelled predictions that North Atlantic thermohaline circulation, the process whereby surface water is drawn into deep water in the North Atlantic, may weaken or stop under changed climatic conditions, are also of significance (Rahmstorf, 1995; DETR, 1998; Schlosser *et al.*, 1991). There appears to be an intricate and intimate relationship between the North Atlantic Oscillation (NAO) and the physical properties and behaviour of deep currents flowing in the Denmark Strait (between Greenland and Iceland). The NAO is the dominant recurrent mode of atmospheric behaviour in the North Atlantic Sector, and its variability can explain around 30% of interannual variance in Northern Hemisphere temperatures over the past 60 years (Dickson, 1998; Dickson *et al.*, 1999). None of the CO_2 disposal studies appear to have considered this aspect which could arise from changes in sea-ice cover under a changed climatic regime (Yang & Neelin, 1993; Hunt *et al.*, 1995).

There is some evidence in the palaeorecord suggestive of changes in bottom water source regions from low to high latitudes which, although highly uncertain, lend weight to the idea that changes in deep ocean circulation could have acted as a climate “switch” (MacLeod & Huber, 1996). The potential for such a change in deepwater circulation remains unknown but could affect the suggested use of the North Atlantic Deep Water for CO_2 disposal (see: Wong & Hirai, 1997) by radically changing ventilation times. Changes in deep water circulation affecting waters where large quantities of carbon dioxide have been disposed of could, therefore, lead to a much more rapid return of carbon dioxide to the atmosphere than is predicted in the various studies which have not considered these factors. This in turn creates the possibility of uncontrollable “runaway” climate feedback loops. At the very least a rapid efflux of disposed CO_2 from deep waters would render the supposed rationale for ocean disposal completely irrelevant. Hence, in addition to current uncertainties attached to our knowledge of ocean circulation, is a lack of understanding of the processes which might lead to it changing and what the consequences of such changes are likely to be. Even relatively small changes in the pattern or location of oceanic upwelling could lead to disposed CO_2 reaching the ocean surface much faster than anticipated.

Another aspect of such potential circulation changes relates to the possibility (IPCC, 1996a) that under conditions of changed climate there could be changes in the frequency and intensity of storms and in the strength of prevailing winds. The rate of working by wind on oceanic general circulation is considered to be one of the fundamental quantitative indicators of the coupling between the atmosphere and ocean. According to modelling exercises supported by observations (Wunsch, 1998), much of the work done by wind occurs in the Southern Ocean. Although the proportion of the applied wind energy available for cross-isopycnal mixing, as opposed to that dissipated in other ways, is far from clear, changes in wind intensity and consequent impacts upon ocean-atmosphere CO_2 exchange could be of considerable importance in determining the residence time of CO_2 in the ocean. Similarly, other research has shown that the depth of convection in the oceans is increased as more heat is removed from surface waters by wind action. In the case of Labrador Sea Water formed by deep wintertime convection in the Labrador Sea, this is reflected in variations of the thickness and temperature of the layer which is formed (Curry *et al.*, 1998). The significance of such phenomena for oceanic CO_2 cycling are not known. Such studies, however, are making it clear that chemical and physical properties of deep water masses are far from immutable and that the signatures of sea surface conditions are translated, in time, to deep waters. The uncertainties which arise as a result of these findings do not appear to have been taken into consideration in analyses of CO_2 disposal (see: Wong & Hirai,1997).

Ecological considerations

The potential acute biological impacts of ocean CO_2 disposal operations have been documented in some detail at a species level. Assuming that understanding of bottom water movements is adequate and accurate, it is recognised that pH levels will be lowered below 7 for a distance of tens of kilometres from the discharge of CO_2 from a single power utility. Small isolated bodies of water are likely to show far-field effects extending hundreds of kilometres from the release (GESAMP, 1997). The precise impacts will depend upon the area and the depth at which CO_2 is introduced into the ocean. A sustained pH of less than 6.5 is lethal to many coastal marine organisms and it is likely that a value of 7-7.5 pH units would be the lower limit of tolerance for many species. The impacts are likely to be more obvious in ocean areas where productivity is high and where commercial exploitation takes place, although benthic organisms in the deep ocean which have evolved in environments with relatively stable physico-chemical characteristics may also be particularly vulnerable. The impact of CO_2 disposed of on the seabed could extend over a wide area. Using as a yardstick the CO_2 generated by 24GW of coal fired power plant over ten years of operation, then reduction of pH by 0.5 units or more would extend from the dumpsite over 250 k^{m2} of seabed (Wong & Hirai, 1997).

In many respects, attempting to predict biological impacts of carbon dioxide upon deep water marine organisms and upon the ecosystems of which they are a part, is an exercise in futility. These habitats are poorly characterised, poorly understood and have not been subjected to systematic sampling or observation. For many deep water organisms, the life cycles have not been elucidated and the environment is now understood to be much more biodiverse than was thought possible a decade ago. There is the possibility too, that layers of low pH water could act as barriers to the known vertical migration which has been observed in open ocean species.

As with the understanding of ocean circulation, scientific knowledge of the deep sea environment and the inhabiting organisms is poor. In relation to the CO_2 disposal issue, this lack of knowledge is a recurring theme. There is a need, for example, to obtain precise information on the responses of deep sea animals to elevated CO_2 exposure over their whole life-cycle under realistic conditions (Omori *et al.*, 1996). More fundamentally there is a need to characterise more fully these environments and ecosystems. The same is true for the deep sea benthic boundary layer (Pfannkuche, 1996) and of the continental slope regions since there have been relatively few large scale programmes which have examined shelf break and slope zone regions and their ecological processes (Angel, 1996). As a consequence, these remain poorly characterised and understood.

Given the above uncertainties and lack of knowledge concerning the fundamental character of the environments proposed as recipients for CO_2 disposal in ecological terms, it is clear that a substantial amount of investigation and research needs to be carried out before any commitment to this route of disposal is entered into. The need to understand deep-sea processes should be seen in much wider terms than to justify CO_2 disposal operations. What is certain, however, is that without such knowledge it is impossible even to begin to justify such a large scale operation and the current efforts to do so are somewhat premature.

In order generally to justify large scale ocean dumping activities, it has been suggested (Angel & Rice, 1996) that large scale *in situ* experiments should be conducted to investigate impacts. The suggestion has been repeated in connection with the CO_2 ocean disposal option by Ormerod & Angel (1996), who state that the biological impacts of large-scale discharges (of CO_2) can only be adequately assessed by a careful manipulation of a total ecosystem. This may be true, but the ecosystem concerned needs to be fully understood at the outset of the experiment. Under current circumstances, therefore, it is difficult to see what such an experiment would achieve since the ecosystems in question are so poorly characterised. Hence only the grossest effects are likely to be detected and the more subtle, but equally important, changes forced upon ecosystem structure and function are likely to be overlooked. Such an experiment, conducted without rigorous preparation over many years and followed up by many years of subsequent observation, would be scientifically worthless.

Planned field experiments

Despite the many unresolved questions concerning CO_2 capture and disposal, research activities have shifted to the proof of concept phase. As described below, the disposal of CO_2 is already being carried out into a sub-seabed aquifer. The direct discharge of carbon dioxide to deep oceanic waters is the subject of a land based experiment planned in the US for the year 2000 as a demonstration project. The experiment is due to take place using a pipeline extending into water ~1000m in depth on the Kona Coast of Hawaii. The experiment is funded jointly by the United States, Japan and Norway with a total budget of 3.8 million US dollars and the possible involvement of Australia (Adams, 1998; Adams *et al.,* 1998). The experiment is planned to last for up to three weeks during the summer of 2000 and is primarily aimed at investigating the physics of the CO_2 plume. This will enable optimisation of the nozzle design and investigation of diffusion of the plume and hydrate clogging. The maximum discharge of CO_2 will be 1 kg s^{-1} and the total amount of carbon dioxide used is projected to be in the region of 100t. The operation will be studied using a remotely operated vehicle together with a fixed platform and a variety of video cameras and analytical equipment. It is also proposed to evaluate impacts on small benthic organisms using core samples collected from a research vessel. Overall, the experiment will presumably be regulated under the terms of local (US) legislation.

The Hawaiian study is designed to provide data suitable for input to Environmental Impact Assessments for larger scale studies, serve as a tool for designing injection scenarios and provide a basis for future field experiments. A second study would be designed to investigate the acute and chronic impacts over a year or more at an enclosed site (Adams, 1998), perhaps a fjord system. The perceived advantages and disadvantages of using a Norwegian fjord system to conduct a longer term experiment have been listed by Golmen (1998). Finally, a third experimental phase is projected in which a demonstration power plant fitted with CO_2 capture facilities would be operated and monitored (Adams, 1998). Recognising the public concern which is likely to be generated by this series of experiments and the full scale operations for which they are laying the foundations, the scientific effort is being complemented by an extensive public outreach programme (Kildow, 1998a & b).

The planned series of experiments will undoubtedly go some way towards answering some of the outstanding engineering and technology design issues in relation to CO_2 disposal, specifically the behaviour of the CO_2 hydrates produced on discharge. They will, however, do little to address the uncertainties inherent in attempting to scale up the techniques to whole ocean basins.

Injection of CO_2 into sub-sea aquifers and formations

The disposal of CO_2 into geological formations has largely been investigated from the point of view of the disposal of power station emissions which comprise the greatest proportion of CO_2 emissions, as well as being point sources of the gas. Such proposals involve the capture of carbon dioxide from the power station flue gas and injection into the formations. Any scheme to capture CO_2 is associated with a considerable energy penalty; this has been discussed in more detail above in relation to direct disposal of CO_2 .

The injection of carbon dioxide into a sub-sea bed aquifer is already taking place at an experimental site in the North Sea. This stems from the standard oil industry practice of re-injecting gas separated from oil at the well head back into oil formations. Such operations are taking place to dispose of sour gas (CO_2 + H_2S) in Alberta, Canada (IEA, 1998a) at some 20 sites. The first began in 1989 (Hanisch, 1998). In the US, CO_2 is used routinely to assist oil recovery from the formation (Todd & Grand, 1993). In general, for such operations, if CO_2 has to be purchased for the purpose it is counter productive to lose it into the formation in excessive amounts since it represents a commercial loss. If the primary intent is to dispose of CO_2 then this commercial objection disappears. Indeed, if large quantities of CO_2 from power stations became available, the practice of using it to flood oil formations would become more widespread (Blunt *et al.*, 1993) but could not be profitably applied to all reservoirs due to the specific properties of the oil that they contain. Other potential uses for CO_2 are in the enhanced recovery of coal bed methane, displaced from seams regarded as non-mineable (Herzog *et al.*, 1997).

In the US at least, statistics suggest that depleted terrestrial oil and gas reservoirs could at present absorb only around 18 months of the national power plant emissions (Winter & Bergman, 1993). In addition, since the power plants are, in general, located some distance from these reservoirs, capture and transport of the CO_2 would involve significant energetic and cost penalties. Hence, effort has also been focused on the use of other geological formations and their potential storage capacity. A study commissioned under the auspices of the European Community (the Joule II non-Nuclear Energy Programme) suggested that a total of 800 Gt of CO_2 could be isolated in this way in the EU and Norway. 6 Gt capacity exists in depleted oil reservoirs, 27 Gt capacity in gas fields while aquifers could in theory provide 700 Gt capacity. Against this background, current European production *per annum* of CO_2 from power generation. (Holloway, 1996) stands at around 1 Gt. In the US, the Mount Simon Sandstone formation has been suggested as having a possible capacity for 100 years of CO_2 generation in the US. (Gupta *et al.*, 1998). Saline aquifers in the US could have a capacity for CO_2 of anywhere between 5-500GT (Herzog *et al.*, 1997).

The operation currently taking place in the North Sea Sleipner field was initiated in late 1996 by Statoil the Norwegian State Oil Company. Around 1 million tonnes of carbon dioxide are being pumped annually into a porous salt water aquifer some 32,000 km^2 in extent (IEA, 1998a). This Utsira sandstone formation lies around 1 km below the sea floor above the gas producing Heimdal formation and below an impermeable shale. Seismic monitoring activities have been emplaced to allow the movement of the gas through the aquifer to be followed. The carbon dioxide in this case is derived from the gas field where the natural gas brought to the surface contains around 9% CO_2. This is reduced to about 2.5% by treatment and the stripped CO_2 is injected into the sandstone formation. This is the first time that injection of carbon dioxide has been practised on such a large scale and the first time that carbon dioxide has been compressed and injected from an offshore platform (Baklid *et al.*, 1996). A similar project is under consideration by a consortium involving Exxon and the Indonesian State Oil Company in the Natuna offshore gas field in the South China Sea. This field is one of the largest in the world and, if the project goes ahead, up to 100 million tonnes of CO_2 would be disposed of annually into a sub-sea bed aquifer (Hanisch, 1998). In this case also, the CO_2 is removed from the natural gas recovered in which it is present at concentrations of around 70% by volume (Herzog *et al.*, 1997). The energy requirements for the capture of CO_2 are discussed in more detail above.

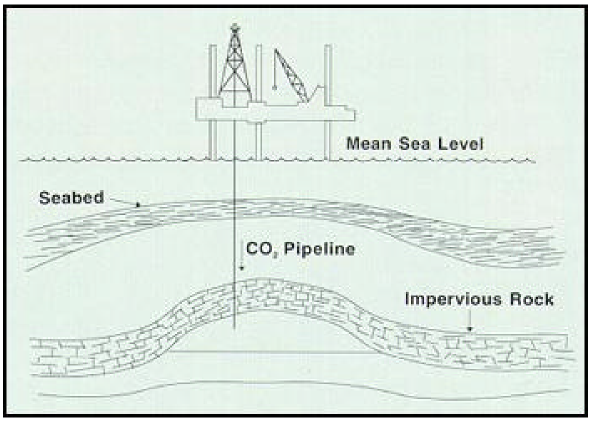


Figure 6: Diagrammatic representation of injection of carbon dioxide into sub-seabed geological formations from a fixed platform. Source IEA (1998c).

Both of these projects differ from conventional oil industry practice insofar as the CO_2 is being injected into formations other than those from which oil or gas has been extracted. In the Norwegian case at least, it appears that in the longer term the operation will be expanded to inject carbon dioxide derived from land based processing activities (Hanisch, 1998). It is also seen as a possibility for removing CO_2 from offshore power generation equipment and disposing of it (Falk-Pedersen *et al.*, 1995).

A key consideration in the viability of these options is the degree of containment which can be achieved for CO_2 disposed of in this way. Among factors which need further evaluation are the potential for dissolution of the rock formation, ground water pollution and ground stability (Ormerod *et al.*, 1993). To a limited extent, some of these questions can be answered by study of conditions which exist in formations which naturally contain carbon dioxide gas (Pearce *et al.*, 1996), such as the three producing fields in the Rio Grande Rift. In addition, laboratory experiments show that common reservoir materials may be corroded or structurally altered when exposed to carbon dioxide or carbon dioxide saturated fluids. These reactions may be complex and could, for example, affect the integrity of the cap formation leading to release of CO_2 (Ipsen & Jacobsen, 1996). Alternatively, it has been suggested that chemical reactions with the formation minerals could have a positive benefit by leading to increased trapping (Gunter & Perkins, 1993). Indeed, the possibility that stratigraphic traps might not be necessary, and that hydrodynamic trapping could be effective has also been proposed (Gunter *et al.*, 1996) together with the notion that CO_2 could also be trapped by reaction with aluminosilicate minerals after injection into siliciclastic aquifers. Alternatively, reactive formations could considerably complicate the way in which the disposal process must be managed in order to avoid collapse of the receiving formation (Krom *et al.*, 1993).

It is expected that current and planned monitoring activities on the Sleipner project will provide information to help resolve some of the gaps in the data (IEA, 1998a). Saline aquifers are generally less well characterised than oil and gas reservoirs due to their lack of commercial importance to date and their long term containment possibilities remain a matter of relative conjecture (Holloway & van der Straaten, 1995).

One aspect that has not been fully considered in the literature is the inherent escape pathway created by drilling into the formations concerned. In the case of exploited oil formations, these have usually been drilled in several tens of locations depending on the properties of the formation and the oil to be recovered. In the case of deep aquifers used for disposal, several injection wells will need to be drilled, introducing potential weaknesses through which escapes could occur. It must be recognised that invasive drilling of formations effectively connects them with contemporary timeframes and processes and does not leave them isolated and exposed only to processes taking place on geological timescales as is implicitly assumed in aquifer disposal analyses.

This lack of knowledge needs to be resolved. In the mean time, however, the existence of such substantial uncertainties demands precaution. In this regard, it is important to recognise that the application of a precautionary approach when considering the dumping of wastes at sea is enshrined both within Resolution LDC.44(14) (under the London Convention 1972) and in the 1996 Protocol to the Convention. Article 3.1 of the 1996 Protocol interprets the application of a precautionary approach in the context of the dumping of wastes at sea:

> *"In implementing this Protocol, Contracting Parties shall apply a precautionary approach to environmental protection from dumping of wastes or other matter whereby appropriate preventative measures are taken when there is reason to believe that wastes or other matter introduced into the marine environment are likely to cause harm, even when there is no conclusive evidence to prove a causal relation between inputs and their effects."*

The safety aspects of long term containment in this way also need to be addressed. Rapid releases of carbon dioxide of volcanic origin have been reported. For example, a release from the crater lake Lake Nyos in Cameroon in 1986 killed more than 1500 people, and livestock was killed up to 14 km from the site (Hanisch, 1998). Even a slow seep of the gas from an aquifer could have serious implications for marine ecology, if not directly for terrestrial systems. If such a seep occurred at the sea-bed, it could cause widespread changes in benthic and water column ecology. Moreover, to date, none of the proposals has addressed the potential ecological role of these deep formations or indeed described any of the associated ecosystems.

International Law

London Convention

Before governments commit themselves to continue to invest in research into the technical feasibility of disposing of fossil fuel generated CO_2 to the oceans there is a need seriously to consider the practicability and feasibility of such options under international law. In short, unless the international regime governing the dumping of wastes at sea, both above and under the seabed, is made the subject of drastic revisions, this practice would violate international law. The possibility of such revisions is neither realistic nor desirable.

It has been pointed out (GESAMP, 1997) that:

> *"For technical and financial reasons CO_2 (dry ice) disposal appears to be an unattractive option unless it is to be dumped from vessels. Dumping from ships, however, comes under the aegis of the Convention on the prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention, 1972). In 1993 Contracting Parties to this Convention adopted a prohibition on dumping of industrial wastes (defined as "wastes generated by manufacturing or processing operations" but with a non-exhaustive list of materials not considered to be industrial waste) at sea that took effect on January 1st 1996. It therefore seems unlikely unless the Convention can be amended to permit the dumping of CO_2, from ships, that any of the current Parties to the Convention which include all the OECD countries except Austria and Turkey, could give approval to such a practice. It should be further noted that the same conclusion would apply to liquid CO_2 disposal from vessels and platforms which would also fall within the purview of the London Convention 1972".*

GESAMP (1997) was correct to point out that that the dumping of CO_2 at sea is a concept that is not in accordance with existing international law. In addition to dumping at sea from ships, aircraft, platforms and other man-made structures at sea, the Convention also covers the disposal of wastes and other matter under the sea bed. This was agreed by the Thirteenth Consultative Meeting of Contracting Parties to the London Convention (1990) which adopted by vote Resolution LDC.41 13 to this effect). Six years later, in adopting the 1996 Protocol to the London Convention, the Contracting Parties unanimously agreed that:

> *" 'Dumping' means: any deliberate disposal into the sea of wastes or other matter from vessels, aircraft. Platforms or other man-made structures at sea;* [….as well as] *any storage of wastes or other matter in the seabed and the subsoil thereof from vessels aircraft platforms or other man-made structures at sea."* (Article I, 4.1.1 and I, 4,1,1.2 of the 1996 Protocol to the London Convention)

According to Article XV 2 of the London Convention 1972, any amendments to the Convention require a two thirds majority of those Contracting Parties in attendance at the time of the vote and:

> *"will be based on scientific or technical considerations."*

The prohibition on the dumping of industrial waste at sea on or under the seabed is legally binding on all Contracting Parties to the London Convention (75 countries by the end of 1998) and also upon all Contracting Parties to the United Nations

Convention on the Law of the Sea (UNCLOS, 1982). This is in accordance with Article 210.6 ("Pollution by Dumping") of UNCLOS which states:

> *"National laws regulations and measures shall be no less effective in preventing reducing and controlling such pollution than the global rules and standards".*

The acceptability under international law of disposing of CO_2 *via* a pipeline from the shore into the marine environment remains an open question. In the preambular text to Resolution LC. 49 (16), banning the dumping of industrial waste at sea, Contracting Parties to the London Convention:

> *"Reaffirm[ed] further the agreement that a better protection of the marine environment by cessation of dumping of industrial waste should not result in unacceptable environmental effects elsewhere."*

This statement was primarily addressing the need to give priority to waste avoidance and clean production and also to avoid wastes previously dumped at sea being placed in land-based dumps in a manner which could not be considered to be environmentally sound. Nevertheless, the need to avoid wastes that could be dumped at sea entering the marine environment via land based sources and activities was also very much present in the minds of the negotiators.

Moreover, in adopting the 1996 Protocol to the London Convention, Contracting Parties reiterated in Article 2 of the Protocol their obligation to:

> *"individually and collectively protect and preserve the environment from ALL SOURCES of pollution".*

Further they also agreed in Article 3.3 of the Protocol that:

> *"In implementing the provisions of this Protocol, Contracting Parties shall act so as not to transfer, directly or indirectly , damage or likelihood of damage from one part of the environment to another or transform one type of pollution into another".*

The most recent expression of the universal trend to eliminate the dumping and land based discharge of wastes to the marine environment is contained in the 1998 Sintra Statement which was adopted unanimously by the Environment Ministers of the countries bordering the North East Atlantic, together with the European Commissioner for the Environment (OSPAR, 1998). The signatories to this statement:

> *"reemphasise*[d] [their] *commitment to prevent the sea being used as a dumping ground for waste, whether from the sea or from land based activities".*

The Independent World Commission on the Oceans (IWCO), formed and chaired by former President and Prime Minister of Portugal Mario Soares, to consider thoroughly all issues of ocean science, ocean conservation and ocean governance, concluded on the issue of CO_2 disposal at sea (IWCO, 1998):

> *In the context of global warming, the importance of ocean-atmosphere interactions, the role of the oceans as a* CO_2 *sink and the precautionary principle, it is imperative that people and governments exploit as a first priority, the manifold opportunities that exist for reducing*

> *carbon emissions and consider only with circumspection the potential of the oceans as a site for CO_2 disposal.* (IWCO 1998)

In common with GESAMP (1997) the IWCO noted that the dumping of CO_2 at sea is banned by the London Convention and that, furthermore:

> *"The Framework Convention on Climate Change and its Kyoto Protocol do not provide for Parties to dump or store CO_2 in international waters and thereby to offset their emissions".*

The provisions of existing Conventions, coupled with the current political reality, would seem, therefore, to rule out the consideration of oceanic disposal of anthropogenic CO_2 as a potential strategy to address current and future emissions. Moreover, in the light of the numerous legal and political uncertainties that would surround any proposal to dump CO_2 in the marine environment, along with the considerable scientific and technical problems and uncertainties outlined elsewhere in this document, it would appear that further investment in such options would represent a wasteful drain on available resources. These resources might be much better utilised in the research, development and promotion of renewable energy alternatives and the implementation of effective energy efficiency programmes. Such an approach would clearly be more consistent with the conclusions expressed by the IWCO (1998).

Kyoto Protocol

The Kyoto Protocol has several provisions which restrict the manner in which "sinks" of greenhouse gases can be used towards offsetting emissions and hence be counted towards meeting obligations to reduce these. These provisions mean that an ocean fertilisation "sink" cannot be counted towards Annex B Parties' obligations to limit emissions.

Article 3.1 of the Protocol specifies that industrialised Parties listed in its Annex B must limit their emissions of greenhouse gases according to an agreed schedule. Article 3.3 and 3.4 provide for Parties to offset their emissions by the use of certain classes of sinks. Article 3.3 limits this to:

> *"direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990".*

Article 3.4 provides for additional sink activities to be agreed by the Conference of the Parties to the FCCC serving as the meeting of the Parties to the Protocol (COP/MOP). These are, however, limited to:

> *"additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories".*

In theory, the Clean Development Mechanism of the Kyoto Protocol could be used, for example, to gain emission credits for ocean fertilisation, if a Party not included in Annex I of the FCCC had appropriate territorial ocean waters. Such a project would, however, violate the requirement that it advance the sustainable development of the non-Annex I Party and also that it provide:

> *"Real, measurable, and long-term benefits related to the mitigation of climate".*

Such projects would require the specific approval of the COP.

In relation to CO_2 disposal at sea or injection into the sea-bed, the Kyoto Protocol is not so clear cut. The current emission reporting guidelines are not clear on this issue and give rise to different interpretations. Parties are required to report emissions and sinks (or in effect CO_2 extracted from combustion products) separately. This still leaves Parties free to net any

extracted carbon from emissions. The FCCC COP should move to indicate that oceanic disposal and/or storage of CO2 (and more generally storage in aquifers and other geological formations) will not be permitted to be counted towards the emissions obligations Parties to the Kyoto Protocol and that full account should be taken of international law in this context.

Summary and Conclusions

The optimistic view (Herzog *et al.*, 1997) that CO_2 disposal strategies allow for wide scale use of fossil fuels into the future can be challenged on fundamental grounds. In the long term it makes no difference to the final level of CO_2 achieved in the atmosphere. The wide spread assumption that *"From a long term perspective (ie at the time scale of a millennium) the question of ethics of using the ocean does not arise because the fate of most CO_2 discharged to the atmosphere will be to finish up in the deep ocean"* (Angel, 1998) is quite astounding. The ocean disposal of CO_2 raises very deep ethical questions indeed, particularly since the strategy likely carries with it a commitment for future generations to a worse equilibrium state than would be the case by accepting the carbon logic, or indeed simply adhering to "business as usual". As carbon cycle modellers have noted, the CO2 does not disappear and that "ignoring the truly long-term effects is a political and ethical choice" (Tans, 1997).

Arguably, it may diminish the extent of the transient peak but certainly would prejudice achievement of the ecological targets outlined above in the long term if applied to "business as usual" emissions over the next century. In effect, the strategy simply delays the full impact of climate change to a point in the future. This key trans-generational failing is not addressed by proponents of the strategy (see: *e.g.* Herzog *et al.*, 1997). Since the final CO_2 stabilisation value will be key determinant of the ambient climate of the time, the ocean disposal option effectively shifts a substantial burden of the responsibility (perhaps 30-50%) into the future at which point it will not be recoverable or avoidable.

Indeed, all the proposals entailing the use of the oceans in climate engineering are subject to the fundamental criticism that they represent an abdication of trans-generational responsibilities to a considerable extent. This is in direct violation of principles of sustainability (Cairns, 1997) and in particular is contrary to Principle 3 of the 1992 Rio Declaration on Environment and Development which states:

> *"The right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations".*

At the same time, the ocean disposal option creates the entirely erroneous impression that it represents a scheme whereby continued use of fossil fuels can be justified at levels above current consumption. At present, by adopting the carbon logic approach and implied allied consumption and emission strategies, the problem can to large extent be avoided. In addition, as noted above, the very considerable costs likely to be associated with a carbon management strategy are likely to be met at the expense of more sustainable schemes based upon the development of renewable energy resources.

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