Report Series HSE 88-001

CONFIDENTIAL

THE GREENHOUSE EFFECT

SHELL INTERNATIONALE PETROLEUM MAATSCHAPPIJ B.V., THE HAGUE

Health, Safety and Environment Division (HSE)

Report Series HSE 88-001

CONFIDENTIAL

THE GREENHOUSE EFFECT

SHELL INTERNATIONALE PETROLEUM MAATSCHAPPIJ B.V., THE HAGUE

Health, Safety and Environment Division (HSE)

CONFIDENTIAL

THE GREENHOUSE EFFECT

Greenhouse effect working group
R.P.W.M. Jacobs HSE/35

M.H. Griffiths PL/15
P.E. Bright PAC/3
J.B. Homer SCCU
J.A.C.M. van Oudenhoven MFPA/435
J. Waller MFPA/435

Shell Internationale Petroleum Maatschappij B.V.
Health, Safety and Environment Division
Environmental Affairs
The Hague

April 1986 (completion of the study)
May 1988 (date of issue in this format)

Prepared for SECC
(Shell Environmental Conservation Committee)

SUMMARY

Man-made carbon dioxide, released into and accumulated in the atmosphere, is believed to warm the earth through the so-called greenhouse effect. The gas acts like the transparent walls of a greenhouse and traps heat in the atmosphere that would normally be radiated back into space. Mainly due to fossil fuel burning and deforestation, the atmospheric CO2 concentration has increased some 15% in the present century to a level of about 340 ppm. If this trend continues, the concentration will be doubled by the third quarter of the next century. The most sophisticated geophysical computer models predict that such a doubling could increase the global mean temperature by 1.3-3.3°C. The release of other (trace) gases, notably chlorofluorocarbons, methane, ozone and nitrous oxide, which have the same effect, may amplify the warming by predicted factors ranging from 1.5 to 3.5°C.

Mathematical models of the earth's climate indicate that if this warming occurs then it could create significant changes in sea level, ocean currents, precipitation patterns, regional temperature and weather. These changes could be larger than any that have occurred over the last 12,000 years. Such relatively fast and dramatic changes would impact on the human environment, future living standards and food supplies, and could have major social, economic and political consequences.

There is reasonable scientific agreement that increased levels of greenhouse gases would cause a global warming. However, there is no consensus about the degree of warming and no very good understanding what the specific effects of warming might be. But as long as man continues to release greenhouse gases into the atmosphere, participation in such a global "experiment" is guaranteed. Many scientists believe that a real increase in the global temperature will be detectable towards the end of this century or early next century. In the meanwhile, greater sophistication both in modelling and monitoring will improve the understanding and likely outcomes. However, by the time the global warming becomes detectable it could be too late to take effective countermeasures to reduce the effects or even to stabilise the situation.

The likely time scale of possible change does not necessitate immediate remedial action. However, the potential impacts are sufficiently serious for research to be directed more to the analysis of policy and energy options than to studies of what we will be facing exactly. Anticipation of climatic change is new, preventing undue change is a challenge which requires international cooperation.

With fossil fuel combustion being the major source of CO2 in the atmosphere, a forward looking approach by the energy industry is clearly desirable, seeking to play its part with governments and others in the development of appropriate measures to tackle the problem.

CONTENTS

FIGURES

TABLES

APPENDICES

1. INTRODUCTION

The life-supporting systems of the earth (such as light, energy, moisture, and temperature) can be affected by changes in global conditions. Many of such changes are occurring at present, some of them subtle and many of them caused by man. These effects on the life-supporting systems can have a substantial impact on global habitability. The rate at which many of these changes are occurring, especially during the past few decades, has been considerable. A obvious example of this is the rising level of atmospheric carbon dioxide (CO2). This has been described as a long-term global experiment, the outcome of which is very uncertain.

The global rise in atmospheric CO2 is well documented. It is estimated that human activities (e.g. fossil fuel burning, deforestation) have increased the CO2 concentration by about 15% during the past century. More than a century ago it was already hypothesised that an increase in the CO2 concentration of the atmosphere would lead to global warming, i.e. the so-called "greenhouse effect". Several other gases, having similar effects, also appear to be increasing as a result of human activities.

Many scientists believe that the major effect of increasing the CO2 content of the atmosphere will be a gradual warming of the earth's surface. Should average global temperatures rise significantly because of the greenhouse effect and should the earth's climate change, this could have major economic and social consequences. However, not everyone agrees with this view of possible disaster. They point to the demonstrable positive effects of elevated CO2 concentrations, and suggest a benefit to the biosphere without the generation of a climatic catastrophe. Against this backlog of disagreement scientists of both persuasions have searched for the first signs of any effects on a global scale.

It is estimated that any climatic change relatable to CO2 would not be detectable before the end of the century. With the very long time scales involved, it would be tempting for society to wait until then before doing anything. The potential implications for the world are, however, so large that policy options need to be considered much earlier. And the energy industry needs to consider how it should play its part.

In this report the latest (1986) state of knowledge is presented regarding the greenhouse effect to judge any counteractive measures. It describes the considerable research work being carried out world wide; it provides information to improve the understanding and it discusses the implications. For this reason additional information is added on legislation and policies (Appendix 3), relevant international organisations and information centres (Appendix 5) and institutes involved in greenhouse effect research (Appendix 6). Moreover, in addition to the references used, a list of relevant reports and books is added (Appendix 7) to provide the interested reader access to the enormous flow of information relative to the greenhouse effect.

References used in this section: 2, 14, 21, 25, 51, 59.

2. SCIENTIFIC DATA

2.1. Introduction

During the last century the concentration of carbon dioxide increased from an estimated 290 ppm in 1860 to 340 ppm in 1980. Approximately 25% of this increase occurred during the 1970s. Although the concentration of CO2 in the atmosphere is relatively small, it is important in determining the global climate. It permits visible and ultraviolet radiation from the sun to penetrate to the earth's surface, but absorbs some of the infrared energy that is radiated back into space. The atmospheric CO2 emits this energy to both the troposphere and to the earth's surface (see Fig. 1), resulting in a warming of the surface and the atmosphere in the way the glass in a greenhouse does - hence the term greenhouse effect.

The best known and most abundant greenhouse gas is carbon dioxide. However, some trace gases, particularly chlorofluorocarbons (CFC's), ozone, methane, and N20 are at least as important in changing the radiation energy balance of the earth-atmosphere system, as, collectively, they might cause an additional warming equal to 50-100% of the warming due to CO2 alone.

It has been generally accepted that any modification in the radiation energy balance of the atmosphere will affect the global circulation patterns. As a consequence regional climatic changes will then occur, which will be greater than the average global changes. The most promising approach to study the effects of increasing gas concentrations on the atmosphere, is to describe and predict the (future) global climate by complex General Climate Models (GCM's). The main factors and processes used to predict the earth's temperature profiles and climatic changes are presented in this section. The extent and rate of the changes, based on scenarios for energy consumption and emission of CO2 and other trace gases, will be discussed in section 3.

2.2. Data on emissions of greenhouse gases

2.2.1. **Carbon dioxide**

Although CO2 is emitted to the atmosphere as a consequence of several processes, e.g. oxidation of humic substances and deforestation, the main cause of increasing CO2 concentrations is considered to be fossil fuel burning. Only fossil fuel burning can be fairly accurately quantified.

Since the beginning of the industrial and agricultural revolutions the average annual increase in CO2 production has been 3.5%, with total emissions from mid-nineteenth century to 1981 being 160 GtC (1 GtC=1 gigaton of carbon = 10^{15} g C). In 1860 the annual emission was approximately 0.093 GtC and in 1981 5.3 GtC. Rising fuel prices in the 1970's slackened the CO2 production to yearly increases of 2.2% per year over the period 1973-1980 (see the first part of Fig. 2).

The CO2 emitted into the atmosphere is very quickly globally distributed. This is mainly due to the fact that the emissions are more or less evenly distributed over the continents. Moreover, the mixing time of the atmosphere within a hemisphere is only a few weeks and the interchange between the hemispheres takes 6-12 months. CO2 has a residence time in the atmosphere of 3-4 years, so is reasonably well mixed globally.

World CO2 emissions based on energy growth rates (see Table 1) show that there has been a slowing in the upwards growth of emissions since 1973. In 1981, of the total emission of 5.3 GtC 44% came from oil, 38% from coal, and 17% from gas.

The production of CO2 differs considerably from country to country. The largest quantities (based on 1975 figures) are produced in the developed countries with a world average of 1.2 tonnes C per person (see Table 3).

During the last century the concentration of carbon dioxide in the atmosphere increased from an estimated 290 ppm in 1860 (measurements from ice cores) to 340 ppm in 1980. More accurate measurements over the last 25 years at the Mauna Loa Observatory, Hawaii, show an average increase of 1.5% per year (see Fig. 4) with season-dependent fluctuations. Moreover, there is a latitudinal difference between ground-level CO2 concentrations, reflecting the location of the main fossil fuel CO2 sources in the northern hemisphere (see Fig. 5). The hypothetical increase of the atmospheric CO2 concentration based on emissions due to fossil fuel burning, is also given in Fig. 4. It appears that only a proportion of the emission is retained in the atmosphere (i.e. the "airborne fraction", AF). The size of AF depends on how the total carbon inventory is partitioned among the oceanic, terrestrial and atmospheric pools. Over the period 1959-1974 the AF was 56%, whereas it was 59% for the period 1975-1980. It is assumes that this increase of AF might be a caused by a reduction of the absorption capacity of the oceans.

References used in this chapter: 1, 5, 18, 20, 30, 44, 54, 69.

2.2.2. Other greenhouse gases

The earth's atmosphere currently contains "trace gases" with atmospheric lifetimes that vary from much less than an hour to several hundred years (see Table 4). From a viewpoint of global climate effects, species with extremely short lifetimes are unlikely to play an important direct role. More persistent trace gases, however, may contribute to modifications of the energy balance of the earth-atmosphere system and amplify the estimated CO2 warming. Increasing concentrations of these gases are directly or indirectly a consequence of human activities. Most of the man-made trace gases are listed in Table 4; the most important ones are briefly discussed below.

Nitrogen compounds

While a number of nitrogen containing compounds are relevant from a climatic point of view, the most important is N2O. N2O emissions result primarily from biological denitrification processes in soil and in the oceans. The global atmospheric concentration of N2O has risen from an estimated pre-industrial value of 285 ppb to 301 ppb in 1980. Over the 4-year period 1976-1980 the rate of increase in N2O concentration was 0.2% per year. Increasing future global food production will require increasing use of fertilisers adding further to atmospheric N2O.

Methane

Principal sources of atmospheric methane are enteric fermentation in ruminant animals, anaerobic decomposition of organic matter (e.g. release from organic-rich sediments below water bodies and rice paddies), biomass decomposition, natural gas leakage, quite possibly production by termites and release of methane during mineral, oil, and gas exploration and gas transmission. The CH_4 concentration has approximately doubled in the last 350 years with a greater rate of increase in the last century. The concentration increased globally by about 0.5% per year between 1965 and 1975 and by 1-2% per year between 1978 and late 1980. In 1980 the concentration was about 1.65 ppm in the northern hemisphere, and about 6% lower in the southern hemisphere.

In the troposphere the CH_4 oxidation chain initiated by the reaction with hydroxyl radical (OH) leads to significant photochemical production of CO, H_2 and O_3:

$$CH_4 + 4O_2 \longrightarrow H_2O + CO + H_2 + 2O_3 \text{ (net cycle)} \qquad (1)$$

The initial reaction of OH with CH_4:

$$CH_4 + OH \longrightarrow CH_3 + H_2O \qquad (2)$$

and the reaction of OH with CO:

$$CO + OH \longrightarrow CO_2 + H \qquad (3)$$

controls the global destruction of OH, the dominant oxidising species in the troposphere. Reaction (2) is such a dominant loss mechanism for CH_4 that more than 90% of the global destruction of CH_4 occurs in the troposphere. So, CH_4 and CO are closely coupled photochemically through OH. The dominant sink of atmospheric CH_4, OH, is thus affected by increased levels of tropospheric CO or of CH_4 itself. Therefore, increasing concentrations of CO due to fossil fuel (incomplete combustion) usage and oxidation of anthropogenic hydrocarbons in the atmosphere , will reduce the rate at which CH_4 is destroyed.

Chlorofluorocarbons

Chlorofluorocarbons (CFC's) are entirely a product of human activity, being present in gas propelled spray cans, refrigeration equipment and insulated packaging materials. These chemicals came into major use in the 1960's and initially exhibited a rapid growth (10-15% per year). The global emissions of the major CFC's then declined somewhat from the mid-1970's through to 1982 in part due to a ban on some nonessential usages (e.g. spray cans) of CFC's and to adverse economic conditions. However, the emissions increased significantly since 1983. Eastern block countries have apparently never reduced their production of CFC's, so world wide use is now rising, and is expected to grow more because of the use in less industrialised countries. When CFC's are released to the atmosphere, their inertness to most biological processes allows them to be transported to the stratosphere, where they are broken down by sunlight. Liberated chlorine catalytically destroys ozone.

Ozone

The climatic effects of changes in ozone (O3) depend very strongly on whether these changes occur in the troposphere or stratosphere. There is some observational evidence that northern hemisphere tropospheric ozone has increased by 0.8-1.5% per year since about 1967, due to increases in combustion releases of NOx, CO2, H2 and increased CH4. In the southern hemisphere, given the smaller anthropogenic influences, O3 does not change at all.

Stratospheric ozone is also thought to be susceptible to perturbing influences, including man-made chloro- and chlorofluorocarbons, increasing CH4 and N2O concentrations and decreases in stratospheric temperature due to increasing CO2. The stratospheric ozone changes largely depend on the altitude, but concentrations are now about 12.5% greater at altitudes from 0 to 12 km than assumed pre-industrial concentrations.

A perturbation of the stratospheric ozone concentrations modulates the solar and infrared fluxes to the troposphere, and this solar effect would tend to warm the surface. On the other hand O3 changes in the lower atmosphere pose potential risks to air quality over the surface of the globe.

References used in this section: 33, 35, 39, 41, 43, 46, 47, 49, 61, 64.

2.3. The global carbon cycle

The carbon cycle (Fig. 6) involves numerous biological, geological, physical and chemical processes and can roughly be divided into two main cycles, a biological and a geological one. The geological cycle is a relatively long-term cycle characterised by slow processes, i.e. the release of CO2 through rock weathering and ultimate precipitation as calcium carbonate. Since man started to burn fossil fuel the slow processes have been unbalanced by affecting the major reservoir.

The worldwide use of fossil fuel in 1981 released about 5.3 GtC to the atmosphere as CO2. This figure seems very small compared to those of the amounts of carbon estimated to be present as organic and inorganic compounds in the four major reservoirs in the carbon cycle, i.e. 700 GtC in the atmosphere, 2,600 GtC in the biosphere, 40,000 GtC in the ocean and 65×10^6 GtC in the lithosphere (i.e. the solid part of the earth). However, taking into account a natural and balanced exchange rate of about 100 GtC per year between atmosphere and biosphere and between atmosphere and ocean, fossil fuel burnt yearly represents about 5% of the natural exchange. About 60% of the CO2 originating from burnt lithospheric carbon is retained in the atmosphere; the ocean is the major sink for the rest.

In contrast, the biological cycle is characterised by very rapid processes and is, in essence, very short and therefore extremely significant. Nearly all CO2 carbon that is assimilated (fixed) by the biosphere (i.e. the plants) is ultimately biodegraded by heterotrophic organisms and subsequently returns from the biosphere to the other major carbon reservoirs. The biological cycle is therefore essentially closed. Solar energy keeps the cycle going by providing the energy for the carbon-fixing process, i.e. photosynthesis.

Contrary to the near constancy of the fluxes in the biological cycle, one of the most important reservoirs therein (the land biota, i.e. the living organisms on land, of which the plants represent the major biomass) has been affected since man started releasing carbon dioxide by deforestation and expansion of arable land.

2.3.1 **Atmosphere - ocean interactions**

The reservoir of the world's oceans represents a volume of about 1.4×10^{18} m^3 water and holds about 40,000 GtC (this is about 57 times the total atmospheric carbon content) or on average 28 g/m^3. The content varies from 22 g/m^3 in cold surface water to 26 g/m^3 in warm surface water and to 29 g/m^3 in the deep-ocean.

The majority of the carbon in the ocean is present as an inorganic fraction, i.e. 39,000 GtC as dissolved inorganic carbon (DIC or C). The DIC is present as dissolved components of the carbon dioxide equilibrium system: CO2, bicarbonate and carbonate.

The remaining carbon is present as an organic fraction, of which only 1.5% is fixed in living organisms, and the rest is dead organic material present as dissolved organic carbon (DOC, about 1000 GtC), and particulate organic carbon (POC, about 30 GtC (see Fig. 6).

The gross exchange of CO2 between atmosphere and ocean is very rapid, characterised by a flux of about 100 GtC per year either way.
This interaction shows the strong regulation of the atmospheric CO2 by the ocean. The natural situation is characterised by a physico-chemical equilibrium. The principal effect of adding CO2 to the atmosphere is the tendency of the ocean to take up the excess in order to reach a new equilibrium with the atmosphere. Although the carbon content of the ocean is much greater than that of the atmosphere, the capacity of the ocean for CO2 uptake is limited (see Appendix 1). The absorption of CO2 by the ocean is buffered by reactions with dissolved carbonate and bicarbonate ions. In the surface mixed layer, the "buffer factor" increases with growing CO2 concentrations (see Fig. 7), and the capacity of the ocean to absorb the CO2 added to the atmosphere will decrease. Hence, the fraction of added CO2 remaining in the atmosphere will rise.

The capacity of the ocean for CO2 uptake is thus a function of its chemistry; the rate at which this capacity can be brought into play is, however, a function of ocean physics. The stratification of low- and mid-latitude oceans is stable and capped by a warm surface layer that is approximately in equilibrium with atmospheric CO2. Most of the deep waters of the world's oceans are formed in winter in the Norwegian and Greenland Seas and in the Weddell Sea. Here winter cooling increases the density of the surface waters until the stratification of the water column breaks down and the deep source regions are renewed. Once formed, the bottom waters flow to the south. The residence time of deep water in the Atlantic Ocean has been estimated as 275 years, in the Pacific Ocean about 600 years and in the Indian Ocean about 335 years. Thus, although the absorptive capability of the ocean is large, it is not rapid due to its slow circulation.

The cycle of organic carbon within the ocean is based on two main processes, i.e. production and decomposition of organic matter. Fixation of CO2 into organic tissues by the photosynthetic activity of phytoplankton occurs only in ocean surface water (the euphotic zone). This is the zone where light energy for photosynthesis and growth is not limited, so that the production of organic material is greater than the breakdown. In the tropics this zone is limited to the upper 100 m of the sea, while in temperate climates it is between 20 and 50 m in summer and zero in winter. In deeper waters, the aphotic zone, there is a net loss of organic material, since breakdown exceeds production.

Organic production and breakdown of organic material can conveniently presented as:

$$CO2 + H2O \underset{\text{breakdown}}{\overset{\text{production}}{\rightleftarrows}} CH2O + O2 \qquad (4)$$

CO2 in (4) represents the total dissolved inorganic carbon content of the water, and CH2O is organic matter. Oxygen is produced in this process and the removal of CO2 concurrently raises the pH. Although the total biomass of the biota is low relative to that on land (see Fig. 6) and the annual productivity is approximately one half that on land, the turnover (i.e. amount of carbon fixed per biomass unit) is very high. Some 90% of the organic matter formed is consumed by grazing organisms within the euphotic zone. The remainder plus the material excreted by grazing organisms and dead animals fall through the water column and is subject to oxidative decomposition (breakdown), whereby CO2 is released (eqn 4). The majority is decomposed in the upper 1000 m of the water column; dissolution of CaCO3 (i.e. calcium carbonate, the main constituent of shells) occurs in deeper water, stimulated by lowered oxygen concentration and pH due to increasing CO2 levels. The dissolved calcium carbonate raises the total CO2 of the deep water further and increases the alkalinity (see Appendix 1). The majority of the CO2 therefore remains available in the oceanic cycle.

Effects of increasing atmospheric CO2 on the CO2 concentration in the ocean are difficult to measure. The most sensitive measurement to determine this is pCO2 (i.e. the pressure of CO2 gas that would be found in a small volume of air that had been allowed to reach equilibrium with a large volume of seawater). From these measurements it is clear pCO2 in ocean surface water is rising, with a rate comparable to the atmospheric increase. However, as a consequence of the oceanic buffering a 10% change in pCO2 produces only a 1% change in the oceanic CO2 concentration (see Appendix 1 for details). The oceanic CO2 concentration has increased 1-2% over this last century. This increase will not induce significant changes in primary production (i.e. growth of algae), as CO2 is already available in excess. Concurrent slight decrease in pH (attached as 0.06 pH units) will not be measurable effect, as the ocean surface pH varies between 8.0 and 8.3. Further increases of the CO2 concentration will certainly lead to detectable effects on pH.

If the increasing atmospheric CO2 causes significant changes in the global climate, indirect effects on primary production can be expected. If there were to be locally increasing cloudiness then this reduces the solar energy reaching the ocean and consequently also the primary production. Any warming of the upper layers would increase the formation of stable water masses, thereby reducing vertical mixing. The subsequent depletion of nutrients in the euphotic zone will cause a decrease in primary production.

If CO2 is added to the ocean surface, the pH decreases and the tendency for dissolution of carbonate minerals (e.g. calcite and aragonite), either in bottom sediments or suspended in the water column, increases, thereby increasing both the alkalinity and the total DIC (see also Appendix 1). However, CaCO3 is also a major constituent of shells of calcareous organisms and corals. Particularly in near-shore areas these organisms will be exposed to waters rich in CO2 and with a low pH. Dissolution of shells and corals and subsequently local but massive deaths of organisms on a local scale is therefore not unrealistic. If dissolution of carbonates occurs, the alkalinity and CO2 content increase and the net effect of the alkalinity increase generates an increasing capacity of the ocean for CO2 uptake. This feedback mechanism might have reducing effects on a rising atmospheric CO2 level, although probably not in the short-term, as there are kinetic limits and controls on carbonate dissolution.

References used in this section: 3, 6, 7, 11, 22, 36, 42, 56, 60.

2.3.2. **Atmosphere - terrestrial biosphere interactions**

The reservoir of carbon in living plant material (phytomass) in the land biota was about 600 GtC in 1980. Compared to this, the organic carbon fixed in animals (zoomass) and microorganisms is negligibly small (about 8 GtC). The total carbon retained in soils and in dead organic material has been estimated globally at about 2000 GtC (see Fig. 6). The biosphere can be roughly subdivided horizontally into six ecosystems (see Table 5) and vertically into leaves, branches, stemwood, roots, litter, young humus and stable soil carbon. By far the largest biotic reservoir is estimated to be in forest systems, which are also both the most active and vulnerable part of the biota. The expansion of human populations and changes in land use in recent centuries have been accompanied by an almost continuous decline in the area of forest (see Table 5). During the past century the reduction in the mass of vegetation (deforestation) and replacement with agricultural crops and urban development resulted in a considerable reduction of the carbon stored in terrestrial biota. The total net release of carbon from the biota between 1860 and 1980 has been estimated as 180 GtC. In recent years the rate of release has dropped slightly, as a consequence of net accumulation of carbon in the forests of North America and Europe (as result of renewed growth of forests and afforestation).

The cycle of carbon between biosphere and atmosphere is in essence a biological one, based on fixation of CO2 by plants with the aid of solar energy (i.e. photosynthesis) and production of CO2 through respiration and decomposition (eqn 4). The driving input of an ecosystem is the net primary production, the increase in biomass (NPP):

$$NPP = GP - R_A \tag{5}$$

where GP is the gross production, the total photosynthesis of the system and R_A is the respiration of autotrophs, the green plants. Four, vertically arranged, components of the biosphere contribute to the NPP, i.e. leaves, branches, stems and roots. Estimates of NPP for the different ecosystems are given in Table 5.

The net flux of carbon between the atmosphere and any ecosystem is determined by the balance between gross production and respiration of all living organisms:

$$NEP = GP - (R_A + R_H) \qquad (6)$$

where NEP is the net ecosystem production, the net flux of carbon into or from an ecosystem and R_H is the respiration of the heterotrophs, including all animals and decomposers. Thus, $R_A + R_H$ represent the natural flux of CO2 from the terrestrial ecosystems to the atmosphere. The primary evidence of the importance of the terrestrial biota for the CO2 content of the atmosphere is shown by the short-term oscillations of atmospheric CO2, reflecting the seasonal fluctuations in photosynthetic and respiratory activities of living organisms.

The NEP tends to be zero in a stable ecosystem, but is permanently positive when human disturbance is present. Estimates of the total NPP for all terrestrial ecosystems vary between 50-60 GtC per year; the mean total plant respiration of all ecosystems (R_A) is about equal to NPP; so, about 50% of GP is needed by the plants for respiration (R_A). The heterotrophic respiration (R_H) is 35-50 GtC per year. These fluxes characterise the natural and well-balanced exchange rate of about 100 GtC per year between terrestrial biota and atmosphere.

Human interference (cutting, burning, shifting of cultivation and changing of ecosystems) has not only large effects on the amount of carbon stored in the ecosystems (the reservoir), but also affects the fluxes. There has been a net release of carbon since at least 1860. Until about 1960, the annual release was greater than the release of carbon from fossil fuels. The total net release from terrestrial ecosystems since 1860 is estimated to have been 180 GtC (with a range of estimates of 135-228 GtC). The estimated net release of carbon in 1980 was 1.8-4.7 GtC, from 1958-1980 the release of C was 38-76 GtC. The ranges reflect the differences among various estimates for forest biomass, soil carbon, and agricultural clearing.

Effects of increasing atmospheric carbon on terrestrial biota can be expected to be caused directly by higher CO2 concentrations and/or indirectly by changed environmental conditions due to the higher CO2 concentrations. Among the factors affecting gross photosynthesis, light, moisture, availability of nutrients (particularly nitrogen and phosphorus) and CO2 are the most important.

Most information relative to CO2 effects on plants is based on data from short-term experiments under controlled conditions. Although considerable variability exists in responses of various species, an increasing growth and rate of photosynthesis is apparent and the following tentative generalisations have been made in the literature resulting mainly from experiments in glasshouses:

- The responses are greater in plants with indeterminate growth (e.g. cotton, soybean) than in plants with determinate growth (e.g. corn, maize, sorghum, sunflower).
  Plants with an indeterminate growth habit have an infinite growth potential and are the most productive, whereas the determinate plants complete their life cycle by primary growth with the production of a

complete plant.

- The response to higher levels of CO2 is greater in C3 plants (e.g. soybean, sunflower, tomato, lettuce, cucumber, velvetleaf, wheat, sugar-beet, potato, rice, trees) than in C4 plants (e.g. corn, sorghum, millet, sugar-cane).
  In C3 plants primary photosynthetic carbon fixation occurs via the enzyme ribulose diphosphate carboxylase (RuDP) and in C4 plants via phospho-enol-pyruvate (PEP). The higher carboxylation efficiency of C4 plants has an advantage in water use efficiency and therefore in exploiting arid environments.

- The largest response is in seedlings; in older plants the response decreases or ceases. Increasing CO2 concentration will therefore probably have the least effect on growth of plants in natural forests (dominating the biotic part of the carbon cycle), where light, water and mineral nutrition already limit the rate of photosynthesis. However, recent increases in the growth of some high-altitude trees (measured as increasing ring width) might be ascribed to increasing CO2 concentrations, although the discussion on the causal relationship is not yet ended.

- Water use efficiency (ratio of C fixed to water consumed) increases for all species with increasing CO2 concentrations, but particularly for C4 plants. Therefore, under conditions of significant water-stress, considerably greater proportional increases in plant productivity occur.

- Early depletion of nutrients causes a shortening of the growing season (only in C4 plants) and a significant increase of the C/N ratio in C3 plants. As N-poor plant tissue decomposes more slowly, nutrient cycling rates will then be affected in ecosystems.

Effects on ecosystems are determined by the stability of the system. In stable (climax) ecosystems (e.g. undisturbed forests) in which gross photosynthesis is equated by total respiration (NEP ≈ 0), the NEP might become positive depending on to what extent other factors are limiting (e.g. nutrients). In developing ecosystems, the NEP is permanently positive and will increase until a new (stable) equilibrium is reached. Increase of NEP will be greater where the supply of nutrients is greater, e.g. in highly productive agricultural systems. However, here the storage of carbon is only a small fraction of the annual production.

References used in this section: 5, 10, 15, 22, 24, 28, 37, 45, 67, 68, 69.

2.3.3. **Carbon cycle modelling**

Climate models are used to investigate the climatic response (e.g. temperature, precipitation) to changes of the atmospheric CO2 concentration (in fact the "airborne fraction", AF). Carbon cycle models (CCM's) are the main tool for predicting the future CO2 levels as a function of the total CO2 emissions. To calculate these levels all processes in which CO2 is exchanged have to be known and quantified, i.e. processes in which CO2 is exchanged, stored and converted between the atmosphere, terrestrial biosphere and ocean.

In the last few years CCM's have become more sophisticated. There are now several dynamic, process-oriented models which represent for example accumulation and decay of dead vegetation, processing of carbon in soils and humus, and chemistry, physics and biology of the ocean. Published models have been calibrated to agree well with the change in atmospheric CO2 concentration observed until now. However, no model has been properly validated against all trends and all data on emission rates. The most important uncertainties are:

- Future paths of energy and CO2 emissions.
  Many of the early analyses have produced estimates of future emissions and concentrations from extrapolative techniques based on present and past emissions.
  In an attempt to address uncertainties, a second generation of studies, employing scenario analysis has arisen, which also take into account future economic and energy developments. However, there are still a number of important uncertainties in the model, e.g. rate of population growth, the availability and cost of fossil fuels, etc. (see also 3.1.).

- Diffusion rate in the ocean.
  Most models represent some features of ocean chemistry quite well, but they represent ocean physics by simple vertical diffusion coefficients, sometimes related to stratification phenomena. These one-dimensional vertical models are viewed with considerable scepticism by physical oceanographers.

- Rate of deforestation and land reclamation.
  There is disagreement about whether significant renewed growth in some areas and stimulation of plant growth by increasing atmospheric CO2 will take place and counter losses from deforestation.

- Stimulation of growth by CO2.
  Most carbon cycle models in estimating biotic response have depended on the so-called beta (β) factor, a measure of how much plant growth increases as a result of atmospheric CO2 concentration.
  The numerical value of β is not known accurately at present, but is still of great importance as a parameter representing the response. However, it has been argued that the use of the β-factor should be replaced by separate analyses of the effects of changes in the area of forest and potential changes in NPP caused by both increased atmospheric CO2 and changes in climate.

References used in this section: 9, 15, 21, 22, 45.

3. SCENARIOS AND CLIMATE MODELLING

3.1. CO2 emissions and future energy demand

It is generally accepted that the increasing concentration of CO2 in the atmosphere is primarily determined by the combustion of fossil fuels. In order to estimate future quantities, it is first necessary to develop pictures of the future use of fossil fuels and then to use these scenarios, in conjunction with carbon cycle models, to calculate the atmospheric CO2 concentrations.

Understandably, many pre-1975 studies assumed that future energy growth rates would be equivalent to the historical average of 4.5% per year. However, it is now acknowledged that the "CO2 community" should make better use of the most recent scenarios in which world energy consumption is chiefly determined by economic and socio-political forces. Most recent estimates from such sources as the US Environmental Protection Agency (EPA), the International Institute for Applied Systems Analysis (IIASA), the International Energy Agency (IEA) and the US National Academy of Sciences show that, based on calculated future CO2 emissions, pre-industrial atmospheric concentrations could double (i.e. pass 600 ppm) some time between 2040 and 2080 (see Fig. 8), the range reflecting the uncertainties with regard to future growth and energy developments.

By combining estimates of energy demand and fuel mix, CO2 emissions can be estimated. In Fig. 2 a number of long range CO2 projections are presented. Estimated average annual rates of increase of CO2 emissions until 2030 generally range from 1 to 3.5%. Estimated annual emissions range from 7 to 13 GtC in the year 2000 and, with few exceptions, from 10 and 30 GtC in 2030. The US National Research Council (NRC) forecast in 1983 that the annual increase would be about 1.6% to 2025 and about 1% thereafter compared with an average growth over the past 120 years of 3.5%. The major reasons for the lower rate are, according to the NRC, an estimated slower growth of the global economy, further conservation and a tendency to substitute non-fossil fuels for fossil fuels. (see Appendix 2 for a discussion of the NRC Report).

The energy scenarios developed by Group Planning give estimates for CO2 emissions in the lower part of the range for a number of reasons. In the first instance, global energy intensity has been falling for many years. Figure 9 shows that in the USA the fall has been continuous since the 1920's. Since 1973, two changes have occurred: oil intensity, which had been rising, began to fall, and the decline in energy intensity accelerated.

Four factors lie behind the fall in intensity: firstly a shift in developed country economies from heavy industry to less energy-consuming light industries and services; secondly, the introduction of new technologies and processes which both directly and indirectly, consume less energy; thirdly, the development of products (cars and refrigerators, for example) which are more energy-efficient, and finally, consumers have changed their behaviour patterns to reduce energy consumption as they have become more aware of the cost of energy. While the last of these is in some sense reversible as costs decline, the first three are structural and are unlikely to be reversed.

In the future, as portrayed in the Group scenarios, the intensity continues its downward course. Indexed to 1973 = 100, the energy intensity in the OECD countries is estimated as 47 (Next Wave) or 57 (Divided World) with a probable range of 45-75. The Next Wave scenario sees a rapid take-up of technology promoting a more rapid fall in intensity. However, this is outweighed by strong economic growth and hence a relatively large increase in energy demand. In Divided World, on the other hand, energy intensity declines more slowly but economic growth is also lower so that, overall, energy demand is less than in the Next Wave.

The impact of new technology is much less in the Less Developed Countries (LDC's) where the capacity to introduce energy efficient equipment and to apply energy conservation is much less. In these countries, energy intensities are still rising although at a lower rate as technology is transferred from the developed world. In part this rise is due to the development process - the introduction of the heavy industries the countries themselves need - and partly there is the move of energy demanding industries from developed to developing countries.

The world energy demands in the year 2005 in the two scenarios are, respectively. New Wave - 209 Mbdoe (million barrels per day oil equipment) and Divided World . 193 Mbdoe. At the same time, the probable ranges are 178-220 Mbdoe and the possible ranges are 158-240 Mbdoe.

While overall energy intensity is an important variable in estimating the future production of carbon dioxide, a second factor is the competition between different fuels in the major markets, in particular, the relative importance of the non-fossil fuels such as hydro and nuclear. The marginal energy sources, wind, waves, hydrogen, etc., are unlikely to make sufficient contributions to have any serious effect on CO2 levels, nor is any large move away from hydrocarbon fuels in the transport market expected and consequently changes will relate to underboiler fuels and electricity generation. Coal is expected to dominate the large industrial under-boiler market with gas and electricity becoming the major energy sources at the commercial and domestic levels. Coal and nuclear will be the chief fuels for electricity generation. Only in the long term is a shift to other energy sources likely to occur. However, as the amount of CO2 emitted per unit of energy differs considerably (see Table 2) for the different fossil fuels, future emissions not only depend on the global energy consumption but also on the relative proportions of the fossil energy sources (see Fig. 3).

On the basis of the demand estimates from the individual fuels in each scenario the CO2 emissions can be calculated. These are given in Table 6.

An important source of energy often ignored because of the difficulty of measurement, is the non-commercial energy (NCE): Wood, crop residues, animal and human wastes burned by the poorest members of society for heating and cooking. The population of the LDC's is approximately 3.6 billion , one third of whom depend on NCE. By 2005 the LDC population will have risen to 5.3 billion (UN estimate) and although NCE cannot rise pro rata because of the constraints on availability, nonetheless there will be an increase and this, based on estimates developed by the FAO, is included in Table 6.

In the next century, the world energy pattern can only be guessed. A key feature, however, is that because of technological change there will be a wider variety of energy sources for exploitation than at present. However, no single new energy source will be able to meet more than 10% of the world's energy supply and coal will probably be the largest single source of hydrocarbon based energy. In addition to the main scenarios which extend only to the year 2005, some studies have been made within Group Planning on the possible use of energy in the year 2050. Based on some heroic assumptions not only of economic factors but also softer issues such as individual lifestyles and the role of government, three proto-scenarios have been developed and from these possible CO2 emissions can be calculated. These are at the very bottom of the span of estimates made by other institutions and range from 10 to 11.5 GtC per annum.

There are, of course enormous uncertainties at this distance in time surrounding not only the fuel consumption but also the split of energy sources between fossil and non fossil fuels. It may be the case that large increases in the direct use of solar energy, indirect solar such as wind or wave energy and in nuclear energy will occur as a result of unforeseen technological developments.

In the light of the possible effects of an increase in greenhouse gases, it is important to examine the likely political responses to expressions of environmental concern. Awareness of environmental matters is much stronger now than it was only a few decades ago. At present, the focus is on acid rain and nuclear energy. While opposition to nuclear is strong in the USA, Australia and some European countries, it is possible that perception of a serious environmental threat could swing opinion away from fossil fuel combustion and lead to a revival of interest in conservation, renewable sources and particularly in nuclear energy. Of course, such a movement would be stillborn if there were to be any further accidents of the Three Mile Island, Sellafield or Tsjernobyl type.

The problem is that no obvious global solution is presently conceivable which would result in a major reduction in the rate of increase of atmospheric CO2. A report issued by the US Environmental Protection Agency (EPA) in late 1983 (see Appendix 2) concluded that only draconian measures such as a global ban on coal combustion could have any significant effect. Since such actions are neither economically or politically feasible, individual countries should be urged to study ways of adapting to the inevitable rise in temperature. The NRC report referred to above, which was published at the same time, is less pessimistic in that it believes that strategies such as substantial taxation of fossil fuels might be effective.

References used in this section: 17, 21 Group Scenarios.

3.2. Projections of non-CO2 greenhouse gases

Changes in atmospheric concentrations of several infrared absorbing gases, besides CO2, result from human activities. Projections of future emissions of these trace gases are mostly at a more primitive stage than are the CO2 projections, as they are usually based on assumptions of linear increase or exponential growth relative to development in recent years.

Recently, calculations have been applied to project the concentration of each gas species. The following data have been used:

- 1980 atmospheric concentrations and recent trend data,

- nature of sources (man-made, natural, etc.),
- projected growth in natural as well as man-made sources due to expected human activities over the next 50 years, and
- atmospheric lifetimes of the species.

The resulting estimates for the year 2030 are presented in Table 4. It appears that by 2030 atmospheric CFC's may increase by a factor of 10, the chlorocarbons by a factor of 3 and the nitrogen compounds and hydrocarbons by 20% and 60%, respectively. These estimates were of course made without taking into account the effects of possible countermeasures to reduce emissions.

References used in this section: 16, 33, 35, 39, 41, 43, 46, 47, 49, 57, 61, 64.

3.3. Temperature and climatic changes

The typical approach to understanding the relationship between atmospheric CO2 and temperature has been the development of increasingly complex models of the geophysical conditions that produce global climate. Several types of mathematical models have been developed differing in comprehensiveness with regard to treatment of the climate system components. Individual models can be broadly classified as either thermodynamic (EBM's, energy balance, and RCM's, radiative-convective models, both accentuating the prediction of temperature) or hydrodynamic (predicting both the temperature and the motion fields, and their mutual interactions) models. The last category includes the now widely favoured "three dimensional" General Circulation Models (GCM's). A new model hierarchy is formed by coupling atmospheric GCM's with different ocean and sea ice models.

The standard reference value for comparing alternative models is ΔT_s (the globally averaged temperature increase due to doubled CO2). The range of surface warming simulated by the groups EBM's and RCM's for doubled CO2 is in remarkable agreement, i.e. 1.3-3.3°C. In comparing results obtained by EBM's the high and low values are usually excluded as the deviation is ascribed to the use of models that require an energy balance for the earth's surface, rather than for the entire earth-atmosphere climate system. The main proponent of the surface energy balance model is S. Idso of the US Water Conservation laboratory. On the basis of empirical observations of climatic change in Arizona and measurements of solar radiation, he concluded that ΔT_s is 0.25°C, i.e. an order of magnitude less than that predicted by the other models. This controversy within the modelling community is fundamental and will continue.

The range of surface warming simulated by the GCM's is somewhat larger than that of the purely thermodynamic models, namely 1.3-3.9°C. For this comparison calculations based on sea surface temperature/sea ice simulations were excluded from consideration, as these show a calculated present temperature lower than the presently observed temperature.

None of the above mentioned computations take the trace gas effects into account. The only, very recent, RCM simulation employing the projected increases of all greenhouse gases refers to the period up to the year 2030, the year characterised by a estimated CO2 concentration of about 450 ppm. In that study the relative importance of about 30 gases, including CO2 is taken into consideration as well as coupled perturbations due to chemical-radiative interactions (see also section 2.2.2.). The simulation indicates that by 2030 the effects of the trace gases will amplify the CO2 surface warming by a factor ranging from 1.5 to 3.5 (see Fig. 10).

However, the warming is not the entire story; all GCM's show an increase in the intensity of the global hydrological cycle. If the planet is warmer more moisture will evaporate from the oceans, resulting in a increase of the atmospheric water concentration. The water vapour will also act as a greenhouse gas. In addition, cloud cover might change, as well as sea ice and snow cover, all producing either an amplification or a reduction of the original effects (positive or negative "feedbacks"). Although the process of CO2-induced warming is reasonably well understood and some of the gross features of the likely climatic change are reasonably well established qualitatively, the likely regional effects cannot be modelled with great confidence at the present time. The impact of the expected climatic change predicted by these models would be large at a doubled atmospheric CO2 concentration, even larger than any since the end of the last ice age about 12,000 years ago (see also Appendix 8):

- precipitable water content of the atmosphere would increase by 5-15%, the precipitation rate being increased particularly at higher latitudes of both hemispheres,
- sea-ice cover of the Arctic would be reduced to a seasonal ice cover,
- snow cover would change dependent on latitude, though extent is difficult to predict,
- ice-cap mass balance change: a warming of 3°C would induce a 60-70 cm rise of the global sea level, about half of which would be due to ablation of the Greenland and Antarctic land ice, the rest to thermal expansion of the ocean; a possible subsequent disintegration of the West Antarctic Ice Sheet would result in a worldwide rise in sea level of 5-6 m,
- rising sea surface temperature would be highly regional, and
- reduced evapo-transpiration of plants would make more water available as runoff and would tend to offset the effects of any CO2-induced reductions in precipitation or enhance the effects of precipitation increases.

Based on the modelling results, reconstruction of historical climatic conditions and studies of recent warm years and seasons, a markedly different climatic response is expected at different latitudes. The rise in the average temperature at the surface would increase from low to high latitudes in the northern hemisphere (see Fig. 1). There the projected increase would be much larger between October and May, than during the summer, thereby reducing the amplitude of seasonal temperature variations over northern lands. The models also show a large increase in the rates of precipitation and runoff at high northern latitudes (see Fig. 10). These changes could have profound effects on the distribution of the world's water resources, and large-scale effects on rain-fed and irrigated agriculture could be expected: large areas of Africa, the Middle East, India and a substantial portion of central China would cease to be water deficient areas and become favourable for agriculture. In contrast, the "food basket" areas of North America and the U.S.S.R. would become considerably drier.

References used in this section: 6, 9, 17, 21, 23, 28, 40, 43, 47, 48, 52, 53, 58, 61, 62.

3.4. Detection of the greenhouse effect

The increase in greenhouse gas concentrations from pre-industrial to the present values might have caused a significant perturbation of the radiative heating of the climate system, resulting in a warming of the global surface and lower atmosphere. The induced warming due to the increase of the CO2 concentration has been computed to be 0.8°C in recent RCM's and to be twice as large in a recent GCM taking into account the increase of the concentration of all (known) greenhouse gases.

Such a warming, had it indeed occurred, should have been detectable. However the search for definite evidence on whether the climate is responding to increasing concentrations of greenhouse gases, in the way that most models predict, has not yet been successful. Scientists argue that the warming is delayed through the inertia of the global system. They expect that the warming will not rise above the noise level of natural climatic variability before the end of this century. By then the ΔT_s may have risen above the natural surface temperature variation (typically ± 0.2-0.4°C for the northern hemisphere). This natural fluctuation in hemispheric or global mean temperatures, observed over the last century (see Fig. 12), is influenced by various climate forcing phenomena, e.g. solar irradiance, volcanic aerosols, and surface radiative properties, thereby making the sought-for CO2 signal unclear.

Other scientists argue that the models overestimate the temperature increase due to the increase of the greenhouse gases.In their view modellers have so far concerned themselves mainly with two climatic feedback processes, which are claimed to amplify any CO2 warming: the so-called ice-albedo feedback and the water vapour feedback. The critics argue that these two feedback processes are currently overestimated while others are completely neglected, underestimated or overestimated (for example, the carbon dioxide-ocean circulation-upwelling feedback, the CO2-ocean stability-winter down welling feedback, the CO2-Arctic sea ice-Artic biomass feedback, the CO2-rainfall distribution-tropical biomass feedback, the permafrost-methane release feedback, and the CO2-weathering of silicate minerals feedback). Overestimation of the ice-albedo feedback is particularly relevant.

It is also argued that the climate models have not been constructed with ocean surface temperature as the fundamental variable. Therefore, the inability to observe the model-calculated CO2 warming is a consequence of a lag due to thermal inertia of the ocean. In other words, the atmosphere cannot warm until the oceans do. Other studies indicate that the absorption of CO2 and heat by the oceans could possibly delay a greenhouse warming by five to twenty years.

Regardless of the continuing debate, confirmation of any view is important. If, as expected, the concentrations of the greenhouse gases gradually increase in the future, then the likelihood of achieving statistical confirmation increases. Improvements in climatic monitoring and modelling and in the historic data bases, would allow an earlier detection of any greenhouse effect with greater confidence.

References used in this section: 4, 12, 13, 17, 28, 31, 47, 58, 60, 63.

4. IMPLICATIONS

Although the greenhouse effect has been undetectable up till now, the atmospheric concentrations of the greenhouse gases are steadily increasing. Whether or not this will result in a significant global warming and if so, when it will occur, is still a matter of debate. However, without the direct need of a clear signal it is useful to give consideration to measures to counteract the likely effects. Potential effects are identified below assuming a future greenhouse effect , irrespective of uncertainties associated with timing and severity of the impact.

4.1. Potential effects of global warming induced by greenhouse gases

In this section possible effects of increasing concentrations of CO2 and the other greenhouse gases are enumerated, as well as the effects of a climate changed by global warming.

4.1.1. Abiotic effects and biotic consequences

I. Oceans

1. Increased water temperature	Increased growth/development rates and metabolic demands of all marine species, i.e. increased survival and growth of natural resources, through shifts of ranges and migration patterns.
2. Increased vertical stability of water masses	In turbulent (subpolar) waters increased phytoplankton production and increased fish yields. In stratified (subtropical) waters decreased phytoplankton production and decreased fish yields.
3. Decreased latitudinal and seasonal sea ice extent	Lower intensity but greater duration of primary production.
4. Temperate decrease and high latitude increase in net precipitation and runoff	Poleward species shifts due to shifts in salinity patterns.
5. Decrease in pH	Increasing tendency of dissolution of carbonate shells (e.g. shellfish), corals and sediments.
6. Rising sea level	Redistribution of nearshore and estuarine habitats, including adaptation or loss of natural resources.

II. **Agriculture**

Of the 20 food crops, that feed the world, 16 have a C3 photosynthetic pathway. The only exceptions are corn, sorghum, millet and sugarcane, which have a C4 pathway (see also chapter 2.3.2.). Of the world's 18 most noxious weeds, 14 have the C4 pathway.

1. Increasing atmospheric CO2	Increasing productivity, providing other factors affecting plant growth (light, water, temperature, nutrients) are not adversely affected; increase in yield and harvest index, improved quality and accelerated maturity. Increase in water use efficiency and a decrease in water requirements, i.e. a greater stability of production and less crop failures.
2. Increasing CO2 and specific crops	Greater water use efficiency with C4 plants than with C3 plants. Growth more stimulated in C3 than in C4 plants. Indeterminate plants benefit more than determinate plants. Thus, C3 plants and indeterminate plants have a higher competitive ability under optimal conditions and C4 plants will be less affected by water stress. Changes in crop/weed interactions and relationships.
3. Increased cloud cover	Increased quantum yield of net photosynthesis, i.e. beneficial effects of high CO2 on growth when light is limited.
4. Climatic change in general	Greater resilience to environmental stress, such as high temperatures and shortage of water. Redistribution of species. Impact of changed weather is sharp in marginal climates.
5. Decrease in precipitation at 40°N and 10°S	Decreased runoff for irrigation, increase of evaporation, and decrease in yield.
6. Increase in precipitation between 10° and 20°N, north of 50°N and south of 30°S	Increase of runoff, destructive floods, and inundation of low-lying farmland.
7. Latitudinal differences in temperature rise	Increased length of growing season in temperate zone and far north latitudes. Latitudinal differences in water requirements by plants.

III. Terrestrial ecosystems

1. Increased atmospheric atmospheric CO2	Increased water use efficiency. Positive response in seeding stage. Stimulation of NEP, competition induced change in total phytomass, and succesive development to a new climax vegetation. Shift of the biospheric action from CO2 source to CO2 sink.
2. Climatic change	Alterations of ecosystems especially in regions with strong gradients in evapotranspiration. Major shifts in the global distributions of species.

References used in this section: 29, 32, 34, 37, 55, 65, 67.

4.1.2. Socio-economic implications

The changes in climate, being considered here, are at an unaccustomed distance in time for future planning, even beyond the lifetime of most of the present decision makers but not beyond intimate (family) association. The changes may be the greatest in recorded history. They could alter the environment in such a way that habitability would become more suitable in the one area and less suitable in the other area. Adaptation, migration and replacement could be called for. All of these actions will be costly and uncertain, but could be made acceptable. Of course, all changes will be slow and gradual and, therefore, adaptation and replacement, even migration, need not to be noticeable against the normal trends. Recognition of any impacts may be early enough for man to be able to anticipate and to adapt in time.

The adaptation of the ecosystems on earth to changes in climate, however, will be slow. It would be unrealistic to expect adaptation to occur within a few decades. Therefore, changes in ecosystem stability, disturbance of ecosystem structure and function and even local disappearance of specific ecosystems or habitat destruction could occur. This will be followed by an almost unpredictable, complex process of adaptation of the ecosystems to the changed conditions to reach a new stable situation, the so-called climax ecosystem. Quite clearly, this process of adaptation would become even more complex when it is interrupted more frequently or even continuously, such as through permanently changing climatic conditions. A new stable situation can only be expected to occur after a global settling of the change in climate. The time it then will take to reach a new stable situation depends largely on the seriousness of the disturbance of the ecosystems and, thus, on the effectiveness of the programmes to protect the earth's climate against change.

Changing temperature and precipitation are the key elements in climatic change. The main effects will be on the sea level and natural ecosystems. Socio-economic implications will be related to agriculture, fisheries, pests, water supply, etc. While the greenhouse effect is a global phenomenon, the consequences and many of the socio-economic implications will be regional and local with large temporal and spatial variations. The following outline of possibilities is therefore incomplete and speculative, but can be a basis for further consideration and study.

1. **Rise in sea level**
   - More than 30% of the world's population live within a 50-kilometre area adjoining oceans and seas, some even below sea level. Large low-lying areas could be inundated (e.g. Bangladesh) and might have to be abandoned or protected effectively.
   - Shallow seas, lagoons, bays and estuaries characterised by extensive tidal flats could become permanently inundated. Loss of these habitats would mean a loss of extremely highly productive and diverse areas, which serve as a nursery for juveniles of all kinds of animal species and which are rich in food for fish. Effects on natural resources dependent on these systems, might therefore be dramatic (e.g. shellfish culture and fishing, seaweed harvesting, some commercially important fish).
   - There might be a shift in distribution of amenities, and as a consequence local loss of income, though at other places new sources of revenue might emerge.

2. **Rise in sea temperature**
   - Survival and growth of marine species may increase in general, though not in stratified subtropical waters. However, shifts in ranges and migration patterns could result in local losses of food sources and revenues, and could require operation in other (more distant) fishing grounds.

3. **Acidification of seawater**
   - Dissolution of $CaCO_3$ increases with a decreasing pH. Particularly in shallow coastal areas, characterised by high concentration of respiratory CO_2 and a low pH, dissolution of carbonate materials (shells, corals and sediment) could be quite rapid and result in damage of natural resources and of natural protection of shorelines, and disappearance of complete coral islands.

4. **Agriculture**
   - The impact depends on both the amplitude of climatic changes and agriculture's vulnerability to climatic variability. This vulnerability varies from region to region and will have great implication for import and export patterns of food of the countries dependent on agriculture for a larger part of their earnings some will lose some will gain. Poorer countries would run the greatest risk, the more so as their capacity to adapt would be the smallest.
   - Most farm labour is applied outdoors and is therefore essentially dependent on weather and climate. Any substantial change therein could necessitate adaptation and require new investments.
   - Model calculations show that a warmer and drier climate could decrease yields of the three great American food crops over the entire grain belt by 5 to 10%, tempering any direct advantage of CO_2 enhancement of photosynthesis. Although estimates for other areas are not available, any decrease may certainly have an impact on the world food supply and its price.
   - A warming in northern latitudes could make additional land suitable for cultivation, although the quality of such land for crops is not promising. This would result in local changes in levels of income and

working arrangements.

5. **Area of forest**
   - With a growth rate of the world population of 1.5% per year the human area increases slowly, presently mainly at the expense of grassland and agricultural land. However, decreasing yields in combination with an increasing human population may require an extension of arable land. This would certainly have implications for the tropical (and temperate) forests.
     Based on the most pessimistic predictions a disappearance of forests is expected during the first half of the 21st century, should human population growth continue indefinitely. Such a decrease in area of forest means a significant decrease of carbon fixed in the terrestrial biosphere reservoir and, consequently, an increase of atmosphere CO2
   - The natural transition line between deciduous and needle-leafed trees and the upper tree-line will shift to higher latitudes and higher elevations. Thus the total area suitable for growth of deciduous trees (mainly temperate and boreal forests) will increase.

6. **Changing air temperature**
   - Local temperature change may necessitate local adaptation of the buildings in which people live and work, technologies for heating or cooling, energy sources for heating and cooling, new food preparation technologies, new cultivation techniques, etc. All such adaptations are costly and some would drastically change the way people live and work.

7. **Water supply**
   - The prospects for water supply (sources, uses, transport, storage and conservation) are evidently of importance. Rainfall, snowfall, and evaporation are among the key elements in climate change. Level of groundwater or need of irrigation or drainage would be main determinants of whether increased rain and snow would be welcome and how costly reduced precipitation would be.
   - Local development of new sources of freshwater would be required. Water storage and transport, and inhibition of evaporation should receive continued attention.

References used in this section: 14, 15, 18, 26, 48, 50, 51.

4.1.3. Implications for the energy industry

Direct operational consequences can be expected from a rising sea level, impacting offshore installations, coastal facilities and operations (e.g. platforms, harbours, refineries, depots) with an uncertain magnitude. Costs of defending against a sea level rise will depend on the local situation (levels of security demanded for contingencies like extreme ocean storms, flooding, etc.) and national policies to compensate industry for the extra costs incurred.

Coal and the combined fuels of oil and gas contribute roughly equal amounts of CO2 (see Table 7). Because natural gas produces less CO2 per unit of energy, a swing from coal towards gas would reduce the CO2 emission. This argument has been used in individual choices of fuels for new power stations, but since almost 90% of the world's recoverable coal is located in the U.S.S.R., China and the U.S., it is these countries which would have to be taking such an initiative if considered feasible.

An overall reduction in fossil fuel use would of course reduce CO2 production and could be achieved by constraint on energy consumption, by improved thermal efficiency and by replacing fossil fuels with e.g. nuclear power. But such a course of action would imply a major shift in world energy supply and use.

Energy policy issues will be difficult to tackle because it is the world wide fossil fuel usage that affects the level of CO2 in the atmosphere, but the mechanisms for developing world wide energy policy do not at present exist. There is little incentive for strong voluntary action by individual countries when the benefits would be shared with the rest of the world, but the costs would be borne wholly internally. Furthermore, world growth in fossil fuel use is expected to be greatest in developing countries, and they are unlikely to wish to constrain their development programmes.

The energy industry will clearly need to work out the part it should play in the development of policies and programmes to tackle the whole problem. It will not be appropriate to take the main burden, for the issues are ones that ultimately only governments can tackle, and users have an important role. But it has very strong interests at stake and much expertise to contribute, particularly on energy supply and usage. It also has its own reputation to consider, there being much potential for public anxiety and pressure group activity.

References used in this section: 2, 8, 14, 30, 50, 51, 66.

4.1.4. Implications for Shell Companies

For the purposes of this discussion, it is assumed that the consequence of increasing levels of carbon dioxide are as already set out, namely, an increase in air temperature, changes in weather patterns, a rise in sea level of less than 1 metre and some small increases in agricultural yields.

Possible implications include:
- Legislation affecting our products and/or processes.
- Location of Shell installations.
- Changing demand for our products:
  - ° liquid fuels
  - ° coal
  - ° chemicals, particularly agrochemicals
- Business opportunities:
  - ° alternative fuels
  - ° forestry
  - ° new varieties of plants (seeds business)

While, theoretically, it is possible to legislate for a reduction in fossil fuel use, it must be the case that any global reduction is most unlikely. However, in a paper produced as background information for the latest set of energy scenarios, Group Planning felt there was a possibility that an increasing awareness of the greenhouse effect might change peoples' attitudes towards non-fossil energy sources, especially nuclear.

Fossil fuels which are marketed and used by the Group account for the production of 4% of the CO2 emitted worldwide from combustion. Of these emissions, 80% comes from Group oil, 12% from Group gas and 8% from Group coal (see Tables 7 and 8).

It is thermodynamically unfavourable and technically very difficult to remove carbon dioxide from the air other than by planting trees. If an international effort were mobilised to do this, and the poor response to the World Bank's call for such effort currently makes it appear unlikely, then there would be some call on companies, including Shell, with experience in tropical forestry.

Of the other greenhouse gases, many are chemicals in commercial use which could in principle be replaced or banned; it is difficult, on the other hand to see what could be done about others such as methane.

There seems little need to consider changes in the location of Shell installations because of the slowness of changes in sea level in the chosen time-frame. Climatic change could alter the relative wealth of certain LDC's and lead us to examine the possibilities of expanding or contracting our business accordingly.

These same changes, by altering the patterns of agriculture could alter up or down the demand for our agricultural products both chemicals and seeds, though it is difficult to forecast the effect of the biotechnological revolution on this area - it might swamp any effect of increasing carbon dioxide.

5. SCOPE FOR FURTHER ACTION

The existing large uncertainties surrounding the possible consequences of the increasing atmospheric CO2 concentration divide those who at least see substance in the theory, in the following three basic categories:

1. Those who believe there is no need for short-term action and insufficient knowledge about how to tackle the problem, so that nothing need be done for the moment other than to narrow the existing uncertainties,
2. Those who believe that the threat is real, and seek to eliminate the problem, and
3. Those who believe that the threat is real and unavoidable, so that "learning to live with climatic change" is the only solution.

Some people may, of course, lie between these categories, e.g. those who believe the threat is not considerable and who seek both to reduce its intensity and to adapt to it.

From these groups came a number of actions and strategies which are believed most appropriate. Current (1986) official, government attitude mainly fit the first approach, though there is a tendency to carry out analyses that would eventually lead to discussion of remedial measures (see also Appendix 3).

First group

- Basic research and monitoring:
  - ° monitoring of causal factors:
    emission of greenhouse gases
    atmospheric concentration of these gases
    solar variations
    volcanic aerosol
    changes in area of forest
  - ° climatic effects:
    temperature
    radiation fluxes
    precipitable water content
    cloud cover
    sea level
    sea temperature
    snow and sea-ice cover (remote sensing)
- Applied research and development:
  - ° agriculture:
    responses of ecosystems
    crop yields
    physiology and growth
  - ° water resources

Second group

- Analysis of economic and social costs associated with climate change
- Reduction of releases of greenhouse gases other than CO2
- Management of biota:
  - ° freezing rate of deforestation
  - ° freezing land reclamation
  - ° freezing rangeland burning
  - ° promotion of re-/afforestation

  - ° fertilisation of the ocean surface with phosphorus and nitrogen, thereby increasing the biotic fixation of CO2 (generating other adverse effects)
- Removal of CO2:
  - ° deep-sea disposal of CO2 produced at centralised location (consequently generating secondary effects)
  - ° re-/afforestation
- Energy research and policy:
  - ° development of renewable energy sources:
    solar energy
    biomass conversion
    geothermal energy
    hydroelectric energy
    utilisation of energy contained in waste
    wind energy
  - ° rational use of energy:
    energy saving
    new energy carriers
  - ° analysis of energy systems (energy-economy models):
    open ended versus closed ended systems (open ended systems are those which through evolution in the use of end products allow satisfaction of energy needs without increasing use of fixed carbon sources)
- Energy management:
  - ° reduction of fossil fuel usage
  - ° usage of low-carbon fuels
  - ° usage of alternative energy sources

Third group

- Adaptation to climatic changes through:
  - ° changes in environmental control
  - ° migration
- Adaptation to sea level rise through:
  - ° migration
  - ° construction of (higher) dikes
- Adaptation to effects on agriculture through:
  - ° migration
  - ° change of crops
  - ° modification of varieties
  - ° alteration of husbandry

If the environmental problem develops as some predict, then the impact would be sufficiently large as to require a policy response. Re-direction of research emphasis towards analysis of energy and policy options will then require particular attention.

It should be noted that, when CO2 becomes the focus of concerted international action, the developing nations will be particularly affected.

References used in this section: 8, 10, 14, 19, 30, 38, 51, 66,69.

6. REFERENCES

1. Ausubel, J.H.; Nordhaus, W.D.
A review of estimates of future carbon dioxide emissions.
In: National Research Council, Changing Climate, Report of the Carbon dioxide Assessment Committee. National Academy Press, Washington, D.C. pp 153-185, 1983.

2. Baxendell, P.
The changing energy balance in Asia Pacific.
Address to the PetroPacific '84 Congress, Melbourne, Australia, 8 pp., 1984.

3. Brewer, P.G.
Carbon dioxide and the oceans.
In: National Research Council, Changing Climate, Report of the Carbon Dioxide Assessment Committee. National Academy Press, Washington, D.C. pp 188-215, 1982.

4. Broecker, W.S.; Peteet, D.M.; Rind, D.
Does the ocean-atmosphere system have more than one stable made of operation?
Nature 315:21-25, 1985.

5. Brown, S.; Lugo, A.E.
Biomass of tropical forests: a new estimate based on forest volumes.
Science 123:1290-1293, 1984.

6. Bryan, K.
The role of the ocean in the transient climate response to increasing atmospheric CO2.
In: Proc. Joint Oceanographic Assembly 1982, Gen. Symp. Halifax, pp 43-46, 1983.

7. Byrne, R.H.; Acker, J.G.; Betzer, P.R.; Feely, R.A.; Cates, M.H.
Water column dissolution of aragonite in the Pacific Ocean.
Nature 312:321-326, 1984.

8. Compton, W.D.
Alternate fuels - a technology that is ready.
UP Front/Agricultural Engineering 66:12-13, 1985.

9. Crane, A.J.
Possible effects of rising CO2 on climate.
Plant Cell Environ. 8:371-379, 1985.

10. Dahlman, R.C.; Strain, B.R.; Rogers, H.H.
Research on the response of vegetation to elevated atmospheric carbon dioxide.
J. Environ. Qual. 14:1-8, 1985.

11. Duplessy, J.-C.; Shackleton, N.J.
Response of global deep-water circulation to earth's climatic change 135,000-107,000 years ago.
Nature 316:500-507, 1985.

12. Ellsaesser, H.W.
The climatic effect of CO2: a different view.
Atmospheric Environment 18:431-434, 1984.

13. Fritts, H.C.; Lough, J.M.
An estimate of average annual temperature variations for North America, 1602 to 1961.
Climatic Change 7:203-224, 1985.

14. Golanty, E.
The global experiment. Carbon dioxide and ocean temperature.
Oceans 17:66-69, 1984.

15. Goudriaan, J.; Ketner, P.
A simulation study for the global carbon cycle, including man's impact on the biosphere.
Climatic Change 6:167-192, 1984.

16. Hameed, S.; Cess, R.D. Hogan, J.S.
Response of the global climate to changes in atmospheric chemical composition due to fossil fuel burning.
J. Geophys. Res. 85:7537-7545, 1980.

17. Hansen, J; Johnson, D.; Lacis, A.; Lebedeff, S.; Lee. P.; Rind, D.; Russel, G.
Climate impact of increasing atmospheric carbon dioxide.
Science 213:957-966, 1981.

18. Hartwig, S.; Heudorfer, W.; Schnatz, G.
Possible climatic change by anthropogenic CO2 emission.
J. Chem. E. Symposium Series, No. 78, T4/15-T4/30, 1982.

19. Heintzenberg, J.; Hansson, H.-C.; Ogren, J.A.; Odh, S.-A.
Concept and realisation of an air pollution monitoring station in the European Arctic.
Ambio 14:152-157, 1985.

20. Hileman, B.
The greenhouse effect.
Environ. Sci. Technol. 16:90A-93A, 1982.

21. Hileman, B.
Recent reports on the greenhouse effect - what are some differences between the EPA and NRC studies?
Environ. Sci. Technol. 18:45A-46A, 1984.

22. Hobbie, J.; Dungan, J.; Houghton, R.A.; Peterson, B.
Role of biota in global CO2 balance: the controversy.
BioScience 34: 492-498, 1984.

23. Hoffert, M.I.; Callegari, A.J.; Hsiek, C.T.
The role of deep sea heat storage in the secular response to climatic forcing.
J. Geophys. Res. 85:6667-6679, 1980.

24. Houghton, R.A.; Hobbie, J.E.; Melillo, J.M.; Moore, B.; Peterson, B.J.; Shaver, G.R.; Woodwell, G.M.
Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO2 to the atmosphere.
Ecol. Monogr. 53:235-262, 1983.

25. Hugill, J.A.
The carbon dioxide greenhouse effect.
KSLA, report AMGR.80.105, 9 pp, 1980.

26. Ichimura, S.
The impacts of climatic change on human society.
In: Carbon dioxide Effects Research and Assessment Program. Workshop on Environmental and Societal Consequences of a Possible CO2 Induced Climate Change. U.S.-DOE, Conf-7904143, pp 442-462, 1980.

27. Idso, S.B.
Temperature limitation by evaporation in hot climates and the greenhouse effects of water vapour and carbon dioxide.
Agric. Meterol. 27:105-109, 1982.

28. Idso, S.B.
The search for global CO2 ect. "Greenhouse Effects".
Environ. Conservation 12:29-35, 1985.

29. Idso, S.B.; Brazel, A.J.
Rising atmospheric carbon dioxide concentrations may increase streamflow.
Nature 312:51-53, 1984.

30. Jaske, R.T.
Carbon dioxide - the premier environmental challenge of our time.
Environ. Progress 2:145-148, 1983.

31. Kellogg, W.W.
Feedback mechanisms in the climate system affecting future levels of carbon dioxide.
J. Geophys. Res. 88:1263-1269, 1983.

32. Kendall, A.C.; Turner, J.C.; Thomas, S.M.
Effects of CO2 enrichment at different irradiances on growth and yield of wheat.
J. Exp. Bot. 36:252-260, 1985.

33. Kerr, R.A.
Doubling of atmospheric methane supported.
Science 226:954-955, 1984.

34. King, D.A.
Estimating the direct effect of CO2 on soybean yield.
J. Environ. Mngt 20:51-62, 1985.

35. Kondratyev, K. Ya.; Bunakova, A.M.
Factors of the greenhouse effect of the atmosphere and their influence on climate.
In: Williams, J. (ed.), Carbon Dioxide, Climate and Society. Pergamon Press, Oxford, pp 201-207, 1978.

36. Kratz, G.
Modelling the global carbon cycle.
In: Hutzinger, O. (ed.), The Handbook of Environmental Chemistry, Vol. 1, Part D. Springer Verlag, Berlin, pp 29-81, 1985.

37. Lallarche, V.C.; Graybill, D.A.; Fritts, H.C.; Rose, M.R.
Increasing atmospheric carbon dioxide: tree ring evidence for growth enhancement in natural vegetation.
Science 225:1019-1021, 1984.

38. Laurmann, J.A.
The global greenhouse warming problem: setting the priorities.
Climatic Change 7:261-265, 1985.

39. Levine, J.S.; Rinsland, C.P.; Tennille, G.M.
The photochemistry of methane and carbon monoxide in the troposphere in 1950 and 1985.
Nature 318:254-257, 1985.

40. Manabe, S.; Stouffer, R.J.
Sensitivity of a global climate model to an increase of CO2 concentration in the atmosphere.
J. Geophys. Res. 85:5529-5554, 1980.

41. Maugh, T.H.
What is the risk from chlorofluorocarbons?
Science 223: 1051-1052, 1984.

42. Mook, W.G.; Engelsman, F.M.R.
Het atmosferische CO2 gehalte en de rol van de oceanen.
Chemisch Magazine, Dec. 1983:669-671, 1983.

43. Nicoli, M.P. Visconti, G.
Impact of coupled perturbations of atmospheric trace gases on earth's climate and ozone.
Pageoph. 120:626-641, 1982.

44. Papaud, A.; Poisson, A.
Le cycle du carbone et sa perturbation par les activités humaines: un apercu du problème.
Oceanologica Acta 8:133-145, 1985.

45. Pearman, G.I.; Hyson, P.
Activities of the global biosphere as reflected in atmospheric CO2 records.
J. Geophys. Res. 85:4468-4474, 1980.

46. Ramanathan, V.
Greenhouse effect due to chlorofluorocarbons: climatic implications.
Science, 190,50-52, 1975.

47. Ramanathan, V.; Cicerone, R.J.; Singh, H.B.; Kiehl, J.T.
Trace gas trends and their potential role in climate change.
J. Geophys. Res. 90:5547-5566, 1985.

48. Revelle, R.
Carbon dioxide and world climate
Sci. Amer. 247:33-41, 1982.

49. Rinsland, C.P.; Levine, J.S.; Miles, T.
Concentration of methane in the troposphere deduced from 1951 infrared solar spectra.
Nature 318:245-249, 1985.

50. Schelling, T.C.
Climatic change: implications for welfare and policy.
In: Natural Research Council, Changing Climate, Report of the Carbon Dioxide Assessment Committee. National Academy Press, Washington, D.C. pp 449-482, 1983.

51. Schelling, T.C.
Climatic change: implications for welfare and policy.
Ambio 13:200-201, 1984.

52. Ichlesinger, M.E.
Climate model simulations of CO2-induced climatic change.
Adv. Geophysics 26:141-235, 1984.

53. Semtner, A.J.
On modelling the seasonal thermodynamic cycle of sea ice in studies of climatic change.
Climatic Change 6:27-37, 1984.

54. Shackleton, N.J.; Hall, M.A.; Line, J.; Shuxi, C.
Carbon isotope data in core V19-30 confirm reduced carbon dioxide concentration in the ice age atmosphere.
Nature 306:319-322, 1983.

55. Shugart, H.H.; Emanuel, W.R.
Carbon dioxide increase: the implications at the ecosystem level.
Plant Cell Environ. 8:381-386, 1985.

56. Smith, S.V.
Physical, chemical and biological characteristics of CO2 gas flux across the air-water interface.
Plant, Cell Environ. 8:387-398, 1985.

57. Stauffler, B.; Fischer, G.; Neftel, A.; Oeschger, H.
Increase of atmospheric methane recorded in Antarctic ice core.
Science 229:1386-1388, 1985.

58. Stewart, T.R.; Glantz, M.H.
Expert judgment and climate forecasting: a methodological critique of "climate change to the year 2000".
Climatic Change 7:159-183, 1985.

59. Tyndall, J.
On the absorption and radiation of heat by gases and vapours, and on the physical connection of radiation, absorption, and conduction.
Philosoph. Mag. Ser. 4:169-194 and 273-285, 1861.

60. Walker, J.C.G.; Hays, P.B.; Kasting, J.F.
A negative feedback mechanism for the long-term stabilisation of earth's surface temperature.
J. Geophys. Res. 86:9776-9782, 1981.

61. Wang. W.C.; Yung, Y.L.; Lacis, A.A.; Mo, T.; Hansen, J.E.
Greenhouse effects due to man-made perturbations of trace gases.
Science 194:685-690, 1976.

62. Washington, W.M.; Meehl, G.A.
Seasonal cycle experiment on the climate sensitivity due to a doubling of CO2 with an atmospheric general circulation model coupled to a simple mixed-layer ocean model.
J. Geophys. Res. 89:9475-9503, 1984.

63. Weller, G.; Baker, D.J.; Gates, W.L.; MacCracken, M.C.; Manabe, S.; Vonder Haas, T.H.
Detection and monitoring of CO2 induced climate changes.
In: National Research Council, Changing Climate, Report of the Carbon Dioxide Assessment Committee. National Academy Press, Washington, D.C. pp 292-382, 1983.

64. Wigley, T.M.L.
Carbon dioxide, trace gases and global warming.
Climate Monitor 13:133-146, 1984.

65. Wigley, T.M.L.; Jones, P.D.
Influences of precipitation changes and direct CO2 effects on streamflow.
Nature 314:149-152, 1985.

66. Williams, R.H.
Potential roles for bioenergy in an energy-efficient world.
Ambio 14:201-209, 1985.

67. Wittwer, A.J.
Carbon dioxide levels in the biosphere: effects on plant productivity.
CRC Crit. Rev. Pl. Sci. 2:171-198, 1985.

68. Woodwell, G.M.
Biotic effects on the concentration of atmospheric carbon dioxide: a review and projection.
In: Natural Research Council, Changing Climate, Report of the Carbon Dioxide Assessment Committee. National Academy Press, Washington, D.C. pp. 216-241, 1983.

69. Woodwell, G.M.; Hobbie, J.E.; Houghton, R.A.; Melillo, J.M.; Moore, B.; Peterson, B.J.; Shaver, G.R.
Global deforestation: contribution to atmospheric carbon dioxide.
Science 222: 1081-1086, 1983.

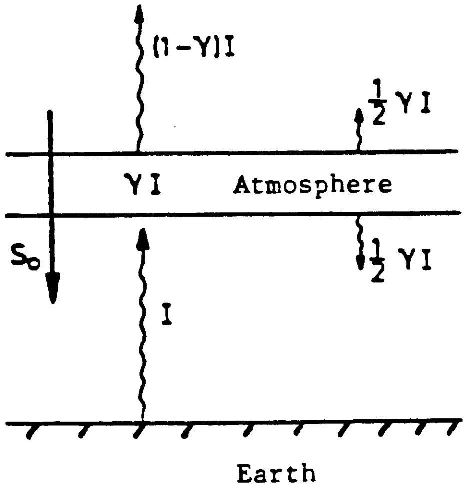
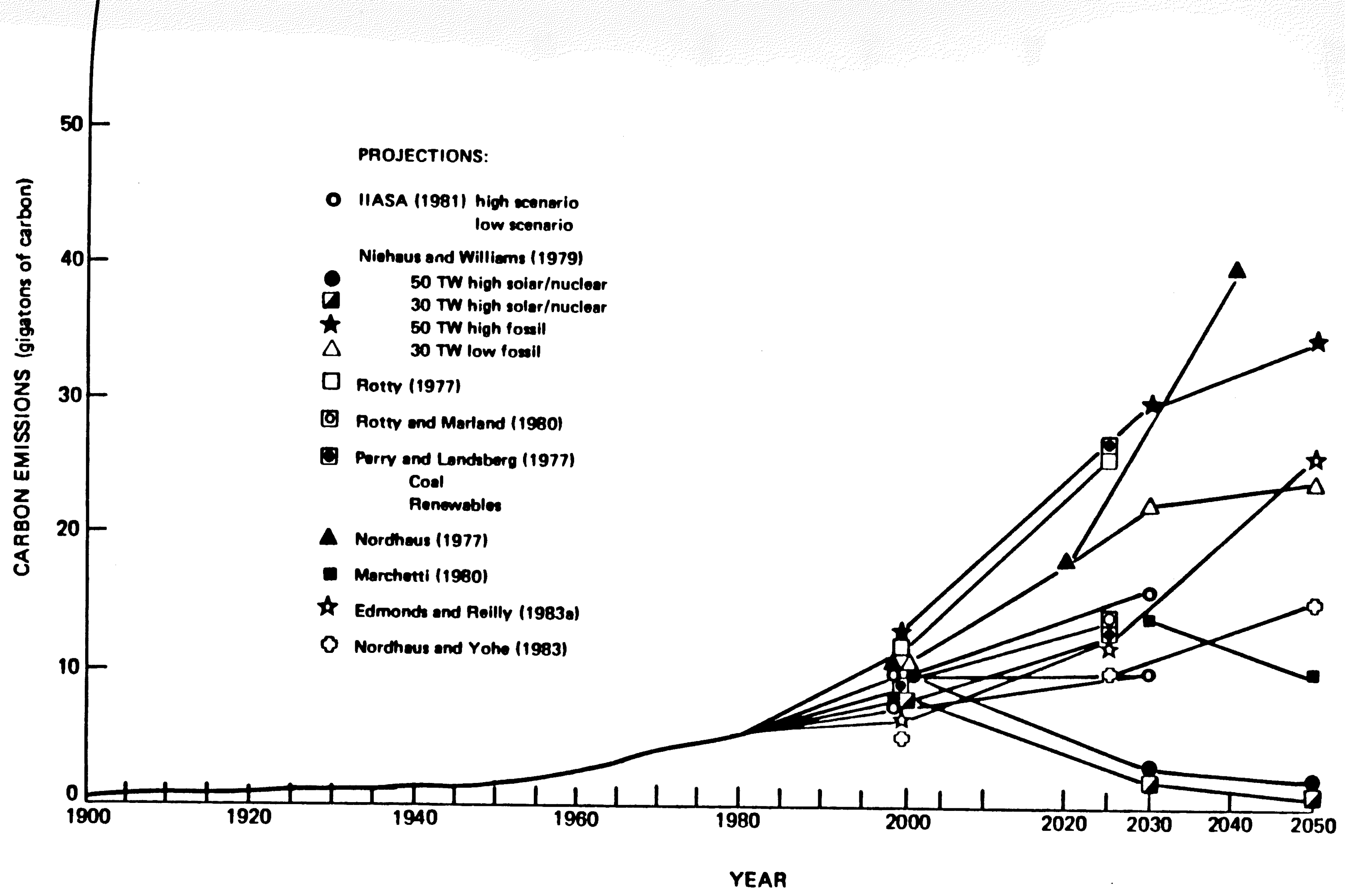


Figure 1

The greenhouse effect: S_o is the solar radiation, I the long-wavelength (infrared) radiation of the earth's surface and Y is the fraction absorbed by the greenhouse gases in the atmosphere (source: Mureau, R. Kooldioxyde (CO_2) en klimaat. In: Hermans, L.J.F.; Hoff, A.J. (eds), Energie een blik in de toekomst. Het Spectrum, Utrecht, The Netherlands, pp 68-86, 1982).

The sun's energy passes through the atmosphere, warms the earth's surface, and is then reradiated into space at longer, infrared wavelengths. The balance of incoming and outgoing radiation determines the planet's temperature. Some atmospheric gases absorb some of the outgoing infrared (e.g. CO_2 in a band of 14-16 µm), trapping heat in a "greenhouse effect".



<u>Figure 2</u>

CO_2 emissions derived from long-range projections and historic production from fossil fuels. Data until 1980 are actual measurements; after 1980 model-calculated projections (source: Carbon Dioxide Assessment Committee, Changing Climate. National Academy Press, Washington, DC, 1983).

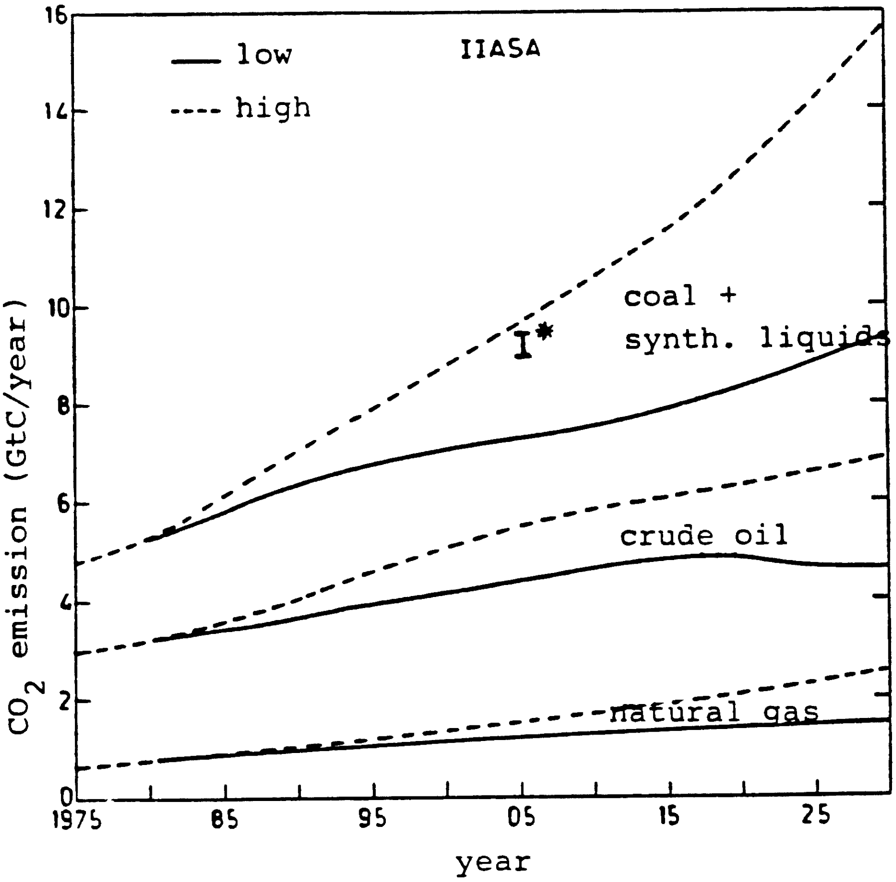


Figure 3

Projected CO_2 emissions generated with the IIASA Energy Systems Programme. For the individual fuels the emissions are cumulatively presented for the lower- and higher-demand cases (source: Deeladvies inzake CO_2-problematiek, Gezondheidsraad, The Hague, The Netherlands, 1983).

* Shell scenario figures for total emissions.

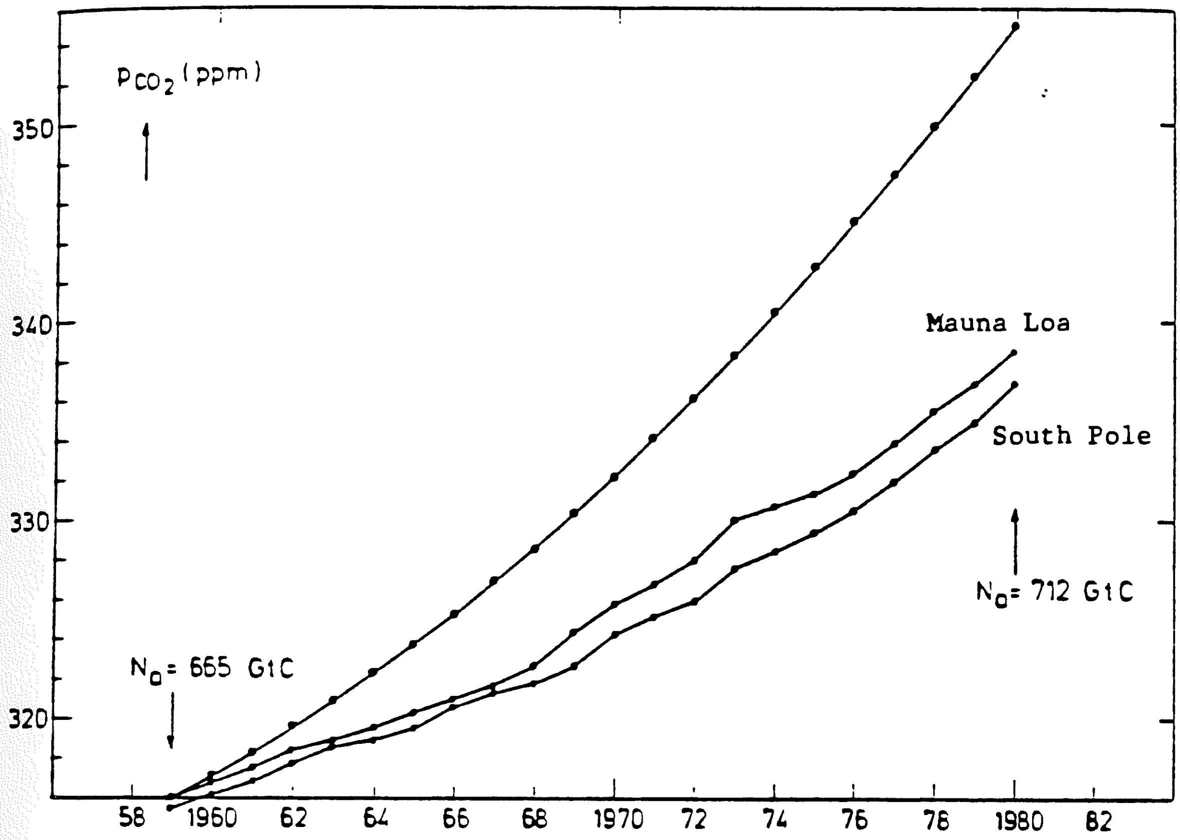


Figure 4

The hypothetical atmospheric CO_2 concentrations based on man-made CO_2 emissions with AF=100% (airborne fraction) and the observed concentrations at Mauna Loa and the South Pole with AF=56%; N_a is the amount of carbon present in the atmosphere (source: Deeladvies inzake CO_2-problematiek, Gezondheidsraad, The Hague, The Netherlands, 1983).

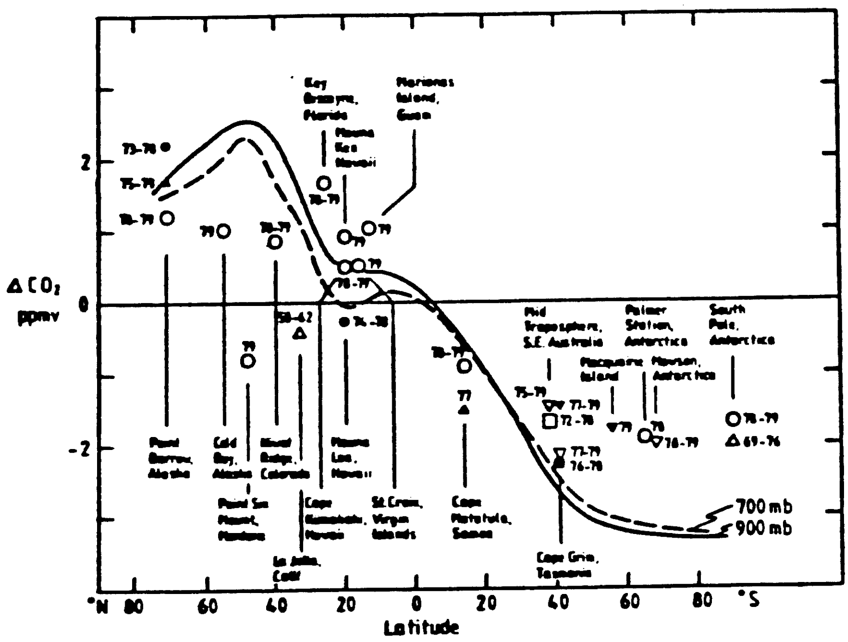


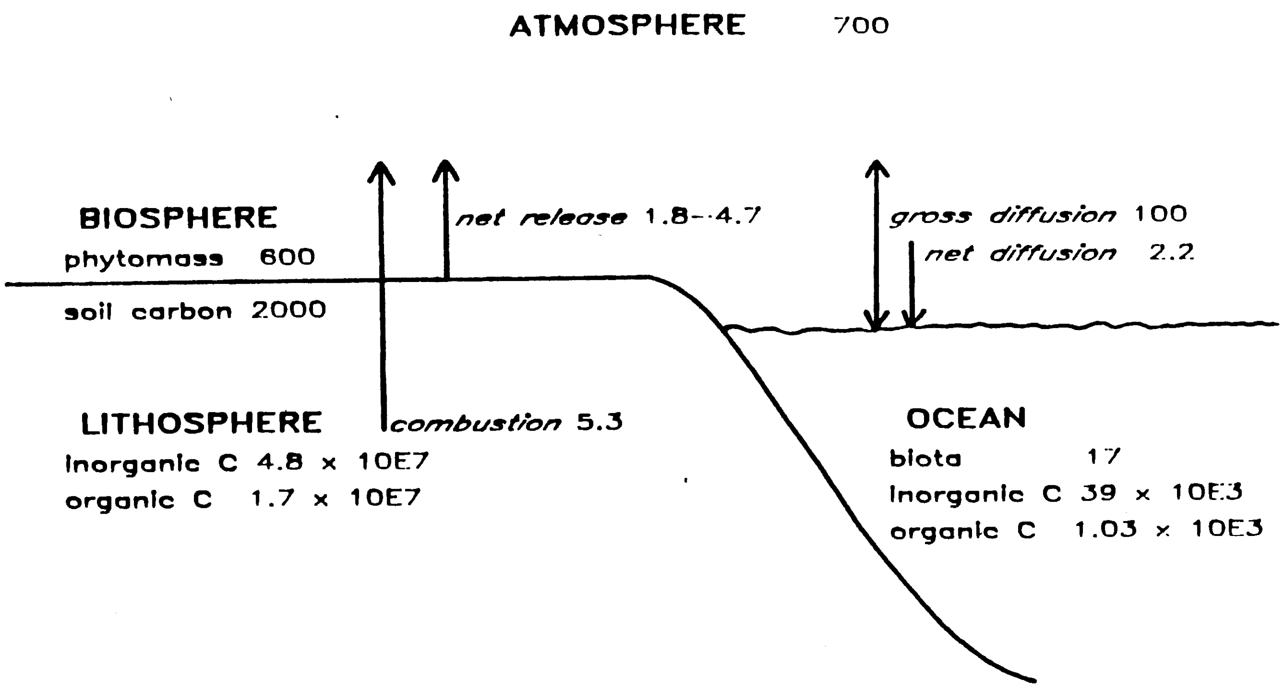
Figure 5

Difference between the annual mean CO_2 concentration in the air at ground-level observed at different places in the world and at Mauna Loa, Hawaii, plotted as a function of latitude. The numbers adjacent to the data points indicate the observation time (source: Papaud, A.; Poisson, A., Le cycle du carbon et sa perturbation par les activités humaines: un apercu du problème. Oceanologica Acta 8:133-145, 1983).

N.B. The two lines represent the model simulations at the altitudes corresponding with 700 and 900 mbar.

Figure 6

The global carbon cycle.
Major carbon reservoirs (in GtC), and natural and (quantified) anthropogenic fluxes (in GtC per year).
1 GtC = 1 gigaton of carbon = 10^{15} g C.



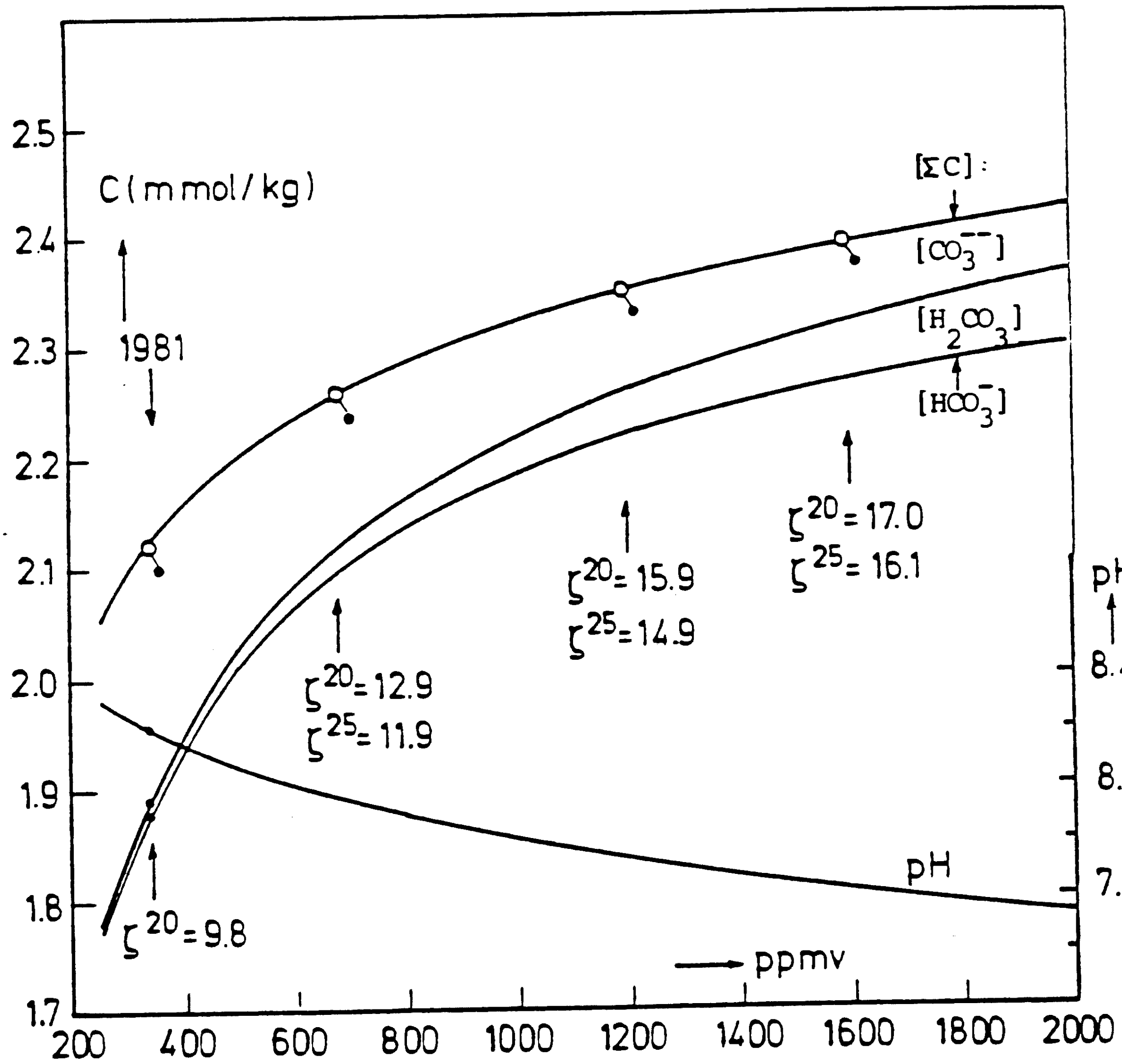


Figure 7

Variation of the buffer factor of seawater with changing total CO_2. Concentrations (at 20°C) of total dissolved inorganic carbon (DIC $= \Sigma C$) and of HCO_3^- in seawater (in mM/kg) are given in relation to the partial pressure of carbon dioxide gas (pCO_2 in ppmv). The concentrations of dissolved CO_2 (H_2CO_3) and of CO_3^{2-} are given as difference between the curves. For a few CO_2 concentrations (e.g. the 1981 value of 340 ppmv and its doubling) the buffer factors ζ^{20} (at 20°C) and ζ^{25} (at 25°C) are given. Increasing CO_2 levels raise the buffer factor, diminish the oceans tendency to absorb CO_2 (i.e. proportionally less increase in oceanic carbon) and decrease pH (source: Deeladvies inzake CO_2-problematiek, Gezondheidsraad, The Hague, The Netherlands, 1983).

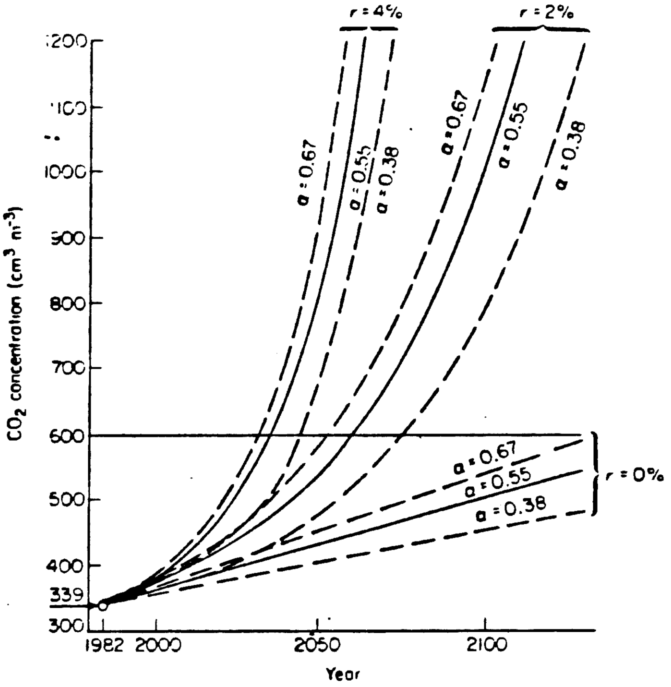


Figure 8

Increase in atmospheric CO_2 concentration over the next 150 years assuming growth rate in emissions of 4, 2 and 0% per year (r) for airborne fractions (α) of 0.38, 0.55 and 0.67 (source: Liss, P.S.; Crane, A.J., Man-made Carbon Dioxide and Climatic Change: a Review of Scientific Problems. Geobooks, Norwich, 1983).

The growth rate of CO_2 emissions from 1973 to the early 1980s fell to below 2% per year and there is a consensus now that the most likely time for a doubling of the CO_2 concentration (i.e. passing 600 ppm) lies in the third quarter of the next century.

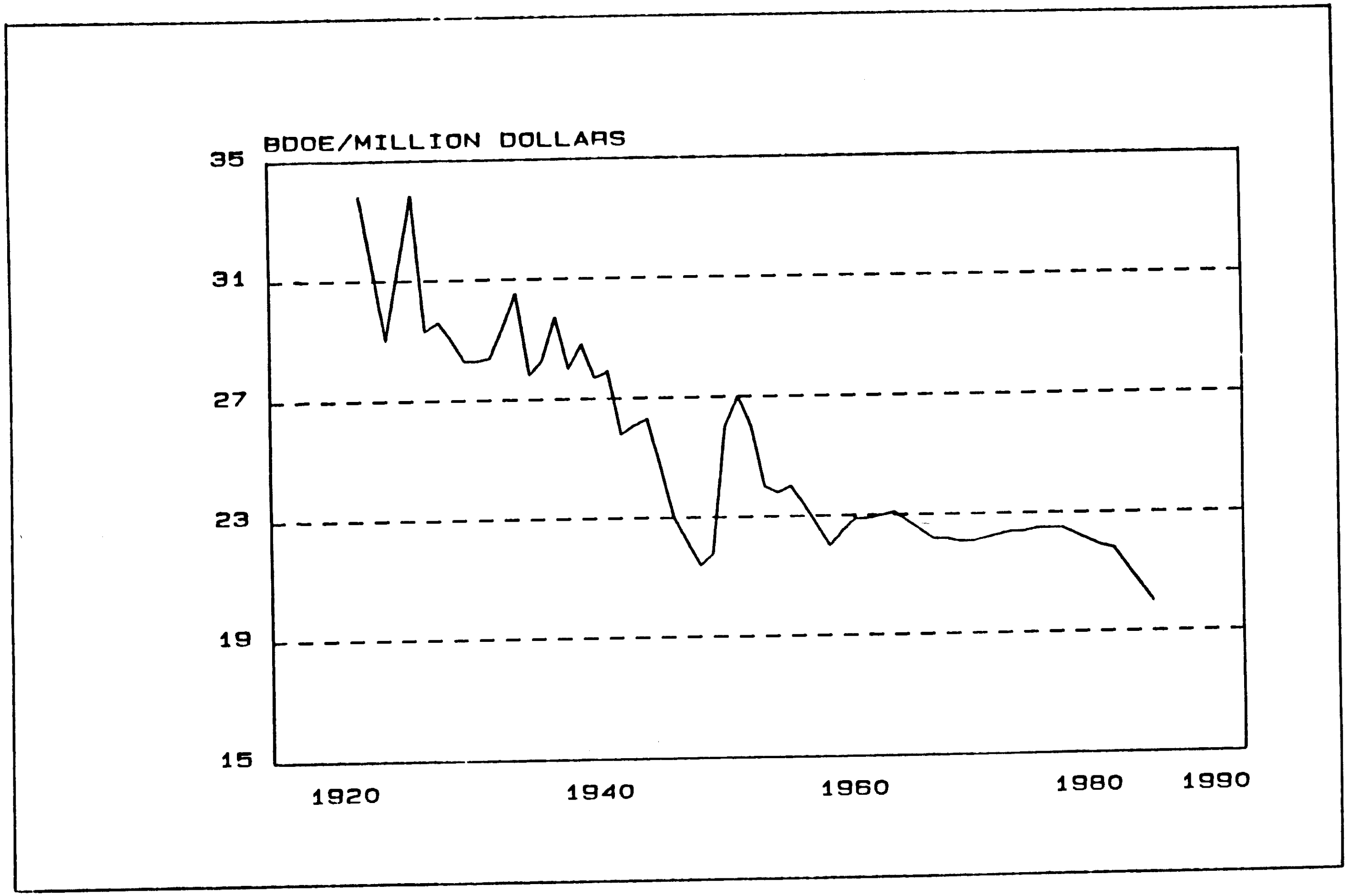


Figure 9

Falling energy intensity in the USA (source: Group Planning Scenarios).

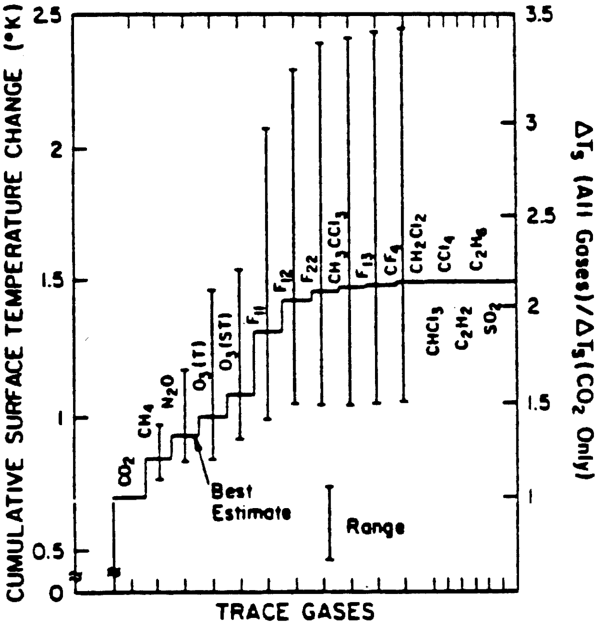


Figure 10

Modelled cumulative surface warming due to increase in CO_2 and other gases over the period 1980 to 2030 (source: Ramanathan, V. et al., Trace gas trends and their potential role in climate change. J. Geophys. Res. 90:5547-5566, 1985).

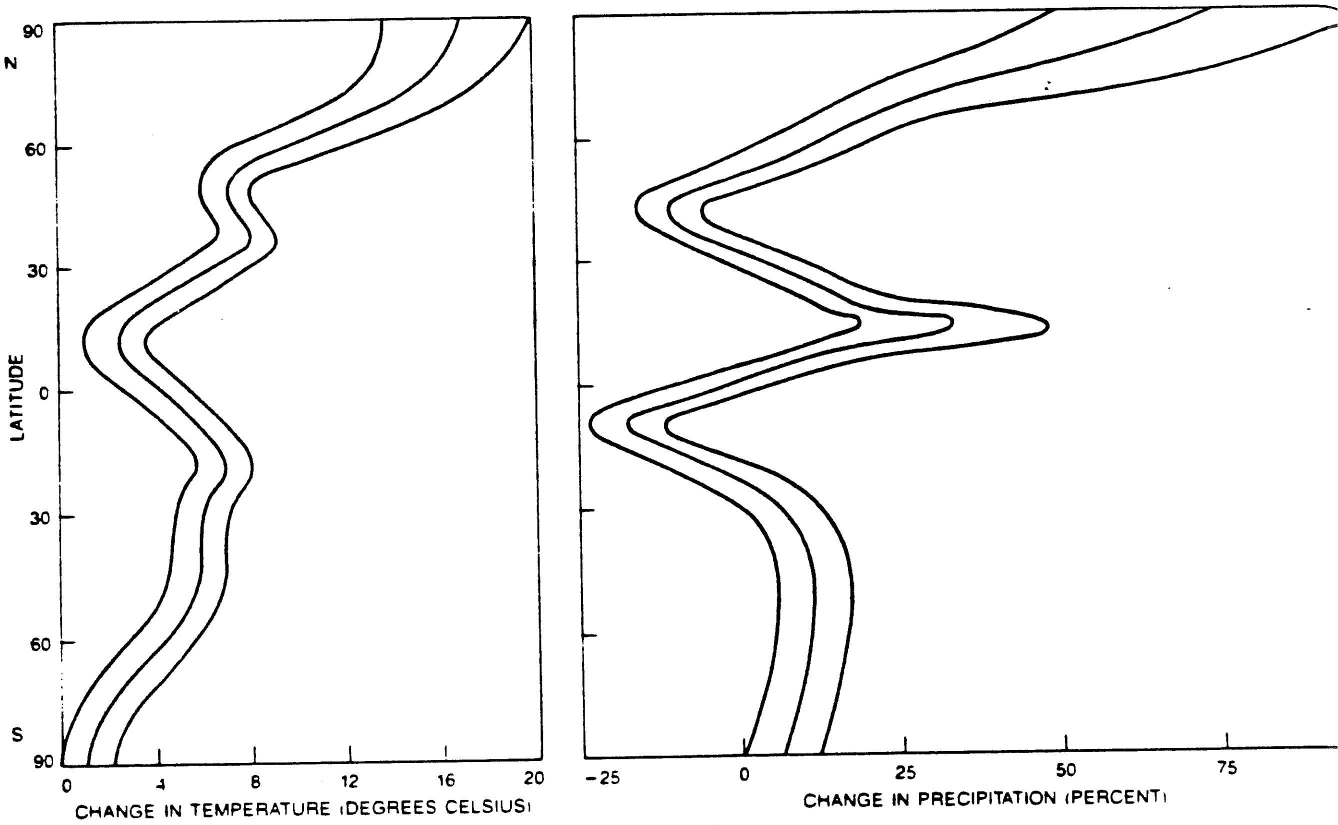


Figure 11

Modelled climatic effects of a doubling of the present atmospheric CO_2 concentration. The graphs show the projected variation by latitude in temperature and precipitation. The three curves in each group reflect the range of possibilities (source: Revelle, R., Carbon dioxide and world climate. Sci. Amer. 247:33-41, 1982).

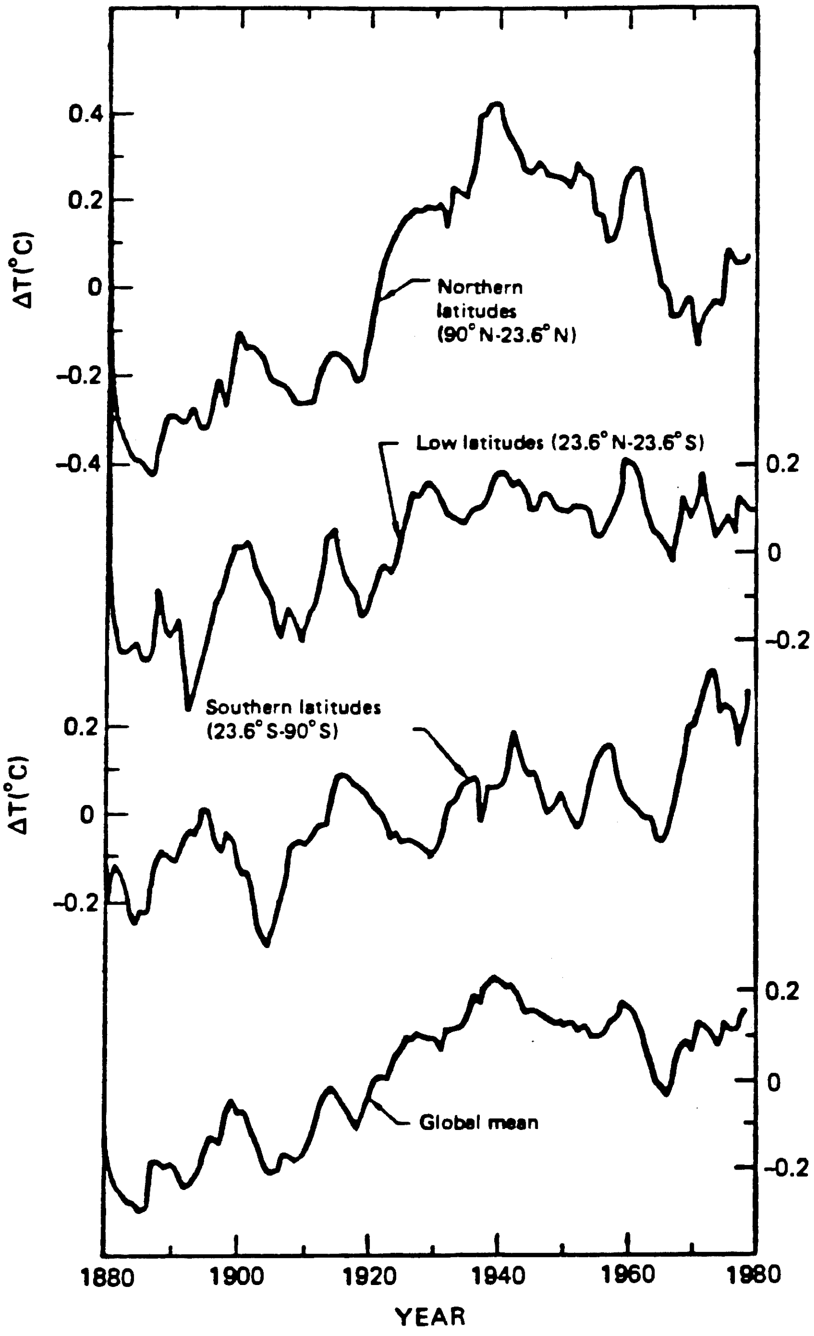


Figure 12

Reconstruction of surface-air-temperature anomalies for various latitude bands (source: Hansen, J. et al., Climate impact of increasing atmospheric carbon dioxide. Science 213:957-966, 1981).

Table 1. CO2 emissions per year by fuel type (10^6 tonnes C/year) (source: Jaske, R.T., Carbon dioxide - the premier environmental challenge of our time. Environ. Progress 2:145-148, 1983)

	1950	1975	1980	% increase	
				1950-75	1975-80
all fossil fuels	1600	4400	5000	4.46	1.86
coal and coal products	1100	1600	1950	1.72	2.57
oil and refined products	400	2200	2300	2.11	1.11
gas and gas by-products	100	600	750	8.06	3.23

Table 2. Carbon produced (as CO2) from selected energy sources (source: Jaske, R.T., Carbon dioxide - the premier environmental challenge of our time. Environ. Progress 2:145-148, 1983)

Fuel source or type	CO2 per fuel energy content (kg/MJ)
coal in direct combustion	23.9
liquid fuel from crude oil	19.7
natural gas	14.1
synthetic liquids from coal	37 - 42
synthetic liquids from shale	43 - 66

Table 3. CO2 emissions per region (in GtC) and per capita (in tC) in 1975 (GtC = 1 gigaton of carbon = 10^9 ton of C = 10^{15} g carbon = 44/12 GtCO2)
(source: Deeladvies inzake CO2-problematiek, Gezondheidsraad, The Hague, The Netherlands, 1983)

region	CO2 emission	population (millions)	CO2 emissions per capita
North America	1.426	237	6.017
USSR + E. Europe	1.218	363	3.355
W. Europe, Japan S. Africa, Australia Israel, New Zealand	1.391	560	2.484
L. and M. America	0.160	319	0.502
M. Africa + S.E. Asia	0.163	1422	0.115
Middle East + N. Africa	0.058	133	0.436
China + Central Asia	0.296	912	0.325
World	4.712	3946	1.194

Table 4. Estimates of the abundance of trace chemicals in the global atmosphere of 1980 and 2030 (source: ref. 47)

Chemical Group	Chemical Formula	Dominant Source*	Dominant Sink*	Estimated Average Residence Time (τ_r), years	Year 1980 Global Average Mixing Ratio, ppb†	Year 2030 Probable Global Average Concentration, ppb		Remarks (also see text for details)
						Best Estimate	Possible Range	
Carbon dioxide	CO_2	N,A	O	2	339 × 10^3	450 × 10^3		Based on a 2.4% increase over the next 50 years
Nitrogen compounds	N_2O	N,A	S(UV)	120	300	375	350-450	Combustion and fertilizer sources
	NH_3	N,A	T	0.01	< 1	< 1		Concentration variable and poorly characterized
	$(NO + NO_2)$	N,A	T(OH)	0.001	0.05	0.05	0.05-0.1	Concentration variable and poorly characterized
Sulfur compounds	CSO	N,A	T(O,OH)?	1(?)	0.52	0.52		Sources and sinks largely unknown
	CS_2	N,A	T	1(?)	< 0.005	< 0.005		Sources uncharacterized
	SO_2	A(?)	T(OH)	0.001	0.1	0.1	0.1-0.2	Given the short lifetime the global presence of SO_2 is unexplained
	H_2S	N	T(OH)	0.001	< 0.05	< 0.05		
Fully fluorinated species	CF_4 (F14)	A	I	> 500	0.07	0.24	0.2-0.31	Aluminum industry a major source
	C_2F_6 (F116)	A	I	> 500	0.004	0.02	0.01-0.04	Aluminum industry a major source
	SF_6	A	I	> 500	0.001	0.003	0.002-0.05	
Chlorofluorocarbons	$CClF_3$ (F13)	A	S(UV),I	400	0.007	0.06	0.04-0.1	All chlorofluorocarbons are of exclusive man-made origin. A number
	CCl_2F_2 (F12)		S(UV)	110	0.28	1.8	0.9-3.5	of regulatory actions are pending. The nature of regulations and
	$CHClF_2$ (F22)	A	T(OH)	20	0.06	0.9	0.4-1.9	their effectiveness would greatly affect the growth of these
	CCl_3F (F11)	A	S(UV)	65	0.18	1.1	0.5-2.0	chemicals over the next 50 years.
	CF_3CF_2Cl (F115)	A	S(UV)	380	0.005	0.04	0.02-0.1	
	$CClF_2CClF_2$ (F114)	A	S(UV)	180	0.015	0.14	0.06-0.3	
	CCl_2FCClF_2 (F113)	A	S(UV)	90	0.025	0.17	0.08-0.3	
Chlorocarbons	CH_3Cl	N(O)	T(OH)	1.5	0.6	0.6	0.6-0.7	Dominant natural chlorine carrier of oceanic origin
	CH_2Cl_2	A	T(OH)	0.6	0.03	0.2	0.1-0.3	A popular reactive but nontoxic solvent
	$CHCl_3$	A	T(OH)	0.7	0.01	0.03	0.02-0.1	Used for manufacture of F22; many secondary sources also exist
	CCl_4	A	S(UV)	25-50	0.13	0.3	0.2-0.4	Used in manufacture of fluorocarbons; many other applications as well
	CH_2ClCH_2Cl	A	T(OH)	0.4	0.03	0.1	0.06-0.3	A major chemical intermediate (global production ≈ 10 tg/yr); possibly toxic
	CH_3CCl_3	A	T(OH)	8.0	0.14	1.5	0.7-3.7	Nontoxic, largely uncontrolled degreasing solvent
	C_2HCl_3	A	T(OH)	0.02	0.005	0.01	0.005-0.02	Possibly toxic, declining markets because of substitution to CH_3CCl_3
	C_2Cl_4	A	T(OH)	0.5	0.03	0.07	0.03-0.2	Possibly toxic, moderate growth due to substitution to CH_3CCl_3
Brominated and iodated species	CH_3Br	N	T(OH)	1.7	0.01	0.01	0.01-0.02	Major natural bromine carrier
	$CBrF_3$ (F13B1)	A	S(UV)	110	0.001	0.005	0.003-0.01	Fire extinguisher
	CH_2BrCH_2Br	A	T(OH)	0.4	0.002	0.002	0.001-0.01	Major gasoline additive for lead scavenging; also a fumigant
	CH_3I	N	T(UV)	0.02	0.002	0.002		Exclusively of oceanic origin
Hydrocarbons, CO, H_2	CH_4	N	T(OH)	5-10	1650	2340	1850-3300	A trend showing increase over the last 2 years has been identified
	C_2H_6	N	T(OH)	0.3	0.8	0.8	0.8-1.2	Predominantly of auto exhaust origin
	C_2H_2	A	T(OH)	0.3	0.06	0.1	0.06-0.16	No trend has been identified to date
	C_3H_8	N,	T(OH)	0.03	0.05	0.05	0.05-0.1	No trend has been identified to date
	CO	N,A	T(OH)	0.3	90	115	90-160	No trend has been identified to date
	H_2	N,A	T(SL,OH)	2	560	760	560-1140	
Ozone	O_3 (Tropospheric)	N	T(UV, SL,O)	0.1-0.3	F(Z)‡	12.5%		A small trend appears to exist but data are insufficient
Aldehydes	HCHO	N	T(OH,UV)	0.001	0.2	0.2		Secondary products of hydrocarbon oxidation
	CH_3CHO	N	T(OH,UV)	0.001	0.02	0.02		1980 concentration estimated from theory

*N, natural; A, anthropogenic; O, oceanic; S, stratosphere; UV, ultraviolet photolysis; T, troposphere; OH, hydroxyl radical removal; I, ionospheric and extreme UV and electron capture removal; SL, soil sink.

†These concentrations are integrated averages; for chemicals with lifetimes of 10 years or less, significant latitudinal gradients can be expected in the troposphere; for chemicals with extremely short lifetimes (0.001-0.3 years) vertical gradients may also be encountered.

‡Varies from 25 ppbv at the surface to about 70 ppbv at 9 km. The concentration was increased uniformly by the same percentage from the surface to 9 km.

Table 5. Net primary productivities (NPP) per given areas, total areas (in 1980), total NPP and actual biomass per ecosystem. The model calculated changes since 1780 are presented in brackets. (source: Ajtay, G.L. et al., Terrestrial primary production and phytomass. In: Bolin, B. et al. (eds), The Global Carbon Cycle, Scope Report No. 13, Wiley, New York, pp 129-187, 1979).

	(NPP) $gC.m^{-2}.yr^{-1}$	area 10^{12} m^2	NPP $GtC\ yr^{-1}$	biomass GtC
tropical forest	720	36.1 (- 8%)	27.8	324.7 (-18%)
temperate forest	510	17.0 (- 6%)	8.7	186.8 (-11%)
grassland	570	18.8 (+25%)	10.7	15.1 (+19%)
agricultural land	430	17.4 (+34%)	7.5	3.0 (+27%)
human area	100	2.0 (+1900%)	0.2	1.4 (+1200%)
tundra and semi-desert	70	29.7 (- 4%)	2.1	13.3 (+ 1%)
total		121.1	57.0	544.3

Table 6. Carbon emissions(in GtC) from the combustion of fossil and fuels (source: Group Scenario).

NEXT WAVE

	commercial fuels				
	oil	coal	gas	total	total + NCE*
1983	2.52	2.36	0.77	5.65	6.28
1985	2.61	2.56	0.83	6.00	
1990	2.61	2.83	0.89	6.33	
1995	2.61	3.14	0.97	6.72	
2000	2.70	3.62	1.07	7.39	
2005	2.84	4.23	1.16	8.23	9.39

DIVIDED WORLD

	commercial fuels				
	oil	coal	gas	total	total + NCE
1983	2.52	2.36	0.77	5.65	6.28
1985	2.59	2.50	0.81	5.90	
1990	2.70	2.66	0.87	6.23	
1995	2.81	2.95	0.92	6.68	
2000	2.88	3.28	0.98	7.14	
2005	3.03	3.66	1.01	7.70	8.87

* Non-Commercial Energy (biomass)

Table 7. Shell Group interest in fossil fuels in 1984 (source: 1985 information Handbook)

fuel	world production	Group interest	%
oil (million bbl/d)	58.2	4.5	7.7
gas (milliard m^3/yr)	1565	56	3.6
coal (million t/yr)	4147	32	0.8

Table 8. Contribution to global CO2 emissions from fuels sold by the Shell Group in 1984 (source: Shell Coal)

	carbon emissions (gigatonnes of carbon)	
fuel	total world	Group share
oil	2.56 (40%)	0.20 (3.1%)
gas	0.80 (12%)	0.03 (0.5%)
coal	2.46 (38%)	0.02 (0.4%)
NCE*	0.63 (10%)	0 (0.0%)
total	6.45 (100%)	0.25 (4%)

* NCE = Non-Commercial Energy (biomass)

APPENDIX 1

The CO_2/carbonate system in the ocean

The majority of carbon present in the ocean is in the form of dissolved inorganic carbon, i.e. 89% as bicarbonate ion (HCO_3^-), 10% as carbonate ion (CO_3^{--}) and 1% as dissolved CO_2. The thermodynamic equilibrium of all forms of inorganic carbon in the atmosphere and the oceans is determined by the following reactions:

$$CO_2 \text{ (atmosphere)} \rightleftharpoons CO_2 \text{ (dissolved)} \tag{1}$$

$$CO_2 \text{ (dissolved)} + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \tag{2}$$

$$HCO_3^- \rightleftharpoons CO_3^{--} + H^+ \tag{3}$$

$$H_3BO_3 \rightleftharpoons H_2BO_3^- + H^+ \tag{4}$$

$$H_2O \rightleftharpoons OH^- + H^+ \tag{5}$$

In water carbonic acid largely dissociates, while only about 10% of bicarbonate dissociates. The chemical equilibria exert a buffering action on the uptake of additional CO_2 by the ocean. The equilibrium constants of the above reactions are:

$$H = p\,CO_2 / [CO_2] \tag{6}$$

$$K_1 = [HCO_3^-]\,[H^+] / [CO_2] \tag{7}$$

$$K_2 = [CO_3^{--}]\,[H^+] / [HCO_3^-] \tag{8}$$

where
$[\ \ ]$ = concentrations in water
H = Henry's law constant
pCO_2 = equilibrium partial pressure in the gaseous phase

The constant H is dependent on the temperature and K depends on temperature and salinity.

The concentration of total inorganic dissolved carbon is:

$$C = [CO_2] + [HCO_3^-] + [CO_3^{--}] \tag{9}$$

and the alkalinity is defined as:

$$A = [HCO_3^-] + 2[CO_3^{--}] + [H_2BO_3^-] + [OH^-] - [H^+] \tag{10}$$

The alkalinity arises from the dissolution of minerals in seawater, principally calcium carbonate. The alkalinity is defined as the amount of acid required to titrate 1 kg of seawater to a constant pH value, corresponding to conversion of bicarbonate and carbonate ions to carbonic acid.

An increasing concentration of CO_2 in seawater shifts equilibrium (2) to the right and by an increasing $[H^+]$ equilibrium (3) to the left. Thus, the principal effect is to consume carbonate ion:

$$\Delta H_2CO_3 + \Delta CO_3^{--} \longrightarrow 2\Delta HCO_3^- \qquad (11)$$

Δ: deviation from stationary state
The CO_2 added to the ocean (i.e. $\Delta\Sigma C$) is therefore:

$$\Delta\Sigma C = -\Delta[CO_3^{--}] \qquad (12)$$

As the concentration of bicarbonate is already very high, a change as a consequence of (11) is negligibly small and the relative changes in $[H_2CO_3]$ and $[CO_3^{--}]$ are practically of the same order:

$$\frac{\Delta[H_2CO_3]}{[H_2CO_3]} = -\frac{\Delta[CO_3^{--}]}{[CO_3^{--}]} \qquad (13)$$

Equations (12) and (13) can be transformed to:

$$\frac{\Delta[H_2CO_3]}{[H_2CO_3]} = \frac{\Delta\Sigma C}{[CO_3^{--}]} = \frac{\Sigma C}{[CO_3^{--}]} \times \frac{\Delta\Sigma C}{\Sigma C} \qquad (14)$$

As already mentioned above $[CO_3^{--}]$ is about 10% of the ΣC, so that the factor $\Sigma C/[CO_3^{--}]$ is about 10. As there is a simple relationship between the atmospheric CO_2 and the oceanic carbon concentration (1, 6), any change may be presented by:

$$\frac{\Delta pCO_2}{pCO_2} = \xi \frac{\Delta\Sigma C}{\Sigma C} \qquad (15)$$

This yields the so-called evasion factor:

$$\xi = \frac{\Delta pCO_2/pCO_2}{\Delta\Sigma C/\Sigma C} \qquad (16)$$

In case pCO_2 is explicitely identified to p_s (CO_2 partial pressure in the ocean surface layer), ξ is the evasion factor or the Revelle factor R, i.e. the "buffer factor". The factor varies with temperature and has a numerical value of about 10. In essence a 10% change in pCO_2 produces only a 1% change in CO_2.

If the CO_2 content of the atmosphere and therefore of the surface ocean increases, $[CO_3^{--}]$ decreases and the value of ξ rises (see also Fig. 7). The resistance to change subsequently increases, the ocean absorbs proportionally less CO_2, and the airborne fraction rises. This complex

system is sensitive to the alkalinity / total CO_2 ratio, and hence pH. Adding CO_2 gas to seawater (11) does not change the alkalinity since charge balance is not altered (10); the dissolution or precipitation of $CaCO_3$, however, does.
The principal forms of $CaCO_3$ in the ocean are calcite and aragonite, which are secreted by calcareous organisms to form their shells. Surface seawater is supersaturated with respect to both calcite and aragonite. The solubility of $CaCO_3$ increases with increasing pressure, decreasing temperature and increasing pH; thus, the deep ocean is undersaturated and dissolution of $CaCO_3$ occurs there.

If CO_2 is added to the surface ocean, the pH decreases and the tendency for $CaCO_3$ dissolution increases. If this occurs, both the alkalinity (10) and the total CO_2 (9) increase. Although this process generates an increase in total CO_2, the net effect of the alkalinity increase would be to enhance the ocean's capacity for CO_2 uptake by keeping the buffer factor constant and providing CO_3^{--}-ions (16).

Recent reports on the greenhouse effect

What are some of the differences between the EPA and NRC studies?

Two reports published in late 1983 reach strikingly different conclusions about the greenhouse effect. A report prepared by a committee under the auspices of the National Research Council (NRC) subscribes to the view that uncertainties in our knowledge of the greenhouse effect are so great that we should take no action now except to study the problem more intensively. An EPA report that was released almost simultaneously concludes that even though a significant warming is likely if we continue on our present path, there is no feasible way to change this path enough to avert the warming by more than a few years. In brief, this view holds that we face almost certain unprecedented changes in the global climate but that we can do nothing but try to adapt to these changes. It is instructive to compare these peer-reviewed studies in terms of their analysis of energy use and resulting CO_2 emissions to ascertain why they arrive at such widely divergent conclusions.

Major findings

The EPA study predicts that CO_2 levels will reach 590 ppm, or twice preindustrial levels, by 2060. Increases in CO_2 and other greenhouse gases would most likely cause a 2 °C warming by 2040 and a 5 °C increase by 2100. Such temperature changes, the report states, "would represent a dramatic departure from historical trends" and "are likely to be accompanied by dramatic changes in precipitation and storm patterns and a rise in global average sea level," thereby causing major geographical shifts in agriculturally productive regions and disrupting established economic systems.

The EPA report examines various strategies to lessen the greenhouse effect. Of these, it concludes that only a worldwide ban on coal combustion instituted in the year 2000 or a ban on coal and shale oil use begun in the same year would have a substantial effect on the temperature increase in the year 2100. A total ban on coal would reduce the temperature increase from 5 °C to 3.5 °C, whereas a total ban on coal and shale oil would reduce the increase from 5 °C to 2.5 °C. However, even if coal were phased out by 2000, the report predicts that the 2 °C warming would be delayed only about 15 years until 2055.

A worldwide tax of 100% on fossil fuels instituted in the year 2000 would be less effective, according to the report, reducing the warming by less than 1 °C in 2100; taxes up to 300% are predicted to delay the 2 °C warming only about five years beyond 2040. Even the alternative energy futures and changes in energy demand analyzed in the report cause a rather minor change, five years or less, in the date of a 2 °C warming. Because a ban on coal is neither economically nor politically feasible and because no other strategies seem to effectively mitigate the global warming, the report urges that individual countries study ways to adapt to rising temperatures.

The NRC report predicts that if no corrective measures are taken, CO_2 levels will most likely double at about the same time as is forecast in the EPA study, during the third quarter of the 21st century. A global temperature change of 1.5 °C to 4.5 °C is expected from this doubling, with values in the lower half of the range more probable. The NRC report differs from the EPA study in that it is far less pessimistic about the effectiveness of strategies that might be used to reduce CO_2 emissions. Substantial taxes on fossil fuel use are seen to have a strong effect on CO_2 emissions and to be "the most predictable in their emission-reducing impact." The report states that steps to change current energy use patterns away from fossil fuels may be necessary at some time in the future, implying that such steps could be effective, and recommends that research into nonfossil energy sources be stimulated. However, it does not recommend that strong steps to limit the burning of fossil fuel be taken in the immediate future, primarily because our knowledge of the CO_2 issue is fraught with uncertainties.

Different analytical techniques

One of the major reasons the EPA report stresses adaptation to what it perceives as inevitable changes and the NRC report stresses uncertainties in our knowledge of the greenhouse effect is that the reports employ quite different analytical techniques to derive their estimates of future fossil fuel use and the resulting future CO_2 emissions. In this area, although not in the entire report, EPA employs a deterministic approach, whereas NRC uses a probabilistic technique which focuses on how the accumulated uncertainties from each segment of its analysis affect the overall conclusions.

The NRC report takes two approaches to projecting future CO_2 emissions, both of which emphasize uncertainties. In one approach, nearly all previous long-range global energy studies are reviewed and the range of projections is used as a guide to the uncertainty inherent in projections of CO_2 emissions.

In the second approach, called "probabilistic scenario analysis," future emissions are estimated after key parameters are assigned a range of values. An attempt is made to estimate the range of current uncertainty as realistically as possible. The conclusion of this approach is that "CO_2 emissions will grow at about 1.6% annually

0013-936X/84/0916-0045A$01.50/0

to 2025, then slow their growth to slightly under 1% annually after 2025." NRC states that its estimates are lower than those in many earlier studies for two major reasons: "First, the expected growth of the global economy is now thought to be slower than had earlier been generally assumed." Second, NRC includes in the analysis incentives to substitute other energy sources for fossil fuels as the prices for fossil fuels rise. Most other studies have downplayed the potential importance of this effect.

Both of NRC's approaches produced not a single value but a range of values for future CO_2 emissions, with higher probabilities assigned to some values than to others. In neither approach was an effort made to resolve uncertainties; rather, both approaches recognize that projections of the future become more and more uncertain as the time horizon expands.

Inevitable results

The EPA report also considers uncertainties in some sections, but in the core of the report, the analysis of future CO_2 emissions, it ignores them. The study adopts a set of economic assumptions to which no ranges of uncertainty are attached, and from these and the use of a global energy model derives what is called a reference mid-range baseline projection or scenario. Various policies intended to slow or limit the rate of CO_2 rise are then tested against this projection. Because the policies are tested against no other projections, the assumptions embedded in this mid-range projection are critical in determining the results of the policy analysis.

If the main elements of EPA's energy analysis are examined, it can be seen that EPA's conclusions follow almost inevitably from its assumptions. First, the agency assumes a rate of economic growth that would be considered high by a number of analysts. Gross world product is projected to increase from 6.06 trillion U.S dollars in 1975 to 184.87 trillion dollars in 2100, in constant 1975 dollars (a factor of 30 increase). The average annual rates of increase over the 125-year period range from about 2.8% per year for the developed regions to over 3% (3.8% after 2050) for the less developed nations. During this same time period, per capita gross national product (GNP) in African countries, for example, grows from an average of $375 per year to $14,000 per year in constant 1975 dollars.

The total energy demand is tied directly to the GNP by what are called income elasticities of demand. These are set at greater than or equal to one over the entire world to the year 2100. This means that as incomes go up, energy use goes up proportionately or greater than proportionately, except as it is affected by prices and enhanced energy efficiency.

The analysis is set up in such a way that no new technology such as solar or fusion becomes competitive with either coal or nuclear as a source of electric power to the year 2100. Solar and biomass both remain minor energy sources. Therefore, except for nuclear power, no economical substitute for fossil fuel emerges over the next 120 years. In contrast, the *EPRI Journal* concluded recently that for just one emerging energy technology, photovoltaics, "three approaches now have a better-than-even chance of meeting the cost and efficiency thresholds needed for bulk power generation."

Further, the EPA report assumes fixed price elasticities for fossil fuel demand that are independent of fuel cost. Thus, the economic attractiveness of increasing the efficiency of energy use or substituting other energy forms is assumed to be independent of fossil fuel prices. This assumption becomes particularly important as the rapidly increasing use of fuels exhausts the conventional oil and natural gas supplies and greater reliance on synthetic fuels from coal and on unconventional gas and oil is required. Many energy analysts believe that these costly forms of fossil fuel may not be economically competitive with other energy options in a number of situations.

A final assumption of the EPA study is that other greenhouse gases such as nitrous oxide, methane, and chlorofluorocarbons will have a warming effect approximately equal to that of CO_2. A large uncertainty is associated with this assumption, but it is used nevertheless in evaluating the effectiveness of various policies such as taxes or bans on various fossil fuels. It assumes that the warming from other greenhouse gases will mitigate the effect of lowering CO_2 emissions. For example, a 30% decrease in emissions produces only a 15% decrease in the expected warming.

Because none of these assumptions is changed in testing the various policies, none but the most stringent and therefore highly infeasible—such as a total ban on coal by the year 2000—substantially reduces CO_2 emissions and the resulting warming. Worldwide taxes of up to 100% on fossil fuels reduce emissions 10–42% in 2100, but the maximum estimated temperature reduction is only 0.7 °C.

Other projections

In the EPA report, a number of other energy scenarios are investigated, but all of them are variants of the mid-range scenario and none of them are used as baselines from which to assess the effects of different policies. The other scenarios are called high renewable, high nuclear, high electric, low demand, and high fossil. These all use the same growth forecast for GNP as is employed in the mid-range scenario. The low-demand scenario is the only one that projects a significant change in energy demand—24% less in 2050—and comparable reductions in CO_2 emissions.

The EPA study includes one scenario in which the growth rate in GNP is lowered somewhat, but it is decreased only after 2050 and only for the less developed regions, where it is reduced from 3.8% to 2.8% per year. The scenario projects a temperature rise in 2100 that is only 0.2 °C lower than it is in the mid-range scenario. From this analysis, EPA concludes in the executive summary that reduced economic growth causes only "minor [i.e., five years or less] changes in the date of a 2 °C warming."

The energy model used by EPA is not intrinsically inaccurate or unrealistic. But, the fact that only one run of the model is used to assess the implications of different policies and that this run involves assumptions to which no range of uncertainty is assigned introduces a certain inevitability to the conclusions. The NRC report describes this model as "the only carefully documented, long-run global energy model operating in the United States," but says that its size and complexity make "identification of critical parameters or assumptions a formidable task." Unfortunately, the EPA report does not even explain the possible importance of these critical assumptions to the conclusions it draws, nor does it analytically test the sensitivity of these conclusions to other sets of assumptions made by credible energy analysts and economists.

The EPA study is interesting because it shows that policies which at first glance appear useful may not be quick and easy answers to the greenhouse problem. It is misleading if it gives the impression that its projections are the only possible or probable ones or that all policies that might be instituted to mitigate the greenhouse effect are doomed to failure.

—Bette Hileman

APPENDIX 3

Current (1986) legislation and policies

General

Air pollution control today is only to a limited extent a local issue as it has become a regional and national matter in most countries. For some countries the main aspect of air pollution is only an international one. This holds particularly for the issue of carbon dioxide/climatic change. National governments are, of course, unlikely to agree as to the appropriate response to the CO2 problem, if they do not share similar views regarding the severity and the causes. Therefore, international forums are used as the appropriate environment for the universe of nations to discuss and debate such national and global concerns. All available knowledge can be registered there and research can be coordinated and stimulated.

It is not surprising that many countries involved in trans-boundary air pollution problems, also seriously fear socio-economic and climatic consequences of increasing CO2 concentrations. Although currently no legislation exists with regard to the CO2 problem, some of these countries are developing environmental policies at a national level. The USA and The Netherlands are here taken as examples because of their activities and initiatives in this field.

United Nations Environment Programme (UNEP)

The issue of carbon dioxide and climatic change has been on the UNEP agenda for many years. From a relatively unimportant subject it developed into a recurrent issue and recently clear links were shown to exist with issues such as deforestation and hazards to the ozone layer posed by chlorofluorocarbons (CFC's).

The following is a short historical overview of the main actions and recommendations related to the greenhouse effect.

During its seventh session in May 1979 the Governing Council of UNEP requested the Executive Director to bring to the attention of the World Meteorological Organisation (WMO) the willingness of UNEP to collaborate with WMO and other organisations concerned with the implementation of the climate impact studies component of the World Climate Programme. This offer was accepted by WMO. Following recommendations by the Scientific Advisory Committee of the World Climate Impact Studies Programme (WCISP), the Governing Council, in its ninth session in May 1981, called upon the Executive Director to proceed with implementation of the WCISP in collaboration with participating international organisations (i.e. WMO and the International Council of Scientific Unions).

During the tenth anniversary of the UN conference on the Human Environment in May 1982 the Governing Council defined the trends, problems and priorities for action which should receive attention by the UN system. With respect to the atmosphere the following items were identified. These include the continuing increase of CO2, other trace gases and particulates

in the atmosphere and possible effects of human activities on weather and climate.
The following actions were given priority:
- integrated monitoring of atmospheric pollutants and their effects
- development and promotion of appropriate global, regional and national programmes
- understanding of factors affecting climate, including ocean-atmosphere interaction

The Council requested the Executive Director to consider the appropriate timing for an assessment of the potential socio-economic impacts of increased CO2 concentrations in the atmosphere and for the establishment of a committee to coordinate related research and information exchange. This in the light of the progress made by WMO and ICSU, in cooperation with the Food and Agriculture Organisation (FAO) of the United Nations and the United Nations Educational, Scientific and Cultural Organisation (UNESCO).

At the Ministerial Conference in June 1982 in Stockholm the UNEP Executive Director summarised UNEP's ten year review of the State of the World with respect to CO2 as follows:
- Concentrations of CO2 are slowly and steadily increasing, chiefly as a result of the increasing use of fossil fuels and forest clearing.
- A world climate programme has been initiated by WMO with UNEP's participation. UNEP has special responsibilities for the assessment of the impacts of climatic changes.
- No systematic attempt has yet been made to address the problem of managing the emissions of CO2, most likely because of the long-term effect of their increase.
- It looks as if any initiative aimed at managing the CO2 problem will not be taken in the near future and perhaps taken too late.

At the eleventh session of the Governing Council in May 1983 many delegations noted the importance of the increase in atmospheric CO2, and several felt that the subjects of rational energy use and of new and renewable energy sources should be considered within the context of the CO2 climate issue.

CO2 related excerpts from the reports presented at the twelfth session of the Governing Council in May 1984 are given in Appendix 4.

European Community (EC)

In December 1979 the Council adopted the proposal for a five-year (1980-1984) indirect-action programme on climatology (1). The main objectives were to contribute to a better understanding of climatic processes and variations, and to assess the potential impact of climatic variations on basic resources and the effect of human activities on climatic variations.
This programme fitted in with the World Meteorological Organisation's World Climate Programme and included the following research areas:

a) understanding climate by reconstruction of past climates,
b) development and improvement of climate modelling, and
c) man-climate interaction studies with special emphasis on the accumulation of CO2 and the effects of release of energy.

In 1980 the Commission submitted a proposal for a Council Decision adopting a sectorial research and development programme (indirect action) 1981-1985 (2). Sub-programme II on climatology outlined two research areas, i.e. understanding climate and man-climate interactions. The main objectives of this programme were to establish a scientific basis for the implementation of the Community's environmental policy and to promote long-term basic research on important environmental problems.

The public and senior governmental scientists grew more and more concerned about the implications of the rising CO2 content of the atmosphere with regard to agricultural and human settlement patterns in the long-term. In the beginning of 1985 this concern was considered sufficiently real to justify the introduction of studies into possible alternative energy strategies.

In the research programme for 1986-1990 the Commission proposes in Sub-programme II on climatology and man-environment interaction to concentrate on the issues: understanding of man's influence on climate and prediction of the resulting impacts, with special emphasis on the increasing atmospheric CO2 concentration.

At the end of October 1985 a comprehensive report on environmental constraints and their implications for EEC energy policy was presented at the plenary session of the Economic and Social Committee of the European Communications (ESC). The authors of this report argue that if the Community is to resolve the environmental problems resulting from energy production and usage, while at the same time ensuring adequate supplies of energy for the fast-growing world population, it must adopt a strategic approach based on a common policy for energy and the environment. The most important task will be to keep environmental pollution (including CO2) from the production, conversion and usage of energy within acceptable limits at acceptable costs. The ESC unanimously decided to forward this report to the European Commission and the EEC's Council of Ministers (3).

1. OJ C247 of 18/10/1978, Bull. EC 12-1979, points 2.1.161
2. OJ C228 of 08/09/1980, p. 1
3. Europe Environment, November 12, 1985 - No. 243, V, 1-26

Organisation for Economic Cooperation and Development (OECD)

During its work on environmental policy, the OECD has established and adopted a series of principles with a view to their incorporation in national legislation and regulations concerning the protection of the environment and also in international agreements (e.g. 1,2,3).
Apart from recommendations with regard to long-range trans-boundary air pollution and reduction of environmental impacts from energy production and use, no special attention was paid to the CO2 problem.

1. Coal and the environment (Recommendation adopted on 8th May, 1979 - C (79) 117)
2. Ministerial declaration on future policies for science and technology, PRESS/A (81) 14 (1981)
3. Reduction of environmental impacts from energy production and use (Recommendation adopted on 12th October, 1976 - C(76) 162)

USA

The Energy Security Act of 1980 (1), while focused on the development of synthetic fuels, also called for examination of some of the environmental consequences of their development. One such consequence perceived by the Congress was the build up of CO2 in the atmosphere, and the National Academy of Sciences (NAS) and the Office of Science and Technology Policy (OSTP) of the Executive Office of the President were requested to prepare an assessment of its implications. In response to a congressional mandate, the Carbon Dioxide Assessment Committee (CDAS) was formed and published a report (Changing Climate) in 1983.

As a result of a scientific conference in 1977 in Miami Beach, Florida and its recommendations, which were followed by the Department of Energy (DOE) and other federal agencies, including NSF, NOAA, NASA, EPA, USGS, and USDA, more than $ 110 million have been spent on CO2 research from 1978 to 1984.

1. Public Law 96-294, June 30, 1980; Title VII - Acid Precipitation Program and Carbon Dioxide Study; Subtitle B - Carbon Dioxide

The Netherlands

Concern about air pollution in general in The Netherlands has led to local, regional and national abatement policies in order to improve the air quality and the chance of survival of nature in remote areas. Over the last few years concern about the issue of carbon dioxide and climatic change has considerably increased and has resulted in a central policy laid down in the indicative multi-year air programme 1985-1989 (IMP-air (1)). There in certain facets were based primarily on advice received from the Health Council (2) and the Advisory Council for Research on Nature and Environment (3). The policy pursues the following principal strategies:

- The government will take the necessary measures to promote the awareness and knowledge of the CO2 problem and of trace gases which might influence the global climate. At the national level this will be elaborated by providing and publishing relevant information. However, it is recognised that the only effective way to tackle the problem is through international cooperation and exchange of information. As the CO2 problem receives attention in only a few countries and scientific organisations, the Dutch government will encourage international organisations such as UNEP, EOSD/IEA and EC, to expand their activities in this field.

- In order to narrow the uncertainties about future climatic changes and to define possible measures to reduce the impact, opportunities for scientific research will be provided in close cooperation with the EC programme on climatology and the World Climate Programme.

- In line with the general air pollution abatement policy, measures to reduce emissions of CO2 will be studied. Special attention will be paid to stimulation of energy conservation, alternative energy sources and reduction of fossil fuel usage.

1. IMP-air, Lower Chamber 18605, September 1984

2. Deeladvies inzake CO2-problematiek, Gezondheidsraad, February 1983

3. Onderzoek in Nederland naar de gevolgen van de toename van CO2 en andere sporengassen in de atmosfeer door menselijke activiteiten, RMNO, May 1984

UNITED NATIONS
ENVIRONMENT PROGRAMME

LIST OF ENVIRONMENTALLY DANGEROUS
CHEMICAL SUBSTANCES AND PROCESSES
OF
GLOBAL SIGNIFICANCE

REPORT OF THE EXECUTIVE DIRECTOR
OF UNEP
TO THE TWELFTH SESSION OF ITS GOVERNING COUNCIL

* * *

IRPTC - GENEVA

CARBON DIOXIDE

Background

Carbon dioxide (CO_2) is a natural trace constituent of the earth's atmosphere. The present mean concentration of CO_2 is around 340 ppm by volume. CO_2 has a critical role in the global heat balance in that it is essentially transparent to the incoming solar radiation but absorbs the infra-red radiation emitted by the earth. This radiation trap causes a warming of the lower atmosphere which is known as the "greenhouse effect".

The global nature of the CO_2 problem results largely from the combustion of fossil fuels (oil, coal and natural gas) whose consumption has been increasing steadily since the beginning of the last century. The corresponding release of CO_2 has resulted in a significant build-up in the atmosphere, from an estimated concentration of less than 300 ppm in the middle of the nineteenth century to a present-day value of about 340 ppm. Reduced energy demand since the mid-1970s has caused a slight reduction in the annual increase in fossil fuel use and consequent CO_2 emissions.

Global impact

Several uncertainties surround the CO_2 issue and these place constraints on the assessment of CO_2's global impact. There are also deficiencies in our knowledge of the natural carbon cycle and its reaction to perturbation by human activities. For example, only about half of the CO_2 discharged from fossil fuels over the last two decades can be found in the atmosphere. It is commonly suggested that the oceans act as the main sink for this "missing" fossil fuel CO_2 although it is uncertain whether net transfer to the oceans can account for all the deficit. There is also uncertainty over the magnitude of CO_2 release arising from man's widescale and increasing forest clearance activities, with estimates ranging from insignificant to an amount comparable with fossil fuel CO_2, although most projections indicate that, in the long term, fossil fuel emissions will be an order of magnitude larger than biospheric emissions. If the latter is true, the fraction of man-made CO_2 which remains airborne is lower than present estimates indicate, suggesting that CO_2 increases will occur more slowly than currently predicted.

Uncertainties also surround the earth's future demand for fossil fuels and consequent CO_2 release. Some recent predictions estimate that atmospheric CO_2 concentrations may pass 600 ppm in the third quarter of the next century; this value represents a doubling of the pre-industrial concentration. It has also been forecast that the greatest increase in CO_2 release from fossil fuels will arise in the developing countries.

It is generally accepted that future increases in the atmospheric CO_2 level will cause a rise in the average global temperature. However, there is still debate over the magnitude of this warming. Calculations with three-dimensional, time-dependent models of the global atmospheric circulation indicate that a doubling of the CO_2 level will cause an average global warming of 1.5°C - 4.5°C with greatest increases predicted for the higher latitudes of the northern hemisphere.

These increases in temperature may lead to effects such as altered precipitation and evaporation regimes, which could affect agriculture and the distribution of food resources. Effects on the oceans may also be significant, as changes in wind circulation would affect ocean currents, causing the relocation of nutrient-rich areas leading to the redistribution of marine organisms and the consequent elimination of some commercial fisheries. Ocean warming and ice cap melting may raise the sea level by the order of one metre. One recent study considers a global rise of between 144 cm and 217 cm likely to occur by the year 2100.

Currently there is no evidence that there has been a CO_2-induced increase in the global temperature. The detection of such an effect is made difficult by the inherent variability in climate. In addition, predictions of the time when a global warming will be detectable are highly dependent on the assumed rate of heat exchange between different parts of the oceans.

Several approaches to control the CO_2 problem have been proposed. The "technical fixes" which involve the collection and disposal of CO_2 are not considered to be practical or economical. Alternative energy systems which do not emit CO_2 might be developed to reduce the reliance on fossil fuels although such actions are currently considered to be of limited effectiveness and prohibitively expensive. Energy conservation is considered to be an important means of reducing CO_2 emissions from fossil fuels.

- - - - - - -

RECOMMENDATIONS

(a) Because replacement of fossil fuels by alternative energy sources is probably still not feasible economically and politically, priority should be given to work geared to the development of long-term energy options not based on combustion of fossil fuels;

(b) The size of reservoirs and fluxes in the biogeochemical cycle of carbon should be determined with greater accuracy;

(c) The modelling of CO_2-induced climate changes should be further refined to reflect, for example, interactions of the ocean-atmosphere interface in order to establish more accurately the size and extent of predicted effects;

(d) Research and development should give priority to better predictions of future fossil fuel use and corresponding CO_2 release to atmosphere;

(e) Updated assessments of the CO_2 climate issue should be undertaken jointly by a WMO/ICSU/UNEP CO_2 study group with an appropriately broad interdisciplinary membership. A second assessment of the role of CO_2 in climate variations and their impact should be made in 1985.

CONFIDENTIAL

UNEP REPORT NO. 2 (1984)

UNITED NATIONS
ENVIRONMENT PROGRAMME

LIST OF ENVIRONMENTALLY DANGEROUS
CHEMICAL SUBSTANCES AND PROCESSES
OF
GLOBAL SIGNIFICANCE

SCIENTIFIC MONOGRAPHS

* * *

IRPTC - GENEVA

CARBON DIOXIDE

Background

Carbon dioxide (CO_2) is a natural constituent of the Earth's atmosphere. It makes up only about three-hundredths of one per cent of the atmosphere, yet plays a crucial role in the planet's heat balance. This is because CO_2 absorbs infra-red radiation emitted from the Earth's surface, producing a warming of the lower atmosphere. This radiation trap is known as the "greenhouse effect".

It is now established that there has been a significant increase in the atmospheric CO_2 concentration since the beginning of the industrial era. Estimates of the airborne CO_2 level in the mid 19th century are in the order of 260-280 ppm (NAS 1983). Regular monitoring measurements from around the world reveal that by 1958 the CO_2 concentration had increased to about 315 ppm, while in 1980 the value had risen further to about 338 ppm (Bacastow and Keeling, quoted in Smith, 1982).

The rise in the atmosphere CO_2 level largely results from the combustion of fossil fuels (oil, coal and natural gas) whose use has been increasing at a steady rate since the beginning of the 19th century. Numerous studies have reported that CO_2 discharges from fossil fuel production have increased at an annual rate of about 4.5 per cent, at least until 1973 (e.g., Rotty 1981). As a result of the oil crisis and subsequent economic recession, there has been a slowing down of this increase to about two per cent. Currently, about 5×10^9 tonnes of CO_2 ($\pm$ 10 per cent) are emitted annually from fossil fuel combustion.

The global carbon cycle

The significance of atmospheric CO_2 accumulation should be examined in the context of the global carbon cycle. Unfortunately, although the principal sources, sinks and transfer kinetics are well established (Bolin et al. 1979), there are still uncertainties in regard to several important details of the cycle. For example, a quantity, somewhat larger than half of the CO_2 released from fossil fuels over the last two decades, is found in the atmosphere, indicating the presence of a CO_2 sink as yet unaccounted for. It is commonly suggested that the oceans act as the main sink for this "missing" fossil fuel CO_2, although it is far from clear whether net transfer to the oceans can account for all the deficit. Uncertainty also exists in the magnitude of CO_2 release from changes in land use, particularly deforestation. Estimates of the CO_2 released from this source range from insignificant to an amount comparable with fossil fuel CO_2 (Rotty 1980; Woodwell, G.M. et al. 1983). If the latter is true, the fraction of man-made CO_2 which remains airborne, is lower than present estimates indicate, suggesting that CO_2 increases will occur slower than currently predicted.

Superimposed upon these deficiencies in our understanding of the carbon cycle is the uncertainty surrounding future energy demands and consequent CO_2 release. Until recently, most forecasts of future fossil use were based on the high growth rates of energy demand in the early 1970s (e.g. Rotty 1978). However, most study groups have now revised their predictions of energy demand downwards (Häfele et al. 1981; Rotty 1980). These later estimates of future CO_2 release can be used in conjunction with currently accepted models of the carbon cycle to produce forecasts of future atmospheric CO_2. The values obtained are dependent on the assumption employed, but several estimates indicate that by the year 2025 atmospheric CO_2 levels could have risen to 450 or even 600 ppm (Rotty 1980; Smith 1982). A more recent study has predicted that atmospheric CO_2 concentrations may pass 600 ppm by the third quarter of the next century. For the year 2000, the most likely concentration is 370 ppm (NAS 1983).

Global effect of increased atmospheric CO_2

It is generally accepted that future increases in atmospheric CO_2 levels will be accompanied by a rise in the average global temperature. There is, however, uncertainty in regard to both the magnitude of this warming and to when the increase will be detectable. Most studies of this subject have used climate models to stimulate the CO_2-induced warming of the Earth. Currently, the most popular types are the General Circulation Models (GCMs). These are complex, three-dimensional atmospheric models which are considered to stimulate average climate conditions well, but to be less accurate in predictions of regional climatic change (NAS 1979). The results of most recent GCM investigations indicate that a doubling of the atmospheric CO_2 concentration from 300 to 600 ppm, if maintained indefinitely, will produce an average global warming of between 1.5 and 4.5°C, although values in the lower half of this range are most probable (NAS 1983). It is forecast that the greatest increases will occur in the higher latitudes, especially in the Northern Hemisphere.

It is conceivable that the consensus obtained between recent GCM studies may be spurious and could result from the common methodology employed by such investigations. In this respect, it is of interest to note that an independent approach, using radiation balance measurements, obtained a value of <0.26°C for the increase in temperature due to a doubling of the CO_2 level (Idso 1980). This study has, however, been widely criticized for several reasons, particularly for ignoring the feedback mechanism whereby greater evaporation from the oceans would cause an increase in the moisture content of the atmosphere, which in turn results in an enhanced "greenhouse effect" (Schneider, Kellogg and Ramanathan 1980).

Results from several GCM investigations indicate that a CO_2-induced increase in global temperature should already be detectable (e.g. Madden and Ramanathan 1980). Currently, however, there is no generally accepted evidence that such an increase has taken place. The detection of such an effect or "signal" is made difficult by the "noise" arising from the inherent variability of climate. This problem is exacerbated because attempts to detect such an effect have relied on observations of a single variable such as mean summer temperatures at a particular latitude. It has, therefore, been proposed that physical as well as statistical evidence should be sought, such as the relationship between tropospheric and stratospheric temperatures (Madden and Ramanathan 1980). In addition, a critical examination of GCM studies (Schlesinger 1983) revealed that the predicted time when a CO_2-induced warming will be detectable is highly dependent on the assumed rate at which heat is exchanged between the oceanic mixed layer and the deeper ocean. This uncertainty needs to be reduced to allow better predictions of the time of first detection.

Regional impact of increased global temperature

An important finding from GCM studies is that regardless of the reason for an increase in global temperature, there are general similarities in the pattern of climatic change. The regional implications of a global warming may therefore be assessed by reference to the past as a guide for future patterns of climatic change. Pollen records from one of the four warm epochs during the last 2.5 million years have been used to reconstruct rainfall patterns for different parts of the world (Kellogg 1978). The findings obtained have been criticized as the records are often poorly dated. The recent past, for which instrumental records are available, is considered to be a more useful guide for establishing possible patterns of climatic change. One such study (Wigley, Jones and Kelly 1980) compared conditions in the five warmest years between 1925 and 1974 with the five coldest in the period, using data from the high northern latitudes, the region where CO_2-induced changes are predicted to be greatest. Temperature increases were obtained for most regions, with maximal warming in the continental interiors at high latitudes. Estimation of the human and environmental consequences of such climatic changes can only be speculative and uncertain. Adverse effects in one part of the world may be compensated by a beneficial effect in another region (WCP 1981).

A warming of the globe will result in changes of wind strength and elevation over the oceans which may alter the location of areas of upwelling and cause shifts in the distribution of marine organisms and the consequent elimination of some commercial fisheries (Stewart 1980).

A global warming will also cause the thermal expansion of the oceans and the transfer of ice and snow from the land to the oceans, resulting in an increase in the sea level. It is not possible to predict the precise increase, but a recent study has forecast that a global warming of about 3 or 4°C over the next 100 years will cause an increase in the sea level of about one metre (NAS 1983). Another study predicts a global rise of sea level of between 144 cm (4.8 ft) and 217 cm (7 ft) by 2100 as most likely, although a global rise as low as 56 cm (1.9 ft) or as high as 345 cm (11 ft) cannot be ruled out (EPA 1983).

Control strategies

It is difficult to suggest specific actions to alleviate the CO_2 problem when so many uncertainties surround the issue. However, if there is a consensus that CO_2 accumulation requires control, then two broad strategies can be considered. The first involves the use of technological countermeasures to collect CO_2 from the air, or from the flue gases of power stations. A detailed assessment of such an approach (Albanese and Steinberg 1980) concluded that the various techniques available were not practical because of the large energy costs involved. It must also be borne in mind that the expertise for such techniques is located in the developed countries, yet future energy growth is expected to be greatest in the developing nations.

The second approach to this problem is a preventive strategy, to reduce CO_2 releas from energy production. A policy of drastically restricting the consumption of fossil fuels is not considered to be practical at the present time, as other forms of energy could not meet the increased demand (Smith 1982). Nevertheless, an expert group on energy demand and supply recommended a "low-climate-risk energy policy" requiring the development of alternative energy systems which do not release CO_2 to the atmosphere (Bach, Pankrath and Williams 1980). The adoption of alternative energy systems would, however, entail additional risks whose nature and magnitude are not always well known. It would, therefore, be beneficial to conserve energy from conventional sources as a means to reduce CO_2 release. Studies from several countries reveal that large savings in energy wastage can, or already have been, made (Kellogg and Schware 1981).

It must be stressed that any effort to minimize the impact of atmospheric CO_2 accumulation should involve the improvement of world agriculture. In this way, it will be possible to reduce the vulnerability of agricultural systems to climatic change. This is a dual-benefit approach, as the climate will fluctuate whether there is CO_2 accumulation or not. An increase in agricultural resilience would result from the protection of soils by improved land management practices and the development of cultivars which are adapted to a wide range of climatic conditions (Schneider and Bach 1980).

APPENDIX 5

International organisations and information centers

Scientific Committee on Problems of the Environment (SCOPE)

SCOPE is one of the 10 scientific committees established by the International Council of Scientific Unions (ICSU). Currently, representatives of 34 member countries and 15 Unions and Scientific Committees participate in the work of SCOPE.

The mandate of SCOPE is to assemble, review, and assess the information available on man-made environmental changes and the effects of these changes on man; to assess and evaluate the methodologies of measurement of environmental parameters; to provide an intelligence service on current research; and by the recruitment of the best available scientific information and constructive thinking to establish itself as a corpus of informed advice for the benefit of centres of fundamental research and of organisations and agencies operationally engaged in studies of the environment.

SCOPE's project on Biogeochemical Cycles has provided a forum to assess existing knowledge on the carbon cycle and to define fields of ignorance. The results and recommendations of a six day workshop (held in 1977 at Ratzeburg, FRG and financially supported by SCOPE, UNEP, the Research Council, the University of Hamburg and Shell), have been laid down in SCOPE Report 13, i.e. The Global Carbon Cycle (1979).

Another relevant publication in this field is SCOPE Report 16, i.e. Carbon Cycle Modelling (1981).

The World Climate Conference of 1979, in Geneva (organised by WMO, UNEP and SCOPE-ICSU) resulted in a World Climate Programme (WCP). The WCP includes a study of impact analysis of a changing climate. A team of 26 authors from 16 countries, led by Robert W. Kates, is preparing a SCOPE report, which will be a prescriptive document for the design of climatic impact assessments.

SCOPE Secretariat
51 Boulevard de Montmorency
75016 Paris
France

World Meteorological Organisation (WMO)

Since a rapid shift in the 1970's from traditional meteorology towards a climatic focus, WMO concentrates on climatic themes. The climatic system is seen as an entire whole, involving interaction between atmosphere, ocean, biota, soils, rocks, ice and human society. WMO's conversion culminated in the World Climate Conference of 1979, in Geneva (organised by WMO, UNEP and SCOPE-ICSU), which concentrated attention on the links between society and variable climate.

Out of this conference came a World Climate Programme, with four component programmes:

- The World Climate Application Programme (WCAP) "to assist societies to improve their capabilities to carry out various activities and to obtain maximum economic and social benefit under different climatic conditions, while maintaining environmental integrity".
- The World Climate Research Programme (WCRP) "to what extent of man's influence on climate".
- The World Climate Impact Studies Programme (WCIP) "the basic studies should aim at an integration of climate, ecological and socio-economic factors which enter into the complex problems facing society, in particular those relating to food, water and energy".
- The World Climate Data Programme (WCDP) "to ensure availability of reliable climate data which are accessible and exchangeable in an acceptable form and time, as required in climate research, applications and impact studies".

WMO
P.O. Box 5
Geneva 20
Switzerland

International Carbon Unit (ICU)

In cooperation with SCOPE/UNEP an International Carbon Unit has been established at the University of Hamburg, aimed at the collection of information on the carbon cycle. The ICU is headed by Prof. Dr. Egon T. Degens. Sub-units are located at the Vrije Universiteit of Brussels (cartography), the University of Stockholm (atmospheric systems and models), the University of Essen (socio-economic aspects) and in Woods Hole Mass. (land biota).

Prof. Dr. Egon T. Degens
Geologisch-Paläontologisches Institut
Universität Hamburg
Bunderstrasse 55
200 Hamburg 13
FRG

Global Environmental Research Organisation (GERO)

Italian and American scientists agreed at the end of October 1985 to set up a new international research institute (GERO) on an island in the Venice lagoon. It will be the first to be dedicated to global, interdisciplinary studies of the environment. Study themes will cover energy flow through the biosphere, including climatic linkages between atmosphere and ocean, biogeochemical cycles, ranging from acid rain, and greenhouse effect to oceanic sediments.

Carbon Dioxide Information Center (CDIC)

The CDIC supports the US carbon dioxide research program and cooperates in information exchange with the international scientific community addressing global atmospheric CO2 problems. CDIC is sponsored by the Department of Energy's (DOE) Carbon Dioxide Research Division and is administered by the Information Division at Oak Ridge National Laboratory.

- CDIC maintains a Bibliographic Information System containing over 7000 keyworded references.
- it maintains an International Directory of approximately 1700 CO2 researchers.
- it publishes CDIC Communications, a biannual newsletter that reports on many aspects of CO2-related research projects, events, meetings, and publications.

CDIC
Oak Ridge National Laboratory
P.O. Box x
Oak Ridge, Tennessee, U.S.

Canada

Environment Canada publishes a quarterly newsletter, CO2 Climate Report, that will stimulate as well as update CO2 information within the Canadian research community.

Atmospheric Environment Service
4904 Dufferin Street
Downsview, Ontario M3H 5T4, Canada

APPENDIX 6

Institutes involved in CO2/climate/greenhouse effect research

A. Use of theoretical climate system models

British Meteorological Office
Bracknell, U.K.
(B.J. Mason; J. Gilchrist)

Department of Atmoshperic Sciences
Oregon State University, Corvallis, Oregon, U.S.
(W.L. Gates)

Department of Meteorology
University of Stockholm, Stockholm, Sweden
(B. Bolin)

Department of Meteorology, U.C.L.A.
Los Angeles, California, U.S.
(Y. Mintz; A. Arakowa)

Geophysical Fluid Dynamics Laboratory
NOAA, Princetown, New Jersey, U.S.
(S. Manabe; K. Bryan; R.T. Wetherald)

Goddard Space Flight Center
Greenbelt, Maryland, U.S.
(M. Hallion; Y. Mintz)

National Center for Atmospheric Research
Boulder, Colorado, U.S.
(W.M. Washington; R.E. Dickinson; W.W. Kellogg)

B. Reconstruction of real climatic change of the past

1. Instrumental record and paleoclimatology

Climate Research Unit
University of East Anglia, Norwich, U.K.
(T.M.L. Wigley; H.H. Lamb)

Institute for Environmental Studies
University of Wisconsin, Madison, Wisconsin, U.S.
(J.W. Kutzbach; R.A. Bryson)

Meteorological Institute
University of Bonn, Bonn, F.R.G.
(H. Flohn; S. Nicholson)

2. Instrumental record

Climatic Diagnostic Center, NOAA
Suitland, Maryland, U.S.
(D. Gilman)

CSIRO, Melbourne, Australia
(B.W. Pittork, B. Tucker)

Department of Meteorology
M.I.T., Cambridge, Massachusetts, U.S.
(R. Newell)

Department of Meteorology
University of Stockholm, Stockholm, Sweden
(S-A. Odh; J. Heintzenberg)

Department of Meteorology
Colorado State University, Fort Collins, Colorado, U.S.
(E. Reiter)

Environmental Data Service and Air Resources Laboratory, NOAA
Silver Spring, Maryland, U.S.
(J.M. Mitchell; J.K. Angell; K. Korchover)

National Center for Atmospheric Research,
Boulder, Colorado, U.S.
(H. van Loon; R.L. Madden)

3. Paleoclimatology

Arctic and Alpine Institute
University of Colorado, Boulder, Colorado, U.S.
(J. Ives; J. Andrews; N. Nichols)

Brown University
Providence, Rhode Island, U.S.
(J. Imbrie)

Geologisch-Paläontologishes Institut
University of Hamburg, Hamburg, F.R.G.
(E.T. Degens)

Lamont Geological Observatory
Columbia University, Palisades, New York, U.S.
(G. Kukla)

C. Sources and sinks for CO2 in the biosphere

Department of Theoretical Production Ecology
Agricultural University, Wageningen, The Netherlands
(J. Goudriaan)

CSIRO, Canberra, Australia
(G. Pearman)

Duke University
(K.R. Kramer)

Lawrence Livermore Labs
California, U.S.
(G. Bingham)

Marine Biological Laboratory
Woods Hole Oceanographic Institute, Massachusetts, U.S.
(G.M. Woodwell)

NOAA Research Labs
Boulder, Colorado, U.S.
(B. Bean)

University of Nebraska, Lincoln
(S.B. Verma; N.J. Rosenberg)

D. Biomass production

University of Ghent, Belgium
(R. Lemeur)

University of Antwerp, Belgium
(I. Impens)

University of California, Berkely, California, U.S.
(M. Calvin)

U.S. Forest Service, Rhinelander, Wisconsin, U.S.
(D. Dawson)

E. Crop modeling related to CO2 and climate change

Crop Simulation Research Unit
Mississippi State College, Mississippi, U.S.
(D.N. Baker)

Department of Agricultural Engineering
Clemson University, South Carolina, U.S.
(J. Lambert)

Evapotranspiration Laboratory
Kansas State University, Manhattan, Kansas, U.S.
(E.T. Kanemasu)

Temple, Texas
(G. Arkin)

University of Florida
(K. Boote)

University of Kentucky, Lexington
(W. Duncan)

University of Nebraska, Lincoln
(J. Norman; G. Meyer)

University of Wisconsin, Madison
(G. Cottam)

U.S. Department of Agriculture (USDA)
Ithaca, New York, U.S.
(T. Sinclair)

USDA
Temple, Texas, U.S.
(J.T. Ritchie)

U.S. Water Conservation Laboratory
U.S. Department of Agriculture, Phoenix, Arizona, U.S.
(S.B. Idso)

F. Social and economic consequences of climate change

Arbeitsgruppe Umwelt, Gesellschaft, Energie
University of Essen, Essen, F.R.G.
(K. Meyer-Abich)

Kennedy School of Government
Harvard University
(T.C. Schelling)

APPENDIX 7

Relevant publications (reports and books)

Andersen, N.R.; Malahoff, A. (eds)
The Fate of Fossil Fuel in the Oceans
Plenum Press, NY, 1977

Bach, W.
Our Threatened Climate: Ways of Averting the CO2 Problem through Rational Energy Use
Kluwer Acad. Publ., Hingham, MA, 1984

Bach, W. (ed.)
Carbon Dioxide: Current Views and Developments in Energy/Climate Research
Kluwer Acad. Publ., Hingham, MA, 1983

Bach, W.; Pankrath, J.; Williams, J. (eds)
Interactions of Energy and Climate
Reidel, Dordrecht, The Netherlands, 1980

Barth, M.C.; Titus, J.G. (eds)
Greenhouse Effect and Sea Level Rise: A Challenge for this Generation
Van Nostrand Reinhold, Florence, KY, 1984

Berger, A.L.; Nocolis, C. (eds)
New Perspectives in Climate Modelling
Elsevier, Amsterdam, The Netherlands, 1984

Bolin, B.
Carbon Cycle Modelling
Scope Report 16, Wiley, NY, 1981

Bolin, B.; Degens, E.T.; Kempe, S.; Ketner, P. (eds)*
The Global Carbon Cycle
Scope Report 13, Wiley, NY, 1979

Carbon Dioxide Assessment Committee
Changing Climate
National Academy Press, Washington, DC, 1983

Clark, W.C. (ed.)
Carbon Dioxide Review: 1982
Oxford Univ. Press, NY, 1982

Cushing, D.H.
Climate and Fisheries
Academic Press, NY, 1983

Geophysics Study Committee (GSC)
Energy and Climate
National Academy Press, Washington, DC, 1977

Häfele, R.*
Energy in a Finite World. A Global Systems Analysis
Ballinger Publ. Co., Cambridge, MA, 1981

Hill, A.E.
Atmosphere - Ocean Dynamics
Academic Press, NY, 1982

Houghton, J.T. (ed.)
The Global Climate
Cambridge Univ. Press., NY, 1984

Idso, S.B.*
Carbon Dioxide: Friend or Foe?
IBR Press, Tempe, Arizona, 1982

Jäger, J.
Climate and Energy Systems: a Review of their Interactions
Wiley, NY, 1983

Kellogg, W.; Schware, R.
Climate Change and Society: Consequences of Increasing Atmospheric Carbon Dioxide
Aspen Institute, Boulder, CO, 1981

Lemon, E.R.
CO2 and plants: The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide
West View Press, Boulder, CO, 1983

Liss, P.S.; Crane, A.J.*
Man-Made Carbon Dioxide and Climate Change: A Review of the Scientific Problems
GEO Books, Norwich, England, 1983

MacDonald, G.J. (ed.)
The Long-Term Impacts of Increasing Atmospheric Carbon Dioxide Levels
Ballinger, Cambridge, Mass, 1982

McBeath, J.H.; Juday, G.P.; Weller, G.; Murray, M. (eds)
The Potential Effects of Carbon Dioxide-Induced Climatic Changes in Alaska
Univ. of Alaska, School of Agriculture and Land Resources Management
Miscellaneous Publication 83-1, Fairbanks, AK, 1984

National Research Council (NRC)
Carbon Dioxide and Climate: a Scientific Assessment
National Academy Press, Washington, DC, 1979

National Research Council
Energy in Transition 1985-2010
Final Report of the Committee on Nuclear and Alternative Energy Systems (CONAES)
W.H. Freeman, San Fransisco, 1979

National Research Council
Carbon Dioxide and Climate: a Second Assessment
Report of the CO2/Climate Review Panel, J. Smagorinski, chairman
National Academic Press, Washington, DC, 1982

Oerlemans, J.; Van der Veen, C.J.
Ice Sheets and Climate
Kluwer Acad. Publ., Hingham, MA, 1984

Organisation for Economic Cooperation and Development / International Energy Aency Workshop on Carbon Dioxide Research and Assessment
Paris, OECD/IEA, 1981

Seidel, S.; Keyes, D.
Can we Delay a Greenhouse Warming?
U.S. EPA, Washington DC, 1983

Smith, I.M.
Carbon Dioxide from Coal Utilization
Technical Information Service, International Energy Agency, Paris, 1982

Smith, I.M.
Carbon Dioxide-Emission and Effects
Report No. ICTIS/TR18, IEA Coal Research, London, 1982

Sundquist, E.T.; Broecker, W.S. (eds)
The Garbon Cycle and Atmospheric CO2: Natural Variations Archean to Present
American Geophysical Union, Washington, DC, 1985

Tucker, G.B.
The CO2-Climate Connection
Australian Academy of Science, Canberra, 1981

UNEP
Meeting of the Scientific Advisory Committee of the World Climate Impact Studies Programme
Nairobi, 23-27 February, 1981

US-DOE
Carbon Dioxide Effects Research and Assessment Program
Series of Publications by the US Department of Energy, CONF-7904143, 1980

Van Loon, H. (ed.)
Climates of the Oceans. Vol. 15, World Survey of Climatology
Elsevier, Amsterdam, The Netherlands, 1984

WMO/ICSU/UNEP
On the assessment of the role of CO_2 on climate variation and their impact
(based on meeting of experts, Villach, Austria, November 1980)
World Meteorological Organization, Geneva, January, 1981

World Meteorological Organization (WMO)
World Climate Conference: extended summaries of papers and declarations
WMO, Geneva, 1979

* Books recommended for general reading.

APPENDIX 8

Visit to Climate Research Unit, 27.11.1985

Meeting with Dr. T.G. Wigley, Director.

The CRU made a study of the greenhouse effect for Shell in about 1981 on the basis of a grant for £10000. This was subsequently extended for the US DOE and was published by them in August 1984 (I was given a copy of the report).

I found Wigley very much had his feet on the ground and was at great pains to emphasise the uncertainties that still exist in this area and the time needed before which it will be possible to reach any very definite conclusions about the greenhouse effect. Having said that, he was prepared to stick his neck out and say that there has been a global warming over the last 100 years, that the 0.5 degrees (range 0.3-0.7) increase is a result of CO2 build-up, that we will see a further 1-2 degree warming over the next 40 years and that the warming will be greater in higher latitudes and more in winter than in summer. Such a rise would be greater than any change in the last 1000 years - at the peak of the last ice age (18000 years ago) the global mean temperature was 4 degrees lower than at present.

The global mean sea level has risen by some 15cm over the last 100 years, one third due to expansion of sea water and one third due to the melting of land ice (the melting of sea ice has no effect on sea level). A 4 degree warming might result in the disappearance of all Atlantic sea ice in the summer months. By 2050, the range of uncertainty of the rise in global mean sea level is 20-120cm.

On a time scale of decades, the role of the oceans as a thermal buffer is as important as the atmosphere and we are not capable at present of modeling the ocean or its coupling with the atmosphere. It is possible that the negative feedback of this coupling could wipe out the forecast rise. The movement of the sea ice boundary and the deep water formation affect the atmosphere and European climate very sensitively to the extent that Europe saw a cooling from 1040 to 1970 while the global mean temperature was static or rising. It is very difficult to model the ice movement which is mostly responding to water movements from below.

While most people agree that the warming will be amplified at higher latitudes this has not been measured because it has been countered by the cooling in the N. Atlantic region.

By the turn of the century we will have a much better idea of what caused past changes - our monitoring of the upper atmosphere, the oceans and solar output will have improved immeasurably. For example, only since the late fifties have we had data that will allow the modeling of the atmospheric behaviour in three dimensions the data suggests that while the lower atmosphere is warming, the upper is cooling.

Wigley is very interested in the effects of trace gases. He believes that it is not realistic to make policy decisions aimed at reducing the effect of CO2 but that we might reasonably do so for the trace gases. On a one-dimensional (global averaging) basis, the overall effects of chlorofluorocarbons, nitrous oxide, methane and ozone are roughly the same as CO2. In a two dimensional model the effects might be slightly less but there is not enough data to be certain. This is another area where will be much better informed in the next 10-15 years.

Water vapour alone has a positive feedback but there is great uncertainty about the effect of clouds. These can be both positive and negative, trapping heat and reflecting incoming radiation. Further, the effects of the same types of clouds can be different at different latitudes. Next to the ocean, this is the biggest uncertainty. For example, we are only now beginning to model the physics of the passage of radiation through clouds.

The most difficult effect of a global warming to predict is that on rainfall. Dynamic climatology is, after all, a very new science! In high latitudes (60-70 degrees, for example), rainfall ought to increase just because of the raised temperature; we may, after all, be doubling the water vapour content. Monsoon rainfall ought to increase also as should the frequency of tropical storms which is again a temperature dependent phenomenon. It is much more difficult to say anything about the mid-latitude drying forecast by some modeling and even more so to make sensible comments on possible changes in equatorial regions.

M.H. Griffiths

28th November 1985.