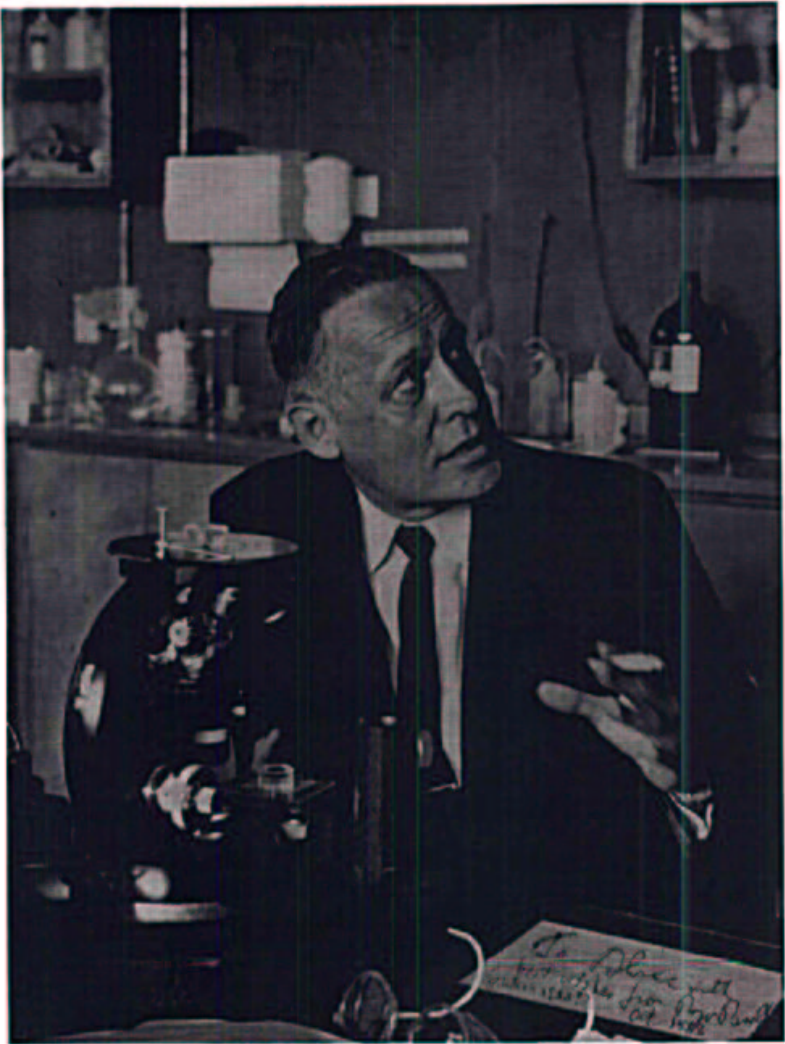




JAN. 1, 1988 / ENVIRONMENTAL SCIENCE & TECHNOLOGY / NEWS # 21 A

JPEG image 767x963 pixels

<http://scilib.ucsf.edu/vio/archives/photos/rv2.jp>



1 of 1

11/3/99 12:39 PM

1957

**Carbon Dioxide Exchange Between Atmosphere and Ocean and the
Question of an Increase of Atmospheric CO₂ during the Past
Decades**

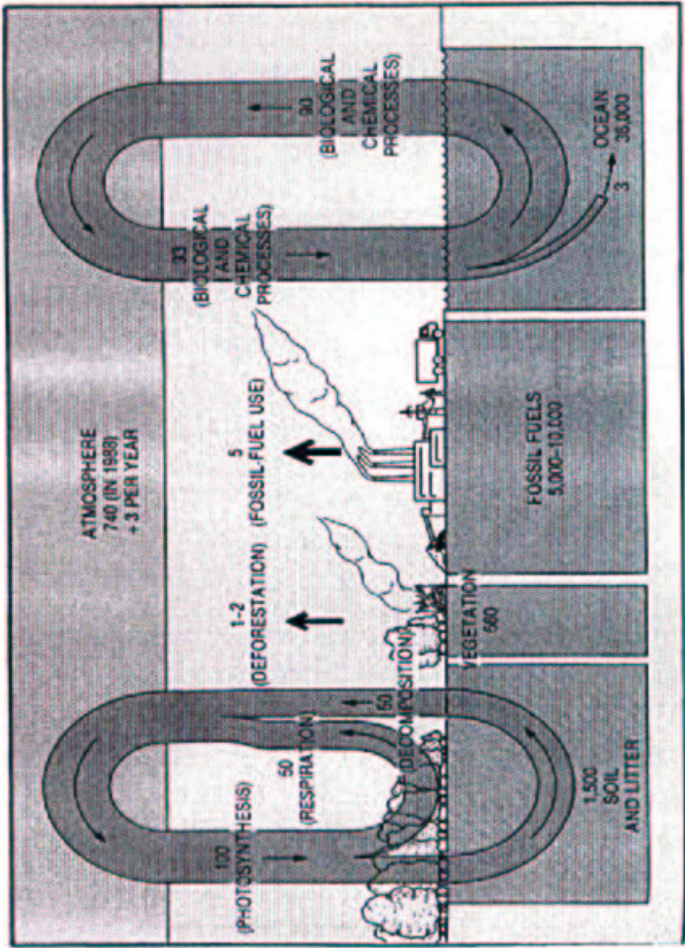
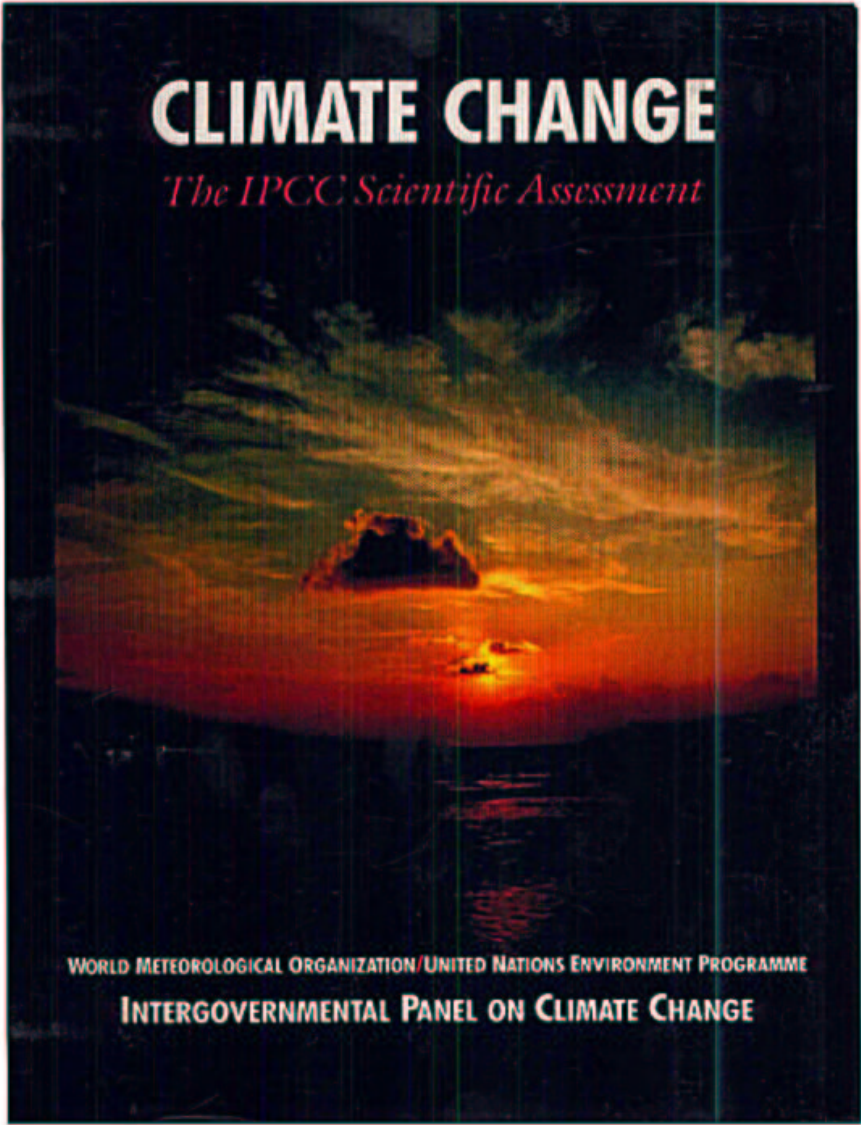
By ROGER REVELLE and HANS E. SUESS

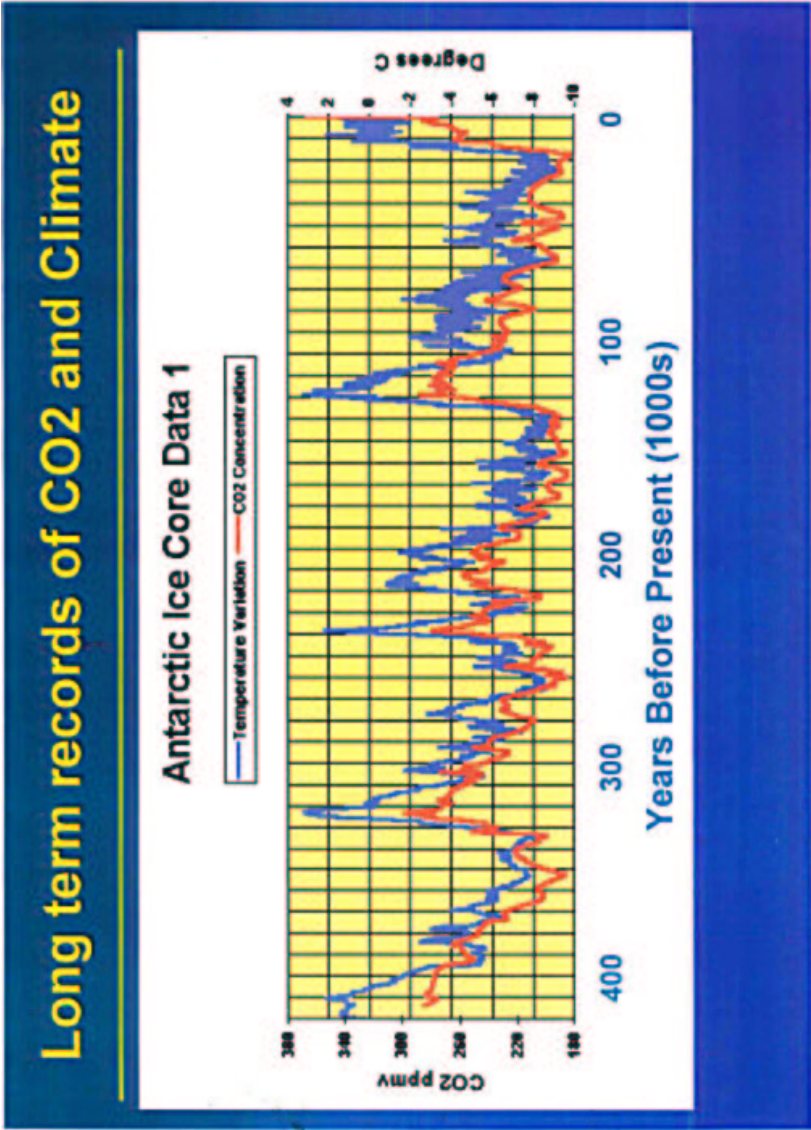
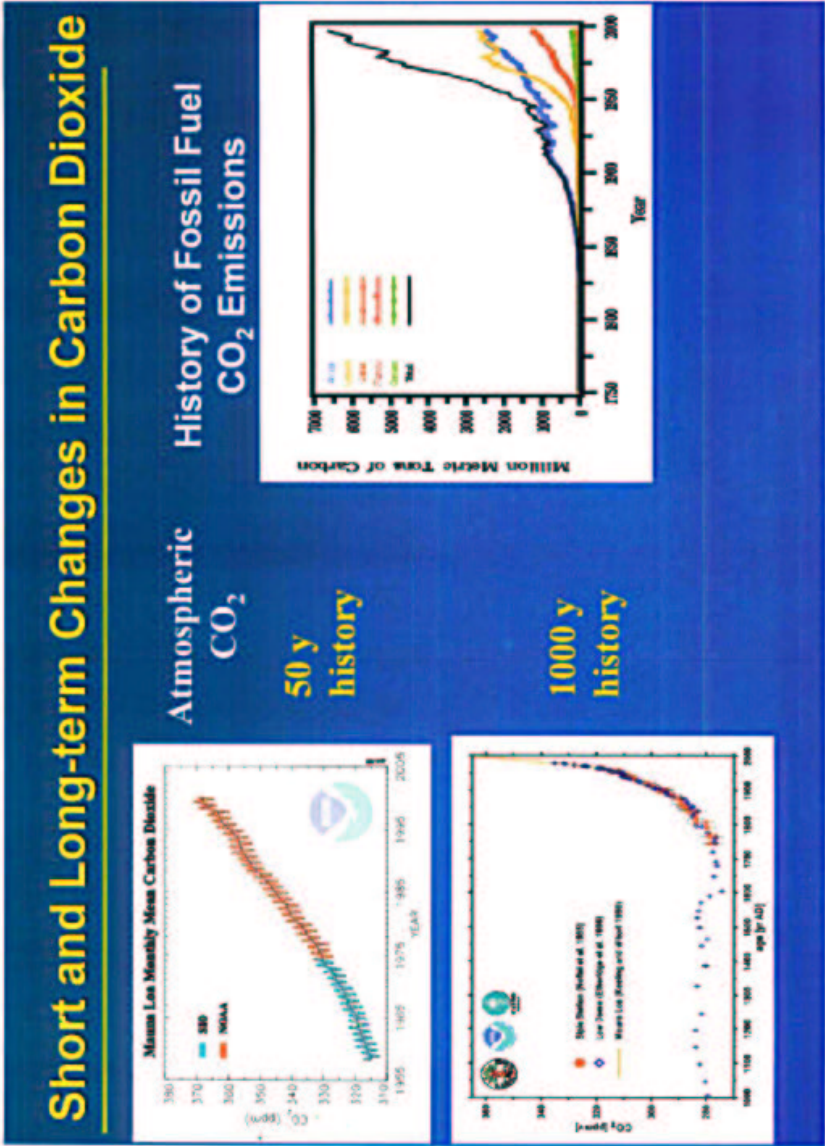
"Thus human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future."

"This experiment, if adequately documented, may yield a far-reaching insight into the processes determining weather and climate."

The End of the Experiment?

- Revelle and Suess (1957): "*...in coming decades we conclude that a total increase of 20 to 40% in atmospheric CO₂ can be anticipated. This should certainly be adequate to allow a deterioration of the effects, if any, of changes in atmospheric carbon dioxide on weather and climate throughout the earth.*"
- Pre Industrial CO₂ levels = 280 p.p.m.v.
- A 30 % increase = 364 p.p.m.v.
- Today's atmospheric CO₂ levels = 364 p.p.m.v.





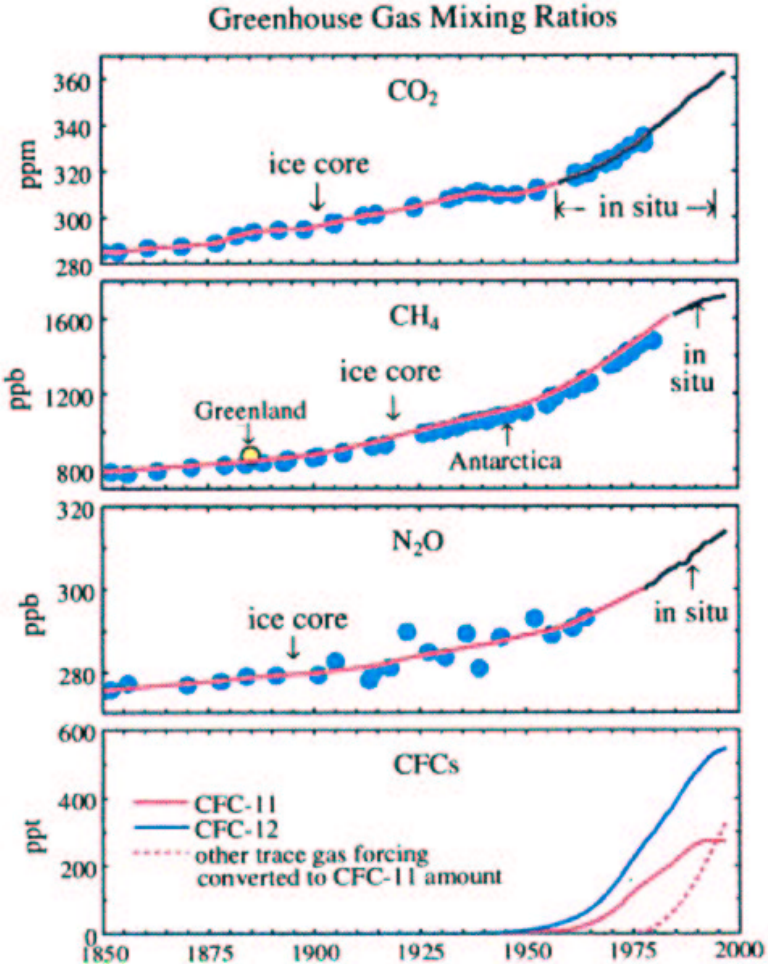


FIG. 1. Principal anthropogenic GHGs in the Industrial era.

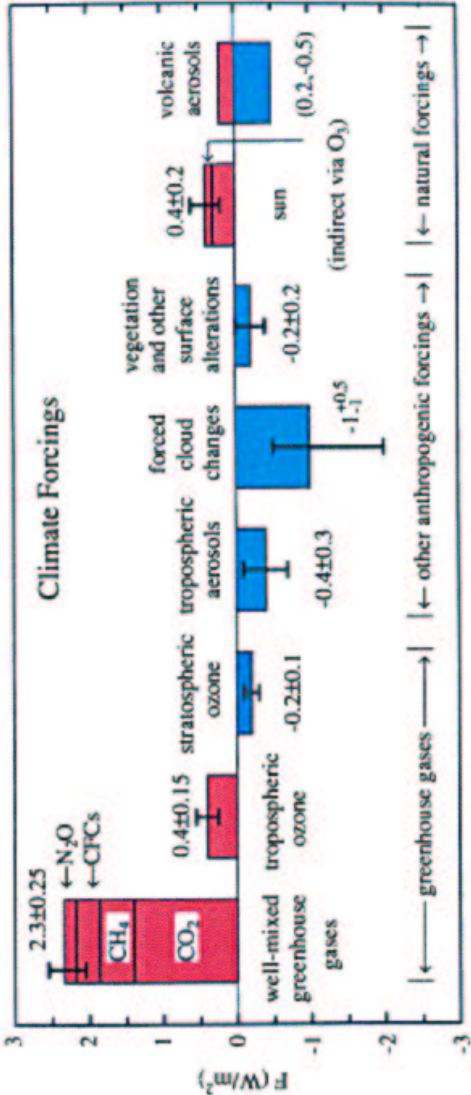


FIG. 2. Estimated radiative forcings between 1850 and the present.

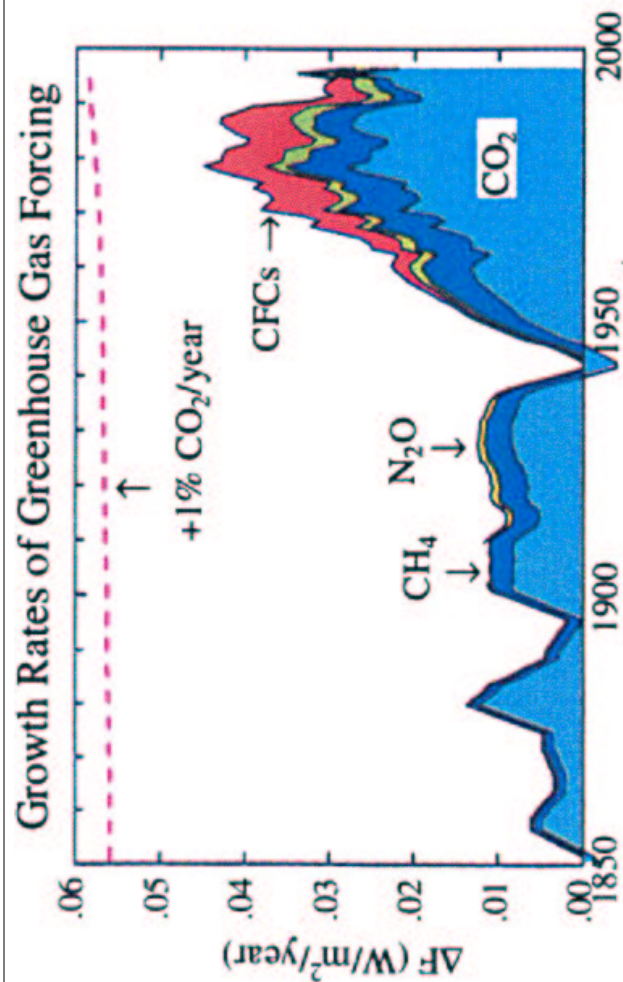


FIG. 5. Growth rate of greenhouse climate forcing based on gas histories shown in Fig. 1. Dashed line is forcing due to 1% CO₂ increase.

Estimating Climate Response Times

Hansen et al. (1985)

1. Atmosphereless Blackbody Planet

$$\tau_b = c/4\sigma T_i^3$$

where c is the time-invariant heat capacity

2. For climate feedback factor f and fixed heat capacity

$$\tau = f\tau_b$$

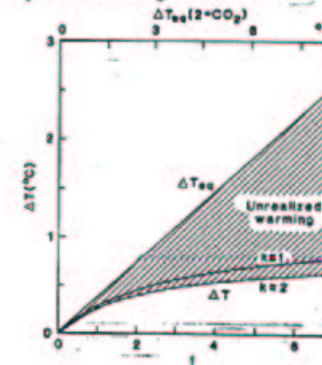
For a planet covered by mixed layer ocean c represents the thermal capacity of the atmosphere-ocean. For a mixed layer depth $d_o = 100\text{m}$ and $T_i = 255\text{K}$, then $\tau_b \approx 3.5$ years. Thus for $f \approx 3$ then $\tau \approx 10$ years.

3. However the oceanic mixed layer is annually renewed, and exchanges heat with the deep ocean. And the ocean covers only 70% of the planet. Using a ¹⁴C calibrated box diffusion model yields apparent vertical mixing coefficient $k = 1 \text{ cm}^2/\text{sec}$, and an effective mixing depth $\approx 170\text{m}$.

$$\tau \text{ proportional to } f^2 \text{ for large } k$$

Result

Time required for mixed layer to achieve 63% of equilibrium response is about 15-25 years for climate sensitivity of 1.5°C at CO₂ doubling, but 50-100 years for 3°C sensitivity. Best estimate today is about 30 years. We have a large quantity of unrealized global warming.



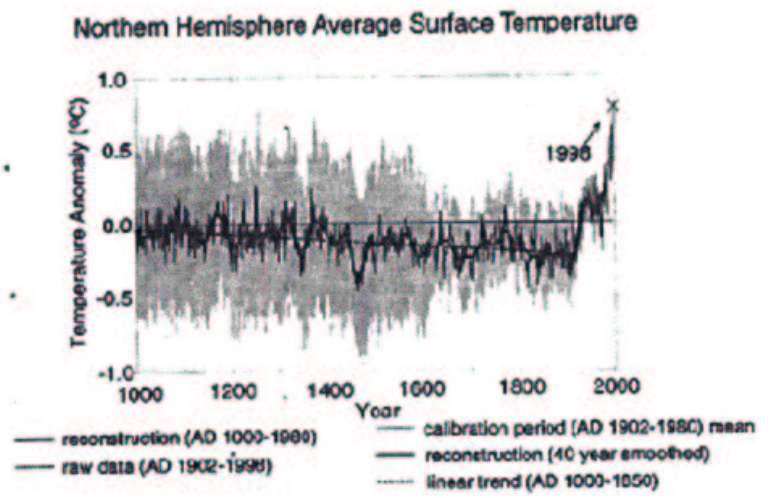


Figure 1. Reconstruction of Northern Hemisphere temperature anomaly trends from 1000 A.D. to present. From Mann et al. (5).

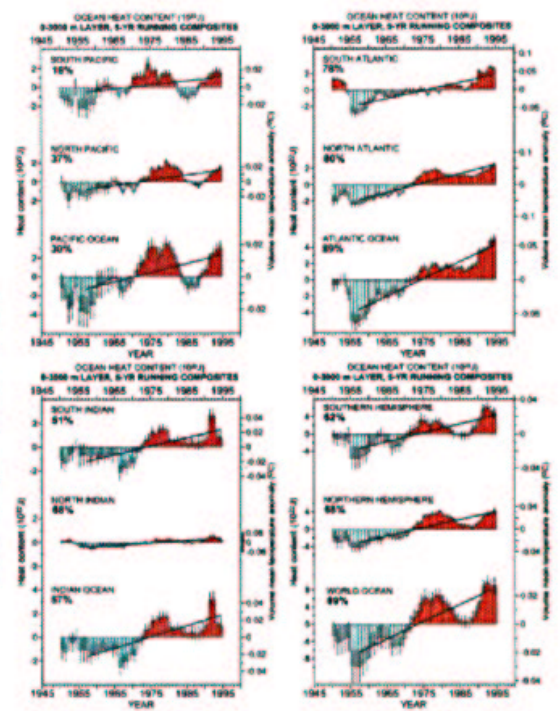


Figure 2. Time series of five-year running composites of heat content (10²¹ J) in the upper 2000 m for each major ocean basin. Vertical lines represent the ± 1 SE of the five-year mean estimate of heat content. The lower trend is estimated for each time series for the period 1955 to 1996, which corresponds to the period of best data coverage. The trend is plotted as a red line. The percent variance accounted for by this trend is given in the upper left corner of each panel. Reprinted with permission from S. Levitus, I. Antonov, T.P. Boyer and C. Stevens, Warming of the world ocean, Science, 287, 2228, 2000. Copyright: 2000 American Association for the Advancement of Science

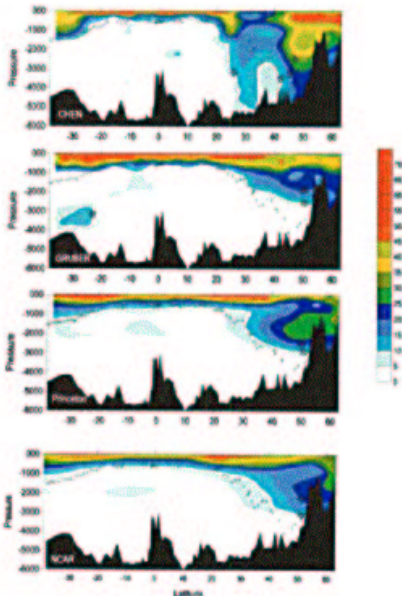
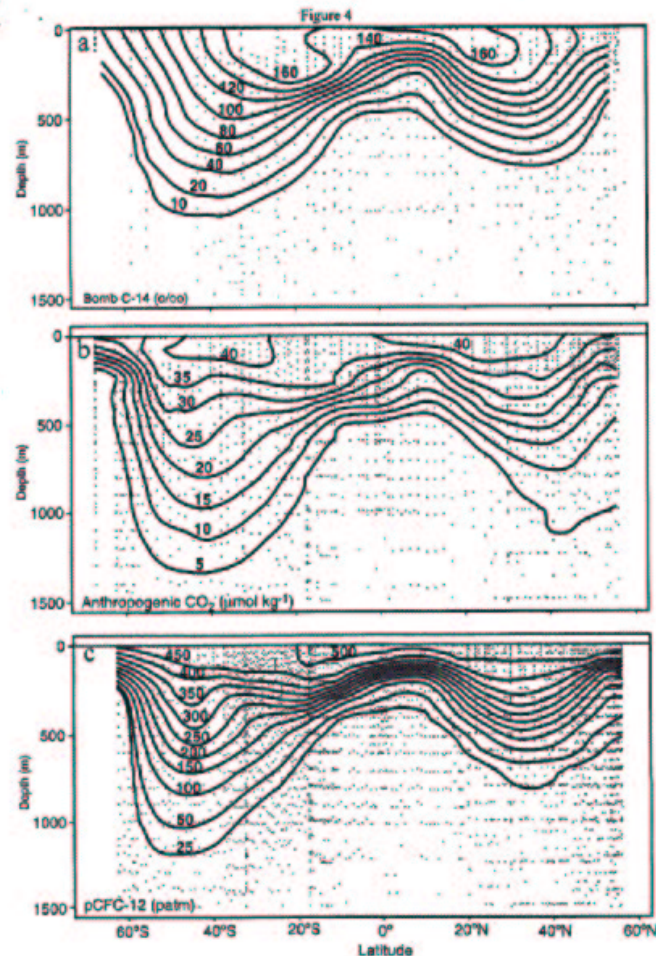


Figure 2. Estimates of anthropogenic carbon dioxide from the Atlantic basin along a meridional section in the center of the basin (approximately 30°W). The fields in the top two panels were generated from observations taken from cruises in 1991 and 1993. The top panel used the methodology of Chan and Mierwa (1979) to generate the concentrations, while the second panel used the approach of Gnanou et al. (1996). The bottom two panels show the simulated anthropogenic carbon dioxide from the two different biogeochemistry models. Figure from Wiersma et al. (1996). R. S. Dong, T. H. Peng, J. L. Bullister, K. Lee, and R. A. Feely. Comparison of methods to determine the anthropogenic CO₂ invasion into the Atlantic Ocean. *Abstracts from the 1996 International Carbon Dioxide Conference*, 118, 1-1, 220, 1996.



4) Meridional sections of bomb C-14 (a), anthropogenic CO₂ (b), and pCFC-12 (c) along 150°W in the central Pacific. Points indicate sample locations. Bomb C-14 calculated from data provided by R. Key (Princeton) using the potential alkalinity method of Key and Rubin [2001]. pCFC-12 calculated using data from J. Bullister (NOAA/PMEL).

TABLE 2. Specimen calculations for the evolving chemical signature of a “typical” surface sea water sample in equilibrium with an atmosphere of increasing CO₂ levels at about the IPCC (Houghton et al., 1990) “Business as Usual” scenario rate. The salinity is taken as 35.00‰, the temperature as constant (15°C), and the alkalinity as constant at 2320 μmol kg⁻¹. The total CO₂ signal is not very temperature sensitive: if we assume a warming of 2° C by the year 2100, then the difference in the total CO₂ content is only -12 μmol kg⁻¹. The carbonate ion concentration drops by 55%. The scenario after the year 2100 is not specified here, but if the march of industrial civilization proceeds then these trends will increase.

The evolving chemistry of surface sea water under “Business as Usual”

Time	pCO ₂	Total CO ₂	pH	HCO ₃ ⁻	CO ₃ ²⁻	H ₂ CO ₃
yr.	μatm	μmol kg ⁻¹		μmol kg ⁻¹	μmol kg ⁻¹	μmol kg ⁻¹
1800	280	2017	8.191	1789	217	10.5
1996	360	2067	8.101	1869	184	13.5
2020	440	2105	8.028	1928	161	16.5
2040	510	2131	7.972	1968	144	19.1
2060	600	2158	7.911	2008	128	22.5
2080	700	2182	7.851	2043	113	26.2
2100	850	2212	7.775	2083	97	31.8

Some Essential Background

- World wide ocean surface uptake/disposal today is about 25 million tons CO₂/day
- The US contribution is 25%, or about 6 million tons/day
- Ultimately some 85% of atmospheric fossil fuel CO₂ will be taken up by the ocean
- Ocean conversion of CO₂ to bicarbonate ion is instantaneous
- By the year 2100 we will have reduced the carbonate ion content of surface ocean waters by >50%
- Mean deep ocean ventilation time = 550 years Pacific 250 years Atlantic
- We are now about 100 years into the CO₂ transient

The evolving chemistry of surface sea water under "Business as Usual"

Time	pCO ₂	Total CO ₂	pH	HCO ₃ ⁻	CO ₃ ²⁻	H ₂ CO ₃
yr.	µatm	µmol kg ⁻¹		µmol kg ⁻¹	µmol kg ⁻¹	µmol kg ⁻¹
1800	280	2017	8.191	1789	217	10.5
1996	360	2067	8.101	1869	184	13.5
2020	440	2105	8.028	1928	161	16.5
2040	510	2131	7.972	1968	144	19.1
2060	600	2158	7.911	2008	128	22.5
2080	700	2182	7.851	2043	113	26.2
2100	850	2212	7.775	2083	97	31.8

CLIMATE
CHANGE
CORAL
BLEACHING
and the
FUTURE
of the
WORLD'S
CORAL
REEFS

by
OVE HOEGH-GULDBERG

ASSOCIATE PROFESSOR,
SCHOOL OF BIOLOGICAL SCIENCES,
UNIVERSITY OF SYDNEY

DIRECTOR,
THE CORAL REEF RESEARCH INSTITUTE,
UNIVERSITY OF SYDNEY

CLIMATE CHANGE, CORAL BLEACHING AND THE FUTURE OF THE WORLD'S CORAL REEFS

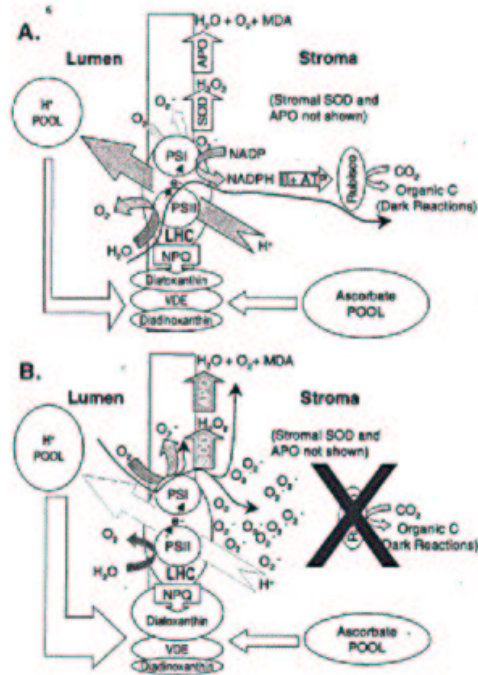


Figure 4. Photoinhibition model of coral bleaching (Jones et al. 1998). Detail of events occurring on the thylakoid membrane of the chloroplast of zooxanthellae. A. Under normal circumstances, the two photosystems (PSI and PSII) pass light energy to the dark reactions where carbon dioxide is fixed and by the enzyme Rubisco. The amount of light energy flowing to the dark reactions is regulated by the interconversion of the two pigments diadinoxanthin and diadinoxanthin. Any active oxygen (O₂) is soaked up by the SOD and APO enzyme systems. B. Heat stress interrupts the flow of energy to the dark reactions. The light reactions are then destroyed by the buildup of light energy which is passed to oxygen rather than the dark reactions, creating active oxygen that then begins to denature the proteins that make up the photosynthetic components of the zooxanthellae. Not shown are the singlet oxygen species that are generated in PSII, by triplet chlorophyll in the reaction centre, and which are more abundant when PSII is over-reduced in high light under heat stress. SOD = Superoxide dismutase, APO = Ascorbate peroxidase, VDE = Violaxanthin de-epoxidase.

measure of the efficiency (activity) of the light reactions of photosynthesis. Fitt and Warner (1995) and Warner et al. (1996) saw a decrease in the efficiency of PS II when corals and their zooxanthellae were exposed to heat. These insightful researchers, along with Iglesias-Prieto and his co-workers, proposed that the primary effect of temperature was to cause a malfunction of the light reactions of photosynthesis.

Jones et al (1998) used the PAM fluorometer with different

of thermal stress in zooxanthellae. Working with corals from One Tree Island on the southern Great Barrier Reef, Jones et al (1998) were able to show that the first site of damage was the dark reactions of photosynthesis and not the light reactions as previously thought (Figure 6). A second important observation was that light amplified the extent of damage caused by thermal stress, almost perfectly replicating reports of coral bleaching on their upper, most sunlit surfaces (Goenaga et al 1988).

Geochemical Consequences of Increased Atmospheric Carbon Dioxide on Coral Reefs

Joan A. Kleypas,^{1*} Robert W. Buddemeier,² David Archer,³ Jean-Pierre Gattuso,⁴ Chris Langdon,⁵ Bradley N. Opdyke⁶

A coral reef represents the net accumulation of calcium carbonate (CaCO₃) produced by corals and other calcifying organisms. If calcification declines, then reef-building capacity also declines. Coral reef calcification depends on the saturation state of the carbonate mineral aragonite of surface waters. By the middle of the next century, an increased concentration of carbon dioxide will decrease the aragonite saturation state in the tropics by 30 percent and biogenic aragonite precipitation by 14 to 30 percent. Coral reefs are particularly threatened, because reef-building organisms secrete metastable forms of CaCO₃, but the biogeochemical consequences on other calcifying marine ecosystems may be equally severe.

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 14, NO. 2, PAGES 639-654, JULY 2000

Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reefChris Langdon, Taro Takahashi, Colm Sweeney, Dave Chipman, and John Goddard
Lamont-Doherty Earth Observatory of Columbia University, Palisades, New YorkFrancesca Marubini,¹ Heather Aceves, and Heidi Barnett
Columbia University's BIOSPHERE 2 Center, Oracle, ArizonaMarlin J. Atkinson
Hawaii Institute of Marine Biology, Kaneohe

Abstract. The concentration of CO_2 in the atmosphere is projected to reach twice the preindustrial level by the middle of the 21st century. This increase will reduce the concentration of CO_3^{2-} of the surface ocean by 30% relative to the preindustrial level and will reduce the calcium carbonate saturation state of the surface ocean by an equal percentage. Using the large 2650 m^3 coral reef mesocosm at the BIOSPHERE-2 facility near Tucson, Arizona, we investigated the effect of the projected changes in seawater carbonate chemistry on the calcification of coral reef organisms at the community scale. Our experimental design was to obtain a long (3.8 years) time series of the net calcification of the complete system and all relevant physical and chemical variables (temperature, salinity, light, nutrients, Ca^{2+} , pCO_2 , TCO_2 , and total alkalinity). Periodic additions of NaHCO_3 , Na_2CO_3 , and/or CaCl_2 were made to change the calcium carbonate saturation state of the water. We found that there were consistent and reproducible changes in the rate of calcification in response to our manipulations of the saturation state. We show that the net community calcification rate responds to manipulations in the concentrations of both Ca^{2+} and CO_3^{2-} and that the rate is well described as a linear function of the ion concentration product, $[\text{Ca}^{2+}]^{0.69}[\text{CO}_3^{2-}]$. This suggests that saturation state or a closely related quantity is a primary environmental factor that influences calcification on coral reefs at the ecosystem level. We compare the sensitivity of calcification to short-term (days) and long-term (months to years) changes in saturation state and found that the response was not significantly different. This indicates that coral reef organisms do not seem to be able to acclimate to changing saturation state. The predicted decrease in coral reef calcification between the years 1880 and 2065 A.D. based on our long-term results is 40%. Previous small-scale, short-term organismal studies predicted a calcification reduction of 14–30%. This much longer, community-scale study suggests that the impact on coral reefs may be greater than previously suspected. In the next century coral reefs will be less able to cope with rising sea level and other anthropogenic stresses.

A Large Terrestrial Carbon Sink in North America Implied by Atmospheric and Oceanic Carbon Dioxide Data and Models

S. Fan, M. Gloor, J. Mahlman, S. Pacala, J. Sarmiento, T. Takahashi, P. Tans

Atmospheric carbon dioxide increased at a rate of 2.8 petagrams of carbon per year (Pg C year^{-1}) during 1988 to 1992 ($1 \text{ Pg} = 10^{15} \text{ grams}$). Given estimates of fossil carbon dioxide emissions, and net oceanic uptake, this implies a global terrestrial uptake of 1.0 to 2.2 Pg C year^{-1} . The spatial distribution of the terrestrial carbon dioxide uptake is estimated by means of the observed spatial patterns of the greatly increased atmospheric carbon dioxide data set available from 1988 onward, together with two atmospheric transport models, two estimates of the sea-air flux, and an estimate of the spatial distribution of fossil carbon dioxide emissions. North America is the best constrained continent, with a mean uptake of $1.7 \pm 0.5 \text{ Pg C year}^{-1}$, mostly south of 51 degrees north. Eurasia-North Africa is relatively weakly constrained, with a mean uptake of $0.1 \pm 0.6 \text{ Pg C year}^{-1}$. The rest of the world's land surface is poorly constrained, with a mean source of $0.2 \pm 0.9 \text{ Pg C year}^{-1}$.

The Not-So-Big U.S. Carbon Sink

Christopher B. Field and Inez Y. Fung
Science, (1999) 285, 544-545.

“Sinks associated with recovery from past land management practices eventually saturate. ...In the U.S., a substantial component of the current sink appears to result from...processes begun in the early decades of this century....This means they are explicitly eliminated from consideration in the Kyoto Protocol as sinks for carbon offsets....”

North American Carbon Sink Science (1999) 283, 1815a

- Fan et al. suggest 1.4 ± 0.4 GtC/yr uptake in North America (mostly south of 51°N), and only 0.1 GtC/yr for Eurasia.
- Holland and Brown report a total northern hemisphere uptake of only 0.58 GtC/yr with no east-west bias. Fan et al. “May have over-extended the limits of uncertainty.”
- Potter and Klooster find that the total carbon sink for the U.S. and Canada was only 0.22 GtC/yr in 1987 and 1988. These years may represent “two of the most favorable years of the 1980s..”. And “merely a transient sink pattern in North America.”

NEWS FOCUS

MEETING ECOLOGICAL SOCIETY OF AMERICA

Superweeds, and a Sinking Feeling on Carbon Sinks

MADISON, WISCONSIN—More than 3000 ecologists gathered here from 5 to 10 August for the 86th annual meeting of the Ecological Society of America (ESA). Hot topics included trees and global warming, the risks of transgenic crops, and vanishing tropical mammals.

Forests: No Greenhouse Antidote?

Some experts claim that the world's forests can absorb enough carbon dioxide to reduce the impact of further global warming. But at least one type of hardwood forest may not be up to the job. Rather than storing extra carbon in long-lasting trunks and branches, an experimental sweetgum stand in Tennessee soaks most of the CO₂ in tiny roots that rapidly die and decompose. That process sends the

canopies of four stands of young sweetgums. As Norby reported at the meeting, during the first year most of the extra carbon went into wood, with the gasped-up sweetgums accumulating 35% more carbon than control trees grown in unenriched air. But 2 years later, that wood differential had narrowed to 7%. More than twice as much carbon as in the controls ended up in the fine roots—thin structures that fall off and die each year. Soil organisms quickly consume the detritus, releasing CO₂ that diffuses out into the air.

Forest ecologist Adrian Finzi of Boston University calls the results "really interesting" but cautions that they may not hold true in other forests. The mechanism of carbon storage certainly differs in an experimental pine stand he studies in North Carolina. Although the loblolly pines there exposed to extra CO₂

gas right back into the atmosphere.

Researchers have long wrangled over the ability of forests to serve as carbon sinks for excess greenhouse gases. It's clear that saplings in open-top enclosures respond to high CO₂ with growth spurts, stepping up photosynthesis and making more leaves and wood than would trees soaking unenriched air. But what's true for a stand of saplings may not be true for a mature forest, says ecologist Rich Norby of Oak Ridge National Laboratory in Tennessee. That's because leaf coverage masks out as a tree matures—putting limits on photosynthesis and, thus, on its capacity to soak up excess CO₂.

To find out how much CO₂ mature trees can absorb, Norby and colleagues built towers 4 years ago to pump CO₂ into

also store less extra carbon in wood after a few years as they run short on nutrients such as nitrogen (*Science*, 6 April, p. 36), the carbon ends up primarily in leaf litter, not the fine roots. That suggests to Finzi that researchers must check more than a couple of stands to understand how different forest types respond to high CO₂ levels.

The bottom line for sweetgum and loblolly pine, anyway, is that neither leaf litter nor fine roots offer long-term carbon storage. For that reason, says biogeochemist William Schlesinger of Duke University, planners shouldn't count on forests as CO₂ saviors. "These terrestrial sinks," he contends, "are just not adding up to much."

-DAN FERREN

Breeding a Hardier Weed

In the vitriolic debate over the potential risks of transgenic crops, one big concern is that wild relatives may commensurate valuable traits and turn into "superweeds" that spread unchecked across the land. Two new studies add hard data to what has been mostly a theoretical discussion. One finds that genes from a crop can persist in a weed for many generations, while a second supports the idea that if genes that protect against viral infection slip into wild plants, there could be serious consequences.

Although neither finding pins down the risks, these and other studies have convinced some ecologists that genetically modified (GM) crops are being rolled out too hastily. "We really need a lot more data before we make assumptions" about safety, says Allison Power of Cornell University in Ithaca, New York, who presented her work on viruses.

Conventional wisdom says that crop traits are unlikely to persist in the wild in part because crossbreeding crops and weeds yields hybrids that tend to reproduce poorly. "In the crop-breeding and weed science world, there's always been a feeling that crop genes would not persist," says Allison Snow of Ohio State University in Columbus, who described a 6-year experiment on half-wild, half-crop radishes planted next to wild radishes in Michigan. Snow's group found that crop genes had no trouble sneaking into the weeds—and staying there.

While the first cross between these relatives (the F1 generation) had low fertility—as few as 60% made seeds—several traits, including white flowers and variants of two enzymes, showed up in subsequent generations of wild radishes. And second-generation hybrids—crosses between F1 and wild plants—grew almost as well as the wild radish. Although it's not a big surprise that traits showed up in the wild radishes, "it's important to quantify persistence," says plant scientist Neal Stewart of the University of North Carolina, Greensboro. Radish, he notes, "is a very nasty weed."

But white flowers and a more crop-like metabolism are hardly the makings of superweeds. What might help weeds outlast the competition, however, is if a jumping gene they acquired were able to help them fend off viral attack, says Power.

Her test case is crops modified to resist the barley yellow dwarf virus. To find out whether the trait could give a leg up to wild plants, Power first looked at whether the virus shows up much in nonagricultural ecosystems. The team tested for virus in wild grasses near Ithaca. Surprisingly, up to 60% of samples of 16 grasses, including

FE has proclaimed a new initiative called Vision 21. The goal of Vision 21 is to develop a power system (which might also produce clean transportation fuels) that is highly efficient (about 65 percent), produces no appreciable air pollutants, and has no net carbon dioxide emissions. In addition, the goal is a system that produces power at less cost than the best pulverized coal plants today and, in fact, at costs competitive with natural gas. This is a most ambitious vision, but it has some chance of being realized (see Figure 4.1), and it is an appropriate target for DOE.

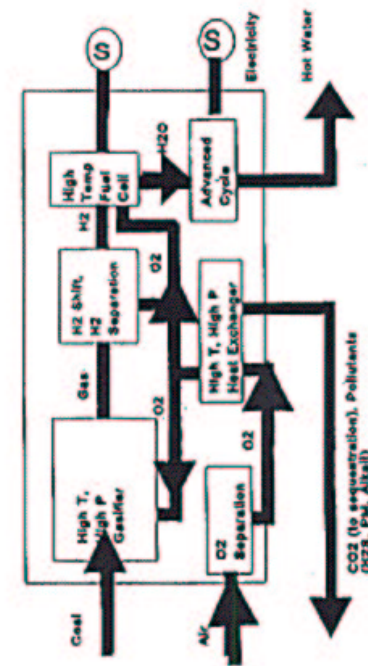


Figure 4.1: The Vision 21 Plant. Vision 21 is the DOE Office of Fossil Energy's idea for freeing coal power from environmental constraints. For this scheme, coal and/or other feedstock fuels such as biomass and some waste materials are gasified in an oxygen-blown gasifier, and the product is cleaned of sulfur and reacted with steam to form hydrogen and CO₂. After heat extraction from the CO₂, it is sequestered from the atmosphere. The hydrogen can eventually be used as a transportation fuel or it could be oxidized in a high-temperature fuel cell and the reactant hot gases could drive a gas turbine and a steam generator to make electricity. This system could have an efficiency of 60 to 65 percent, which is the goal. Air pollutants are negligible and net CO₂ emissions are zero or nearly so. The overall cost goal is 10 percent less than that of a state-of-the-art pulverized coal plant.

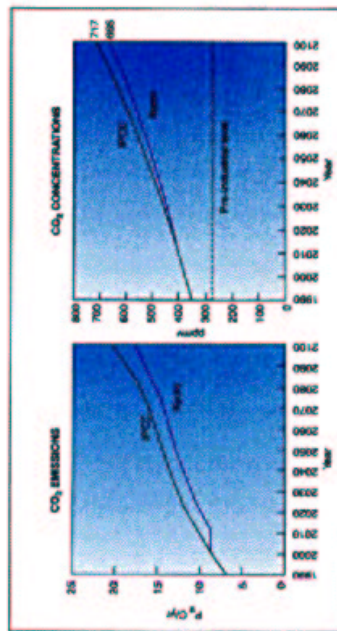
Coal and Gas Power and Fuels. The Panel endorses Vision 21, as the long-term objective and recommends reorientation of DOE R&D priorities toward it. This should include continued emphasis to improve efficiency of the combined cycle using high temperature fuel cells, development of advanced gasification technologies (for coal, biomass, or waste) for the flexible production of power and clean transportation liquid fuels (ultimately hydrogen and separated CO₂). It should also include initiating a science-based CO₂-sequestration program in cooperation with the US Geological Survey, industry, and universities, with an annual budget rising to \$20 million dollars or more in 2003. Hydrogen may prove to be the transportation fuel of the future if fuel cells become the power source of choice for vehicles, and fossil fuels are the likely least expensive route to hydrogen assuming sequestration is practical.

PCAST
Energy R&D Panel
1997

Oil and Gas Production and Processing. Because of its importance as a transition fuel for the United States in controlling CO₂ emissions, the Panel recommends more intense effort on natural gas production and processing, including a major initiative for DOE to work with USGS, the Naval Research Lab, Mineral Management Services, and the industry to evaluate the production potential of methane hydrates in US coastal waters and worldwide. The resource is very large indeed, in the range of 100,000 to 1,000,000 Tcf (trillion cubic feet). This research might well interface with hydrogen-production and CO₂-sequestration efforts with CO₂ hydrates as the sequestered state of the gas.

Transportation Fuels Strategy. The Panel recommends that DOE develop a comprehensive transportation fuels strategy, beginning with an analysis of the potential for technologies to increase the price elasticity of oil supply and demand including the impact of substitutes. This effort should include, for example, R&D focused on reducing the cost of producing transportation fuels from natural gas and work on indirect liquefaction of coal and biomass. Such an effort is supportive of Vision 21 and may improve its flexibility for combined fuel and power generation, including eventually producing hydrogen for central or distributed use with CO₂ sequestering.

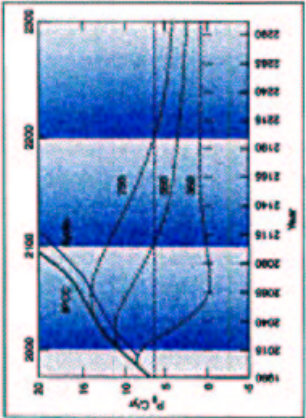
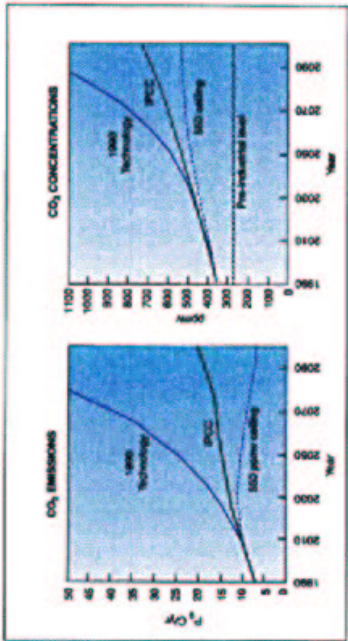
PCAST
Energy R&D Panel
1997



IPCC 1990 Assumptions for “Business as Usual”

1. In 100 years renewable and nuclear technologies will provide more than 75% of all electric power, compared to 24% in 1990.
2. Non-carbon technologies (including solar and wind) are assumed to grow to about twice the size of the entire global energy system in 1990.
3. Energy consumed per unit of economic activity declines to 1/3 of 1990 levels.

These assumptions pose huge technical challenges



A fairly clear sense of the quantities required for climate control has emerged. For example, if a target of stabilization of atmospheric CO_2 levels at about 550 ppm (about twice pre-industrial values) is set, then deviations from present trends of about 3.7 billion tons CO_2 per year by 2025, and 14.6 billion tons per year by 2050 will be required. This may be achieved by a combination of conservation/efficiency, fuel substitution, and geologic/ocean CO_2 sequestration.

Each option has its advocates, and major policy choices have yet to be made. However if equal weight is given then the global sequestration target may approach 1.2 billion tons CO_2 per year by 2025. An advantage of sequestration is that it makes enhanced use of most of the trillion dollar fossil fuel infrastructure and workforce that we depend on to create wealth, and provide power for our technologically advanced society, until such time as new power systems emerge.

The U.S. share of this target is likely to be about 25%, or 0.3 billion tons per year. This includes both geologic (land based) and oceanic options. If the ocean option is taken as 25% of this, then we would consider 75 million tons CO_2 per year (or 0.2 million tons per day). This impressive number is less than 1% of even present day global surface ocean uptake.

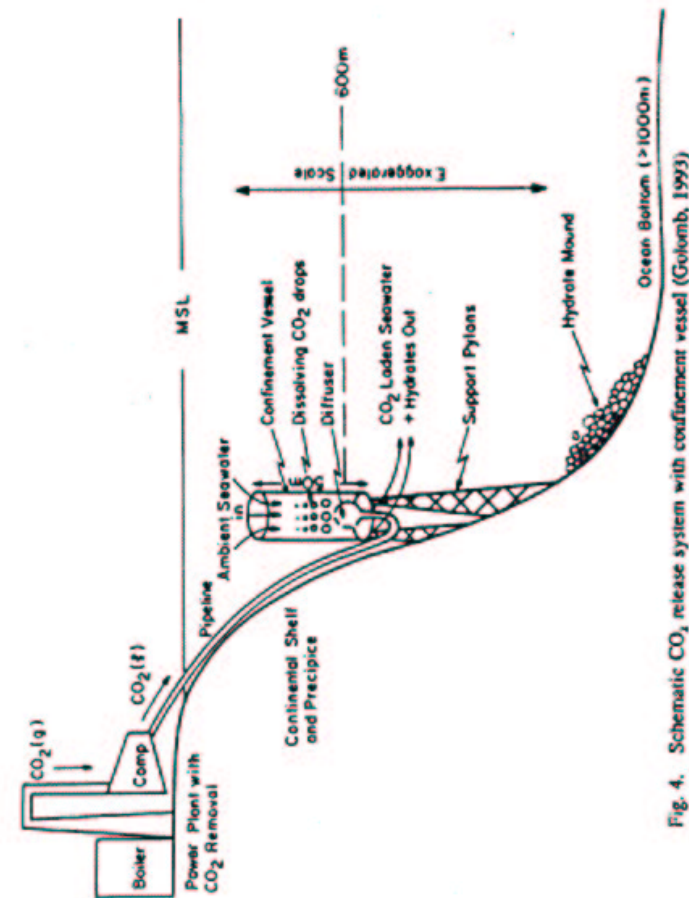


Fig. 4. Schematic CO_2 release system with confinement vessel (Golomb, 1993)

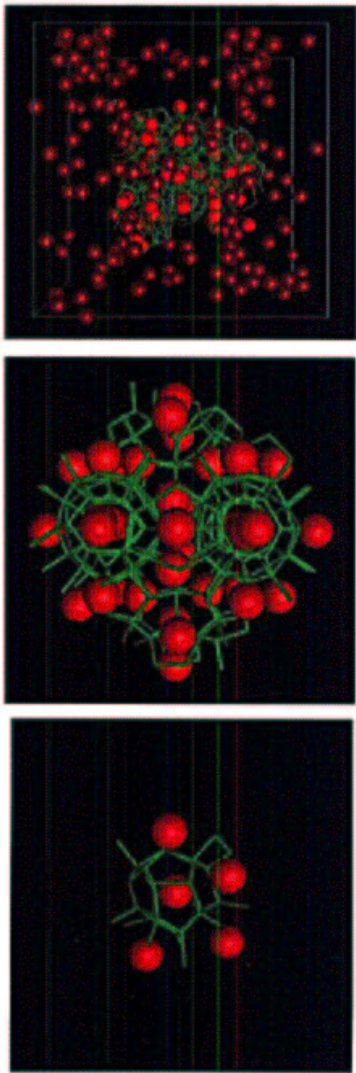
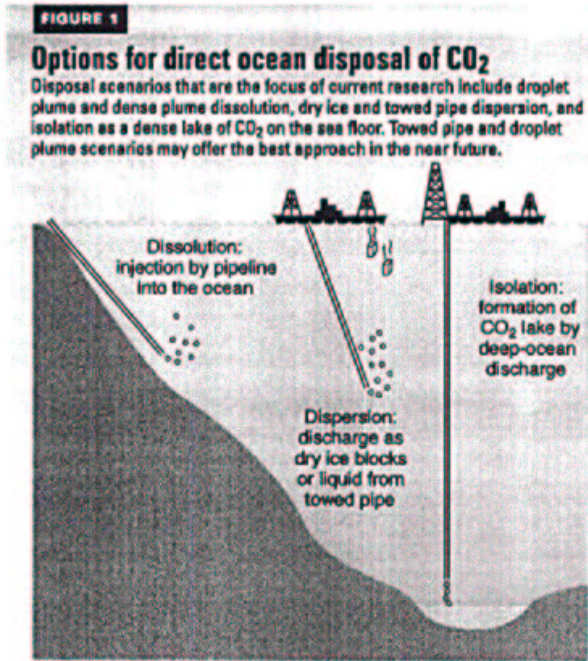
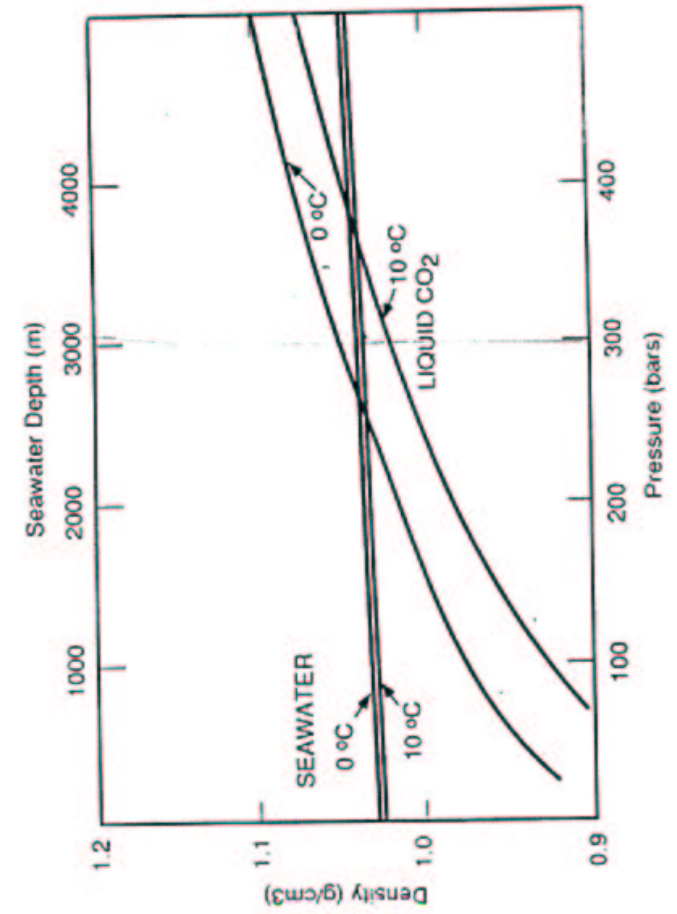
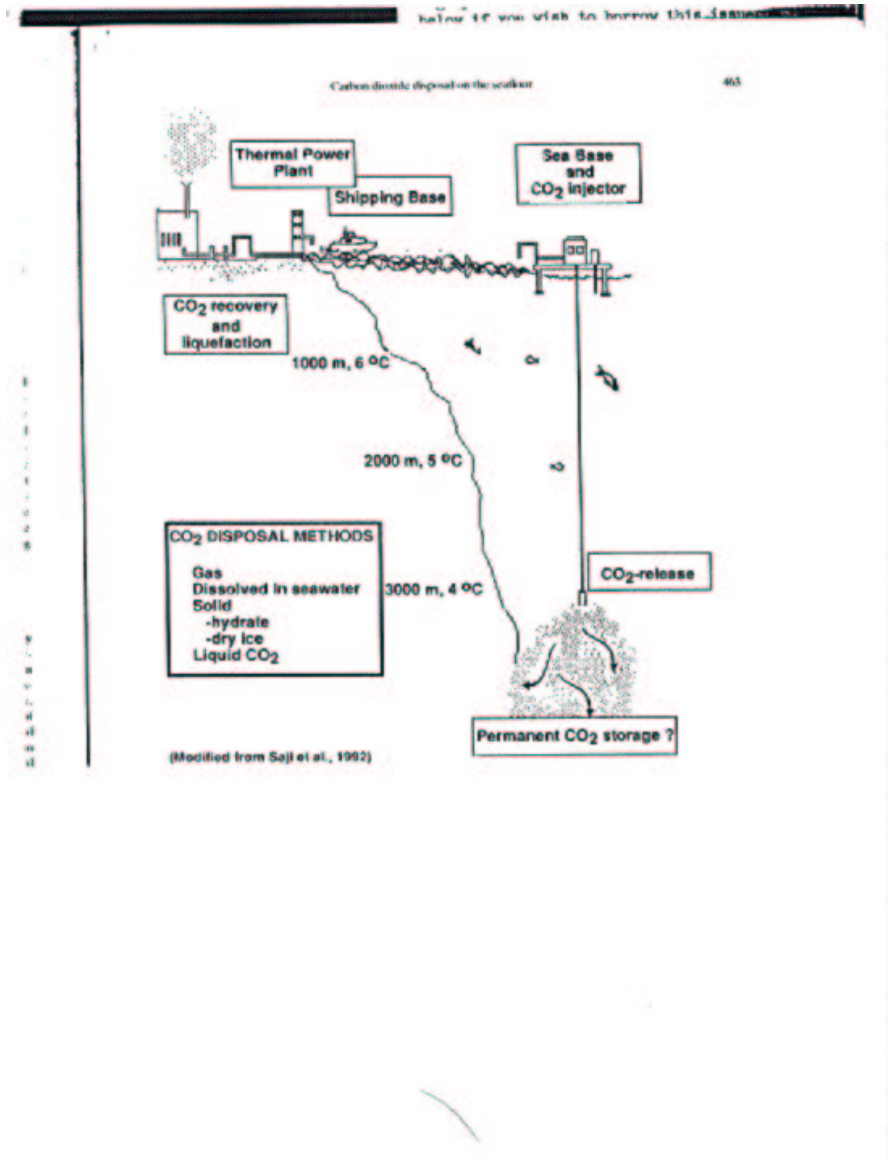
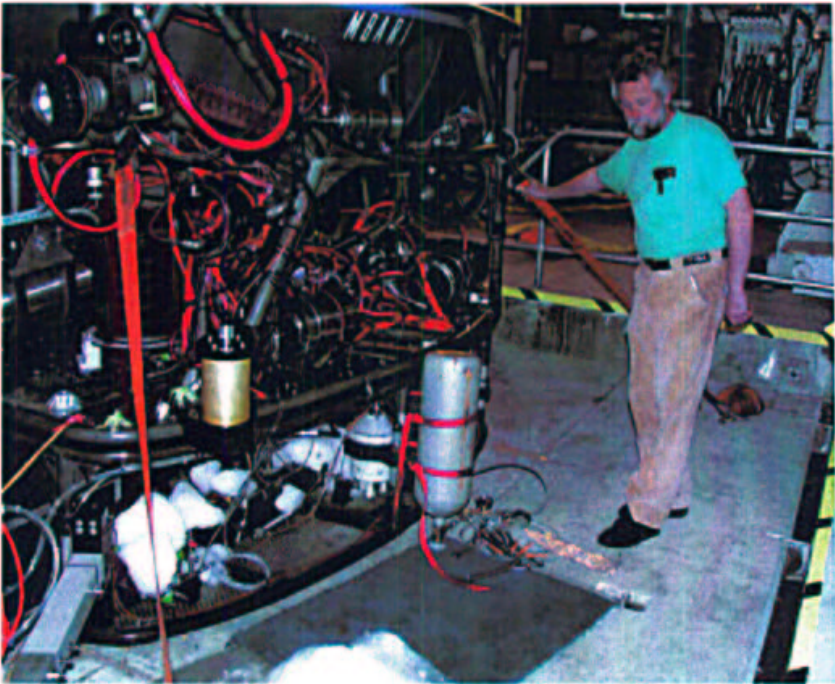
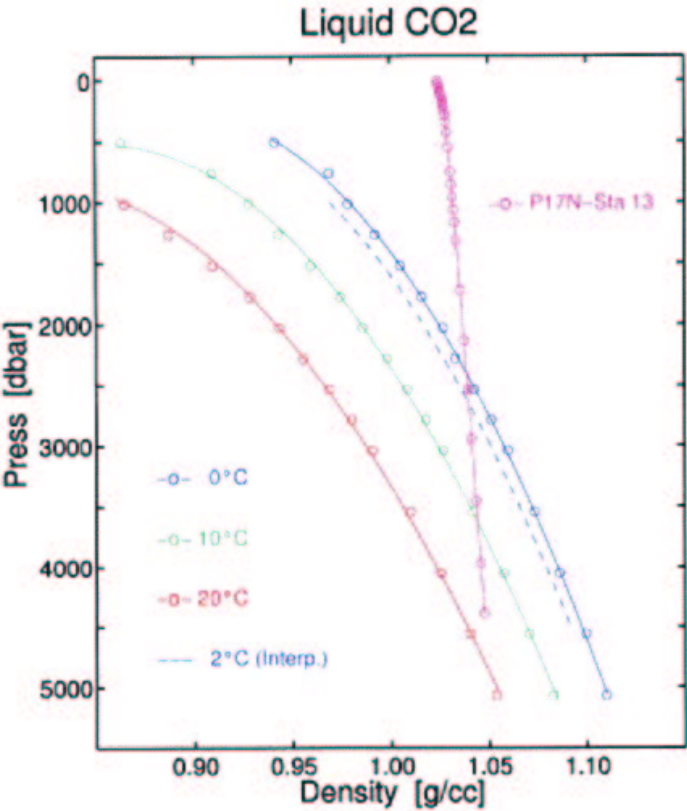


Figure: Options for direct ocean disposal of CO₂
<http://pubs.acs.org/subscribe/jour...thag-a732001.html/4752han1.ev.htm>



[Back to article.](#)





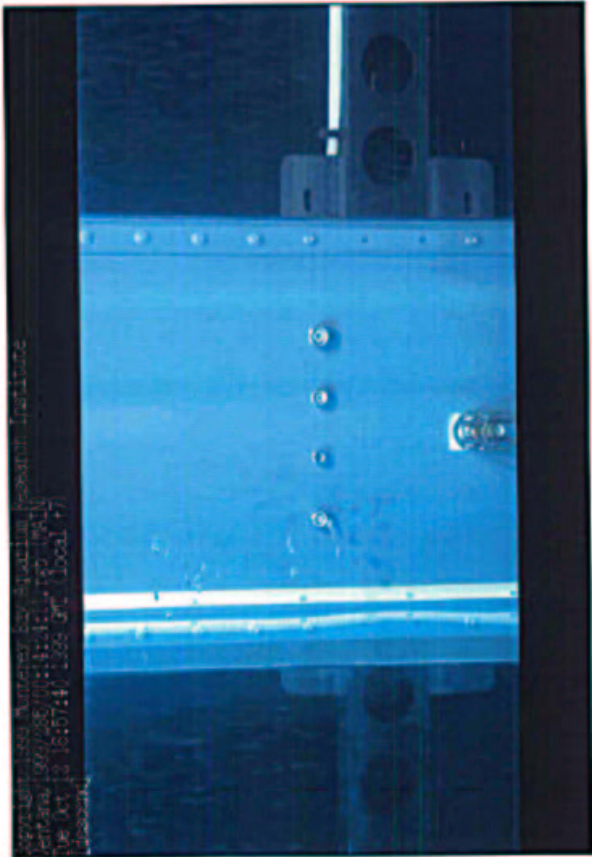
Page 1 of 1



1052066

file:///D:/DigiPic/10001013/PI0008.JPG

Page 1 of 1



<http://www.mbari.org/ARCHIVE/frameGrabs/Ventana/stills/1999/285/00:14:24:11.jpg>

1021599

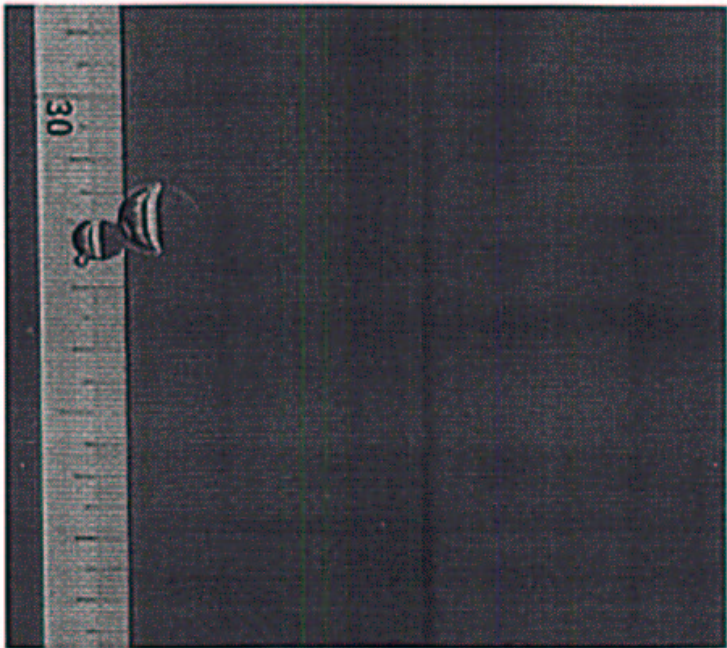


Figure 3. Image of the two CO₂ droplets tracked during ascent as they cross the scale (mm. divisions). The bubbles are in free motion with a mean upward velocity of 13 cm/sec. The image was taken from a video frame grab at 654m depth, 23 minutes after release. The droplets became attached and moved together, but did not merge and their dimensions could be separately determined.

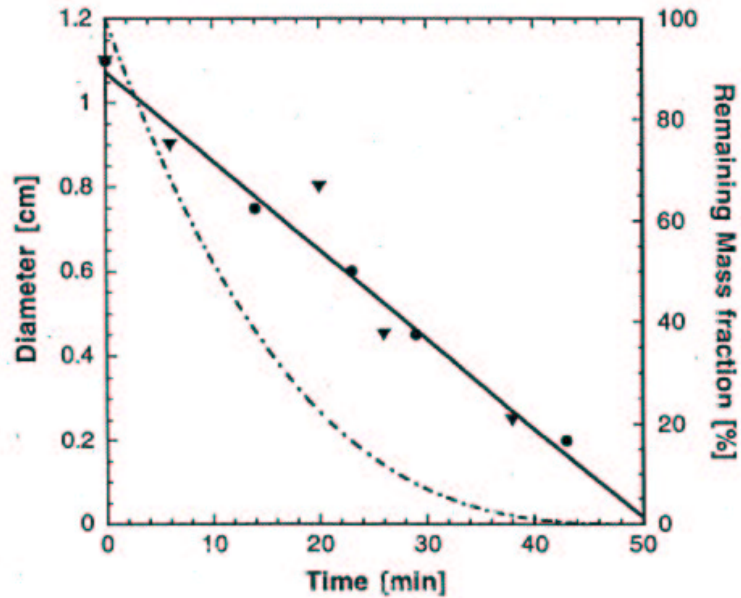


Figure 4. Plot of the changing droplet diameter with time, and remaining mass fraction of the droplets. The droplet size derived from HDTV video analysis, as listed in Table 1, is shown by points (a) and triangles (b), respectively. The solid line indicates the trend of diameter versus time calculated from equation (1) with a dissolution rate of 3.7 $\mu\text{mol}/\text{cm}^2/\text{sec}$. The dashed line shows the remaining mass fraction relative to the initial mass of the CO₂ droplets.

Table 1
Measured Liquid CO₂ Droplet Characteristics during Ascent from 800m Depth

Elapsed Time (minutes)	Depth (m)	Temperature (°C)	Droplet Diameter (cm)		Mass of CO ₂ (mol * 10 ⁻³)	
			(a)	(b)	(a)	(b)
0	804	4.40	1.1		14.7	
14	706	4.74	0.75		4.65	
23	650	4.99	0.6	1.1	2.38	14.4
29	602	5.16	0.45	0.9	1.00	7.90
43	496	5.45	0.2	0.8	0.09	5.55
49	447	6.00		0.45		0.99
61	341	7.28		0.25		0.17

The initial droplet tracked (a) was joined at about 650m depth by a second, larger, bubble (b) which became attached. No change in rise rate could be detected due to the attachment, and the changing size of each droplet could be independently determined. The mean density of liquid CO₂ during the rise of the droplets was 0.93 (a) and 0.91 (b), respectively. Thus, a 1 cm³ droplet contains 21.1 (a) or 20.7(b) millimoles CO₂. We calculate the dissolution rate (Γ) from the slope of

$$1/V_m(r_0) - r_0) = - \Gamma(t - t_0) \tag{1}$$

where V_m is the specific volume (mmol/cm³), r_0 and r_t are initial droplet radius and droplet radius at time t , and t_0 and t are initial time and the time elapsed since t_0 . The observed rate is 3.7 μmol/cm³/sec.

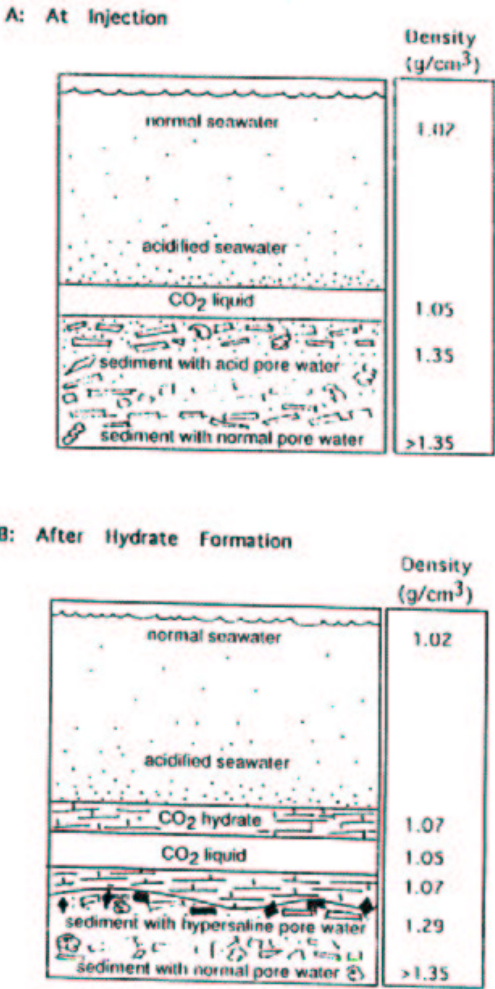


Figure 1 (a)

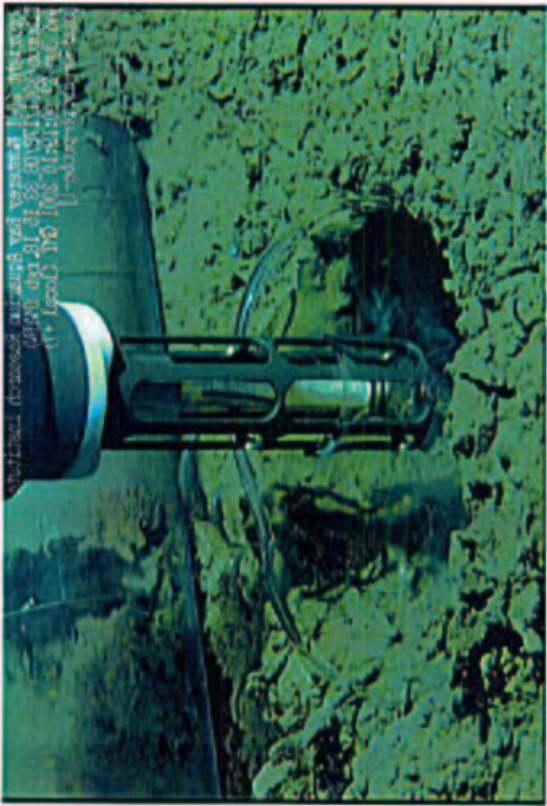
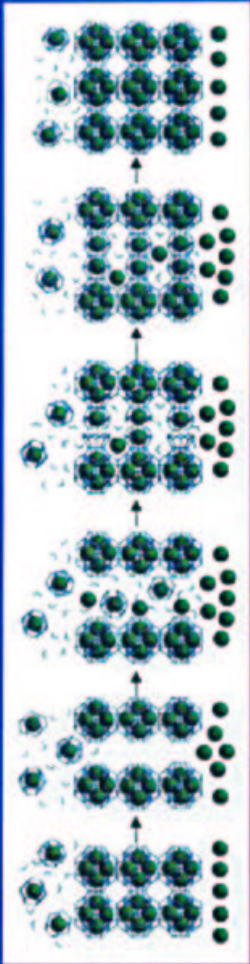


Figure 1 (b)

file:///C:/TEMP/CMCoul/bil/buope_08_23_12_18.jpg

Rebuilding of Hydrate Membrane

The Free Water Molecule Model



Yamane et al., (2000)

Aya et al., (2001)

