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GLOBAL ENVIRONMENTAL MANAGEMENT:

A HISTORICAL PERSPECTIVE*

by

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Abstract

Our understanding of the Earth system has been developing rapidly over the past few decades in response to major global environmental problems such as the depletion of the ozone layer and the impact of global climate change. Our desire to understand the Earth system is partly driven by the need to manage the human impacts. In the case of human-induced global climate change, mathematical models have been instrumental in defining the existence of the potential for global warming. We can study the evolution of our understanding in global climate change over the past 200 years and critically assess how our changing understanding of the earth system has influenced our management decisions.

1. Introduction

The greenhouse effect and the potential for inducing climate change have attracted considerable attention from the scientific community and the public over the past few years. A large body of technical and popular literature has been published on virtually every aspect of the enhanced greenhouse effect. Accordingly, this paper can present only an overview of the greenhouse effect and some of the key issues raised focusing on our management decisions. In the first section of the paper, the sources and impact of the greenhouse gases are discussed. The following sections examine the greenhouse gases and the problem of forecasting and responding to climate change. In the final section, the need for the long-term management of global climate is raised.

2. The Greenhouse Effect

The term "greenhouse effect" has been employed extensively in both the technical and the popular literature to refer to the predicted future warming of the planet over the next 50 to 100 years (Schneider 1989, Gribbin 1982, Boyle and Ardill 1989, Henderson-Sellers and Blong 1989, Tucker 1981). More specifically, the term greenhouse effect refers to the effect of the warming of the planet through the presence of the greenhouse gases, such as water, carbon dioxide (CO_2), and methane (CH_4), which absorb the heat radiated from the Earth's surface. These greenhouse gases already produce atmospheric warming of approximately 33°C. Strictly, then, the concern associated with the release of greenhouse gases due to human activities is with their potential for producing substantial and rapid climate change – the enhanced greenhouse effect.

The greenhouse effect may represent the greatest single challenge that society has yet faced. The challenge of reducing the impact of climate change induced by the greenhouse effect is one that involves every member of our global society. Each person is responsible, either directly or indirectly, for a small contribution to the global release of greenhouse gases to the atmosphere. However, the contributions of greenhouse gases from the different countries vary dramatically. Table 1 lists carbon emissions by regions for the world. Citizens of the industrialized countries are, on average, contributing the largest amounts of greenhouse gases, particularly chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), to the atmosphere. Nevertheless, developing countries are contributing an increasing proportion of global carbon emissions. Carbon dioxide emissions from China, for example, have increased 28% between 1990 and 1998.

Just as the releases of the greenhouse gases are widely distributed, so too are the potential impacts (Schneider 1989, Jaeger 1988, Pearman 1988, Watson et al. 1998). The impacts may, however, bear no relation to the point of release of the greenhouse gases, since the long lifetime of these gases ensures that they will be distributed throughout the global atmosphere. In particular, we observe the rapid transport and mixing of the release of greenhouse gases in the northern hemisphere, where the vast majority of greenhouse gas emissions occur, into the southern hemisphere (Logan et al. 1981, Ramanathan et al. 1985, Taylor 1989). As a consequence, average greenhouse gas concentrations in the southern hemisphere are only a few percent lower than the corresponding average northern hemisphere concentrations.

In summary, because of individual contributions to the emission of greenhouse gases, the long lifetime of these gases, and their rapid mixing throughout the global atmosphere, the release of greenhouse gases has become a global problem that can be addressed only by concerted global action.

Understanding the relationship between trace gases in the atmosphere and climate has been increasing for some time. The history of research on the greenhouse effect has spanned nearly two centuries. Table 2 provides a brief summary of this research and the potential for climate change. We note that the development of climate models has had a similarly long history; Washington and Parkinson (1986) discuss the historical development of climate models.

3. The Greenhouse Gases

The important greenhouse gases are listed in Table 3, along with their major sources, an estimate of the percentage attributed to the industrial release of the greenhouse gas, and the percentage attributed to the release from the biosphere. Table 3 clearly indicates that, with the exception of CFCs, the biosphere represents an important source of greenhouse gases. We note that the percentage attributed to the biosphere includes releases through both natural processes and anthropogenically induced changes to the biosphere. For example, for CO_2, the biospheric emission value in Table 3 is largely associated with the clearing of the forests. For methane, however, the biospheric release occurs when anaerobic oxidation breaks down waste material containing carbon to methane. This waste material includes natural wetland sources, particularly the tundra, landfills (garbage dumps), and rice paddies, an important form of agriculture (Cicerone and Oremland 1988). Methane is also released in large quantities through enteric (intestinal) fermentation, particularly from sheep and cattle (Cicerone and Oremland 1988, Ward et al., 1993).

The observation that the biosphere contributes a substantial proportion of the release of greenhouse gases to the atmosphere has important implications for the control of climate change. If policies for the control of greenhouse gases are to succeed in the longer term, then an aspect of these policies must include control of the biospheric emissions of the greenhouse gases. This means, for example, not just reducing the rate of deforestation, but also examining the wider range of agricultural practices and their contributions to the emissions of greenhouse gases. Humans are continuing to appropriate an increasing proportion of the biosphere and its products (Vitousek et al. 1986). A global study is required that focuses on current and proposed land-use practices from the viewpoint of assessing current levels and potential changes in greenhouse gas emissions. If one assumes that substantial reductions in greenhouse gas emissions are achieved by industry, then the global temperature will ultimately be determined by changes in land use and concomitant changes in greenhouse gas fluxes.

In addition, since the biosphere is a major source of greenhouse gases and since the biosphere is expected to change in response to global warming, a significant potential for feedbacks exists (Lashof 1989). Such feedbacks may be positive, leading to increasing emissions of greenhouse gases with increasing temperature, or negative, where increased temperature produces greater uptake of greenhouse gases, due to increased plant growth, for example (Gifford 1988, Pittock and Nix 1986, Schimel et al. 1996). Hence, the greatest uncertainty associated with forecasting future greenhouse gas emissions is associated with changes in the biospheric sources.

4. Climate Change

The state-of-the-art approach to assessing the impact of greenhouse gases upon global climate is through global climate modeling studies. According to Gates et al. (1990), “Such models are the only available means to consider simultaneously the wide range of interacting physical processes that characterize the climate system, and their objective numerical solution provides an opportunity to examine the nature of both past and possible future climates under a variety of conditions.”

Climate models, while of great complexity themselves, are considerable simplifications of the immensely complex global climate system (Washington and Parkinson 1986, Peixóto and Oort 1984). However, in spite of this complexity in climate models, all climate modeling studies to date indicate that significant global warming will occur if greenhouse gases are allowed to increase over the next century. In a review of climate model results for a doubling of CO_2, Schneider (1989) concluded that the likely global warming will be of the order of 2-6°C over the next century. The Intergovernmental Panel on Climate report (IPCC 1996) narrowed this range to 2-3°C. The relative contribution of each greenhouse gas is listed in Table 4. Maxwell and Barrie (1989) note that temperature changes at high latitudes could be as much as 2.4 times greater than the global average temperature change during winter.

Schneider (1989), Mitchell (1989), Dickinson (1989), and Cess et al. (1989) found that the parameterization of the hydrological cycle, cloud climate feedbacks, and the response of the oceans to global warming were key factors in producing the variability of the predicted responses of the models to increases in greenhouse gas concentrations. Currently the median estimated global warming for an equivalent doubling of atmospheric CO_2 is ~2.0°C (Kattenberg et al. 1996). Jouzel et al. (1987) note that a change in average temperature of more than 2°C could be outside the usual range of temperatures experienced in the past 160,000 years. In the face of the consensus of climate models, it appears very unlikely that no global warming will take place (Kattenberg et al. 1996).

Atmospheric CO_2 has increased from a preindustrial level of ~280 ppm to ~370 ppm in 2000, implying that potentially significant climate change may have already occurred. Evidence for such a global warming has been obtained from the analysis of all available surface air temperature measurements, where care has been taken to remove systematic errors such as the urban heat island effect and the relocation of measurement sites, for example, up and down mountains and to or from coastlines (Jones et al. 1988). Measured surface temperatures have been found to increase between 0.3 and 0.6^{o} C (Jones et al. 1997, Hegerl et al. 1997, Hegerl et al. 1996, Jones and Hegerl, 1998, Santer et al. 1995). These data reveal that a warming of 0.5°C has occurred over the past century and that the past two decades have seen many of the warmest years on record. Other evidence includes rapidly warming oceans (based on the satellite measurements of the global radiation budget experiment), record cold stratospheric temperatures (Karoly 1989), and analysis of tree-ring data (Jacoby 1989) and other proxy temperature reconstructions (Mann et al. 1999), all of which are consistent with the possibility of global warming induced by the increase in greenhouse gases.

While these results are indicative of a climate warming, they do not represent definite proof that the anthropogenic greenhouse effect produces climate warming. Establishing a direct causal link between the apparent global warming and the greenhouse effect on the basis of observational data will remain problematic, partly because of the complexity of the natural system and partly because of the natural variability of the system, which may explain the observed climate behavior. Put another way,. unknown factors or unknown combinations of known factors, other than the greenhouse effect, may be producing the observed climate change. Natural variability therefore limits our ability to determine the best management decisions.

5. Impacts of Global Warming

The impacts of global warming are, at present, predicted to affect all peoples. It is also highly likely that the effects will be substantial and will not be restricted to a single aspect of our lives. Many excellent early studies of the potential impacts of climate change at the continental scale have been prepared (Pearman (1988) and Henderson-Sellers and Blong (1989). Table 5 lists the broad range of potential impacts on the natural environment and human society that have been attributed to climate change induced by the release of greenhouse gases. Glantz (1988) uses forecasting by analogy to study societal responses to regional climate change in the United States. Such an approach could usefully be applied to other regions. Watson et al. (1998) provide a recent survey of the possible regional impacts of climate change.

While a wide range of potential impacts can be identified as arising from the greenhouse effect (Pearman 1988, Henderson-Sellers and Blong 1989, Watson et al. 1998) and despite identification of a 0.5°C rise in temperature (Jones et al. 1988, 1997), no single weather event or climate change can be attributed with 100% certainty to the enhanced greenhouse effect. This does not mean that the impacts of climate change have not occurred or will not occur. Rather, it reflects the problem of identifying with reasonable certainty significant departures from the normal when the climate system exhibits considerable natural variability (Karoly 1989, Hegerl et al. 1996, 1997, Jones et al. 1988, 1997). However, Tsonis and Fisher (1989) noted that six of the warmest years on record occurred during 1980-1988. They calculated that the probability of this being a manifestation of the natural variability of the system was between .010 and .032. Recent analysis has found also that 1998 was possibly the warmest year in at the past 1000 years (Mann et al. 1999). Record of continuously increasing temperature, with identifiable departures from the usual climate, may take another decade or longer to materialize. In the meantime, the opportunity to delay or significantly reduce the magnitude of the enhanced greenhouse effect will be lost, thus limiting our future management choices.

It is hoped that by examining climate model predictions, a greenhouse warming fingerprint can be identified that can then be used with existing climate data to test the greenhouse warming hypothesis. We would also expect that climate models should be able to reproduce the climate of the past century during which greenhouse concentrations have risen dramatically. Recent climate modeling studies that include the effects of atmospheric aerosols continue to improve the match between observed and modeled temperature trends (Hasselmann 1997, Mitchell et al. 1995, Roeckner et al. 1996). As we continue to refine our climate modeling skill, so we will improve our ability to determine both desirable, and potentially undesirable consequences, associated with global climate change.

6. Responding to Climate Change

If we are convinced that we will be subjected to the broad range of impacts arising from the enhanced greenhouse effect, we must act to reduce the flux of greenhouse gases to the atmosphere. The enforcement of the UN Framework Convention on Climate Change (UNFCCC) in 1994 indicates that a broad consensus has been achieved that action must be taken to limit the emissions of greenhouse gases to the atmosphere. The UNFCC includes a statement of a desirable goal that includes "stabilising greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system."

However, it is also clear that a complete consensus concerning action on limiting greenhouse gas emissions has not been achieved to date. Most notably the United States, which is the largest emitter of greenhouse gases, has not ratified the UNFCCC. Complications in international negotiations will continue to arise in that any decisions concerning the limitation of greenhouse gas emissions to the atmosphere will be taken in a much broader social, political, and economic context, thus applying a strong constraint on what is achievable in terms of long term greenhouse gas emission reductions. The lifetime of greenhouse gases being of the order of years to decades means that emission reductions should ideally be implemented as soon as possible. It would be unwise to wait for improved observational information or more definitive research results to become available because the eventual global warming by, say, 2030 will represent not only the annual release of greenhouse gases but the accumulated atmospheric concentration up to that year. The addition of CO_2 to the atmosphere is also fundamentally irreversible, again limiting our management options. The eventual equilibrium of atmospheric CO_2 with the oceans and biosphere will leave 15-30% of the CO_2 in the atmosphere for thousands of years (Broecker and Peng 1982, Sarmiento et al. 1992, Archer et al. 1998).

A further problem associated with the timing and level of required control of greenhouse gas emissions arises from the delay in the observed warming of the atmosphere due to the large heat capacity of the oceans (Mitchell 1989). This apparent delay in global warming may also delay action to reduce greenhouse gas emissions because of a lack of clear evidence of global warming. Yet, while the oceans may slow the climatic response to the greenhouse gases, the atmospheric temperature will ultimately rise to a temperature determined by the ability of the greenhouse gases to absorb and re-radiate heat back to the earth's surface. By analogy, we have switched on a global heater for the lifetime of the greenhouse gases, which we cannot easily turn off when faced with an undesirable rise in temperature.

In many instances of local-scale pollution, such as in London, air pollution levels were allowed to reach dangerous levels before controls were implemented. The unfortunate consequence of such action in the case of London was a reported 4000 additional deaths for the period of 5-9 December 1952 (Seinfeld 1986). However, even though we are aware of the causes of these local-scale problems, air pollution levels are still allowed to exceed acceptable levels in many cities around the world.

The lesson to be learned here is that action at the local scale, with clearly identifiable and desirable goals, has proceeded to date with only limited success, over many decades using a wide range of techniques. Comprehensive new approaches are needed to solve the problem of atmospheric pollution, approaches that can be applied not only at the local-scale but also at the regional and global scales.

Current proposals for the reduction of greenhouse gases center on an increase in energy efficiency, largely based on “no regrets” actions. This approach has as its chief advantage the economic benefits associated with reduced expenditure on energy and the concomitant reduction in local- and regional-scale pollution associated with energy generation. However, increased energy efficiency will, at best, only delay the eventual climate warming. Increases in the total energy demand will rapidly overcome any gains in energy efficiency that may be achieved.

What is required in the longer term is the development and application of alternative energy sources that do not release greenhouse gases during energy generation. Two current competing methods of energy generation are terrestrial nuclear energy and solar energy. Either route will probably require similar and substantial capital input in order to overcome technical problems associated with its large-scale application if it is to replace fossil fuel energy generation (International Energy Agency 1987).

Since terrestrial nuclear energy is not currently a sustainable alternative in the long term because of the continual generation of waste, the threat of nuclear proliferation, and the release of radioactive environmental pollutants with extremely long half-lives, a major long-term investment should be made into sustainable alternatives. The development of economically competitive alternative energy systems would be advantageous to developed countries such as the United States because of the possibility of exporting both the technology and its products, such as liquid hydrogen. We note that solar energy may be converted to liquid hydrogen, which may then be employed as a substitute for liquid hydrocarbon fuels, particularly in transport (International Energy Agency 1987). Australia and other countries, such as those in the Middle East, would probably enjoy a competitive advantage in that they have large amounts of sunshine and relatively inexpensive land on which to base solar energy generating facilities.

Table 6 presents estimates of the cost of reduction of carbon dioxide emissions. It also indicates that solar thermal technology may represent an economic alternative to nuclear power at the present. Table 6 also shows the relatively low cost of improving energy efficiency to reduce CO_2 emissions. For comparison, the estimated current levels of investment in the development of new technologies in the United States to reduce CO_2 emissions are presented in Table 7. Unfortunately, the levels of investment in improvements in energy efficiency and solar energy do not reflect their cost effectiveness in reducing CO_2 emissions, as indicated in Table 6. Carbon sequestration has also been adopted as a major strategy for the reduction of greenhouse gas emissions in the United States and is now the subject of a major program of research by the U.S. Department of Energy. Most likely, however, a combination of approaches will be needed to substantially reduce greenhouse gas emissions.

Every day each person in a developed country adds to the global atmosphere ~12 kg of carbon as CO_2, and lesser amounts of the other greenhouse gases. Since each individual is contributing to the greenhouse effect, it is possible to address the problem not only from national and international perspectives, but also from the perspective of the individual. While the need to assess national contributions to the release of greenhouse gases and the development of a national strategy are important goals, if they are to be achieved they must include a component that addresses the individual contribution to the release of greenhouse gases. Detailed information on both the direct and the indirect release of greenhouse gases should be provided to all persons so that they can assess their contribution to the release of greenhouse gases and develop a personal plan for the reduction of greenhouse gases by selecting alternative activities that result in lower greenhouse gas emissions. Examples of potential reductions in the release of greenhouse gases should also be presented. The provision of detailed and reliable information should ensure a greater reduction in greenhouse gas emissions than can be achieved by ad hoc measures alone, particularly where proper account of the indirect release of greenhouse gases is included. This will also allow individuals the freedom to decide with confidence how they can best contribute to the reduction of greenhouse gas emissions.

While only limited action has been taken to reduce greenhouse gas emissions at the global scale, important developments have been occurring in the past few years. Table 8 lists some of significant international actions on global environmental change. While this list is impressive, it is questionable whether the present rate of progress at the international level will lead to significant reductions in CO_2 emissions before the next century. On a more positive note, Hansen et al. (1989) found that, had the growth rates of CFC production occurring in the 1970s been allowed to continue to the present, then the current annual growth in global warming would be equivalent to that of CO_2. They note that CFCs now provide one-quarter of current annual increase in anthropogenic greenhouse climate warming.

7. Global Climate Control and Fossil Fuels

The conservation of fossil fuels may also play an important long-term role as a means of stabilizing global climate. Available evidence clearly indicates that the normal state of the Earth's climate over the past 160,000 years has been much cooler, an ice age (Jouzel et al. 1987). If we wish to avoid a catastrophe where global temperatures fall to ice age conditions, then retaining a large global store of fossil fuels that could be released in a controlled fashion to stabilize the global climate may be an important long-term consideration (Callendar 1938). The present release of fossil fuels should be sufficient in the near future to calibrate and validate regional-scale resolution global climate models and so facilitate the global-scale management of the human influence on the world's climate and biosphere. A component of such a management approach to global climate would be an internationally agreed global land use management plan, which would enable the exchange of greenhouse gases (emissions and sinks) between the biosphere and atmosphere to be monitored and evaluated. Such a management plan could potentially be more beneficial than the current ad hoc and uncontrolled global experiment with the Earth's climate and would provide the means to achieve the UNFCCC goals.

8. Conclusions

Climate modeling will continue to play a central role in evaluating the potential impact of increased in greenhouse gas concentrations in the global atmosphere and in finding acceptable management options for controlling greenhouse gas emissions. We can influence global climate in the future through modification of current greenhouse gas emissions to the atmosphere. Decisions concerning the path of future greenhouse gas emissions will be influenced by the level of certainty that we can place in our scientific knowledge concerning climate change. These decisions, however, will have to be made in a much broader social, political, and economic context based on a global consensus. Clearly, while building on existing international agreements such as UNFCCC, much more work is urgently required if we are to realize the desirable goal of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system

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Table 1: Carbon emissions by region for the world for 1988

	Total (million tonnes)	Per capita (tonnes)
USSR and Eastern Europe	1428	3.55
North America	1379	5.07
Latin America	910	2.09
Far East Asia	833	0.55
Western Europe	774	2.03
Centrally Planned Asia	774	0.66
Africa	534	0.86
Oceania	336	2.27
Middle East	187	1.14
WORLD	7319[1]	1.42

Source: Flavin (1989).

1. World total does not equal column total because of reporting irregularities by the United Nations.

Table 2: A brief history of carbon dioxide and climate change

1820s	Fourier (1827) suggested that heat could be retained by the atmosphere and described the effect as acting in a manner similar to a hothouse (greenhouse).
1860s	John Tyndall (1861) performed measurements of the capacity of water vapor, CO_2 and other gases to absorb heat (infrared radiation).
1890s	Svante Arrhenius (1896), using S. Langley's measurements of infrared radiation from the moon, estimated the ability of CO_2 and water vapor to absorb infrared radiation. He calculated that a doubling of CO_2 would increase temperatures by 5-6°C while a 1/3 decrease would reduce temperatures 3-3.4°C.
	T. C. Chamberlin (1897, 1898, 1899), in a series of papers, developed a theory of climate change over geological timescales, based on changes in atmospheric CO_2 to explain the cyclic behavior of the extent of glaciation.
1900-1950s	The carbon dioxide theory of climate change fell into disuse as water vapor was considered to absorb all infrared radiation from the earth's surface (Brooks 1951). G.S. Callendar (1938) found that CO_2 is remaining in the atmosphere and will lead to a global warming of 2°C for a doubling of CO_2 concentration. G. N. Plass (1956) revives the carbon dioxide theory of climate and predicts a 3.6°C increase in temperature for a doubling of CO_2 concentration.
1957	Roger Revelle and Hans Suess (1957) state that mankind is carrying out a "global scale experiment" through the release of carbon dioxide to the atmosphere.
1960s	Numerous studies confirm potential and extent of perturbation of climate due to CO_2. Importance of feedback mechanisms is identified (e.g., Moller 1963).
1970s	Other trace gases such as CH_4, nitrous oxide, and CFCs are identified as greenhouse gases. First 3-dimensional climate studies are performed. (Ramanathan 1975, Wang et al. 1976).
1980s	Many 3-dimensional global climate model studies support climate warming of 2-6°C. Detailed studies of the potential impacts commence at the regional scale. First developments of global action commence, to delay and reduce the impact of climate change. (e.g., Washington and Parkinson 1986, Schneider 1989).
1990s	Climate system models are developed linking atmosphere, oceans, land surface, and biosphere. Global action to reduce greenhouse gas emissions commences in earnest through the Kyoto Protocol and establishment of the UN Framework Convention on Climate Change. The balance of evidence suggests a discernible human influence on global climate (IPCC 1995).
2000s	Comprehensive regional resolution (1-10 km) climate models are developed and used to assess and mitigate the impacts of climate change on a routine basis.

Table 3: Important greenhouse gases and their sources

Gas	Industrial/ Biosphere	Major Source
CO_2	80%/20%	Industrial Deforestation
CH_4	10%/90%	Rice paddies Ruminants Termites Biomass burning Natural wetlands Coal mining Gas drilling Land fills
N_2O	20%/80%	Agricultural Activities Oceans

Table 4: Predicted temperature changes relative to CO_2 associated with trace gases by 2030

Trace gas	Temperature change (˚C) relative to CO_2
Carbon dioxide	1.000
Nitrous oxide	0.620
CFCs	0.620
Methane	0.197
Tropospheric ozone	0.085

Source: Derived from Ramanathan et al. (1985).

Table 5: Potential impacts of a global warming

Climate changes:

- changing weather patterns
- increased number, range, and severity of cyclones
- changes in rainfall and run-off
- changes in cloudiness

Coastal impacts:

- inundation of coast lines
- coastal recession changes in coastal vegetation, e.g., salt marshes
- increase in storm surge levels
- increased drowning of the Great Barrier Reef
- changing fishery production

Hydrology and water resources:

- increased erosion from wind and water
- changes in groundwater recharge and salinity
- increased salinity of streams
- greater probability of large and damaging floods
- need to redesign flood carrying structures
- changes in soil moisture during the growing season
- changes in availability of irrigation water
- changes in extent and duration of snow cover

Natural biosphere:

- shifts in bioclimatic zones
- changes in the distribution and abundance of native flora and fauna
- local and regional extinction of species
- increased growth due to CO_2 fertilization
- increased frequency of bushfires

Food production:

- reduced gain production capacity
- increased year-to-year crop variability
- increased growth due to CO_2 fertilisation
- reduced production from increases in cloudiness
- reduced yields of warm temperature crops because of less winter chilling

Society

- relocation of industry and populations
- economic impacts of the costs and response to climate change
- increased energy costs
- increased food costs
- increased insurance costs
- increase in diseases
- increases in natural hazards
- institutional responses to climate change national
- regional and industrial action to reduce greenhouse gas emissions
- changing international cooperation and policies uncertainty

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Source: Based in part upon Pearman (1988); Henderson-Sellers and Blong (1989), and Watson et al. (1998).

Table 6: Cost of avoiding carbon emissions using new power technologies, 1989

	Estimated generating cost[1] (¢/kwh)	Carbon reduction[2] (percent)	Carbon pollution cost (¢/kwh)	Avoid-ance cost ($/ton)
Improving energy efficiency	2.0-4.0	100	0.19[3]	
Steam-injected gas Turbine	4.8-6.3	61	0.5	109-200
Combined-cycle	5.4	10	1.	814
Geothermal energy	5.8	99	1.0	123
Wind power	6.4	100	0.3	107
Solar thermal (gas)	7.9	84	0.216	
Nuclear power	12.5	99	5.0	617
Photovoltaics	28.4	100	0.0	921

Source: Flavin (1989)

1. Leveled cost over the life of the plant, assuming current construction costs and a range of natural gas prices.
2. Compared with existing coal-fired power plants.
3. Some energy-efficiency improvements cost less than operating a coal-fired plant, so avoiding carbon emissions is actually free.

Table 7: Estimates of the annual cost of research and development into reducing CO_2 emissions in the USA

Strategy	Cost per annum ($US million) 1989[1]	1999[3]
Technology transfer to developing countries	100-200	100-200
Solar and other renewable technologies	200	384
Improvements in efficiency	300	745
Safer nuclear power reactors	350	75
Fusion	1000-2000[2]	230

1. Fulkerson et al. (1989)
2. Estimated expenditure 1991
3. Source: DOE Budget Tables FY99

Table 8:	International actions on the greenhouse effect and global environmental change
1985	Villach Conference (UNEP, ICSU, WMO) on effect of increased CO_2 and other greenhouse gases on climate and ecosystems.
1986	ICSU launches the International Geosphere Biosphere Programme.
1987	Montreal agreement limits the manufacture of chlorofluorocarbons (CFCs).
1987	UN World Commission on Environment and Development (Brundtland Commission) releases *Our common future*, a manifesto for socio-economic change.
1988	Toronto accord is formulated to limit fossil fuel CO emissions.
1989	Declaration of 24 nations at the Hague places concerns for the world environment ahead of the national interest.
1989	Environmental concern of Margaret Thatcher, following an invited briefing by British scientists.
1989	President Bush invites the world to hold an international conference in the US.
1989	President Mitterrand hosts 275 scientists from 40 nations for a conference on Planet Earth.
1989	President Gorbachev announces January 1990 Moscow meeting on global actions to save the planet's environment.
1989	Environment ministers from 68 countries attend the Conference on Atmospheric Pollution and Climate Change in the Netherlands organized by the Dutch Government and intended to provide the political impetus to efforts to achieve early action.
1990	First Intergovernmental panel on Climate Change (IPCC) Reports
1994	UN Framework Convention on Climate Change, which includes commitments to reduce greenhouse gas emissions, enters into force
1995	Second IPCC Reports in which it is found that the balance of evidence supports human induced climate change due to the enhanced greenhouse effect
2000	Third IPCC Report due for release

Note: UNEP - United Nations Environment Program, ICSU - International Council of Scientific Unions, WMO-World Meteorological Organization.