Ciba Foundation Symposium 175

EUROPEAN ENVIRONMENTAL RESEARCH ORGANISATION

ENVIRONMENTAL CHANGE AND HUMAN HEALTH

A Ciba Foundation Symposium
jointly with the European Environmental Research Organisation

A Wiley-Interscience Publication

1993

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ENVIRONMENTAL CHANGE AND HUMAN HEALTH

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Introduction

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A meeting on Environmental Change and Human Health is timely. Almost every day news reaches us of famines, of areas newly heavily polluted where the people's health is affected by contaminated air or drinking water, of the degradation of stratospheric ozone, and of the increase in CO_2 in the atmosphere and consequent higher temperatures on earth. Scenarios about environmental and human future are painted, ranging from frightening to reassuring. Besides these scenarios are predictions of an explosive growth in world population, which raise questions about how we are to feed and provide shelter for this growing population without exhausting fundamental resources.

Against this background, the Ciba Foundation and the European Environmental Research Organisation (EERO) agreed to hold a joint symposium on various aspects of the changing environment and human health. The combination of these two organizations was perfect—the Ciba Foundation with its special emphasis on advancing cooperation in medical, chemical and biological research, and EERO with its programme to promote the most effective use of intellectual and technological resources and to stimulate interdisciplinary collaboration in environmental research and on environmental issues.

This symposium brings together scientists from a range of disciplines, including physics, chemistry, biology, agriculture and medical science, to discuss the various questions related to the theme of environmental change and human health. The discussions should be used not only to define current knowledge better, but also—and I consider this to be more important—to find new solutions, and where new solutions cannot be identified, to highlight crucial research areas and directions. Ladies and gentlemen, let us start with our work.

CO_2 and the greenhouse effect: present assessment and perspectives

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Abstract. Our present knowledge on the increasing greenhouse effect is based on the 1990 assessment of the Intergovernmental Panel on Climate Change (IPCC) and its 1992 supplement. Model predictions suggest that a doubling of atmospheric CO_2 concentration would increase global temperature by 2–4 °C. Because time is needed for the upper layers of the oceans to warm up, there is a delay between the realized increase and the estimated equilibrium increase. The 0.5 °C increase in global temperature over the past 100 years is in accordance with model predictions but also within the range of natural variability. The IPCC's assessment suggests that if fossil fuel consumption continues according to a 'business as usual' scenario, global temperature will increase at 0.3 °C per decade; droughts, flooding and storms would become more frequent and more severe, and sea-level would continue to rise. Analysis of gas in ice cores from Antarctica and Greenland provides estimates of CO_2 concentrations in pre-industrial ages; accurate measurement of atmospheric CO_2 began in 1958. Atmospheric CO_2 concentration has increased from 280 p.p.m. in AD 1800 to 355 p.p.m. at present. Between 1945 and 1973 global emissions of CO_2 increased at a rate of 4.4% per year; after 1973 the rate of increase decreased to 1.6% per year. This change permits a test of the CO_2 model. Reconstructed CO_2 emission agrees within less than 10% with estimated fossil fuel-generated CO_2 emission; contributions to CO_2 emission from non-fossil fuel sources must be smaller than assumed previously. There are strong indications that in the past changes in atmospheric greenhouse gas concentrations inherent to the glacial–interglacial cycles did play an important climatic role. For example, they were probably responsible for interhemispheric coupling during the major climatic changes. Measures which might stabilize the greenhouse effect include energy conservation and improved energy efficiency, a transition to hydrogen rather than carbon as a source of fuel, and reforestation.

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Roughly 30% of the solar energy falling onto the earth is reflected directly back into space; 20% is absorbed by the atmosphere and 50% by the ground (Fig. 1). With an average temperature of 15 °C (288 K) the surface of the earth and the air near the ground emit infrared radiation. Whereas the cloud-free atmosphere is almost transparent for the incoming solar radiation, most of the emitted

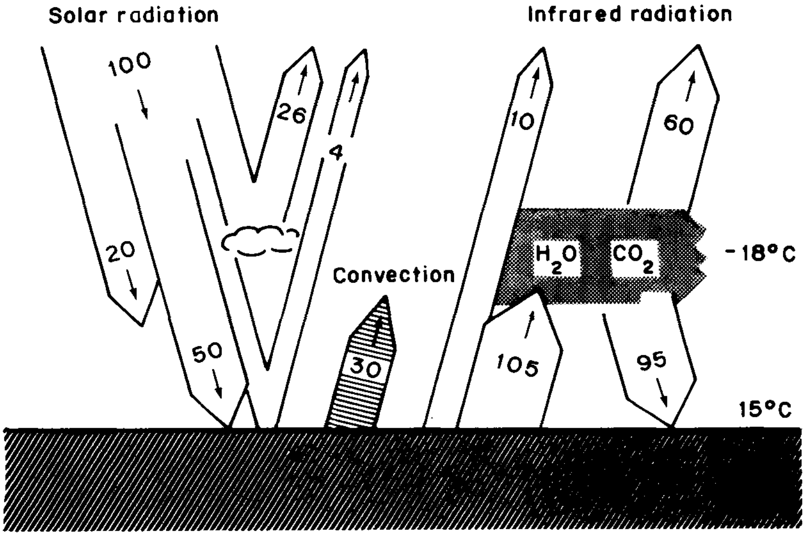


FIG. 1. The energy budget of the earth. Solar irradiation = 100 units. *Left*, solar radiation; *right*, infrared radiation. The infrared radiation emitted from the atmosphere to the surface (95 units) exceeds the absorbed solar radiation (70 units).

infrared radiation is absorbed by water vapour, CO_2 and trace gases. Part of the absorbed energy is re-emitted back to the ground. This increases the temperature of the earth's surface and the air near the ground above that produced by the absorption of solar energy alone.

This warming of the ground is called the greenhouse effect. For a radiation equilibrium to be established at the top of the atmosphere, the temperature of the surface and the near-ground atmosphere must be high enough to result in emission of infrared radiation corresponding to 115% of the solar energy falling on the earth, in spite of the fact that only 70% of the solar energy is absorbed. The temperature of the near-ground air is 15 °C, 33 °C higher than the planetary temperature (as derived from the emission at the top of the atmosphere).

Satellite observations have allowed us to determine the greenhouse effect on Venus and Mars; the temperature increases found are compatible with the greenhouse theory.

Changes of the greenhouse effect and their consequences

If the atmospheric concentrations of CO_2 and other greenhouse gases increased, initially less infrared radiation would be released to space and the radiation balance at the top of the atmosphere would be disturbed. The surfaces of the continents and the oceans, as well as the low air masses, would then become warmer and emit more and more infrared radiation until a new radiation equilibrium became established.

Detailed calculations show that for a doubling of CO_2 (or the radiative equivalent) the emission of infrared radiation to space is reduced by about $4\,W/m^2$. To compensate for this loss in emission the surface of the earth and the near-ground air layers need to heat up by 1.2 °C. This temperature increase is termed the primary forcing for a CO_2 doubling. It is a well-assessed quantity.

Feedbacks

A change in the temperature of the earth's surface induces a series of feedback effects which amplify the primary forcing. These feedbacks are summarized in (1). The absolute humidity increases and reinforces the

$$\Delta T = 1.2\,°C \times \frac{1}{1 - 0.4(H_2O - \text{Vapour}) - 0.1(\text{Snow, Ice}) - (0.2 \text{ to } -0.1\,[\text{Clouds}])} \tag{1}$$

greenhouse effect, and the back-scattering of solar radiation is amplified because of the decrease in the snow and ice cover. Both these feedback effects are positive. Less is known about the feedback effect of changing cloud cover; it can be positive (clouds in higher, colder layers which emit less infrared radiation) or negative (higher water content leading to brighter clouds).

Equation (1) suggests there would be a temperature increase (ΔT) of 2–4 °C in response to a doubling of CO_2. The estimates obtained with general circulation models (GMCs) are also in this range (Intergovernmental Panel on Climate Change [IPCC]; Houghton et al 1990, 1992).

Equilibrium and realized temperature increases

The lower atmospheric layers are strongly coupled to the surface of the oceans and, because of ocean mixing for the present rate of increase of the greenhouse forcing, the equivalent of an ocean layer several hundred metres deep needs to be warmed up. (For comparison, the heat capacity of the atmosphere corresponds to that of an ocean layer approximately two metres deep). For this reason, the realized atmospheric temperature increase lags behind the equilibrium temperature increase, and for the present rate of increase corresponds to only 60% of the equilibrium value. In addition, the warming is expected to show an ocean–continent asymmetry, the temperature increase over the oceans lagging behind that over the continents.

Sea-level rise

The temperature increase of a relatively thick ocean layer leads, because of thermal expansion, to a rise in sea-level. The thermal expansion coefficient depends on the temperature of the water. It is significantly greater for warm surface water of low latitudes than for the cold water which sinks at high northern latitudes of the Atlantic ocean to the deep sea and then flows to the south. In estimating the sea-level rise caused by thermal expansion it is therefore important to consider how the excess heat penetrates the ocean. A substantial part of the excess heat is thought to be transported with cold water into deeper ocean layers.

Even more difficult than estimating the sea level rise caused by thermal expansion is predicting the effects of melting of continental ice. It is believed that the ablation of ice in the Greenland ice sheet will increase. Accumulation in the interior part is also expected to increase because of increased precipitation, which should compensate for part of the loss of land ice in the marginal zones. For the Antarctic ice sheet, an initial increase in accumulation seems likely. In the longer term, over centuries, instability in parts of the ice sheet could have drastic consequences for sea-levels.

Biotic feedback effects

It is difficult to estimate the feedback effects on climate resulting from changes in the sources and sinks of greenhouse gases. Important information can be obtained by using ice core analysis to reconstruct the history of atmospheric greenhouse gas concentrations. The atmospheric concentrations of CH_4 and N_2O are positively correlated with global temperature, a strong indication of a positive feedback effect in the context of global warming. The relationship between CO_2 and temperature is more complex. Hitherto, biotic feedback has not been quantitatively considered in the estimates of future climate.

Increases in the greenhouse effect

The temperature increase of the past hundred years

The trend in global temperature over the last hundred years is shown in Fig. 2. The average yearly temperatures show variations of about ± 0.2 °C around the five-year average temperatures, but the latter also do not show a smooth trend. The variations can partly be explained by volcanic eruptions (Mount Agung in 1962 and El Chichón in 1982), which lead to increased atmospheric turbidity. Also, the El Niño southern oscillation phenomenon leads to small global temperature deviations, and also possibly smaller variations in solar luminosity. The eight warmest years of the entire observation period were in the 1980s and the beginning of the 1990s.

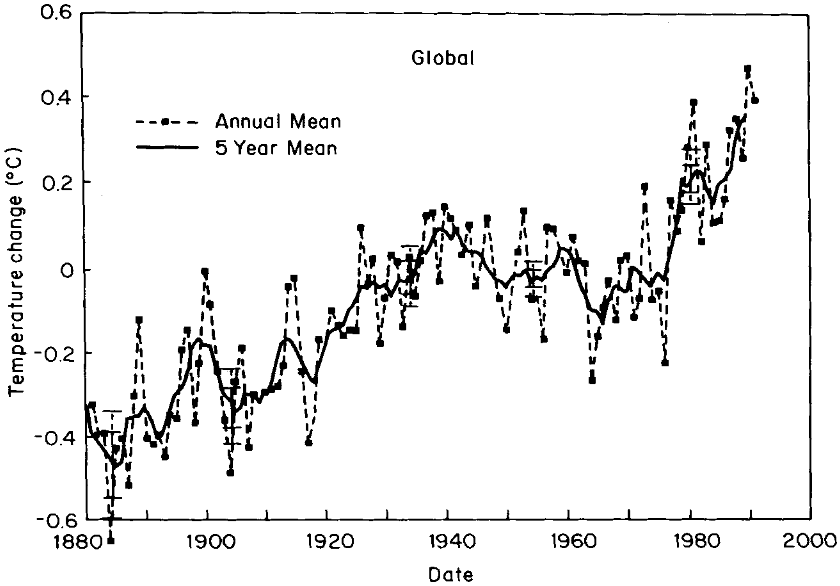


FIG. 2. Global temperature change; annual (-----) and five-year (——) means. Figure kindly provided by J. Hansen and H. Wilson, National Aeronautics and Space Administration Goddard Institute for Space Studies.

The observed increase in temperature of 0.5 °C over the past 100 years is in accordance with what one would expect on the basis of model calculations, but it is also still within the range of natural variability. The fact that one cannot yet unambiguously attribute this warming to the increasing greenhouse effect does not mean that scientists do not agree that the identified increase of the greenhouse forcing will lead to global warming in the range given above.

The increase in atmospheric CO_2 since AD 1800

Continuous high precision measurements of atmospheric CO_2 began in only 1958, at Mauna Loa, Hawaii, and at the South Pole. As shown in Fig. 3, CO_2 has increased from 315 p.p.m. to 355 p.p.m. at both stations. The pronounced seasonal variations, as observed at Mauna Loa, appear to be strongly dampened at the South Pole. Figure 4 shows in schematic form the exchange fluxes of atmospheric CO_2 with the carbon in the ocean and in vegetation and soils. During one year about a quarter of the CO_2 in the atmosphere is exchanged with the other reservoirs. This raises two questions: why can this system not buffer the relatively small CO_2 input generated by human activities, and do these large exchange fluxes between the reservoirs always balance each other out or are there periods of disequilibrium? If there are periods of

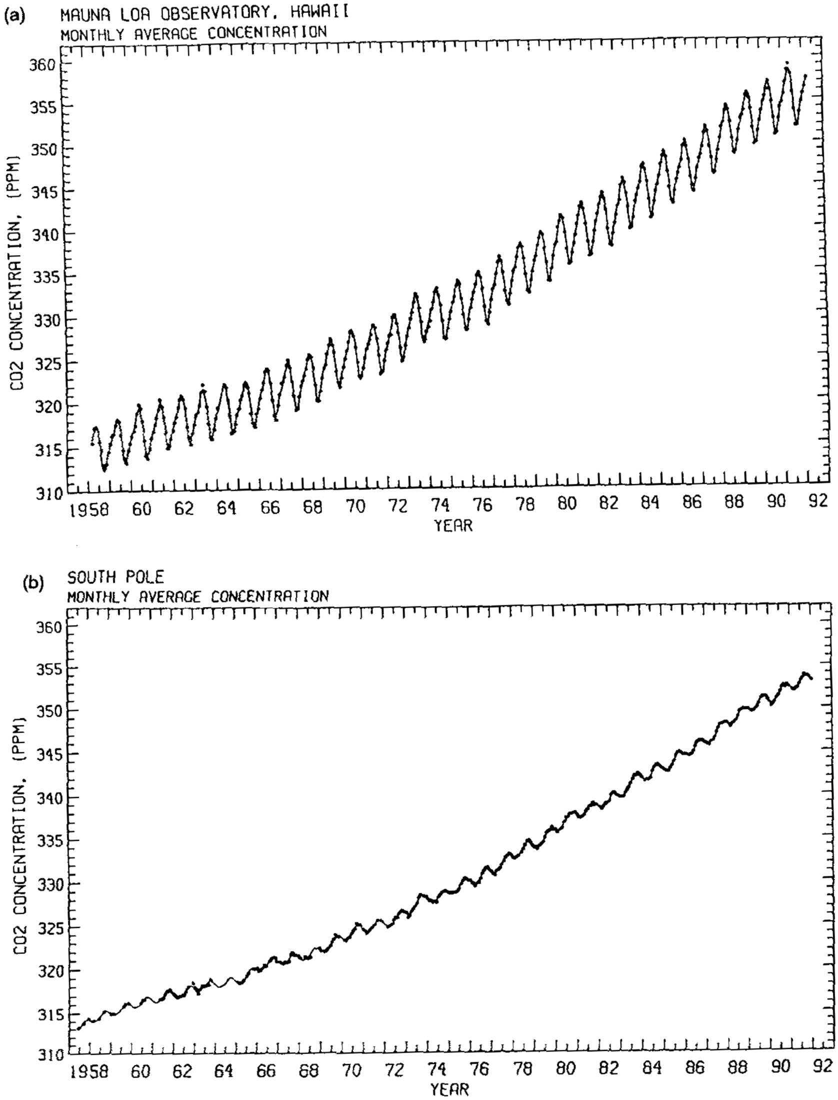


FIG. 3. Atmospheric CO_2 concentrations (p.p.m. dry air) from 1958 to 1992 measured at (a) Mauna Loa Observatory, Hawaii, and (b) at the South Pole. The dots indicate monthly average concentration. Figures kindly provided by C. D. Keeling and T. P. Whorf (Keeling et al 1989, 1987). Mauna Loa Observatory is operated by US National Oceanic and Atmospheric Administration (NOAA). The measurements were obtained in a cooperative programme between NOAA and the Scripps Institution of Oceanography.

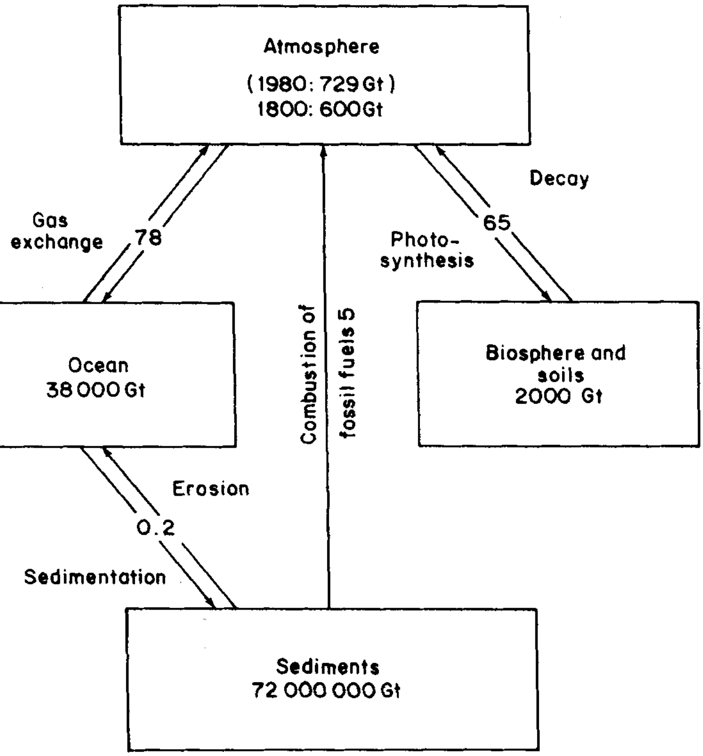


FIG. 4. The exchange of CO_2 between the atmosphere, the biosphere, oceans and sediments. CO_2 contents of the reservoirs are indicated in gigatonnes (Gt) C per year.

disequilibrium, could the recent CO_2 increase not reflect such a disequilibrium? To give convincing answers to these questions, one needs to reconstruct the history of atmospheric CO_2 concentrations from the pre-industrial age. It is possible to do this because air bubbles in natural ice constitute physically occluded samples of the ancient atmosphere. Atmospheric CO_2 concentrations of the past 200 years have been reconstructed from analysis of samples from an ice core retrieved at Siple Station, Antarctica (Neftel et al 1982, Friedli et al 1986). The concentrations reconstructed from the uppermost ice layers overlap with the Mauna Loa record (Keeling et al 1989). In the second part of the 18th century the CO_2 concentration was about 280 p.p.m. Analysis of another core at South Pole Station showed that during the last, pre-industrial, millenium the concentration of CO_2 was in the range 280–290 p.p.m. These data allow us to conclude unequivocally that the increase evident in the 19th century (compare also the direct atmospheric CO_2 measurements; Fig. 3) is a consequence of human impact on the biomass and of the later rapidly increasing use of fossil energy.

The prognoses of the assessment of the IPCC

Some of the important conclusions of the IPCC assessment are given below. The IPCC has assessed the relative contributions of anthropogenic greenhouse gases to the greenhouse forcing in 1990. The most important of these is CO_2, contributing 55%. The other gases and their relative contributions are: 11 and 12 chlorofluorocarbons (CFCs), 17%; other CFCs, 7%; nitrous oxide, 6%; and methane, 15% (Houghton et al 1990). The contribution of ozone is difficult to assess and is not considered. Figure 5a shows the assumed future increases of CO_2, CH_4 and CFC-11, on which the IPCC calculations of future climate forcing are based. The 'business as usual' scenario is coal-intensive, and under this scenario CFC emissions would be partly reduced. Under scenario B there would be a transition to fuels with higher H:C ratios (predominantly natural gas). Scenarios C and D involve a shift to renewable energies and nuclear energy. The increases of global temperature and sea-level predicted under the different scenarios are shown in Fig. 5b. If emissions continue at the present rate there would be an increase in global temperature of 0.3 °C per decade, whereas under scenario D the temperature increase would stabilize at 2 °C by the year 2100.

Temperature and greenhouse gas concentrations of the past 150 000 years

Figure 6 shows changes in atmospheric CO_2 and CH_4 concentrations and (Antarctic) temperature over the past 150 000 years. The deviations shown in temperature are roughly double those in global temperature derived from independent information. As indicated above, global climatic changes are coupled with changes in greenhouse gas concentrations. There is an amazingly good correlation between temperature and CH_4 concentrations, which varied by a factor of up to two over this period. Increasing global temperature probably increases the area of wetlands and thus leads to increased anaerobic decomposition and methane sources; during warmer periods methane may have been released in large quantities from thawing permafrost. The CO_2 concentrations also vary in parallel with temperature; the transitions from the coldest glacial temperatures to the warm interglacial ones are accompanied by drastic increases in CO_2. However, the relationship is more complicated; a kind of hysteretic effect is evident. This is probably caused by emission of CO_2 during (and after) climatic deterioration resulting from a decrease of terrestrial biomass, and by the uptake of CO_2 by a growing biomass during (and after) a considerable climatic improvement. Changes in ocean chemistry are probably the main driving force for the changes in CO_2. Particularly important are processes in the ocean surface in which the partial pressure of CO_2 is strongly affected by the biological pump (the sinking of organic particles to greater depth). Changes in the biological pump could result in large changes in

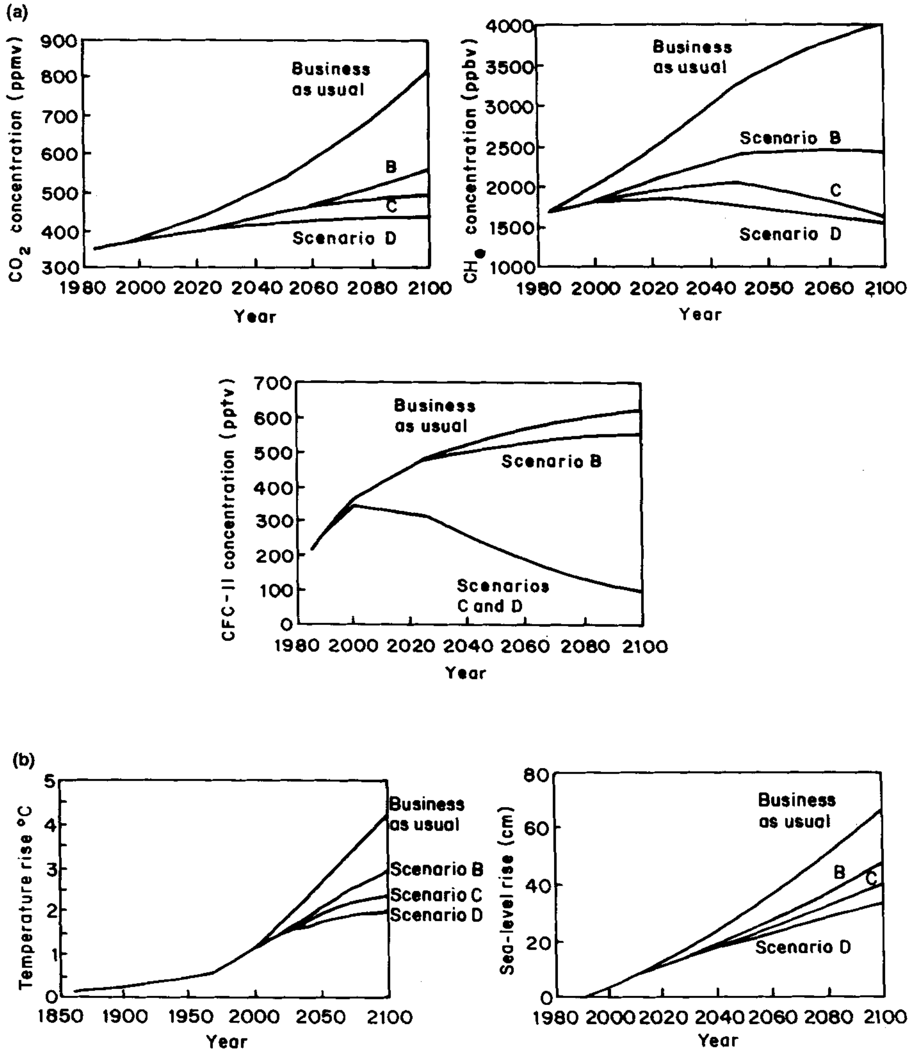


FIG. 5. The prognoses of the Intergovernmental Panel on Climate Change (IPCC). (a) The predicted atmospheric concentrations of *top left*, CO_2 (in parts per million by volume), *top right*, CH_4 (parts per billion by volume) and *middle*, chlorofluorocarbon (CFC)-11 (parts per trillion by volume) to the year 2100 under four different scenarios: the 'business as usual' scenario; scenario B, with a transition to fuels of higher H:C ratio; scenario C, with a transition to renewable energy forms and nuclear energy in the second half of the next century; and scenario D, involving renewable energy and use of nuclear energy in the first half of the next century. (b) The increase in temperature (*bottom left*) and sea level (*bottom right*) predicted under the four scenarios.

atmospheric CO_2: were all the nutrients in the surface ocean to be used up by organic processes, the partial pressure of CO_2 (in the water and in the atmosphere) would decrease to only 150 p.p.m. If there were no biological activity in the ocean surface, the partial pressure of CO_2 would rise to about 500 p.p.m.

A question often posed is, which was cause and which effect—the shift in temperature or that in the greenhouse gases (mainly CO_2) over the past 160 000 years? Present knowledge suggests the changes of temperature and greenhouse gases are due to interactive processes inherent to the climate system which lead to a positive feedback effect.

According to the theory of ice ages, one can consider the glaciations of the northern hemisphere as a result of changes in the orbital elements which induced ice cover over large areas of the continents, leading to a significantly enhanced albedo. It is, however, very difficult to understand why the temperature oscillations in the southern hemisphere were in parallel with those in the northern hemisphere. Global greenhouse gas variations might provide an explanation for this. They generate a forcing of 3 W/m^2, about three-quarters of that provided by a doubling of CO_2, during the transition from the coldest part of a glaciation to the following interglacial period. It thus seems probable that the climate of the past million years was strongly influenced by changes of the greenhouse effect (of the order of magnitude of those caused by humans). It is obvious that the interhemispheric coupling during a glaciation cycle is worthy of study; the changing greenhouse effect might have played a major role.

Further lessons from the past

How will climate change as a consequence of human activity, and how stable will future climate be? The analysis of ice cores from Greenland shows that between 80 000 BP and 30 000 BP the climate of the north Atlantic region oscillated more than a dozen times back and forth between a cold and a mild state, probably because of changes in ocean circulation patterns. In our present interglacial era climatic variability has been much less pronounced. How variable was climate during the last interglacial period, 120 000 to 130 000 years ago, when temperature was about 2 °C higher and sea-level about 5 m higher than at present? Does global warming lead to a more stable climate or to a period with strong climatic fluctuations? An indication of the answers to these questions will be obtained soon from the analysis of the newly drilled ice core from the summit of the Greenland ice sheet. One could imagine that in a warmer climate there could be more states of the earth system, and more transitions between them. This would be in disagreement with the observed strong climatic variability during the last interglacial era, but during a glaciation instabilities of the land ice could lead to an enhanced variability of the earth system.

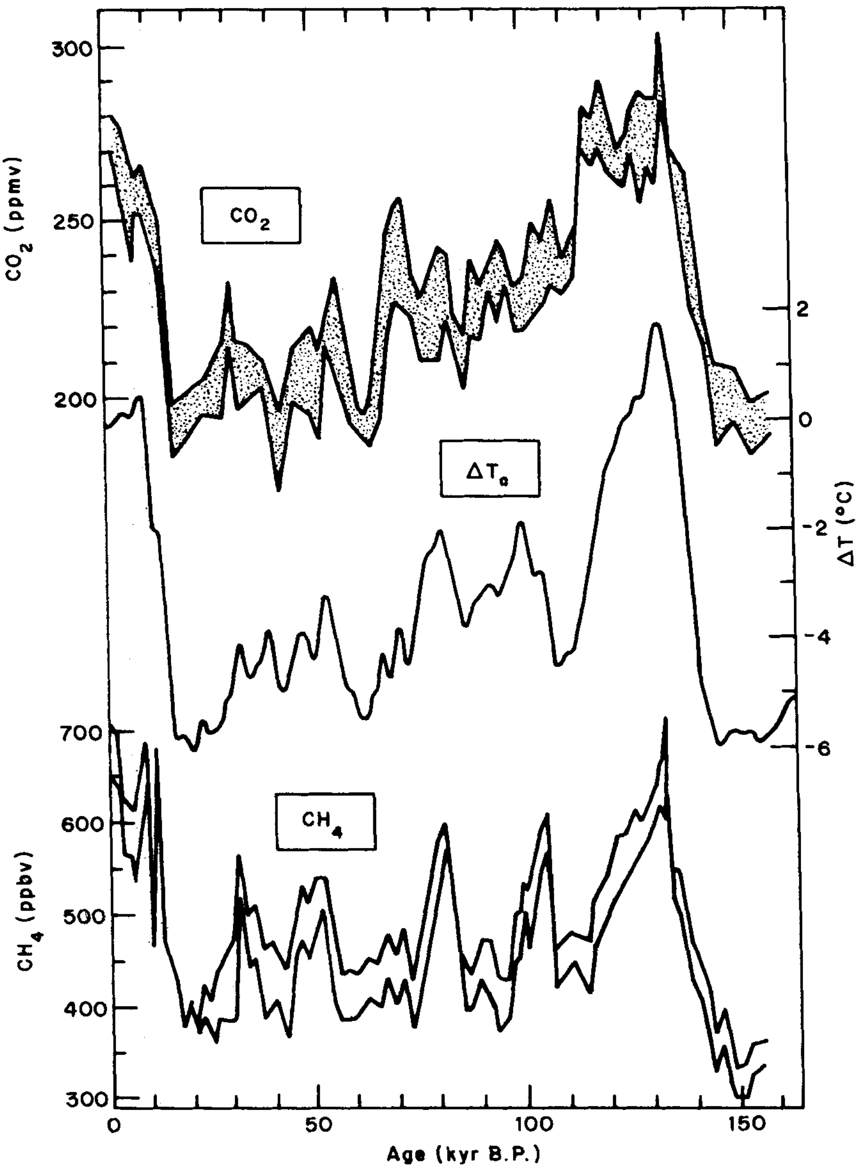


FIG. 6. Ice records from Vostok, Antarctica, for methane (Chappellaz et al 1990), deviations in isotope temperature above the inversion layer (as a difference from the present value of about −40 °C) and CO_2 (Barnola et al 1987). The CH_4 and CO_2 curves have been adjusted to fit the timescale given (taking into consideration gas occlusion time). Taken from Oeschger (1991), with permission. ©Cambridge University Press.

CO_2 emissions and their increase over the last few decades

Figure 7 shows a logarithmic plot of the estimated global emissions of CO_2 over the last four decades. From 1950 to 1973 the growth rate was essentially constant at 4.4% per year; it then decreased to 1.6% per year, on average. The present emission of CO_2 resulting from consumption of fossil fuels is about 6 Gt C per year. Had the high growth rate continued, this emission would have risen to 10 Gt C per year. This decrease in the rate of increase of CO_2 emissions is very important for attempts to stabilize atmospheric CO_2 concentration. If one aimed to stabilize atmospheric CO_2 at 420 p.p.m., i.e. 150% of the pre-industrial concentration, one would, according to the present models for CO_2 uptake by the ocean, need to reduce emissions from 6 Gt C per year to 3 Gt C per year by the year 2050, that is, by about 50%. Had emissions continued to increase at 4.4% per year, it would be necessary to reduce emissions from 10 Gt C per year to 2 Gt C per year, that is, by 80%. This clearly demonstrates that early action on control of CO_2 emissions is necesary, in

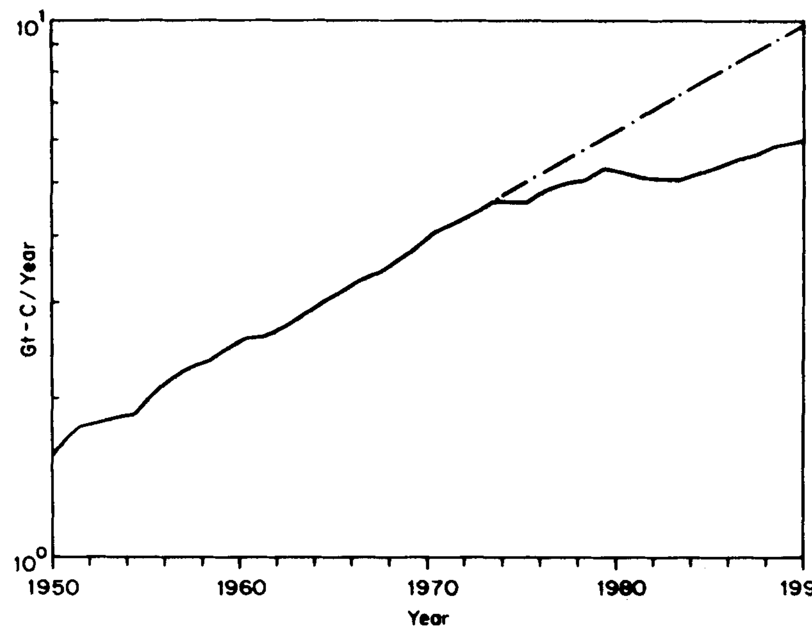
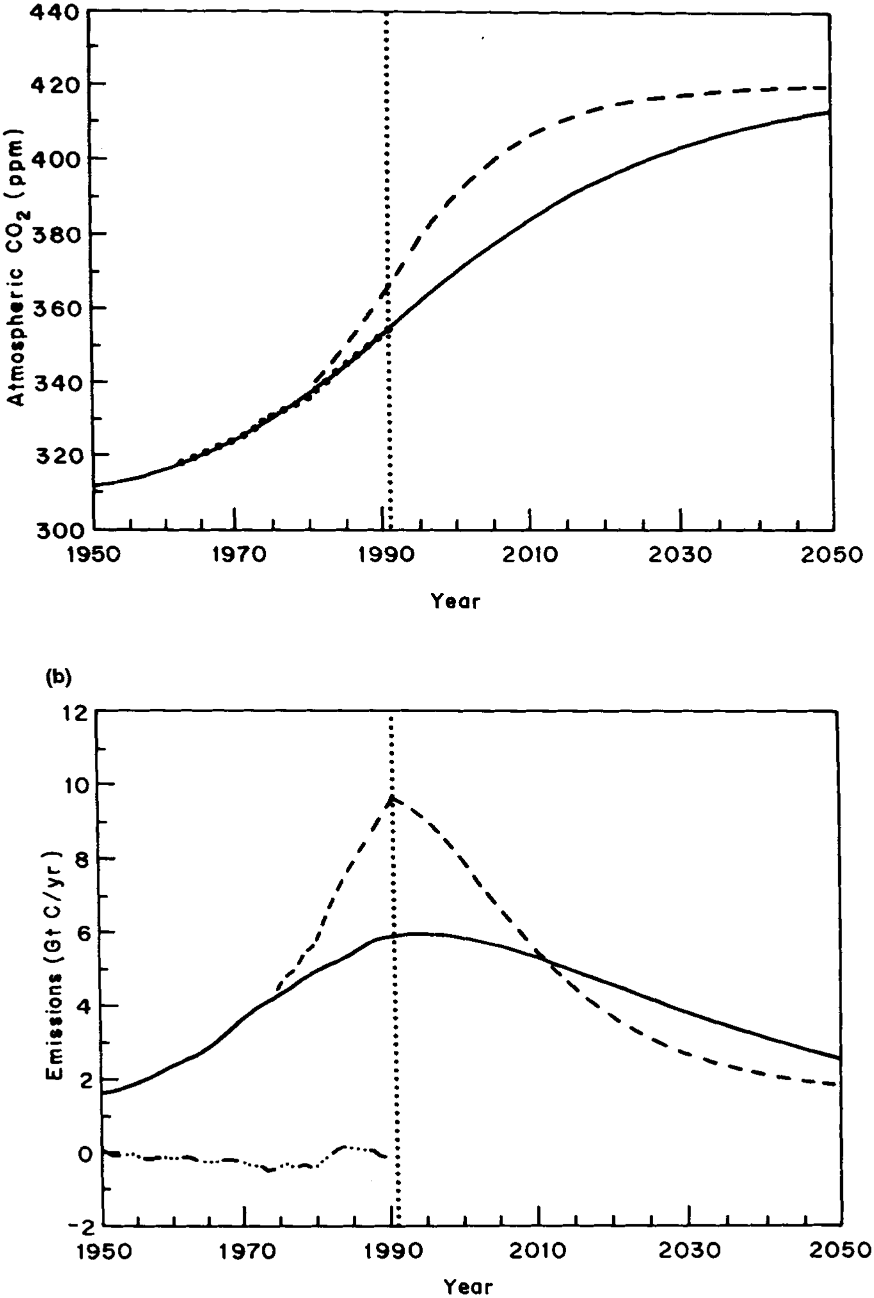


FIG. 7. Logarithmic plot of estimated CO_2 emission resulting from consumption of fossil energy from 1950 to 1990. Up to 1973, the rate of increase in emissions was 4.4% per year; between 1973 and 1990 the average growth rate was 1.6% per year (F. Joos, H. Oeschger & U. Siegenthaler, unpublished work). The dotted line shows the amount of CO_2 that would have been emitted had fossil fuel consumption continued to increase at a rate of 4.4% per year.

(a)

(b)


440
420
400
380
360
340
320
300
Atmospheric CO_2 (ppm)
1950
1970
1990
2010
2030
2050
Year
12
10
8
6
4
2
0
-2
Emissions (Gt C/yr)
Year

contradiction to the opinion of some that action is not urgent because CO_2 is a long-term problem!

The decrease in the rate of increase of CO_2 emission permits an interesting test of the CO_2 model and our present understanding of the perturbation of the carbon cycle by human activities. Figure 8 shows the measured atmospheric CO_2 concentration from 1945 to 1990. With a carbon cycle model describing the uptake of excess CO_2 by the ocean (calibrated on the basis of data about ^3H and ^{14}C produced by nuclear weapons and about CFCs in the ocean) the total (from fossil fuel consumption and the impact on the biomass) CO_2 emission history can be deconvolved from the observed CO_2 increase. The pattern of emission so generated agrees within better than 10% with the estimated fossil CO_2 emission over the entire period. The difference is small in comparison with the overall uncertainties. This result suggests that (i) the atmospheric CO_2 data and the estimates of emissions from fossil fuel consumption are in close agreement with reality; (ii) the CO_2 model fairly precisely describes CO_2 uptake by the oceans, including the shift to greater uptake during the period of lower growth; and (iii) the non-fossil contribution to CO_2 emissions is smaller than generally assumed. There is no indication of a large missing sink.

Measures to stabilize the greenhouse effect

Measures intended to reduce CO_2 emissions involve saving energy, increasing efficiency of energy use, a transition from carbon to hydrogen as a source of fuel, development and use of non-fossil energies and reforestation.

To what extent would reforestation compensate for CO_2 emission? Assume that during the next 40 years 10 million ha forest are planted every year. In 2030 40 million ha (100 times the area of Switzerland) of new forest would absorb 1 Gt C. The process would continue for about 40 to 100 years, until the trees had reached an equilirbium. According to this scenario, up to 2030 20 Gt C

FIG. 8 *(opposite).* (a) Atmospheric CO_2 concentrations measured at Mauna Loa, Hawaii (dots); the solid line is fitted to the data up to 1990 and then extrapolated up to the value of 420 p.p.m. The dashed line shows the increase that would occur if CO_2 emissions had continued to increase by 4.4% per year, then levels off at 420 p.p.m. (b) The solid line represents the deconvolved measured CO_2 increase (see solid line in [a]). The dashed/dotted line is the difference between the deconvolved emission and the estimated emission. The dashed line reflects the total emission that would have resulted had the high growth continued up to 1990. Between 1990 and 2050 the solid and the dashed lines represent the emissions corresponding to the projected atmospheric CO_2 concentrations shown in part (a) (F. Joos, H. Oeschger & U. Siegenthaler, unpublished work).

and in 100 years time some 80 Gt C could be fixed. This accumulation of CO_2 would, however, correspond to only 5–10% of the CO_2 emissions from fossil fuel consumption predicted under the IPCC's business as usual scenario.

In the past, various types of energy replaced one another (wood, carbon, petrol, natural gas). In the beginning of the 1970s it was expected that nuclear energy would, to a significant extent, replace fossil energy, but nuclear energy was considered to be too risky in most countries. An exception is France, where at present 80% of electrical energy is produced by nuclear power. It is interesting to compare France's CO_2 emissions with those of other Western countries which developed nuclear energy to a lesser extent, such as the USA. The difference is striking. CO_2 emissions from fossil fuel consumption in the USA have remained essentially constant, whereas from 1977 to 1987 they decreased in France, essentially because of the intensive use of nuclear energy, by 29%. This clearly contradicts some intellectual constructions which claim that nuclear energy would lead to an increase in CO_2 emissions.

Conclusions

If the emissions of greenhouse gases continue according to the IPCC's 'business as usual' scenario, global temperature in the next century would increase by as much as 0.3 °C per decade, a rate of change greater than any over the past 10 000 years. Droughts and flooding would become more frequent and more violent. Regions important for growing food for the world's population would become infertile, and others infertile at present would become fertile. Storm activity would become more intense and unexpected developments could have negative impacts on the survival of people in certain parts of the world. Sea-level would continue to rise.

Over the last years and months, doubts have been raised about the results of global change science and the validity of the IPCC's assessments. Science needs a continuous questioning of its results in order to make progress. However, the arguments and the criticisms raised are largely of mediocre quality and cannot put in doubt the essential conclusions of the scientific community who have been involved in this research for decades. It is sometimes argued that when we estimate the sum of the positive and the negative changes we may come to the conclusion that global warming would be beneficial; even if this were the case, would it be possible to make use of the positive developments in time to compensate for the negative ones? Already it is not possible for those suffering from famine to profit from the excess of food production in other areas. Divergence in living conditions will increase further, intensifying the problems of population migration. There is an urgent need to slow down global climatic change, but this is possible only if we have a sound economy. We have to find a way which minimizes both the stress on the environment and that on the economy. Technology and economy should take the lead in a move towards sustainable development.

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DISCUSSION

Edwards: Do ruminants make any appreciable contribution to methane emissions?

Oeschger: Detailed figures do not exist, but I think they are estimated to contribute about a quarter or so of the total production.

Hoffmann: The primary source of methane is rice paddy-fields. Anaerobic decomposition there provides the largest fraction of methane flux into the atmosphere. About 10 years ago the ruminant contribution was thought to be quite high, but after fairly careful and serious analyses in different locations around the globe, it was realized that ruminants contribute much less than previously thought (Cirerone & Oremland 1988).

de Haan: Waste disposal sites produce a substantial amount of methane. Is this negligible in comparison with other sources?

Hoffmann: Certainly. If you consider the acreage devoted to rice growing you realize this is the dominant global source.

Avnimelech: To what extent do wetlands contribute?

Hoffmann: They contribute about 115 teragrammes (Tg) per year to the methane flux. The people who do research on global change have gone out into the field and measured methane fluxes from each of these environments, and after about 10 years of this type of research they have been able to get pretty good measurements of the fluxes from different environmental settings and different situations.

Oeschger: The contribution from natural gas leakage, on the basis of carbon isotope studies, appears to be of the order of 20%.

Edwards: If the carbon atom in methane is oxidized to generate CO_2, is that better or worse for the environment? You pointed out that methane and CO_2 are both undesirable in excess. If you turn one into the other, which you do if you burn methane, is that good or bad?

Oeschger: Methane has an estimated mean life of about 12 years in the atmosphere, where it is burnt to CO_2 through chemical processes anyway. Per molecule, CH_4 has a much higher greenhouse effect than CO_2. Thus, by burning CH_4 into CO_2 one avoids this period (12 years) during which it has a high greenhouse effect.

Hoffmann: The concentration of methane in the atmosphere, 1.7 p.p.m. by volume, is much lower than that of CO_2, 350 p.p.m.v., so its relative contribution to CO_2 loading in the atmosphere is quite small.

Mansfield: Professor Oeschger, are you convinced that we know enough about the future production of N_2O? We are adding soluble nitrogen compounds to the atmosphere all the time in the form of NO_x and ammonia, which then get taken up by vegetation and deposited in leaf litter, and will contribute to future microbiological activity. Isn't it likely that by putting NO_x and ammonia into the atmosphere, which do not by themselves contribute much to the greenhouse effect, we might be appreciably accelerating the future production of N_2O? This might be some distance into the future, with a lag of 10 or 20 years or more, but that could be very important in view of the role of N_2O within the atmospheric window.

Oeschger: I agree. It's difficult to estimate what the increase will be. The problem of N_2O sources is very complex.

Lake: We have been reducing nitrogen from the atmosphere to produce nitrogen fertilizers for world agriculture. We will discuss population growth later, but it's worth pointing out here that to feed the extra people we will be combining atmospheric nitrogen in a form which could contribute to the greenhouse effect when later it's released .

Mansfield: That's essentially what's going on. On top of that is the production of NO_x during combustion processes.

Zehnder: How much N_2O or NO_x comes from agriculture and how much from combustion processes?

Mansfield: Over much of Western Europe, the rate of wet and dry deposition of nitrogen is about 40 kg/ha/year. About 60% of that comes from agricultural