

THE IMPLICATIONS OF FOSSIL FUEL COMBUSTION ON GLOBAL CLIMATE CHANGE:

AN OVERVIEW

Charles W. Garrett

Office of Technical Coordination
Fossil Energy
U.S. Department of Energy
Washington, DC 20585

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INTRODUCTION

The potential for future global climate change (GCC) and its implications for fossil fuels (FF) currently are hot issues. They are the subject of much ongoing research and scientific debate and they have policy ramifications with international repercussions. The recently completed environmental conference in Rio de Janeiro is a case in point, testifying to the encompassing importance of the topic.

GCC is very complicated and our understanding is far from adequate, hindering our ability to deal effectively with it from either the technical or the policy standpoint. Uncertainties and controversies abound. To highlight the subject for those of us who must deal with it in our daily tasks, the Fuel Chemistry Division of the American Chemical Society is conducting this one-day "pedagogical" symposium. The purpose is not to put forth any specific policy or to advocate any particular scientific position. Rather, it is to provide information on the current state-of-the-science so that as we return to our continuing responsibilities we might be better able to formulate our own decisions regarding both the conduct of our profession and policy alternatives which, as knowledgeable representatives of the scientific and engineering communities, we will be asked to explain and support.

The topic can be divided into two major areas: atmospheric science and fossil fuel implications. This symposium will focus on both. At the conclusion, two papers on policy underpinnings will suggest some techniques that can aid in policy determinations, but policies *per se* are beyond our horizon. We leave them for your personal consideration upon departure this afternoon.

ATMOSPHERIC SCIENCE

There are some things concerning GCC that are well known and beyond serious debate. Among them is the "greenhouse effect" (GHE) which has an unquestioned scientific basis. It is, for example, a major cause of the earth's average surface temperature of 15°C, Mars' -47°C and Venus' 477°C. Figure 1

illustrates the GHE. The GHE and the characteristics of the six principal greenhouse gases will be examined in our first paper.

Essential to our analysis of the present is an understanding of what has happened in the past. One GH gas of great importance to fossil fuel is, of course, CO_2 , a major product of combustion. CO_2 enters the globe's carbon cycle which, although generically illustrated on figure 2, is not fully understood. The material balance, for example, cannot be closed. The atmospheric concentration of CO_2 has undergone significant variation over the earth's history and some of those variations have been correlated with climatic changes. Those of the ice ages are an example. Most variations were before man and thus stemmed from natural causes. But over the industrial revolution of the last 150 years, anthropogenic (i.e. man-produced) carbon emissions have caused the atmospheric CO_2 concentration to increase some 25 percent, and this is one basis of the present concern. The world's carbon emissions and resulting atmospheric concentrations of CO_2 over the industrial revolution are shown on figures 3 and 4.

The earth's climate, characterized by such things as temperature, precipitation and soil moisture, has varied considerably over its billion-year history. I show on figure 5 temperature variations over a million-year period. That significant variations have occurred over these long time intervals is not disputed. What has happened over the past 150 years, however, is. Some conclude the earth has warmed perhaps a half degree C during that period; others aren't so sure. Our second paper will address these data of our climatic record.

Large mathematical climate simulations, performed by "General Circulation Models" (GCMs), are essential to both analyze collected raw data and to predict the future. While necessary and useful, they are lacking in several ways. First, present computing hardware and algorithms that solve the huge but necessary multi-dimensional partial differential equation sets are not yet fully up to the task, at least when the cost of calculation is considered. Second, our knowledge of the fundamental processes involved (including complicated and significant climatic feedback mechanisms) is not sufficient even if they were. Third, the data presently available are not complete enough nor understood well enough to enable full validation of our models. Nevertheless, GCMs are a major tool in our armamentarium. Two papers will focus on GCMs, the first on the characteristics of the models, and the second on differences among the computed results (testifying, thereby, to the present state of affairs).

As is now clear, there is a great deal of uncertainty in our present ability to draw causal relationships between the GHE and GCC. Research results are reported almost daily that affect them; a recent example being new data on the role of atmospheric aerosols. Significant scientific controversies remain. These ambiguities are bases for differing policy alternatives as well as food for future research. Wrapping up our morning will be a paper directly focusing on these uncertainties and controversies.

FOSSIL FUEL IMPLICATIONS

The fossil fuels of interest are natural gas, petroleum, and coal. The fuels have different properties that cause them to produce different amounts of CO₂ as one of their combustion products. To release equal amounts of energy from combustion (assuming 100 percent efficiency) and normalized to natural gas, these three fuels create approximately the following ratios of CO₂ (on a weight basis):⁵

Natural gas -- 1.0 Petroleum -- 1.4 Bituminous Coal -- 1.8

The differences are significant enough to make fuel selection an important determinant. But even the lowest, natural gas, creates sufficient CO₂ to itself be a concern. Thus ways of minimizing CO₂ releases from fossil fuel combustion have received considerable attention. In the first of two papers this afternoon, we will learn more details of the fuel's chemical and physical properties and how, through better combustion efficiencies and fuel switching, we can mitigate the problem. The second paper will deal specifically with the post-combustion capture and sequestration of CO₂, a technology presently in its infancy.

POLICY FORMULATION

While this symposium will not address or analyze specific policy proposals, either those already on the table or those lingering in the background, their existence and importance cannot be ignored. Science plays a part in policy formation. In addition to developing better means of climatic prediction and CO₂ control, there are other ways in which science can help. Closing out our symposium will be two papers that suggest ways in which objective analysis can contribute to the elucidation of crucial factors surrounding these policies. The first will deal with a unified economic analytical framework. The second will demonstrate a way in which uncertainties quantitatively can be dealt with in GCMs, significantly reducing the spread of possible outcomes.

Finally, we will round out our day in a panel session with all authors fielding questions from the audience.

SOME OTHER IMPORTANT ASPECTS

There are additional factors that are now and will remain major determinants of future events. As important to an understanding of the issue as the science of GCC and FF combustion *per se*, they include, for example:

- *International differences* as represented by differing aspirations and priorities among the developed and the lesser developed nations.
- *Political differences* as represented by the various positions taken by environmental protectionists and CO₂-producing industries.

-- *Philosophical and moral issues* as represented by population and its control.

We do not have the time to delve into these matters in detail. But do not take their limited mention as an indication of relative influence. It is only time, not importance, that forces us to deal primarily with other things; in the end, these issues may well prove to have the greatest influence of all on the world's response to the threat of GCC from the GHE. It is important that we technologists also appreciate them and I'll finish this overview with a very inadequate coverage of a few of the most important . . .

GH gases are worldwide, and dealing with them will, of necessity, require a coordinated, international approach. But not all nations are involved equally. First, the predicted climate changes vary; some nations may even benefit as the agricultural environment of their country is bettered at the expense of another nation's loss. Second, many of the developing countries are wrestling with horrendous health and economic woes; their priorities are on the present and not on what might (or might not) be done to affect GCC many years hence. Relatively poor and technically primitive, whatever they do will require both technological and economic aid. (I note in passing that the Montreal Protocol on CFC control was first rejected by these countries who joined in only after the developed nations offered economic assistance.) And third is the question of equity these struggling nations raise: "It is the rich nations of the world that have polluted the global nest while achieving their status of well-being; they should pay for it, not us," one hears them exclaim, adding, "The well-off nations should now help us reach equal wealth."

One cannot escape the economic consequences of the moment, as policy discussions in the U.S. reveal. It is no simple matter to suggest the present economic base of this country, which is highly dependent upon fossil fuel combustion, should be quickly altered. At the same time, there are those with a genuine concern for long-term environmental consequences who auger for immediate constraints on CO₂. Feeling we cannot afford the time it will take to obtain a better scientific basis for policy, they believe the downside risk is too large to wait. So even in a single nation, legitimate differences of perspective lead to radically different political positions.

Finally, there are some moral factors that cannot be escaped. One major determinant of the magnitude of future CO₂ emissions will be the number of people generating it -- the world's population, which is rapidly rising. If the trend continues as predicted, it will swamp CO₂ emission controls. That, in turn, suggests population control, a highly emotional and contested factor but nonetheless a very important determinant.

SUMMARY

To illustrate how factors affected by technology and those that are not are interminably intertwined, I use an identity proposed by Gibbons⁶ several years ago. One can estimate CO₂ emissions at some time, T, by:

$$\begin{aligned}
\text{CO}_2 \text{ Emitted} &= \text{CO}_2 \text{ Emitted per Unit of Consumed Energy @ } t=T & (1) \\
\text{@ time } t=T & & \\
&\times \text{ Energy Consumed per Unit of Gross Domestic Product @ } t=T & (2) \\
&\times \text{ Gross Domestic Product (GDP) per person @ } t=T & (3) \\
&\times \text{ Population @ } t=T & (4)
\end{aligned}$$

Letting E represent consumed energy, we rearrange and define four quantities, A, B, C, and D, in the process:

$$\begin{aligned}
\text{CO}_2 \text{ Emitted} &= A \frac{(\text{CO}_2 \text{ emitted/E}) @ t=T}{(\text{CO}_2 \text{ emitted/E}) @ t=0} & \times & \frac{\text{CO}_2 \text{ emitted @ } t=0}{E @ t=0} \\
\text{@ Time T} & & & \\
&\times B \frac{(E/\text{GDP}) @ t=T}{(E/\text{GDP}) @ t=0} & \times & \frac{E @ t=0}{\text{GDP @ } t=0} \\
&\times C \frac{(\text{GDP/person}) @ t=T}{(\text{GDP/person}) @ t=0} & \times & \frac{\text{GDP @ } t=0}{\text{person @ } t=0} \\
&\times D \frac{(\text{population @ } t=T)}{(\text{population @ } t=0)} & \times & \text{population @ } t=0
\end{aligned}$$

The beauty of this representation is that the four quantities on the left are merely ratios of the future ($t = T$) to the present ($t = 0$), while the right-hand quantities contain information only on the present. Further, it separates effects of energy technology (A & B) from other determinants (C & D). "A" reflects emissions from the generation of such useful energy forms as heat, electricity and motion; improving system efficiencies and fuel switching can lower it. "B" measures "energy efficiency" changes -- how we use that energy -- and reflects (among other things) end-use conservation. These first two terms embody just about all that energy technology can do. "C" is a measure of the change in productivity of a people. It goes up with an improved standard of living and the objective is to *increase* this parameter. "D" invokes all kinds of controversial considerations if there is an attempt to control it.

Relative to the present, one can estimate future emissions of CO_2 for a local region, a nation or, indeed, the world by insertion of the proper values for A, B, C, and D. If their product is lower than one, emissions at T are less than those at present; if it is greater than one, they will be more. As we shall see, all four are important and each must be appreciated.

Using available data and predictions of the experts, I have estimated the values of the four quantities, updating similar values computed earlier⁷ for the 35-year period ending in the year 2025 for three different regions; the U.S., Africa, and the world. Assuming the percentage of useful energy generated by all fossil fuels remains constant, my predictions of improved

efficiencies and fuel switching were optimistic; for example, in the U.S. average overall system efficiency improves some 38%, coal use drops 30% and oil use drops 20% (both replaced by natural gas) over that time. The results were:

	A	B	C	D	AxBxCxD
United States	0.67	0.71	1.74	1.21	1.00
Africa	0.76	1.91	0.73	2.44	2.58
World	0.71	0.74	1.67	1.60	1.40

The implications are clear. Under these high-efficiency, high-gas, low-coal assumptions, CO₂ emissions stay the same only in an advanced-technology nation where population growth is simultaneously limited. They increase elsewhere despite what technology can do. To control worldwide emissions, non-energy technology factors (e.g. productivity, population) also must be dealt with, with significant international and moral implications. It should be noted, however, that without technology providing large reductions in A and B, the situation would be far worse -- technology is doing its part!

Our symposium today focuses only on the first parameter, A, which deals with energy generation by fossil fuel combustion. That in itself will be difficult to do in only a few hours' time. The impacts of the others should not be minimized, however. For they also have a critical importance in matters concerning global climate change.

1. Adapted from Schneider, S. H., *Science* 243, 772 (1989). Copyrighted by the AAAS; reprinted by permission.
2. *Changing By Degrees: Steps to Reduce Greenhouse Gases*, U.S. Office of Technology Assessment report OTA-0-482, U.S. Government Printing Office, Washington, DC (Feb. 1991).
3. *Trends '90*, Carbon Dioxide Information Analysis Center report ORNL/CDIAC-36 (1990).
4. Intergovernmental Panel on Climate Change, *Climate Change - The IPCC Scientific Assessment*, Cambridge Univ. Press (1990). Copyrighted by the IPCC; reprinted by permission.
5. Garrett, C. W., On Global Climate Change, Carbon Dioxide, and Fossil Fuel Combustion, *Progress in Energy and Combustion Science*, in press.
6. Gibbons, J. H., The Interface of Environmental Science and Policy, in *Energy and the Environment in the 21st Century*, Tester, J. W., Wood, D. O. and Ferrari, N. A., eds.; MIT Press, Cambridge, MA (1991).
7. *Op. Cit.* 5.

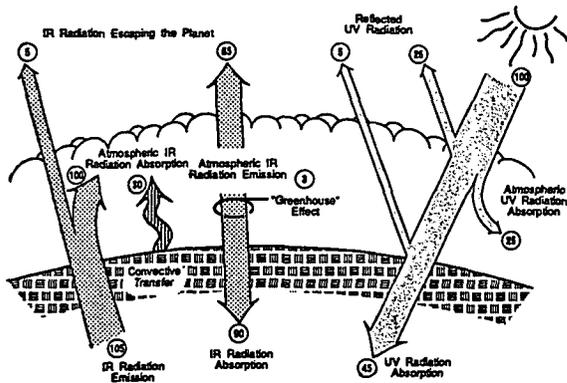


Figure 1

THE GREENHOUSE EFFECT

Source: Ref. 1

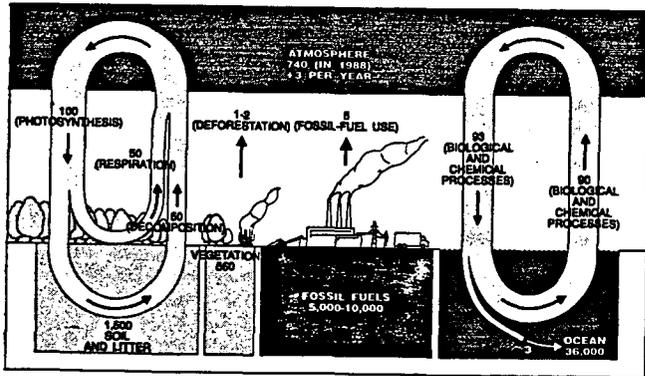


Figure 2

GLOBAL CARBON CYCLE

Source: Ref. 2

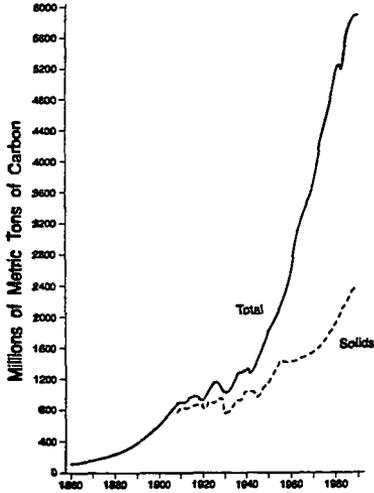


Figure 3
GLOBAL CARBON EMISSIONS
 Source: Ref. 3

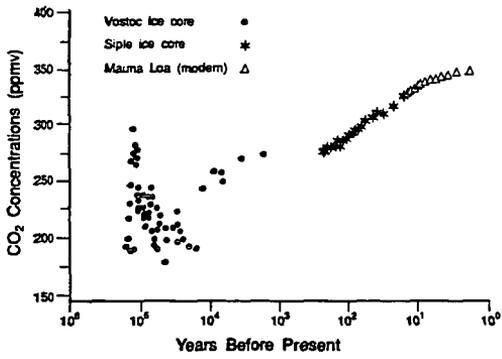


Figure 4
CO₂ ATMOSPHERIC CONCENTRATIONS
 Source: Ref. 3

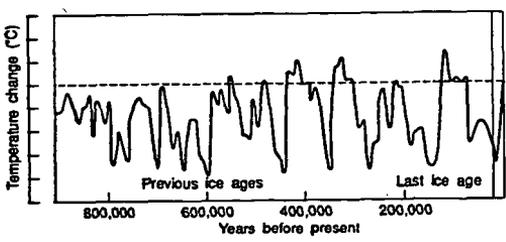


Figure 5
HISTORIC TEMPERATURE VARIATIONS
 (dashed line = 1900)
 Source: Ref. 4

THE BASICS OF THE GREENHOUSE EFFECT: The Role of Greenhouse Gases and Aerosols

R. T. Watson

Introduction:

Although there have been no major changes in our understanding of the sources and sinks of greenhouse gases and aerosols during the last two years, i.e., since the 1990 Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment, there have been a number of important advances. These advances include an improved quantitative understanding of the atmospheric distributions, trends, sources and sinks of greenhouse gases, their precursors and aerosols, and an improved understanding of the processes controlling their global budgets. In addition, there have been significant advances in our understanding of the impact of ozone depletion and sulphate aerosols on radiative forcing and of the limitations of the concept of the Global Warming Potential (GWP). The contents of this paper are taken from the 1992 IPCC Scientific Assessment.

The role of greenhouse gases and aerosols in changing the Earth's climate:

Increases in the concentration of the greenhouse gases reduce the efficiency with which the Earth cools to space and tend to warm the lower atmosphere and surface. The amount of warming depends on the size of the increase in concentration of each greenhouse gas, the radiative properties of the gases involved, and the concentration of other greenhouse gases already present in the atmosphere. It also can depend on local effects such as the variation with height of the concentration of the greenhouse gas, a consideration that may be particularly germane to water vapour which is not uniformly mixed throughout the atmosphere.

Aerosols (small particles) from volcanoes, natural and industrial emissions of sulfur containing gases, and biomass burning can absorb and reflect radiation. Moreover, changes in aerosol concentrations can alter cloud reflectivity through their effect on cloud properties. In most cases increases in the atmospheric abundance of aerosols tend to cool climate. In general, they have a much shorter lifetime than greenhouse gases so they are not uniformly distributed and their concentrations respond much more quickly to changes in emissions.

A necessary starting point for the prediction of changes in climate due to increases in greenhouse gases and aerosols is an estimate of their future concentrations. This requires a knowledge of both the strengths of their sources (natural and man-made) and also the mechanisms of their eventual removal from the atmosphere (their sinks). The projections of future concentrations can then be used in climate models to estimate the climatic response.

Recent Improvements in Scientific Understanding of the Sources and Sinks of Greenhouse Gases and Aerosols:

Atmospheric Concentrations and Trends of Long-lived Greenhouse Gases:

The atmospheric concentrations of the major long-lived greenhouse gases, carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), chlorofluorocarbons (CFCs), and carbon tetrachloride (CCl₄), continue to increase because of human activities. While the growth rates of most of these gases have been steady or increasing over the past decade, that of CH₄ and some of the halocarbons has been decreasing. The rate for CH₄ has declined from about 20 ppbv/yr in the late 1970s to possibly as low

as 10 ppbv/yr in 1989. While a number of hypotheses have been forwarded to explain these observations, none is completely satisfactory.

Sources and Sinks of Carbon Dioxide:

The two primary sources of the observed increase in atmospheric CO₂ are combustion of fossil fuels and land-use changes; cement production is a further important source.

The emission of CO₂ from the combustion of fossil fuels grew between 1987 and 1989. Preliminary data for 1990 indicate similar emissions to 1989. The best estimate for global fossil fuel emissions in 1989 and 1990 is 6.0 ± 0.5 GtC (1 GtC (gigatonne of carbon) equals one billion [one thousand million (10^9)] tonnes of carbon), compared to 5.7 ± 0.5 GtC in 1987 (IPCC, 1990). The estimated total release of carbon in the form of CO₂ from oil well fires in Kuwait during 1991 was 0.065 GtC, about one percent of total annual anthropogenic emissions.

The direct net flux of CO₂ from land use changes (primarily deforestation), integrated over time, depends upon the area of land deforested, the rate of reforestation and afforestation, the carbon density of the original and replacement forests, and the fate of above-ground and soil carbon. These and other factors are needed to estimate annual net emissions but significant uncertainties exist in our quantitative knowledge of them. Since IPCC (1990) some progress has been made in reducing the uncertainties associated with the rate of deforestation, at least in Brazil. A comprehensive, multi-year, high spatial resolution satellite data set has been used to estimate that the average rate of deforestation in the Brazilian Amazonian forest between 1978 and 1989 was 2.1 million hectares (Mha) per year. The rate increased between 1978 and the mid-1980s, and has decreased to 1.4 Mha/yr in 1990. The Food and Agriculture Organization (FAO), using information supplied by individual countries, recently estimated that the rate of global tropical deforestation in closed and open canopy forests for the period 1981-1990 was about 17 Mha/yr, approximately 50% higher than in the period 1976-1980.

Despite the new information regarding rates of deforestation, the uncertainties in estimating CO₂ emissions are so large that there is no strong reason to revise the IPCC 1990 estimate of annual average net flux to the atmosphere of 1.6 ± 1.0 GtC from land-use change during the decade of the 1980s.

Since IPCC (1990) particular attention has focussed on understanding the processes controlling the release and uptake of CO₂ from both the terrestrial biosphere and the oceans, and on the quantification of the fluxes. Based on models and the atmospheric distribution of CO₂, it appears that there is a small net addition of carbon to the atmosphere from the equatorial region, a combination of outgassing of CO₂ from warm tropical waters and a terrestrial biospheric component that is the residual between large sources (including deforestation) and sinks. There appears to be a strong Northern Hemisphere sink, containing both oceanic and terrestrial biospheric components, and a weak Southern Hemisphere (SH) sink. The previous IPCC global estimate for an ocean sink of 2.0 ± 0.8 GtC per year is still a reasonable one. The terrestrial biospheric processes which are suggested as contributing to the sinks are sequestration due to forest regeneration, and fertilization arising from the effects of both CO₂ and nitrogen (N), but none of these can be adequately quantified. This implies that the imbalance (of order 1-2 GtC/yr) between sources and sinks, i.e., "the missing sink", has not yet been resolved. This fact has significant consequences for estimates of future atmospheric CO₂ concentrations and the analysis of the concept of the Greenhouse Warming Potential.

Sources and Sinks of Methane:

A total (anthropogenic plus natural) annual emission of CH₄ of about 500Tg can be deduced from the magnitude of its sinks combined with its rate of accumulation in the atmosphere. While the sum of the individual sources is consistent with a total of 500Tg CH₄, there are still many uncertainties in accurately quantifying the magnitude of emissions from individual sources. Significant new information includes a revised rate of removal of CH₄ by atmospheric hydroxyl (OH) radicals (because of a lower rate constant), a new evaluation of some of the sources (e.g., from rice fields) and the addition of new sources (e.g., animal and domestic waste). Recent CH₄ isotopic studies suggest that approximately 100Tg CH₄ (20% of the total CH₄ source) is of fossil origin, largely from the coal, oil, and natural gas industries. Recent studies of CH₄ emissions from rice agriculture, in particular Japan, India, Australia, Thailand and China, show that the emissions depend on growing conditions, particularly soil characteristics, and vary significantly. While the overall uncertainty in the magnitude of global emissions from rice agriculture remains large, a detailed analysis now suggests significantly lower annual emissions than reported in IPCC 1990. The latest estimate of the atmospheric lifetime of CH₄ is about 11 years.

Sources and Sinks of Nitrous Oxide:

Adipic acid (nylon) production, nitric acid production and automobiles with three-way catalysts have been identified as possibly significant anthropogenic global sources of nitrous oxide. However, the sum of all known anthropogenic and natural sources is still barely sufficient to balance the calculated atmospheric sink (stratospheric photolysis) or to explain the observed increase in the atmospheric abundance of N₂O.

Sources of Halogenated Species:

The worldwide consumption of CFCs 11, 12, and 113 is now 40% below 1986 levels, substantially below the amounts permitted under the Montreal Protocol. Further reductions are mandated by the 1990 London Amendments to the Montreal Protocol. As CFCs are phased out, HCFCs and HFCs will substitute, but at lower emission rates.

Atmospheric Concentrations and Trends of Other Gases that Influence the Radiative Budget:

Ozone (O₃) is an effective greenhouse gas both in the stratosphere and in the troposphere. Significant decreases have been observed during the last one to two decades in total column O₃ at all latitudes - except the tropics - in spring, summer and winter. The downward trends were larger during the 1980s than in the 1970s. These decreases have occurred predominantly in the lower stratosphere (below 25km), where the rate of decrease has been up to 10% per decade depending on altitude. In addition, there is evidence to indicate that O₃ levels in the troposphere up to 10km altitude above the few existing ozonesonde stations at northern middle latitudes have increased by about 10% per decade over the past two decades. Also, the abundance of carbon monoxide (CO) appears to be increasing in the NH at about 1% per year. However, there is little new information on the global trends of other tropospheric O₃ precursors, (non-methane hydrocarbons (NMHC) and oxides of nitrogen (NO_x)).

Stratospheric Ozone Depletion:

Even if the control measures of the 1990 London amendments to the Montreal Protocol were to be implemented by all nations, the abundance of stratospheric chlorine and bromine will increase over the next several years. The Antarctic ozone hole, caused by industrial halocarbons, will therefore recur

each spring. In addition, as the weight of evidence suggests that these gases are also responsible for the observed reductions in middle- and high latitude stratospheric O₃, the depletion at these latitudes is predicted to continue unabated through the 1990s.

Sources of Precursors of Tropospheric Ozone:

Little new information is available regarding the tropospheric ozone precursors (CO, NMHC, and NO_x), all of which have significant natural and anthropogenic sources. Their detailed budgets therefore remain uncertain.

Source of Aerosols:

Industrial activity, biomass burning, volcanic eruptions, and sub-sonic aircraft contribute substantially to the formation of tropospheric and stratospheric aerosols. Industrial activities are concentrated in the Northern Hemisphere where their impact on tropospheric sulphate aerosols is greatest. Sulphur emissions, which are due in large part to combustion effluents, have a similar emissions history to that of anthropogenic CO₂. Estimates of emissions of natural sulphur compounds have been reduced from previous figures, thereby placing more emphasis on the anthropogenic contribution.

Scenarios of Future Emissions of Greenhouse Gases, Greenhouse Gas Precursors, and Aerosol Precursors

Scenarios of net greenhouse gas and aerosol precursor emissions for the next 100 years or more are necessary to support study of potential anthropogenic impacts on the climate system. The scenarios provide inputs to climate models and assist in the examination of the relative importance of relevant trace gases and aerosol precursors in changing atmospheric composition and climate. Scenarios can also help in improving the understanding of key relationships among factors that drive future emissions.

Scenario outputs are not predictions of the future, and should not be used as such; they illustrate the effect of a wide range of economic, demographic and policy assumptions. They are inherently controversial because they reflect different views of the future. The results of scenarios can vary considerably from actual outcomes even over short time horizons. Confidence in scenario outputs decreases as the time horizon increases, because the basis for the underlying assumptions becomes increasingly speculative. Considerable uncertainties surround the evolution of the types and levels of human activities (including economic growth and structure), technological advances, and human responses to possible environmental, economic and institutional constraints. Consequently, emission scenarios must be constructed carefully and used with great caution.

Since completion of the 1990 IPCC Scenario A (SA90) events and new information have emerged which relate to that scenario's underlying assumptions. These developments include: the London Amendments to the Montreal Protocol; revision of population forecasts by the World Bank and United Nations; publication of the IPCC Energy and Industry Sub-group scenario of greenhouse gas emissions to 2025; political events and economic changes in the former USSR, Eastern Europe and the Middle East; re-estimation of sources and sinks of greenhouse gases (reviewed in this Assessment); revision of preliminary FAO data on tropical deforestation; and new scientific studies on forest biomass. There has also been recognition of considerable uncertainty regarding other important factors that drive future emissions.

These factors have led to an update of the SA90. Six alternative IPCC Scenarios (IS92 a-f) now embody a wide array of assumptions (population growth, economic growth, role of nuclear power, renewable energy costs), that affect how future greenhouse gas emissions might evolve in the absence

of climate policies beyond those already adopted. This constitutes a significant improvement over the previous methodology. However, the probability of any of the resulting emission paths has not been analyzed. IPCC WGI does not prefer any individual scenario. Other combinations of assumptions could illustrate a broader variety of emission trajectories. The different worlds which the new scenarios imply, in terms of economic, social and environmental conditions, vary widely. The current exercise provides an interim view and lays a basis for a more complete study of future emissions of greenhouse gas and aerosol precursors.

Scenario Results:

The range of possible annual emissions of greenhouse gases is very wide as shown by the selected results of six IPCC Greenhouse gas scenarios below:

Scenario	Year	CO ₂ (GtC)	CH ₄ (Tg)	N ₂ O (TgN)	CFCs (kt)	SO _x (TgS)
IS92a	1990	7.4	506	12.9	827	98
	2025	12.2	659	15.8	217	141
	2100	20.3	917	17.0	3	169
IS92b	2025	11.8	659	15.7	36	140
	2100	19.1	917	16.9	0	164
IS92c	2025	8.8	589	15.0	217	115
	2100	4.6	546	13.7	3	77
IS92d	2025	9.3	584	15.1	24	104
	2100	10.3	567	14.5	0	87
IS92e	2025	15.1	692	16.3	24	163
	2100	35.8	1072	19.1	0	254
IS92e	2025	14.4	697	16.2	217	151
	2100	26.6	1168	19.0	3	204

All six scenarios can be compared to SA90. IS92a is slightly lower than SA90 due to modest and largely offsetting changes in the underlying assumptions. (For example, compared to SA90, higher population forecasts increase the emission estimates, while phaseout of halocarbons and more optimistic renewable energy costs reduce them.) The highest greenhouse gas levels result from the new scenario IS92e which combines, among other assumptions, moderate population growth, high economic growth, high fossil fuel availability and eventual hypothetical phaseout of nuclear power. The lowest greenhouse gas levels result from IS92c which assumes that population grows, then declines by the middle of the next century, that economic growth is low and that there are severe constraints on fossil fuel supplies. Overall, the scenarios indicate that greenhouse gas emissions could rise substantially over the coming century in the absence of new measures explicitly intended to reduce their emission. However, IS92c has a CO₂ emission path which eventually falls below its starting 1990 level. IS92b, a modification of IS92a, suggests that current commitments by many OECD Member countries to stabilize or reduce CO₂ might have a small impact on greenhouse gas emissions over the next few decades, but would not offset substantial growth in possible emissions in the long run. IS92b does not take into account that such commitments could accelerate development and diffusion of low greenhouse gas technologies, nor possible resulting shifts in industrial mix.

Carbon Dioxide:

The new emissions scenarios for CO₂ from the energy sector span a broad range of futures. Population and economic growth, structural changes in economies, energy prices, technological advance, fossil fuel supplies, nuclear and renewable energy availability are among the factors which could exert major influence on future levels of CO₂ emissions. Developments such as those in the republics of the former Soviet Union and in Eastern Europe, now incorporated into all the scenarios, have important implications for future fossil fuel carbon emissions, by affecting the levels of economic activities and the efficiency of energy production and use. Biotic carbon emissions in the early decades of the scenarios are higher than SA90, reflecting higher preliminary FAO estimates of current rates of deforestation in many - though not all - parts of the world, and higher estimates of forest biomass.

Halocarbons:

The revised scenarios for CFCs and other substances which deplete stratospheric ozone are much lower than in SA90. This is consistent with wide participation in the controls under the 1990 London Amendments to the Montreal Protocol. However, the future production and composition of CFC substitutes (HCFCs and HFCs) could significantly affect the levels of radiative forcing from these compounds.

Methane, Nitrous Oxide, Ozone Precursors and Sulphur Gases:

The distribution of CH₄ and N₂O emissions from the different sources has changed from the SA90 case. Methane from rice paddies are lower, and emissions from animal waste and domestic sewage have been added. N₂O emission factors for stationary sources and biomass burning have been revised downwards. Adipic and nitric acid have been included as additional sources of N₂O. Preliminary analysis of the emissions of volatile organic compounds and sulphur dioxide suggests that the global emissions of these substances are likely to grow in the coming century if no new limitation strategies are implemented.

Relationship Between Emissions and Atmospheric Concentrations and the Influence on the Radiative Budget

A key issue is to relate emissions of greenhouse gases, greenhouse gas precursors and aerosol precursors to future concentrations of greenhouse gases and aerosols in order to assess their impact on the radiative balance. A number of different types of model have been developed.

Carbon Cycle Models:

While there is a variety of carbon cycle models (including 3-D ocean-atmosphere models, 1-D ocean-atmosphere box-diffusion models, and box models that incorporate a terrestrial biospheric sink) all such models are subject to considerable uncertainty because of an inadequate understanding of the processes controlling the uptake and release of CO₂ from the oceans and terrestrial ecosystems. Some models assume a net neutral terrestrial biosphere, balancing fossil fuel emissions of CO₂ by oceanic uptake and atmospheric accumulation, others achieve balance by invoking additional assumptions regarding the effect of CO₂ fertilization on the different parts of the biosphere. However even models that balance the past and contemporary carbon cycle may not predict future atmospheric concentrations accurately because they do not necessarily represent the proper mix of processes on land and in the oceans. The differences in predicted changes in CO₂ concentrations are up to 30%. This does not represent the major uncertainty in the prediction of future climate change compared with uncertainties in estimating future patterns of trace gas emissions, and in quantifying climate feedback processes. A

simple empirical estimate can be based on the assumption that the fraction of emissions which remains in the atmosphere is the same as that observed over the last decade; i.e., $46 \pm 7\%$.

Atmospheric Gas Phase Chemistry Models:

Current tropospheric models exhibit substantial differences in their predictions of changes in O₃, in the hydroxyl radical (OH) and in other chemically active gases due to emissions of CH₄, non-methane hydrocarbons, CO and, in particular, NO_x. These arise from uncertainties in the knowledge of background chemical composition and our inability to represent small-scale processes occurring within the atmosphere. These deficiencies limit the accuracy of predicted changes in the abundance and distribution of tropospheric O₃, and in the lifetimes of a number of other greenhouse gases, including the HCFCs and HFCs, all of which depend upon the abundance of the OH radical. Increases in CH₄, NMHCs, and CO all lead to increases in O₃, and decreases in OH, thus leading to an increase in radiative forcing. On the other hand because increases in NO_x lead to an increase in both O₃ and OH, the net effect on radiative forcing is uncertain.

Atmospheric Sulphate Aerosol Models:

The atmospheric chemistry of sulphate aerosols and their precursors has been extensively studied in relation to the acid rain issue. While our understanding of processes related to chemical transformations has increased significantly in recent years, substantial uncertainties remain, especially regarding the microphysics of aerosol formation, interaction of aerosols with clouds, and the removal of aerosol particles by precipitation.

How has our Understanding of Changes in Radiative Forcing Changed?

Since IPCC (1990), there have been significant advances in our understanding of the impact of ozone depletion and sulphate aerosols on radiative forcing and of the limitations of the concept of the Global Warming Potential.

Radiative Forcing due to Changes in Stratospheric Ozone:

For the first time observed global depletions of O₃ in the lower stratosphere have been used to calculate changes in the radiative balance of the atmosphere. Although the results are sensitive to atmospheric adjustments, and no GCM studies of the implications of the O₃ changes on surface temperature have been performed, the radiative balance calculations indicate that the O₃ reductions observed during the 1980s have caused reductions in the radiative forcing of the surface-troposphere system at mid- and high- latitudes. This reduction in radiative forcing resulting from O₃ depletion could, averaged on a global scale and over the last decade, be approximately equal in magnitude and opposite in sign to the enhanced radiative forcing due to increased CFCs during the same time period. The effect at high latitudes is particularly pronounced and, because of these large variations with latitude and region, studies using GCMs are urgently required to further test these findings.

Radiative Forcing due to Changes in Tropospheric Ozone:

While there are consistent observations of an increase in tropospheric ozone (up to 10% per decade) at a limited number of locations in Europe, there is not an adequate global set of observations to quantify the magnitude of the increase in radiative forcing. However, it has been calculated that a 10% uniform global increase in tropospheric ozone would increase radiative forcing by about a tenth of a watt per square metre.

Radiative Effects of Sulphur Emissions:

Emissions of sulphur compounds from anthropogenic sources lead to the presence of sulphate aerosols which reflect solar radiation. This is likely to have a cooling influence on the Northern Hemisphere (there is negligible effect in the Southern Hemisphere). For clear-sky conditions alone, the cooling caused by current rates of emissions has been estimated to be about 1 Wm^{-2} averaged over the Northern Hemisphere, a value which should be compared with the estimate of 2.5 Wm^{-2} for the heating due to anthropogenic greenhouse gas emissions up to the present. The non-uniform distribution of anthropogenic sulphate aerosols coupled with their relatively short atmospheric residence time produce large regional variations in their effects. In addition, sulphate aerosols may affect the radiation budget through changes in cloud optical properties.

Global Warming Potentials:

Gases can exert a radiative forcing both directly and indirectly: direct forcing occurs when the gas itself is a greenhouse gas; indirect forcing occurs when chemical transformation of the original gas produces a gas or gases which themselves are greenhouse gases. The concept of the Global Warming Potential (GWP) has been developed for policymakers as a measure of the possible warming effect on the surface-troposphere system arising from the emission of each gas relative to CO_2 . The indices are calculated for the contemporary atmosphere and do not take into account possible changes in chemical composition of the atmosphere. Changes in radiative forcing due to CO_2 , on a kg basis, are non-linear with changes in the atmospheric CO_2 concentrations. Hence, as CO_2 levels increase from present values, the GWPs of the non- CO_2 gases would be higher than those evaluated here. For the concept to be most useful, both the direct and indirect components of the GWP need to be quantified.

Direct Global Warming Potentials:

The direct components of the Global Warming Potentials (GWPs) have been recalculated, taking into account revised estimated lifetimes, for a set of time horizons ranging from 20 to 500 years, with CO_2 as the reference gas. The same ocean-atmosphere carbon cycle model as in IPCC (1990) has been used to relate CO_2 emission to concentrations. Table 3 shows values for a selected set of key gases for the 100 year time horizon. While in most cases the values are similar to the previous IPCC (1990) values, the GWPs for some of the HCFCs and HFCs have increased by 20 to 50% because of revised estimates of their lifetimes. The direct GWP of CH_4 has been adjusted upward, correcting an error in the previous IPCC report. The carbon cycle model used in these calculations probably underestimates both the direct and indirect GWP values for all non- CO_2 gases. The magnitude of the bias depends on the atmospheric lifetime of the gas, and the GWP time horizon.

Indirect Global Warming Potentials:

Because of our incomplete understanding of chemical processes, most of the indirect GWPs reported in IPCC (1990) are likely to be in substantial error, and none of them can be recommended. Although we are not yet in a position to recommend revised numerical values, we know, however, that the indirect GWP for methane is positive and could be comparable in magnitude to its direct value. In contrast, based on the sub-section above, the indirect GWPs for chlorine and bromine halocarbons are likely to be negative. The concept of a GWP for short-lived, inhomogeneously distributed constituents, such as CO, NMHC, and NO_x may prove inapplicable, although, as noted above, we know that these constituents will affect the radiative balance of the atmosphere through changes in tropospheric ozone and OH. Similarly, a GWP for SO_2 is viewed to be inapplicable because of the non-uniform distribution of sulphate aerosols.

"GLOBAL WARMING": OBSERVED VARIATIONS AND CHANGES

Thomas R. Karl
National Climatic Data Center
NOAA/NESDIS/EIS
37 Battery Park Ave.
Federal Building
Asheville, NC 28801

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ABSTRACT

There are several parameters of fundamental importance with respect to understanding why the climate is or is not changing, especially as related to the "greenhouse effect". These parameters include integrated changes of temperature (horizontal and vertical), precipitation (horizontal) and water vapor (horizontal and vertical). It is also of fundamental importance however to determine how these parameters respond to an enhanced anthropic greenhouse. This includes knowledge about temporal and spatial the details of climate variations. The details of how they are expected to change is often of fundamental importance with respect to the impact on socio-economic, biochemical, and geophysical systems. This implies that we must understand both why and how the climate may change. Monitoring and analysis for why the climate is changing is not synonymous with having how the climate has or will change.

UNDERSTANDING WHY TEMPERATURES HAVE INCREASED

The most pervasive consequence of an enhanced greenhouse effect is the projected increase of global average temperatures. For this reason there has been considerable effort expended in obtaining accurate representations of the instrumented and proxy thermometric record (Jones et al., 1986a; Jones et al 1986b; Jones, 1988; Hansen and Lebedeff, 1987; Hansen and Lebedeff, 1988; Vinnikov et al., 1990; Cook et al., 1991; Bradley and Jones, 1992; Folland et al., 1990). At present, the best estimates of the observed change in global mean temperatures over the past 100 years is in the range of 0.3 to 0.6°C (IPCC, 1990, 1992). The rather wide confidence interval stems from a variety of monitoring problems including: 1) changes of observing methods, 2) incomplete global monitoring, and 3) the separation of local micro- and meso- scale climate variations (including urban heat island effects) from large-scale changes.

Over the past 100 years increases of anthropic greenhouse gases such as CO₂, N₂O, CH₄, O₃, and CFCs have lead to an enhanced greenhouse effect. This has resulted in increases in the radiative forcing at the top of the troposphere. Using the physics from radiative transfer models the IPCC (1990) estimates this increase close to 2 W/m² when averaged over the globe. This is equivalent to about a 1.5 increase in equivalent CO₂ forcing.

The sensitivity of the climate system to this forcing at the earth's surface is of critical importance. There are many indirect effects, such as ancillary changes in clouds and water vapor, that can occur with an increase of global mean temperature which affect the sensitivity of the climate system to increases in greenhouse gases. For this reason, comparison of actual changes of surface temperature with projected changes of temperature from General Circulation Models (GCMs) has taken on special importance. The GCMs include many, but not all, of the indirect forcing functions. Assuming all other forcing functions are near zero, such comparisons yield estimates of climate sensitivity to a doubling of equivalent CO₂ in the range of 1° to 2°C using an observed 100-year warming rate of 0.5°C. If a lower estimate of observed warming (0.3°C) is used the sensitivity is less than 1°C, but if the high end (0.6°C) is used the sensitivity is about 2°C.

It may be overly simplistic to simply compare the greenhouse induced climate change with the observed record. The instrumented climate record may be affected by other important forcing functions besides greenhouse forcings. For example, atmosphere/ocean GCMs (AOGCMs) have indicated that the climate system could have internal chaotic variations of the order of several tenths of °C over periods as short as a Century (Hansen et al., 1988; Manabe et al., 1991; Manabe et al., 1992). Proxy records of global temperature suggest that the climate has fluctuated by at least several tenths of degrees over the past several Centuries (Bradley and Jones, 1992). On shorter time-scales volcanic forcing will clearly lead to a cooling effect at the surface (Hansen et al., 1991). Additionally, recent evidence suggests that manmade sulfate aerosol forcing (Charlson et al., 1992) and biomass burning may have significantly altered the radiative balance (-1 W/m²) of the planet, partially offsetting the greenhouse effect.

Some have argued (Madden and Ramanathan, 1980; Baker and Barnett, 1982; MacCracken and Moses, 1982) that the greenhouse forcings should leave a fingerprint in the climate record which could then be specifically attributed to the greenhouse effect. Such a strategy focuses around a multivariate selection of parameters to analyze. These parameter should possess high signal to noise ratios, reliable and "long" records, and appropriate time and space scales. Some of the simultaneous changes expected in the climate record include: 1) Increases of global mean temperature, 2) A reduction in the pole to equator temperature gradient in the Northern Hemisphere (primarily the cold half of the year), 3) Stratospheric cooling and tropospheric warming, 4) A Global increase of precipitation with mid-continent drying during summer, 5) Tropospheric water vapor increase, 6) A rise of sea-level, and 7) An increase of the land surface temperature relative to the sea-surface temperature. Some aspects of the observed climate record are consistent with these projected changes while others are problematic (Barnett and Schlesinger, 1987, IPCC, 1990). Nonetheless, there has been insufficient

research to separate out the signature or pattern of change which might arise due to a global warming from other causes, e.g. natural variability.

UNDERSTANDING HOW TEMPERATURES HAVE INCREASED

Knowing why the climate has changed is only part of the challenge of understanding the climate system. We must also be able to project how the climate will change as it relates to man-made and natural systems on earth. As a prerequisite this means documenting and understanding the interaction between relevant climate parameters as they may affect these systems. Several examples are presented to illustrate the challenge.

Changes in the frequency of extreme temperatures is an important aspect of understanding how the recent warming has evolved over the past several decades. Many systems, both natural and man-made, are more sensitive to the tails of the distribution. To illustrate the complexity of the problem Karl et al. (1991) show that the changes in mean maximum and minimum temperatures over the past several decades have not been symmetric in the USA, the PRC, and the former USSR. The rate increase of the mean daily minimum temperature in these areas was more than three times the rate of the mean daily maximum temperature. Similarly the rate of increase of the 1-day seasonal extreme high temperatures was negligible, but an increase was apparent for the 1-day seasonal extreme minimum temperature. This has effectively lead to a decrease in variability of the extreme temperature range. It is uncertain whether this change is related to an enhanced greenhouse effect, anthropic increases in aerosols, or perhaps natural climate variability. Whatever its cause, it is a fundamental characteristic of the observed change of temperature in much of the Northern Hemisphere. It must be better understood before we can hope to confidently project the impact of any anticipated change of temperature.

The ability to project the frequency of major "weather" events is often of critical importance to many systems. Even if we could project seasonal temperature changes with perfect accuracy over relatively small space-scales, in many instances we would require still higher time resolution in order to project the impact of the changes. For example, the frequency of killing freezes which have destroyed both citrus fruit as well as citrus trees has occurred both during winters with very cold temperatures as well as during more mild winters, especially those during the mild winters of the 1980s (Figure 1). Clearly, changes in the frequency of extreme weather events is very important.

UNDERSTANDING CHANGES OF PRECIPITATION

Precipitation is arguably the most important climate parameter related to life on Earth. Unfortunately, it is very difficult to accurately document important changes of this parameter. This is related to its high frequency variability, and measurement

problems. Moreover, it is exceptionally difficult to accurately project long-term regional-scale changes of this parameter. It requires detailed understanding of changes in large-scale and meso-scale thermodynamics as well as micro-scale cloud physics. Karl et al. (1991) demonstrate the problem in the central USA. They show that the IPCC (1990) projected changes of precipitation in this region (due to enhanced greenhouse gases) for summer and winter will not be detectable until well beyond the year 2030. Ironically, the magnitude of the change projected could have major impacts before we could be confident that we have detected a real change. Summer precipitation is projected to decrease by 5 to 10% and winter precipitation is projected to increase up to 15%. To make matters more complicated the observed change in the ratio of summer to winter precipitation during the Twentieth Century in the Central USA is not consistent with the projected changes, if greenhouse forcings are the only important factor.

Our ability to work with projected changes of seasonal mean precipitation that may be of the order of 5 to 10% is fraught with difficulties. First, virtually all in-situ operational measurements of precipitation, the data we use to measure climate variations, have significant measurement biases due to a number of factors, e.g. evaporation losses, aerodynamic losses around the precipitation gauge, wetting losses inside the gauge, etc. (Karl et al., 1992). These biases are exposure and weather dependent. Moreover, the biases change over time as instruments change as illustrated in Figure 2. Second, just as knowledge of a seasonal mean temperature is often insufficient to project its impact on a variety of systems, changes in the short-term temporal variability of precipitation cannot be ignored. Extreme precipitation events and their frequency determine the climatology of floods and droughts. At the present time, there is not a clear picture that emerges with respect to systematic changes of temporal precipitation variability. Projected changes appear to be model and regionally dependent (IPCC, 1992). Lastly, as the temperature warms, the form of precipitation can change. This has important implications with respect to the water balance. The source term of the water balance equation (frozen versus liquid) can significantly affect the timing and distribution of water availability, and the diurnal changes of temperature affect the evaporative losses from the soil, lakes, and reservoirs.

In order to obtain more realistic estimates of the projected changes of day-to-day precipitation variability due to increased concentrations of greenhouse gases a number of statistically-based procedures have been developed to interpret the large and local-scale state of the AOGCMs free atmosphere with respect to the precipitation received at the surface. These statistical approaches (Wigley et al., 1990; Karl et al., 1990; Von Storch et al. 1991) can improve our ability to project more realistic precipitation simulations, but they too, are limited by our ability to project the state of the atmosphere in the future as well as the bounds of the data sample used to develop the

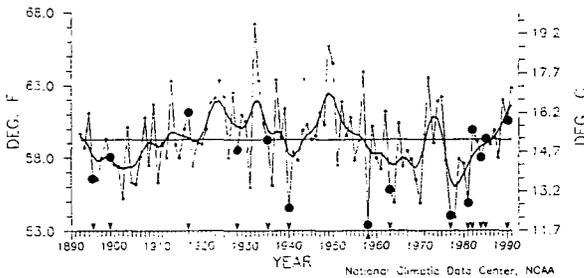


Figure 1 Mean winter temperature area-averaged over the state of Florida. Large bold dots indicate those years which had freezes so severe that extensive damage was inflicted upon both the citrus crop and the trees that bore the fruit.

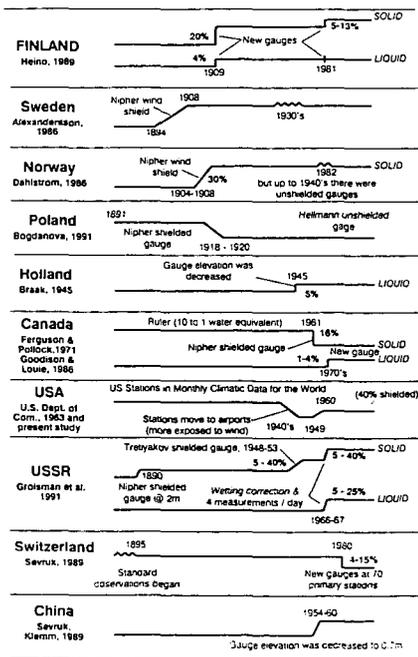


Figure 2 Changes of precipitation measurement which have led to biases in time series of precipitation data within national precipitation networks across the globe.

statistics. Because of these limitations efforts are now underway to mesh large-scale and meso-scale models to obtain a better understanding of the impact of large-scale changes at shorter time and smaller space-scales (Giorgi and Mearns, 1991).

CONCLUSIONS

Several steps need to be taken to reduce the uncertainties now associated with both understanding why and how climate has changes especially as related to the greenhouse effect.

- 1) Improve the reliability, continuity, and resolution of existing observations and data bases.
- 2) Expand the observational data base necessary to incorporate the physics necessary to include additional forcing functions, not now included in atmosphere/ocean GCMs. This includes those observations which may lead to a better understanding of anthropic and natural aerosol generation, and their subsequent interaction with water vapor, cloudiness, and the solar radiation budget.
- 3) Develop more sophisticated analysis techniques to assess the consistency or inconsistency of model projection with observed changes.

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THE USE OF CLIMATE MODELS IN FORECASTING FUTURE CLIMATE CHANGE

Anthony J. Broccoli
Geophysical Fluid Dynamics Laboratory/NOAA
Princeton University
P. O. Box 308
Princeton, NJ 08542

ABSTRACT

For more than 25 years, climate models have been used to investigate the impact of greenhouse gases on the earth's climate. These models, which have become increasingly comprehensive, have provided much of the scientific evidence regarding the potential changes in climate due to anthropogenic increases in greenhouse gases. Recently, the advent of more realistic models of the coupled atmosphere-ocean system have made it possible to simulate the response of climate to gradually increasing greenhouse gases. Is it appropriate to regard the output from such models as forecasts of future climate change? The answer depends on a careful analysis of the mechanisms affecting climate and the ability to incorporate them faithfully in climate models.

DESIGN OF CLIMATE MODEL EXPERIMENTS

Climate models have been used to investigate the impact of greenhouse gases on the earth's climate for more than 25 years. The state of the art has progressed dramatically during this period, from relatively simple one-dimensional models of radiative-convective equilibrium to three-dimensional models of the coupled atmosphere-ocean system. The development of a hierarchy of climate models for the study of climate change due to anthropogenic increases in greenhouse gases has led to a variety of research studies. Most of these can be separated into three categories based on their experimental design. Using terminology taken from the recent Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment (Houghton et al.¹), these are equilibrium response studies, transient response studies, and time-dependent response studies. Experiments in the last category will be the primary subject of this paper.

Time-dependent response studies use models of the coupled atmosphere-ocean system to simulate a change in climate in response to gradually increasing greenhouse gas concentrations. Such gradually increasing concentrations are similar to what is occurring in the real climate system. A number of time-dependent response studies have been performed, primarily using general circulation models of the atmosphere coupled with dynamical ocean models. An important result from these studies has been the identification of important regional variations in the rate of warming due to increasing greenhouse gases. In addition, these studies have allowed estimates to be made of the rate of warming in response to an increase in greenhouse gas concentrations with a rate similar to that occurring presently. But can these estimates be regarded as forecasts of climate change? To answer this question, it is necessary to consider the mechanisms influencing climate and the ability to represent them faithfully in climate models.

FACTORS INFLUENCING CLIMATE

A variety of external factors can be important on the time scales relevant to anthropogenic climate change (i.e., years to decades). These include atmospheric greenhouse gas concentrations,

volcanic aerosols, variations in solar radiation, and anthropogenic sulfate aerosols. In addition, internal variability inherent to the climate system may produce variations in climate comparable in magnitude to some of the externally forced variations.

A number of greenhouse gases have been increasing in concentration since the pre-industrial era as a result of human activities. These gases, which include carbon dioxide, chlorofluorocarbons, methane, and nitrous oxide, produce a tropospheric heating effect by increasing the infrared opacity of the atmosphere. The increases of all of these gases provide an enhancement of the heating associated with the natural greenhouse effect.

Large volcanic eruptions can inject sulfur dioxide gas into the stratosphere, forming sulfuric acid aerosols that can scatter incoming solar radiation, increase planetary albedo, and thus have a significant impact on the earth's radiation balance. The combination of a reduction of total solar radiation with the warming due to the thermal infrared effects of the aerosols results in a small net cooling effect at the earth's surface, which can persist for 1 or 2 years following an eruption.

Variations in solar radiation are capable of producing changes in changes in climate. Changes in the latitudinal and seasonal distribution of insolation associated with periodic variations in the earth's orbital parameters are believed to be responsible for the glacial-interglacial cycles of the Quaternary era. These orbital variations have time scales of 10^4 to 10^5 years. Much less is known about changes in insolation on shorter time scales (10 to 10^3 years), since precise monitoring of solar irradiance has existed for little more than a decade. However, some evidence has been offered for irradiance variations of up to 0.5 percent on these time scales.

Anthropogenic sulfur emissions may also have potential climatic effects through two mechanisms. A direct effect is the scattering of incoming solar radiation by sulfate aerosols. However, this effect may not necessarily result in an increase of planetary albedo, depending on other factors such as the albedo of the underlying surface and the solar elevation angle. An indirect effect is the potential of aerosol particles to increase cloud albedo by acting as cloud condensation nuclei. Both of these effects are extremely difficult to assess quantitatively, although recent work suggests a net cooling effect at the surface.

In addition to variations in climate resulting from these external forcing factors, substantial variability appears to occur in the climate system even in the absence of external forcing, spanning a wide range of time scales. Much of this variability involves interactions between the atmospheric and oceanic components of the climate system. The well-known El Niño-Southern Oscillation phenomenon is an example, with climatic effects in widespread areas around the globe. More recently, models of the coupled ocean-atmosphere system have displayed variability of oceanic overturning (with accompanying atmospheric variations) on interdecadal time scales. On shorter time scales, climate model experiments have demonstrated that substantial variability can occur even without changes in the ocean. Interactions with the land surface and internal atmospheric dynamics are likely sources of this variability.

REPRESENTATION IN CLIMATE MODELS

The extent to which these external forcing factors can be incorporated in climate model calculations is crucial in determining whether model output can be used as forecasts of future climate change. Two conditions must be met for each to be successfully incorporated. First, we need to

know how to model the physical effect of that factor. Second, we need to know how that factor varies in time. For hindcasts (i. e., attempts to reproduce the variations in climate up to the present) only past variations in forcing need be known; for forecasts, both past and future variations are necessary. In this section, the state of our current ability to represent the external forcing factors in hindcasts and forecasts will be examined.

Greenhouse gases seem by far to be the external forcing factor most readily represented in a climate hindcast. The development of more accurate radiative transfer models has enabled reasonable estimates of the radiative effects of the various greenhouse gases as a function of their atmospheric concentration. Despite some uncertainties in the basic spectroscopic data for many gases (particularly the chlorofluorocarbons) and differences among the radiative transfer models, the radiative effects of greenhouse gases is a relatively mature and well-understood component of the climate modeling problem. Evidence of past increases in concentration of the various greenhouse gases are readily available from two sources. In recent decades, direct measurements have been taken at locations relatively free of local contamination (e. g., CO₂ at Mauna Loa). Records from earlier times have been extracted from ice cores in Greenland and Antarctica. As snow is transformed into glacial ice, air becomes trapped as bubbles in the ice. These bubbles contain fossil air, which can be dated based on ice accumulation rates.

Representing the past history of the other forcing factors is much more problematic. In principle it should be relatively straightforward to model the effect of volcanic aerosols in the stratosphere, although in practice it can be difficult to do so quantitatively. Measurements have only been available in recent years. Historical records provide clues to earlier eruptions, although it can be quite difficult to reconstruct the sulfur content of the erupted material and whether or not it reaches the stratosphere. This is important, since the sulfate aerosol particles have much longer lifetimes in the stratosphere than in the troposphere. Increased acidity in glacial ice cores has also been linked to sulfate aerosol-producing eruptions, but again there are difficulties in interpreting these proxy data. Thus reconstructions of past volcanic activity often differ from each other.

For changes in solar irradiance, the difficulty is in documenting past changes in this quantity based on the short period of precise observations. These have indicated that irradiance varies in conjunction with the 11-year cycle of solar magnetic activity (i. e., the sunspot cycle), with a total variation of approximately 0.1 percent. There has been speculation that variations in solar output may occur on longer timescales. Proxies of solar magnetic activity, such as sunspot numbers, carbon-14, and beryllium-10, indicate substantial variations on time scales of decades to centuries. Observations of solar radius also show variations on these time scales. There has been some suggestion that these changes may be correlated with solar irradiance, with variations of as large as 0.5 percent. Substantial work is underway to explore possible mechanisms for such variations, including physically-based modeling and astronomical studies of Sun-like stars. But at this time, little evidence exists to quantify them.

The radiative properties of tropospheric sulfate aerosols resulting from industrial activity contribute to substantial difficulty in representing them in climate model hindcasts. Large uncertainties exist in both their direct and indirect effects. Because of their relatively short lifetimes in the troposphere (days to weeks), the distribution of sulfate aerosols is not as uniform in space and time as those of the greenhouse gases, since their sources are confined to the continents, particularly the densely populated and industrialized areas. This adds another complication to including

their effects in climate model calculations, even though there are some estimates of the history of sulfur emissions which could be used in chemistry/transport models to estimate aerosol concentrations.

Many of the problems in representing the effects of these external forcing factors are exacerbated when forecasting future climate. Future changes in greenhouse gas concentrations depend on the emission rates of the gases and biogeochemical processes operating in the atmosphere-ocean system. Since future emission rates will be affected by economic conditions, technology, and public policy, substantial uncertainty exists as to their magnitude. To account for this, the IPCC used a variety of scenarios of future greenhouse gas concentrations, yielding a range of time-dependent climate change estimates. This method may be the only reasonable way to quantify the uncertainty inherent in estimates of future greenhouse gas concentrations. Projecting future concentrations of anthropogenic sulfate aerosols involves similar difficulties, including the added complication that their spatial patterns can be affected by changes in the geographical distribution of sulfur emissions.

Estimating future variations in solar radiation would probably require such a reconstruction of past variations along with evidence of a periodic nature that can be extrapolated forward in time. Until the causes of solar variability are better understood and the variations in solar output are better quantified, this remains a daunting problem. The obvious difficulty of forecasting future volcanic eruptions makes it impossible to include this effect in climate change projections more than a year or two in length. Fortunately, the climatic effects of an individual eruption are felt for no more than a few years, so only a period of frequent large eruptions would influence temperature on decadal time scales.

In making forecasts (or hindcasts) of climate change, the internal variability inherent in the climate system can be an additional complicating factor. While the coupled atmosphere-ocean climate models used for time-dependent response studies have shown an ability to simulate such variability in the frequency domain, there is no reason why the time variations in climate associated with this variability should be synchronous with those in the real climate system. While deterministic predictions of some of this variability may be possible given accurate specification of initial conditions in the atmosphere and ocean (as evidenced by reports of skillful forecasts of the El Niño phenomenon), further research is required to explore this possibility. For the time being, the manifestations of internal variability must of necessity be regarded as climatic "noise" that can obscure the climate variations associated with external forcing factors.

ARE CLIMATE MODEL SIMULATIONS FORECASTS?

In the time-dependent response studies that have been conducted to date, the impact of increasing greenhouse gases typically has been the only external forcing included. The time-dependence of this forcing (i. e., the time series of greenhouse gas concentrations) has generally been idealized. In some experiments, the CO₂ concentration (taken as a surrogate for all greenhouse gases) has been increased at an annual rate approximately equivalent to the current rate of increase. In others, a range of future growth rates for atmospheric greenhouse gas concentrations have been used to yield a series of future climate change scenarios, in an effort to explicitly incorporate some of the uncertainty associated with future emission rates.

Representing only the greenhouse gas forcing (and doing so in an idealized manner) may have

a number of interesting consequences for the interpretation of these experiments. The idealized time-dependent greenhouse gas forcing differs from that actually observed. Thus quantitative comparisons of simulated and observed temperature changes may be of limited value. This is of particular concern given the possibility that changes in the other external forcing factors, along with internal variability, may also have influenced global temperature during this period. Since the increase in greenhouse gas forcing has been relatively small until the past few decades and the ocean should delay the response of the climate system, the effect of this forcing over the historical record may be comparable in magnitude to those associated with other factors. Thus there is no reason to expect quantitative agreement between the simulated and observed evolution of global temperature during this period.

For estimates of future climate change, these difficulties could become somewhat better resolved. For the range of emission scenarios considered by IPCC, the greenhouse gas forcing is expected to grow well beyond the plausible contributions of volcanic aerosols and solar variability during the next century. Thus the greenhouse gas effect would be expected to become dominant over that time, such that an estimate of its magnitude could be a good approximation of a climate change forecast. However, the effect of anthropogenic sulfate aerosols is a complicating factor. Because the sulfate forcing has been hypothesized to have the opposite sign and could also increase as a result of economic growth, some fraction of the greenhouse gas effect may be counteracted as a result.

Thus to increase the ability to make climate forecasts on time scales from decades to centuries, it seems important that the anthropogenic sulfate effect be better quantified. Much work also needs to be done on the effects of volcanic aerosols, solar radiation variations, and internal variability of the atmosphere-ocean system. Concurrently, progress in climate modeling is also necessary to narrow the range of uncertainty regarding climate feedback mechanisms that can amplify or reduce the direct effects of external forcing. Better observations of oceanic variations and processes may prove useful in understanding the role of the oceans. In the meantime, caution is required when interpreting the results from climate modeling experiments.

ACKNOWLEDGMENTS

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GLOBAL CLIMATE CHANGE:
THE UNCERTAINTIES AND THE CONTROVERSIES

Richard A. Kerr
Research News section, Science
1333 H St., N.W., Washington, DC 20005

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ABSTRACT

Uncertainties abound with respect to global climate change. Records of past climate change are imperfect because measuring devices and practices have changed and because urban areas have encroached on observation sites. Past and future climate change may be affected to uncertain degrees by volcanic eruptions, solar variability, and ocean variability. Global warming itself can interact with numerous Earth systems to produce enhanced warming--positive feedbacks--and diminished warming--negative feedbacks. Potential feedbacks present some of the greatest uncertainties about global warming. Controversy arises from the two ways of treating these uncertainties: viewing them as a reason for further study, before taking action that may be unnecessary, or as a justification for action that may avert serious if not catastrophic consequences at low or modest cost.

Much of the United States was hot and dry in the summer of 1988. So when NASA climate expert James Hansen claimed that global warming was here, intensified public concern became inevitable. But in parts of the scientific community there was just as inevitable a response--skepticism. Some experts not only saw no evidence of greenhouse warming, they saw no clear prospect of a significant warming in the future.

And yet over the past 4 years, the tempest has abated, scientific support for a middle ground has solidified, and even the Bush Administration seems to be dropping its unqualified opposition to action on the greenhouse threat. In part, the administration is hearing from the scientific community that the consensus is as strong as ever--greenhouse warming does pose a serious threat for the planet's future. Indeed, a four-agency memo recently leaked to the press hews closely to the latest assessment of greenhouse science released recently by the Intergovernmental Panel on Climate Change (IPCC). Echoing the IPCC, the memo concedes that continued increases in greenhouse gases will likely lead to "significant changes in the climate system."

The administration memo cited "a consensus view of a broad range of scientists, including most U.S. scientists," and quoted likely limits to greenhouse warming due to a doubling of carbon dioxide as a modest 1.5°C at the lower end and a hefty, if not catastrophic, 4.5°C at the upper end. That's the same range that National Academy of Sciences panels have been coming up with for the past 15 years. Not that there is unanimity about greenhouse warming. Academy reports come from highly competent but very small groups. The IPCC reports each involved dozens of chapter authors, hundreds of reviewers, and a half dozen rewrites, but dissenters are still scarce in these circles. In the media they number less than half a dozen, although they are usually paired with Hansen, an environmentalist, or a mainstream scientist, giving the appearance of a raging controversy between implacable opposites. The true proportions of

the debate are difficult to pin down, but there is no doubt that a consensus-- in the sense of a majority opinion--exists in the scientific community.

Eventually, a quiet majority found fault with both extremes of the public greenhouse debate. For example, when Hansen, director of NASA's Goddard Institute for Space Studies in New York City, argued that the half-degree warming of the past century was driven by the steady increase of greenhouse gases, most greenhouse researchers eventually concluded that although the warming is consistent with an intensifying greenhouse, it is not clearly a result of it.

At the other extreme of the debate, questions were raised about temperature trends in general. If Earth is getting warmer, why is Minneapolis getting colder? Why isn't the United States getting warmer? Is the global warming of the past century even real? Most climatologists see no fundamental problems with the temperature trends seen so far. The lack of clear warming trends at every spot on Earth does not mean greenhouse warming is not at work, they say, because temperature varies too much to see a clear warming in every area at this early stage, even if the area is as large as the United States. And, contrary to a few critics, the globe as a whole has already warmed several tenths of a degree, even after accounting for warming due to urbanization. That a global warming is not obvious in the satellite temperature record does not surprise climatologists either. This record covers only the past decade, when temperatures were uniformly high after jumping upward in the 1970s. Climatologists are intrigued by the tendency of the warming, for the time being at least, to occur predominately during the nighttime, when presumably the least stress would be placed on living things.

The main problem with the temperature records is that greenhouse warming carries no distinctive signature that could have been clearly distinguished at this point from natural climatic variability. But if mainstream estimates of future greenhouse warming are anywhere near correct, most researchers feel, the warming should become obvious during the next decade or two as it overwhelms the coolness of the oceans and the protective effect of pollutant hazes that reflect some sunshine back to space.

Other uncertainties have been cited as justifications for complacency about the greenhouse. Could the sun possibly dim slightly during the next century and counteract any greenhouse warming? Maybe, maybe not. So many claims of a connection between the sun and climate have come and gone that most scientists believe no firm link of significant magnitude has been demonstrated. And those who do dabble in the field can't even agree whether the sun will dim or brighten in coming years. Won't plants just love the warmer, generally more moist greenhouse world rich in the atmospheric carbon dioxide that plants need for growth? Won't plants then store away the extra carbon dioxide we're putting in the atmosphere? Not necessarily. Greenhouse experiments at elevated concentrations of carbon dioxide have shown increased growth and carbon storage, but terrestrial ecologists are at a loss to predict how complex ecosystems will react. Natural plant communities might help out, but only until they get their fill of carbon, or rapid climate change might be so disruptive that the biosphere could become a net source of carbon dioxide rather than a sink. Most researchers view either salvation as dubious justification for skepticism.

Other uncertainties have attracted more serious attention within the climate community. In 1989, prominent meteorologist Richard Lindzen of MIT proposed that the computer climate models predicting a few degrees' warming for a doubling of carbon dioxide misrepresented the way that the atmosphere controls the abundance of water vapor--a greenhouse gas--in the upper troposphere. If a warming atmosphere tended to dry the upper troposphere, as Lindzen suggested, that could limit warming to a few tenths of a degree--that

is, nothing to worry about (Science, 1 December 1989, p. 1118). Lindzen argued that the greenhouse effect has an inherent limit--indeed, one that has nearly been reached, due to the water vapor and other natural greenhouse gases that already warm the atmosphere by 33AC. Such a renegade proposal coming from a prominent researcher made front page news and prompted considerable new study. But after several years of scrutiny, most climatologists would agree that Lindzen has not proven his case. Among the strongest evidence against Lindzen's self-limiting greenhouse are satellite and balloon observations showing that water vapor in the upper troposphere increases, not decreases, whenever and wherever the lower troposphere is warmer--in summer versus winter, in the warm western Pacific versus the cooler eastern Pacific.

Most scientists in the mainstream readily admit that greenhouse science is still pervaded by uncertainties. The single largest uncertainty in the climate models is the behavior of clouds as the world warms. In one model, created by researchers at the United Kingdom's Meteorological Office, the warming due to a doubling of carbon dioxide dropped from 5.2AC to 1.9AC when the computer was switched from one "equally plausible" way of rendering clouds to another. Getting clouds right will take 10 to 20 years because researchers must understand better how clouds work, not just increase the speed of their computers, and then get computer clouds to act like the real ones. In addition, the interconnected system of ocean-atmosphere-biosphere has a host of ways of changing its behavior in response to warming that might in turn affect global temperature. Ice and snow, for example, might recede, exposing darker ground or ocean that would absorb more sunlight and accelerate the warming. Other possible feedbacks involve everything from methane production in wetlands to increased decomposition of soil organic matter. Most feedbacks that researchers have been able to imagine tend to enhance any warming. And most are not included in present climate models.

Uncertainties abound, but climate researchers see some constraints on the uncertainties. First there is the basic physics of the greenhouse, which is already responsible for warming Earth 33 degrees C through water vapor and carbon dioxide. This physics must continue to operate as humankind's enhancement of the greenhouse since 1765 is doubled during the next 35 year, assuming no action is taken to avoid it. And then there is the performance of climate models. They are rudimentary, everyone agrees, but their behavior bears a considerable resemblance to reality. They produce reasonable seasonal changes. They do not wildly overreact to injections of volcanic debris or small changes in solar output. With all this in mind, the IPCC has twice now accepted the 1.5- to 4.5-degree warming for a doubling of carbon dioxide as sound, characterizing their confidence in these numbers as falling midway between "virtual certainty" and "low confidence."

Given the uncertainties, some researchers are arguing for a delay of perhaps 10 years in reining in greenhouse emissions while the science settles down. If the climate system turns out to be relatively insensitive to added greenhouse gases, they reason, no harm will be done, and if it is highly sensitive, the effort to avert rapid warming will be so great that a mere 10-year delay will not make it perceptibly more harsh. Another line of reasoning is that society can adapt to climate change reasonably well and with less expense than required to limit the emission of greenhouse gases.

But environmentalists and many scientists can't agree with even this modest wait-and-see approach. Even 10 years of increasingly faster computers won't narrow the uncertainties enough, they say. A decade will see only the beginning of crucial observations of the behavior of oceans and clouds. The 1990 IPCC report foresaw the cloud and ocean uncertainties narrowing only in the 10- to 20-year range, by which point the globe might be committed to major climate change. And the ability to adapt will vary greatly from society to society;

natural ecosystems could be even harder pressed to adapt to rapid climate change.

The other reason for not waiting is uncertainty itself, some say. The possibility that greenhouse-induced change could turn out to be much more dramatic than any model predicts is spooking a generation of Earth scientists who remember the nasty surprise sprung on stratospheric ozone. No one foresaw the Antarctic ozone hole or accelerated ozone losses at mid latitudes due to natural atmospheric particles. Greenhouse specialists, too, are wondering what they might have overlooked. One possibility is an abrupt change in ocean circulation, although some studies have now discounted that idea. Or perhaps unanticipated feedbacks from polar ice caps or green plants, other workers venture.

The philosophy that many scientists are now espousing amounts to buying some insurance--in the form of no-cost or low-cost reductions in greenhouse gas emissions. Even some greenhouse skeptics, if pressed, would concede the prudence of no-cost measures that can be supported by other justifications. Greater energy efficiency seems a reasonable goal in a country that consumes energy profligately while importing half of its oil. While such measures fall far short of complete coverage, advocates admit, such tie-in steps seem prudent against the possibility that the higher predictions of global warming turn out to be right or some nasty surprise is lurking in the greenhouse.

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Greenhouse Gas Emissions from Fossil Fuel Use and
Technical Approaches to their Control

John A. Ruether, Dennis N. Smith, and Nagaraja S. Rao¹
U.S. Department of Energy
Pittsburgh Energy Technology Center
Pittsburgh, PA 15236

1. Burns and Roe Services Corp.

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Introduction

Radiative trapping or forcing by so called greenhouse gases in the atmosphere causes the mean surface temperature of Earth to be 33 K higher than it would be in their absence. While the greenhouse effect is thus necessary for life as we know it, there is concern that additional unwanted warming may occur as a result of increasing concentrations of greenhouse gases. Analysis of air bubbles trapped in glacial ice shows that starting roughly with the onset of industrialization in the late 18th and early 19th centuries, the concentration of all greenhouse gases found in nature began to increase. Through 1991 the concentration of CO₂, the gas causing the greatest amount of radiative forcing, had increased by over 25% from its preindustrial value. The other main greenhouse gases that occur in nature, CH₄ and N₂O, exhibit similar increases since the early 1800s. While the timing and extent of global warming that may result from increased concentrations of greenhouse gases is uncertain, it is prudent to understand the main sources of anthropogenic greenhouse gases and the conditions governing their release. All three of the principal greenhouse gases existing in nature are released in the course of fossil fuel use, and for all three, fossil fuel emissions are a significant component of total anthropogenic emissions¹. In this paper the emissions of CO₂, CH₄, and N₂O in the contemporary United States due to use of the fossil fuels natural gas, oil, and coal are presented. Details of the calculations will be given in a subsequent publication². The relative importance of each of these gases for radiative forcing is shown. Some technologies under development that can reduce emissions of these trace gases per unit of useful heat or work obtained are discussed.

The amount of radiant energy a mole of a particular greenhouse gas absorbs during its atmospheric lifetime depends on its lifetime and its absorption strength, integrated over all active wavelength bands. An index called the global warming potential, or GWP, has been developed to compare the lifetime effect of one mole (or one kg) of a particular greenhouse gas to that of a similar amount of CO₂. The GWP for trace gas *i* is defined²:

$$GWP_i = a_i \int_0^T c_i(t) dt / a \int_0^T c(t) dt \quad (1)$$

Here *a_i* is an absorption coefficient, *c_i* is concentration in mass or molar units, and *t* is time. Unsubscripted values refer to CO₂. The average atmospheric

lifetimes of the trace gases are as follows: CO₂, 100-120 y; CH₄, 10-12 y; N₂O, 150-180 y. When eq. 1 is integrated over a time T of 100 y, the computed GWPs for CH₄ and N₂O are 7.6 and 290, respectively, expressed on a molar basis³.

1. Emissions of CO₂

For complete combustion of any fuel, the specific carbon emission, or carbon emission factor, defined as g C as CO₂ per MJ heat released, is determined by its composition and heating value. It is preferable to use the lower heating value (LHV) for the calculation, since in most applications water produced in combustion leaves the process as a vapor. A correlation of heating value as a function of elemental composition of a fuel shows how the carbon emission factor depends on fuel composition⁴. Although developed specifically for coal, it describes oil and natural gas as well.

$$\Delta H_L = 341 C + 1102 H + 68.4 S - 15.3 A - 119 (O + N) (2)$$

Here, C, H, S, and (O+N) are the percentage of elements and A is ash or other inert by weight on a moisture free basis. The heating value is in J/g (LHV). It is seen that on a weight basis, hydrogen is the component with the largest energy content. Carbon is next largest, but it figures in the numerator as well as denominator of the expression for carbon emission factor. Oxygen and nitrogen have negative values because their presence in a fuel causes it to be partially oxidized. For coal, the combined effect of C, H, and O dependence causes the carbon emission factor to go through a minimum with the rank of hv bituminous.

Natural Gas

Consumption of natural gas in the U.S. in 1989 was 481 billion m³ (20.3 EJ (HHV)). To convert this figure into CO₂ emissions requires information on composition of the gas at the wellhead and also at the burner tip. The difference between the two compositions is due to processing of the natural gas before transmission by pipeline. In processing, undesirable components including CO₂ are removed, the CO₂ being vented. The CO₂ produced due to flaring at the well must also be counted. Equations are developed for a carbon emission factor for natural gas that takes into account CO₂ emissions from venting and flaring. Application to domestically produced natural gas in 1989 yields an emission factor of 15.17 gC/MJ (LHV). Imported gas is analyzed similarly. Total CO₂ emissions in 1989 from consumption of natural gas is estimated to be 278.2 M tonne C.

Oil

In 1989, total crude oil processed in the U.S. was about 13.5 million barrels per day with the balance of liquid fuel consumption comprising natural gas liquids and imported refined products. A small fraction of petroleum (about 5 %) was exported. Total oil-based energy consumed in the U.S. was about 36 EJ. Emission factors for imported refined products and for crude oil (combined domestic production and imports) were computed and used to calculate carbon emissions by product class. The carbon emission factor for crude oil is 19.96 gC/MJ (LHV). The factor for products falls in the range 18.4-21.5 gC/MJ (LHV) depending on fuel composition. Total estimated CO₂ emissions from petroleum consumption in the U.S. during 1989 was 625.1 M tonne C.

Coal

The carbon content of coal per unit of heat content is found to vary with coal rank. Equation 2 has been used with composition data for U.S. coals to compute carbon emission factors by rank. The emission factor for lignite, the highest for all coal ranks, is 26.9 gC/MJ (LHV), about 8 % higher than for hVA bituminous, the lowest at 24.6 gC/MJ (LHV). The emission factors have been used with U.S. coal consumption by rank in 1989 to compute carbon emissions. In 1989 total U.S. coal production was 890 M tonnes, and coal consumption, expressed as energy, was 19.69 EJ (HHV). The largest carbon emission was from the bituminous grades, which represented 70% of total emissions, but supplied 74% of the total energy. Overall carbon emissions are calculated as 490.5 M tonnes C, which agrees well with the estimate of Marland⁵, which was prepared without use of rank-specific carbon emission factors.

2. Emissions of CH₄

Methane emissions result from the production and distribution of oil and gas, and from the mining of coal. The losses from oil and gas operations are considered in three categories.

- o Venting and flaring of methane occurring at the well head in the production of natural gas and oil.
- o Production, gathering, and processing losses.
- o Transmission and distribution losses.

The following discussion provides estimates of methane emissions from fossil fuel use in the U.S. during 1989.

Venting/Flaring Emissions in Oil/Gas Production

Venting and flaring of methane during production and processing of oil and gas is due to purposeful venting, routine maintenance, and system upsets and mishaps. There are insufficient data to apportion these emissions to oil or gas and to determine their composition. We estimate the fraction of methane in venting/flaring emissions to be 20%. Based on total reported venting and flaring emissions for the U.S. in 1989, emissions of methane are estimated to be 0.41 Tg.

Production Losses

Leakage of methane occurs from field production and processing operations. These are primarily from fugitive emissions such as leaks from valves, pipes, compressors, and other equipment during normal operation of gas gathering, separation from condensate/oil, reinjection, and processing. The leakage rate varies between oil and gas wells and between offshore and onshore operations, due to significantly different processing equipment and conditions. Production losses of CH₄ are calculated to be 0.44 Tg.

Transmission/Distribution Losses

Natural gas is transported via high pressure pipeline throughout the U.S. with

local distribution networks consisting of low pressure delivery systems. Including low pressure distribution lines, the total length of pipe is estimated to be over 1.5 million miles. Several key components are subject to leakage: compressor shaft seals, valve stem packing, relief valve escapes, and flanged joints. Methane emissions from transmission/distribution losses is estimated as 1.77 Tg.

In addition to the three categories of CH_4 losses tabulated above, a relatively small amount is added for incomplete methane combustion. Allowing 0.5 g CH_4 per GJ adds an additional 0.009 Tg to 1989 emissions in the U.S. Total estimated CH_4 losses due to oil and gas operations thus sum to 2.63 Tg in 1989. By use of the GWP for CH_4 developed above, the importance of these losses for radiative forcing relative to the CO_2 emitted in the combustion of the oil and gas consumed in the U.S. in 1989 can be computed. The radiative forcing due to CH_4 emissions is 1.7% of that due to CO_2 from natural gas and oil combustion.

Methane Emissions as a Result of Coal Mining Activities

Correlations have been developed to relate CH_4 emissions to coal production by use of an overall emission factor. Such a factor, in m^3/tonne , expresses the ratio of total methane emissions to total coal production. Emission factors depend on in-place coal methane content. However, in addition to the gas contained in coal that is removed, methane may be released from adjacent gas-bearing strata and exposed but unmined coal during and after mining. Emissions from these sources are also included in computing an overall emission factor.

Overall emission factors have been developed by several workers in recent years and used to estimate CH_4 emissions from coal mining^{6,7,8,9}. The emission factors fall in the range 6.02-11.77 m^3/tonne . Smith and Ruether calculate the emission factor as 7.74 m^3/tonne and estimate total CH_4 emissions in 1989 as 5.0 Tg⁹. The greatest fraction, 4.2 Tg, was due to deep mining operations. The importance of these emissions for radiative forcing relative to those of the CO_2 produced in coal combustion can be estimated as above. In 1989, U.S. production of deep mined coal was 357 million tonnes, and the radiative forcing of CH_4 emissions from deep mines was equivalent to about 9% of the forcing due to combustion of deep mined coal.

3. Emissions of N_2O

Production of N_2O in the course of fossil fuel use occurs via direct emissions and also via an indirect route from emissions of NO and NO_2 , collectively called NO_x . In the atmosphere, NO_x are oxidized and return to the earth as acid precipitation. It is known that soil-bearing microbes reduce nitrates applied as fertilizer, resulting in N_2O emissions to the atmosphere. This mechanism presumably applies to nitrates originating as acid precipitation as well¹³. The extent of conversion of nitrate to N_2O by soil microbes is not well known, but Robertson estimated N_2O formation to be 1% of total fertilizer nitrogen, nitrate and ammonia¹⁰. If 1% of N as NO_x is converted by microbes to N_2O , this is an important indirect route in fossil fuel combustion to N_2O .

About 30% of fossil fuels consumption in the U.S. is for the transportation sector with the remainder used in stationary sources ranging from residential heating to electric utility boilers. The N_2O emissions from the largest stationary sources, utility boilers, have been most studied. Early estimates of

N₂O emissions from stationary sources were erroneously high due to an artifact of the analysis procedure¹¹. More recent results are given in Table 1 where both NO_x and N₂O emissions are shown for a number of utility boilers firing all three fossil fuels¹². It is seen that except for the circulating fluidized bed combustor, the greater contribution to N₂O emissions is due to the indirect route if the assumed 1% conversion of NO_x to N₂O is correct. Because per molecule N₂O has two atoms of N while NO_x has one, a 1% conversion of NO_x to N₂O is equivalent to a direct N₂O emission of 0.5% of NO_x. The right hand side of Table 1 shows the effect on NO_x emissions of several technologies being developed for their control. The effect of these technologies on direct N₂O emissions is poorly understood at present.

The transportation sector produced 44% of total NO_x emissions from fossil fuel use in 1989. It is thus an important producer of N₂O via the indirect route. It is also responsible for significant direct emissions of N₂O. These emissions vary with vehicle type and whether a catalytic converter is employed. (Catalytic converters increase N₂O emissions 10-fold¹⁰.) On an energy basis, direct N₂O emissions from vehicles are substantially higher in general than those from high temperature stationary boilers. Due in large part to the unknown extent of indirect production of N₂O from NO_x, estimates of N₂O production from fossil fuel use are highly uncertain. For instance, two recent estimates for global emissions were 0.3 Tg and 5.0 Tg^{13,14}.

4. Technologies to Reduce Greenhouse Gas Emissions

Carbon Dioxide

For a given fossil fuel, reduction of CO₂ emissions per unit of useful heat or work output requires increased energy conversion efficiency. Natural gas consumption is expected to rise in the U.S. in the 1990s primarily for increased power generation using gas turbines. The efficiency for power generation via simple cycle, e.g., gas turbine, for current typical units is 25-30% and for combined cycle units, 35-40%. With recent improvements, cycle efficiency has improved considerably to 35.5% for simple cycles and 52.5% for combined cycle. Further advances now on the horizon may increase combined cycle efficiencies to the range of 55-60%. Synthesis gas, the fuel for molten carbonate and solid oxide fuel cells, can be made by reforming natural gas. These fuel cells alone yield an efficiency in the range 45-50%, and when combined with a thermal bottoming cycle may give an overall efficiency of 60-65%.

There are similarly both short term and longer term efficiency improvements for coal-fired power cycles. In the current population of coal-fired power plants, 22% of the plants operate with an efficiency of less than 31%. Only about 10% have an efficiency of greater than 36%. Typical operating conditions for current pulverized coal-fired boilers are 2400 psig steam with 1000 °F superheat and reheat. Commercially proven technology is available with steam operating conditions in the range 3500-4500 psig with main and reheat temperatures in the range 1050-1100 °F, which yield efficiencies of about 40%. This is close to the efficiency expected for pressurized fluidized bed combustors, in an advanced state of development. In the medium term, new or revisited power cycles (Kalina cycle, employing water/ammonia working fluid; indirectly heated gas turbine combined cycle) are expected to yield efficiencies of 45-50%. Other high efficiency approaches are combined cycle gasification/fuel cell, and combined cycle gasification/gas turbines. Longer term, magnetohydrodynamics (MHD) shows

promise of an efficiency in the neighborhood of 60%.

Methane

The main contributor to CH_4 emissions from oil and gas operations is the transmission and distribution system, which accounts for two-thirds of the total. A more rigorous maintenance schedule and accelerated replacement of aging pipelines would help reduce these emissions. New transmission systems are estimated to leak only one-fourth as much as older systems, on average. One possible pipeline replacement program would result in about 0.6 Tg reduction in annual emissions after 10 years. There also appears to be scope for reduction of CH_4 currently vented. At a minimum, if this methane is flared (burned) before release, its effect on radiative forcing is reduced by a factor of about 7. Where venting or flaring is currently practiced on a regular schedule, it may be possible to install transportable electrical generating equipment employing gas turbine or internal combustion engines (see below). This would have the double benefit of converting CH_4 to CO_2 and generating usable power with no additional use of fossil fuel.

Much of the estimated 5.0 Tg CH_4 emitted from U.S. coal mines in 1989 has the potential for useful recovery. Components that are potentially useful are ventilation gas (2.8 Tg), typically 0.3-1.0% CH_4 , gas produced by degasification systems (1.3 Tg), typically 25-95% CH_4 , and emissions from abandoned deep mines (0.5 Tg), of variable composition. Ventilation gas is too dilute to support combustion by itself, but if used as the source of combustion air with another high concentration CH_4 source, it could contribute about 15% of the fuel to a gas turbine. Degasification gas can serve as the sole fuel source for power generation by internal combustion engines, as is presently being demonstrated¹⁵. Transportable generator modules are being developed that can be taken to remote mine sites to generate power used at the mine and potentially also for export to a power grid. If gas is purposely withdrawn from abandoned deep mines, it also could serve as the fuel for such a generator module.

Nitrous Oxide

As discussed above, both the transportation sector and stationary sources are significant sources of N_2O . Improvement of vehicle mileage would obviously reduce N_2O emissions from the transportation sector. Redesign of catalytic converters should be possible to reduce direct N_2O emissions. These emissions were not a consideration in the original design. Development of electric vehicles would also reduce N_2O emissions, since on an energy basis, stationary sources needed to generate the electricity to charge vehicle batteries, emit less N_2O and NO_x than do vehicles.

For stationary sources, the Clean Air Act Amendments of 1990 will require a 2 million ton per year reduction in NO_x emissions. A number of technologies for NO_x control, some of them listed in Table 1, are being demonstrated at commercial scale through the U.S. DOE Clean Coal Technology program.

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**TABLE 1
NO_x AND N₂O EMISSIONS FROM UTILITY AND INDUSTRIAL COMBUSTION**

Combustor Type	MWe	Fuel	Uncontrolled Emissions, (PPM)			Controlled Emissions, (PPM)				
			NO _x		N ₂ O	Control Technology ¹	NO _x		N ₂ O	
			Direct	Indirect	Total		Direct*	Indirect	Total	
1. Tangential	160	Coal	490	1	2.5	3	OFA	223	@	1.1
2. Tangential	165	Coal	400	1	2.0	3	LNCFA	292	@	1.5
3. Wall Fired	500	Coal	950	1	4.8	6	AOFA	730	@	3.7
4. Wall Fired	800	Coal	800	2	4.0	6	LNB	360	@	1.9
5. Wall Fired	800	Coal	730	1	3.7	3	GRB	80	@	0.4
6. Wall Fired	110	Coal	120	2	0.6	2	LNB	80	@	0.4
7. Cyclone	N/A	Gas	258	1	1.3	2	GRB	-	-	-
8. Wall Fired	185	Oil	81	84	0.4	16	-	-	-	-
9. Wall Fired	N/A	Coal	430	14	2.2	-	-	-	-	-
10. CFBC	N/A	Coke	-	-	-	-	-	-	-	-
11. Fluid Bed Catalytic Cracker	75	Coal	200*	1	1.0	2	SNCR	120	33	0.5
12. Tangential	N/A	Coal	300*	1	1.5	3	SCR	60	10.6	0.3
13. Tangential	110	Oil	291	1	1.5	3	SNCR	117	23	0.6

LNB (low-NO_x burner)

AOFA (advanced over-fire air)

AOFA (advanced over-fire air)

SNCR (selective non-catalytic reduction of NO_x)

SNCR (selective non-catalytic reduction of NO_x)

CFBC (circulating fluidized bed combustor)

AOFA (advanced over-fire air)

THE CAPTURE AND SEQUESTRATION OF POWER PLANT CO₂

Howard J. Herzog, Elisabeth M. Drake, Jefferson W. Tester
Energy Laboratory
Massachusetts Institute of Technology
77 Massachusetts Avenue, Room E40-489
Cambridge, MA 02139-4307

Keywords: Greenhouse Effect, Carbon Dioxide, Fossil-Fueled Power Plants

INTRODUCTION

Electrical utilities in the U.S. produce about 7% of the world's CO₂ emissions from energy use. Worldwide, about one-third of all CO₂ emissions from fossil-fuel energy sources comes from electric power plants. Since power plants have the highest density of CO₂ emissions in terms of mass per area per time, they provide an appropriate focus as a control target.

Assuming that the build-up of CO₂ in the atmosphere will have some adverse climatological and geohydrological affects, we can mitigate these effects by either counteracting the CO₂ emitted by the power plants or directly reducing the CO₂ emissions themselves (see Figure 1). In terms of counteracting power plant CO₂ emissions, natural fixation of biomass is the most serious contender. Some geoengineering options, such as fertilizing the ocean to increase CO₂ uptake from the atmosphere or dusting the upper atmosphere to reduce incident solar radiation, have also been suggested (National Academy of Sciences, *et al.*, 1991). In terms of direct reduction of power plant CO₂ emissions, improved efficiency is the most practical approach for the short-term, while switching to alternative energy sources (e.g., solar, wind, geothermal) or nuclear energy will probably be required for the long-term. However, power plants have traditionally dealt with adverse airborne emissions, such as NO_x and SO₂, through flue gas clean-up. In this paper, we will review the options for CO₂ reduction by flue gas clean-up followed by the use or disposal of the captured CO₂.

CO₂ CAPTURE

The idea of capturing CO₂ from the flue gas of power plants did not start with concern about the greenhouse effect. Rather, it gained attention as a possible economic source of CO₂, especially for use in enhanced oil recovery (EOR) operations. A very simplified flow diagram of a power plant is shown in Figure 2. A typical composition of the flue gas from a coal-fired power plant is 75% (by volume) N₂, 15% CO₂, 6% water, and 4% residual components (O₂, SO₂, NO_x). To be useful, capture processes should concentrate the CO₂ to over 90% by volume. Potential processes include:

- Water absorption systems
- Chemical solvent systems
- Physical solvent systems
- Molecular sieves
- Cryogenic fractionation
- Membrane diffusion

All of these processes have significant energy requirements, which reduce the plant's conversion efficiency or net power output, increasing the amount of CO₂ produced per net kWh_e of electricity generated. Therefore, in evaluating the cost of these processes, the amount of CO₂ emissions avoided (CO₂ emissions with capture compared to a no capture baseline) is more important than the total amount of CO₂ captured. For example, for a coal-fired power plant using a monoethanolamine (MEA) scrubbing process, it costs \$25 to capture a ton of CO₂, but due to the large energy losses resulting from the capture process itself, the cost per ton of CO₂ emissions avoided is \$62 on an equivalent power output basis.

Several commercial CO₂ recovery plants using MEA scrubbing have been built and operated in the U.S., with the North American Chemical Plant in Trona, CA being in operation the longest (since 1978). The Trona plant is based on Kerr-McGee technology, which is now licensed by ABB Lummus Crest (Barchas and Davis, 1992). An alternative process has been developed by Dow and is licensed by Fluor-Daniel (Sander and Mariz, 1992). Studies have shown that capture of power plant CO₂ by the MEA process will more than double the cost of electricity for reducing CO₂ emissions by 85% (Booras and Smelser, 1991; Herzog, *et al.*, 1991). Other capture techniques, such as membrane separation, cryogenic fractionation, or molecular sieves are even more expensive (see Table 1).

Because flue gas capture of CO₂ primarily requires separating N₂ and CO₂, the idea of separating the N₂ prior to combustion in the power plant has been investigated by Wolsky, *et al.* (1991). This is shown schematically in Figure 3. An air separation plant removes most of the nitrogen prior to combustion, while flue gas is recycled to moderate the temperature in the furnace. Water is easily removed by condensation either before or after the recycle, yielding a flue gas that contains over 95% by volume CO₂. Analysis shows that this process is somewhat more economical than the MEA process (Herzog, *et al.*, 1991).

The use of physical solvents, such as Selexol, in pressure-swing absorption processes are not competitive with the MEA process for atmospheric combustion because the cost of compressing the flue gas is prohibitive. However, for integrated gasification combined cycle (IGCC) plants that operate at elevated pressures, the use of a pressure swing absorption process is very efficient. CO₂ capture and disposal from an IGCC plant would only increase electricity costs in a range estimated from 30% (Hendriks, *et al.*, 1991) to 70% (Booras and Smelser, 1991).

CO₂ UTILIZATION AND DISPOSAL

Once the CO₂ is captured, concern shifts to disposal or sequestering. In the U.S., over 1.8 billion tons of CO₂ is produced each year from power plants. One option is to use the CO₂. However, the amount of CO₂ used annually in the U.S. is only 1-2% of the total amount produced by power plants, and much of the current supply of CO₂ comes from very inexpensive sources - natural formations or chemical by-products (e.g., from an ammonia process). Therefore, for utilization to be a significant sink of CO₂, new uses need to be identified. Also, many of the uses proposed for CO₂ only delay its eventual release to the atmosphere for a very short time.

One proposal that would satisfy the key criteria of reducing atmospheric emissions of CO₂ and of being able to process large quantities of CO₂ is to transform the CO₂ to a fuel, such as methanol. By producing a fuel, our need for "virgin" fuels would be reduced, thereby reducing our total CO₂ emissions. However, carbon in the form of carbon dioxide is in a low energy state and would require significant amounts of energy to be transformed to a high energy fuel. Two types of processes have been proposed to supply this energy, "light" processes utilizing photosynthetic pathways and "dark" processes utilizing chemical reformation (Aresta, *et al.*, 1992). The source of energy proposed in the *dark* processes is frequently hydrogen (H₂). However, if large amounts of inexpensive H₂ are available, it would be more efficient to burn them directly in a power plant and displace fossil fuel use rather than to try to reprocess the CO₂. The *light* processes use solar energy as a power source. For example, large microalgae ponds would be located near a power plant and the captured CO₂ would be distributed through the ponds. The microalgae would be routinely harvested, processed, and used as a fuel. While this scheme has many barriers (large land requirements, limited geographical applicability etc.), it is still the most promising large-scale utilization option currently available.

For CO₂ disposal, there are four primary candidates: oil reservoirs, gas reservoirs, aquifers, and the deep ocean. CO₂ is currently injected in oil reservoirs for EOR and, therefore, may also be considered utilization of CO₂. However, current EOR practices also inject water, which is not consistent with maximizing CO₂ sequestering. Also, the capacity of oil reservoirs is limited and they are not ubiquitously located. Depleted gas reservoirs have a somewhat larger capacity, but using CO₂ to enhance gas recovery is not a practical technique. Frequently, depleted gas wells have been cemented closed as required by law, so using them for CO₂ disposal requires reopening old wells or drilling new wells. The final land base disposal option is in aquifers, which are widely available. However, there is a great lack of geotechnical data on the behavior of pressurized CO₂ in such reservoirs. Some simulations suggest that flow processes would be dominated by viscous fingering and gravity segregation, resulting in a sweep efficiency of only 1-5% (van der Meer, 1992). Also, the integrity of aquifers as a long-term CO₂ storage system may be risky. Since CO₂, unlike natural gas, is heavier than air, a large release displaces oxygen and may cause death by suffocation. A relevant example occurred in 1986 in Cameroon, where naturally trapped CO₂ was released in large quantities from Lake Nyasa resulting in 1,200 deaths.

The deep ocean has the advantage of being an almost limitless repository for CO₂. However, the residence time of CO₂ sequestered in the deep ocean is finite, depending on the depth of injection; estimates range from 50 years at 500 m to 1000 years at 3000 m (Liro, *et al.*, 1992). Of course, the deeper the injection, the more the cost. While environmental concerns have been raised about ocean disposal of CO₂, impacts will probably be very localized. Transport and injection of CO₂ into the ocean, while expensive, is technologically feasible today. If CO₂ is injected below 500 m, the possibility of hydrate formation exists. Research into the kinetics of hydrate formation and how to use hydrates to increase sequester time and/or reduce costs is needed.

STATUS OF CURRENT RESEARCH

Research on global climate change can be divided into science, engineering, and policy. While the U.S. is the leader in global change science research, spending about

\$1 billion per year, Japan is the leader in engineering research directed at mitigation. In FY91, the Japanese government's research budget just for CO₂ capture and fixation technology was about \$22 million. In addition, research is also being funded by Japanese industry and utilities. The Japanese research on CO₂ capture is spread over most of the topics discussed in this paper, with a special emphasis on deep ocean disposal (Shindo, *et al.*, 1992).

In addition to Japan, both Norway and The Netherlands have very aggressive research programs. The Netherlands have focused on capture from IGCC plants, with storage in depleted gas wells. Their research agenda also includes studying membrane separation, the use of fuel cells, and storage in aquifers. The Norwegians' research projects include looking for improved chemicals for CO₂-removal from exhaust gas, new and improved gas turbines, EOR research, studying CO₂-hydrates, and funding system studies. Much of this research is being carried out through Statoil, the national oil company. Statoil is currently considering a project to inject a million tonnes/year of CO₂ into an offshore aquifer (Kaarstad, 1992).

An international effort (including the U.S.) under the auspices of the International Energy Agency (IEA) is underway, with British Coal as the operating agent. The goal of the IEA effort is to evaluate "technology options for the control of greenhouse gas emissions from fossil fuel utilisation." They will identify and conduct research into the most promising capture and disposal options (Jack, *et al.*, 1992). The U.S. Department of Energy's Office of Coal Technology budgeted \$150,000 this fiscal year, focused mainly on biological utilization of CO₂. Next year's estimated budget is \$900,000 for projects yet to be specified. In Canada, a project is underway in Alberta on using CO₂ for EOR and maximizing the storage potential of oil reservoirs (Bailey, 1992). In Germany, an IGCC demonstration plant with CO₂ capture using Purisol (a physical sorbent) is under construction for start-up in 1995 (Schütz, *et al.*, 1992). The above list is not complete, but gives a flavor of the activity currently on-going for CO₂ capture and disposal research.

CONCLUSIONS

While the capture of CO₂ from power plant flue gas may be energy intensive and expensive, it is technically feasible. Several flue gas CO₂ capture plants are currently in operation, producing CO₂ for industrial uses. While further research on CO₂ capture processes may reduce costs or lower energy requirements, the major research challenge is to find methods of sequestering or utilizing the captured CO₂ that are technically feasible, economically viable, and environmentally sustainable.

FURTHER DOCUMENTATION

For a more detailed analysis of the issues outlined in this paper, we refer the reader to the proceedings of the *First International Conference on Carbon Dioxide Removal*. The proceedings are scheduled for publication in the June issue of *Energy Conversion and Management* (Pergamon Press). Also, our report to the U.S. Department of Energy on *A Research Needs Assessment for the Capture, Utilization, and Disposal of Carbon Dioxide from Fossil Fuel-Fired Power Plants* should be available in the fall of 1992.

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Table 1
Comparison of CO₂ Capture Technologies

Process	Energy Penalty (%)	Nominal CO ₂ Recovery (%)	Net Reduction of CO ₂ Emissions (% of Base Case)	Relative Cost of Electricity
Base Case -- No CO ₂ Removal	0	0	0	1.0
IGCC ^a	13	88	86.2	1.3
IGCC ^b	20	90	87.5	1.7
Air Separation FG Recycling ^c	25	100	100	1.9
Amine Scrubbing with Congenerated Steam ^b	35	90	84.6	2.6
Molecular Sieves ^d	80	90	50	5.1
Cryogenic Fractionation ^c	75	90	60	---
Membrane Separation ^c	63	80	46	---

Sources:

^aHendriks, *et al.* (1991)

^bBooras and Smelser (1991)

^cHerzog, *et al.* (1991)

^dFulkerson, *et al.* (1990)

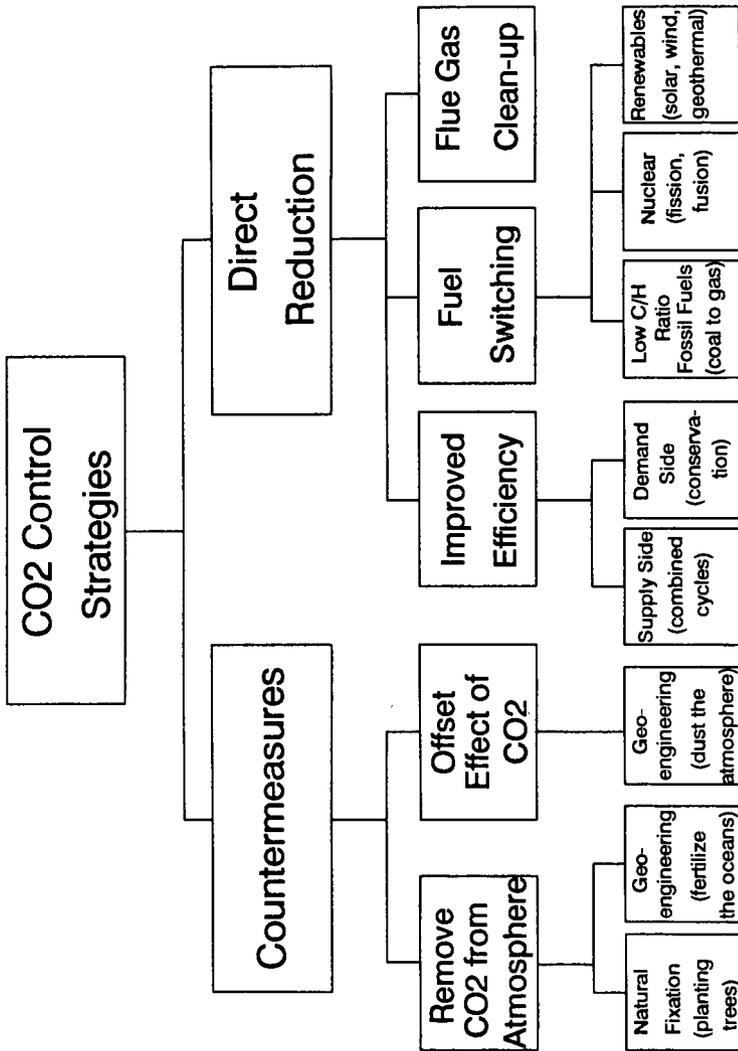


Figure 1: CO₂ Control Strategy Options.

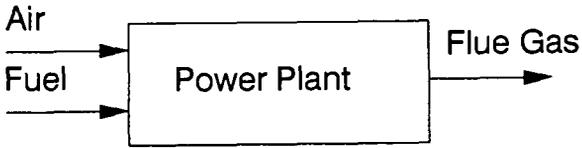


Figure 2: Power Plant Schematic.

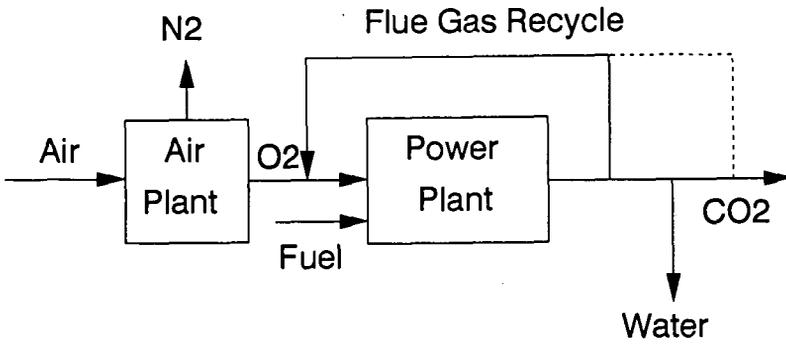


Figure 3: Air Separation/Flue Gas Recycle Power Plant Schematic.

AN ECONOMIC FRAMEWORK FOR THE CONSIDERATION OF CLIMATE CHANGE POLICY

Joel Darmstadter
Energy and Natural Resources Division
Resources for the Future
1616 P Street, N.W.
Washington, DC 20036

Keywords: Climate change policy, costs, benefits

BACKGROUND

While lacking unanimity, an emerging scientific consensus suggests that unconstrained trends in the growth of greenhouse gas emissions might, before the end of the next century, raise global mean temperature by 2-5^o Celsius, raise sea levels by 30-100 cm, and significantly alter weather patterns. Through damage to coastal infrastructure and settlements, impaired agricultural productivity, and a variety of impacts on both unmanaged ecosystems and manmade assets, these consequences of greenhouse gas emissions could seriously threaten social well-being. The offending gases principally include carbon dioxide (CO₂)—whose elevated presence in the atmosphere is attributed primarily to fossil-fuel combustion and secondarily to deforestation--nitrous oxide (N₂O), methane (CH₄), and chlorofluorocarbons (CFCs). Notwithstanding CFCs' assault on the stratospheric ozone layer, their pending phaseout under the Montreal Protocol and succeeding restrictions and recent scientific judgments questioning the severity of their contribution to greenhouse warming puts the spotlight on the other gases, principally CO₂, estimated to account for about half of the greenhouse warming that may now be materializing.

Given the public prominence accorded to the greenhouse question at UNCED in June 1992 and other forums, it seems almost superfluous to note the many interrelated ways--scientific, political, economic--in which this issue confronts us with an environmental challenge of truly formidable dimensions:

- On the *scientific* front, notwithstanding broad agreement as to the likelihood of increases in global mean temperature, there are widely acknowledged uncertainties, notably the regional nature of climatic change and the feedbacks (positive or negative) set in motion by greenhouse warming.
- Such uncertainties and the fact that there are at least some doubters about the general expectation of global warming undermine, or can be used to undermine, the basis for response strategies. In part, this feeds the *political* circumspection regarding greenhouse mitigation initiatives, which policy makers are loath to embrace, fearing unacceptably high costs to constituents and reluctant to address problems likely to manifest themselves over time scales that seem light years in the future.
- Questions of cost and time horizons underscore as well the important *economic* aspect of managing the greenhouse problem. Simply put, and in the disembodied language of benefit-cost analysis, efforts to lessen the severity or prospect of climatic change entails

spending money--mostly in the near term--on mitigating activities responsible for a heightened greenhouse effect or deploying measures to adapt to such degree of warming as may be inevitable or deemed tolerable. Such mitigation or adaptation investments should be weighed against the benefits thereby obtained; the value of those benefits is reckoned in terms of the avoidance of damage due to global warming.

The economic perspective on the greenhouse dilemma is, of course, largely an abstract formulation. Yet, even within such a limited conceptual framework, some important points can be usefully highlighted. The balance of these remarks will focus on greenhouse warming in its economic orientation.

RECKONING COSTS

An unexceptional statement that can be made right at the start is that, to the extent that emission reduction efforts are costless or even profitable (the so-called "win-win" or "no regrets" strategy), the benefit-cost conundrum dissolves: we can only be better off economically and environmentally if greenhouse gases and other pollutant emissions can be curtailed at minimum expense. (Proponents of the efficacy of a warmer climate--probably a very small minority--and those perceiving as great a likelihood of global cooling as warming would question that observation.) This self-evident statement of principle takes on practical significance when we take cognizance of a number of studies that attempt to show the feasibility of actually realizing such potential savings. As an example, a widely-publicized National Academy of Sciences (1991) report, assessing greenhouse gas mitigation possibilities in the United States, identified significant opportunities for emission reduction at negative, zero, low, or moderate cost. Depending on how aggressive an effort was mounted to exploit these available opportunities, between around 12-25 percent of this country's greenhouse gas emissions could be eliminated at negative or zero cost. Under the most favorable circumstances--100 percent implementation and marginal costs not exceeding \$2.50 per ton of carbon equivalent reduction--emissions might be reducible by as much as 60 percent below levels otherwise prevailing. (That \$2.50 translates into, say, 13¢ per gallon of gasoline.) It is important to note that the National Academy's graphic representation of these possibilities, many of which involve enhanced energy efficiency in transportation and housing, depicts a "timeless"--but otherwise unspecified--long-run adjustment path, presumably sufficient to allow capital turnover, behavioral change, and policy changes needed to realize the projections. All that might easily require 2-3 decades to accomplish.

To a greater or lesser extent, opportunities for emission reductions exist throughout the world--perhaps somewhat less in a place like Japan, with its energy-efficient industrial operations; but no doubt more in countries emerging from communist dictation, with their lack of economic incentives and rampant inefficiency, as well as in numerous developing countries. But to point to elimination of prevailing economic waste and energy inefficiency as priority routes to greenhouse gas mitigation does not remove the prospect that, sooner or later, attempts to limit emissions to some maximum level may mean rising marginal costs--whether due to a shift to costlier low- or non-carbon fuels or other economic losses attributable to greenhouse gas constraints. Of course, induced technological advances might blunt, and in the extreme case, offset these cost increases.

RECKONING BENEFITS

To the extent that some considerable cost increases would follow in the wake of greenhouse gas mitigation policies, the problem shifts to one of valuing of the benefits--that is, what damages are avoided?--so obtained. Only limited analysis has focused on that question. The principal effort along this line has been that by Yale economist, William Nordhaus (1991). Nordhaus, concentrating principally on the United States, but then broadening his discussion (to the extent data allow) to the world as a whole, spotlights those economic sectors particularly vulnerable to the degree of global warming associated with a doubling of CO₂-equivalent atmospheric concentrations: agriculture, forestry, energy, and several other sectors assumed to be more moderately affected. Considering the weight of each of these activities in the overall economy and subjecting them to net damage impacts leads, in the author's own words, "to a surprising conclusion:"

...Our best guess is that CO₂-induced climate change will produce a combination of gains and losses with no strong presumption of substantial net economic damages. However, these changes are likely to take place over a period of a half century or more and may get lost in the background noise of social, economic, and political change. This conclusion should not be interpreted as a brief *in favor of* climate change. Rather, it suggests that those who paint a bleak picture of desert Earth devoid of fruitful economic activity may be exaggerating the injuries and neglecting the benefits of climate change.

In Nordhaus' assessment, those surprisingly mild damage estimates content with greenhouse gas control costs that, as he suggests, grow rapidly and become extreme for substantial reductions. Thus, while 10 percent of worldwide CO₂ emissions can be reduced at the modest cost of \$10 per ton, a 50 percent reduction entails a cost of \$150 per ton and a drain on world GNP of about \$180 billion--or around one percent of prevailing price and output levels. The moral of the story: "count before you leap," which, as it happens, was the title assigned to a short summary article Nordhaus wrote on the climate-change question in *The Economist* a couple of years ago (Nordhaus 1990).

Notwithstanding Nordhaus' welcome effort to frame the greenhouse dilemma in benefit-cost terms, it must be emphasized that the scope of such an analysis lends itself to greater or narrower latitude, with potentially marked effect on the numerical outcome. For example, economists' kit of tools are much more congenial to the valuation of resources denominated in market prices than to those things which, while highly prized, are not easily amenable to dollar estimation that would allow them to be combined with market assets. Unmanaged forests, wetlands, and other ecosystems, biodiversity, endangered species--all of which may be perturbed by climatic change--fall into this "difficult to measure" category. Whether, and to what extent, their inclusion would alter Nordhaus' more restrictive benefit-cost calculus is open to question. It should be noted that efforts and techniques to allow for consideration of these non-market assets need not be unavailing, although progress along these lines presupposes close collaboration between physical and social scientists. (A workshop conducted at Resources for the Future in March 1992 focused precisely on this issue.)

What may be another limitation in Nordhaus' perspective--though, again, one not easily handled--is that of the assumed time horizon. By restricting the analysis to the doubled CO₂-

equivalent atmospheric concentrations likely to materialize around the middle of the 21st century, one ignores the prospects for and consequences of steadily rising concentrations in the decades--indeed, centuries--beyond that milestone. Insofar as subsequent impacts may be nonlinear--coastal resources may be resilient to a one-meter sea-level rise but devastated by greater increases--the question of what time perspective to employ can become critical.

A recent study by William Cline (1992) begins to confront these problems. Cline extends his analysis 300 years into the future. By varying such parameters as discount rates, temperature increases, and damage functions, he develops multiple trajectories over this period, but settles on a "central" estimate based on 10⁰ Celsius warming and a damage estimate approximating 6 percent of world GNP. Incorporating those factors in a benefit-cost analysis, Cline derives an overall benefit-cost ratio of 1.3, stating that "if policy makers are risk averse...this study finds that aggressive action to restrain global warming is desirable from the standpoint of social benefit-cost analysis."

THE ROLE OF ADAPTATION

Although, in the somewhat stark schematics presented here, the choices pit emission reduction against damage avoided, there is bound to be a role for adaptation in steps taken to deal with climate change. Adaptation could, in principle, be a purposeful least-cost rational strategy: it's cheaper to build seawalls or inhibit coastal development than to limit emissions leading to sea-level rise. But more realistically, adaptation is likely to involve the ability to cushion climatic impacts across a range of affected activities--e.g., farmers' ability to shift to crop varieties more resilient to climatic stress, thereby substantially (though not totally) offsetting the reductions in crop yield they would otherwise face under climatic change. (See Rosenberg and Crosson 1991). Of course, such adaptation presupposes an evolutionary process whereby one is always forced to adjust to new circumstances, climatic or otherwise. But if climatic change were sudden, severe and triggering major discontinuities in economic and social affairs, this presumption of adaptive capabilities would be a very fragile one.

CONCLUDING REMARKS

The principal purpose here has been to sketch out a simple economic framework as one way of viewing the global warming problem. The idea has been to sharpen our thinking, certainly not to use such a framework as a unifying device to integrate the many strands--scientific, economic, political--that make up the problem. Indeed, the political impediment to addressing the issue forthrightly may be the thorniest one of all. That is understandable in situations where many resource needs compete for policy makers' attention. It is also understandable--but a lot more disheartening--where the policy process, operating within its own glaze of myopia and by its own set of rules, finds it impossible to focus far beyond the elective term of office, let alone over the time horizon that a problem such as greenhouse warming demands.

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