UNEP

REGIONAL SEAS

Interaction of the oceans with greenhouse gases and atmospheric aerosols

UNEP Regional Seas Reports and Studies No. 94

Prepared in co-operation with

WHO UNESCO

Note: This document is an extract from the report entitled "Pollutant Modification of Atmospheric and Oceanic Processes and Climate" prepared for the Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) sponsored by the United Nations, United Nations Environment Programme (UNEP), Food and Agriculture Organization of the United Nations (FAO), United Nations Educational, Scientific and Cultural Organization (UNESCO), World Health Organization (WHO), World Meteorological Organization (WMO), International Maritime Organization (IMO) and International Atomic Energy Agency (IAEA).

The report was prepard by the WMO-led GESAMP Working Group No. 14 on the Interchange of Pollutants between the Atmosphere and the Oceans, which is also supported by UNEP and UNESCO. The eighteenth session of GESAMP (Paris 11-15 April 1988) approved the report of the Working Group and decided that it should be published by WHO as GESAMP Reports and Studies No. 36.

For bibliographic purposes, this document may be cited as:

WHO/UNCP/UNESCO: Interaction of the oceans with greenhouse gases and atmospheric aerosols: UNEP Regional Seas Reports and Studies No. 94, UNEP, 1988.

CONTENTS

1. EXECUTIVE SUMMARY

The Sixth Session of the GESAMP Working Group on the Interchange of Pollutants between the Atmosphere and the Oceans stressed the impact of contaminants on climate. This included the effects of such "greenhouse" gases as CO_2 increasing temperature and aerosols decreasing temperature, as well as contaminants and processes at the air-sea interface that affect the interchange of energy and material which could affect climate regionally and even globally.

Carbon dioxide is clearly increasing in the atmosphere at the rate of about 1 ppmv (parts per million by volume) per year, starting at 315 ppmv in 1958 when good records commenced. It is estimated that the near-surface global temperature will increase by 1.5° to 4.5°K with a doubling of the atmospheric CO_2.

The global cycle of carbon dioxide indicates that the terrestrial biosphere and the oceans each cycle about 10^2 Gt (1 gigaton = 10^{15} g) carbon per year between themselves and the atmosphere, in a two-way flux if the system is in a steady state. This equilibrium has been perturbed naturally in the last 10^4–10^5 years at least, as shown by the analysis of air trapped in bubbles of glacial ice cores. Since the start of the agricultural/industrial revolution, man has added another perturbation by burning fossil fuels and mobilizing CO_2 from the fixed carbon in the land biosphere. For the period around 1980, the release of CO_2 from fossil fuel combustion is about 5 GtC yr^{-1} and estimates of the release from biomass destruction, e.g., deforestation, ranges from 0 to 2 GtC yr^{-1}, depending on the technique of estimation. The major sink for man-mobilized CO_2 is the ocean which is estimated to accept about 2-3 GtC annually. The atmosphere retains about 2.5 GtC yr^{-1}; it is this residual CO_2 that contributes to the annual increase in atmospheric CO_2 concentration. The discrepancy between sources and sinks of man-made CO_2 is in the range of 0.5 to 1.5 GtC yr^{-1}, depending on the net biospheric input. Arguments are presented to show that the current input of CO_2 from the biosphere is no more that 1 GtC yr^{-1}, but uncertainty regarding the biomass contribution of CO_2 continues.

Some of the factors affecting the oceanic uptake of CO_2 from the atmosphere are presented. The gas transfer velocity is controlled mainly by the wind speed. The other variable that controls the CO_2 exchange flux is the partial pressure difference between the air and the sea. It is noted that there is a latitudinal variation in CO_2 flux, based on the observed CO_2 partial pressure distribution in the surface ocean. A net CO_2 flux of the order of 2 GtC yr^{-1} emanates from the sea in the equatorial region between 16°S and 16°N. To balance this contribution, there would have to be a net flux of about 4 GtC yr^{-1} from the atmosphere to the ocean north and south of this region.

Various models of the oceanic carbon cycle exist to estimate uptake of atmospheric CO_2 by the oceans. Diagnostic models have been developed in which the ocean is subdivided into a few well-mixed reservoirs connected by first-order exchange fluxes. Stationary tracers (e.g., natural ^{14}C) and transient tracers (e.g., bomb-produced ^{14}C and ^{3}H, ^{85}Kr, halocarbons) have been used to calibrate the models by circulating the advective and diffusive fluxes between the various boxes. Effects of the marine biosphere and its associated cycle of nutrients have been included.

Recently, new types of circulation models of the oceanic carbon cycle, based on a realistic three-dimensional flowfield and mixing parameters of a general circulation model of the global ocean, have been introduced. These models make it possible to assess the effects of changes in the oceanic circulation, arising from climatic changes, on tracer distributions and the oceanic uptake capacity for CO_2. They are preliminary, however, and lack certain features of the real ocean, particularly a realistic representation of the surface layer, including the marine biosphere.

With increasing temperatures due to rising atmospheric CO_2 concentration, inhomogeneities in sea-surface warming are expected owing to faster surface warming in areas with a shallow mixed layer and a strong thermocline than in areas of deep winter mixing or upwelling. Cold sea-surface temperature anomalies (SSTAs), relative to the temperature pattern expected at equilibrium with the CO_2 increase, would likely develop. SSTAs influence global weather patterns, as has been demonstrated by numerical experiments with weather forecast models. Good agreement has been found between the numerical experiments and available observations for both middle-latitude and tropical SSTAs. Rainfall increased near to warm anomalies and decreased in adjacent tropical regions. Major associated changes in atmospheric circulation arose. The response to equatorial SSTAs in middle latitudes is two to three times greater than for mid-latitude SSTAs of similar magnitude.

A second way that the ocean may modify the climatic response to a CO_2 increase is through the effect on ocean circulation and the distribution of temperature and salinity of changes in the atmospheric forcing at the surface due directly to the increase in CO_2. Increased high-latitude precipitation would cause greater annual mean run-off, thus decreasing coastal salinities. Changes in the tropical rainfall distribution would effect changes in the density structure of the tropical oceans.

It was recognized that other man-made substances besides CO_2, e.g., chlorofluorocarbons, nitrous oxide, methane and ozone, could influence the earth's radiative energy balance. Many authors claim that these radiatively active trace gases could cause a warming of the surface-tropospheric system of the same magnitude as that projected for increases in CO_2. Such trace gases pose radiative/chemical/dynamical problems that are distinctly different and more complex than those of CO_2. They could influence global climate through the greenhouse effect, but unlike CO_2, they exhibit no important exchange processes with the oceans.

Both natural and man-made aerosols may influence climate by direct reduction of solar insolation transfer to the earth's surface and by change in the earth's albedo through aerosol interaction with cloud processes. Natural aerosols, e.g., volcanic emission, may play a more important role in climate changes than anthropogenic aerosols. During periods of extended air stagnation, accumulation of aerosols could be enough to change the solar energy input to coastal areas and regional seas. But it is not expected that anthropogenic aerosols would have much influence on global ocean climate through direct intervention with solar energy. The interaction of aerosols and clouds, on the other hand, may have a more significant impact on climate. Recently, investigators have postulated that natural sources of sulfur over the oceans may play an important role in regulating the cloud-condensation nuclei and hence the albedo. Others conclude that the effects of aerosols will probably not overshadow the impact of greenhouse gases as the most important cause of climate change over the next century.

2. CARBON DIOXIDE

2.1 Introduction

There is considerable evidence from climate models that the observed increase in the atmospheric concentration of carbon dioxide (CO_2) will lead to a significant warming of the atmosphere-ocean system [e.g., see the Villach, October 1985, Conference Report (WMO, 1986)].

In the models, this warming is due to the direct radiative effect of CO_2 enhanced by positive feedbacks due to water vapour, snow and ice and cloud extent. The equilibrium global near-surface warming for a doubling of CO_2 is estimated to be 1.5° to 4.5°K, with most recent results with model-dependent cloud cover nearer to the larger figure. This warming is larger in middle and high than in low latitudes.

The ocean is expected to modify this climate response directly in two ways. Firstly, the ocean's large thermal inertia will cause the ocean (and atmosphere) warming to lag behind that which would be in equilibrium with the CO_2 increase. Secondly, the atmospheric forcing of the ocean through momentum, heat and water transfer will be changed, thus modifying the ocean circulation and temperature and salinity structure. These aspects are discussed in Section 2.7.

The ocean's role in the global carbon cycle is crucial to predictions of future atmosphere CO_2 levels. Increases in other trace gases including methane, chlorofluorocarbons and nitrous oxide are together expected to lead to a warming of comparable magnitude to that caused by CO_2 (see Section 3). The following discussion of CO_2 can also be applied to these gases except that the ocean plays a lesser part in their geochemical cycles.

2.2 The global carbon cycle

A summary of the principal carbon reservoirs on the earth and the major fluxes between them is given in Figure 1. Examination of the reservoir sizes immediately highlights the smallness of the atmosphere as a reservoir for carbon relative to the land biosphere, sedimentary deposits, the oceans and fossil fuel reserves. This means that even small transfers of carbon as CO_2 from the other reservoirs to the atmosphere can have a disproportionately large effect on the latter.

Both the land biosphere and the oceans each cycle approximately 10^2 Gt*C yr^{-1} between themselves and the atmosphere; this is a balanced two-way flux if the system is stationary. Perturbation of the steady-state situation can come about when the two-way fluxes are out of balance, which is what must have happened in the past to explain the atmospheric CO_2 variations over at least the last 10^4-10^5 years, shown by analysis of air trapped in ice cores (Neftel et.al., 1982).

Since the industrial/agricultural revolution, man has applied another perturbation by burning fossil fuel and by net conversion of land biosphere (fixed carbon) to CO_2. The sizes of these anthropogenic mobilizations are currently 5 GtC yr^{-1} from fossil fuel burning and anywhere from 0 to 2 GtC yr^{-1} from deforestation and changes in land use (see Section 2.6). The CO_2 enters the atmosphere and about 2.5 GtC yr^{-1} appears to remain there and leads to the well documented increase observed in atmospheric CO_2 partial pressure.

The major sink for man-mobilized CO_2 is the ocean which, according to current estimates, could get 2-3 GtC yr^{-1} of CO_2 during the last 25 years.

2.3 Ocean carbonate chemistry

In pure water CO_2 gas, although reasonably soluble, can be accommodated to only a very limited extent. Seawater, on the other hand, due to dissolved carbonates, contains about 150 times more carbon in the form of dissolved ionic species, primarily HCO_3^-, than does an equal volume of air at normal CO_2 partial pressure in equilibrium with it.

This fact makes the ocean the most important reservoir taking up CO_2 released by man to the atmosphere (Liss and Crane, 1983). As we shall see, however, the accommodating capacity of the ocean is much smaller than it might look at first sight. This is so for two reasons: (1) the time needed to spread the CO_2 taken up over the whole ocean depth is considerable (see below); and (2) the uptake capacity of seawater is about a factor of 10 (the so-called buffer or Revelle factor) smaller than anticipated from the static equilibrium partition factor of 150 quoted before. As a consequence of both (1) and (2), it turns out that the oceans take up the equivalent of half of the CO_2 released by fossil fuel combustion.

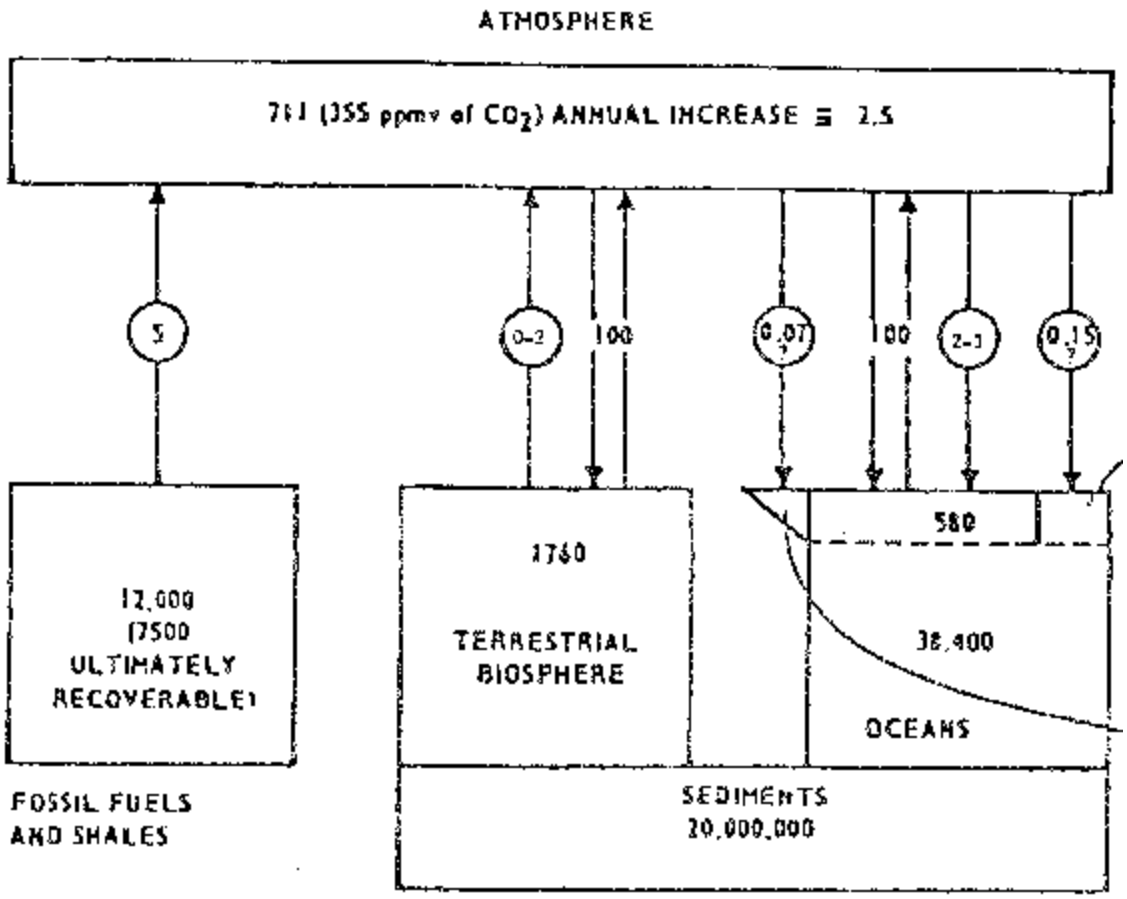

Figure 1 . Global carbon reservoirs and present natural and anthropoge reservoirs. Reservoir sizes in GtC. Fluxes between reserv Anthropogenic fluxes are circled.

2.4 Transfer of CO_2 between the air and the sea

The net flux (j) of CO_2 across the air-sea boundary can be expressed as the product of essentially two factors, the gas transfer velocity w and the difference ($\Delta pCO_2 = p_a - p_s$) between the partial pressures of CO_2 in the atmosphere p_a and the surface layer p_s of the ocean:

$$j = w \alpha \Delta pCO_2$$

Hence both quantities may be assessed separately. The third factor, the gas solubility α (i.e., the amount of CO_2 dissolved in a unit volume of water per unit CO_2 partial pressure) is a quantity comparatively easy to estimate and therefore of minor interest here.

The gas transfer velocity is controlled primarily by wind speed driving the near-surface turbulence in the water and thus enhancing gas transfer. In the absence of surface waves, the gas transfer velocity w is a linear function of wind speed or rather of the friction velocity and nicely follows the hydrodynamical prediction by Deacon (1977). Laboratory experiments (Jähne et.al., 1986) show, however, that with the onset of wind-induced surface waves the transfer velocity starts to exceed Deacon's prediction by up to a factor of 10. This excess factor can reasonably well be correlated with the mean square slope of the surface waves. This indicates that a highly irregular wind-induced wave field enhances surface renewal by the generation of additional turbulence. Since surface films damp or even suppress waves, they also reduce gas transfer to the predictions of the smooth surface model. Whether, and if so to what extent, over the open ocean surface films do reduce gas exchange, at a given wind speed, is essentially unknown. The definite degree of gas transfer enhancement by air bubbles at very high wind speed is also still an open question.

Nevertheless, it seems (Broecker et.al., 1986) that laboratory experiments, field experiments by the radon deficiency method, and the geochemical ^{14}C techniques yield consistent global average values for w. However, uncertainty still exists concerning the dependence of w on wind speed, which is knowledge required to estimate the latitudinal dependence of w needed for ocean CO_2 uptake modelling and for local estimates of air-sea CO_2 fluxes.

The other quantity which determines the CO_2 exchange flux is the partial pressure difference ΔpCO_2 between air and sea. Considerable efforts have been undertaken to document this quantity on a global scale (Keeling, 1968; Takahashi et.al., 1983).