A carbon sink that can no longer cope?

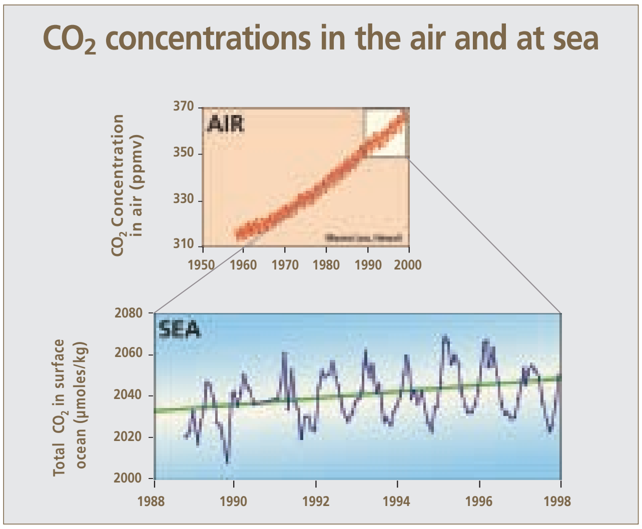
The oceans provide us with a valuable service by absorbing half of the carbon dioxide (CO_2) emitted by the burning of fossil fuels, thereby reducing the impact of this greenhouse gas on climate. A symposium held at UNESCO in May[16] has concluded, however, that we may soon pay a very high price for this service.

When, last May, over 100 of the world's leading ocean carbon scientists from different branches of marine biology and chemistry pieced together some of the best scientific information available, the results were alarming. The compiled research suggests that the increasing acidity of the ocean could seriously harm corals and other calcifying organisms, such as shellfish and some phytoplankton, the base of the marine food chain. If this food chain becomes disrupted, it could lead to the collapse of fisheries industries in many parts of the world, as well as of the billion dollar tourism industry that surrounds healthy coral reefs. These changes may also alter the ocean's ability to absorb fossil-fuel CO_2 in ways that are not yet fully understood.

The May meeting went on to fix urgent research priorities to probe the possible consequences of an acidifying ocean on marine ecosystems and assess the safety of proposed geo-engineering strategies for mitigating the impact on climate by storing excess CO_2 in the deep ocean.

How the carbon–climate connection was made

In the mid-1800s, the hot topic in the scientific world was the ice ages, a new hypothesis that much of the northern land masses had been covered in thick layers of ice tens of thousands of years previously. In investigating how the climate of the planet could change so dramatically, scientists discovered that certain gases in the Earth's atmosphere trap heat from the sun. Calculations showed that the conditions experienced during the ice ages could be brought on by halving the abundance of CO_2 in the atmosphere. But what natural processes might cause such large changes in concentrations of CO_2? This question launched one of the most challenging – and enduring – investigations of earth science: that of understanding the global carbon cycle.



Courtesy C.D. Keeling and N. Bates, U.S. JGOFS Program.

Increases in atmospheric and oceanic CO2 levels. The dips in the sea curve correspond to seasonal variation

At the beginning of the industrial revolution in the mid-eighteenth century, human activities like the burning of fossil fuels began adding CO_2 to the atmosphere but the amounts were small when compared with the amount of CO_2 naturally present in the atmosphere. Early concerns about the long-term build up of this CO_2 in the atmosphere were not taken seriously because most scientists at the time believed that the oceans would naturally absorb 90% of the industrially produced CO_2 emitted to the atmosphere.

In the late 1950s, geochemists Roger Revelle (the founder of UNESCO's Intergovernmental Oceanographic Commission, IOC) and Hans Suess sounded the alarm. Their calculations showed that ocean uptake of CO_2 was much slower than originally thought and that the oceans could absorb no more than 50% of the CO_2 being emitted annually by fossil-fuel burning. The remainder, they warned, would build up in the atmosphere, where it would increase the atmosphere's ability to trap heat, producing a 'greenhouse effect'. In 1958, Charles David Keeling began taking the first high-quality measurements of atmospheric CO_2 at the Mauna Loa Observatory in Hawaii (USA); he would soon give the world proof of the steady climb in the concentration of CO_2 in the atmosphere. Twenty-five years later, measurements of ocean CO_2 began, in turn, at the Bermuda Atlantic Time Series Station, documenting the slow penetration of this excess CO_2 into the surface oceans.

Solving the riddle of the missing carbon sink

Of the fossil-fuel CO_2 emitted globally, only half has accumulated in the atmosphere. The fate of the other half has prompted a decades-long search for the 'missing carbon sink'. The two possible sinks for this CO_2 are the terrestrial biosphere (e.g. via photosynthesis) and the ocean. The ocean represents the largest natural stockpile

16. The Ocean in a High CO_2 World. International Science Symposium sponsored by the Scientific Committee on Oceanic Research and UNESCO's Intergovernmental Oceanographic Commission (IOC) of carbon and has a dynamic interaction with the atmosphere over 70% of the planet's surface. The only direct method of calculating the amount of CO_2 absorbed by the ocean is through direct measurements on a global scale. From 1990 to 1998, a multinational research programme called the World Ocean Circulation Experiment/Joint Global Ocean Flux Study amassed data from nearly 10 000 stations around the world's oceans from 95 separate expeditions and produced the first global survey of carbon distribution in the ocean.

Recent results from the global survey have solved the mystery of the missing carbon sink: the data show that the oceans have taken up approximately 118 billion tons of the CO_2 emitted since 1800, roughly 48% of the total; currently, some 20–25 million tons of CO_2 are being added to the oceans daily, calculates the study, which was published in *Science* in July[17]. Without the ocean sink, atmospheric CO_2 would be much higher and its climatic impacts more severe[18]. But scientists are now faced with a new question, 'Will the oceans continue to take up almost half of the CO_2 emitted to the atmosphere, even in a warmer climate with changed ocean mixing patterns?' A second global survey and several international research programmes were launched in 2003 to find out.

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Acid ocean?

A second and perhaps more pressing question is, 'How are these higher levels of ocean CO_2 going to affect ocean ecosystems?' Today, there is growing concern that this natural service provided by the oceans may have a steep ecological cost, the acidification of the oceans.

As CO_2 dissolves in seawater, the pH of the water decreases, making it more acidic. Since the beginning of the industrial revolution, the pH has dropped globally by 0.12 pH units[19].

Photos courtesy of Professor Ulf Riebesell, Leibniz-Institut für Meereswissen-schaften, IFM-GEOMAR

Experiments in a floating corral (or mesocosm) in this Norwegian fjord help to understand how marine ecosystems will behave in a more acidic environment

While these pH levels are not particularly alarming, the rate of change and the downward trend is cause for concern. To the best of our knowledge, the oceans have never experienced such a rapid acidification. By the end of this century, if concentrations in the atmosphere continue to rise exponentially, we may expect to see changes in pH that are three times greater and 100 times faster than those experienced during the transitions from glacial to interglacial periods. Such large changes in ocean pH have probably not been experienced on the planet for the past 21 million years.

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Marine ecosystems under threat

Corals, calcareous phytoplankton, mussels, snails, sea urchins and other marine organisms use calcium carbonate ($CaCO_3$) in seawater to construct their shells or skeletons. As the pH decreases, such as when water is more acidic, it becomes more difficult for organisms to secrete $CaCO_3$ to form their skeletal material. It is this effect that has marine scientists concerned: since the oceans have never experienced such a rapid acidification, it is not clear how ocean chemistry will change or how ecosystems will adapt.

The penetration of CO_2 into the ocean occurs very slowly but scientists can accelerate this process in the laboratory or in field experiments to study the effects that increasing CO_2 may have on marine ecosystems in the coming decades. One method is to set up floating corrals (mesocosms) in the ocean that encircle natural populations of phytoplankton and to manipulate the CO_2 concentration in the air above the corral to study the effects of varying levels of CO_2 on the ecosystem. Since the lifespan of phytoplankton is of the order of one week, scientists can observe the effects on many generations over a short period of time.

From laboratory and mesocosm experiments conducted to date, almost all calcifying organisms have shown decreased calcification in more acidic environments. This is true for both the smallest single-celled organisms and for reef-building corals. Under such conditions, calcareous phytoplankton, which constitutes part of the basis of the marine food chain, will form thinner skeletons and thus experience difficulties in growth and reproduction. This, in turn, may have profound effects on the marine food web, causing shifts in fish population size or geographic location.

17. Sabine et al. (2004) The Oceanic Sink for Anthropogenic CO_2, Science, **305**, *367–371*

18. The cost of avoiding CO_2 emissions is currently US$40–60 per ton of CO_2 (International Energy Agency Greenhouse Gas Research and Development Programme). By absorbing 118 billion tons of fossil fuel since the beginning of the industrial revolution, the ocean has provided a natural ecosystem service of the order of US$6 trillion

19. The lower the pH, the more acidic the solution. Natural seawater has a range of 7.7–8.2 pH units

Coral reefs face two challenges from increasing atmospheric CO_2. Firstly, higher CO_2 concentrations in the atmosphere are linked to warmer global temperatures, which in turn lead to warmer water temperatures. Corals are very sensitive to temperature change: a 1–2º C change in local temperature above their normal summer maximum can lead to a phenomenon called 'bleaching', whereby the corals expel their vital algal symbionts (algae which live in symbiosis with the coral), leaving the coral tissues translucent. In 1998, a single bleaching event led to the loss of almost 20% of the world's living coral. Corals can recover from these events but repeated episodes are likely to weaken the coral ecosystem, making them more susceptible to disease and causing a loss of biodiversity. The second challenge faced by corals is the increasing acidity of the water caused by higher CO_2 concentrations. Lowered calcification rates affect the reef's ability to grow its carbonate skeleton, leading to slower growth of the reef and a more fragile structural support, which makes the reef more vulnerable to erosion. By the middle of this century, the estimated reduction in calcification rates may lead to a situation where we are losing more reef area to erosion than can be rebuilt through new calcification.

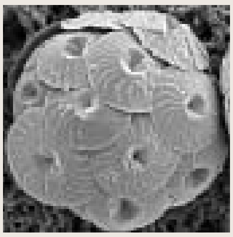
Invertebrates and even some fish may be affected by lower pH environments, leading to lowered resistance, metabolic depression, behavioural depression affecting physical activity and reproduction, and asphyxiation.

Higher marine life forms, such as invertebrates and even some fish, may be affected by lower pH environments through acidosis (an increase in carbonic acid in body fluids) leading to lowered resistance, metabolic depression, behavioural depression affecting physical activity and reproduction, and asphyxiation.

How does phytoplankton react to high levels of CO_2 ?

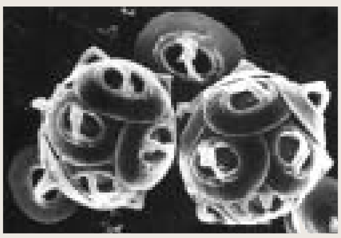
Today's world (pCO_2: 280–380 ppm)

High CO_2 world (pCO_2: 580–720 ppm)

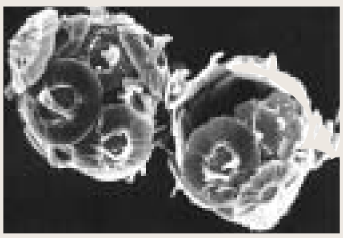


Scanning electron microscopy photographs of two calcifying phyto-plankton under pCO_2 conditions of today (pCO_2 from 280 ppm to 380 ppm) and under the high CO_2 conditions expected by the end of this century. Experimental results show that increased CO_2 con-centrations lead to malformations of calcium carbonate shells

Calcidiscus leptoporus



Gephyrocapsa oceanica



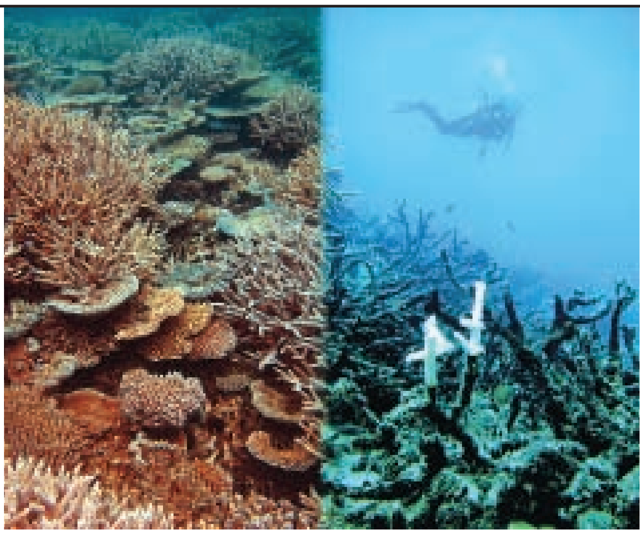
Photos courtesy of Professor Ulf Riebesell, Leibniz-Institut für Meereswissen-schaften, IFM-GEOMAR. Adapted and reprinted with permission of Nature (www.nature.com): Riebesell et al. (2000) Reduced calcification of marine phytoplankton in response to increased atmospheric CO2 Nature 407, 364-367.

While these projections of our future oceans may seem like doomsday scenarios, we will probably never see dramatic, rapid changes. Instead, there will be slow, progressive shifts in the equilibrium conditions of marine ecosystems over many decades. Scientists will be watching for indications that these ecosystem changes are occurring.

Dodging the impacts

Many scientists believe that stabilizing atmospheric CO_2 concentration at 550 parts per million (ppm) may avoid the worst impacts on climate. Atmospheric concentration of CO_2 is currently ~380 parts per million (ppm) and, if no precautionary action is taken, is expected to reach 550 ppm by the middle of this century. Stabilizing CO_2 at 550 ppm will be a global challenge on an unprecedented scale. According to the Intergovernmental Panel on Climate Change (IPCC), the most authoritative source for scientific assessments of climate change, this may not be achieved through emissions reductions alone but rather through a carefully crafted portfolio of actions that also includes investments to develop low-cost, low-carbon or no-carbon energy sources, improvements in energy efficiency and carbon management options. The latter include storing carbon in the terrestrial biosphere (e.g. planting trees, limiting deforestation), or capturing the CO_2 emitted from an industrial source and storing it in geological formations or in the deep ocean. The IPCC is currently assessing these options for their feasibility, efficacy and safety, and calling for more research wherever information is insufficient to make a sound policy decision.

Scientists participating in the UNESCO symposium were asked to examine the issue of the potential efficiency and ecological impacts of using the ocean purposefully to store atmospheric CO_2. Much relevant research has been conducted in the past decade but the potential effectiveness and risks of ocean carbon sequestration have been neither thoroughly discussed nor assessed. Moreover, the science itself has become trapped in a tug of war between environmental groups and commercial entrepreneurs seeking financial compensation for artificially sequestering carbon in the ocean. Frustrated scientists have asked the IOC to provide a safe-haven



Photos courtesy of Dr Ove Hoegh-Guldberg, Centre for Marine Studies, University of Queensland, Australia

Increasing CO_2 and sea temperatures can rapidly change coral reefs from healthy ecosystems into virtual graveyards of bleached and decaying coral

for scientific discussions, free from the influences of special interest groups.

Storage strategies and research requirements

Debate centres on two methods of using the ocean to store excess CO_2. One strategy is to induce and enhance artificially the growth of carbon-fixing plants in the surface ocean. When these organisms die, they sink to the deep ocean, carrying the carbon with them. In many regions, phytoplankton growth is limited by lack of an essential micro-nutrient, iron. Over the past decade, eight small-scale experiments have shown that introducing iron to iron-poor regions can stimulate phytoplankton growth to 20–30 times the natural rate.

Symposium participants agreed that iron fertilization experiments have been, and will continue to be, important for understanding the links between marine ecosystems and the global carbon cycle. However, all available research indicates that iron fertilization would be a very inefficient method for sequestering atmospheric CO_2, both from the viewpoint of the limited amount of carbon that could be sequestered by this method and the likelihood that, even if iron limitations were eliminated, other nutrients and environmental factors would eventually limit growth.

Another method of ocean carbon sequestration is to capture CO_2 from industrial sources, compress it into a liquid and store it in natural reservoirs out of contact with the atmosphere, such as deep geological formations or the deep ocean. Many important questions remain about the efficiency and impacts of injecting liquid CO_2 into the deep ocean and experimental data are extremely limited. The efficiency of this method would depend on the location and depth of the injection, since the goal is to keep the injected CO_2 out of contact with the atmosphere for as long as possible, while minimizing environmental damage around the area of the injection. Reproducing the temperature, pressure and the biological communities found in the deep ocean in a laboratory is extremely difficult. Carrying out small-scale experiments *in situ* in the deep ocean is no simple matter either, often requiring the use of deep-sea remotely operated vehicles or special instruments that must be lowered to great depths from a research vessel.

To further complicate matters, several attempts to perform experiments *in situ* have been blocked by environmental groups over concerns that these experiments represent the first step towards industrial-scale dumping. This has been a very divisive issue within the scientific community itself, with many strongly opposed to ocean carbon sequestration, even to the extent of suggesting that the community should not pursue research on the subject.

Unfortunately, because of the ocean's large natural capacity to store CO_2, ocean carbon sequestration will continue to interest commercial companies, some of whom may attempt to promote this technique without regard for potential environmental impacts. Symposium participants agreed that, even in the face of strong ethical opposition, investigations into the technical and economic feasibility of implementing this mitigation strategy are likely to continue. The international scientific community must be ready to respond accurately and without bias to questions of potential environmental impacts, long-term efficiency or benefits of this technique, weighing ocean carbon sequestration against other options and the critical need to stabilize atmospheric CO_2 at a concentration that will avoid the majority of impacts on human life and welfare.

Keeping watch

The ultimate objective of the UN Framework Convention on Climate Change is 'to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.' Whereas 'dangerous anthropogenic interference with climate' has been widely discussed, no such debate has taken place over acceptable oceanic CO_2 levels. As a result, there are no standards to apply to judge what oceanic CO_2 levels should be considered tolerable for marine life or how proposed carbon management strategies might moderate or exacerbate effects on ocean chemistry and biology.

The IOC will maintain its Watching Brief on ocean carbon sequestration science and will continue to bring together the international and intergovernmental scientific community to develop unbiased policy-relevant scientific information for use by scientists, policy makers and the general public.

Maria Hood[20]

Read the report of the symposium and the IOC Watching Brief :http://ioc.unesco.org/iocweb/co2panel/

20. UNESCO Programme Specialist in marine sciences