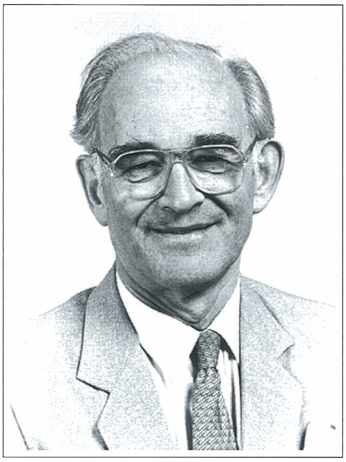
The Winners of the Blue Planet Prize
1995

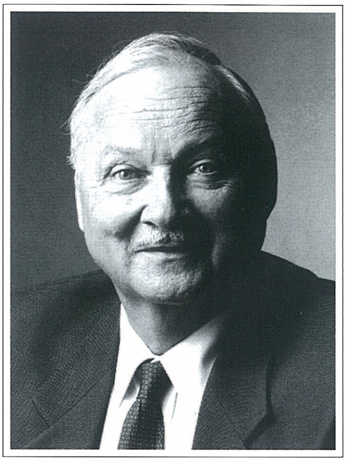
1995

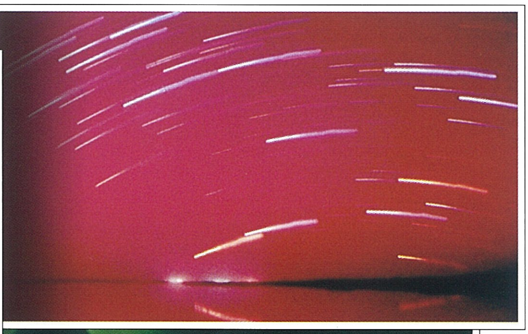
Blue Planet Prize

Dr. Bert Bolin
(Sweden)
Professor Emeritus at the University of Stockholm

Maurice F. Strong
(Canada)
Chairman of the Earth Council







As 1995 marked the 100th anniversary of the birth of Kenji Miyazawa, excerpts from his literary works on nature were featured in the 1995 awards ceremony slide presentation. The bountiful gifts of nature and humankind's hopes for the future were depicted in the photographs of Takeshi Hosokawa, an eminent nature photographer.

His Highness Prince Akishino congratulates the laureates.

His Highness Prince Akishino and Her Highness Princess Kiko at the congratulatory party.

The prizewinners receive their trophies and certificates of merit from Foundation Chairman Jiro Furumoto.

Dr. Syukuro Manabe, the first Blue Planet laureate, asks a question from his seat in the audience after Dr. Bolin's lecture.

Alf M. Vahlquist (left), ambassador of Sweden to Japan, and Donald W. Campbell, ambassador of Canada to Japan, congratulate the award recipients.

Profile

Dr. Bert Bolin

Professor Emeritus at the University of Stockholm

Education and Academic and Professional Activities

1946	Received B.Sc. from the University of Uppsala
1947–50	Studied under Professor C.G. Rossby and received M.Sc. from the University of Stockholm
1956	Earned doctorate degree from the University of Stockholm
1956	Became assistant director for the International Meteorological Institute (IMI) in Stockholm
1957–90	Served as director of the IMI
1961–90	Served as professor of meteorology at the University of Stockholm
1965–67	Served as scientific director of the European Space Research Organization in Paris
1967	Proposed the establishment of the Global Atmospheric Research Program (GARP) while serving as the president of the Committee of Atmospheric Sciences (CAS) of the International Council of Scientific Unions (ICSU)
1967–71	Served as the first chairman of the Joint Organizing Committee of GARP, which was jointly launched by ICSU and the World Meteorological Organization (WMO)
1974	Organized and chaired the first major planning effort for global climate research, which formed the starting point for the World Climate Research Program (WCRP), established in 1980
1979	Edited Report No. 13, entitled "Global Carbon Cycle," of the monograph series of ICSU's environmental committee (SCOPE)
1983–86	Led the ICSU-UNEP-WMO Scientific Assessment of Climate Change, which gave rise to the publication of SCOPE Report No. 29, entitled "Greenhouse Effect, Climatic Change, and Ecosystems"
1983–86	Served as a member of the Scientific Advisory Board (Forskningsberedningen) to the Swedish government
1985–91	Chaired an ICSU committee that proposed the establishment of the International Geosphere Biosphere Program (IGBP)
1986–88	Served as scientific advisor to the prime minister and deputy prime minister of Sweden
1988–97	Served as Chairman of the Intergovernmental Panel on Climatic Change (IPCC)

As professor of meteorology at the University of Stockholm and director of the International Meteorological Institute, Dr. Bolin has conducted basic research on global biogeochemical cycles, particularly the carbon cycle. Early in his career, he developed a sophisticated model of the carbon cycle that takes full account of influences of the oceans, atmosphere, and biosphere. His work is well known throughout the world and serves as a basis for today's general understanding of global warming. As head of numerous international scientific committees, Dr. Bolin has helped provide a sound scientific basis for policy decisions about global warming and greenhouse gases.

Since 1988, Dr. Bolin has chaired the Intergovernmental Panel on Climate Change (IPCC), which was established to assess the scientific body of knowledge concerning climate change which served as the basis for negotiations aimed at preventing global warming at the Earth Summit in 1992. These led to the adoption of the Framework Convention on Climate Change, which was adopted at the Earth Summit in 1992. In addition, Dr. Bolin has published more than 100 papers in his field and continues to play a major role in promoting academic research. Throughout his career, Dr. Bolin's research and leadership activities have served to shed light on the problem of global warming and to provide suggestions for its solution.

Essay

What We Know and What We Don't Know about Human-Induced Climate Change And What Should Be Done?

Dr. Bert Bolin

May 1997

Key findings
We know that:

- the global mean surface temperature has increased by 0.3–0.6°C during the 20th century, the uncertainty primarily being due to the natural variability of climate on time scales from decades to a century not being well known;
- atmospheric greenhouse gas concentrations (carbon dioxide, methane, nitrous oxide, halogenated hydrocarbons, tropospheric ozone) continue to increase, leading to an enhanced positive radiative forcing of the climate system;
- the enhanced concentrations of tropospheric aerosols primarily resulting from combustion of fossil fuels and biomass burning cause some negative forcing;
- our ability to determine the human influence on the global climate is still limited because the expected signal is only now emerging from the noise of natural variability, but the IPCC has nevertheless concluded that "the balance of evidence suggests that there is now a discernible human influence on climate;"
- the sensitivity of the climate system to greenhouse gas forcing is not yet well known; the earlier assessment—that an equilibrium warming of 1.5–4.5°C for a doubling of carbon dioxide concentrations in the atmosphere (or an equivalent increase of a mixture of greenhouse gases)—remains.

(See: IPCC Second Assessment Report, 1995; IPCC Synthesis Report: An Assessment of Scientific and Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change; and Policy Makers of Working Groups I, II and III. WMO, Geneva)

Simple climate models, calibrated against complex models, can be used to assess the expected global temperature change due to the enhanced concentrations of greenhouse gases that have occurred so far, and in doing so the inertia of the climate system can also be recognized. Accepting the observed increases of greenhouse gas concentrations, the enhanced radiative forcing so far is about 2.7 Wm^{-2}, the central value for the negative aerosol forcing is assumed to be $-1.1\ \mathrm{Wm}^{-2}$ as given by the IPCC, and spanning the full range of uncertainty of the climate sensitivity, this yields an expected increase of the global surface mean temperature of 0.3°–0.7°C. (cf. IPCC Technical Paper No. 3. Stabilization of Atmospheric Gases: Physical, Biological and Socio-Economic Implications. WMO, Geneva (TP 3)). Considering also the uncertainty of the negative aerosol forcing this range becomes about 0.1°—0.9°C, where the lower bound results from the combination of low sensitivity of the climate system to human forcing and a large influence of aerosols, while the upper bound corresponds to high climate system sensitivity and small forcing due to aerosols. In light of the observed changes so far, none of these extreme values seem likely, but neither can any be excluded because of the uncertainty of the computations.

It is appropriate in this context to recall the conclusion drawn already in the IPCC First Assessment Report that "...the observed increase of global mean temperature could largely be due to natural variability; alternatively this variability and other human factors could have offset a still larger human induced warming." As a matter of fact using (a) the central values for the sensitivity of the climate system to radiative disturbances, and (b) the radiative forcing due to enhanced greenhouse gas and aerosol concentrations, brings the calculated and observed changes of the global mean surface temperature into reasonable agreement. This must not, however, be viewed as proof of the human influence on global climate but it represents supporting evidence that this might indeed be the case.

Although we now have evidence for human-induced change to the global climate, we cannot yet tell how the occurrence of extreme events, such as storms, floods, and droughts, might change. This implies also that it is not yet possible to describe the impacts of climate change either globally or for individual countries, even though we can predict generally that floods as well as droughts might become more frequent. An increase of temperature by 2°C would have a marked influence on the forests—as much as 30% might no longer be well adjusted to the surrounded abiotic conditions. Finally, the sea level would rise by 15–95 cm if no mitigation were undertaken, but this would not be the same all around the world.

Stabilizing Greenhouse Gas Concentrations

The UN Framework Convention on Climate Change (FCCC) considers a stabilization of greenhouse gas concentrations and thereby also a stabilization of climate as the prime objective, but sets no specific level as a goal. Actually, such a level can hardly be determined accurately until better estimates of the likely damage due to changes of climate become available, which cannot be expected in the near future. Justifications for mitigation efforts must therefore be based largely on qualitative judgments. It is not surprising that the views on what should be done differ.

In view of this situation the IPCC has asked the question: What emissions scenarios for carbon dioxide are "permissible" in order not to exceed a set of alternative concentration levels? Those chosen are 450, 550, 650, 750, and 1000 ppmv, which should be compared with the preindustrial concentration of about 280 ppmv and present concentrations of about 360 ppmv. Alternative stabilization paths and the resulting emissions profiles are shown in Figures 1 and 2.

According to the FCCC, it is, however, important not to restrict analysis to the role of carbon dioxide; rather, all greenhouse gases should be considered. IPCC Technical Paper III also included considerations of methane, nitrous oxide and sulfur dioxide (which is transformed into sulfate aerosols). Table 1 shows the radiative forcing of the climate system in

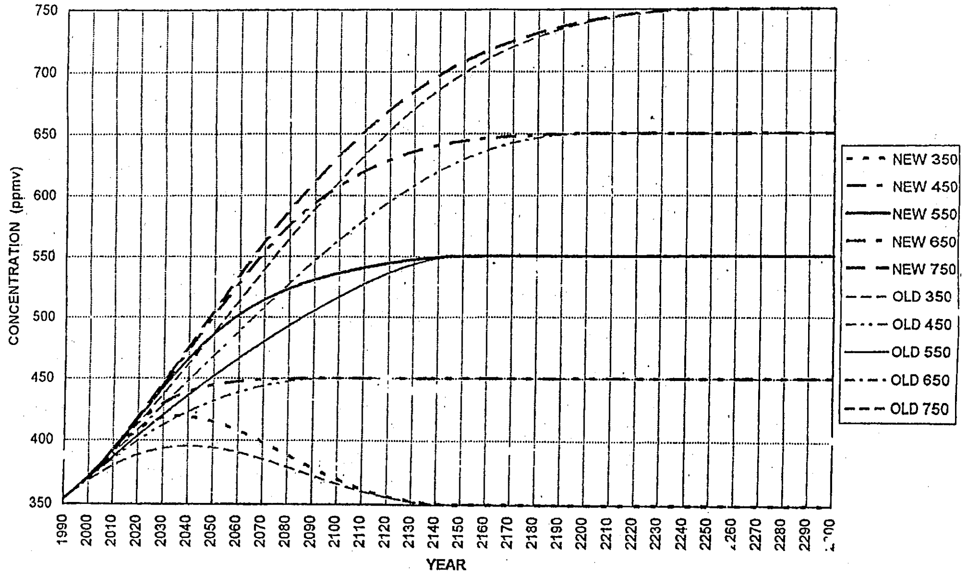


Figure 1. Alternative concentrations scenarios for stabilization of atmospheric carbon dioxide at 350, 450, 550, 650, and 750 ppmv. The "old" scenarios imply an immediate change of the energy supply infrastructure. The "new" scenarios, on the other hand, follow the IPCC Scenario IS92a ("Business as Usual") during one or a few decades in order to permit the change over of the energy supply infrastructure into one that can satisfy the restrictions that are required in order to reach the prescribed stabilization levels.

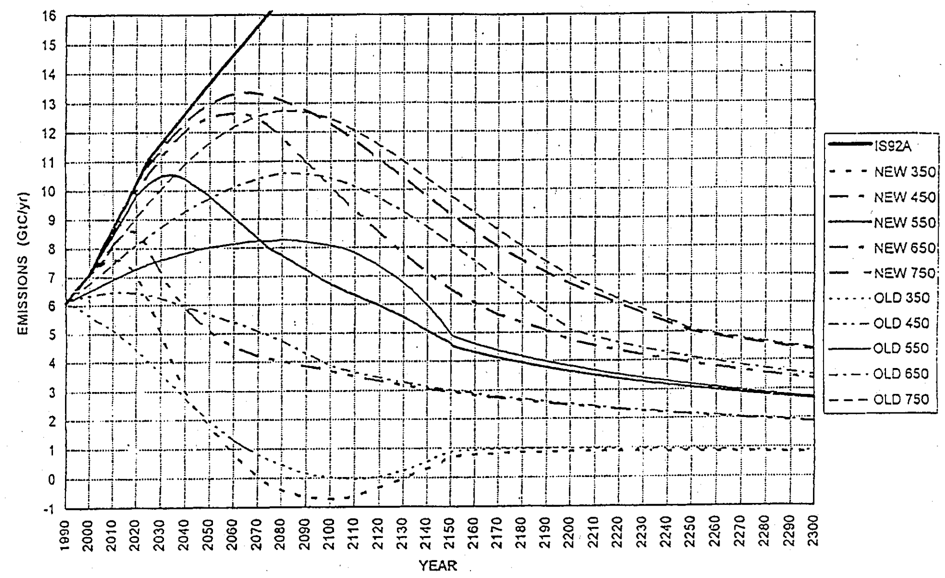


Figure 2. Emissions scenarios for stabilization of atmospheric carbon dioxide concentrations in accordance with the scenarios as given in Figure 1.

Table 1. Radiative forcing and temperature changes at the time of stabilization for alternative levels of stabilization. It has been assumed that methane,. nitrous oxide and sulfur dioxide will be emitted in according to the IPCC Scenario IS92a until 2100 and thereafter to remain constant. (See further Table 3 in TP 3.)

Level of stabilization (ppmv)	Radiative forcing (Wm^{-2})	Temp change lower bound (°C)	Temp change central value (°C)	Temp change upper bound (°C)
450	3.59	1.2	2.1	3.6
550	5.04	1.7	2.9	5.2
650	6.16	2.1	3.5	6.4
750	7.10	2.5	4.1	7.4

2100 for the different stabilization levels with the further assumption that the emissions of methane, nitrous oxide and sulfur dioxide increase in accordance with the IPCC Scenario IS92a ("Business as Usual") until 2100 and remain constant thereafter. The changes to the radiative forcing of the climate system due to these human emissions and aerosols so far are 2.3 Wm^{-2} and -1.1 Wm^{-2}, respectively. The emissions of sulfur dioxide presumably will decrease in the process of stabilization, because about 90% of present emissions occur when burning fossil fuels, an activity that will decline when stabilization is being approached. The computed temperature changes may therefore be underestimates. It should also be noted that the temperature changes as given in Table 1 refer to the time at stabilization, which for higher levels may be far into the 22nd century.

It should be noted that the European Union has agreed that a future change of the global mean surface temperature due to human emissions should not exceed 2°C. In order to keep the risk of this happening reasonably low, carbon dioxide concentrations should not exceed about 450 ppmv, which is really quite a difficult task to achieve. It remains to be seen what the negotiations, which are under way in preparation for the third Conference of the Parties to the Convention in Kyoto in December 1997, will lead to.

Some comments are also warranted with regard to the issue of the timing of mitigation efforts and the relative importance of future measures taken by developed and developing countries to stabilize carbon dioxide concentrations in the atmosphere. The upper curve in Figure 3 shows total carbon dioxide emissions for the central IPCC Scenario IS92a, and the similarly rising curve below gives the part of the emissions due to developing countries. The areas below these respective curves are proportional to the cumulative emissions and therefore the area *between* them shows the cumulative emissions caused by developed countries.

Assuming that only developed countries stabilize or reduce their emissions, the top curve would be lowered as indicated in the figure. Three cases are shown that embrace *all* proposals for mitigation efforts so far made by countries for consideration in the ongoing negotiations:

1. Developed countries keep their emissions constant
2. Developed countries reduce emissions annually by 1%
3. Developed countries reduce emissions annually by 2%

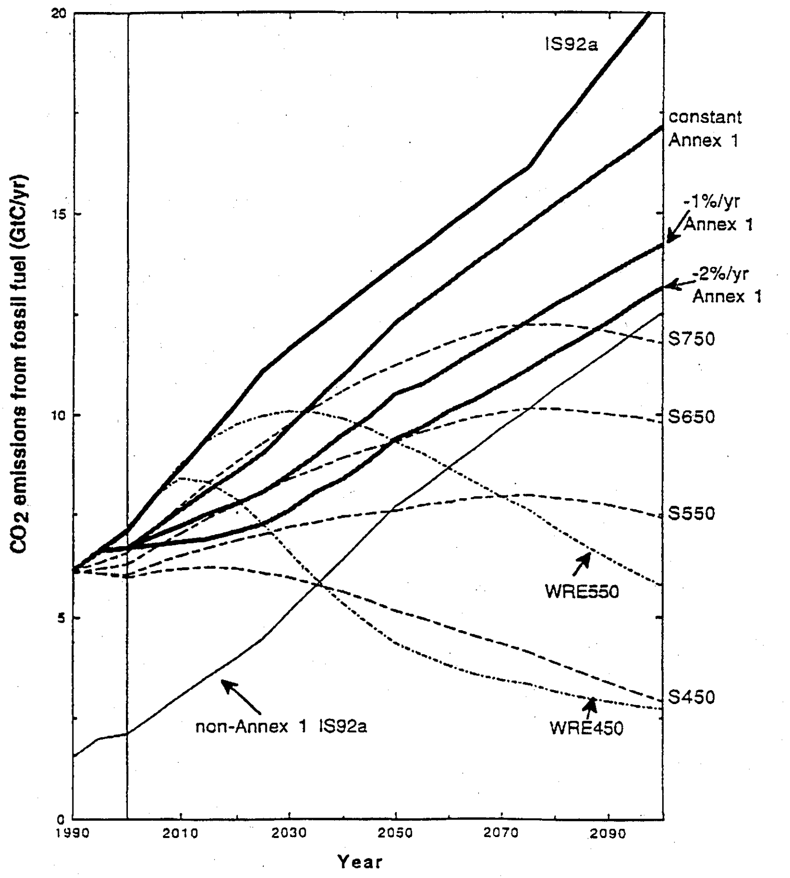


Figure 3. The IPCC Scenario IS92a for total emissions (upper bold line) and emissions from non-Annex 1 countries, i.e. developing countries (the similarly rising curve, thin line). The areas below these two curves are proportional to the cumulative emissions, and therefore the area between them shows the cumulative emissions by developed countries (Annex 1 countries). The three additional bold lines show the total emissions if the developed countries (a) stabilize their emissions at the 1990 level, (b) reduce them annually by 1%, and (c) by 2% during the next century. The emissions required to reach stabilization at 450 and 550 ppmv (in accordance with Figure 2) are also shown (dashed or dash-dotted lines).

It is obvious from this graph that no reasonable future reductions by developed countries would stabilize either global emissions or, hence, the global mean surface temperature. Several questions arise: How soon is it possible to reach agreements with developing countries that they reduce their rate of increasing emissions? When will they be able to rely instead on non-carbon-emitting energy sources and thus able to reduce their emissions? How can developed countries assist in this effort?

A simple carbon dioxide model can be employed to deduce the atmospheric carbon dioxide concentrations for the cases of stabilizing or reducing developed country emissions as illustrated in Figure 3. Slightly lower concentrations are obtained than those deduced from the IS92a scenario. The cumulative total emissions due to fossil fuel burning during the 25 years 1995–2020 according to IS92a are projected to be about 210 Gt, an amount that would be reduced by about 21, 29 and 36 Gt in the three cases referred to above. This is of course in itself important as the beginning of a long-term effort. It is, however, clear that the reduction of the rate of increase of atmospheric carbon dioxide concentrations during this period, 5–9 ppmv, is small compared with the projected increase according to the IS92a scenario, i.e. 50–55 ppmv. The induced increase of the global mean temperature during these 25 years due to emissions, according to the IS92a scenario, would actually in any one of the cases shown be reduced by less than 0.1°C, which would not be detectable.

The results described above are a consequence of the inertia of the climate system. They also show why it is important to analyze extended emissions profiles in order to understand the implications of different actions. Agreed actions would, however, presumably within only a few years be replaced by new agreements in the light of improved knowledge about the climate issue. In any case, collaboration among all countries will be required to stabilize and then gradually reduce total emissions. How quickly this can be achieved is a matter of political judgment which implies weighing risks against costs.

It is of interest to insert into the figure the emission profiles required for stabilization of atmospheric carbon dioxide concentrations at different levels. Alternative pathways towards stabilization can be chosen (two are shown, i.e. stabilization at 450, and 550 ppmv). It is interesting to note the stage, according to IS92a, when the emissions from developed countries begin to exceed the total emissions, that lead to stabilization at 450 ppmv, is reached rather early during next century. On the other hand, higher stabilization levels than 550 ppmv hardly require early actions.

The range of projected changes of the global mean surface temperature is large, particularly because of the uncertainty of the sensitivity of the climate system to changing greenhouse gas concentrations. The issues of how much and when to mitigate a climate change therefore need to be considered in terms of weighing the risks for a possible change of climate against the costs for mitigation. This remains difficult, particularly because of the difficulty of determining how serious a climate change might be.

Policies and Measures to Stabilize Greenhouse Gas Concentrations

The IPCC has prepared an extensive summary of available technologies, policies and measures for mitigating climate change (IPCC Technical Paper I. Technologies, Policies and Measures for Mitigating Climate Change. WMO, Geneva.) It provides an overview and analysis of technologies and measures to limit and reduce greenhouse gas emissions and to enhance greenhouse gas sinks under the FCCC. The paper focuses on technologies and measures for the countries listed in Annex I of the FCCC (industrialized countries), while noting information as appropriate for the use by Non-Annex I countries (developing countries). They are examined over three time periods, with a focus on the short term (present to 2010) and the medium term (2010–2030), but also including discussions on long-term (e.g. 2050) possibilities and opportunities.

The Technical Paper includes discussions of technologies and measures that can be adopted in three end-use sectors (commercial, residential, and institutional buildings; transportation; and industry); in the energy supply sector; and in the agriculture, forestry, and waste management sectors. Broader measures affecting national economies are discussed in a final section on economic instruments.

It is important to recognize the differences between technical, economic and market potentials for mitigation, defined as follows.

- Technical potential
  The amount by which it is possible to reduce greenhouse gas emissions or improve energy efficiency by using technology or practice in all applications in which it could technically be adopted, without considering its costs or practical feasibility.
- Economic potential
  The portion of the technical potential for greenhouse gas emissions reductions or energy efficiency improvements that could be achieved cost-effectively in the absence of market barriers. The achievement of the economic potential requires additional policies and measures to break down market barriers.
- Market potential
  The portion of the economic potential for greenhouse gas emission reductions or energy efficiency improvements that currently can be achieved under existing market conditions, assuming no new policies and measures.

Such distinctions have not always been made, which has led to unrealistic claims with regard to the possibility of quickly achieving substantial reductions of emissions. On the other hand IPCC Technical Paper No. 1 (TP 1) clearly shows that there are many possibilities to do gradually what may be required and, to begin with, at modest costs. Analyses are needed to clarify the situation for individual countries, since the opportunities vary considerably. Examples from TP 1 will illustrate some of the possibilities and opportunities that exist, but close analyses by countries are recommended, if this has not already been done.

Examples

Residential, commercial, and institutional buildings sector

Technical development is under way in many countries. It is today possible to construct houses that in temperate climates (e.g. in Germany) use exclusively solar energy, photovoltaics and direct solar heating. This includes the use of, for example, specially designed walls and windows, energy storage through the use of batteries (short-term storage) and hydrogen (seasonal storage), and the employment of heat exchange systems for ventilation. The technical feasibility has been proven, but costs are as yet excessive. The potential for the future is large.

A lot of specific equipment (e.g. household appliances) that reduce the need for energy are, however, available already today in many cases at competitive costs. The major administrative, institutional, and political issues in implementing market-based programs for residential and commercial building equipment are:

- Difficulties in improving integrated systems
- The need for, and shortage of, skilled persons capable of diagnosing and rectifying systems problems
- The fact that energy users are often not those responsible for paying energy bills, creating

a barrier to increased efficiency

- The need to structure incentives so that intervention in buildings aims at achieving all cost-effective energy efficiency measures
- The need to create institutional structures for market-based programs to work effectively
- Perception (or reality) of cross substitutes and related unfairness of expenditures.

Transport Sector

About 20% of today's emissions of carbon dioxide comes from the transport sector, and its relative contribution is expected to increase in the future, particularly from aviation. It may double within 25 years and triple by the middle of next century.

It is technically feasible to reduce the gasoline consumption substantially already today. Rapid changes are difficult to achieve because of the infrastructure that has developed during the 20th century. There are, however, several social and environmental costs associated with road transport at local, regional, and global levels that can be addressed simultaneously. Market instruments such as road-use charges can be used to reflect many of these costs, especially those at the local and regional levels. These instruments can also contribute to greenhouse gas mitigation by reducing traffic. Fuel taxes are an economically efficient means of greenhouse gas mitigation, but may be less efficient for addressing local objectives.

Changes in urban and transport infrastructure, to reduce the need for motorized transport and shift demand to less energy-intensive transport modes, may be the most important elements of a long-term strategy for greenhouse gas mitigation in the transport sector.

Industrial Sector

During the past two decades, the industrial sector fossil fuel carbon dioxide emissions of most developed countries have declined or remained constant as their economies have grown. Still, the present emissions from this sector contribute almost 50% of the total emissions, of which the industrialized countries are responsible for about three quarters. It is estimated that these countries could still lower their industrial sector emissions by 25 % relative to 1990 levels, by simply replacing existing facilities and processes with the most advanced technological options currently available (assuming a constant structure for the industrial sector). If such upgrading occurred at the time of normal capital stock turnover it would in most cases be cost-effective.

Energy Supply Sector

Energy consumed in 1990 resulted in the release of 6 Gt C (in 1995 6.3 Gt C). About 72% of this energy was delivered to end users, accounting for 3.7 Gt C, the remaining was used in energy conversion and distribution. It is technically possible to realize deep emissions reductions in the energy supply sector in step with the normal timing of investments to replace infrastructure and equipment as it wears out or becomes obsolete.

The efficiency of electricity production can be increased from the present world average of about 30% to more than 60% sometime between 2020 and 2050. Presently the best available coal and natural gas plants have efficiencies of about 45% and 52%, respectively.

While the costs associated with these efficiencies will be influenced by numerous factors, there are advanced technologies that are cost-effective, comparable with some existing plant and equipment. The combination of electricity generation with the utilization of the waste heat for local (or regional) supply of heat for the residential/commercial/institutional sector provide many opportunities for saving energy, particularly in temperate and cold climates.

Historically, the energy intensity of the world economy has improved, on average, by 1% per year, largely due to technology performance improvements that accompany the natural replacement of depreciated capital stock. Improvements beyond this rate are unlikely to occur in the absence of specific measures.

Agricultural Sector

Agriculture accounts for about 20% of the anthropogenic greenhouse effect, primarily due to the emissions of methane and nitrous oxide, but only about 5% of the anthropogenic carbon dioxide emissions come from agriculture. Considerable reductions of greenhouse gas emissions from the agricultural sector can be accomplished, primarily from offsets by biofuel production on land currently under cultivation. Reduction of anthropogenic methane production is primarily an issue for developing countries. It is still relatively small and is increasing only slowly. The need for systems analyses by country for determination of possible reductions of greenhouse gas emissions from the agricultural sector is apparent.

Forestry Sector

High- and mid-latitude forests are currently estimated to be a net carbon sink of about 0.7 ±0.2 Gt C/year. Low-latitude forests, on the other hand are estimated to be a net source of 1.6 ±0.4 Gt C/year, caused mostly by clearing and degradation of forests. These sources and sinks may be compared with the carbon release from fossil fuel combustion, estimated to have been 6 Gt C/year in 1990. It is to be noted, however, that emissions due to fossil fuel burning represent injection of carbon that has been buried in the ground for millions of years, while increases and decreases of carbon in forests should be viewed as redistributions of carbon between terrestrial reservoirs, which will necessarily remain rather limited in a long-term perspective, because of the comparatively limited amounts that they contain. Still, it is obviously important to halt deforestation. Governments in a few developing countries, such as Brazil and India, have instituted measures to achieve this.

Wood residues are used regularly to generate steam and/or electricity in most paper mills and rubber plantations, and in specific instances for utility electricity generation.

Solid Waste and Wastewater Disposal

An estimated 50–80 Mt CH_4 was emitted by solid waste disposal facilities and waste water treatment facilities in 1990. Although there are large uncertainties in such emissions estimates for a variety of reasons, overall emissions levels are projected to grow significantly in the future.

Technical options to reduce CH_4 emissions are available and, in many cases, may be profitably implemented by paper recycling, composting, and incineration and also through

CH_4 recovery from landfills and waste water, which in turn may be used as an energy source. This might be cost-competitive with other energy alternatives.

These few examples from different sectors of society should only be viewed as examples, since there are major differences between countries, the analysis of which requires special efforts.

Concluding remarks

Neither the climate system nor the world socio-economic system will be changing rapidly because of their great inertia. The oceans are the prime factor that slows down the response of the climate system, while the reluctant response by people—not the least in the political system—as well as the slow turnover of capital invested in the major infrastructures of a modern society, imply that mitigation will come about neither easily nor rapidly. Both these factors should be considered seriously when setting new goals for the FCCC to be realized in the 21st century.

Lecture

Biogeochemical Cycles and Climate Change

Dr. Bert Bolin

It is a great joy for me to be here and give this lecture on the very memorable occasion of having received the Blue Planet Prize of 1995. I will, however, change slightly what I originally thought I would present to you. Facts will not change, nor knowledge as presented. They are basic ingredients of my talk. But it is so important for science to express its findings in terms that are useful to society and therefore helpful for possible action. Having listened to Mr. Strong for a couple of hours, I find it even more important to see how we should best present the scientific issues to serve properly in this regard. It cannot be overemphasized that science has this responsibility and maybe does not always fulfill it adequately. Much of what we as scientists are saying is not easily understood. I hope indeed that I will be understood.

The world has existed for a long, long time—thousands of millions of years. What we see around us today has gradually evolved during this period, and we, as human beings, are part of it and we indeed wish, of course, to remain as part of it. We must therefore not do things that jeopardize our own existence—for example, change our environment excessively.

Life is dependent upon the availability of a rather few basic elements that were present already when the Earth was created. It is not surprising that the most important element is carbon. All organic matter is built around the carbon atom. But a number of other constituents are also important, e.g., nitrogen, phosphorus, and sulfur. We sometimes, however, consider them as pollution in the environment. They may appear as pollution because of their enhanced concentrations that are the result of the increasing number of people on Earth whereby more of these nutrients are being brought into circulation. Sustainable development for us as human beings means that we accept the requirement not to change the environment unduly and to respect the living part of our environment, the biosphere.

Satellites have given us a bird's-eye view of the Earth. Figure 1 is based on measurements from space and shows photosynthetic activity on Earth. The colors range from brown, which implies no photosynthesis, to green to white to purple, which show areas with maximum photosynthesis. Figure 1 displays conditions during August and February, i.e., during summer and winter as they alternate between the two hemispheres. During summer in the Northern Hemisphere, life is at full swing up to high latitudes but is slowed down in the Southern Hemisphere. On the other hand, in the Northern Hemisphere during winter the situation is reversed. The Sahara, as might be expected, is constantly characterized by very little plant growth. In contrast, the rain forests in the tropics show very high rates the year round; there, life is abundant.

These realities of today must not change too much in the future. They are indeed basic for life on Earth. Photosynthesis provides the energy we need and energy is required for a sustainable future for the human race and its society. We also know a lot about life on Earth in the past because the circulation of the fundamental elements of life has varied and these changes can be seen in remnants of life as found in lake and sea sediments, in the soils, and in ice as preserved in the major ice sheets. From these findings we can also deduce past climatic conditions because there is such a close relationship between climate and life.

Figure 2 shows what can be deduced from ice cores that have been extracted down to a depth of several kilometers from both the Greenland and Antarctic ice sheets. Measurements of the abundance of the oxygen isotope ^{18}O tell us about temperature variations during the past 220,000 years. The last ice age shows up very clearly with temperatures more than 10 degrees below present temperatures. The last interglacial epoch, about 120,000 years ago, was somewhat warmer even than the present one, which by now has lasted for about 10,000 years. The human civilization has developed during this geologically short period of time.

Methane in the atmosphere has also varied markedly (see Figure 2). We know this from

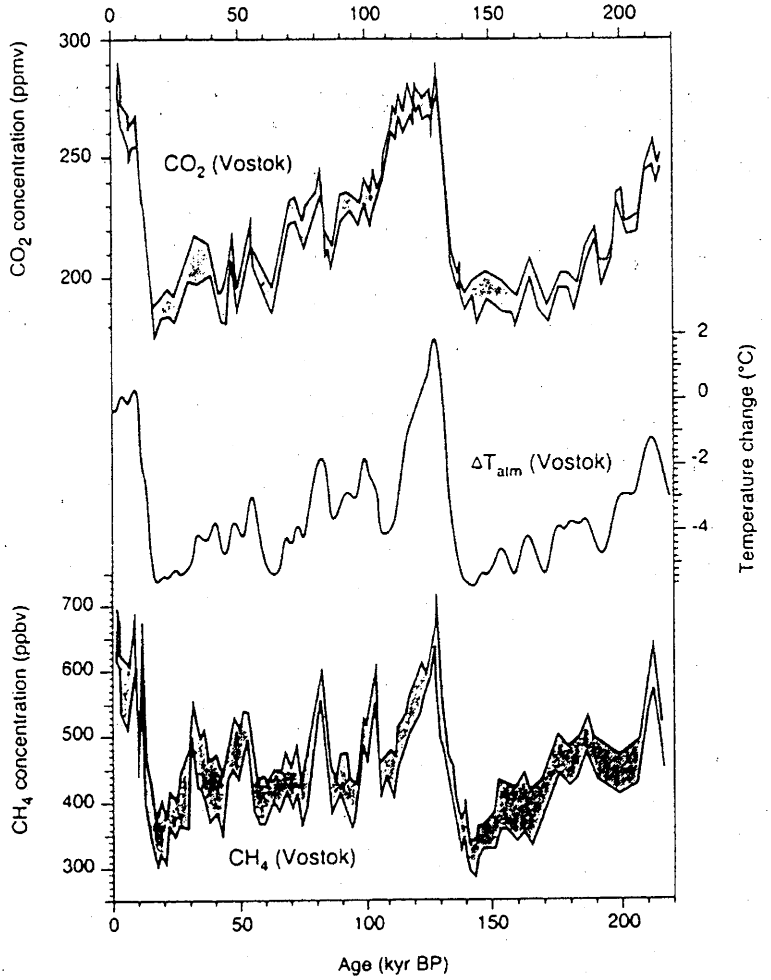


Figure 2. Variations of temperature, carbon dioxide, and methane during the past 220,000 years as deduced from analyses of glacier ice and air bubbles enclosed in the ice from an ice core record at Vostok in Antarctica (IPCC Special Report, 1994).

analyses of air buried in the form of small bubbles in the ice from Greenland and Antarctica. Records from approximately the past 220,000 years are available. The preindustrial concentration was about 0.7 ppmv (parts per million) and also about the same during the previous interglacial epoch. During the glacial period, on the other hand, it dropped to about half that. Methane is produced during the decomposition of organic matter and is therefore also an expression for the intensity of life on Earth. Apparently life was less active during glacial times, which is not surprising. The ice cores now also provide for a quantitative measure. Methane concentrations are at present about 1.7 ppmv, i.e., more than twice the undisturbed interglacial concentrations. This enhanced concentration is brought about by the expansion of rice cultivation and increasing numbers of cattle to provide food for humankind, but it is also due to leakage when exploiting coal, oil, and natural gas as sources of energy.

Carbon dioxide in the atmosphere shows similar major variations during the last glacial and interglacial epochs. It dropped to about 200 ppmv during the long glacial period as compared with about 280 ppmv before industrialization began early last century. A close interrelation between atmospheric concentrations of carbon dioxide and methane on the one hand and life on the other is obvious.

Figure 3 shows the steady increase of carbon dioxide, from 280 ppmv about 200 years ago to about 360 ppmv at present—an increase of almost 30%. About 80% of this increase is owing to manmade emissions of carbon dioxide by burning fossil fuels and about 20% owing

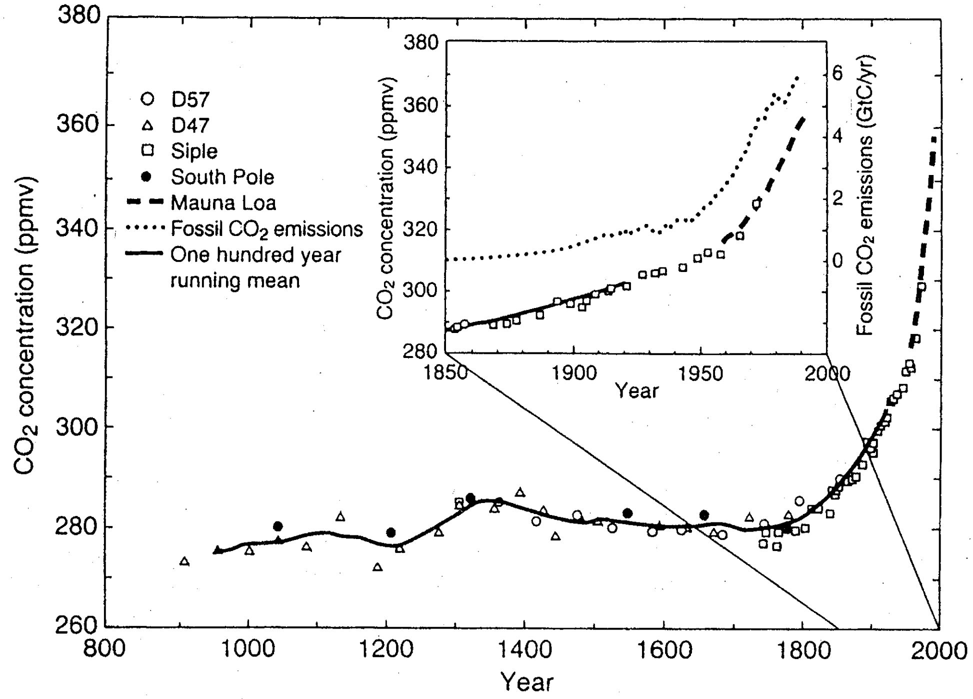


Figure 3. Carbon dioxide in the atmosphere, 900–1958, deduced from analyses of the composition of air in bubbles from glacier ice and since 1957 from direct measurements in the atmosphere. D57, D47, Siple, and South Pole show data from four different ice cores in Antarctica. Inserted, annual emissions of carbon in the form of carbon dioxide are also given (IPCC Special Report, 1994).

to deforestation and changing land use. Thus, there is less carbon in living plants on Earth and in cultivated soils today than a few hundred years ago. We think it is profitable to plow our fields, but we decrease their content of organic matter, which may not be sustainable from a long-term perspective.

Another graph, Figure 4, shows the changes of nitrous oxide. Its presence in the atmosphere is also related to decomposition processes. Figure 4 shows changes during approximately the past 2,000 years, also derived from analyses of air bubbles in ice from Greenland and Antarctica. A marked increase during the past few hundred years can be seen. We can thus see in the measurements from Antarctica the effects of 1,500 million cows and other animals kept for husbandry, primarily in the Northern Hemisphere.

As a matter of fact, we are today changing the composition of the atmosphere in many ways. We therefore urgently need to understand what is at stake and which parts of the biosphere take part in this process. We need to understand how the biogeochemical cycles function and how they interact in the processes of photosynthesis and plant growth. The key is of course the carbon cycle, but its interactions with and dependence on the cycles of the other elements must not be forgotten. They are indeed also part of the story.

We find carbon in the atmosphere, in living plants on land, as dead organic matter in the soils, in the oceans (both dissolved as inorganic carbon and as plants and animals, as well as dissolved organic carbon), and as deposits in the sediments at the bottom of the oceans (see Figure 5). There is about 50 times more carbon in the ocean's waters than there is in the air as carbon dioxide. Carbon dioxide stays on average about four years in the atmosphere before it

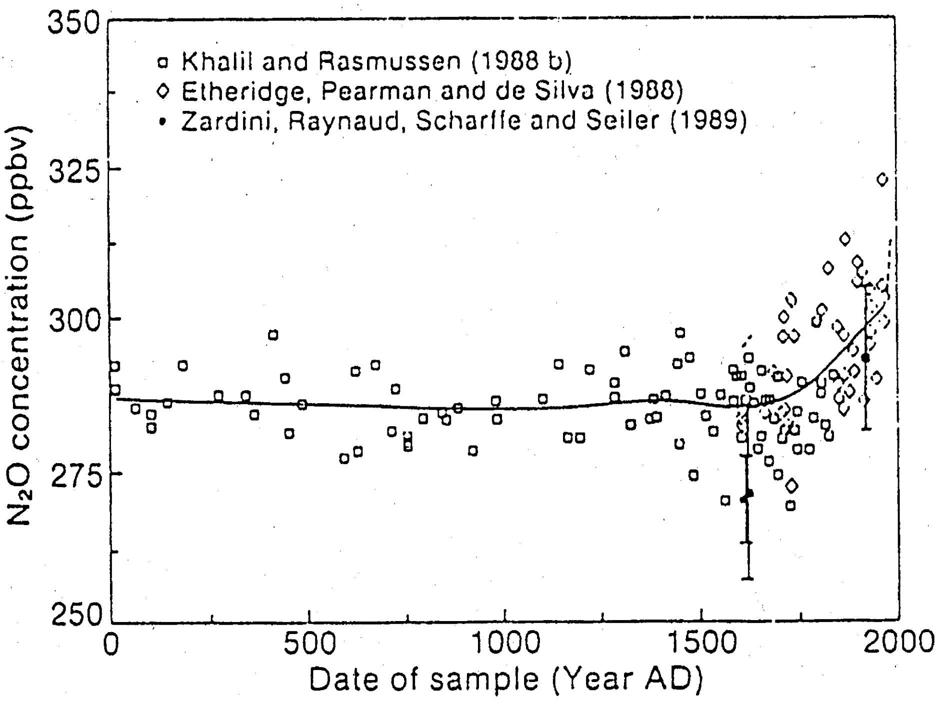


Figure 4. Nitrous oxide concentrations in the atmosphere measured in samples from ice cores (IPCC, 1990).

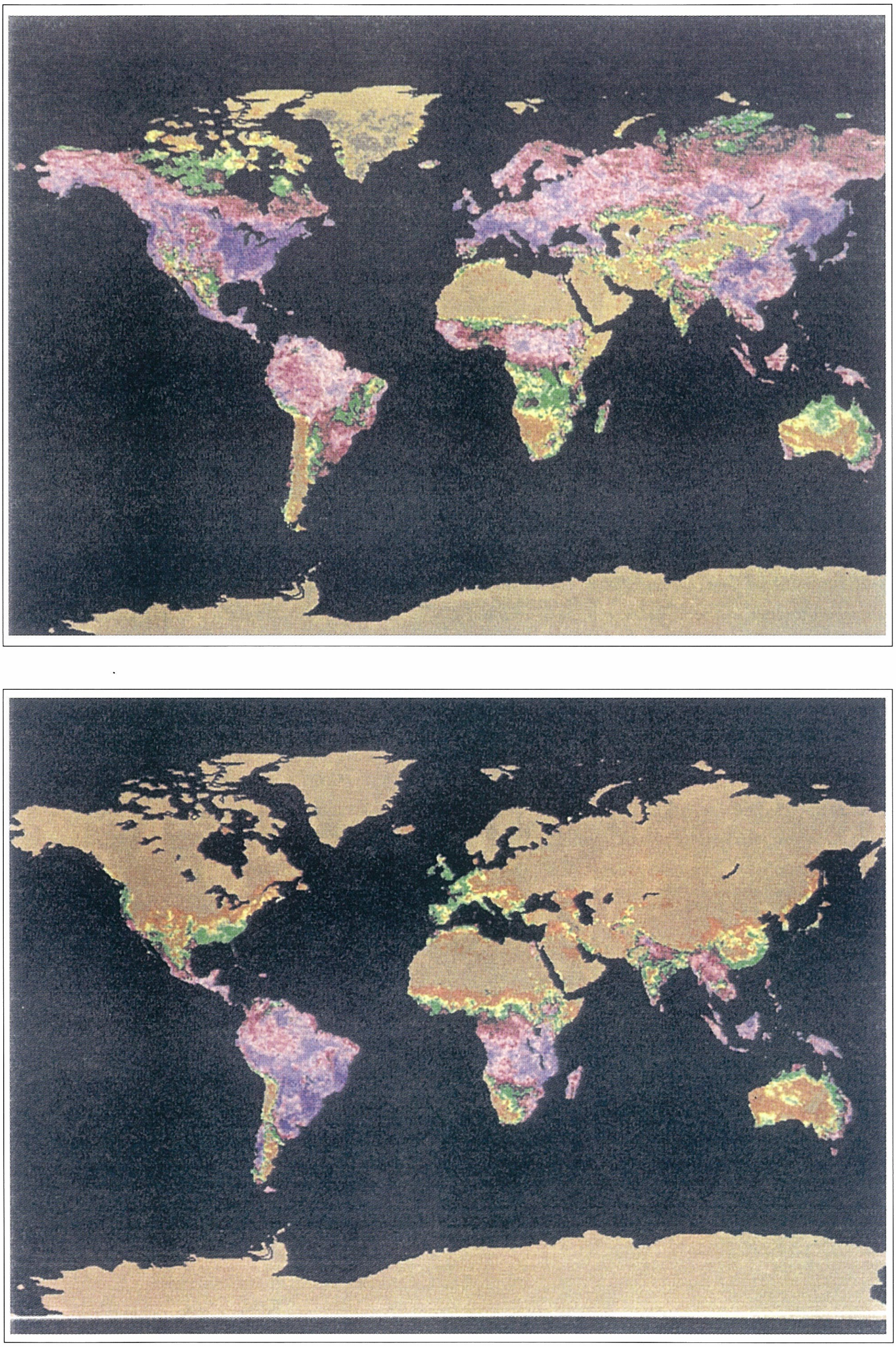


Figure 1. Rate of photosynthesis as deduced from satellite measurements (AVHRR) for August 1982 and February 1983 (Tucker et al., 1986).

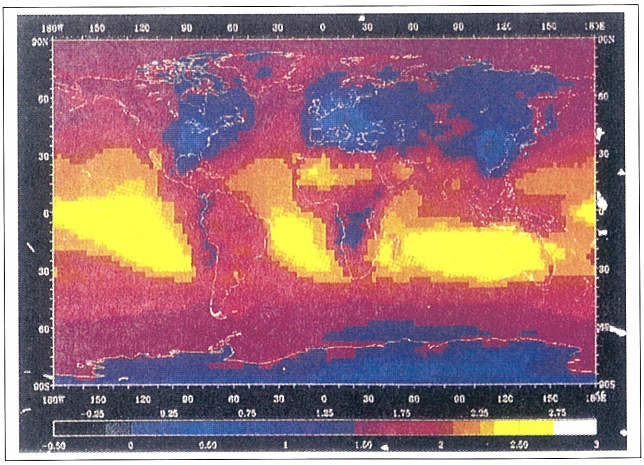


Figure 7. Global distribution of radiative forcing (Wm^{-2}), including the effects of enhanced concentrations of both greenhouse gases and aerosols (Kiehl and Briegleb, 1993).

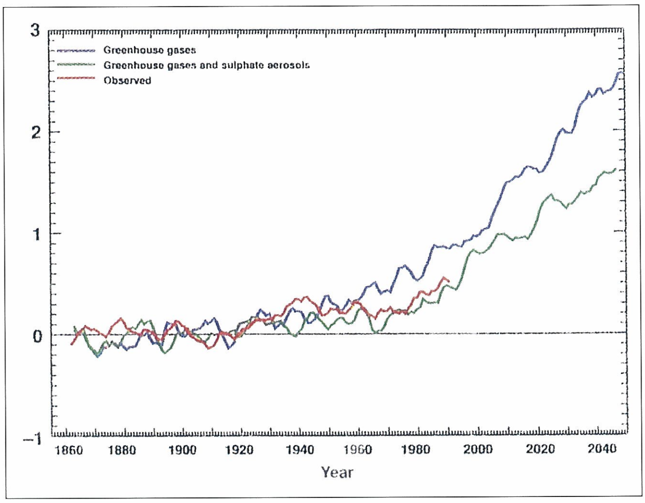


Figure 8. Observed changes of the global mean surface temperature, 1860–1994 (red curve), and model computations of expected changes, 1860–2050, based on likely changes of atmospheric composition in the past (until 1994) and projections of future changes estimated by IPCC until 2050, Scenario IS92a (no mitigation of a possible climate change). Temperature projections have been computed based on radiative forcing due only to enhanced greenhouse gas concentrations (blue curve) and also if including the effects of aerosol emissions (green curve) (Hadley Centre, 1995).

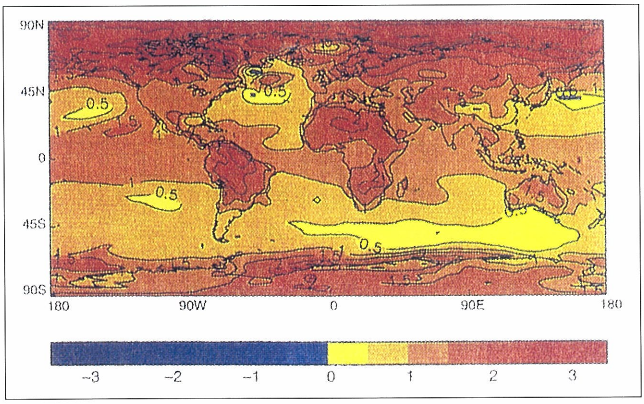


Figure 9. Changes of surface temperature between the average conditions computed for the 20-year periods 2030–2050 and 1970–1990 in the projections, including the effects of aerosols as shown in Figure 8 (Hadley Centre, 1995).

either enters the oceans or is assimilated by plants on land. In a natural equilibrium, about the same amounts are returned to the atmosphere and a balance is maintained. Because of its size and the fact that the sea is not well mixed, carbon stays in the oceans for centuries to millennia. Human emissions of carbon dioxide into the atmosphere are now disturbing this natural balance because we are burning carbon that was accumulated in the Earth's crust during hundreds of millions of years and is now being extracted. It is being and possibly will be released in increasing amounts in a matter of perhaps a few centuries. This represents a major disturbance of the carbon cycle. What will it mean in a longer perspective?

It is well known that many plants grow better if the atmospheric carbon dioxide concentration is enhanced, but only if there are enough water and nutrients. It is therefore reasonable to expect that the global rate of photosynthesis will increase, but it is difficult to tell by how much. The rate of decomposition may, however, also change in response to an increased rate of primary production and higher temperature. The total enhancement of the carbon reservoirs in the form of plants and dead organic matter in the soil is also limited. Eventually, most of the carbon dioxide from burning fossil fuels will therefore end up in the oceans. We will thus also gradually change the composition of the sea. We will increase its acidity because the dissolution of carbon dioxide means the formation of carbonic acid. This is, however, a slow

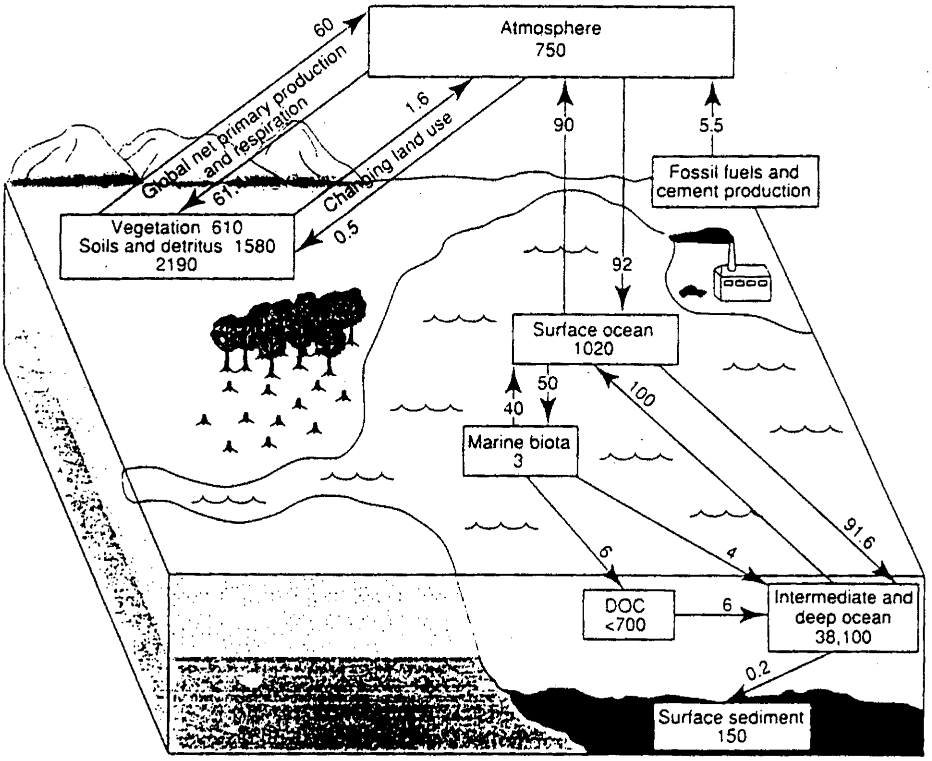


Figure 5. The carbon cycle. The numbers in the boxes indicate the size in GtC (billion tons of carbon) of each reservoir. On each arrow is indicated the magnitude of flux between the reservoirs in GtC/year; DOC=dissolved organic carbon (IPCC Special Report, 1994).

process and has as yet hardly influenced the oceans at all. If the accumulated emissions are ultimately many times more than what has been emitted so far, the pH of sea water might decrease by possibly as much as half a unit. In the long term, the natural equilibrium between ocean water and the sediments as well as the carbonate structures of marine plants and animals might also be disturbed. This all goes to show that life on Earth as we know it has been built on the availability of the basic elements in approximately the proportions as we now know them. But let us not forget that life is "clever." If some basic nutrients are lacking, the biochemical processes of plants and animals may be able to accumulate them in order to provide for what is required to create the molecules that are needed.

Let us return to what man has been doing in the recent past and what may happen over the decades and centuries to come. Is it likely that we may reach a level of carbon dioxide concentration in the atmosphere which might be destructive for the present ecosystems on Earth and therefore ultimately also for humankind? The increase so far has been about 30%. We know, however, that plenty of coal, oil, and natural gas is available in the Earth's crust. The amount in the atmosphere could be tripled or quadrupled. This would, of course, require a lot more industrial activity on Earth, but rapid economic growth is under way in, for example, East

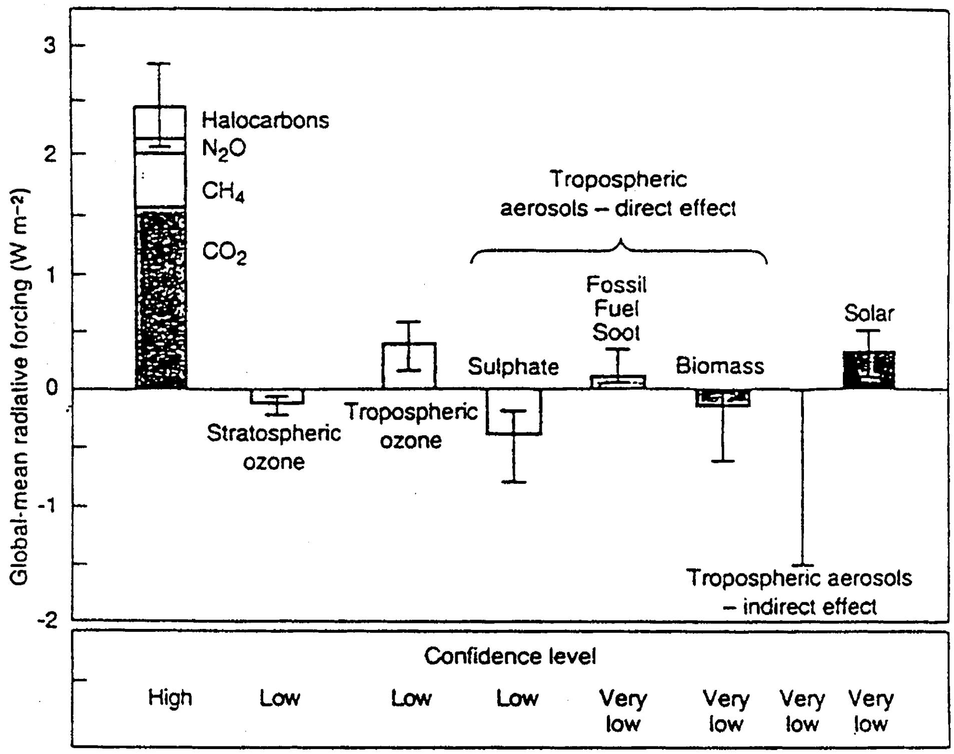


Figure 6. Percent of radiative forcing (in Wm^{-2}) of the atmosphere due to changes in the composition of the atmosphere because of human emissions, 1850–1990. The uncertainties of the different estimates are also given. It should be noted that the estimates of the forcing due to enhanced concentrations of tropospheric aerosols (not including sulfate aerosols) range between 0 and 1.5 Wm^{-2}. For comparison, variations of solar forcing are also given (IPCC Working Group I, 1996).

and Southeast Asia. It is only because of the lull in the expansion of industrial activities in former Soviet Union and Eastern European countries, in turn owing to a process of major economic restructuring, that the global emissions are temporarily not increasing at present.

Carbon dioxide, methane, and nitrous oxide, as well as some other gases that humankind is emitting into the atmosphere, are so-called greenhouse gases, which change the radioactive balance of the Earth with space. Figure 6 shows that this change is equivalent at present to an additional radiative forcing of the Earth's system by about 2.5 Wm^{-2}. This is just about 1% of the total solar forcing, but, on the other hand, about 100 times larger than the present rate of energy use by humankind. It means that the atmosphere in equilibrium might become or may already have become somewhat warmer than it was during the undisturbed conditions that preceded the industrial revolution.

Other things, however, have happened simultaneously. The increasing concentrations of halocarbons in the atmosphere reduce the amount of ozone in the stratosphere, which in turn tends to cool the Earth's surface. Humankind also emits particulate matter. When we burn oil and coal, the sulfur in these fuels is also burned and sulfate aerosols are formed. Similarly, biomass burning in the tropics causes emissions of large amounts of particles. They settle to the Earth's surface or are washed out by precipitation within a week or two, but the emissions are being maintained constantly and therefore so also is an enhanced atmospheric concentration. These aerosols tend to scatter the sun's rays and in this way counteract the greenhouse gas warming. It has been estimated that the warming due to the greenhouse gases being emitted by humans and reinforced by an expected enhancement of the amounts of water vapor in the atmosphere may be reduced by 20–40% by the scattering of solar radiation that the aerosols bring about (see Figure 6). It is important to emphasize, however, that the aerosols are not as evenly distributed over the Earth as are the greenhouse gases and their scattering is therefore not a simple offset of the global mean warming due to enhanced concentrations of greenhouse gases.

There is an additional complication. Soot is also emitted by burning organic matter. Soot is elemental carbon, which absorbs solar radiation very effectively. The present view is, however, that the amounts of soot are insufficient to play a significant role in the radiative balance of the Earth, but measurements are still too few to permit a firm conclusion.

An assessment of the radiative forcing that might be caused by enhanced concentrations of greenhouse gases in the atmosphere does not directly tell us how much the climate of the Earth might change. There are many processes that interact in the creation of the present-day climate. Elaborate models of the climate system are needed in order to interpret the changes of atmospheric composition in terms of a climate change. Even though these models are still rather simple, they give a rough idea about the climate changes to be expected for a given change of the radiative forcing that humankind's interventions bring about. Some of the most valuable analyses are due to Dr. S. Manabe, the first laureate of the Blue Planet Prize in 1992. When embarking on a discussion of this field of scientific endeavor I also leave my own field of expertise and will rather rely on results as achieved by researchers such as Dr. Manabe and above all on the broad assessments of our present knowledge that has been carried out by the Intergovernmental Panel on Climate Change (IPCC), which I have led since 1988.

Climate models are first used to deduce the present climate due to forcing by solar radiation and an atmosphere with preindustrial concentrations of greenhouse gases and aerosols. A reasonable agreement between model results and observations is obtained (the "control run"). Then another experiment is conducted in which changes of the radiative forcing that result from changing concentrations due to humankind's emissions during the past 200 years. The climate system is thus subject to a changing radiative forcing, and the change of the climate brought about in this way can be computed. Figure 7 is an example of the global distribution of the enhanced forcing that has been deduced for 1990 (Kiehl and Briegleb, 1993). We can see the rather uniform forcing between about 1.5 Wm^{-2} (in polar regions) and 2.5 Wm^{-2} (in tropical regions) due to greenhouse gases, on which the spatially very inhomogeneous negative forcing that aerosols bring about is superimposed. In small areas over central Europe and the eastern United States, the total forcing is negative, i.e., the aerosols more than compensate for the warming due to enhanced greenhouse gas concentrations.

Figure 8 shows the changes of the global mean surface temperature as derived both with and without forcing due to aerosols and also, for comparison, observed changes until 1994 (Hadley Centre, 1995). Until about 1950 there are irregular changes of a similar kind in both, as deduced by model experiments and those observed. The observed irregular changes during this period of time are therefore not likely to be due to humankind's emissions. During the latter part of the century, however, all three curves bend upwards. Good agreement between observations and the model experiments is found when the effects of aerosols are included, but this may be fortuitous, since the sensitivity of the model to a given forcing still is quite uncertain. Although the model results and observations agree, this finding is hardly a proof of the quality of the model. It has recently, however, also been found that some of the more detailed features of model results and observations are in accord: warming is essentially restricted to the troposphere, while the stratosphere cools. It is more pronounced in the Southern Hemisphere, where there is no enhanced cooling due to aerosols. The regional patterns of change show some similarities, particularly with regard to the effects of the rather patchy forcing due to the inhomogeneous distribution of aerosols in the atmosphere. This has led the IPCC to the conclusion that "the balance of evidence suggests that there is a discernible human influence on global climate." Humankind does play a role in changing the global climate. The sensitivity of the climate to human interventions is, however, still not well determined.

These findings mean that the climate models may be considered to be somewhat more reliable than was the view a year or two ago. This means that their use in projecting plausible scenarios for the future also has become more reliable. We do encounter another difficulty, however. Projections of likely future human emissions are most uncertain. The IPCC therefore commonly presents alternative projections of such emissions and emphasizes that we as yet cannot tell whether one or the other of such projections is the most plausible one. A number of experiments have been carried out using a "central" projection of emissions, which need not be the most likely one to occur, but still gives an idea about what might happen. Figure 8 (Hadley Centre, 1995) includes projections for approximately the next 50 years. The uncertainty of it is, however, at least ±50% owing to the uncertainty of both projections of future emissions and sensitivity of the climate system to disturbances in the radiative forcing.

Presumably the curve that includes the consideration of aerosols is the most plausible one, but it is still uncertain. It is important to stress that uncertainty means that high projections should be considered to be as plausible as low ones, until we know more accurately the reasons for the remaining uncertainties.

Figure 9 shows the projected global distribution of surface temperature change at about the middle of the next century. It should be recalled that regional changes in different areas may differ significantly from the mean global change and are also subject to stochastic variations that cannot be foreseen. We note, for example, that although a significant change of the global temperature is projected, the spatial distribution shows two regions in the world, one in the North Atlantic and the other one in the North Pacific, that do not experience any warming at all. It is thus important to recognize that spatial variations of the expected changes of climate may well be considerable. This should be considered statistically when assessing impacts of climate change.

A change of climate does not, of course, mean only a change of temperature. Availability of water or, in other words, precipitation and evaporation, may also change what is most important for life on Earth. Generally, the warmer it gets, the more water is being circulated between the oceans, the land, and the atmosphere. But more water is also required to avoid droughts. Since it is by no means certain that the regional distribution of warming will mean a similar increase of precipitation, the prospects for agriculture in a warmer world may change significantly in some regions but less so elsewhere. We cannot foresee the changes very well, and a precautionary approach to climate change therefore becomes the most appropriate.

What should and what can be done? Obviously all greenhouse gases as well as the aerosols play a role, but it is also very clear that carbon dioxide is the most important constituent to consider. We can of course not rely on the cooling effects of enhanced concentrations of aerosols to prevent climate change, since their acidification of precipitation and fresh waters implies that their unrestricted increase is not acceptable. Carbon dioxide is at present responsible for about 60% of the enhanced radiative forcing due to increasing amounts of greenhouse gases in the atmosphere, and it may well grow to 75% or even perhaps 80% if no restrictions on their emissions are imposed. Scientists have tried to derive the "permissible" emissions, if a condition is imposed that atmospheric concentrations must not exceed a given level and that thus a stabilization at that level is aimed for.

We do not know which level of stabilization to be aiming for, however, and the choice really is a political one to be based on careful consideration of costs and benefits of various mitigation options, not by considering the matter exclusively in terms of money. A set of alternative stabilization paths therefore has been chosen to achieve stable concentrations at 450, 550 (close to doubling of preindustrial concentrations), 650, 750, and 1,000 ppmv (see Figure 10). The highest level is not far from quadrupling preindustrial concentrations and would represent a major disturbance of the heat balance of the Earth, i.e., by 6–8 Wm^{-2}. Few consider that this would be acceptable.

Figure 11 shows the outcome of such an analysis. It should be noted that two different pathways toward a certain level of stabilization have been considered in several cases. One can see clearly that delaying preventive measures and thus permitting emissions to rise more steeply to begin with will require stricter reductions later. Also, quite soon, emissions will have to be considerably below what has been projected to occur without restrictions being imposed on the use of fossil fuels in all cases, the more so the lower a level of stabilization is pre-

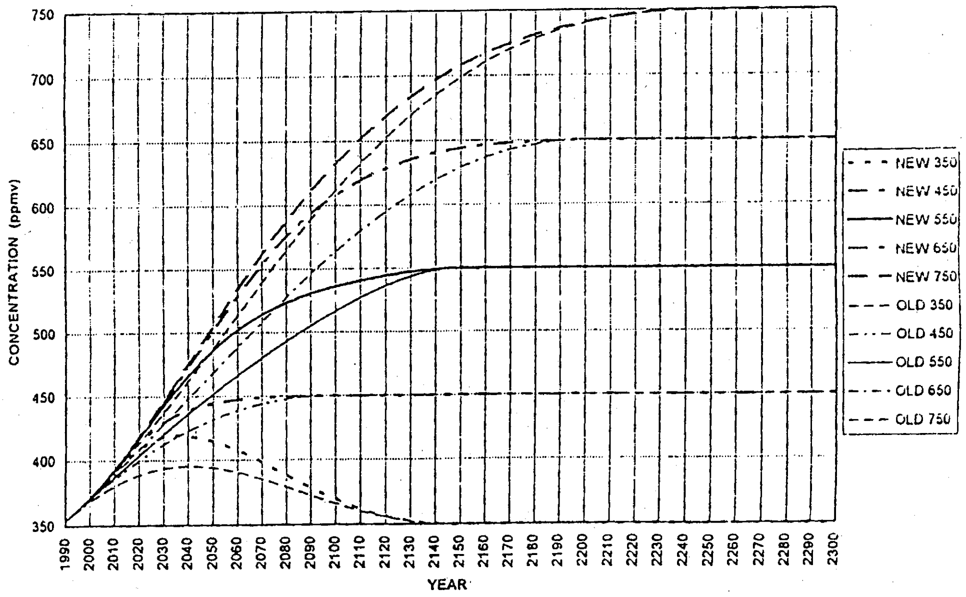


Figure 10. Alternative assumed future changes of atmospheric carbon dioxide concentrations to serve as a basis for assessing alternative future emissions (according to Wigley; see IPCC Working Group I, 1996).

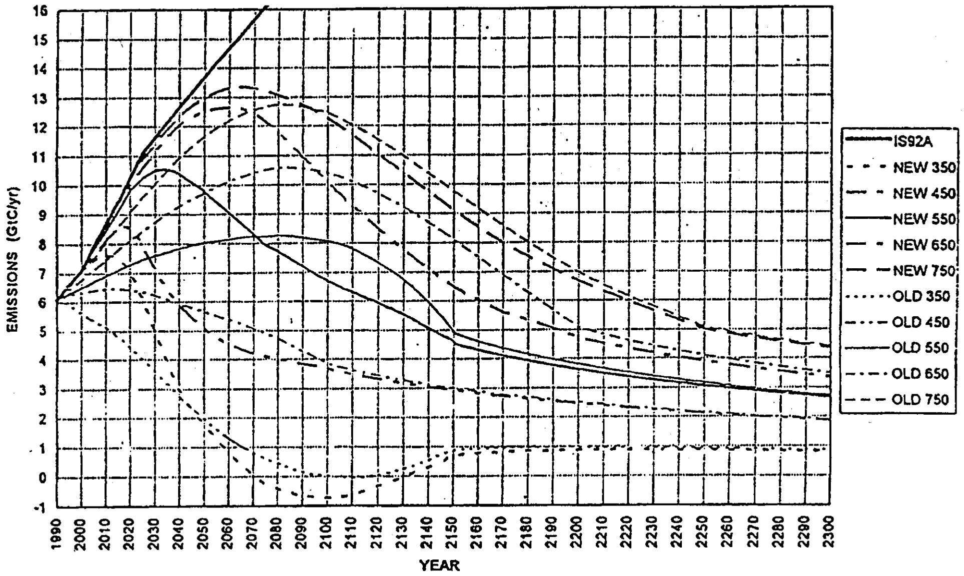


Figure 11. Emission scenarios to ascertain changes of atmospheric carbon dioxide as shown in Figure 10 (according to Wigley). Uncertainty of the values given is ±10–20%. "NEW" and "OLD" show the two alternative stabilization paths as given in Figure 10. The steeply increasing curve shows emissions according to IPCC Scenario IS92a ("Business as Usual"). See IPCC Working Group I and *Synthesis Report*, 1996.

scribed. Although this analysis still is somewhat uncertain because of our limited knowledge about the carbon cycle, it becomes very clear that nature puts some restrictions on how much we may allow ourselves to disturb the global environment, and we are able to give an approximate indication of what may be required.

To be more specific, consider as an example the stabilization level of 550 ppmv. If emissions are permitted to rise to about 10.5 billion tons of carbon per year, the emissions will have to be reduced rather quickly thereafter and need to be well below present emissions of about 7 billion tons before the end of the century (also including emissions due to net deforestation and changing land use). A more precautionary approach would lead to maximum emissions of merely 8–9 billion tons of carbon per year and permit somewhat higher emissions during the latter part of next century.

Some further insight is gained if, for a moment, we instead consider the emissions per capita and also take note of the marked prevailing differences between developed and developing countries. The global average annual per capita emissions of carbon dioxide due to the combustion of fossil fuels is at present about 1.1 tons (as carbon). In addition, a net amount of about 0.2 ton per capita is emitted owing to deforestation and changing land use, i.e., in total about 1.3 tons per capita. The average fossil fuel emissions per capita in developed and transitional economy countries is about 2.8 tons, and emissions range from about 1.5 to 5.5 tons for individual countries. The figure for developing countries, on the other hand, is 0.5 ton on average, ranging from 0.1 ton to, for a few countries, above 2.0 tons (figures are for 1990).

Because of the expected growth of the world population during the first half of the next century, the emissions as given in Figure 11 imply that per capita emissions must not increase

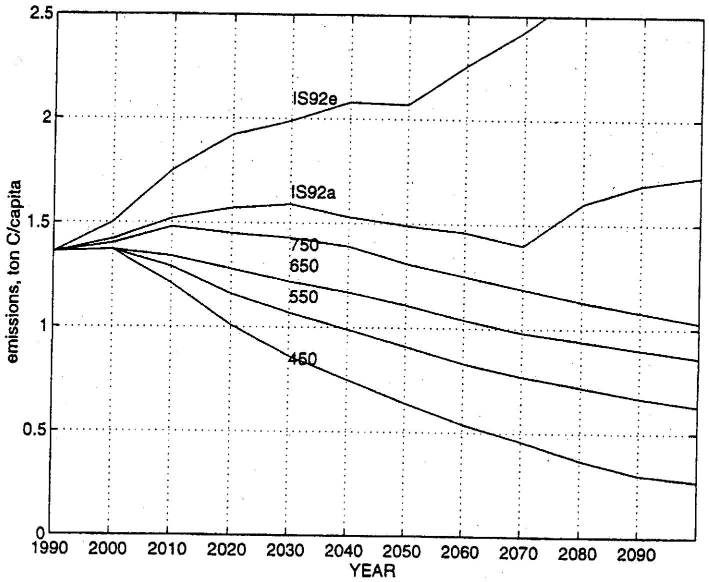


Figure 12. Projected future emissions of carbon dioxide in tons per capita, based on the scenarios given in Figure 11 and assuming an increase in world population according to the central scenario given by the United Nations. Emissions due to net deforestation and changing land use have been included. The uppermost curve is the IPCC Scenario IS92a ("Business as Usual"). See also IPCC *Synthesis Report*, 1996.

at all if stabilization at or below 550 ppmv is aimed for (see Figure 12). It is likely, however, that developing countries will consider themselves entitled to some increase of per capita emissions above their present levels because of the prevailing major differences between developed and developing countries that I referred to before. This reinforces the need for developed countries to take early steps to reduce their emissions of carbon dioxide, if stabilization below doubling is to be accomplished. But even very drastic reductions in developed countries would not permit developing countries to exceed by much the present annual per capita emissions for the world—1.3 tons, a figure which includes emissions owing to deforestation.

Sustainable development would become easier if more efficient energy use could be achieved in both developing and developed countries. In this way, some more time would become available for finding long-term solutions, since it is obviously not enough to provide and use energy more efficiently. We must find other sources for energy besides fossil fuels, something which cannot be accomplished quickly, since about 80% of the energy used in the world today comes from burning fossil fuels. To develop the technology, demonstrate its feasibility, and introduce it into the energy market will necessarily take time if the costly early retirement of capital investments in the existing energy system is to be avoided.

The choices we have are, on one hand, solar energy or other forms of energy derived from it, particularly bioenergy and hydropower, or on the other hand, nuclear energy. There is plenty of solar energy available, directly in the form of solar radiation and indirectly as hydropower, wind energy, bioenergy, and geothermal energy. We will never run out of it, but it is not always easy to harness efficiently and cheaply. The resources of nuclear energy are limited, and for a long-term supply breeder reactors (and in the very long term, fusion reactors) will in any case be required. Major development projects will be required and funding for research and development must increase substantially rather than decrease, as is presently the case. Developed countries must take the lead also in this regard, and it is doubtful that private initiatives will be adequate until the prospects for new markets become much more obvious. Only the governments of the world can provide the incentives to achieve this by agreeing that new energy systems will be required in the future.

The previous analysis is important because some semiquantitative bounds are established for future development, but it should be emphasized that they are still only indicative. Merely carbon dioxide was considered. We should also recall that whenever burning coal and oil, sulfur is emitted into the atmosphere in the form of sulfur dioxide. It ameliorates the warming due to enhanced greenhouse gas concentrations. Emissions of sulfur, however, contribute in a major way to the acidification of fresh waters and soils as well as to air pollution in industrialized regions. Some developing countries are at present trying to cope with these environmental issues by decreasing such emissions, and many more will have to do so rather soon. Their elimination would obviously imply that the greenhouse gas warming would be more fully realized. Similarly, the gradual decrease of CFC gases, which is expected at about the beginning of the next century as a result of human efforts to prevent the destruction of the ozone layer, would also decrease greenhouse warming. On the other hand, stratospheric ozone concentrations would then be restored and also the full effect of ozone as a greenhouse gas. These examples, and there are more of them, illustrate that the global environmental issues are all more or less interrelated. The global system needs to be considered as a whole.

The difficulty is, of course, that only a small part of the global population and politicians of the world as yet really consider these environmental issues as sufficiently serious to justify more concerted action. It is then interesting to dwell for a moment on the ozone issue, which was dealt with remarkably quickly once it had been established and generally accepted that humankind's emission of CFC gases was the cause of the development of the "ozone hole" over Antarctica. The warnings of possible serious modifications of the ozone layer due to our emissions of CFC gases had been voiced already during the early 1970s. Almost 10 years of negotiations finally led to an agreement on a convention for the protection of the ozone layer in 1985. However, it did not really contain any specific restrictions on the use of CFC gases. But when the ozone hole was discovered in 1985, it took only about 18 months to reach an agreement on rather powerful measures, known as the Montreal Protocol. These were made even more stringent by international agreements reached in 1990 and 1993. The measures that entered into force at the beginning of 1996 will presumably stabilize the atmospheric concentrations of these compounds at about the turn of the century.

The climate change issue is, however, a much more difficult one. Its possible consequences, as well as measures to prevent a change of climate, affect the global society as a whole. The CFC gases were produced by merely a handful of companies and their use was limited to rather few products on the market. The emissions of carbon dioxide and the use of energy that it signifies really concern almost everybody.

One may of course ask the question if we will one day see climate change become politically equivalent to the ozone hole. I think, however, that this is a dangerous attitude to the issue. Even though the increased occurrence of extreme events such as severe storms, floods, and droughts may be the signature of a climate change, it will for some time yet be difficult to ascertain whether one or another event of this kind is really due to an ongoing human-induced change of the global climate. This constitutes a real dilemma and may delay actions. My simple answer at this moment is that scientists will have to pursue their research but perhaps plan their theoretical and observational efforts in a manner that is most useful to the politicians and others who will have to deal with this issue. But, perhaps more droughts, floods, and the like will be necessary anyway before more far-reaching measures will be taken.

A few additional words about the role of the scientific community in the context of climate change might be of interest. The research process will of course go on and may be financed more or less adequately. The key questions I want to address, however, are how to assess and synthesize our knowledge, and how might interaction be best organized between scientists on the one hand and politicians, representatives of industry, the press, and the public in general on the other.

- It is first of all important to aim at participation by scientists from all over the world in the assessment of the climate change issue. By far most of the relevant research, particularly concerning truly global aspects of the problem, is carried out in developed countries, although increasing numbers of researchers from developing countries are becoming engaged. The most efficient way of communicating new scientific findings to a broad community all over the world is through the scientists. Leading politicians, not the least in developing countries, are likely to take more notice of views held by scientists in their own country than to accept advice from scientists abroad. A global network of scientists is therefore essential.

- The scientific process must be open. The aim is, however, not necessarily to reach agreement on every relevant issue. Scientific controversy is, after all, the basis for scientific progress. It then becomes essential to clearly bring to the public those issues on which agreements can be reached, and at the same time describe where the scientific frontier is to be found and what the controversies are. To achieve this, it is important also to reach out to the scientific community in a scientific review process so that the core groups that are given the responsibility to carry out scientific assessments cannot be accused of not being fair and objective in carrying out their tasks. Even though there are some that are not satisfied with the way the IPCC has been carrying out this task, there is in reality a broad backing of IPCC views from the scientific community. This credibility is essential in order for the assessment process to be recognized. If there were some other group of scientists that in a credible, scientific manner could maintain a different view on the issue of climate change, the world would of course be bewildered and it would be difficult to achieve anything politically.

Future actions to address the issue of climate change cannot be successfully initiated unless cooperation within the business community, i.e., the industrial complex, is established. Some kind of partnership is desirable. I would like to see leading representatives from these communities present their views on how to best approach these environmental issues on the basis of the IPCC assessment of technological and financial implications. What would their difficulties and priorities be? The IPCC would welcome such cooperative efforts.

Social considerations also become very important when attempting to assess damage due to a climate change as well as judge the implications of measures to be taken. The IPCC addresses these issues in its most recent assessment. It is clear that the economic evaluations usually do not yet adequately include social aspects of the issues at stake. Rather, exclusively economic analyses dominate. And yet we know that major changes in social systems might well be necessary in order to deal with climate change. And also, we see daily around us how easily crises develop when stress on people or groups of people, i.e., countries, cannot be managed peacefully. Not only is the climate system complex and in a sense chaotic, but so is society. Presently available socioeconomic models then usually break down and science then is hardly any longer the key to finding solutions. Perhaps it will be possible to judge on the basis of further research when such situations may be on the way. A dialogue between the scientific community and the political community is in any case a prerequisite for making use of what scientific research can possibly achieve. This is not really well developed yet, but perhaps on the way.

References

Hadley Centre (1995). Modelling Climate Change, 1860–2050. Department of the Environment, the Met Office, UK.

IPCC (1990). Assessments: Climate Change 1990.

I Working Group I, The IPCC Scientific Assessment, Cambridge University Press.
II Working Group II, The IPCC Impact Assessment, Canberra: Australian Government Printing Service.
III Working Group III, The IPCC Response Strategies, Geneva: WMO/UNEP.

IPCC Scientific Assessment (1992). I, Working Group I, Chapters 1–5; III, Working Group III, Chapter 6, Cambridge University Press.

IPCC (1996). *Climate Change 1995.* IPCC Second Assessment Report.
Synthesis Report. An Assessment of Scientific Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change. Geneva: WMO (to be published).
Working Group I. The Science of Climate Change.
Working Group II. Impacts, Adaptation and Mitigation Options.
Working Group III. Economic and Social Dimensions of Climate Change.

Kiehl, J.T. and Brieleb, P. (1993). "The Relative Roles of Sulfate Aerosols and Greenhouse Gases in Climate Forcing." *Science*, 260, 16 April, 311–314.

Tucker, C.J., Fung, I.Y., Keeling, C.D., and Gammon, R.H. (1986). "The Relationship of Global Green Leaf Biomass to Atmospheric Carbon Dioxide Concentrations." *Nature*.

Major Publications
Dr. Bert Bolin

Articles

Berggren, R., B. Bolin and C. Rossby. "An Aerological Study of Zonal Motion, Its Perturbations and Break-down." *Tellus*, 1 (1949),14–37.

Bolin, B., and J. Charney. "Numerical Tendency Computations from the Barotropic Vorticity Equation." *Tellus*, 3 (1951), 248–257.

Bolin, B. "The Adjustment of a Non-Balanced Velocity Field Towards Geostrophic Equilibrium in a Stratified Fluid." *Tellus*, 5 (1953), 373–385.

—. "Numerical Forecasting with the Barotropic Model." *Tellus*, 7 (1955), 27–49.

—. "An Improved Barotropic Model and Some Aspects of Using the Balance Equation for Three-Dimensional Flow." *Tellus*, 8 (1956), 61–75.

Bolin, B. and E. Eriksson. "Changes in the Carbon Dioxide Content of the Atmosphere and Sea Due to Fossil Fuel Combustion." In *The Atmosphere and the Sea in Motion*. A scientific contribution to the Rossby Memorial Volume edited by B. Bolin. New York, Rockefeller Institute Press, 1959, 130–142.

Bolin, B. "On the Use of Tritium as a Tracer for Water in Nature." In *Second UN International Conference on the Peaceful Uses of Atomic Energy*, Geneva (1958), Session D-19, 176, 336–343.

—. "On the Exchange of Carbon Dioxide Between the Atmosphere and the Sea". *Tellus* 12, 274–281.

Bolin, B. and H. Stommel. "On the Abyssal Circulation of the World Ocean, IV. Origin and Rate of Circulation of Deep Ocean Water as Determined with the Aid of Tracers." *Deep Sea Research*, 8 (1961), 95–110.

Bolin, B. *Transfer and Circulation of Radioactivity in the Atmosphere. Nuclear Radiation in Geophysics*, edited by H. Israël and A. Krebs. Springer-Verlag, 1962, 136–168.

Bolin, B. and C.D. Keeling. "Large-Scale Atmospheric Mixing as Deduced from the Seasonal and Meridional Variations of Carbon Dioxide." *Journal of Geophysical Research*, 68 (1963), 3899–3920.

Keeling, C.D. and B. Bolin. "The Simultaneous Use of Chemical Tracers in Oceanic Studies I. General Theory of Reservoir Models." *Tellus*, 19 (1967), 566–581.

Keeling, C.D. and B. Bolin. "The Simultaneous Use of Chemical Tracers in Oceanic Studies II. A Three-Reservoir Model of the North and South Pacific Oceans." *Tellus*, 20 (1968), 17–54.

Bolin, B. and W. Bischof. "Variations of the Carbon Dioxide Content of the Atmosphere in the Northern Hemisphere." *Tellus*, 22 (1970), 431–442.

Multiple Authorship. "Sweden's Case Study. Air Pollution Across National Boundaries: The Impact of Sulfur in Air and Precipitations. Sweden's Case Study for the UN Conference on the Human Environment." Stockholm, The Royal Ministry for Foreign Affairs and the Royal Ministry of Agriculture, 1971, 96.

Bolin, B. "Atmospheric Chemistry and Environmental Pollution." In *Meteorological Challenges: a History*, edited by D. P. McIntyre. 1972, 237–266.

Bolin, B., and H. Rodhe. "A Note on the Concepts of Age Distribution and Transit Time in Natural Reservoirs." *Tellus*, 25 (1973), 58–62.

Bolin, B. and C. Persson. "Regional Dispersion and Deposition of Atmospheric Pollutants with Particular Application to Sulfur Pollution over Western Europe." *Tellus*, 27 (1975), 281–310.

Bolin, B. "A Critical Appraisal of Models for the Carbon Cycle." In *The Physical Basis of Climate and Climate Modeling*. Report of the International Study Conference in Stockholm July–August 10, 1974. Appendix 8, WMO/GARP Publication series No.16, 225–235.

Bolin, B. and R.J. Charlson. "On the Role of the Tropospheric Sulfur Cycle in the Short-Wave Radiative Climate of the Earth." *Ambio*, 5 (1976), 47–54.

Bolin, B. "Changes of Land Biota and Their Importance for the Carbon Cycle." *Science*, 196 (1977), 613–615.

—. "Modeling the Oceans and Ocean Sediment and their Response to Fossil Fuel Carbon Dioxide Emissions." In *The Fate of Fossil Fuel CO_2 in the Oceans*, edited by N.R. Andersen and A. Malahof. New York: Plenum Press, 1977, 81–95.

Bolin, B., E.T. Degens, P. Duvigneaud and S. Kempe. "The Global Biogeochemical Carbon Cycle." In *The Global Carbon Cycle*, edited by B. Bolin, E.T. Degens, S. Kempe and P. Ketnner. SCOPE 13 . Chichester: John Wiley & Sons, 1979, 1–56.

Bolin, B. "Climatic Changes and Their Effects on the Biosphere." Fourth IMO Lecture 1979. Geneva: WMO No.542, 49.

Bolin, B., A. Björkström, C.D. Keeling, R. Bacastow and U. Steigenthaler. SCOPE 16: *Carbon Cycle Modeling*. New York: John Wiley & Sons, 1981, 1–28.

Bolin, B. "Changing Global Biochemistry." In *Oceanography. The Present and Future*, edited by P.G. Brewer. New York: Springer-Verlag, 1983, 305–326.

Bolin, B., A. Björkström, K. Holm O and B. Moore. "The Simultaneous Use of Tracers for Ocean Circulation Studies." *Tellus* , 35B (1983), 206–236.

Bolin, B., P.J. Crutzen, P.M. Vitousek, R.G.. Woodmansee, D.E. Goldberg and R.B. Cook. "Interactions of Biogeochemical Cycles." In *The Major Biogeochemical Cycles and their Interactions*, edited by B. Bolin and R.B. Cook, SCOPE 21. Chichester: John Wiley & Sons, 1983, 1–39

Bolin, B. "Biogeochemical Processes and Climate Modeling." In *The Global Climate*, edited by J.T. Houghton. Cambridge: Cambridge University Press, 1984, 213–223.

Bolin, B. "How Much CO_2 Will Remain in the Atmosphere? The Carbon Cycle and Projections for the Future." In *The Greenhouse Effect, Climatic Change, and Ecosystems*, edited by B. Bolin, B.R. Döös, J. Jäger and R.A. Warrick. SCOPE 29 . Chichester: John Wiley & Sons, 1986, 93–155.

Bolin, B., J. Jäger and B.R. Döös and R.A. Warrick (Eds). "The Greenhouse Effect, Climatic Change, and Ecosystems. A Synthesis of Present Knowledge." In *The Greenhouse Effect, Climatic Change, and Ecosystems*, edited by B. Bolin, B.R. Döös, J. Jäger and R.A.

Warrick. SCOPE 29 . Chichester: John Wiley & Sons, 1986, 1–32.

Bolin, B., A. Björkström, and B. Moore. "Uptake by the Atlantic Ocean of Excess Atmospheric Carbon Dioxide and Radiocarbon." In *Contribution of Geophysics to Climate Change Studies*, edited by A. Berger, R. Dickinson and J. Kidson. Proceedings of IUGG Symposium, Vancouver. Washington: IUGG/AGU, 1989, 57–78.

Moore, B., B. Bolin, A. Björkström, K. Holm O and C. Ringo. "Ocean Carbon Models and Inverse Methods." In *Oceanic Circulation Models: Combining Data and Dynamics*, edited by D.L.T Anderson and J. Willebrand. Dordrecht: Kluwer Academic Publishers, 1989, 409–449.

Others

SCOPE Reports, ICSU Science Committee on Problems of the Environment.

Bolin, B., E.T. Degens, S. Kempe, P. Ketner (Eds). "The Global Carbon Cycle", 13 (1979).

Bolin, B., "Carbon Cycle Modeling", 16 (1981).