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[Global Climate Change Policy - Kyoto Protocol Analysis] [Binder] [1]

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GCC Policy - Kyoto Protocol Analysis

2

July 9, 1998

TO: Joe Aldy

FROM: Zachary Candelario

SUBJECT: Technical Support Document Data and Chart Files

The data for the TSD are located on H:GCCWHITE/Appendx, Main, Misc, Risk.

- Appendx: appintl, car_gdp, co2globe, ec_grat, fsu, gdp_rat, joe427, nation~1.
- Main: co2_pop, gccwhite.
- Misc: korea
- Risk: gat, icecore, mauna, oldtemp

The charts for the TSD are located on H:GCCWHITE/GCCchart.

- GCCchart: appendx3, gccappen, gccmast3

Attached is a list of the charts in the TSD by figure number, chart title, and data file name.

FIGURE #	TITLE	SOURCE (File/Publication)
1	U.S. Greenhouse Gas Emissions, Actual and Projected without New Abatement Policies	ERP
2	Major Annex I Nations' Carbon Dioxide Emissions, 1950-1992	JOE427
3	World Carbon Dioxide Emissions from Fossil Fuel Combustion, 1996	EC_GRAT
4	Projected Carbon Dioxide Emissions of Major Annex I Countries without New Abatement Policies	GCCWHITE, Sheet B
5	Projected Growth in Carbon Dioxide Emissions Among Annex I Countries without New Abatement Policies	GCCWHITE, Sheet B
6	Projected Emissions Among Annex I and Non-Annex I Countries without New Abatement Policies	GCCWHITE, Sheet D
7	Projected Emissions Among the U.S. and China without New Abatement Policies	GCCWHITE, Sheet B
8	Projected Growth in Carbon Dioxide Emissions Among the U.S. and Several Developing Countries without New Abatement Policies	GCCWHITE, Sheet B
9	The Greenhouse Effect	OSTP
10	Carbon Dioxide Concentrations	GCCWHITE, Sheet I
11	Global Average Temperature	GAT
12	Atmospheric Carbon Dioxide Concentration and Temperature Change	ICECORE, OLDTEMP
13	U.S. Coastal Lands at Risk from a 20-inch Sea Level Rise in 2100	TITUS, 1997
14	1995 Energy/GDP Ratios for the U.S. and Several Other Annex I Countries	EC_GRAT, Sheet B
15	1995 Energy/GDP Ratios for the U.S. and Several Developing Countries	EC_GRAT, Sheet B
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18	Cumulative Projected Electric Power Investments, 1995-2010	1998, IEO, Page 116

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Economic Analysis

of the
Kyoto Protocol and the Administration's Policies to Address Climate Change:

Technical Support Document

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Divider Title: 1

EXECUTIVE SUMMARY

The primary purpose of this analysis is to examine the costs and benefits of taking action to mitigate the threat of global warming. In particular, we examine the costs and benefits of complying with the emissions reduction target for the United States set forth in the Kyoto Protocol on Climate Change, negotiated in December 1997. For reasons discussed at length in this paper, it is our conclusion that, with the flexibility mechanisms included in the treaty, the United States can reach its Kyoto target at a relatively modest cost. And the benefits of mitigating climate change are likely to be substantial.

Before considering the economics of taking action, however, we ought to step back and ask the threshold question -- whether taking action to mitigate global climate change is necessary in the first place.

The Rationale for Taking Action

The great weight of scientific authority suggests that climate change is a serious problem and that prudent steps to mitigate it are in order. In essence, we need to take out an insurance policy with reasonably priced premiums. As long ago as 1991, the National Academy of Sciences, in a study entitled *Policy Implication of Greenhouse Warming*, concluded that "...even given the considerable uncertainties in our knowledge of the relevant phenomena, greenhouse warming poses a potential threat sufficient to merit prompt responses. ...Investment in mitigation measures acts as insurance protection against the great uncertainties and the possibility of dramatic surprises." P68

What the science tells us is that greenhouse gases are rapidly building up in the atmosphere as a result of the burning of fossil fuels and deforestation; that the concentration of these gases is 30 percent higher than it was at the beginning of the industrial revolution; and that this concentration is expected to reach twice current levels by 2100 -- a level not seen in 50 million years. Theory and computer models suggest that this increased concentration of greenhouse gases could warm the earth by about 2-6.5° F by 2100. By way of comparison, the last ice age was only about 9° F colder than today. Moreover, much evidence suggests that warming is already underway. For example, we know from ice cores and other data that we are living in the hottest century since at least 1400, that the 1990s are the hottest decade on record, that 1997 is the hottest year, and that the nine hottest years have all occurred since 1987.

Scientists predict a range of likely effects from global warming. For example, the rate of evaporation is expected to increase as the climate warms, leading to increasingly frequent and intense floods and droughts. Sea level is projected to rise 6-38 inches by 2100. A 20-inch rise could

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submerge around 7000 square miles of U.S. territory. Warmer temperatures would be expected to increase the risk of mortality from heat stress, aggravate respiratory disease, and increase the range and rates of transmission of some infectious diseases.

Scientific opinion is not unanimous on these points, but most independent climate scientists believe that global climate change poses real risks. A few scientists contest the notion that increasing concentrations of greenhouse gases will warm the planet, while a few others argue that the earth is indeed getting warmer, but that this is a good thing -- "a wonderful...gift from the industrial revolution," in the words of one. But these are distinctly minority views. The prevailing view is that the risks of climate change warrant prudent and prompt action. Prompt because to wait for greater scientific certainty could have very large costs. Greenhouse gases are long-lived and the decisions being taken by governments and firms in the next decade, with respect, for example, to the kinds of power plants to build or the kinds of energy sources to develop, are likely to have significant consequences for our ability to limit the buildup of greenhouse gases.

Consequently, there is a substantial rationale for acting now. Our task is to act in a manner that responds appropriately to the scope of the risk while at the same time being economically sensible.

The Kyoto Protocol

The Kyoto Protocol, which requires the industrialized nations to take on binding targets for greenhouse gas emissions, includes three basic kinds of flexibility provisions that were proposed by the United States. These provisions -- commonly referred to as "when", "what", and "where" flexibility -- have great potential to significantly lower the costs of meeting the Kyoto targets. "When" flexibility appears in the form of a multi-year commitment period (2008-2012), and allowance for "banking" of emissions reductions. The freedom for countries or companies to delay or accelerate reductions within an agreed upon time frame can help lower costs. "What flexibility" is provided by the inclusion of all six greenhouse gases -- so that reductions in emissions of one gas can be used to substitute for increases in emissions of another -- and the coverage of certain "sink" activities, such as afforestation or reforestation, that absorb carbon. Most important, the Protocol incorporates "where" flexibility in the form of international emissions trading and joint implementation among countries that take on binding targets, coupled with a "clean development mechanism" allowing industrial countries or firms to earn emissions reduction credit for investments in clean energy projects in the developing world. These mechanisms can provide opportunities for industrial countries and firms to secure low-cost reductions and for developing countries to achieve sustainable growth.

Developing countries did not take on binding emissions targets at Kyoto. The President has said that he will not submit the Protocol to the Senate without meaningful participation from key developing countries. The Clean Development Mechanism provides a down payment on such

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participation, and the Administration is actively engaged in seeking greater participation from key developing countries. Robust developing country participation would likely lead to new opportunities for low cost reductions, benefitting developing and developed countries alike.

Costs and Benefits of Mitigation

Analyzing the costs and benefits of mitigating climate change is a difficult undertaking for three reasons. First, uncertainties remain about significant details of certain provisions in the Protocol. Second, available models have inherent limitations in their abilities to analyze even short-term costs and benefits. Third, it is extremely difficult to quantify the long-term economic benefits of climate change mitigation, so we have made no effort to quantify these benefits in our analysis.

Recognizing these difficulties, our conclusion is that the net costs for the United States to meet its Kyoto emissions target are likely to be modest if those reductions are undertaken in an efficient manner employing the flexibility measures of international trading, joint implementation, and the Clean Development Mechanism. This would be so even without considering the benefits of mitigating climate change itself or the impact certain additional factors -- such as the President's domestic climate change proposals, the ancillary benefits of improved air quality, or the inclusion of sinks -- could have on lowering the costs of mitigation.

The conclusion about the costs of complying with the Kyoto Protocol is not entirely dependent on, but is fully consistent with, formal model results. For example, given the flexibility measures just noted, with key developing countries participating in trading, and *excluding* the benefits of both mitigating climate change and restructuring the electricity sector, estimates derived using Battelle's Second Generation Model suggest that the resource costs of attaining the Kyoto targets for emission reductions might amount to $7-12 billion per year in 2008 to 2012 or just 0.1 percent of projected GDP. The same model predicts that emission permits in 2010 would cost between $14 and $23 per ton of carbon equivalent -- which would translate into an increase of about 4 to 6¢ per gallon of gasoline. The increase in energy prices would raise the average household's energy bill in 2010 by between $70 and $110 per year -- a relatively small amount compared to typical energy price changes. Moreover, this increase would be substantially offset by the decline in electricity prices resulting from the Administration's electricity restructuring proposal.

Further, even if international trading occurred only among developed countries, with developing countries limiting their use of flexibility measures to the Clean Development Mechanism, the costs of complying with Kyoto, and the price of emissions permits, would still be just a fraction of what they would be if we had to reach our target entirely through domestic action.

Several factors not included in the estimate using the Battelle model could reduce cost further and/or increase the amount of reductions accomplished through domestic action. These factors include the benefits of reducing net emissions through carbon sinks; the Administration's electricity

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restructuring proposal; the Administration's $6.3 billion budget proposal to improve energy efficiency and spur the development of renewable energy, a proposal that could help increase the rate of technology diffusion above the conservative estimate used in this analysis; the Administration's consultations to encourage and support voluntary efforts by U.S. industry to undertake emissions reductions; and the ancillary benefits of reducing greenhouse gas emissions.

All of the cost calculations above exclude the substantial long-term benefits of mitigating global climate change. Monetary estimates of damages from the environmental, health, and economic impacts of global warming during the next century range in the tens of billions of dollars per year. One noted economist, William Cline, has estimated that a doubling of pre-industrial concentrations of greenhouse gases would cost the U.S. economy about 1.1% of GDP annually -- some $89 billion a year in today's terms. Moreover, these estimates do not reflect the potential costs of so-called "non-linearities" -- the risk that global warming will lead not to gradual and predictable problems, but to relatively abrupt, unforeseen, and potentially catastrophic consequences. Although we do not think the benefits of mitigating climate change are, at this stage, quantifiable with adequate precision, they are nonetheless likely to be very real and very large in the long run.

Conclusion

The current state of the science provides a powerful rationale to take prompt, prudent action to mitigate climate change; the agreement negotiated in Kyoto includes flexibility mechanisms that will allow the United States to meet its Kyoto target at a modest cost. Additional factors not included in the Battelle model we reference -- such as the President's domestic climate change policies, the inclusion of sinks and the ancillary benefit of improving air quality -- could lower costs even further and increase the percentage of reductions made through domestic action. The benefits of avoiding long-term impacts of global climate change, while not precise enough to quantify at this stage, are likely to be very important. In short, this is an insurance policy we should buy and it is one we can buy for reasonably priced premiums.

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Divider Title: **3**

INTRODUCTION

The earth's surface appears to be warming as a result of the accumulation of greenhouse gases from myriad sources worldwide. None of the emitters of these gases presently pays the cost to others of the adverse effects of warming. No individual firm, nor any single country, has an incentive to reduce emissions sufficiently to protect the global environment against climate change. Each has an economic incentive to "free ride" on the efforts of others. Without an international agreement limiting emissions abroad, even if one country sharply reduces its emissions unilaterally, greenhouse gas emissions from all other countries would continue to grow, and the risks posed by climate change would not be significantly reduced. The complex nature of the climate change problem requires global cooperation and a long-term solution.

In June of 1992, the Framework Convention on Climate Change, the first international agreement to address the risks of climate change, was signed during the Earth Summit in Rio de Janeiro. This treaty, ratified by the United States with the advice and consent of the Senate in October 1992, established the following ultimate objective:

> "[To achieve] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent the dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner" (Framework Convention on Climate Change, Article 2).

The Framework Convention laid the foundation for international cooperation to reduce emissions of greenhouse gases to achieve this objective. The treaty encouraged industrial countries to return their greenhouse gas emissions to their 1990 levels by 2000.

Since the Framework Convention entered into force, the world's scientists have continued to warn of the potential negative environmental and economic effects of climate change. In 1995, the Intergovernmental Panel on Climate Change (IPCC), jointly established by the World Meteorological Organization and the United Nations Environment Programme, and representing the work of more than 2,000 scientists, concluded that "the balance of evidence suggests that there is a discernible human influence on global climate" (Houghton et al. 1996, p. 5). Without measures to abate the expected increase in greenhouse gas emissions over the next century, the IPCC projected that average global temperatures would increase by 1.8 to 6.3° F (1 to 3.5° C), resulting in coastal damage from rising sea levels, greater frequency of severe weather events, shifts in agricultural growing conditions from changing weather patterns, threats to human health from increased range and incidence of diseases, changes in availability of freshwater supplies, and damage to ecosystems and biodiversity.

Economic Report of the President

Transmitted to the Congress
February 1998

sions trading could undercut the effectiveness of pollution controls if it resulted in shifting emission reductions farther upwind. Trading ratios that weight the reductions made at different sources according to their distance from the downwind nonattainment area might be considered to address this problem. In reality, however, there are a large number of nonattainment areas spread out over the region, and several different weather patterns and wind conditions characterize the ozone pollution episodes that the program is trying to remedy. Sources affect multiple nonattainment areas in a variety of directions from them, and it affects any single nonattainment area differently under different weather conditions. The polycentric nature of this problem complicates the identification of a unique and stable set of trading ratios that would work for all relevant cases. Thus, striking the proper balance between achieving the cost savings from larger geographic scope and limiting the potentially significant adverse environmental effects of trading is an ongoing challenge.

Like most air pollution control programs, NO_X trading programs would require an estimate of emissions from each regulated source in order to ensure compliance. The estimation method can have significant implications for cost-effectiveness, both directly, through the cost of performing the estimate, and indirectly. One indirect implication is that more costly requirements may limit the number of sources that could meet the estimation requirements and participate in trading, and thereby raise costs. On the other hand, a more reliable estimation method may offer regulators and sources greater confidence in the permits, and thereby increase the willingness of sources to buy them or offer them for sale. For example, the SO_2 program requires continuous emissions monitoring to provide precise information on emissions. Such monitoring is expensive and impractical for many smaller sources and thus may effectively exclude such sources from participating. But such precise monitoring may not always be necessary. Methods for estimating emissions that provide unbiased, although less precise, estimates of emissions may be accurate enough to ensure accountability.

CLIMATE CHANGE

Climate change is a global environmental externality: warming of the earth's surface results from the accumulation of greenhouse gases from myriad sources worldwide, none of which presently pay the cost to others of warming's ill effects. The Intergovernmental Panel on Climate Change, jointly established by the World Meteorological Organization and the United Nations Environment Programme, concluded in 1995 that "the balance of evidence suggests that there is a discernible human influence on global climate." Current concentrations of carbon dioxide (SO_2), methane, nitrous oxide (N_2O), and other so-called greenhouse gases have reached levels well above those of preindustrial times. Of these, CO_2 is the most important: net cumulative CO_2 emissions resulting from the burning of fossil fuels and deforestation account for about two-thirds of potential warming from changes in greenhouse gas concentrations related to human activity. If growth in global emissions continues unabated, the atmospheric concentration of CO_2 will likely double, relative to its preindustrial level, midway through the next century.

The accumulation of greenhouse gases poses significant risks to the world's climate and to human well-being. Potential impacts include a rise in sea levels, greater frequency of severe weather events, shifts in agricultural growing conditions from changing weather patterns, threats to human health from increased range and incidence of diseases, changes in availability of freshwater supplies, and damage to ecosystems and biodiversity.

Climate change is a complex, long-term problem requiring global cooperation and a long-term solution. No single country has an incentive to reduce emissions sufficiently to protect the global environment against climate change. Even if the United States sharply reduced its emissions unilaterally, greenhouse gas emissions from all other countries would continue to grow, and the risks posed by climate change would not be significantly abated. Since many of these gases remain in the atmosphere for a century or more, the climatic effects of actions taken today will primarily benefit future generations. But delaying action to reduce greenhouse gas emissions until the disruptive effects of climate change become widespread will considerably reduce the options for remedial or preventive measures.

The Framework Convention on Climate Change

The threat of disruptive climate change has led to coordinated international efforts to reduce the risks of global warming by reducing emissions of greenhouse gases. The first international agreement to address global warming was the Framework Convention on Climate Change signed during the Earth Summit in Rio de Janeiro in 1992. This convention established a long-term objective of limiting greenhouse gas concentrations and encouraged the established industrial countries to return their emissions to 1990 levels by 2000. Since then it has become clear that the United States and many other participating countries will not meet this goal.

To address the lack of progress among many industrial countries toward meeting this first target, the United States and approximately 159 other nations, in negotiations held in Kyoto, Japan, last December, agreed to take substantial steps to stabilize atmospheric concentrations of greenhouse gases. The Kyoto agreement, which requires the advice and consent of the Senate, would place binding limits on industrial countries' emissions of the six principal categories of greenhouse gases: CO_2, methane, N_2O, sulfur hexafluoride, perfluorocarbons, and hydrofluorocarbons. Each industrial country's "1990

Status of Ratification

in alphabetical order

The text of the Convention was adopted at the United nations Headquarters, New York on the 9 May 1992; it was open for signature at the Rio de Janeiro from 4 to 14 June 1992, and thereafter at the United Nations Headquarters, New York, from 20 June 1992 to 19 June 1993. By that date the Convention had received 166 signatures. The Convention entered into force on 21 March 1994. Those States that have not signed the Convention may accede to it at any time.

For those States that ratify, accept or approve the Convention or accede thereto after the date of entry into force, the Convention shall enter into force on the ninetieth day after the date of the deposit by such State of its instrument of ratification, acceptance, approval or accession.

These pages contains information concerning dates of signature and ratification received from the Secretary-General of the United nations, as at 29 May 1997. The dates in the column entitled "date of ratification" are those of the receipt of the instrument of ratification **(R)**, acceptance **(At)**, approval **(Ap)** or accession **(Ac)**. (For an explanation of these legal terms, please follow this link

as at 28-January-98 the Convention received 174 instuments of ratification

Status of Ratification

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Country Name	Date of Signature	Date of Ratification	Type	Enter into Force
Uganda	13-Jun-92	08-Sep-93	R	21-Mar-94
Ukraine	11-Jun-92	13-May-97	R	11-Aug-97
United Arab Emirates		29-Dec-95	Ac	28-Mar-96
United Kingdom of Great Britain and Northern Ireland	12-Jun-92	08-Dec-93	R	21-Mar-94
United Republic of Tanzania	12-Jun-92	17-Apr-96	R	16-Jul-96
United States of America	12-Jun-92	15-Oct-92	R	21-Mar-94
Uruguay	04-Jun-92	18-Aug-94	R	16-Nov-94
Uzbekistan		20-Jun-93	Ac	21-Mar-94

(2) (3)

[The Convention][The Secretariat][What is Climate Change][CC:INFO Products]
[Official Documents][Country Information][Emissions and other Data]
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"Sink" means any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere.

9...."Source" means any process or activity which releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas into the atmosphere.

* Titles of articles are included solely to assist the reader.

ARTICLE 2
OBJECTIVE

The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

ARTICLE 3
PRINCIPLES

In their actions to achieve the objective of the Convention and to implement its provisions, the Parties shall be guided, INTER ALIA, by the following:

1....The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof.

2....The specific needs and special circumstances of developing country Parties, especially those that are particularly vulnerable to the adverse effects of climate change, and of those Parties, especially developing country Parties, that would have to bear a disproportionate or abnormal burden under the Convention, should be given full consideration.

3....The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost. To achieve this, such policies and measures should take into account different socio-economic contexts, be comprehensive, cover all relevant sources, sinks and reservoirs of greenhouse gases and adaptation, and comprise all economic sectors. Efforts to address climate change may be carried out cooperatively by interested Parties.

EPA United States Environmental Protection Agency — Global Warming

Intergovernmental Panel on Climate Change (IPCC)

The Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Programme and the World Meteorological Organization in 1988. The purpose of the IPCC is to assess information in the scientific and technical literature related to all significant components of the issue of global climate change. The IPCC provides the scientific underpinnings for understanding global climate change and its consequences for society and the environment. It relies upon preparation and review of documents by 2,500 of the world's leading experts on climate change and its consequences from some 60 nations. With its capacity for reporting on climate change, the IPCC also functions as the official advisory body to the world's governments on the state of science of the issue.

#8

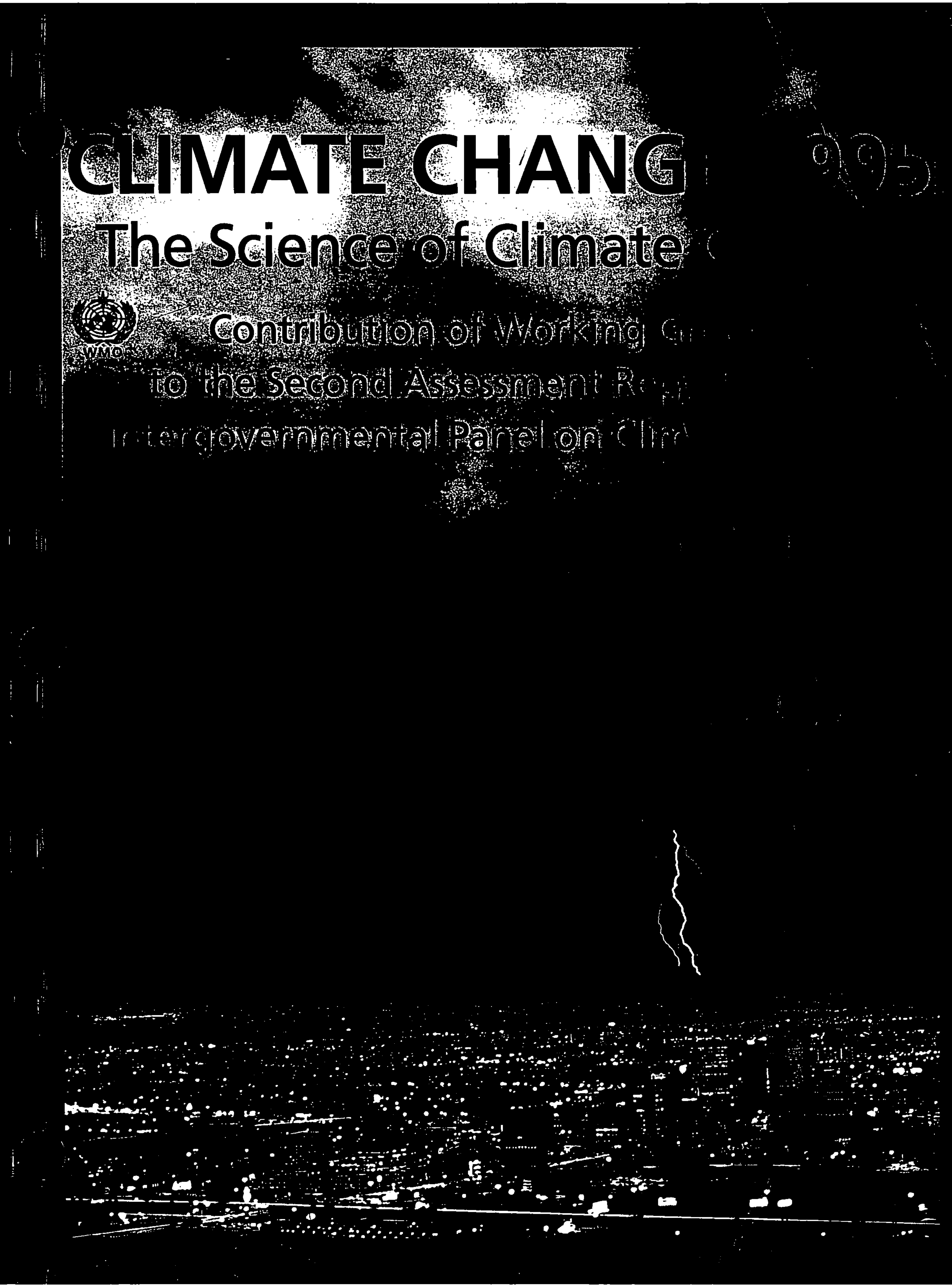
Over the past two years the IPCC prepared its Second Assessment Report (SAR), which considers results from approximately 20,000 peer-reviewed articles pertaining to the science of climate change and its consequences. This exhaustive review represents the consensus of scientific understanding of global climate change.

The SAR confirms earlier findings that anthropogenic (i.e., human-induced) greenhouse gas emissions are altering the chemical composition of the atmosphere. An important new conclusion in this report is that "the balance of evidence suggests that there is a discernible human influence on global climate."

The IPCC further concludes that unless the world takes steps to reduce emissions of these greenhouse gases, global temperatures could rise another 1.4 to 6.3 degrees Fahrenheit by the year 2100. This would be the fastest rate of warming since the end of the last ice age more than 10,000 years ago.

You can find additional information about the IPCC and its work by clicking on the two documents listed below. Also, you can click on "IPCC" below to access the web site of the Intergovernmental Panel on Climate Change.

- Key Findings of the Second Assessment Report of the Intergovernmental Panel on Climate Change
- IPCC Fact Sheet
- Slide Presentation on IPCC Conclusions and Observations from the 1995 Second Assessment Report


CLIMATE CHANG 995
The Science of Climate
WMO
Contribution of Working
to the Second Assessment R
Intergovernmental Panel on Clim

change in climate is highly unusual in a statistical sense, but does not provide a reason for the change. "Attribution" is the process of establishing cause and effect relations, including the testing of competing hypotheses.

Since the 1990 IPCC Report, considerable progress has been made in attempts to distinguish between natural and anthropogenic influences on climate. This progress has been achieved by including effects of sulphate aerosols in addition to greenhouse gases, thus leading to more realistic estimates of human-induced radiative forcing. These have then been used in climate models to provide more complete simulations of the human-induced climate-change "signal". In addition, new simulations with coupled atmosphere-ocean models have provided important information about decade to century time-scale natural internal climate variability. A further major area of progress is the shift of focus from studies of global-mean changes to comparisons of modelled and observed spatial and temporal patterns of climate change.

The most important results related to the issues of detection and attribution are:

- The limited available evidence from proxy climate indicators suggests that the 20th century global mean temperature is at least as warm as any other century since at least 1400 AD. Data prior to 1400 are too sparse to allow the reliable estimation of global mean temperature.

- Assessments of the statistical significance of the observed global mean surface air temperature trend over the last century have used a variety of new estimates of natural internal and externally forced variability. These are derived from instrumental data, palaeodata, simple and complex climate models, and statistical models fitted to observations. Most of these studies have detected a significant change and show that the observed warming trend is unlikely to be entirely natural in origin.

- More convincing recent evidence for the attribution of a human effect on climate is emerging from pattern-based studies, in which the modelled climate response to combined forcing by greenhouse gases and anthropogenic sulphate aerosols is compared with observed geographical, seasonal and vertical patterns of atmospheric temperature change. These studies show that such pattern correspondences increase with time, as one would expect as an anthropogenic signal increases in strength. Furthermore, the probability is very low that these correspondences could occur by chance as a result of natural internal variability only. The vertical patterns of change are also inconsistent with those expected for solar and volcanic forcing.

- Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitude and patterns of long term natural variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land-surface changes. Nevertheless, the balance of evidence suggests that there is a discernible human influence on global climate.

Climate is expected to continue to change in the future

The IPCC has developed a range of scenarios, IS92a-f, of future greenhouse gas and aerosol precursor emissions based on assumptions concerning population and economic growth, land-use, technological changes, energy availability and fuel mix during the period 1990 to 2100. Through understanding of the global carbon cycle and of atmospheric chemistry, these emissions can be used to project atmospheric concentrations of greenhouse gases and aerosols and the perturbation of natural radiative forcing. Climate models can then be used to develop projections of future climate.

- The increasing realism of simulations of current and past climate by coupled atmosphere-ocean climate models has increased our confidence in their use for projection of future climate change. Important uncertainties remain, but these have been taken into account in the full range of projections of global mean temperature and sea level change.

- For the mid-range IPCC emission scenario, IS92a, assuming the "best estimate" value of climate sensitivity[1] and including the effects of future increases in aerosol, models project an increase in

[1] In IPCC reports, climate sensitivity usually refers to the long term (equilibrium) change in global mean surface temperature following a doubling of atmospheric equivalent CO_2 concentration. More generally, it refers to the equilibrium change in surface air temperature following a unit change in radiative forcing (°C/Wm^2).

global mean surface air temperature relative to 1990 of about 2°C by 2100. This estimate is approximately one third lower than the "best estimate" in 1990. This is due primarily to lower emission scenarios (particularly for CO_2 and the CFCs), the inclusion of the cooling effect of sulphate aerosols, and improvements in the treatment of the carbon cycle. Combining the lowest IPCC emission scenario (IS92c) with a "low" value of climate sensitivity and including the effects of future changes in aerosol concentrations leads to a projected increase of about 1°C by 2100. The corresponding projection for the highest IPCC scenario (IS92e) combined with a "high" value of climate sensitivity gives a warming of about 3.5°C. In all cases the average rate of warming would probably be greater than any seen in the last 10,000 years, but the actual annual to decadal changes would include considerable natural variability. Regional temperature changes could differ substantially from the global mean value. Because of the thermal inertia of the oceans, only 50-90% of the eventual equilibrium temperature change would have been realised by 2100 and temperature would continue to increase beyond 2100, even if concentrations of greenhouse gases were stabilised by that time.

- Average sea level is expected to rise as a result of thermal expansion of the oceans and melting of glaciers and ice-sheets. For the IS92a scenario, assuming the "best estimate" values of climate sensitivity and of ice melt sensitivity to warming, and including the effects of future changes in aerosol, models project an increase in sea level of about 50 cm from the present to 2100. This estimate is approximately 25% lower than the "best estimate" in 1990 due to the lower temperature projection, but also reflecting improvements in the climate and ice melt models. Combining the lowest emission scenario (IS92c) with the "low" climate and ice melt sensitivities and including aerosol effects gives a projected sea level rise of about 15 cm from the present to 2100. The corresponding projection for the highest emission scenario (IS92e) combined with "high" climate and ice-melt sensitivities gives a sea level rise of about 95 cm from the present to 2100. Sea level would continue to rise at a similar rate in future centuries beyond 2100, even if concentrations of greenhouse gases were stabilised by that time, and would continue to do so even beyond the time of stabilisation of global mean temperature. Regional sea level changes may differ from the global mean value owing to land movement and ocean current changes.

- Confidence is higher in the hemispheric-to-continental scale projections of coupled atmosphere-ocean climate models than in the regional projections, where confidence remains low. There is more confidence in temperature projections than hydrological changes.

- All model simulations, whether they were forced with increased concentrations of greenhouse gases and aerosols or with increased concentrations of greenhouse gases alone, show the following features: greater surface warming of the land than of the sea in winter; a maximum surface warming in high northern latitudes in winter, little surface warming over the Arctic in summer; an enhanced global mean hydrological cycle, and increased precipitation and soil moisture in high latitudes in winter. All these changes are associated with identifiable physical mechanisms.

- In addition, most simulations show a reduction in the strength of the north Atlantic thermohaline circulation and a widespread reduction in diurnal range of temperature. These features too can be explained in terms of identifiable physical mechanisms.

- The direct and indirect effects of anthropogenic aerosols have an important effect on the projections. Generally, the magnitudes of the temperature and precipitation changes are smaller when aerosol effects are represented, especially in northern mid-latitudes. Note that the cooling effect of aerosols is not a simple offset to the warming effect of greenhouse gases, but significantly affects some of the continental scale patterns of climate change, most noticeably in the summer hemisphere. For example, models that consider only the effects of greenhouse gases generally project an increase in precipitation and soil moisture in the Asian summer monsoon region, whereas models that include, in addition, some of the effects of aerosols suggest that monsoon precipitation may decrease. The spatial and temporal distribution of aerosols greatly influence regional projections, which are therefore more uncertain.

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Divider Title: **4**

To address these climate change risks better and to build on the existing treaty, approximately 160 countries met in Kyoto, Japan in December of 1997 and agreed to take substantial steps toward meeting the Convention's ultimate objective. The Kyoto Protocol, which requires the advice and consent of the Senate, would place binding limits on industrial countries' emissions of the six principal types of greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs). The Protocol embraces several flexible, market-based approaches to allow for the emissions targets to be achieved at least cost. While the Protocol includes some participation by developing countries -- for example, through the Clean Development Mechanism[1] -- it does not currently include adequate participation by key developing countries, and the Administration is working to promote such participation.

The Administration will continue its efforts to promote meaningful participation by key developing countries and will work for effective implementation rules for international trading, the Clean Development Mechanism, and joint implementation. The risks of climate change are global and thus they require a global effort. The Administration will not submit the Kyoto Protocol to the Senate for advice and consent until key developing countries agree to participate meaningfully.

Independent of the agreement reached in Japan, the Administration has proposed a suite of measures to reduce emissions domestically.

- Corresponding to the first stage of the three stage domestic strategy that the President announced in October 1997, the Administration has proposed a five-year $6.3 billion package of tax incentives and R&D investments to improve energy efficiency and spur the development of renewable energy; commenced a set of consultations with our energy-intensive sectors aimed at achieving voluntary agreements on how, with government support where needed, including the provision of credit for early action they can most effectively reduce greenhouse gas emissions; submitted a proposal for electricity restructuring that will reduce greenhouse gas emissions; and commenced an intensive review of how to improve the Federal government's own energy use and procurement.

Complementing these measures are the second and third stages of the Administration's plan that would be implemented subsequent to ratification of the Kyoto Protocol.

- The second stage will include a review of our program and an evaluation of next steps as we prepare for a market-based trading system for greenhouse gas emissions. The details of the domestic trading system would be refined and possibly tested.

[1] For a discussion of the Clean Development Mechanism, see p. 25.

Economic Report of the President

Transmitted to the Congress
February 1998

preindustrial times. Of these, CO_2 is the most important: net cumulative CO_2 emissions resulting from the burning of fossil fuels and deforestation account for about two-thirds of potential warming from changes in greenhouse gas concentrations related to human activity. If growth in global emissions continues unabated, the atmospheric concentration of CO_2 will likely double, relative to its preindustrial level, midway through the next century.

The accumulation of greenhouse gases poses significant risks to the world's climate and to human well-being. Potential impacts include a rise in sea levels, greater frequency of severe weather events, shifts in agricultural growing conditions from changing weather patterns, threats to human health from increased range and incidence of diseases, changes in availability of freshwater supplies, and damage to ecosystems and biodiversity.

Climate change is a complex, long-term problem requiring global cooperation and a long-term solution. No single country has an incentive to reduce emissions sufficiently to protect the global environment against climate change. Even if the United States sharply reduced its emissions unilaterally, greenhouse gas emissions from all other countries would continue to grow, and the risks posed by climate change would not be significantly abated. Since many of these gases remain in the atmosphere for a century or more, the climatic effects of actions taken today will primarily benefit future generations. But delaying action to reduce greenhouse gas emissions until the disruptive effects of climate change become widespread will considerably reduce the options for remedial or preventive measures.

The Framework Convention on Climate Change

The threat of disruptive climate change has led to coordinated international efforts to reduce the risks of global warming by reducing emissions of greenhouse gases. The first international agreement to address global warming was the Framework Convention on Climate Change signed during the Earth Summit in Rio de Janeiro in 1992. This convention established a long-term objective of limiting greenhouse gas concentrations and encouraged the established industrial countries to return their emissions to 1990 levels by 2000. Since then it has become clear that the United States and many other participating countries will not meet this goal.

To address the lack of progress among many industrial countries toward meeting this first target, the United States and approximately 159 other nations, in negotiations held in Kyoto, Japan, last December, agreed to take substantial steps to stabilize atmospheric concentrations of greenhouse gases. The Kyoto agreement, which requires the advice and consent of the Senate, would place binding limits on industrial countries' emissions of the six principal categories of greenhouse gases: CO_2, methane, N_2O, sulfur hexafluoride, perfluorocarbons, and hydrofluorocarbons. Each industrial country's "1990

12

stabilize the amount of greenhouse gases in the atmosphere. Moreover, some of the least cost opportunities for reducing greenhouse gas emissions are in developing countries, because those countries now use energy relatively inefficiently. Moreover, those that are industrializing rapidly have greater scope to build their industry around cleaner and more efficient energy technologies and fuels than do mature economies whose capital stock is already in place.

Failure to involve developing countries in an international agreement limiting greenhouse gas emissions could lead to a more rapid rate of increase in emissions in those countries than would occur without any agreement at all. This "leakage" effect of emissions reductions could come about in any of several ways. As industrial countries reduce their use of fossil fuels in response to emissions controls, future world oil and coal prices are likely to be lower than they would be otherwise. This is likely to increase energy consumption in countries not bound to limit their emissions. U.S. industries are also concerned about their international competitiveness if some countries remain outside an international agreement, since factories in those countries will face lower costs for producing goods that take relatively large amounts of energy to manufacture. Some may be concerned that energy-intensive industries might choose to relocate to countries not subject to emissions constraints, although there is little evidence to suggest that this would pose a significant problem in most industries. For example, energy costs for manufacturing industries average just 2.2 percent of total costs.

Given the projected growth of developing countries' emissions, the Administration's position is to seek meaningful participation by key developing countries in the reduction of greenhouse gas emissions as a condition for the United States taking on binding emissions reductions. The President has indicated he will not submit the Kyoto agreement for Senate ratification until there is meaningful participation by key developing countries.

Joint Implementation and the Clean Development Mechanism

To encourage participation by developing countries in the climate change initiative even before they formally sign on for binding emissions limits, the President has proposed a program known as joint implementation. This program would provide incentives to developing countries to reduce their emissions of CO_2 and other greenhouse gases. The Kyoto agreement embraces the President's proposal in its designation of a "clean development mechanism" (CDM): U.S. companies that undertake projects that reduce greenhouse gas emissions in developing countries could count those reductions to meet their commitments. Institutionalizing key elements of joint implementation through this mechanism would encourage firms in the United States to transfer a larger volume of cleaner and more energy-efficient technology to developing countries, especially in the electric power

Climate Change Technology Initiative

1999 Budget Briefing Materials

February 2, 1998

> ... So while we recognize that the challenge we take on today is larger than any environmental mission we have accepted in the past, climate change can bring us together around what America does best -- we innovate, we compete, we find solutions to problems, and we do it in a way that promotes entrepreneurship and strengthens the American economy.
>
> If we do it right, protecting the climate will yield not costs, but profits; not burdens, but benefits; not sacrifice, but a higher standard of living.
>
> President Clinton, October 22, 1997

Climate Change Technology Initiative

Introduction

Last October the President outlined the three-stage approach the US will take in addressing climate change. The first stage consists of immediate actions to stimulate development and use of technologies that can minimize the cost of meeting US goals in reducing greenhouse gas emissions. Stage two will review options created through ongoing technology development and lead to detailed plans for a market-based permit trading system for carbon emissions. Stage three will begin to implement a market-based emissions-trading system.

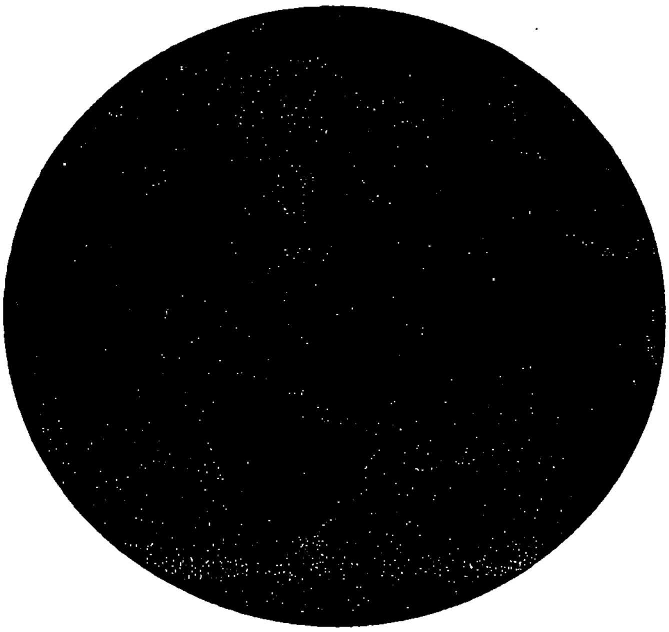
The President's 1999 budget includes $2.7 billion over five years for increased R&D and deployment of energy efficiency, renewable energy, and carbon-reduction technologies, and an additional $3.6 billion over five years in tax incentives. These provide a total initiative of $6.3 billion in new funding and tax expenditures over five years to stimulate adoption of more efficient technologies in buildings, industrial processes, vehicles, and power generation.

During the coming year, federal agencies will supplement these activities with three other actions outlined in the President's plan:

- Active support for industry-by-industry consultations with all major business sectors.
- Changes in federal procurement policy to ensure that Federal agencies make all cost-effective energy investments and take advantage of energy savings performance contracts and other services available from private investors.
- Introduction of utility restructuring proposals that will reduce carbon emissions while saving customers billions of dollars in electric bills.

Section 1 below shows several summary tables that provide a variety of views or perspectives on the Climate Change Technology Initiative (CCTI) – by agency, by type of activity, direct spending, and tax incentives. Following that, in Section 2, are programmatic details organized by the sector or technical topic on which they are focused.

PRESIDENT CLINTON ANNOUNCES THE UNITED STATES CLIMATE CHANGE POLICY



NATIONAL GEOGRAPHIC SOCIETY
GILBERT H. GROSVENOR AUDITORIUM
Washington, D.C.

October 22, 1997

SOLID PRINCIPLES: The President's five climate change principles include: that the policies should be guided by science, rely on market-based, common-sense tools, that we should seek win-win solutions, that global participation is essential to addressing the global problem of climate change, and that we must have regular common-sense reviews of the economics and science of climate change.

SOUND AND SENSIBLE THREE-STAGE APPROACH: Reflecting his five key principles, the President's plan includes three stages: Stage 1 includes priming the pump through programs such as R&D, tax incentives, incentives for early action, and Federal leadership, and industry consultations. Stage 2 builds upon the first stage by including a review and evaluation in preparation for the permit trading system. Stage 3 -- which does not occur for a decade -- involves meeting binding targets through a domestic and international emissions trading program. The President is committed to working with labor and Congress to insure that we give proper assistance to any workers dislocated by the changes in energy usage inherent in any climate change plan.

INITIAL ACTION PLAN: The President's immediate action plan includes 9 elements:

1. $5 Billion in Tax Cuts and Federal R&D: To spur energy efficiency and encourage the development and deployment of lower-carbon energy sources, the Administration supports a major new package of tax cuts and R&D spending amounting to $5 billion over five years.

2. Credit for Early Action: To provide an immediate incentive for near-term actions, the President is committed to ensuring that firms acting early are rewarded appropriately.

3. Industry-by-Industry Consultations: The Administration challenges key industry sectors to prepare plans over the next 9 months on how they can best reduce emissions.

4. Encouraging the Use of Energy-Efficient Products: The President will complement his tax incentives, commitment to early action credit, and industry consultations by engaging in a broad-based effort to expand the use of *existing* energy-efficient technologies.

5. Federal Procurement and Energy Use: The Department of Energy will spearhead a comprehensive effort to reduce greenhouse gas emissions from Federal sources.

6. Electricity Restructuring: To deliver a significant downpayment on emission reductions, while saving consumers billions, we will pursue a bold plan for electricity restructuring.

7. Setting a Concentration Goal: The United States supports developing a specific, long-term concentration goal with the assistance of the National Academy of Sciences and other bodies.

8. Bilateral Dialogues: In addition to pursuing agreement in Kyoto, the Administration will pursue bilateral dialogues with key developing countries to promote clean energy.

9. Economics and Science Reviews: The President proposes regular scientific and economic reviews. These reviews will ensure that policy-makers have the best possible information on climate change.

WIN-WIN: There are numerous win-win solutions to reducing carbon emissions. For example, a breakthrough in fuel cell technology announced yesterday will clear the way toward developing cars that are three times as efficient as today's models -- cutting pollution while also cutting driving costs.

THE PRESIDENT'S THREE-STAGE PLAN ON CLIMATE CHANGE

October 22, 1997

Reflecting his five key principles, the President's plan will proceed in three stages:

- **Stage 1: Priming the Pump Through R&D, Tax Incentives, Incentives for Early Action, Federal Leadership, and Industry Consultations.** The first stage of the President's package includes a 9-point action plan -- including $5 billion in tax incentives and spending for R&D and energy efficiency, incentives for early action, a set of Federal government energy initiatives, and industry-by-industry consultations to explore their best ideas on how to reduce emissions in a cost-effective manner (including market-oriented standards for energy efficiency). The first economic review would occur near the end of Stage 1. 15

- **Stage 2: Review and Evaluation.** The second stage, which would begin around 2004, will build upon the programs adopted in Stage 1, by including a review of our progress and an evaluation of next steps as we move toward a market-based permit trading system for carbon emissions. During this second stage, the details of the permit system would be refined and perhaps tested. Such a permit system is similar in concept to the one that dramatically cut acid rain emissions -- although the scale would be significantly larger than the current acid rain program. The second economic review would occur near the end of Stage 2. 18

- **Stage 3: Meeting Binding Targets Through Domestic and International Emissions Trading Program.** In the third stage, we would reduce emissions to 1990 levels by 2008-2012, and below 1990 levels in the 5-year period after that, through a market-based domestic and international emissions trading system. Before beginning this third stage, the second economic update and review would allow Congress and the President to evaluate how the economy had responded to a decade's worth of experience in the first two stages of the President's plan. The President is committed to working with labor and Congress to insure that we give proper assistance to any workers dislocated by the changes in energy usage inherent in any climate change plan. 19

This three-stage program recognizes the long-term nature of the effort to address climate change in three ways:

- By adopting a graduated approach to emissions reductions, it allows us to exploit the tremendous opportunities for win-win reductions first.

- By adopting a system of regular scientific and economic updates and reviews, it allows us to monitor our progress and re-assess our success in reducing emissions, the state of scientific knowledge, and how the economy is responding to our efforts. Only after we have accumulated ten years of experience with the first two stages of the program would we enter the internationally binding period.

- By insisting that the United States will not adopt binding obligations without developing country participation and by emphasizing the importance of an international trading system and joint implementation, we take advantage of low-cost reduction possibilities wherever they occur -- either here or abroad.

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19

- In the final stage, emissions reductions would occur through the domestic trading program, integrated with international flexibility mechanisms, including international trading of emissions allowances, the Clean Development Mechanism, and joint implementation.

The international agreement that was reached in Kyoto this past December is a crucial step forward in addressing global climate change. But it is only one step in a journey. Since the international effort to reduce greenhouse gas emissions is still in some respects a work-in-progress, it is not yet possible to provide a full authoritative analysis of it. However, key elements of the Kyoto Protocol and the Administration's policy, such as international emissions trading, meaningful developing country participation, inclusion of carbon sinks and six categories of gases, as well as domestic initiatives, can ensure that reductions in global greenhouse gas emissions are consistent with continued strong economic growth.

This report provides the reasoning underlying the Administration's conclusion that, with the flexibility represented by key provisions of the Kyoto agreement, the economic impacts of complying with the Kyoto Protocol are likely to be modest. First, the report provides a discussion of trends in greenhouse gas emissions, both in the United States and internationally. Second, it presents a brief survey of the scientific literature on the risks of climate change. Third, it provides an overview of the Kyoto Protocol, with emphasis on its flexibility mechanisms, and the evidence in the economic literature for cost-savings through these mechanisms. Fourth, it describes the methodology used to provide illustrative cost estimates of the Administration's policy to address climate change and presents the results of this illustrative cost analysis.

PRESIDENT CLINTON ANNOUNCES THE UNITED STATES CLIMATE CHANGE POLICY

NATIONAL GEOGRAPHIC SOCIETY
GILBERT H. GROSVENOR AUDITORIUM
Washington, D.C.

October 22, 1997

THE PRESIDENT'S THREE-STAGE PLAN ON CLIMATE CHANGE

October 22, 1997

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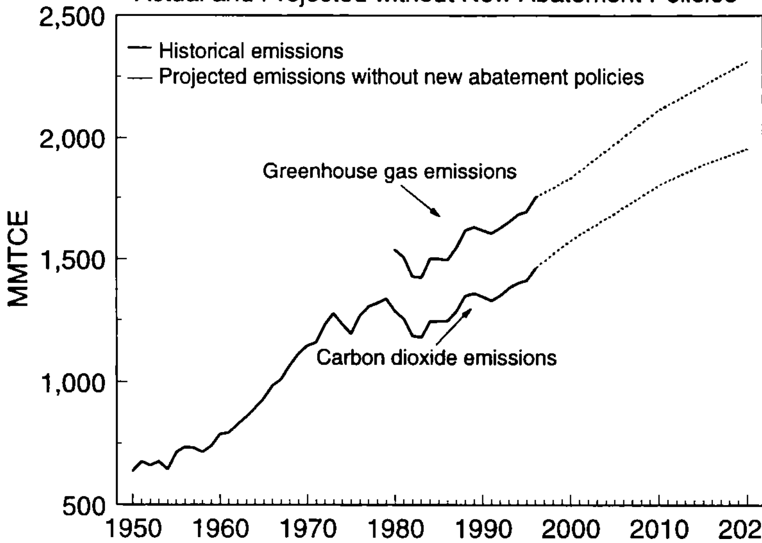
TRENDS IN GREENHOUSE GAS EMISSIONS

Historical Emissions

The increase in atmospheric concentrations of greenhouse gases reflects in part the growth in anthropogenic emissions of these gases. In the United States, emissions of carbon dioxide have increased more than 2 ½ times since 1950, and are projected to continue to increase over the next twenty years absent any new emissions abatement policies and efforts (see Figure 1). Most of the projected increase in domestic greenhouse gas emissions results from anticipated growth in carbon dioxide emissions; emissions of methane and nitrous oxide are likely to remain roughly flat over the next decade (Energy Information Administration 1997a; Climate Action Report 1997).[2] More than 98% of all carbon dioxide emissions in the United States result from the combustion of fossil fuels (Energy Information Administration 1997b).[3] Although emissions of the synthetic gases, HFCs, PFCs, and SF_6, are projected to increase, they will still comprise only a small share of total U.S. greenhouse gas emissions in 2010 (Climate Action Report 1997).[4]

Figure 1. U.S. Greenhouse Gas Emissions, Actual and Projected without New Abatement Policies



Source: Energy Information Administration 1997a, 1998b; Climate Action Report 1997.

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[2] A recent draft report by the Environmental Protection Agency (1998) indicates that N_2O emissions may have been higher in the past than previously reported, based on a new emissions accounting methodology. This analysis implies that future N_2O emissions may grow.

[3] Measures of carbon dioxide emissions from the Energy Information Administration and the Carbon Dioxide Information Analysis Center do not include the effects of land use change (such as reforestation, afforestation, and deforestation) on total net emissions of carbon dioxide.

[4] Emissions of greenhouse gases are presented in terms of million metric tons of carbon equivalent (MMTCE). Carbon equivalence is based on the 100 year global warming potentials for greenhouse gases (see Table 2 for a review of global warming potentials).

figure 1

Projected Greenhouse Gas Emissions: 1990–2020

Emissions of greenhouse gases are projected to rise at a decreasing rate between now and the year 2020 (Table 4–2 and Figure 4–3). Between 1990 and 2000, emissions increase by 12 percent; between 2000 and 2010, they increase by an additional 11 percent; and between 2010 and 2020, they increase by another 9 percent. The growth of overall greenhouse gas emissions is due to the continued but slowing growth in projected baseline emissions.

Among all gases, net carbon emissions increase the most in absolute terms, while emissions from halogenated gases increase the most in percentage terms. Net carbon emissions are projected to increase by 195 MMTCE between 1990 and 2000, by 137 MMTCE between 2000 and 2010, and 117 MMTCE between 2010 and 2020. The largest percentage increase in net carbon emissions, 16 percent, occurs between 1990 and 2000. (Net carbon emission is equal to gross domestic energy-related carbon emissions, minus international bunker fuel, plus Adjustments to U.S. Energy, plus emissions from Other Sources, minus sequestered carbon.)

Although the projected absolute increase in carbon-equivalent emissions for halogenated gases is relatively small compared to net carbon emissions, halogenated gases increase by 73 percent between 1990 and 2000, by 115 percent between 2000 and 2010, and by 46 percent between 2010 and 2020. The largest absolute increase for these gases was 49 MMTCE, which is projected to occur between 2000 and 2010.

Table 4-2

Historical and Projected 1997 CAR Greenhouse Gas Emissions (MMTCE)

Greenhouse Gas	Historical Emissions		Projected Emissions		
	1990	1995	2000	2010	2020
Net CO_2	**1,228**	**1,305**	**1,423**	**1,560**	**1,677**
Energy	1,327	1,391	1,504	1,634	1,737
Adjustments and Other Sources	26	31	31	35	34
Carbon Sequestration	-125	-117	-112	-109	-95
Methane	**170**	**177**	**150**	**152**	**154**
N_20	**36**	**40**	**31**	**34**	**34**
HFCs, PFCs and SF_6	**24**	**37**	**42**	**91**	**133**
Total	**1,458**	**1,559**	**1,646**	**1,837**	**1,998**
Difference from 1990		**101**	**188**	**378**	**540**

(21)

Note: Projections assume timely receipt of legislative authority for parking cash-out. Program funding is based on funding proportional to current funding with respect to 1993 CCAP funding levels. Columns may not sum due to independent rounding.

figure 1

U. S. Department of Energy

TELEFAX TRANSMISSION

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Office of Integrated Analysis and Forecasting (EI-80)
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Washington, D.C. 20585

DATE: 12/29/97

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FAX NUMBER: 202 395 6370

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OTHER GASES 1980-96
GPP

Table ES-1. Summary of Estimated U.S. Emissions of Greenhouse Gases, 1980-1996
(Million Metric Tons of Gas)

Greenhouse Gas	Units	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Carbon Dioxide	MMT	4,853.7	4,728.4	4,459.3	4,430.6	4,669.0	4,667.2	4,665.9	4,819.5	5,044.1	5,091.8	5,037.1	4,987.3	5,059.8	5,175.9	5,256.1	5,286.9	5,484.9
Methane	MMT	28.6	29.2	29.8	29.6	30.4	30.6	29.9	30.7	31.3	31.3	31.6	31.6	31.7	30.8	31.4	30.9	30.9
Nitrous Oxide	MMT	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.4
Halocarbons and Minor Gases																		
CFC-11, CFC-12, CFC-113		0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1
HCFC-22		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
HFCs, PFCs and SF6	MMT	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Methyl Chloroform	MMT	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.1	0.1	*	*
Criteria Pollutants																		
Carbon Monoxide	MMT	104.9	103.5	98.7	104.6	103.7	104.0	99.0	97.9	105.0	93.5	91.3	88.3	85.3	85.4	89.6	83.5	NA
Nitrogen Oxides	MMT	21.1	20.9	20.4	20.2	21.0	20.7	20.3	20.3	21.4	21.1	20.9	20.6	20.7	21.1	21.5	19.7	NA
Nonmethane VOCS	MMT	23.5	22.3	21.3	22.3	23.2	23.4	22.7	22.5	23.3	21.7	21.4	20.8	20.3	20.5	21.1	20.7	NA

Sources: This report

Carbon Dioxide	MMTC	1323.7	1289.6	1216.2	1208.3	1273.4	1272.9	1272.5	1314.4	1375.7	1388.7	1373.8	1360.2	1379.9	1411.6	1433.5	1444.6	1495.9
memo HFCs, PFCs, & SF6		0.0068	0.007	0.00513	0.00609	0.0069	0.0063	0.008511	0.00881	0.008081	0.0083	0.0085	0.00915	0.0128	0.0145	0.0206	0.0229	0.03412

Table ES-2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1988-1995
(Million Metric Tons of Carbon Equivalent)

Greenhouse Gas	GWP	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Carbon Dioxide	1	1,324	1,290	1,216	1,208	1,273	1,273	1,273	1,314	1,376	1,389	1,374	1,360	1,380	1,412	1,433	1,445	1,496
Methane	5.7	164	167	170	170	174	175	171	176	179	179	181	181	182	177	180	177	177
Nitrous Oxide	85	29	29	27	27	31	32	32	33	38	38	38	38	38	39	40	38	38
HFCs, PFCs, and SF6	(a)	20	21	16	19	21	20	21	22	26	26	25	28	28	27	31	36	42
Total		1,537	1,507	1,429	1,424	1,500	1,500	1,497	1,546	1,616	1,632	1,618	1,606	1,628	1,654	1,684	1,696	1,753

Sources: Emissions Estimates: EIA, Greenhouse Gas Report, 1995
GWP: United Nations, Intergovernmental Panel on Climate Change (IPCC).

Table 3.1. U.S. Methane Emissions from Anthropogenic Sources, 1980-1996
(Million Metric Tons of Methane)

Source	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	P1996
Energy Sources																	
Coal Mining	3.05	2.80	3.23	3.02	3.60	3.88	3.73	4.01	4.24	4.31	4.63	4.38	4.28	3.50	3.90	3.98	3.93
Oil and Gas	5.31	5.93	6.09	6.21	6.30	6.26	6.22	6.37	6.47	6.48	6.59	6.73	6.78	6.78	6.73	6.32	6.80
Stationary Combustion	0.83	0.83	0.89	0.88	0.88	0.84	0.82	0.81	0.84	0.87	0.57	0.60	0.63	0.55	0.54	0.59	0.59
Transportation	0.38	0.38	0.37	0.36	0.35	0.33	0.32	0.31	0.30	0.29	0.27	0.26	0.26	0.25	0.24	0.25	0.25
Total Energy Sources	9.57	9.93	10.57	10.46	11.13	11.31	11.09	11.50	11.85	11.95	12.07	11.97	11.96	11.08	11.42	11.15	11.57
Waste Management																	
Landfills	9.85	10.02	10.18	10.34	10.48	10.58	10.61	10.81	10.89	10.89	10.96	10.85	10.74	10.68	10.57	10.45	10.28
Waste Water Treatment	0.1369	0.1382	0.1395	0.1408	0.1421	0.1433	0.1446	0.1459	0.1473	0.1487	0.1502	0.1519	0.1536	0.1553	0.1568	0.1583	0.1598
Total Waste Management	9.99	10.16	10.32	10.49	10.62	10.72	10.76	10.96	11.04	11.04	11.11	11.00	10.89	10.83	10.73	10.60	10.44
Agricultural Sources																	
Ruminat Animals	5.47	5.56	5.50	5.46	5.33	5.27	5.13	5.08	5.10	5.08	5.13	5.31	5.39	5.46	5.62	5.61	5.46
Animal Waste	2.88	2.75	2.66	2.71	2.64	2.64	2.39	2.63	2.64	2.60	2.63	2.73	2.81	2.81	2.88	2.88	2.76
Rice Paddies	0.48	0.54	0.47	0.31	0.40	0.36	0.34	0.33	0.41	0.38	0.40	0.39	0.44	0.40	0.46	0.43	0.40
Agricultural Residue	0.12	0.14	0.14	0.10	0.13	0.14	0.13	0.12	0.10	0.12	0.13	0.12	0.14	0.11	0.15	0.12	0.14
Total Agriculture Sources	8.95	8.99	8.77	8.59	8.51	8.41	7.99	8.16	8.24	8.18	8.29	8.55	8.77	8.79	9.11	9.05	8.75
Industrial Processes	0.13	0.14	0.10	0.11	0.11	0.11	0.10	0.11	0.12	0.12	0.12	0.11	0.12	0.12	0.13	0.13	0.13
Total	28.64	29.23	29.75	29.64	30.37	30.55	29.94	30.73	31.26	31.29	31.59	31.63	31.74	30.82	31.38	30.93	30.90

Table 4.1. Estimated U.S. Nitrous Oxide Emissions, 1980-1996
(Thousand Metric Tons of Nitrous Oxide)

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	P1996
Agriculture																	
Fertilizer	166	163	143	144	161	156	147	148	150	154	159	162	163	171	174	154	141
Crop Residue Burning	4	5	5	4	5	5	5	5	4	5	5	5	5	4	6	5	5
Total	171	168	149	148	166	162	152	152	154	159	164	167	168	176	179	159	146
Energy Use																	
Transport	50	52	54	64	79	91	101	116	134	147	150	148	150	147	147	148	148
Stationary Combustion	35	34	32	33	35	35	35	36	38	38	38	37	37	38	39	39	41
Total	84	86	86	96	113	126	136	152	172	184	188	185	188	186	186	187	189
Industrial Sources	90	87	82	81	89	90	85	90	95	100	97	100	96	101	107	108	111
Total	**345**	**341**	**317**	**325**	**368**	**378**	**374**	**394**	**420**	**444**	**449**	**452**	**452**	**463**	**472**	**454**	**446**
Total (10^6 Metric Tons)	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.4

Table 5-2. Estimated U.S. Emissions of Halocarbons and Other Greenhouse Gases, 1980-1996
(Thousand Metric Tons)

Item	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	P199
CFCs																	
CFC-11	52.299	60.189	54.195	71.752	78.237	77.035	84.511	84.999	84.999	80.004	60.004	53.996	48.043	39.359	37.000	36.000	10.292
CFC-12	76.940	81.272	87.218	92.630	98.862	111.294	109.280	110.210	110.378	114.177	112.999	107.626	96.606	90.291	59.002	52.002	47.473
CFC-113	40.520	42.408	44.170	51.888	66.641	72.362 •	77.596	83.259	82.843	77.720	49.998	38.540	27.826	19.702	17.000	17.000	16.143
Other CFCs	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	9.000	8.750	8.500	8.250	8.000	5.000	4.000
Halons	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3.000	3.000	3.000	3.000	3.000	3.000	2.000
HCFCs																	
HCFC-22	58.646	64.374	67.762	73.176	73.617	70.350	70.325	68.113	73.951	76.369	71.997	82.332	91.799	100.064	104.996	91.996	92.634
HCFC-141b	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	*	0.500	3.000	8.000	16.000	22.047	32.796
HCFC-142b	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.500	3.000	6.000	10.000	8.204	10.966
Other HCFCs	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.000	2.500	3.000	3.500	4.000	7.000	9.000
HFCs																	
HFC-23	3.097	3.425	2.371	3.206	3.458	3.203	3.687	3.741	4.525	4.661	4.165	4.279	4.486	3.965	4.160	4.200	4.200
HFC-134a	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500	0.900	3.470	5.920	10.410	12.031	21.660
HFC-152a	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	*	*	1.030	1.040	1.530	0.910	1.000
Other HFCs	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.020	4.680	6.500
PFCs/PFPEs	3.071	2.962	2.160	2.212	2.705	2.310	2.004	2.206	2.603	2.660	2.672	2.720	2.668	2.439	2.177	3.258	3.472
Other Chemicals																	
Carbon Tetrachloride	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	30.000	NA	25.600	21.600	16.000	5.000	4.745
Methyl Chloroform	294.801	283.790	252.460	252.598	276.438	261.120	296.089	281.137	323.429	295.616	316.004	224.365	215.012	121.886	77.997	46.000	25.840
Sulfur Hexaflouride	0.629	0.644	0.603	0.666	0.771	0.794	0.819	0.861	0.932	0.989	1.000	1.071	1.132	1.170	1.213	1.290	1.404

Source: 1990 emissions estimates: Unpublished information, EPA Office of Air and Radiation
Other estimates, EIA estimates described in this chapter.

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October 1, 1997

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TOTAL P.02

Emissions of Carbon Dioxide by Sector, 1949-1996

Sector	Units	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960
Residential	10^6 MTC	83.8	91.1	96.0	98.0	98.0	101.5	109.0	114.8	114.9	120.8	126.8	136.0
Commercial	10^6 MTC	75.3	79.2	78.8	77.9	75.4	74.9	79.2	81.3	78.0	80.6	82.6	88.0
Industrial	10^6 MTC	268.4	295.7	321.2	309.0	328.1	300.3	347.0	357.7	356.8	331.8	346.0	353.8
Transportation	10^6 MTC	164.5	172.0	180.6	175.6	174.8	168.5	179.6	182.1	182.5	181.4	185.7	203.2
Total	10^6 MTC	591.9	637.9	676.7	660.5	676.4	645.2	714.7	735.9	732.1	714.6	741.0	781.0
Electric Utility	10^6 MTC	67.6	75.1	83.5	87.3	96.7	98.3	114.8	124.0	128.3	125.1	138.1	144.5

Emissions of Carbon Dioxide By Fuel, 1949-1996

Sector	Units	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960
Petroleum	10^6 MTC	218.2	244.5	264.1	271.1	281.0	283.9	307.5	316.2	317.2	324.0	335.8	358.5
Coal	10^6 MTC	297.6	306.5	310.9	280.4	281.7	240.9	276.9	281.3	268.1	236.5	236.5	244.2
Natural Gas	10^6 MTC	76.1	86.9	101.8	109.0	113.7	120.3	130.3	138.4	146.9	154.1	168.8	178.3
Geothermal	10^6 MTC												
Total	10^6 MTC	591.9	637.9	676.7	660.5	676.4	645.2	714.7	735.9	732.1	714.6	741.0	781.0

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NSN 7540-01-317-7368 5099-101 GENERAL SERVICES ADMINISTRATION

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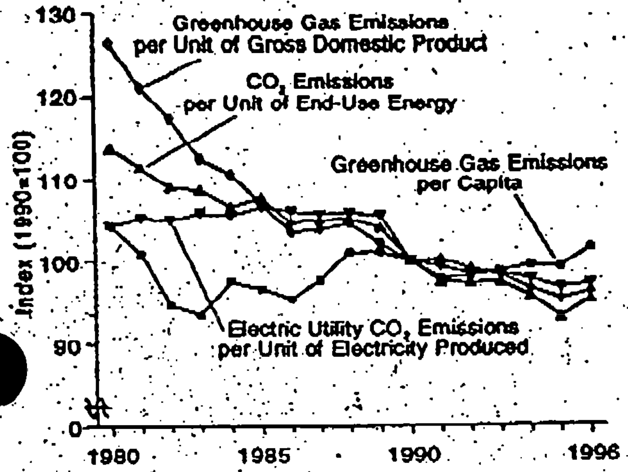
(20)

Carbon Dioxide

Some 98.5 percent of U.S. anthropogenic carbon dioxide emissions come from the combustion of fossil fuels. Changes in carbon dioxide emissions can be traced to energy consumption trends and changes in the composition of fossil fuels burned to provide energy services. During the 1980s and early 1990s, the energy intensity of the U.S. economy and the carbon intensity of U.S. energy consumption steadily declined (Figure ES2).

Figure ES2. Emissions Intensity of U.S. Gross Domestic Product, Population, Energy Use, and Electricity Production, 1980-1996



Sources: EIA estimates documented in this report.

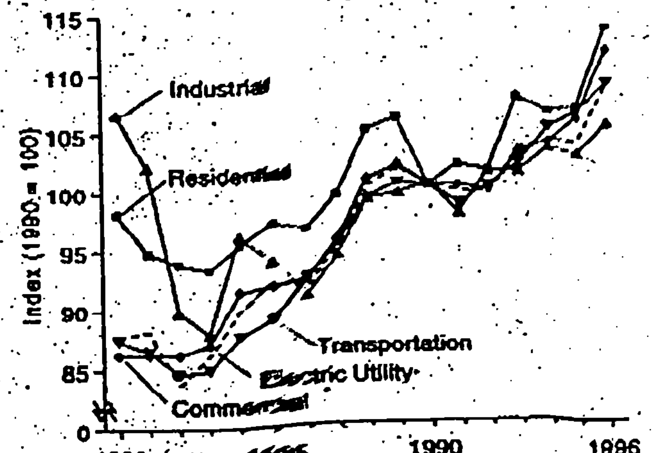
Several unrelated factors caused the decline:

- The deregulation of the natural gas industry bore fruit in the form of greatly increasing gas supplies at low prices. Natural gas use expanded rapidly in the residential, commercial, and industrial sectors, accounting for much of the growth of energy consumption.
- Many events of the period—including the Gulf War, the oil price spike of 1990, the recession of 1991, and the vogue for utility demand-side management programs—tended to restrain the growth of energy consumption.
- Utility operators began to solve nuclear power plant operating problems and, by 1995, were able to produce 17 percent more electricity from nuclear plants than in 1990.
- With more snowfall in the Pacific Northwest, hydroelectric power generation has returned to the levels of the early 1980s. Despite widespread allocation of water to accommodate salmon, 1996 hydroelectric generation was the second highest on record.

Currently, however, the growth in nuclear power generation has leveled off, and it is unlikely that future hydroelectric generation will often match 1996 levels. World oil prices remain relatively low, and the U.S. economy is growing rapidly.

Severe weather conditions in 1996 produced a series of anomalous results: residential and commercial natural gas consumers used 7.8 percent more natural gas and 3.5 percent more electricity than in 1995, and natural gas prices increased sharply. In response to the price signals, electric utilities reduced their gas consumption by 15 percent and substituted coal. The result was a sharp increase in both total carbon emissions and emissions per kilowatthour for the electric utility sector, accompanied by rapid increases in both direct (from natural gas and heating oil) and indirect (from electricity) emissions from the residential and commercial sectors. Emissions from the industrial and transportation sectors increased by a "more normal" 2.6 percent and 2.3 percent, respectively, in 1996 (Figure ES3).

Figure ES3. U.S. Carbon Dioxide Emissions by Sector, 1980-1996



Source: EIA estimates documented in Chapter 2 of this report.

Methane

Methane emissions estimates are more uncertain than those for carbon dioxide. U.S. anthropogenic methane emissions have three principal sources: production and transportation of coal, natural gas, and oil; anaerobic decomposition of municipal waste in landfills; and

Including missing emission sources. Quantitative estimates of some of the sources and sinks of greenhouse gas emissions are not available at this time. In particular, emissions from some land-use activities and industrial processes are not included in the inventory either because data are incomplete or because methodologies do not exist for estimating emissions from these source categories.

Improving the accuracy of emission factors. Further research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the accuracy of current emission factors applied to methane and nitrous oxide emissions from stationary and mobile source fossil fuel combustion are highly uncertain.

Collecting detailed activity data. Although methodologies exist for estimating emissions for some sources, problems arise in obtaining activity data at a level of detail in which aggregate emission factors can be applied. For example, the ability to estimate emissions of methane and nitrous oxide from jet aircraft is limited due to a lack of activity data by aircraft type and number of landing and take-off cycles.

Applying Global Warming Potentials. GWP values have several limitations including that they are not applicable to unevenly distributed gases and aerosols such as tropospheric ozone and its precursors. They are also intended to reflect global averages and, therefore, do not account for regional effects (IPCC 1996).

Emissions calculated for the U.S. inventory reflect current best estimates; in some cases, however, estimates are based on approximate methodologies, assumptions, and incomplete data. As new information becomes available in the future, the U.S. will continue to improve and revise its emission estimates.

Changes in U.S. Greenhouse Gas Inventory Report

This year's inventory of greenhouse gas emissions and sinks includes several significant additions and methodological changes that, depending on the source, improve the accuracy, precision, or comprehensiveness of the estimates presented relative to previous U.S. inventories. A summary of these additions and changes is provided below:

- An improved methodology for estimating methane and nitrous oxide emissions from mobile sources was employed that accounts for changes in emission control technologies over time and vehicle miles traveled by model year. Improved CH_4 and N_2O emission factors were also used, which had the primary result of revising N_2O emission estimates from highway vehicles upward significantly. 22
- An additional analysis of carbon dioxide emission from fossil fuel combustion in the transportation end-use sector is provided showing emissions by fuel and vehicle type.
- Carbon sequestration from non-fuel uses of fossil fuels in U.S. territories was included for the first time in emission estimates of CO_2 from fossil fuel combustion.
- Due to inconsistencies in natural gas production and consumption data available from the Energy Information Agency, CO_2 emissions from unmetered natural gas consumption were not included. This exclusion had a insignificant effect on reported emissions.
- Carbon dioxide emissions from geothermal steam extraction for electric power generation are included for the first time, although its contribution to total emissions is less than 0.1 MMTCE.
- Improved emission factors and a more detailed analysis of activities contributing to methane emissions from natural gas systems have been employed.
- Several new industrial processes were included for the first time. Methane emissions from the production of select petrochemicals and silicon carbide production were added, although their contribution is minor. Carbon dioxide emissions from ammonia, iron and steel, and ferroalloy production were estimated, even though their emissions are accounted for under the fossil fuel combustion of industrial coking coal and natural gas.
- The discussion of HFC, PFC, and SF_6 emissions has been expanded to include multiple sources and improved estimating methodologies.

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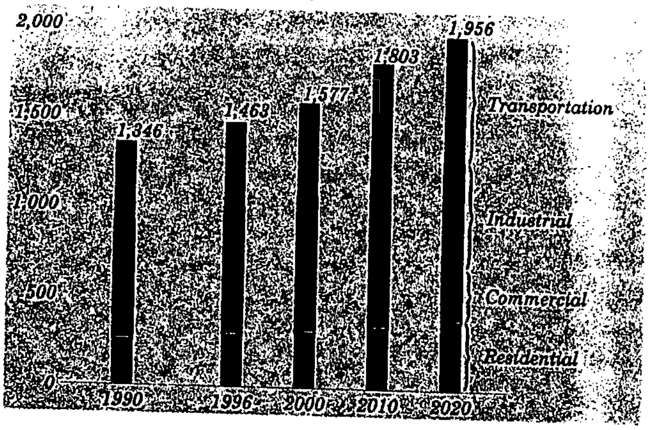
Annual Energy Outlook 1998

With Projections Through 2020

Energy Information Administration

AEO98 Projects Higher Carbon Emissions Than *AEO97*

Figure 106. Carbon emissions by sector, 1990-2020 (million metric tons per year)



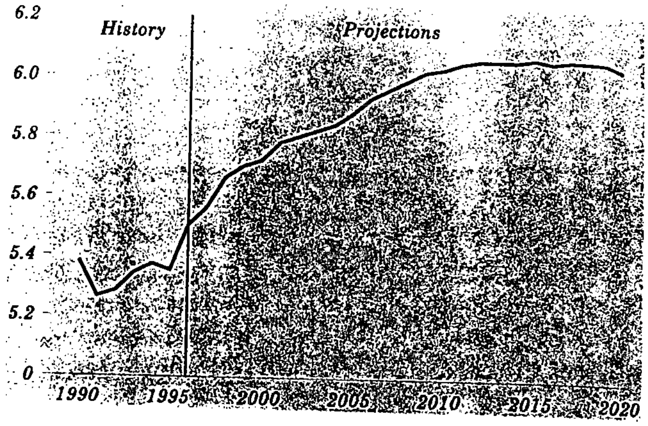
Carbon emissions from energy use are projected to increase by an average of 1.2 percent a year from 1996 to 2020, reaching 1,956 million metric tons (Figure 106). The 2015 projection of 1,888 million metric tons is higher than the *AEO97* projection of 1,799 million metric tons, due to higher energy consumption and a reduced share of renewable fuels.

Increasing concentrations of greenhouse gases—carbon dioxide, methane, nitrous oxide, and others—may increase the Earth's temperature and, in turn, affect the climate. The *AEO98* projections include analysis of the Climate Change Action Plan (CCAP), developed by the Clinton Administration in 1993 to stabilize U.S. greenhouse gas emissions by 2000 at 1990 levels. Carbon emissions from fuel combustion, the primary source of carbon emissions, were about 1,346 million metric tons in 1990. The analysis does not account for carbon-absorbing sinks, the 13 CCAP actions that are related to non-energy programs or gases other than carbon dioxide, nor any future mitigation actions that may be proposed.

Emissions in the 1990s have grown more rapidly than projected at the time the plan was formulated, partly due to moderate energy price increases and higher economic growth, which have led to higher energy demand. In addition, some CCAP programs have been curtailed. Additional carbon mitigation programs, technology improvements, or more rapid adoption of voluntary programs could result in lower emissions levels than projected here.

U.S. Carbon Emissions per Capita Level Off Late in the Projections

Figure 107. Carbon emissions per capita, 1990-2020 (metric tons per person)



U.S. carbon emissions from energy use are projected to grow at an average annual rate of 1.2 percent; however, per capita emissions grow by only 0.4 percent a year (Figure 107). To achieve stabilization of total emissions, population growth would need to be offset by reductions in per capita emissions.

Emissions in the residential sector, including emissions from the generation of electricity used in the sector, are projected to increase by 1.2 percent a year, reflecting the ongoing trends of electrification and penetration of new appliances and services. Significant growth in office equipment and other uses is also projected in the commercial sector, but growth in consumption—and in emissions, which increase by 1.1 percent a year—is likely to be moderated by slowing growth in floorspace, coupled with efficiency standards, voluntary efficiency programs, and technology improvements. Transportation emissions grow at an average annual rate of 1.6 percent as a result of increases in vehicle-miles traveled and freight and air travel, combined with slow growth in the average light-duty fleet efficiency. Industrial emissions are projected to grow by only 0.9 percent a year, as shifts to less energy-intensive industries and efficiency gains moderate growth in energy use.

Further reductions in emissions could result from Climate Wise and Climate Challenge, voluntary programs for emissions reductions by industry and electricity generators, which are cosponsored by the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy.

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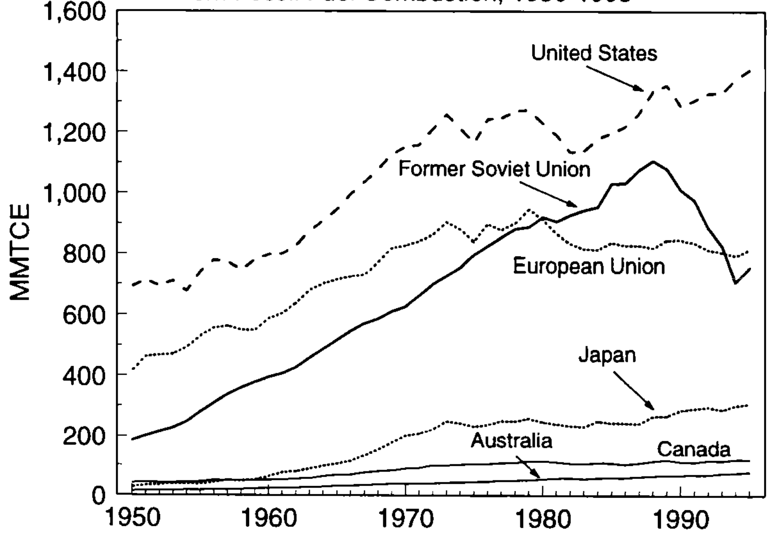
The pattern of emissions growth in the United States is similar to that of most other Annex I nations (see Figure 2) (Marland and Boden 1998).[5] In many cases, the emissions increases have tracked the output of these nations' economies. For example, the rapid development of Japan since World War II resulted in a large increase in carbon dioxide emissions in spite of that economy's high energy efficiency. Further, the nations of the former Soviet Union have experienced a decline in their carbon dioxide emissions since the beginning of this decade because of the significant fall in economic output during their transitions to market economies.

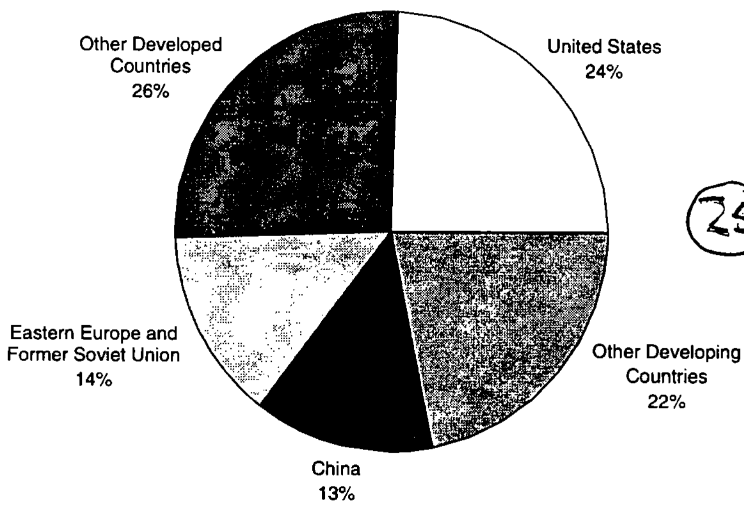
Figure 2. Major Annex I Countries' Carbon Dioxide Emissions from Fossil Fuel Combustion, 1950-1995



Source: Marland and Boden 1998.

In 1996, the industrial countries emitted a majority of the world's energy-related carbon dioxide emissions. The United States emitted approximately 1/4 of the world's carbon dioxide emissions from fossil fuel combustion (see Figure 3). China, the world's second largest emitter, had emissions almost equal to those of all of Eastern Europe and the former Soviet Union. The industrial world's share of global emissions has declined over time as developing countries' economies have grown (Energy Information Administration 1998).

Figure 3. World Carbon Dioxide Emissions from Fossil Fuel Combustion, 1996



Source: Energy Information Administration 1998a.

[5] Annex I includes most of the world's industrial countries (see Appendix A for a description of Annex I and a list of these countries).

Boden T A <tab @ tab.esd.ornl.gov>
06/09/98 01:23:17 PM

Please respond to Boden T A <tab@tab.esd.ornl.gov>

Record Type: Record

To: Zachary M. Candelario/CEA/EOP

cc: tab @ ornl.gov
Subject: Re: Vostok temperature record

Dear Zachary,

You are welcome for the data. I truly enjoy providing data to people.

I've attached an ASCII file (global.dat) that contains the Jones et al. global monthly and annual temperature anomalies for 1856-1997. If you need to convert the anomalies to actual temperatures use 16 degrees C as the reference period mean. For example, an annual anomaly of -0.20 equals 15.8 degrees C. An anomaly of +0.08 equals 16.08 degrees C.

The CO2 emissions file you have is old and out-of-date. Based on the header on your file I'm guessing you got this from the World Resources Institute or some similar organization. I suggest you use a more current version of our database. I've attached the latest version of the file containing the national estimates (nation95.ems) and recommend the following citation.

Marland, G., and T.A. Boden. 1998. Global, Regional, and National CO2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn., U.S.A. (24)

Please contact me if you have further questions or need additional information.

Sincerely,

Tom Boden

> Delivered-To: tab@tab.esd.ornl.gov
> X-Lotus-Fromdomain: EOP
> From: Zachary_M._Candelario@cea.eop.gov
> To: Boden T A <tab@tab.esd.ornl.gov>
> Date: Mon, 8 Jun 1998 15:43:52 -0400
> Subject: Re: Vostok temperature record
> Mime-Version: 1.0
>
> Thank you for the data.
> I have two more questions for you.

DOE/EIA-0383(9
December 1997

Annual Energy Outlook 1998

With Projections Through 2020

Energy Information Administration

Table A9. World Total Carbon Emissions by Region, Reference Case, 1990-2020
(Million Metric Tons)

Region/Country	History			Projections					Average Annual Percent Change, 1995-2020
	1990	1995	1996	2000	2005	2010	2015	2020	
Industrialized									
North America	**1,550**	**1,629**	**1,687**	**1,829**	**1,967**	**2,105**	**2,217**	**2,313**	**1.4**
United States[a]	1,346	1,411	1,463	1,577	1,689	1,803	1,888	1,956	1.3
Canada	126	135	140	152	161	170	183	198	1.5
Mexico	78	82	84	99	117	132	145	159	2.7
Western Europe	**971**	**925**	**947**	**978**	**1,037**	**1,101**	**1,169**	**1,239**	**1.2**
Industrialized Asia	**364**	**379**	**389**	**409**	**434**	**461**	**485**	**514**	**1.2**
Japan	274	281	291	303	320	342	361	385	1.3
Australasia	90	99	99	107	113	119	124	129	1.1
Total Industrialized	**2,885**	**2,933**	**3,023**	**3,216**	**3,437**	**3,667**	**3,870**	**4,066**	**1.3**
EE/FSU									
Former Soviet Union	991	636	613	653	720	792	850	913	1.5
Eastern Europe	299	230	228	249	266	280	293	310	1.2
Total EE/FSU	**1,290**	**866**	**842**	**903**	**986**	**1,072**	**1,144**	**1,223**	**1.4**
Developing Countries									
Developing Asia	**1,065**	**1,427**	**1,474**	**1,758**	**2,161**	**2,603**	**3,158**	**3,835**	**4.0**
China	620	792	805	978	1,202	1,481	1,866	2,340	4.4
India	153	222	230	281	340	399	456	523	3.5
Other Asia	293	413	439	499	620	723	836	971	3.5
Middle East	**194**	**229**	**241**	**253**	**285**	**322**	**363**	**409**	**2.3**
Africa	**178**	**192**	**198**	**219**	**247**	**276**	**306**	**341**	**2.3**
Central and South America	**174**	**194**	**206**	**250**	**318**	**391**	**475**	**574**	**4.4**
Brazil	57	64	71	85	111	139	170	208	4.9
Other Central/South America	117	130	135	165	206	252	305	366	4.2
Total Developing	**1,611**	**2,043**	**2,118**	**2,480**	**3,011**	**3,591**	**4,302**	**5,158**	**3.8**
Total World	**5,786**	**5,841**	**5,983**	**6,598**	**7,434**	**8,330**	**9,315**	**10,447**	**2.4**

[a]Includes the 50 States and the District of Columbia. U.S. Territories are included in Australasia.

Notes: EE/FSU = Eastern Europe/Former Soviet Union. The U.S. numbers include carbon emissions attributable to renewable energy sources.

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 1996*, DOE/EIA-0219(96) (Washington, DC, February 1998). **Projections:** EIA, *Annual Energy Outlook 1998*, DOE/EIA-0383(98) (Washington, DC, December 1997), Table A19; and World Energy Projection System (1998).

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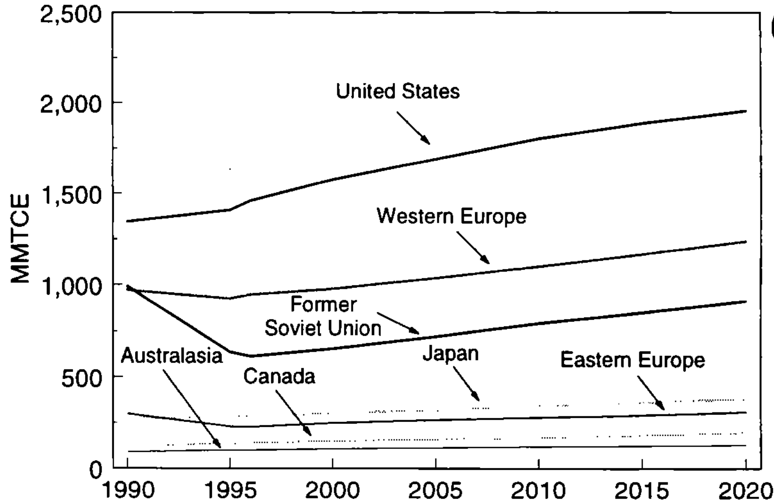
Projected Emissions

Absent new measures to abate emissions in industrial countries, emissions of carbon dioxide will grow in all Annex I nations (see Figure 4).[6] The Energy Information Administration (1998) projects that the United States will experience the largest absolute increase in emissions, while nations of the former Soviet Union are not expected to achieve their 1990 carbon emissions level before 2020.

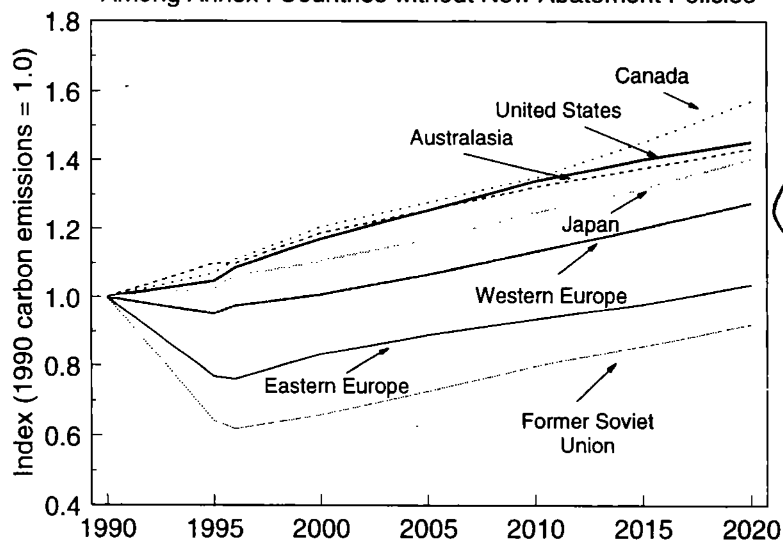
Figure 4. Projected Carbon Dioxide Emissions of Major Annex I Countries without New Abatement Policies



Note: Data represent carbon dioxide emissions from fossil fuel combustion.
Source: Energy Information Administration 1998a.

The United States is projected to experience the second fastest rate of emissions growth among the major Annex I nations (see Figure 5). Canada is projected to experience the fastest growth rate. After declines in emissions during most of this decade, nations of the former Soviet Union and eastern Europe will also have comparable growth rates.

Figure 5. Projected Growth in Carbon Dioxide Emissions Among Annex I Countries without New Abatement Policies



Source: Energy Information Administration 1998a.

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[6] The Energy Information Administration defines Australasia to include Australia, New Zealand, and U.S. Territories. Western Europe includes all of OECD Europe except for the Czech Republic, Hungary, and Poland.

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International Energy Outlook 1998

April 1998

Energy Information Administration
Office of Integrated Analysis and Forecasting
U.S. Department of Energy
Washington, DC 20585

Preface

The Energy Information Administration's outlook for world energy trends is presented in this report. Model projections now extending to the year 2020 are reported, and regional trends are discussed.

The *International Energy Outlook 1998 (IEO98)* presents an assessment by the Energy Information Administration (EIA) of the outlook for international energy markets through 2020. The report is an extension of the EIA's *Annual Energy Outlook 1998 (AEO98)*, which was prepared using the National Energy Modeling System (NEMS). U.S. projections appearing in *IEO98* are consistent with those published in *AEO98*. *IEO98* is provided as a statistical service to energy managers and analysts, both in government and in the private sector. The projections are used by international agencies, Federal and State governments, trade associations, and other planners and decisionmakers. They are published pursuant to the Department of Energy Organization Act of 1977 (Public Law 95-91), Section 205(c). The *IEO98* projections are based on U.S. and foreign government policies in effect on October 1, 1997.

Projections in *IEO98* are displayed according to six basic country groupings (Figure 1). The industrialized region includes projections for four individual countries—the United States, Canada, Mexico, and Japan—along with the subgroups Western Europe and Australasia (defined as Australia, New Zealand, and the U.S. Territories). The developing countries are represented by four separate regional subgroups: developing Asia, Africa, Middle East, and Central and South America. China and India are represented in developing Asia. New to this year's report, country-level projections are provided for Brazil—which is represented in Central and South America. Eastern Europe and the former Soviet Union (EE/FSU) are considered as a separate country grouping.

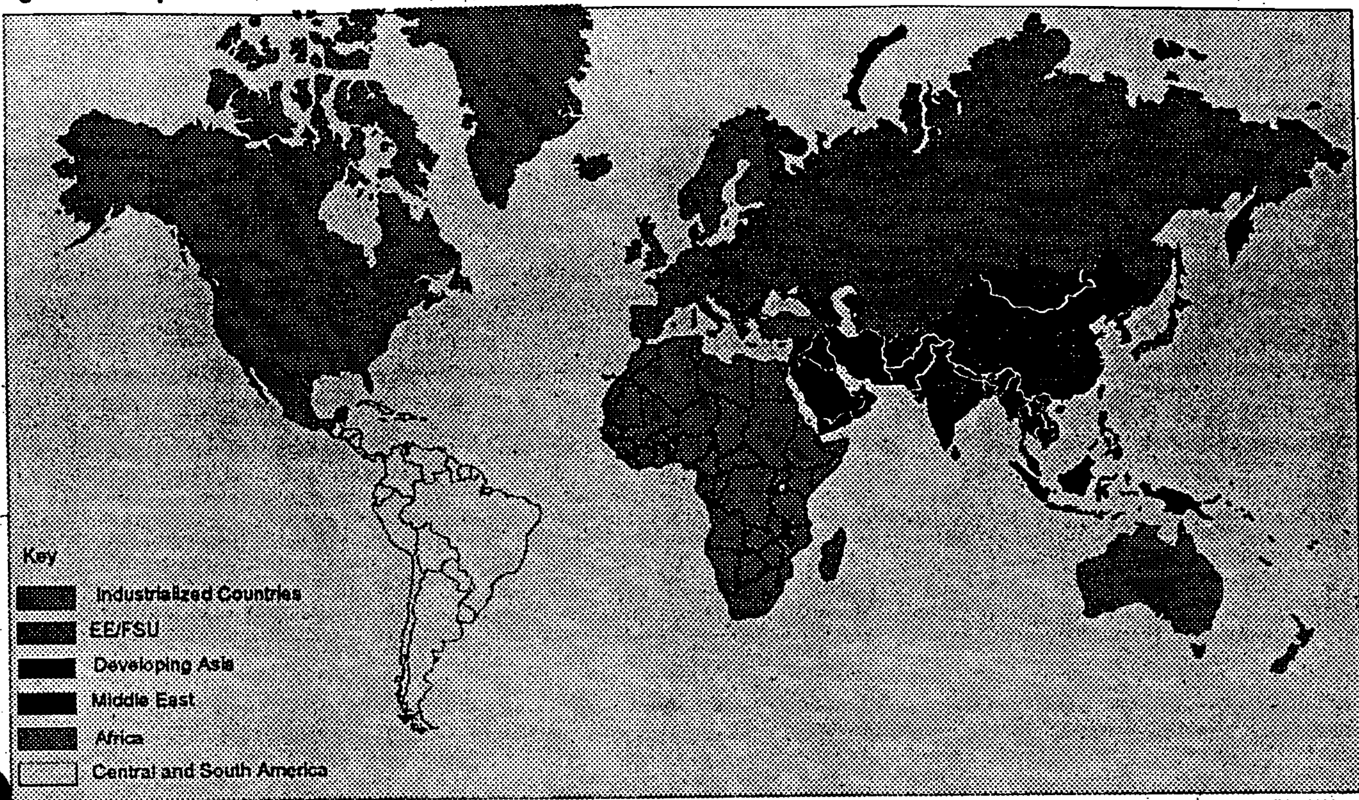
The report begins with a review of world trends in energy demand. The historical time frame starts with data from 1970 and extends to 1996, providing readers with a 26-year historical view of energy demand. For the first time, *IEO98* projections are extended to 2020, so that the forecasts cover a 24-year period.

High economic growth and low economic growth cases, based on different rates of growth in regional gross domestic product (GDP), are used to depict a set of alternative growth paths for the energy forecast. The projections and the uncertainty associated with making international energy projections in general are discussed in the first chapter of the report. The status of environmental issues, including global carbon emissions, is reviewed. Comparisons of the *IEO98* projections with other available international energy forecasts are also included in the first chapter, along with a review of the performance of EIA's international energy projections from previous editions of the *IEO*.

The next part of the report is organized by energy source. Regional consumption projections for oil, natural gas, coal, nuclear power, and renewable energy (hydroelectricity, geothermal, wind, solar, and other renewables) are presented in five fuel chapters, with a review of the current status of each fuel on a worldwide basis. This *IEO98* includes expanded coverage of the transportation sector. A discussion of energy use in the transportation sector—where EIA expects robust growth over the next 25 years—has been added to the chapter on world oil markets. The last chapter of the report contains a discussion of energy use for electricity production.

Summary tables of the *IEO98* projections for world energy consumption, carbon emissions, oil production, and nuclear power generating capacity are provided in Appendix A. The reference case projections for total foreign energy consumption and for natural gas, coal, and renewable energy were prepared using EIA's World Energy Projection System (WEPS) model, as were projections of carbon emissions, net electricity consumption, and energy use for electricity generation. Reference case projections of foreign oil production and consumption were prepared using the International Energy Module of the National Energy Modeling System (NEMS). The NEMS Coal Export Submodule (CES) was used to derive flows in international coal trade. Nuclear *consumption* projections were derived from the International Nuclear Model, PC Version (PC-INM). Alternatively, nuclear *capacity* projections were developed by two methods: the nuclear reference case and low growth case projections were based on analysts' knowledge of the nuclear programs in different countries; the high growth case was generated by the World Integrated Nuclear Evaluation System (WINES), a demand-driven model.

Figure 1. Map of the Six Basic Country Groupings



Source: Energy Information Administration, Office of Integrated Analysis and Forecasting.

The six basic country groupings used in this report (Figure 1) are defined as follows:

- **Industrialized Countries** (the industrialized countries contain 18 percent of the 1997 world population): ~~Australia,~~ Austria, Belgium, ~~Canada~~, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, ~~Japan~~, Luxembourg, ~~Mexico~~, the Netherlands, ~~New Zealand~~, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the ~~United States~~. The industrialized countries actually represent all the countries that are members of the Organization for Economic Cooperation and Development (OECD), with the exceptions of the most recent additions—the Czech Republic, Hungary, Poland, and South Korea.

- **Eastern Europe and the former Soviet Union (EE/FSU)** (7 percent of the 1997 world population):

  - Eastern Europe: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Macedonia, Poland, Romania, Serbia and Montenegro, Slovakia, and Slovenia.

  - Former Soviet Union (FSU): The Baltic States of Estonia, Latvia, and Lithuania, as well as Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan.

- **Developing Asia** (54 percent of the 1997 world population): Afghanistan, Bangladesh, Bhutan, Brunei, Cambodia (Kampuchea), China, Fiji, French Polynesia, Hong Kong, India, Indonesia, Kiribatia, Laos, Malaysia, Macau, Maldives, Mongolia, Myanmar (Burma), Nauru, Nepal, New Caledonia, Niue, North Korea, Pakistan, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, South Korea, Sri Lanka, Taiwan, Thailand, Tonga, Vanuatu, and Vietnam.

- **Middle East** (2 percent of the 1997 world population): Bahrain, Cyprus, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, the United Arab Emirates, and Yemen.

- **Africa** (12 percent of the 1997 world population): Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo (Brazzaville), Congo (Kinshasa), Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion,

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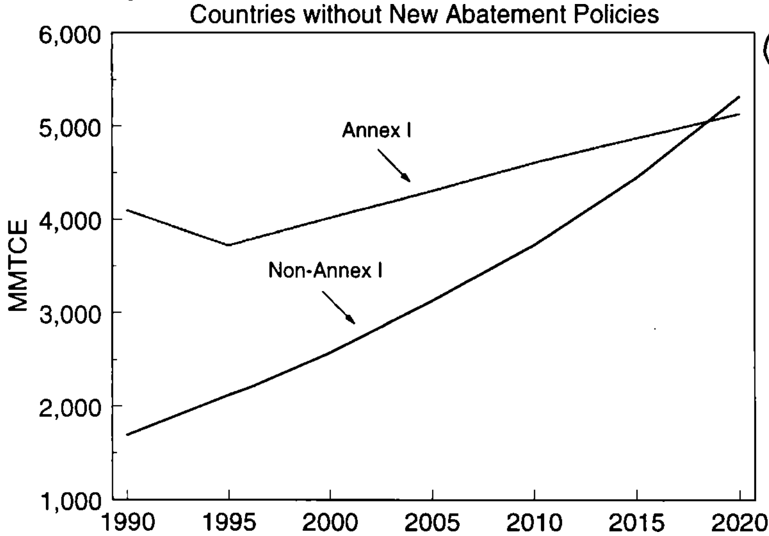
The Energy Information Administration (1998) projects that Non-Annex I countries' emissions will surpass the emissions of Annex I countries between 2015 and 2020 (see Figure 6).[7]

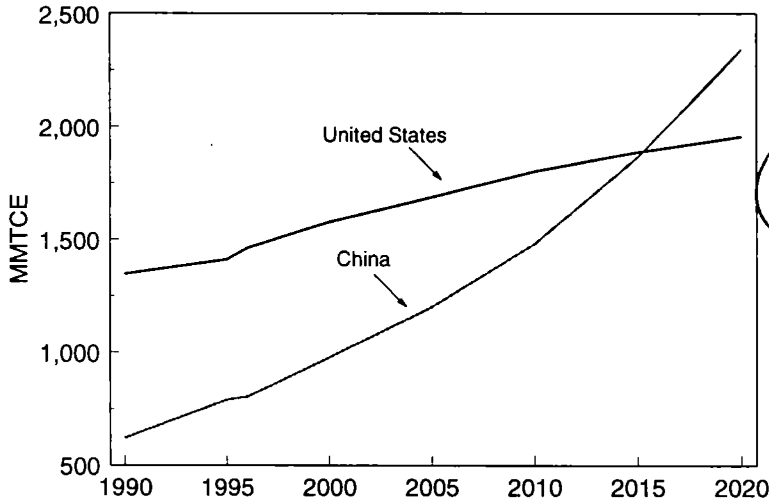
Figure 6. Projected Emissions of Annex I and Non-Annex I Countries without New Abatement Policies



Note: Data represent carbon dioxide emissions from fossil fuel combustion.
Source: Energy Information Administration 1998a.

According to projections, China will surpass the United States as the world's largest annual emitter of carbon dioxide around 2015 (Energy Information Administration 1998). China's emissions will surpass 2 billion metric tons between 2015 and 2020 because of its expected rapid economic growth and its reliance on its vast coal reserves (see Figure 7).

Figure 7. Projected Emissions of the U.S. and China without New Abatement Policies



Note: Data represent carbon dioxide emissions from fossil fuel combustion.
Source: Energy Information Administration 1998a.

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[7] See Appendix A for a discussion of Annex I and Non-Annex I countries.

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December 1997

Annual Energy Outlook 1998

With Projections Through 2020

Energy Information Administration

Table A9. World Total Carbon Emissions by Region, Reference Case, 1990-2020
(Million Metric Tons)

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[a]Includes the 50 States and the District of Columbia. U.S. Territories are included in Australasia.

Notes: EE/FSU = Eastern Europe/Former Soviet Union. The U.S. numbers include carbon emissions attributable to renewable energy sources.

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 1996*, DOE/EIA-0219(96) (Washington, DC, February 1998). **Projections:** EIA, *Annual Energy Outlook 1998*, DOE/EIA-0383(98) (Washington, DC, December 1997), Table A19; and World Energy Projection System (1998).

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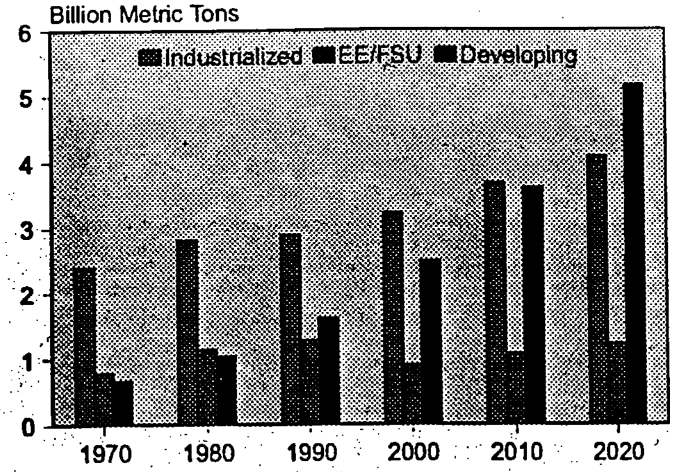
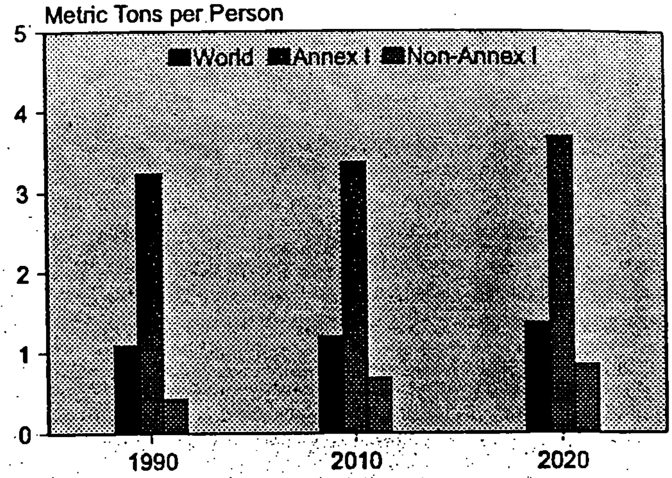
Figure 22. World Carbon Emissions by Region, 1970-2020



Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1996*, DOE/EIA-0219(96) (Washington, DC, February 1998). **Projections:** EIA, World Energy Projection System (1998).

Figure 23. Carbon Emissions per Capita by Region, 1990, 2010, and 2020



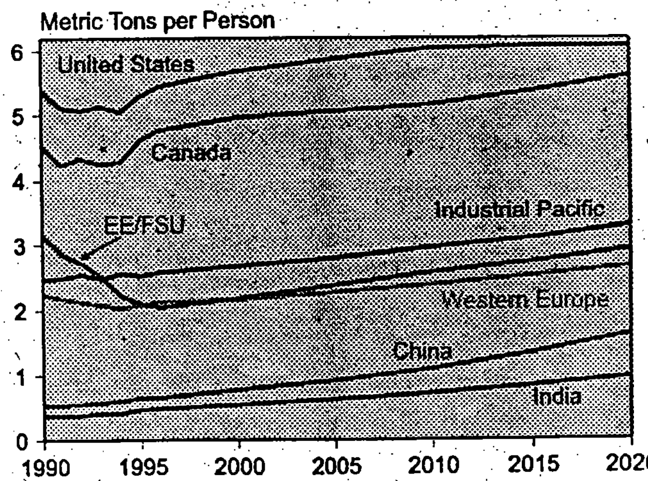
Sources: **1990:** Energy Information Administration (EIA), Office of Energy Markets and End Use, *International Energy Annual 1996*, DOE/EIA-0219(96) (Washington, DC, February 1998). **Projections:** EIA, World Energy Projection System (1998).

carbon emissions between 1990 and 2020 and three-fourths of the increment for all the developing countries. The increase reflects the region's continuing heavy reliance on coal, the most carbon-intensive of the fossil fuels. Increased coal use accounts for 1.7 billion metric tons of developing Asia's 2.8 billion metric ton increment in carbon emissions. At the end of the forecast period, emissions in China alone surpass those of the United States.

Worldwide, carbon emissions per person grow from 1.1 metric tons in 1990 to 1.2 metric tons in 2010 and to 1.4 metric tons in 2020 (Figure 23). Per capita carbon emissions for the Annex I countries remain markedly higher than those for other countries throughout the forecast period, increasing from a 1990 level of 3.2 metric tons of carbon per person in 1990 to 3.7 metric tons per person in 2020. In comparison, the 1990 level for non-Annex I countries was 0.4 metric tons per person, and the projected 2020 level of 0.8 metric tons is one-fourth the 1990 level of per capita emissions for the Annex I countries. On the other hand, the increments for the Annex I and non-Annex I countries over the forecast period are actually equivalent. The non-Annex I countries accounted for 75 percent of the world's population in 1990; in 2020 they will account for almost 82 percent of the world's population; therefore, the effects of relatively small increases in per capita emissions for non-Annex I countries on overall emissions levels will be far greater than the effects of equivalent per capita increases for the Annex I countries.

Within the Annex I countries, the United States and Canada have the highest per capita emissions levels throughout the forecast, reaching 6.1 and 5.6 metric tons per person in 2020, respectively (Figure 24). However, the growth rate of per capita emissions in both countries is projected to be fairly flat after 2000. In contrast, outside the Annex I countries, per capita emissions are projected to increase more rapidly. In China, for instance, per capita carbon emissions in 2020 are projected to be more than triple their 1990 level, reflecting fast-paced industrialization based largely on fossil fuel consumption over the forecast period.

Figure 24. Carbon Emissions per Capita for Selected Regions and Countries, 1990-2020



Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, *International Energy Annual 1996*, DOE/EIA-0219(96) (Washington, DC, February 1998). **Projections:** EIA, World Energy Projection System (1998).

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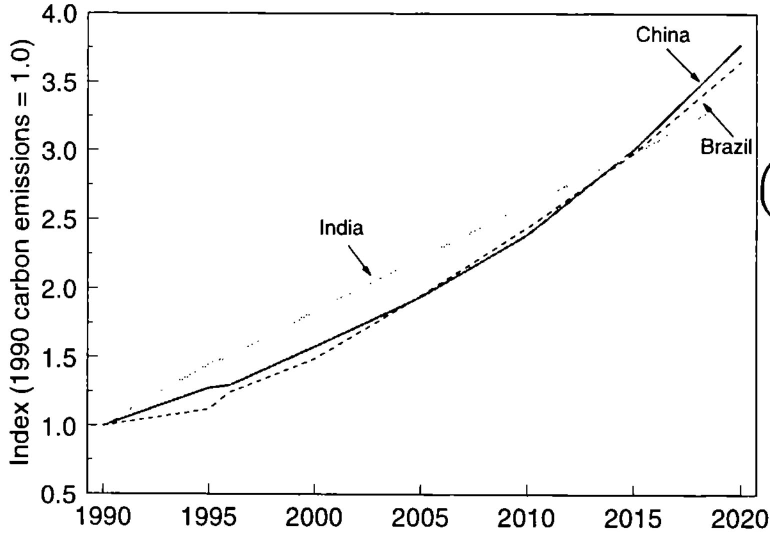
The rapid increase in Non-Annex I emissions is not solely the result of rapid emissions growth in China. The emissions of several other large developing economies are also projected to grow at nearly the same rate (Energy Information Administration 1998; see Figure 8).[8]

Figure 8. Projected Growth in Carbon Dioxide Emissions of Several Developing Countries without New Abatement Policies



Source: Energy Information Administration 1998a.

The projected growth in emissions of carbon dioxide and other greenhouse gases can increase atmospheric concentrations of these gases, and further accelerate climate change. The next section details the risks associated with continuing along the business as usual emissions path.

[8] For additional country specific energy and emissions data, refer to Appendix E.

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Table A9. World Total Carbon Emissions by Region, Reference Case, 1990-2020
(Million Metric Tons)

Region/Country	History 1990	History 1995	History 1996	Projections 2000	Projections 2005	Projections 2010	Projections 2015	Projections 2020	Average Annual Percent Change, 1995-2020
Industrialized									
North America	**1,550**	**1,629**	**1,687**	**1,829**	**1,967**	**2,105**	**2,217**	**2,313**	**1.4**
United States[a]	1,346	1,411	1,463	1,577	1,689	1,803	1,888	1,956	1.3
Canada	126	135	140	152	161	170	183	198	1.5
Mexico	78	82	84	99	117	132	145	159	2.7
Western Europe	**971**	**925**	**947**	**978**	**1,037**	**1,101**	**1,169**	**1,239**	**1.2**
Industrialized Asia	**364**	**379**	**389**	**409**	**434**	**461**	**485**	**514**	**1.2**
Japan	274	281	291	303	320	342	361	385	1.3
Australasia	90	99	99	107	113	119	124	129	1.1
Total Industrialized	**2,885**	**2,933**	**3,023**	**3,216**	**3,437**	**3,667**	**3,870**	**4,066**	**1.3**
EE/FSU									
Former Soviet Union	991	636	613	653	720	792	850	913	1.5
Eastern Europe	299	230	228	249	266	280	293	310	1.2
Total EE/FSU	**1,290**	**866**	**842**	**903**	**986**	**1,072**	**1,144**	**1,223**	**1.4**
Developing Countries									
Developing Asia	**1,065**	**1,427**	**1,474**	**1,758**	**2,161**	**2,603**	**3,158**	**3,835**	**4.0**
China	620	792	805	978	1,202	1,481	1,866	2,340	4.4
India	153	222	230	281	340	399	456	523	3.5
Other Asia	293	413	439	499	620	723	836	971	3.5
Middle East	**194**	**229**	**241**	**253**	**285**	**322**	**363**	**409**	**2.3**
Africa	**178**	**192**	**198**	**219**	**247**	**276**	**306**	**341**	**2.3**
Central and South America	**174**	**194**	**206**	**250**	**318**	**391**	**475**	**574**	**4.4**
Brazil	57	64	71	85	111	139	170	208	4.9
Other Central/South America	117	130	135	165	206	252	305	366	4.2
Total Developing	**1,611**	**2,043**	**2,118**	**2,480**	**3,011**	**3,591**	**4,302**	**5,158**	**3.8**
Total World	**5,786**	**5,841**	**5,983**	**6,598**	**7,434**	**8,330**	**9,315**	**10,447**	**2.4**

[a]Includes the 50 States and the District of Columbia. U.S. Territories are included in Australasia.

Notes: EE/FSU = Eastern Europe/Former Soviet Union. The U.S. numbers include carbon emissions attributable to renewable energy sources.

Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 1996*, DOE/EIA-0219(96) (Washington, DC, February 1998). **Projections:** EIA, *Annual Energy Outlook 1998*, DOE/EIA-0383(98) (Washington, DC, December 1997), Table A19; and World Energy Projection System (1998).

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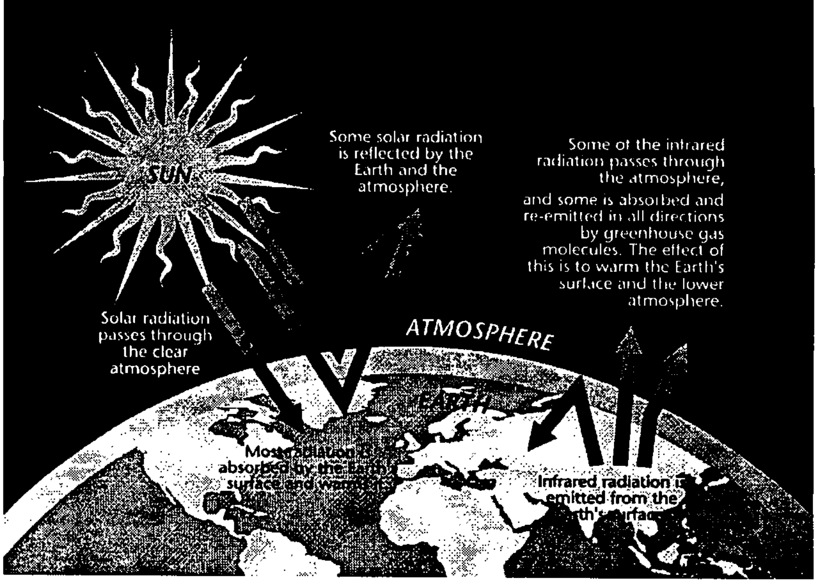
THE RISKS OF CLIMATE CHANGE

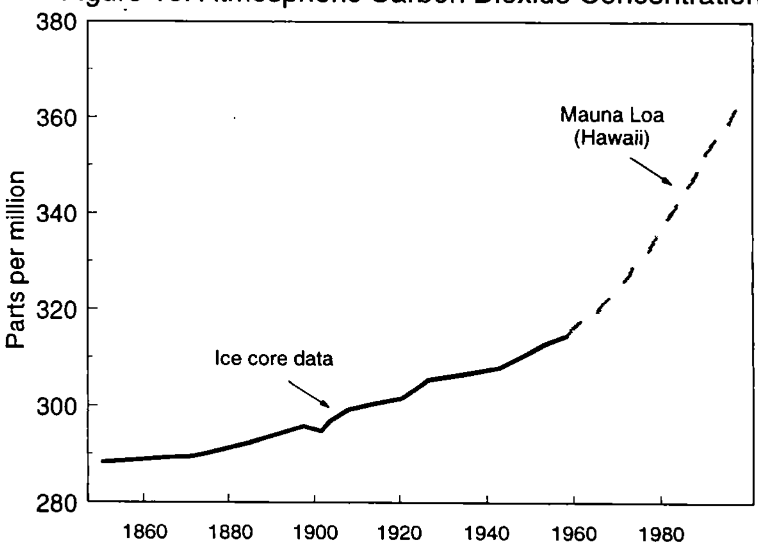
The greenhouse effect naturally warms the Earth's surface (see Figure 9). Without it, the Earth would be 60° F cooler than it is today -- uninhabitable for life as we know it. Water vapor, carbon dioxide, and other trace gases such as methane and nitrous oxide, trap solar heat by slowing the loss of heat by radiative cooling to space, thereby keeping the Earth's surface warmer than it otherwise would be.

Figure 9: The Greenhouse Effect



Since the beginning of the Industrial Era in the middle of the 19th century, the concentration of CO_2 in the atmosphere has been steadily increasing (Neftel et al. 1985, 1994; Keeling and Whorf 1997; see Figure 10). Beginning in 1957, continual measurements of atmospheric CO_2 concentrations have been made by scientists at an observatory on Mauna Loa, Hawaii (Keeling and Whorf 1997). The seasonal cycle of vegetation in Northern latitudes is evident in this record; each spring the vegetation "inhales" and absorbs CO_2, and each autumn most of that CO_2 is released back to the atmosphere. Overall, atmospheric CO_2 has increased over 30% from 280 parts per million (ppm) to over 360 ppm since 1860 (Schimel et al. 1996).

Figure 10. Atmospheric Carbon Dioxide Concentration



Sources: Neftel et al. 1985; Keeling and Whorf 1997.

CLIMATE CHANGE

State of Knowledge

October 1997

The Greenhouse Effect and Historical Emissions

Life as we know it is possible on Earth because of a natural greenhouse effect that keeps our planet about 60° F warmer than it otherwise would be (Figure 1). Water vapor, carbon dioxide (CO_2), and other trace gases, such as methane and nitrous oxide, trap solar heat and slow its loss by re-radiation back to space. With industrialization and population growth, greenhouse gas emissions from human activities have consistently increased. These steady additions have begun to tip a delicate balance, significantly increasing the amount of greenhouse gases in the atmosphere, and enhancing their insulating effect.

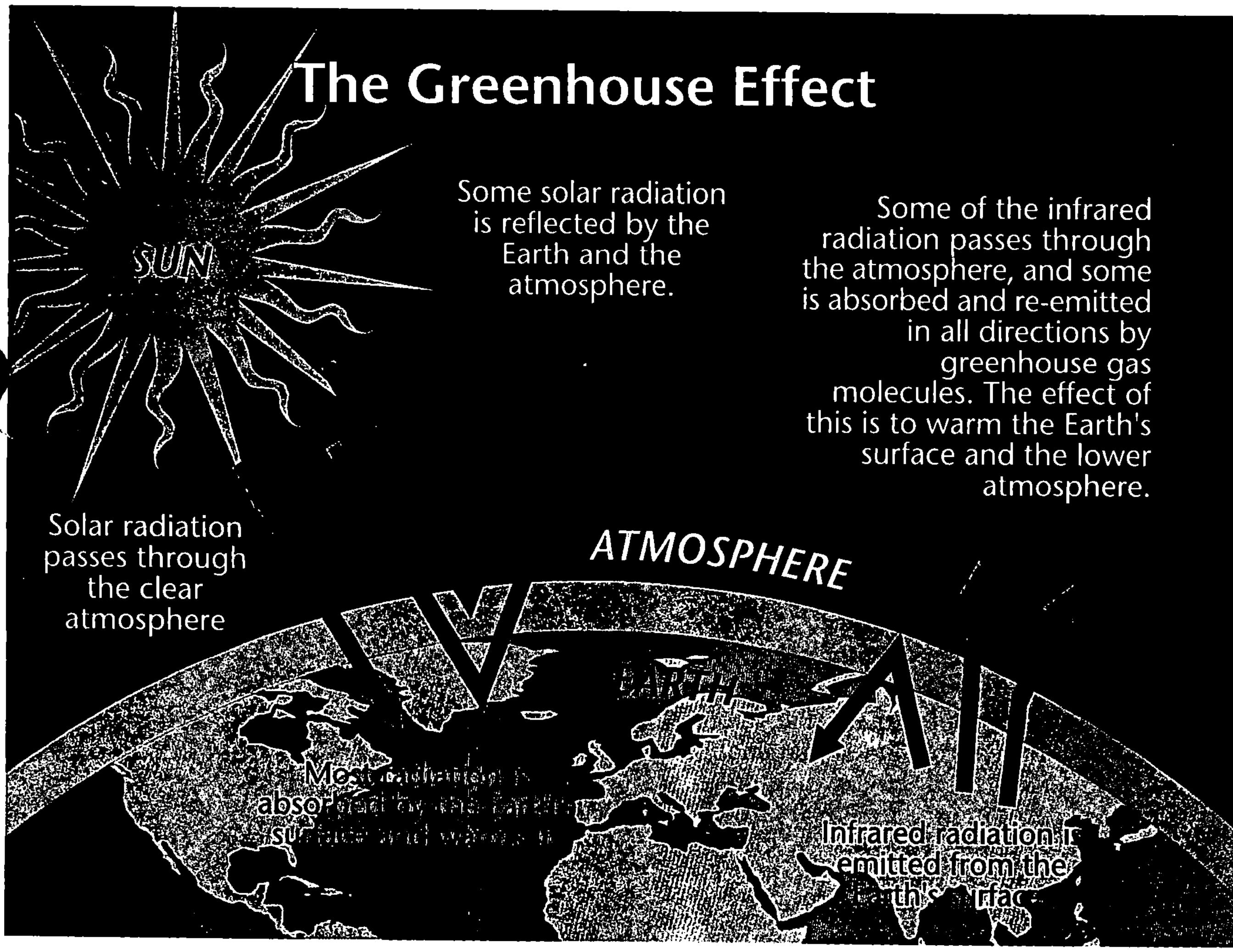


Figure 1. The greenhouse effect naturally warms the Earth's surface. Without it, Earth would be 60° F cooler than it is today – uninhabitable for life as we know it.

The result is that the atmospheric level of CO_2, the most important human-derived greenhouse gas, has increased 30 percent, from 280 to 360 parts per million (ppm) since 1860 (Figure 4). Over the same time period, agricultural and industrial practices have also substantially increased the levels of other potent greenhouse gases -- methane concentrations have doubled and nitrous oxide levels have risen by about 15 percent. These gases have atmospheric lifetimes ranging from decades to centuries; today's emissions will be affecting the climate well into the 21st century.

The overall emissions of greenhouse gases are growing at about 1 percent per year. For millennia, there has been a clear correlation between CO_2 levels and the global temperature record. Fluctuations of CO_2 and temperature have roughly mirrored each other over the last 160,000 years (Figure 5). The current level of CO_2 is already far higher than it has been at any point during this period. If current emissions trends continue over the next century, concentrations will rise to levels not seen on the planet for 50 million years.

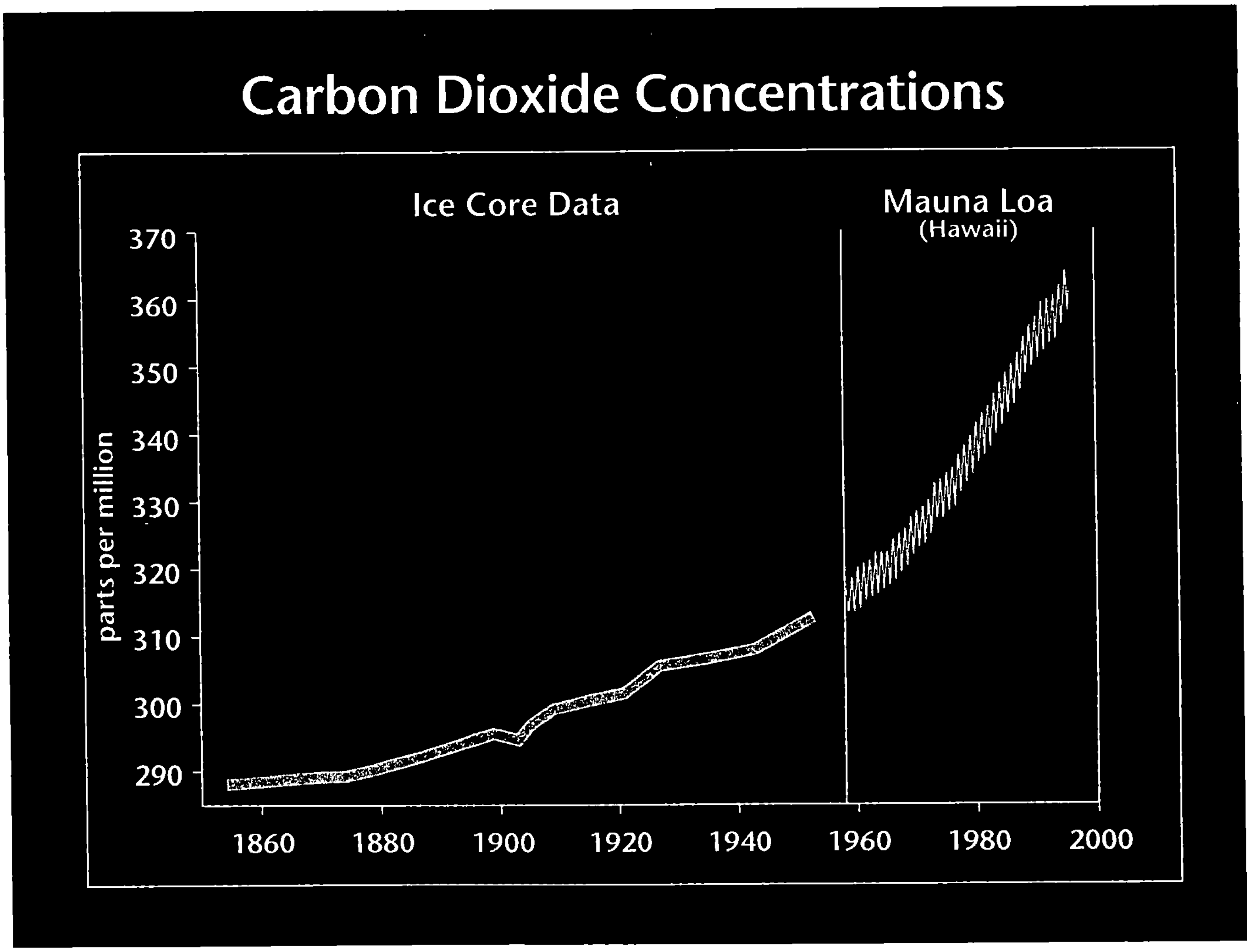


Figure 4. Since the beginning of the Industrial Revolution in the middle of the 19th century, the concentration of carbon dioxide (CO_2) in the atmosphere has steadily increased. Beginning in 1957, continual measurements of atmospheric CO_2 concentrations have been made by scientists at an observatory in Mauna Loa, Hawaii. The seasonal cycle of vegetation in Northern latitudes can be seen in this record: each spring the vegetation "inhales" and absorbs CO_2, and each autumn most of that CO_2 is released back to the atmosphere.

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2

Radiative Forcing of Climate Change

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SUMMARY

Climate change can be driven by changes in the atmospheric concentrations of a number of radiatively active gases and aerosols. We have clear evidence that human activities have affected concentrations, distributions and life cycles of these gases. These matters, discussed in this chapter, were assessed at greater length in IPCC WGI report "Radiative Forcing of Climate Change" (IPCC 1994). The following summary contains some material more fully discussed in IPCC (1994): bullets containing significant new information are marked "***"; those containing information which has been updated since IPCC (1994) are marked "**"; and those which contain information which is essentially unchanged since IPCC (1994) are marked "*".

Carbon dioxide (CO_2)

* Carbon dioxide concentrations have increased by almost 30% from about 280 ppmv in the late 18th century to 358 ppmv in 1994. This increase is primarily due to combustion of fossil fuel and cement production, and to land-use change. During the last millennium, a period of relatively stable climate, concentrations varied by about ± 10 ppmv around the pre-industrial value of 280 ppmv. On the century time-scale these fluctuations were far less rapid than the change observed over the 20th century.

*** The growth rate of atmospheric CO_2 concentrations over the last few years is comparable to, or slightly above, the average of the 1980s (~1.5 ppmv/yr). On shorter (interannual) time-scales, after a period of slow growth (0.6 ppmv/yr) spanning 1991 to 1992, the growth rate in 1994 was higher (~2 ppmv/yr). This change in growth rate is similar to earlier short time-scale fluctuations, which reflect large but transitory perturbations of the carbon system. Isotope data suggest that the 1991 to 1994 fluctuations resulted from natural variations in the exchange fluxes between the atmosphere and both the land biota and the ocean, possibly partly induced by interannual variations in climate.

*** As well as the issue of natural fluctuations discussed above, other issues raised since IPCC (1994) have been addressed. There are some unresolved concerns about the ^{14}C budget which may imply that previous estimates of the atmosphere-to-ocean flux were slightly too high. However, the carbon budget remains within our previously quoted uncertainties and the implications for future projections are minimal. Suggestions that the observed decay of bomb-^{14}C implies a very short atmospheric lifetime for CO_2 result from a mis-understanding of reservoir lifetimes. Current carbon cycle modelling is based on principles that have been well-understood since the 1950s and correctly accounts for the wide range of reservoir time-scales that affect atmospheric concentration changes.

** The major components of the anthropogenic perturbation to the atmospheric carbon budget, with estimates of their magnitudes over the 1980s, are: (a) emissions from fossil fuel combustion and cement production (5.5 $\pm$ 0.5 GtC/yr); (b) atmospheric increase (3.3 $\pm$ 0.2 GtC/yr); (c) ocean uptake (2.0 $\pm$ 0.8 GtC/yr); (d) tropical land-use changes (1.6 $\pm$ 1.0 GtC/yr); and (e) Northern Hemisphere forest regrowth (0.5 $\pm$ 0.5 GtC/yr). Other potential terrestrial sinks include enhanced terrestrial carbon storage due to CO_2 fertilisation (0.5–2.0 GtC/yr) and nitrogen deposition (0.2–1.0 GtC/yr), and possibly response to climatic anomalies. The latter is estimated to be a sink of 0–1.0 GtC/yr over the 1980s, but this term could be either a sink or a source over other periods. This budget is changed from IPCC (1994) by a small adjustment (from 3.2 to 3.3 GtC/yr) to the atmospheric rate of increase and a corresponding decrease in "other terrestrial sinks" from 1.4 to 1.3 GtC/yr.

* In IPCC (1994) calculations of future CO_2 concentrations and emissions from 18 different carbon cycle models were presented based on the IPCC (1992) carbon budget. Concentrations were derived for the IS92 emission scenarios. Future CO_2 emissions were derived leading to

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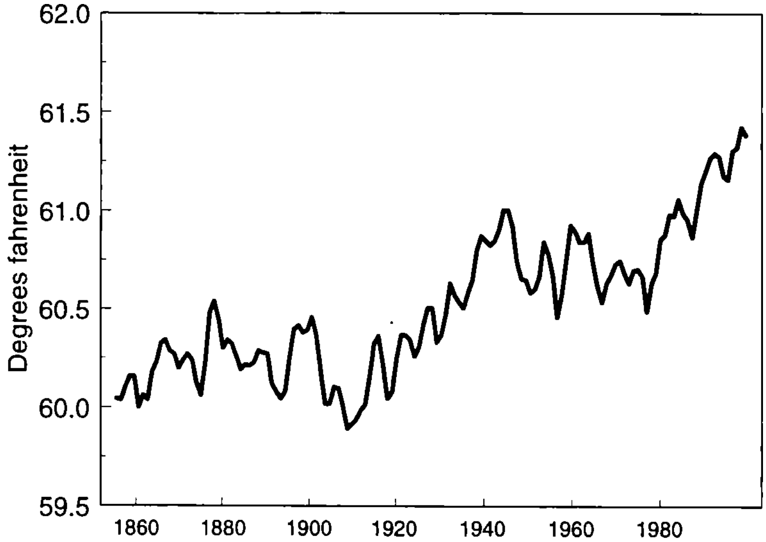
Figure 11. Global Average Temperature

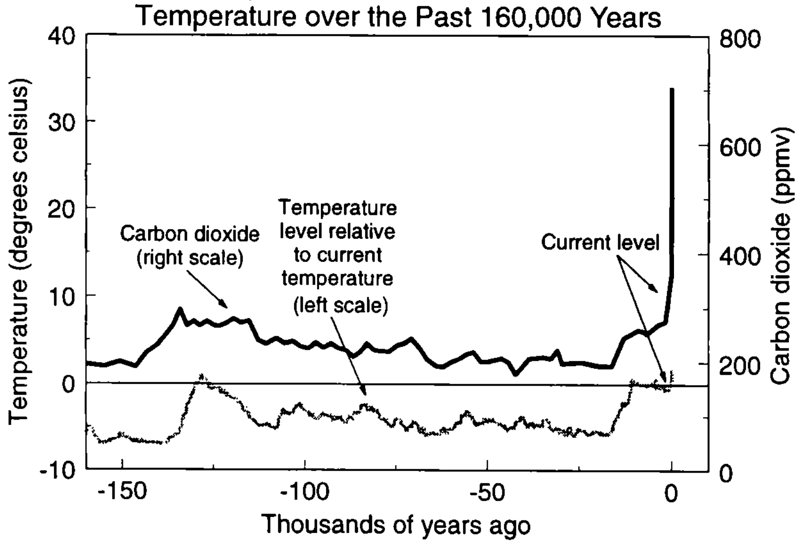


Note: Data are expressed as 3-year centered averages.
Source: Jones et al. 1998.

Over the past century, the global average temperature has risen by approximately 1° F (Nicholls et al. 1996; Jones et al. 1998; see Figure 11).[9] Further, recent analyses have indicated that 1997 was the warmest year on record (Quayle et al. 1998, Karl 1998), and that the decade of the 1990's will be the warmest decade for at least the past 600 years (Mann et al. 1998).

+ Rosina's Email

Figure 12. Atmospheric Carbon Dioxide Concentration and Temperature over the Past 160,000 Years



Sources: Barnola et al. 1994; Energy Information Administration 1998; Chapellaz and Jouzel 1992.

Temperature changes in recent decades bear out the close correlation between carbon dioxide concentration and temperature found in ice core data going back 160,000 years (Barnola et al. 1987, 1994). Since the beginning of the Industrial Era, the CO_2 level has increased steadily and is already outside the bounds of variability seen in the 160,000 year record (see Figure 12). Continuation of current levels of emissions is projected to raise concentrations to over 700 ppm by the year 2100, a level not experienced on Earth since about 50 million

[9] The approximate 1° F temperature rise over the past century is derived from a regression analysis of the temporal data. Because the annual global average temperature is variable from year to year, it is inappropriate to simply select two years to quantify the increment. The trend or regression is a more appropriate means to calculate the century's temperature rise.

CLIMATE CHANGE

State of Knowledge

October 1997

Climate Change Over the Last 100 Years

Global surface temperature has been measured since 1880 at a network of ground-based and ocean-based sites. Over the last century, the average surface temperature of the Earth has increased by about 1.0° F. The eleven warmest years this century have all occurred since 1980, with 1995 the warmest on record (Figure 7). The higher latitudes have warmed more than the equatorial regions.

Beginning in 1979, satellites have been used to measure the temperature of the atmosphere up to a height of 30,000 feet. The long-term surface record and the recent satellite observations differ, but that fact is not surprising: the two techniques measure the temperature of different parts of the Earth system (the surface, and various layers of the atmosphere). In addition to this, a variety of factors, such as the presence of airborne materials from the 1991 eruption of the volcano Mt. Pinatubo, affect each record in a different way. Satellite observations were initially interpreted as showing a slight cooling, but more recent analyses accounting for natural, short-term fluctuations imply warming, just as the ground-based measurements have indicated over a longer time period. As more data from the satellite record become available, and as the quality of measurements is improved, comparison of these two records should yield additional insights.

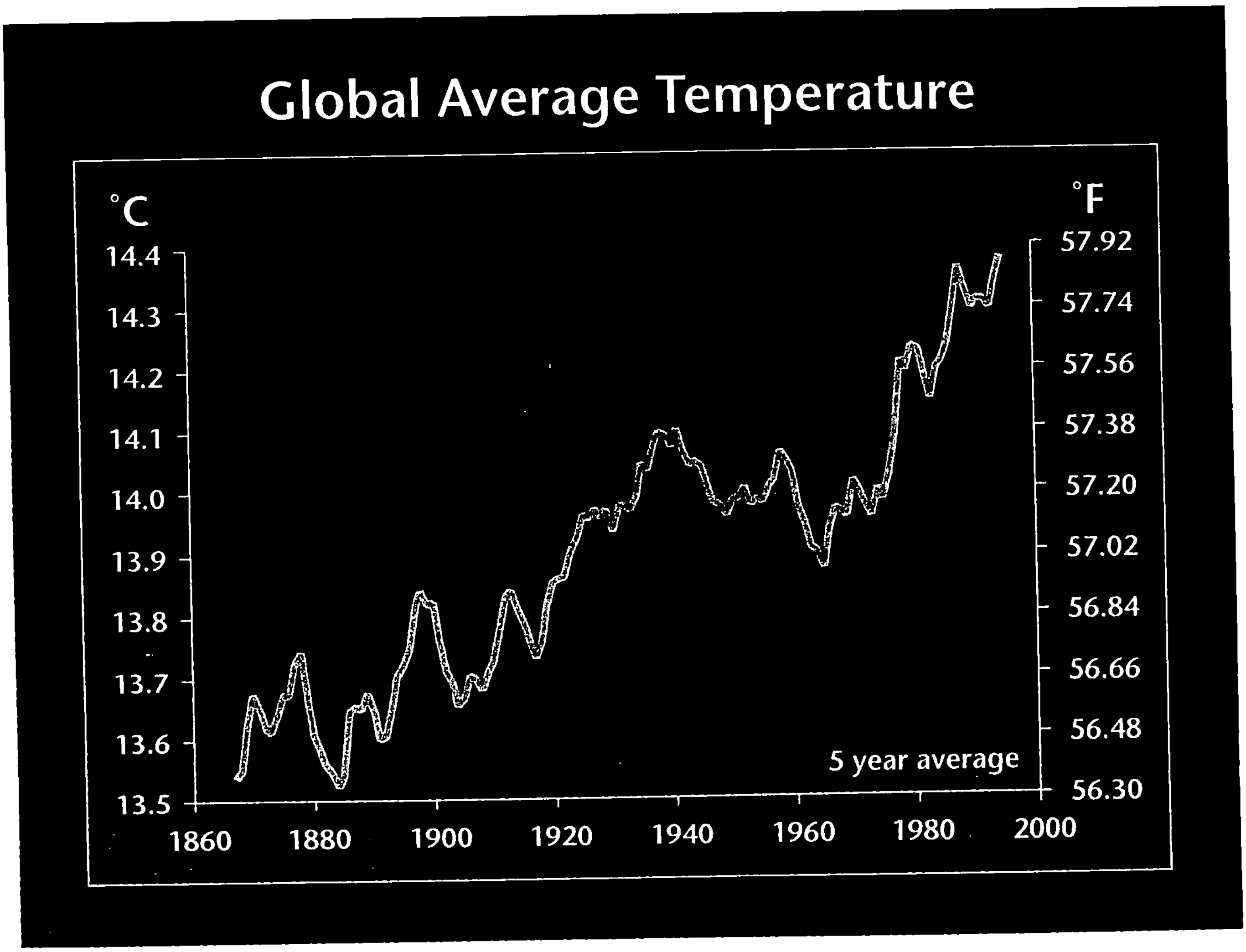


Figure 7. The global average temperature has risen by approximately 1° F over the last century.

3

Observed Climate Variability and Change

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SUMMARY

Has the climate warmed?

- The estimate of warming since the late 19th century has not significantly changed since the estimates in IPCC (1990) and IPCC (1992), although the data have been reanalysed, and more data are now available. Global surface temperatures have increased by about 0.3 to 0.6°C since the late-19th century, and by about 0.2 to 0.3°C over the last 40 years (the period with most credible data). The warming has not been globally uniform. Some areas have cooled. The recent warming has been greatest over the continents between 40° and 70°N.

- The general, but not global, tendency to reduced diurnal temperature range over land, at least since the middle of the 20th century, noted in IPCC (1992), has been confirmed with more data (representing more than 40% of the global land mass). The range has decreased in many areas because nights have warmed more than days. Cloud cover has increased in many of the areas with reduced diurnal temperature range. Minimum temperature increases have been about twice those in maximum temperatures.

- Radiosonde and Microwave Sounding Unit observations of tropospheric temperature show slight overall cooling since 1979, whereas global surface temperature has warmed slightly over this period. There are statistical and physical reasons (e.g., short record lengths; the different transient effects of volcanic activity and El Niño-Southern Oscillation) for expecting different recent trends in surface and tropospheric temperatures. After adjustment for these transient effects, which can strongly influence trends calculated from short periods of record, both tropospheric and surface data show slight warming since 1979. Longer term trends in the radiosonde data, since the 1950s, have been similar to those in the surface record.

- Cooling of the lower stratosphere since 1979 is shown by both Microwave Sounding Unit and radiosonde data (as noted in IPCC, 1992), but is larger (and probably exaggerated because of changes in instrumentation) in the radiosonde data. The current (1994) global stratospheric temperatures are the coolest since the start of the instrumental record (in both the satellite and radiosonde data).

- As predicted in IPCC (1992), relatively cool surface and tropospheric temperatures, and a relatively warmer lower stratosphere, were observed in 1992 and 1993, following the 1991 eruption of Mt. Pinatubo. Warmer surface and tropospheric temperatures reappeared in 1994. Surface temperatures for 1994, averaged globally, were in the warmest 5% of all years since 1860.

- Further work on indirect indicators of warming such as borehole temperatures, snow cover, and glacier recession data, confirm the IPCC (1990) and (1992) findings that they are in substantial agreement with the direct indicators of recent warmth. Variations in sub-surface ocean temperatures have been consistent with the geographical pattern of surface temperature variations and trends.

- As noted in IPCC (1992) no consistent changes can be identified in global or hemispheric sea ice cover since 1973 when satellite measurements began. Northern Hemisphere sea ice extent has, however, been generally below average in the early 1990s.

Has the climate become wetter?

- There has been a small positive (1%) global trend in precipitation over land during the 20th century, although precipitation has been relatively low since about 1980. Precipitation has increased over land in

*** (Februa 1998) ***
***
*** Source: P. D. Jones D. E. Parker ***
*** T. J. Osborn Hadley Centre for Climate ***
*** K. R. Briffa Prediction and Researc***
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YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL	GAT Level Celsius	Far	3-YEAR CE
1856	-0.22	-0.38	-0.53	-0.39	-0.37	-0.16	-0.33	-0.3	-0.37	-0.4	-0.6	-0.32	-0.36	15.64	60.152	60.044
1857	-0.3	-0.33	-0.51	-0.53	-0.63	-0.42	-0.43	-0.4	-0.53	-0.63	-0.73	-0.35	-0.48	15.52	59.936	60.038
1858	-0.62	-0.83	-0.65	-0.38	-0.36	-0.31	-0.32	-0.28	-0.23	-0.22	-0.65	-0.28	-0.43	15.57	60.026	60.104
1859	-0.29	-0.24	-0.15	-0.14	-0.11	-0.32	-0.3	-0.18	-0.47	-0.18	-0.34	-0.27	-0.25	15.75	60.35	60.158
1860	-0.14	-0.49	-0.57	-0.46	-0.36	-0.14	-0.28	-0.28	-0.22	-0.39	-0.63	-0.72	-0.39	15.61	60.098	60.158
1861	-0.85	-0.53	-0.46	-0.45	-0.71	-0.25	-0.25	-0.11	-0.35	-0.4	-0.48	-0.32	-0.43	15.57	60.026	60.002
1862	-0.74	-0.79	-0.38	-0.22	-0.19	-0.25	-0.49	-0.66	-0.39	-0.38	-0.87	-0.78	-0.51	15.49	59.882	60.062
1863	0.02	-0.08	-0.33	-0.17	-0.39	-0.38	-0.53	-0.36	-0.3	-0.34	-0.37	-0.29	-0.29	15.71	60.278	60.038
1864	-0.8	-0.59	-0.46	-0.45	-0.43	-0.21	-0.25	-0.42	-0.44	-0.6	-0.48	-0.53	-0.47	15.53	59.954	60.182
1865	-0.06	-0.52	-0.57	-0.15	-0.16	-0.28	-0.2	-0.28	-0.11	-0.33	-0.25	-0.29	-0.27	15.73	60.314	60.23
1866	0.1	-0.09	-0.34	-0.16	-0.49	0.07	-0.11	-0.25	-0.19	-0.36	-0.31	-0.38	-0.21	15.79	60.422	60.326
1867	-0.27	0.01	-0.44	-0.24	-0.41	-0.35	-0.28	-0.29	-0.2	-0.24	-0.37	-0.64	-0.31	15.69	60.242	60.344
1868	-0.56	-0.35	-0.11	-0.29	-0.09	-0.26	-0.1	-0.15	-0.16	-0.24	-0.4	-0.13	-0.24	15.76	60.368	60.29
1869	-0.29	0.2	-0.53	-0.21	-0.2	-0.38	-0.34	-0.3	-0.25	-0.43	-0.45	-0.48	-0.3	15.7	60.26	60.272
1870	-0.16	-0.47	-0.41	-0.25	-0.35	-0.31	-0.15	-0.33	-0.33	-0.4	-0.25	-0.67	-0.34	15.66	60.188	60.2
1871	-0.46	-0.6	-0.06	-0.22	-0.39	-0.34	-0.12	-0.29	-0.44	-0.54	-0.38	-0.47	-0.36	15.64	60.152	60.242
1872	-0.3	-0.34	-0.36	-0.17	-0.13	-0.24	-0.14	-0.08	-0.19	-0.3	-0.21	-0.34	-0.23	15.77	60.386	60.272
1873	0.03	-0.29	-0.27	-0.45	-0.36	-0.31	-0.22	-0.2	-0.32	-0.33	-0.44	-0.3	-0.29	15.71	60.278	60.242
1874	-0.05	-0.36	-0.6	-0.57	-0.56	-0.44	-0.17	-0.4	-0.22	-0.49	-0.57	-0.49	-0.41	15.59	60.062	60.128
1875	-0.58	-0.58	-0.61	-0.47	-0.14	-0.24	-0.39	-0.29	-0.37	-0.43	-0.56	-0.41	-0.42	15.58	60.044	60.062
1876	-0.34	-0.33	-0.37	-0.36	-0.52	-0.34	-0.24	-0.22	-0.37	-0.45	-0.66	-0.65	-0.4	15.6	60.08	60.23
1877	-0.25	-0.05	-0.3	-0.37	-0.49	-0.14	-0.03	-0.05	-0.02	-0.05	-0.04	0.17	-0.13	15.87	60.566	60.482
1878	0.04	0.32	0.42	0.26	-0.12	-0.02	-0.1	-0.06	-0.07	-0.14	-0.21	-0.3	0	16	60.8	60.542
1879	-0.22	-0.19	-0.23	-0.3	-0.24	-0.28	-0.29	-0.24	-0.26	-0.25	-0.49	-0.57	-0.3	15.7	60.26	60.452
1880	-0.14	-0.28	-0.19	-0.18	-0.31	-0.36	-0.32	-0.15	-0.3	-0.41	-0.46	-0.25	-0.28	15.72	60.296	60.302
1881	-0.43	-0.28	-0.25	-0.19	-0.03	-0.23	-0.15	-0.12	-0.29	-0.37	-0.45	-0.17	-0.25	15.75	60.35	60.344
1882	0.05	-0.04	0.01	-0.28	-0.3	-0.35	-0.22	-0.2	-0.15	-0.37	-0.39	-0.48	-0.23	15.77	60.386	60.326
1883	-0.42	-0.36	-0.33	-0.39	-0.3	-0.11	-0.22	-0.24	-0.3	-0.43	-0.31	-0.28	-0.31	15.69	60.242	60.26
1884	-0.32	-0.28	-0.33	-0.44	-0.38	-0.33	-0.38	-0.33	-0.27	-0.3	-0.59	-0.39	-0.36	15.64	60.152	60.194
1885	-0.51	-0.49	-0.38	-0.4	-0.45	-0.48	-0.25	-0.33	-0.22	-0.27	-0.19	-0.07	-0.34	15.66	60.188	60.218
1886	-0.31	-0.44	-0.39	-0.19	-0.11	-0.26	-0.19	-0.15	-0.21	-0.31	-0.35	-0.26	-0.27	15.73	60.314	60.212

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1887	[illegible]	-0.52	-0.33	-0.43	-0.28	-0.38	-0.18	-0.36	[illegible]	-0.47	-0.33	-0.4	-0.37	15.63	60.134	60.23
1888	-0.66	-0.53	-0.53	-0.27	-0.28	-0.24	-0.28	-0.26	-0.17	-0.09	-0.2	-0.19	-0.31	15.69	60.242	60.29
1889	-0.12	-0.08	-0.01	-0.02	-0.05	-0.16	-0.18	-0.22	-0.34	-0.25	-0.38	-0.2	-0.17	15.83	60.494	60.278
1890	-0.29	-0.31	-0.32	-0.3	-0.42	-0.34	-0.34	-0.44	-0.47	-0.48	-0.58	-0.37	-0.39	15.61	60.098	60.272
1891	-0.52	-0.49	-0.41	-0.39	-0.2	-0.32	-0.26	-0.23	-0.17	-0.3	-0.54	-0.06	-0.32	15.68	60.224	60.122
1892	-0.42	-0.1	-0.44	-0.43	-0.4	-0.38	-0.48	-0.37	-0.22	-0.38	-0.64	-0.78	-0.42	15.58	60.044	60.08
1893	-1.08	-0.79	-0.37	-0.53	-0.55	-0.34	-0.23	-0.33	-0.35	-0.25	-0.38	-0.31	-0.46	15.54	59.972	60.044
1894	-0.43	-0.33	-0.33	-0.4	-0.37	-0.43	-0.34	-0.33	-0.43	-0.38	-0.44	-0.38	-0.38	15.62	60.116	60.08
1895	-0.48	-0.71	-0.51	-0.34	-0.38	-0.36	-0.35	-0.26	-0.18	-0.27	-0.2	-0.32	-0.36	15.64	60.152	60.26
1896	-0.23	-0.19	-0.35	-0.35	-0.14	-0.08	-0.11	-0.08	-0.04	-0.06	-0.24	-0.06	-0.16	15.84	60.512	60.398
1897	-0.2	-0.12	-0.18	-0.03	-0.01	-0.09	-0.07	-0.13	-0.05	-0.16	-0.44	-0.38	-0.15	15.85	60.53	60.416
1898	-0.05	-0.35	-0.74	-0.49	-0.36	-0.2	-0.25	-0.23	-0.24	-0.44	-0.36	-0.27	-0.33	15.67	60.206	60.38
1899	-0.14	-0.46	-0.47	-0.22	-0.24	-0.34	-0.19	-0.11	-0.08	-0.08	0.1	-0.39	-0.22	15.78	60.404	60.392
1900	-0.2	-0.2	-0.2	-0.15	-0.14	-0.06	-0.11	-0.1	-0.15	0.03	-0.28	-0.02	-0.13	15.87	60.566	60.458
1901	-0.16	-0.23	-0.15	-0.13	-0.14	-0.11	-0.11	-0.13	-0.36	-0.27	-0.45	-0.39	-0.22	15.78	60.404	60.368
1902	-0.19	-0.22	-0.37	-0.43	-0.39	-0.36	-0.36	-0.34	-0.35	-0.42	-0.48	-0.49	-0.37	15.63	60.134	60.182
1903	-0.17	-0.09	-0.3	-0.47	-0.45	-0.52	-0.46	-0.55	-0.54	-0.58	-0.56	-0.63	-0.44	15.56	60.008	60.02
1904	-0.65	-0.52	-0.59	-0.59	-0.51	-0.5	-0.5	-0.49	-0.5	-0.4	-0.31	-0.31	-0.49	15.51	59.918	60.02
1905	-0.47	-0.71	-0.44	-0.53	-0.33	-0.31	-0.3	-0.3	-0.28	-0.37	-0.25	-0.18	-0.37	15.63	60.134	60.104
1906	-0.14	-0.35	-0.29	-0.12	-0.27	-0.26	-0.32	-0.31	-0.34	-0.39	-0.53	-0.29	-0.3	15.7	60.26	60.098
1907	-0.49	-0.55	-0.38	-0.55	-0.61	-0.55	-0.45	-0.49	-0.45	-0.37	-0.6	-0.48	-0.5	15.5	59.9	60.008
1908	-0.44	-0.39	-0.6	-0.54	-0.51	-0.44	-0.49	-0.53	-0.43	-0.6	-0.65	-0.57	-0.52	15.48	59.864	59.894
1909	-0.56	-0.54	-0.67	-0.61	-0.58	-0.5	-0.54	-0.34	-0.29	-0.36	-0.35	-0.61	-0.49	15.51	59.918	59.918
1910	-0.33	-0.49	-0.38	-0.4	-0.49	-0.49	-0.4	-0.44	-0.38	-0.48	-0.61	-0.59	-0.46	15.54	59.972	59.942
1911	-0.52	-0.66	-0.63	-0.64	-0.54	-0.49	-0.44	-0.44	-0.43	-0.4	-0.35	-0.24	-0.48	15.52	59.936	59.99
1912	-0.33	-0.24	-0.39	-0.3	-0.35	-0.27	-0.46	-0.57	-0.54	-0.61	-0.49	-0.39	-0.41	15.59	60.062	60.014
1913	-0.4	-0.47	-0.52	-0.49	-0.58	-0.52	-0.48	-0.37	-0.42	-0.48	-0.24	-0.07	-0.42	15.58	60.044	60.158
1914	-0.04	-0.19	-0.26	-0.34	-0.22	-0.26	-0.32	-0.24	-0.32	-0.1	-0.32	-0.29	-0.24	15.76	60.368	60.326
1915	-0.13	0.05	-0.36	0.03	-0.14	-0.07	-0.07	-0.13	-0.11	-0.26	-0.1	-0.29	-0.13	15.87	60.566	60.362
1916	-0.19	-0.24	-0.41	-0.29	-0.41	-0.48	-0.3	-0.28	-0.34	-0.27	-0.47	-0.68	-0.36	15.64	60.152	60.2
1917	-0.51	-0.84	-0.89	-0.52	-0.75	-0.33	-0.17	-0.24	-0.16	-0.41	-0.33	-0.92	-0.51	15.49	59.882	60.044
1918	-0.4	-0.46	-0.38	-0.56	-0.63	-0.38	-0.4	-0.4	-0.33	-0.03	-0.32	-0.39	-0.39	15.61	60.098	60.08
1919	-0.21	-0.17	-0.42	-0.01	-0.35	-0.25	-0.28	-0.26	-0.18	-0.31	-0.67	-0.47	-0.3	15.7	60.26	60.248
1920	-0.16	-0.45	-0.07	-0.17	-0.09	-0.17	-0.21	-0.1	-0.18	-0.24	-0.47	-0.48	-0.23	15.77	60.386	60.368
1921	-0.09	-0.22	-0.2	-0.13	-0.16	-0.07	-0.14	-0.27	-0.22	-0.18	-0.43	-0.17	-0.19	15.81	60.458	60.368
1922	-0.36	-0.31	-0.31	-0.32	-0.31	-0.28	-0.27	-0.29	-0.29	-0.33	-0.32	-0.26	-0.3	15.7	60.26	60.344
1923	-0.15	-0.45	-0.34	-0.42	-0.29	-0.19	-0.39	-0.39	-0.34	-0.28	0.01	-0.01	-0.27	15.73	60.314	60.26
1924	-0.33	-0.24	-0.31	-0.36	-0.29	-0.24	-0.27	-0.25	-0.31	-0.3	-0.45	-0.58	-0.33	15.67	60.206	60.308
1925	-0.42	-0.31	-0.23	-0.19	-0.29	-0.26	-0.23	-0.12	-0.18	-0.32	-0.12	0.01	-0.22	15.78	60.404	60.422
1926	0.12	0.08	0.04	-0.2	-0.15	-0.14	-0.2	-0.01	-0.13	-0.07	-0.1	-0.14	-0.08	15.92	60.656	60.506
1927	-0.21	-0.14	-0.27	-0.23	-0.24	-0.16	-0.11	-0.1	-0.06	-0.04	-0.2	-0.47	-0.19	15.81	60.458	60.506
1928	-0.1	-0.19	-0.41	-0.32	-0.26	-0.29	-0.16	-0.2	-0.21	-0.18	-0.13	-0.2	-0.22	15.78	60.404	60.332
1929	-0.48	-0.81	-0.41	-0.43	-0.38	-0.34	-0.32	-0.21	-0.28	-0.11	-0.11	-0.6	-0.37	15.63	60.134	60.368

1930	[illegible]34	-0.19	-0.15	-0.17	-0.21	-0.17	-0.09	-0.05	[illegible]2	-0.07	0.1	-0.07	-0.13	15.87	60.566	60.47
1931	0.04	-0.26	-0.07	-0.14	-0.12	0.07	0.07	0.04	-0.01	0	-0.17	-0.07	-0.05	15.95	60.71	60.632
1932	0.21	-0.27	-0.3	-0.05	-0.15	-0.1	-0.08	-0.06	0.03	-0.01	-0.21	-0.18	-0.1	15.9	60.62	60.572
1933	-0.27	-0.31	-0.32	-0.19	-0.19	-0.14	-0.12	-0.1	-0.19	-0.13	-0.29	-0.55	-0.23	15.77	60.386	60.536
1934	-0.24	-0.11	-0.36	-0.23	-0.06	0	-0.05	-0.01	-0.11	-0.01	-0.02	-0.1	-0.11	15.89	60.602	60.506
1935	-0.25	0.21	-0.21	-0.29	-0.31	-0.16	-0.1	-0.05	-0.1	0.03	-0.33	-0.22	-0.15	15.85	60.53	60.584
1936	-0.22	-0.38	-0.22	-0.22	-0.11	-0.05	0.11	0.04	-0.05	-0.02	-0.06	0	-0.1	15.9	60.62	60.65
1937	-0.16	0.05	-0.24	-0.11	-0.03	0.07	0.1	0.13	0.21	0.15	0	-0.16	0	16	60.8	60.8
1938	0.08	0.08	0.18	0.19	0.07	0.06	0.11	0.12	0.16	0.25	0.12	-0.26	0.1	16.1	60.98	60.872
1939	0.03	0	-0.19	-0.04	0	0.11	0.09	0.11	-0.01	-0.17	-0.06	0.37	0.02	16.02	60.836	60.848
1940	-0.34	-0.12	-0.14	0.07	-0.07	-0.02	0.13	-0.02	0.08	-0.04	-0.11	0.13	-0.04	15.96	60.728	60.824
1941	0.03	0.14	-0.09	0.11	-0.03	0.08	0.06	0.07	-0.07	0.31	0.04	0.08	0.06	16.06	60.908	60.848
1942	0.25	-0.03	0.04	0.05	0.06	0.14	-0.02	0	0.06	0.12	0.03	-0.04	0.06	16.06	60.908	60.908
1943	-0.19	0.12	-0.21	0.04	0.11	-0.07	0.08	0.07	0.07	0.35	0.1	0.29	0.06	16.06	60.908	61.004
1944	0.47	0.29	0.2	0.11	0.19	0.24	0.24	0.27	0.35	0.32	0.02	-0.06	0.22	16.22	61.196	61.004
1945	0.05	-0.07	-0.02	0.16	-0.08	0.05	0	0.31	0.2	0.28	0.07	-0.21	0.06	16.06	60.908	60.92
1946	0.26	0.2	-0.14	0.13	-0.18	-0.23	-0.1	-0.19	-0.02	-0.07	-0.14	-0.43	-0.08	15.92	60.656	60.74
1947	-0.22	-0.2	-0.04	0.03	-0.13	-0.06	-0.07	-0.11	-0.09	0.08	-0.03	-0.19	-0.08	15.92	60.656	60.656
1948	0.12	-0.18	-0.26	-0.09	0.05	0.06	-0.13	-0.03	-0.08	-0.04	-0.12	-0.22	-0.08	15.92	60.656	60.65
1949	0.15	-0.16	-0.23	-0.02	-0.05	-0.14	-0.14	-0.01	-0.1	-0.01	-0.08	-0.25	-0.09	15.91	60.638	60.584
1950	-0.38	-0.3	-0.16	-0.18	-0.1	-0.1	-0.1	-0.15	-0.07	-0.1	-0.43	-0.23	-0.19	15.81	60.458	60.602
1951	-0.36	-0.5	-0.27	-0.07	0.02	0.07	0.04	0.13	0.11	0.12	-0.03	0.19	-0.05	15.95	60.71	60.668
1952	0.16	0.1	-0.11	0.07	0.04	0.07	0.06	0.1	0.11	0	-0.27	-0.06	0.02	16.02	60.836	60.842
1953	0.09	0.19	0.12	0.22	0.13	0.14	0.07	0.09	0.09	0.09	-0.09	0.06	0.1	16.1	60.98	60.782
1954	-0.28	-0.08	-0.17	-0.22	-0.24	-0.12	-0.19	-0.1	-0.07	-0.04	0.03	-0.28	-0.15	15.85	60.53	60.674
1955	0.11	-0.14	-0.41	-0.27	-0.17	-0.09	-0.16	-0.02	-0.09	-0.09	-0.23	-0.31	-0.16	15.84	60.512	60.458
1956	-0.22	-0.36	-0.32	-0.3	-0.29	-0.21	-0.21	-0.22	-0.28	-0.18	-0.27	-0.2	-0.26	15.74	60.332	60.578
1957	-0.16	-0.11	-0.11	-0.03	0.08	0.15	0.07	0.14	0.11	0.06	0.13	0.25	0.05	16.05	60.89	60.746
1958	0.34	0.23	0.08	0.12	0.11	0.06	0.08	0.07	0	0.08	0.07	0.14	0.12	16.12	61.016	60.926
1959	0.13	0.06	0.14	0.09	0.02	0.11	0.05	0.05	0.11	-0.02	-0.15	-0.08	0.04	16.04	60.872	60.896
1960	0	0.22	-0.29	-0.12	-0.11	0.06	0.01	0.07	0.08	0.03	-0.1	0.19	0	16	60.8	60.842
1961	0.04	0.17	0.1	0.1	0.1	0.12	0	0.03	-0.05	-0.07	-0.02	-0.11	0.03	16.03	60.854	60.842
1962	0.04	0.15	0.03	0.04	0	-0.04	0.04	0.03	0.03	0.1	0.01	0.03	0.04	16.04	60.872	60.884
1963	-0.02	0.22	-0.1	-0.03	-0.02	-0.02	0.11	0.12	0.14	0.25	0.17	-0.01	0.07	16.07	60.926	60.734
1964	-0.01	-0.19	-0.28	-0.23	-0.16	-0.12	-0.16	-0.25	-0.29	-0.3	-0.28	-0.39	-0.22	15.78	60.404	60.614
1965	-0.15	-0.29	-0.23	-0.27	-0.15	-0.11	-0.18	-0.14	-0.1	-0.03	-0.15	-0.08	-0.16	15.84	60.512	60.536
1966	-0.08	-0.08	-0.05	-0.11	-0.12	0.05	0.05	0	0.02	-0.06	-0.08	-0.24	-0.06	15.94	60.692	60.632
1967	-0.19	-0.24	-0.09	-0.04	0.07	-0.07	-0.06	-0.02	-0.05	0.14	-0.08	-0.09	-0.06	15.94	60.692	60.674
1968	-0.27	-0.2	0.09	-0.15	-0.17	-0.06	-0.06	-0.04	-0.06	0.01	-0.03	-0.1	-0.09	15.91	60.638	60.728
1969	-0.25	-0.17	0.02	0.12	0.11	0.03	0.06	0.02	0.04	0.04	0.11	0.18	0.03	16.03	60.854	60.746
1970	0.07	0.21	-0.05	0.09	-0.01	-0.01	-0.05	-0.09	-0.06	-0.12	-0.06	-0.24	-0.03	15.97	60.746	60.686
1971	-0.1	-0.35	-0.3	-0.25	-0.2	-0.25	-0.16	-0.13	-0.14	-0.13	-0.08	-0.18	-0.19	15.81	60.458	60.632
1972	-0.42	-0.3	-0.13	-0.04	-0.05	0.02	-0.02	0.05	-0.04	0.05	0.01	0.15	-0.06	15.94	60.692	60.698

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1973	[illegible]	0.28	0.2	0.15	0.12	0.15	0.07	0.04	-0.03	0	-0.09	-0.05	0.08	16.08	60.944	60.704
1974	[illegible]	-0.36	-0.2	-0.15	-0.13	-0.11	-0.09	-0.07	[illegible]	-0.12	-0.18	-0.27	-0.18	15.82	60.476	[illegible]
1975	-0.03	-0.07	-0.02	-0.06	-0.03	-0.08	-0.11	-0.16	[illegible]	-0.2	-0.27	-0.3	-0.12	15.88	60.584	[illegible]
1976	-0.17	-0.31	-0.39	-0.16	-0.28	-0.18	-0.18	-0.18	-0.16	-0.33	-0.19	-0.14	-0.22	15.78	60.404	60.632
1977	-0.15	0.08	0.14	0.14	0.1	0.13	0.05	0	0.08	0.01	0.16	-0.05	0.06	16.06	60.908	60.686
1978	0.05	0.01	0.06	-0.01	-0.07	-0.13	-0.05	-0.16	-0.05	-0.08	0.07	-0.06	-0.03	15.97	60.746	60.854
1979	-0.05	-0.1	0.04	-0.09	-0.02	0.07	0.01	0.07	0.12	0.16	0.16	0.39	0.06	16.06	60.908	60.878
1980	0.16	0.16	0.05	0.13	0.19	0.13	0.08	0.05	0	0.02	0.19	0.08	0.1	16.1	60.98	60.98
1981	0.34	0.2	0.23	0.18	0.05	0.1	0.02	0.1	0.06	0.03	0.05	0.28	0.14	16.14	61.052	60.974
1982	0	0.05	-0.06	0.09	0.07	-0.02	0.01	0	0.11	0.09	0.02	0.3	0.05	16.05	60.89	61.058
1983	0.47	0.4	0.28	0.18	0.16	0.16	0.18	0.25	0.23	0.15	0.28	0.14	0.24	16.24	61.232	60.986
1984	0.17	0.04	0.09	-0.01	0.15	0.01	0.01	0.09	0.02	-0.01	-0.11	-0.27	0.02	16.02	60.836	60.956
1985	0.02	-0.13	0.01	0.02	0.05	-0.04	-0.05	0.05	0	0.05	-0.02	0.02	0	16	60.8	60.866
1986	0.17	0.14	0.11	0.11	0.1	0.13	0.04	0.05	0.07	0.12	0.02	0.06	0.09	16.09	60.962	60.992
1987	0.17	0.35	0.06	0.15	0.19	0.17	0.3	0.28	0.33	0.22	0.2	0.38	0.23	16.23	61.214	61.142
1988	0.42	0.24	0.31	0.32	0.27	0.28	0.2	0.21	0.24	0.2	0.09	0.22	0.25	16.25	61.25	61.196
1989	0.12	0.2	0.2	0.13	0.12	0.12	0.22	0.21	0.18	0.23	0.15	0.26	0.18	16.18	61.124	61.268
1990	0.28	0.37	0.58	0.38	0.27	0.33	0.27	0.3	0.24	0.41	0.42	0.3	0.35	16.35	61.43	61.292
1991	0.35	0.4	0.24	0.42	0.31	0.39	0.36	0.27	0.25	0.24	0.15	0.15	0.29	16.29	61.322	61.274
1992	0.39	0.37	0.31	0.15	0.19	0.17	-0.02	0.04	0.01	0.02	-0.02	0.15	0.15	16.15	61.07	61.178
1993	0.35	0.36	0.3	0.23	0.25	0.16	0.15	0.11	0.05	0.15	-0.01	0.15	0.19	16.19	61.142	61.16
1994	0.23	-0.01	0.26	0.28	0.29	0.27	0.23	0.25	0.26	0.35	0.44	0.31	0.26	16.26	61.268	61.304
1995	0.5	0.64	0.4	0.3	0.29	0.37	0.4	0.44	0.33	0.4	0.38	0.25	0.39	16.39	61.502	61.322
1996	0.18	0.36	0.23	0.16	0.28	0.25	0.28	0.22	0.17	0.13	0.16	0.28	0.22	16.22	61.196	61.424
1997	0.28	0.36	0.36	0.32	0.31	0.43	0.45	0.48	0.52	0.59	0.49	0.53	0.43	16.43	61.574	61.385

Anomalies are expressed in degrees Celsius and are relative to the 1961-1990 mean.

26

National Oceanic and Atmospheric Administration

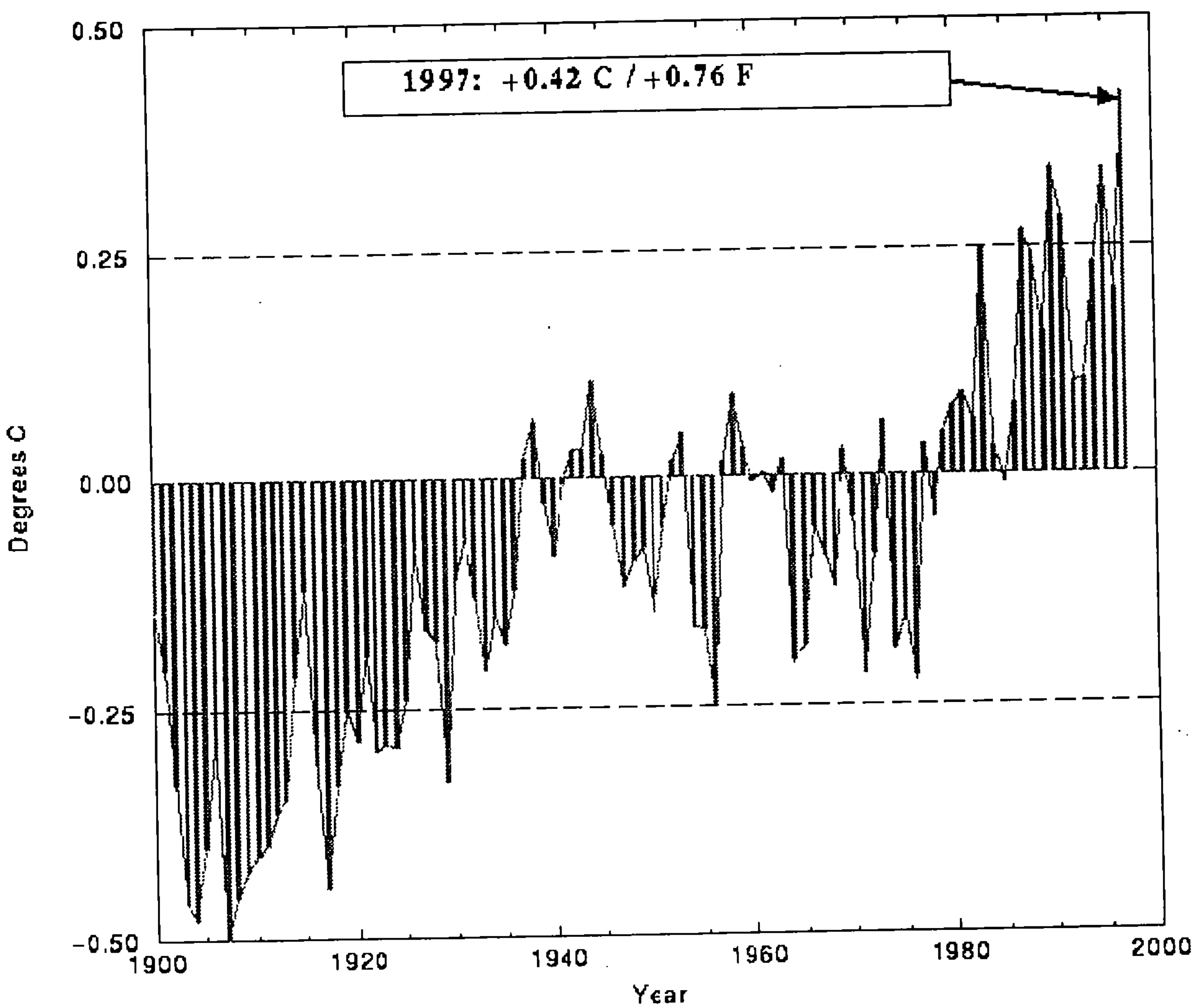
The Climate of 1997 Global Temperature Index: 1997 Warmest Year of Century

Rob Quayle, Tom Peterson, Catherine Godfrey, Alan Basist
National Climatic Data Center, Asheville, NC

January 12, 1998

Global Temperature Index

National Climatic Data Center / NESDIS / NOAA



1997 was the warmest year of this century, based on land and ocean surface temperature data, reports a team of scientists from the National Oceanic and Atmospheric Administration's National Climatic Data Center in Asheville, NC.

UNITED STATES DEPARTMENT OF
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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

NOAA 98-1

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FOR IMMEDIATE RELEASE
1/8/98

1997 WARMEST YEAR OF CENTURY, NOAA REPORTS

1997 was the warmest year of this century, based on land and ocean surface temperature data, reports a team of scientists from the National Oceanic and Atmospheric Administration's National Climatic Data Center in Asheville, N. C.

Led by the center's Senior Scientist Tom Karl, the team analyzed temperatures from around the globe during the years 1900 to 1997 and back to 1880 for land areas. For 1997, land and ocean temperatures averaged three-quarters of a degree Fahrenheit above normal. (Normal is defined by the mean temperature, 61.7 degrees F, for the 30-years 1961-90.) The 1997 figure exceeds the previous record warm year, 1990, by 0.15 degrees Fahrenheit.

The record-breaking warm conditions of 1997 continues the pattern of very warm global temperatures. Nine of the past eleven years have been the warmest on record.

"Land temperatures did not break the previous record set in 1990, but 1997 was one of the five warmest years since 1880," said Karl. Including 1997, the top ten warmest years over the land have all occurred since 1981, and the warmest five years all since 1990. Land temperatures for 1997 averaged three-quarters of a degree above normal, falling short of the 1990 record by one-quarter of a degree.

Ocean temperatures during 1997 also averaged three-quarters of a degree above normal, which makes it the warmest year on record, exceeding the previous record warm years of 1987 and 1995 by 0.3 of a degree Fahrenheit.

With the new data factored in, global temperature warming trends now exceed 1.0 degree Fahrenheit per 100 years, with land temperatures warming at a somewhat faster rate. "It is likely that the sustained trend toward increasingly warmer global temperatures is related to anthropogenic increases in greenhouse gases," Karl said.

###

Joseph E. Aldy
07/19/98 10:43:35 PM

Record Type: Record

To: Matthew C. Weinzierl/CEA/EOP

cc:
Subject: annotated input on aldy questions

Below you will find Rosina's comments on some of the outstanding issues in the report. I would appreciate it if you could follow up on a couple of these:

On #2, could you copy pp. 28, 37 of the Working Group I report (science) -- this should have the quotes Rosina references.

On #3, could you check figure 12 and see if it has CO2 ppm of 710 in 2100.

On #4, could you read Gibbons testimony (see my Admin Testimonies binder on the right wall of my office; Gibbons testified at the 2/12 hearing) and find/copy the part of his testimony that says this.

Could you also print out Rosina's email and include that in our fact-check binder.

Thanks,

Joe

---------------------- Forwarded by Joseph E. Aldy/CEA/EOP on 07/19/98 10:33 PM ---------------------------

Rosina M. Bierbaum 07/17/98 07:33:19

Record Type: Record

To: Joseph E. Aldy/CEA/EOP

cc: Peter W. Backlund/OSTP/EOP
Subject: annotated input on aldy questions

More on Monday
1. p. 9, continual measurements of atmospheric CO2 at Mauna Loa began in 1957. The data set we received from the CDIAC web page for Keeling and Whorf's work indicates that the period of the record is 1958-1996. One of our interns spoke with Keeling today who told us the measurement at Mauna Loa began in 1958 (while measurement at the South Pole began in 1957). Is your understanding that 1957 or 1958 is the right year? ***March '58***

2. p. 10, the 1990's will be the warmest decade for at least the past 600 years. I read the Mann et al paper last night, and they do not make this point. The paragraph in our report refers to global average annual temperature, while the Mann et al results that are related to this statement are based on analyses of northern hemisphere climate/temperature proxies since 1400. Further, the authors note simply that 3 years in this decade are "hotter" than any others with a statistical significance at the 99.7% level (pp. 783-784 of Nature article). I did not see any statistical tests by decade to determine if the 1990's (or the past ten years) are "hotter" than any decade in the constructed temperature record. I think we have two options: 1) cite this paper, and use a line like "A recent study indicates that the Northern Hemisphere appears to have experienced its three warmest years since 1400 during the present decade"; or 2) make a reference to the historical temperature record, where I believe we can say something like "The 1990's will likely be the warmest decade on record." If we go with the second option, we will need a paper to back it up. Note that this appears to be related to the reference to this century being the hottest since 1400 on p. i of the Executive Summary. ***ipcc wg1 spm (p. 32) says" As an average over the Northern Hemisphere for summer, recent decades appear to be the warmest since at least 1400 from the limited available evidience." It also says "Ice core data from several sites suggest that the 20th century is at least as warm as any century in the past 600 years, although the recent warming is not exceptional everywhere." So these are two separate points that can be cited, and then Mann et al could be used to speak about the 1990's. See also memo developed for POTUS by NOAA/USGCRP in next e-mail***

3. p. 10, Figure 12, CO2 Concentration in 2100 under IS92a scenario. As I understand from our RA who used to work on the charts (he left CEA last week as a part of the annual CEA summer turnover), we do not have the exact value for the 2100 CO2 concentration. Do you have any paper that indicates explicitly the CO2 concentration in 2100 in the IS92a scenario? ***i forwarded wigley's and Mike M's answer on this to you, which is that ipcc did not publish a number. But, 710 was the number the IPCC and the GCRP leadership agreed we should cite.***

4. pp. 10-11, Earth has not experienced CO2 concentrations at 700 ppm for 50 million years. We could not find the reference to this in the Berner 1994. If someone on your staff who is familiar with this paper or this reference could point it out for us, I would appreciate it ***Hope Peter sent you the file we have on this. You can cite Jack Gibbon's testimony***

5. p. 11, thermal lag and sea level rise from a doubling of CO2. In reading the Manabe and Stouffer papers, it appears that the 1% concentration increase per annum to 2xCO2 refers to a doubling of pre-industrial, not current CO2 concentration. While the authors appear to not explicitly state the concentration that serves as their starting point, they do call it the "normal value" (Manabe and Stouffer 1993, p. 215) and the "initial condition, which is in a quasi-equilibrium state" (Manabe and Stouffer 1994, p. 6). I have interpreted these to mean pre-industrial. If I have missed the reference to the exact concentration they use as their starting point, or have misinterpreted this, please let me know. If not, then we will change the reference to approximately twice pre-industrial (about 560 ppm) from approximately 700. Further, their analysis tends to indicate that a 1% concentration increase per annum to 2xCO2 would reach this concentration in 70 years, stabilize through 500 years, and in total result in a 1 meter sea level rise, not an additional 1m rise after 2100 (Manabe and Stouffer 1993, p. 216; Manabe and Stouffer 1994, p. 9 and Figure 3). Below is how I propose to rewrite the second half of this paragraph:

"Even if greenhouse gas concentrations were stabilized at about 560 ppm (double pre-industrial concentration) within the next century, the sea level would continue to rise for several centuries because of the large inertia in the coupled ocean-atmosphere-climate system (Warrick et al. 1996). If the carbon dioxide concentration were to increase 1% per year until it reached approximately 560 ppm, and then were to stabilize, the sea level would continue to rise from thermal expansion alone (Manabe and Stouffer 1993, 1994)."

This is ok,

Climate Change 1995

The Science of Climate Change

Edited by J.T. Houghton,
L.G. Meira Filho, B.A. Callander, N. Harris,
A. Kattenberg and K. Maskell

Production Editor: J.A. Lakeman

Contribution of WGI to the Second Assessment Report
of the Intergovernmental Panel on Climate Change

Published for the Intergovernmental Panel on Climate Change

CAMBRIDGE
UNIVERSITY PRESS

term events such as volcanic eruptions and El Niño are taken into account. After adjustment for these transient effects, both tropospheric and surface data show slight warming (about 0.1°C per decade for the troposphere and nearly 0.2°C per decade at the surface) since 1979.

Cooling of the lower stratosphere has been observed since 1979 both by satellites and weather balloons, as noted in IPCC (1992) and IPCC (1994). Current global mean stratospheric temperatures are the coldest observed in the relatively short period of the record. Reduced stratospheric temperature has been projected to accompany both ozone losses in the lower stratosphere and atmospheric increases of carbon dioxide.

C.2 Is the 20th century warming unusual?

In order to establish whether the 20th century warming is part of the natural variability of the climate system or a response to anthropogenic forcing, information is needed on climate variability on relevant time-scales. As an average over the Northern Hemisphere for summer, recent decades appear to be the warmest since at least 1400 from the limited available evidence (Figure 10). The warming over the past century began during one of the colder periods of the last 600 years. Prior to 1400 data are insufficient to provide hemispheric temperature estimates. Ice core data from several sites suggest that the 20th century is at least as warm as any century in the past 600 years, although the recent warming is not exceptional everywhere.

Large and rapid climatic changes occurred during the last glacial period (around 20,000 to 100,000 years ago) and during the transition period towards the present interglacial (the last 10,000 years, known as the Holocene). Changes in annual mean temperature of about 5°C occurred over a few decades, at least in Greenland and the North Atlantic, and were probably linked to changes in oceanic circulation. These rapid changes suggest that climate may be quite sensitive to internal or external climate forcings and feedbacks. The possible relevance of these rapid climate changes to future climate is discussed in Section F.5.

Temperatures have been less variable during the last 10,000 years. Based on the incomplete evidence available, it is unlikely that global mean temperatures have varied by more than 1°C in a century during this period.

C.3 Has the climate become wetter?

As noted in IPCC (1992), precipitation has increased over land in high latitudes of the Northern Hemisphere, especially during the cold season. A step-like decrease of precipitation occurred after the 1960s over the subtropics and tropics from Africa to Indonesia. These changes are consistent with changes in streamflow, lake levels and soil moisture (where data analyses are available). Precipitation, averaged over global land areas, increased from the start of the century up to about 1960. Since about 1980 precipitation over land has decreased (Figure 11).

There is evidence to suggest increased precipitation over the central equatorial Pacific Ocean in recent decades, with decreases to the north and south. Lack of data prevents us from reaching firm conclusions about other precipitation changes over the ocean.

Estimates suggest that evaporation may have increased over the tropical oceans (although not everywhere) but decreased over large portions of Asia and North America. There has also been an observed increase in atmospheric water vapour in the tropics, at least since 1973.

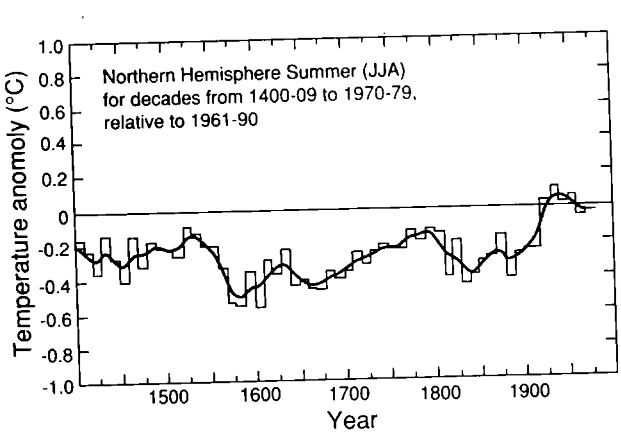

Figure 10: Decadal summer (June to August) temperature index for the Northern Hemisphere (to 1970–1979) based on 16 proxy records (tree-rings, ice cores, documentary records) from North America, Europe and East Asia. The thin line is a smoothing of the same data. Anomalies are relative to 1961 to 1990.

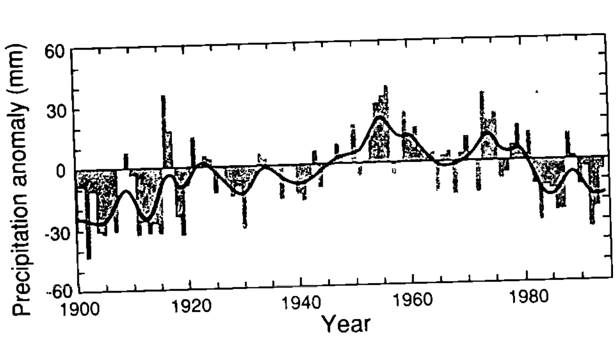

Figure 11: Changes in land-surface precipitation averaged over regions between 55°S and 85°N. Annual precipitation departures from the 1961–90 period are depicted by the hollow bars. The continuous curve is a smoothing of the same data.

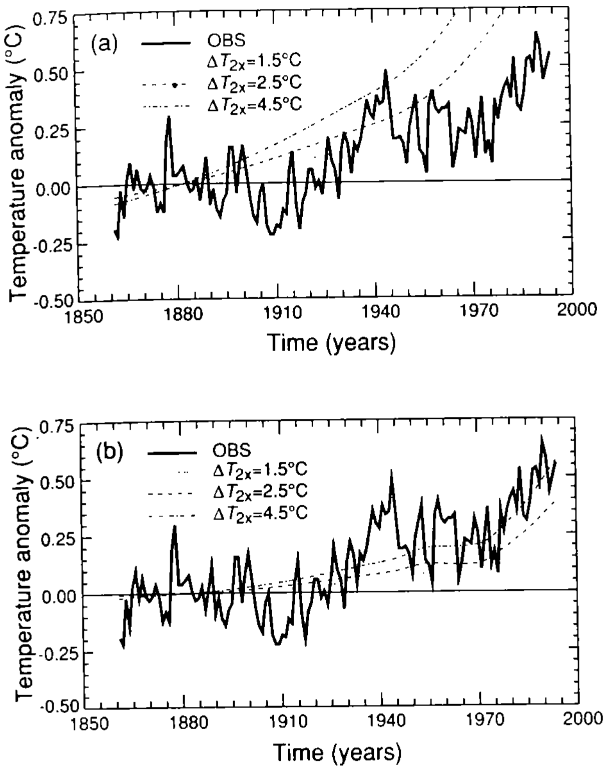

Figure 16: Observed changes in global mean temperature over 1861 to 1994 compared with those simulated using an upwelling diffusion-energy balance climate model. The model was run first with forcing due to greenhouse gases alone (a) and then with greenhouse gases and aerosols (b).

the model-observed correspondence in these experiments occurs at the largest spatial scales – for example, temperature differences between hemispheres, land and ocean, or the troposphere and stratosphere. Model predictions are more reliable at these spatial scales than at the regional scale. Increasing confidence in the identification of a human-induced effect on climate comes primarily from such pattern-based work. For those seasons during which aerosol effects should be most pronounced the pattern correspondence is generally higher than that achieved if model predictions are based on changes in greenhouse gases alone (Figure 17).

As in the global mean studies, pattern-oriented detection work relies on model estimates of internal natural variability as the primary yardstick for evaluating whether observed changes in temperature patterns could be due to natural causes. Concerns remain regarding the reliability of this yardstick.

E.5 Qualitative consistency

In addition to quantitative studies, there are broad areas of qualitative agreement between observations and those model predictions that either include aerosol effects or do not depend critically on their inclusion. As in the quantitative studies, one must be cautious in assessing consistency because the expected climate change signal due to human activities is still uncertain, and has changed as our ability to model the climate system has improved. In addition to the surface warming, the model and observed commonalities in which we have most confidence include stratospheric cooling, reduction in diurnal temperature range, sea level rise, high latitude precipitation increases and water vapour and evaporation increase over tropical oceans.

E.6 Overall assessment of the detection and attribution issues

In summary, the most important results related to the issues of detection and attribution are:

- The limited available evidence from proxy climate indicators suggests that the 20th century global mean temperature is at least as warm as any other century since at least 1400 AD. Data prior to 1400 are too sparse to allow the reliable estimation of global mean temperature (see Section C.2).

- Assessments of the statistical significance of the observed global mean temperature trend over the last century have used a variety of new estimates of natural internal and externally forced variability. These are derived from instrumental data, palaeodata, simple and complex climate models, and statistical models fitted to observations. Most of these studies have detected a significant change and show that the observed warming trend is unlikely to be entirely natural in origin.

- More convincing recent evidence for the attribution of a human effect on climate is emerging from pattern-based studies, in which the modelled climate response to combined forcing by greenhouse gases and anthropogenic sulphate aerosols is compared with observed geographical, seasonal and vertical patterns of atmospheric temperature change. These studies show that such pattern correspondences increase with time, as one would expect as an anthropogenic signal increases in strength. Furthermore, the probability is very low that these correspondences could occur by chance as a result of natural internal variability only. The vertical patterns

Global-scale temperature patterns and climate forcing over the past six centuries

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† Laboratory of Tree Ring Research, University of Arizona, Tucson, Arizona 85721, USA

Spatially resolved global reconstructions of annual surface temperature patterns over the past six centuries are based on the multivariate calibration of widely distributed high-resolution proxy climate indicators. Time-dependent correlations of the reconstructions with time-series records representing changes in greenhouse-gas concentrations, solar irradiance, and volcanic aerosols suggest that each of these factors has contributed to the climate variability of the past 400 years, with greenhouse gases emerging as the dominant forcing during the twentieth century. Northern Hemisphere mean annual temperatures for three of the past eight years are warmer than any other year since (at least) AD 1400.

Knowing both the spatial and temporal patterns of climate change over the past several centuries remains a key to assessing a possible anthropogenic impact on post-industrial climate[1]. In addition to the possibility of warming due to increased concentrations of greenhouse gases during the past century, there is evidence that both solar irradiance and explosive volcanism have played an important part in forcing climate variations over the past several centuries[2,3]. The unforced 'natural variability' of the climate system may also be quite important on multidecadal and century timescales[4,5]. If a faithful empirical description of climate variability could be obtained for the past several centuries, a more confident estimation could be made of the roles of different external forcings and internal sources of variability on past and recent climate. Because widespread instrumental climate data are available for only about one century, we must use proxy climate indicators combined with any very long instrumental records that are available to obtain such an empirical description of large-scale climate variability during past centuries. A variety of studies have sought to use a 'multiproxy' approach to understand long-term climate variations, by analysing a widely distributed set of proxy and instrumental climate indicators[1,5–8] to yield insights into long-term global climate variations. Building on such past studies, we take a new statistical approach to reconstructing global patterns of annual temperature back to the beginning of the fifteenth century, based on the calibration of multiproxy data networks by the dominant patterns of temperature variability in the instrumental record.

Using these statistically verifiable yearly global temperature reconstructions, we analyse the spatiotemporal patterns of climate change over the past 500 years, and then take an empirical approach to estimating the relationship between global temperature changes, variations in volcanic aerosols, solar irradiance and greenhouse-gas concentrations during the same period.

Data

We use a multiproxy network consisting of widely distributed high-quality annual-resolution proxy climate indicators, individually collected and formerly analysed by many palaeoclimate researchers (details and references are available: see Supplementary Information). The network includes (Fig. 1a) the collection of annual-resolution dendroclimatic, ice core, ice melt, and long historical records used by Bradley and Jones[6] combined with other coral, ice core, dendroclimatic, and long instrumental records. The long instrumental records have been formed into annual mean anomalies relative to the 1902–80 reference period, and gridded onto a 5° × 5° grid (yielding 11 temperature grid-point series and 12 precipitation grid-point series dating back to 1820 or earlier) similar to that shown in Fig. 1b. Certain densely sampled regional dendroclimatic data sets have been represented in the network by a smaller number of leading principal components (typically 3–11 depending on the spatial extent and size of the data set). This form of representation ensures a reasonably homogeneous spatial sampling in the multiproxy network (112 indicators back to 1820).

Potential limitations specific to each type of proxy data series must be carefully taken into account in building an appropriate network. Dating errors in a given record (for example, incorrectly assigned annual layers or rings) are particularly detrimental if mutual information is sought to describe climate patterns on a year-by-year basis. Standardization of certain biological proxy records relative to estimated growth trends, and the limits of constituent chronology segment lengths (for example, in dendroclimatic reconstructions), can restrict the maximum timescale of climate variability that is recorded[9], and only a limited subset of the indicators in the multiproxy network may thus 'anchor in' the longest-term trends (for example, variations on timescales greater than 500 years). However, the dendroclimatic data used were carefully screened for conservative standardization and sizeable segment lengths. Moreover, the mutual information contained in a diverse and widely distributed set of independent climate indicators can more faithfully capture the consistent climate signal that is present, reducing the compromising effects of biases and weaknesses in the individual indicators.

Monthly instrumental land air and sea surface temperature[10] grid-point data (Fig. 1b) from the period 1902–95 are used to calibrate the proxy data set. Although there are notable spatial gaps, this network covers significant enough portions of the globe to form reliable estimates of Northern Hemisphere mean temperature, and certain regional indices of particular importance such as the 'NINO3' eastern tropical Pacific surface temperature index often used to describe the El Niño phenomenon. The NINO3 index is constructed from the eight grid-points available within the conventional NINO3 box (5° S to 5° N, 90–150° W).

Multiproxy calibration

Although studies have shown that well chosen regional paleoclimate reconstructions can act as surprisingly representative surrogates for

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Vostok ice core provides 160,000-year record of atmospheric CO_2

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† Arctic and Antarctic Research Institute, Beringa Street 38, Leningrad 199226, USSR

Direct evidence of past atmospheric CO_2 changes has been extended to the past 160,000 years from the Vostok ice core. These changes are most notably an inherent phenomenon of change between glacial and interglacial periods. Besides this major 100,000-year cycle, the CO_2 record seems to exhibit a cyclic change with a period of some 21,000 years.

ALTHOUGH the first direct CO_2 measurements in the atmosphere were made in the second half of the nineteenth century, atmospheric CO_2 variations have been monitored in a systematic and reliable manner only since 1958. Fortunately, nature has been taking continuous samples of the atmosphere at the surface of the ice sheets throughout the ages. This natural sampling process takes place when snow is transformed into ice by sintering at the surface of the melt-free zones of the ice sheets, with air becoming isolated from the surrounding atmosphere in the pores of the newly formed ice. After pore closure the gas remains stored in the ice moving within the ice sheet. During this natural air sampling and storage process, different mechanisms could alter the original atmospheric composition[1,2]. But by choosing appropriate sampling sites, ice cores (for example see ref. 1) and experimental methods[3], past CO_2 changes in the atmosphere can be determined with high confidence by analysing the air enclosed in the pores of the ice.

Previous results from ice-core analysis have already provided important reliable information on the 'pre-industrial' CO_2 level and the recent CO_2 increase induced by anthropogenic activities[4-6]. Striking CO_2 changes have also been detected in this way in the ice record covering the last 30-40 kyr[7-10], including the large CO_2 increase associated with the climatic shift from the Last Glacial Maximum (~18 kyr BP) to the Holocene.

Because of the extremely low temperatures at Vostok (present-day mean annual temperature is −55.5 °C) and the good core quality, the 2,083-m-long ice core recovered by the Soviet Antarctic Expeditions at Vostok (East Antarctica) provides a unique opportunity to extend the ice record of atmospheric CO_2 over the last glacial-interglacial cycle back to the penultimate ice age about 160 kyr ago[11]. Over this timescale a high correlation is found between CO_2 concentrations and Antarctic climate, with significant oscillatory behaviour of CO_2 between high levels during interglacial and low levels during glacial periods. The CO_2 record also seems to exhibit a cyclic change with a period of ~21 kyr, that is, around the orbital period corresponding to the precession.

Experimental procedure

Gas extraction and measurements were performed with the 'Grenoble analytical setup' described by Barnola *et al.*[12]. The method is based on crushing the ice under vacuum without melting, expanding the gas released during the crushing in a pre-evacuated sampling loop, and analysing the CO_2 concentrations by gas chromatography.

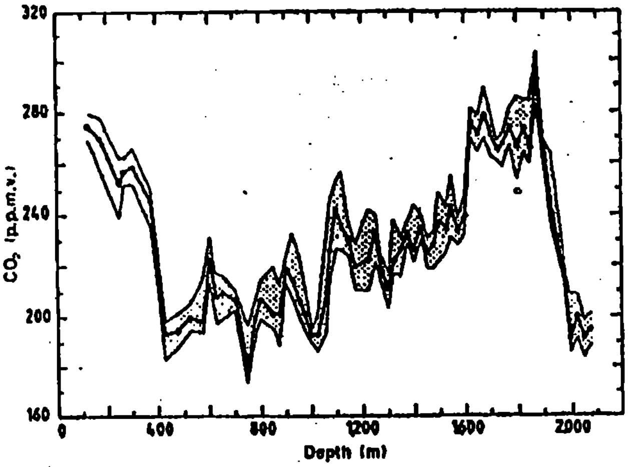

Fig. 1 CO_2 concentrations (p.p.m.v.) plotted against depth in the Vostok ice core. The 'best estimates' of the CO_2 concentrations are indicated by dots and the envelope shown has been plotted taking into account the different uncertainty sources.

The analytical system, except for the stainless steel container in which the ice is crushed, is calibrated for each ice sample measurement with a standard mixture of CO_2 in nitrogen and oxygen. The corresponding accuracy (2σ) is evaluated from the standard deviation of the residuals corresponding to the calibration regression and ranges from 3 to 12 parts per million by volume (p.p.m.v.) for the measurements presented in this article.

We recently discovered an additional error due to our experimental system when a significant amount of water vapour is detected by the gas chromatograph. In such a case, selective CO_2 transport by water vapour (similar to that observed by Neftel *et al.*[4]) back to the ice crushing container is suspected of depleting the CO_2 from the air extracted from the ice and injected

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Climate Change Over the Next 100 Years

Where is the climate headed? If the world proceeds on a "business as usual" path, atmospheric CO_2 concentrations will likely be more than 700 ppm by 2100, and they will still be rising. This is nearly double the current level and much more than double the preindustrial level of 280 ppm (Figure 10). State-of-the-art climate models suggest that this will result in an increase of about 3.5° F in global temperatures over the next century. This would be a rate of climate change not seen on the planet for at least the last 10,000 years. It is the combined threat of elevated concentrations of greenhouse gases and this unprecedented rate of increase that causes great concern.

What are the projected extent and pattern of warming over the globe? The higher latitude regions will warm relatively more than areas nearer to the equator. The land surface will warm more than the oceans, and there will be less variation in temperature from night to day.

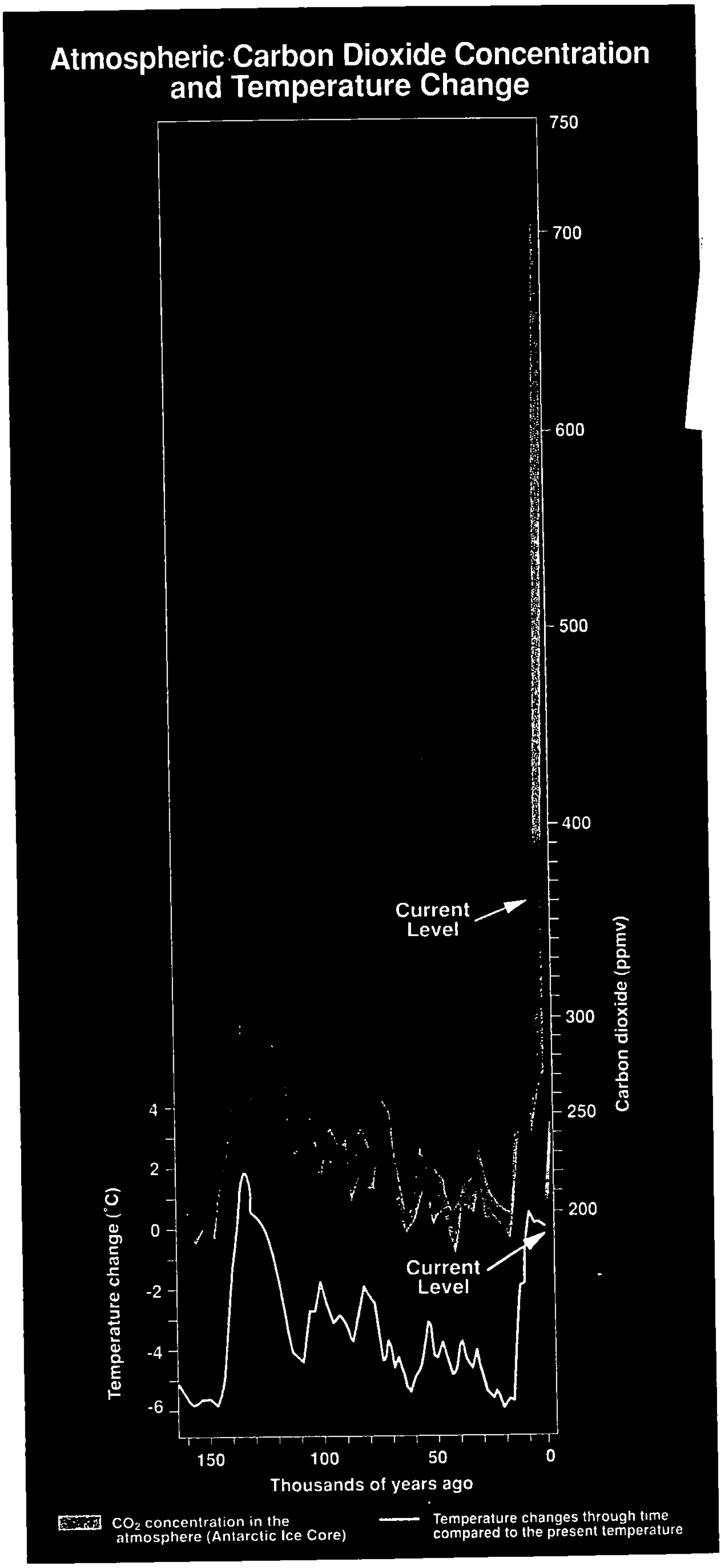

Figure 10. The CO_2 level has increased sharply since the beginning of the Industrial Era and is already outside the bounds of natural variability seen in the climate record of the last 160,000 years. Continuation of current levels of emissions will raise concentrations to over 700 ppm by 2100, a level not experienced since about 50 million years ago.

and fresh and wastewater treatment and distribution. This infrastructure is extremely vulnerable to extreme weather events. I want to emphasize that one can't point to any single extreme weather event today and say for sure that global warming caused it. But we can say that such events are examples of the kinds of impacts we expect to occur with greater frequency in a warmer world. There are likely to be more "storms of the century," "100-year floods," and severe droughts in the future than there were in the past.

The temperature increases, intensification of the water cycle, and sea-level rise already observed over the past century are all consistent with theoretical predictions of the consequences of an enhanced greenhouse effect. They are also consistent with the projections from simulations of global climate by general circulation models.

The IPCC "business as usual" scenario indicates that even with continued technological improvement (such as energy efficiency increases of about 1 percent per year), unless policies to control emissions of greenhouse gases are implemented, the atmospheric concentrations of these gases will be much higher by 2100. Assuming "business as usual" CO_2 concentrations will reach about 710 parts per million by volume (ppm), a level higher than any seen on this planet in the last 50 million years (Figure 2). For context, the pre-industrial level of CO_2 was about 280 ppm, and has increased to the current level of about 360 ppm. If realized, this increase is expected to result in significant future climate changes:

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- Global surface temperature would increase an average of another 2-6 °F by 2100, with a best estimate of 3.5 °F. Higher Northern latitudes are projected to warm by more. Temperature change of this magnitude would be faster than any observed changes in the last 10,000 years.
- Global mean sea level would rise another 6 to 38 inches by the end of the 21st century.
- The rate of evaporation would increase as the climate warms, leading to an increase in average global precipitation as well as frequency of intense rainfall and floods in some regions. In some regions, the soil moisture will decrease, leading to increased frequency and intensity of droughts.

Most of the climate impacts have been evaluated for a world at equilibrium after greenhouse gases have reached either 550 or 700 ppm. But stabilizing at double the pre-industrial concentration of greenhouse gases, or 550 ppm, would require massive intervention. On the other hand, a continuation of "business as usual" implies a world with far higher concentrations and far greater effects. The Geophysical Fluid Dynamics Laboratory at Princeton has recently modeled the effects of doubling and quadrupling the level of greenhouse gases:

- A quadrupling of such concentrations (to about 1100 ppm) is likely to increase temperatures in North America by 15 - 20° F, as opposed to the 5-10° F expected from doubling.
- In the growing season, soil moisture deficits would approach 30 - 50 percent for quadrupling, as opposed to 10 - 30 percent for doubling.

TESTIMONY OF
JOHN H. GIBBONS
ASSISTANT TO THE PRESIDENT FOR SCIENCE AND TECHNOLOGY
BEFORE THE
COMMITTEE ON SCIENCE
UNITED STATES HOUSE OF REPRESENTATIVES

HEARING ON GLOBAL CLIMATE CHANGE
FEBRUARY 12, 1998

Introduction

Thank you for providing the opportunity to talk to you today about the U.S. Global Change Research Program's (USGCRP) current and planned activities. The best way to describe how these activities relate to the Kyoto Protocol is to describe the current state of scientific knowledge of climate change, a significant portion of which is the product of our Nation's strong support for the USGCRP since its inception.

The USGCRP began as a Presidential Initiative in 1989, and was codified by the Global Change Research Act of 1990. The program has been strongly backed by every Administration and Congress since its inception. The FY 1999 Budget Request demonstrates President Clinton's ongoing commitment to the program, with an overall request of approximately $1.86 billion dollars. The President and the Vice President believe that global change research is one of the foundations of a sustainable future. The Administration looks forward to working with the Congress to carry on this bipartisan tradition of support for sound science.

I want to emphasize that the planning of the USGCRP budget and research programs for this year, or any year, were not directly impacted by the Kyoto negotiations. The USGCRP is not a policy-driven program, but rather is driven by critical science questions and the need to develop a long term understanding of the scientific information that is of most relevance to U.S. policy makers. The results obtained through the sustained USGCRP research effort over the past decade have been very helpful in U.S. government climate change policy deliberations. As we look ahead to the next decade of global change research, it is apparent that much of the USGCRP research effort is addressing questions of ecological impacts and rates of change, both of which are relevant to the decisions the world must make about long term emissions trajectories beyond 2010.

The USGCRP, along with the global change research efforts supported by other countries such as Japan and the European nations, has provided the knowledge base for national and international decision making on climate change issues, both by providing research results directly to national governments and to the international process of the Intergovernmental Panel

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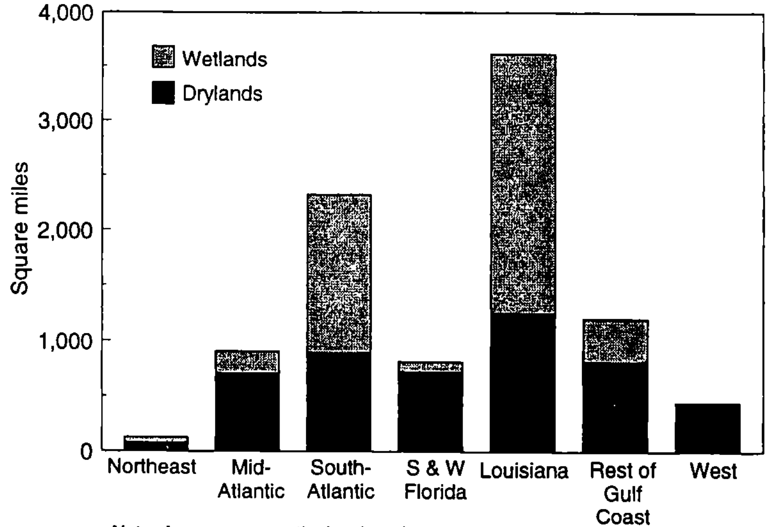
years ago (Berner 1994). It is anticipated that if the CO_2 levels increase to this level, then the global average temperature will rise by between 1.8 and 6.3° F by the year 2100 (Kattenberg et al. 1996). This range of temperature impacts was developed by the Intergovernmental Panel on Climate Change using a set of alternative plausible assumptions about climatic response to higher greenhouse gas concentrations, the effects of aerosols (such as sulfate particles) that can offset warming, and several economic parameters. In general, the temperature change experienced would be greater at higher latitudes than at lower latitudes, and greater over land than over the oceans (Kattenberg et al. 1996).

Global warming of the magnitude projected by the IPCC will have many effects due to changes in local temperature and precipitation patterns, an induced rise in sea level, and altered distribution of freshwater supplies. By 2100, sea level is expected to rise by 6 to 37 inches (Warrick et al. 1996). An average 20-inch sea level rise would result in substantial loss of coastal land in the United States especially along the southern Atlantic and Gulf Coasts, which are currently subsiding and are particularly vulnerable (Titus et al. 1991; Smith and Tirpak 1989; see Figure 13). Even if greenhouse gas concentrations were stabilized within the next century, the sea level would continue to rise for several centuries because of the large inertia in the coupled ocean-atmosphere-climate system (Warrick et al. 1996). For example, if the carbon dioxide concentration were to increase 1% per year until it reached approximately 700 ppm, roughly double the current level, and then were to stabilize, the sea level would continue to rise from thermal expansion alone. Several researchers estimate that after 500 years, the sea level would have risen one meter in addition to the rise experienced through 2100 due to thermal expansion of the ocean waters and would still be rising, even though the temperature changes had largely been stabilized (Manabe and Stouffer 1993, 1994).

Figure 13. U.S. Coastal Lands at Risk from a 20-inch Sea Level Rise in 2100



Note: Assumes currently developed areas are protected.
Source: Titus et al. 1991.

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Climate Models – Projections of Future Climate

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Modelling Contributors: see tables

SUMMARY

General circulation models (GCMs), and in particular coupled atmosphere-ocean general circulation models (AOGCMs), are the state-of-the-art tool for understanding the Earth's present climate, and for estimating the effects on past and future climate of various natural and human factors. This chapter focuses on the estimation of the effects on future climate of changes in atmospheric composition due to human activities. An important development since IPCC(1990) is the improved quantification of some radiative effects of aerosols, and climate projections presented here include, in addition to the effects of increasing greenhouse gas concentrations, some potential effects of anthropogenic aerosols.

Climate simulations using GCMs require substantial computer resources and it is not generally feasible to carry out separate simulations for a large number of forcing scenarios. In order to interpolate and extrapolate global mean projections from GCMs to a wider range of greenhouse gas and aerosol scenarios, simple upwelling diffusion-energy balance models are employed. These models are calibrated to give the same globally averaged temperature response as the global coupled GCMs. Since the amount of anthropogenic aerosols has most probably grown alongside the growth in fossil fuel use since pre-industrial times, the estimated historical changes of radiative forcing up to 1990 used in this report for global mean temperature projections include a component due to aerosols.

Projections of global mean temperature

Using the IS92 emission scenarios, projected global mean temperature changes were calculated up to 2100 assuming low (1.5°C), "best estimate" (2.5°C) and high (4.5°C) values of the climate sensitivity (similar to IPCC (1990)). Taking account of increases of greenhouse gas concentrations alone (i.e., assuming aerosol concentrations remain constant at 1990 levels) the models project an increase in global mean temperature relative to the present of between 1 and 4.5°C by 2100 for the full range of IPCC scenarios. These projections are lower than the corresponding projections presented in IPCC (1990) partly because of the inclusion of aerosols in the pre-1990 radiative forcing history and partly for other reasons, including revised understanding of the carbon cycle (see Chapter 2). Incorporating possible effects of future changes of anthropogenic aerosol concentrations implied by the IS92 scenarios leads to lower projections of temperature change of between 1°C and 3.5°C by 2100. In all cases these projections would represent a substantial warming of climate. Uncertainty in the projections is introduced by uncertainty in the climate sensitivity and by uncertainty in the radiative forcing scenarios.

Projections of continental scale climate change

Spatial patterns of climate change in recent publications tend to confirm and extend the 1990 results. With increasing greenhouse gases, the warming of the land is generally more than that of the oceans, similar to equilibrium simulations. There is a minimum warming around Antarctica and in the northern North Atlantic which is associated with deep oceanic mixing in those areas. The maximum annual mean warming occurs in high northern latitudes associated with reduced sea ice cover. The warming here is largest in late autumn and winter, but becomes negligible for a short period in summer. There is little seasonal variation of the warming in low latitudes or over the southern circumpolar ocean. The diurnal range of land temperature is reduced in most seasons and most regions.

Including the effects of aerosols in simulations of future climate leads to a somewhat reduced warming in middle latitudes of the Northern Hemisphere and the maximum winter warming in high northern latitudes is less extensive.

All models produce an increase in global mean precipitation. If the direct effect of sulphate aerosol forcing is taken into account, the total increase in global precipitation is smaller, as would be expected with the smaller net warming. Precipitation increases in high latitudes in winter and in most cases the increases extend well into mid-latitudes. In the tropics, the patterns of

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transmission. This could result in 50 million to 80 million additional malaria cases per year worldwide by 2100.

Rising Sea Level - Rising sea level erodes beaches and coastal wetlands, inundates low-lying areas, and increases the vulnerability of coastal areas to flooding from storm surges and intense rainfall. By 2100, sea level is expected to rise by 6 to 37 inches. A 20-inch sea level rise will result in substantial loss of coastal land in the United States, especially along the southern Atlantic and Gulf coasts, which are subsiding and are particularly vulnerable. The oceans will continue to expand for several centuries after temperatures stabilize. Because of this, the sea level rise associated with CO_2 levels of 550 ppm (double pre-industrial levels) could eventually exceed 40 inches. A CO_2 level of 1100 ppm could produce a sea level rise of 80 inches or even more, depending on the extent to which the Greenland and Antarctic ice sheets melt.

- A 20-inch sea level rise would double the global population at risk from storm surges, from roughly 45 million at present to over 90 million, and this figure does not account for any increases in coastal populations. A 40-inch rise would triple the number.

- South Florida is highly vulnerable to sea level rise (Figure 16). A third of the Everglades has an elevation of less than 12 inches. Salt water intrusion would adversely affect delicate ecological communities and degrade the habitat for many species.

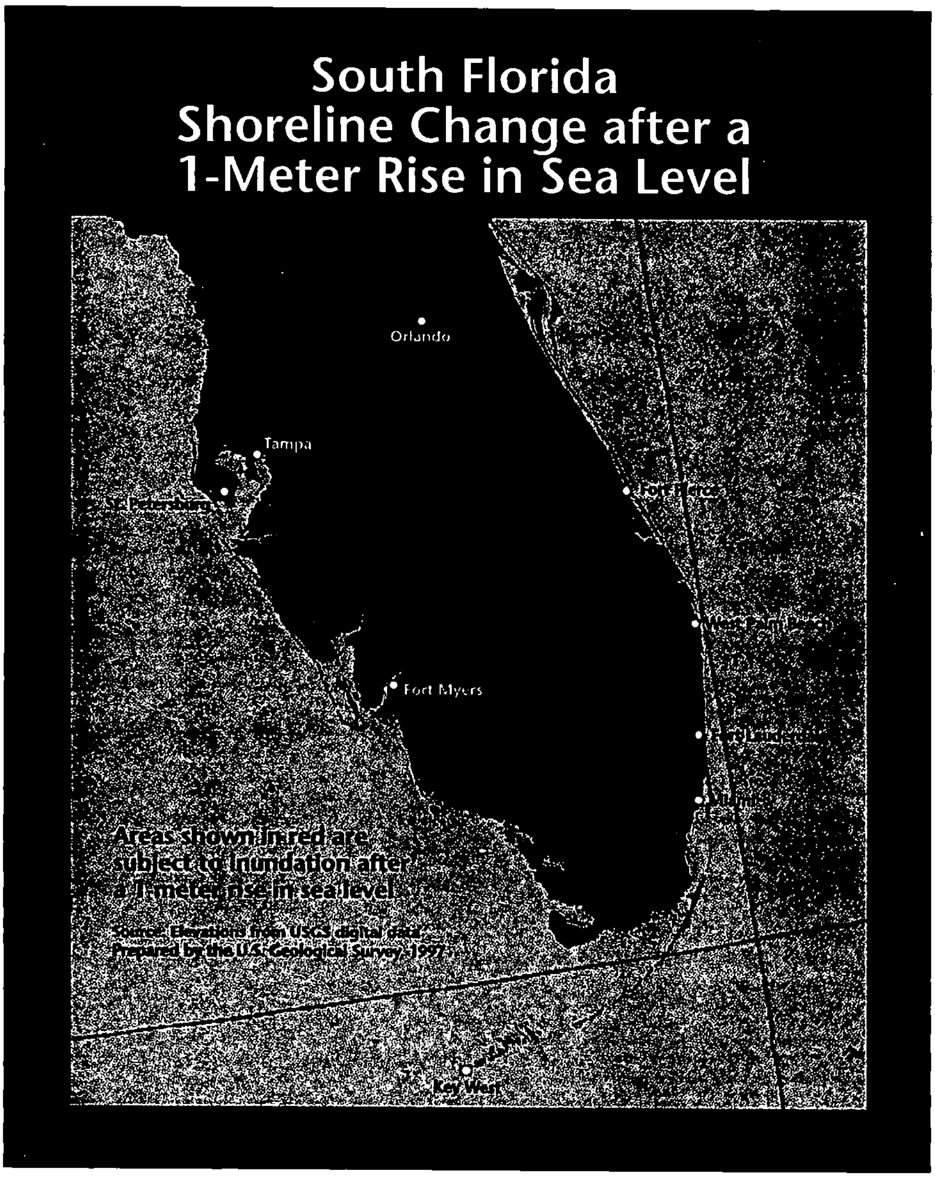

Figure 16. Sea level rise could inundate many low-lying coastal areas in Florida, and will increase the vulnerability of all such areas to storm surges.

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Changes in Sea Level

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P.L. WOODWORTH

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which tend to raise sea level. However, the potential future effect on sea level from such sources is probably relatively small, of the order of a few centimetres during the next century.

An exact accounting of the past sea level rise is difficult, particularly in the light of the large uncertainties associated with the mass balances of the ice sheets. However, the observed rise lies well within the combined ranges of uncertainty of the above factors.

Projections of future changes in sea level as a consequence of greenhouse-gas-induced warming were made for each of the six IPCC IS92 emission scenarios, with and without the effect of aerosol changes after 1990, for the period 1990 to 2100. In addition, high, middle and low estimates, using a range of parameter values based on key model uncertainties, were made for IS92a (the emission scenario most comparable to the IPCC (1990) Scenario A, the so-called "Business-as-usual" scenario). The results showed that:

- for Scenario IS92a, sea level is projected to be about 50 cm higher than today by the year 2100, with a range of uncertainty of 20–86 cm;

- for the range of emission scenarios IS92a–f using "best-estimate" model parameters, sea level is projected to be 38–55 cm higher than today by the year 2100;

- the extreme range of projections, taking into account both emission scenarios and model uncertainties, is 13–94 cm;

- most of the projected rise in sea level is due to thermal expansion, followed by increased melting of glaciers and ice caps. On this time-scale, the contributions made by the major ice sheets are relatively minor, but are a major source of uncertainty.

It is evident that the choice of emission scenario makes relatively little difference to the projected rise in sea level, especially for the first half of the next century. This is because much of the rise has already been determined by past changes in radiative forcing, due to lags in the response of the oceans and ice masses. For this same reason, in model simulations sea level continues to rise over many centuries even after concentrations of greenhouse gases are stabilised. In contrast, the scientific uncertainties – as reflected partly in intra-model uncertainties in the choice of individual model parameter values, and partly in inter-model uncertainties in the choice of methods for climate, glacier and ice sheet modelling – make a very large difference in the estimate of future sea level rise.

A major source of uncertainty concerns the polar ice sheets. Not only is there a lack of understanding of the current mass balance, but there is also considerable uncertainty regarding the possible dynamic responses on time-scales of centuries. Concern has been expressed that the West Antarctic Ice Sheet might "surge", causing a rapid rise in sea level. The current lack of knowledge regarding the specific circumstances under which this might occur, either in total or in part, limits the ability to quantify the risk. Nonetheless, the likelihood of a major sea level rise by the year 2100 due to the collapse of the West Antarctic Ice Sheet is considered low.

The changes in future sea level will not occur uniformly around the globe. Recent coupled atmosphere-ocean model experiments suggest that the regional responses could differ significantly, due to regional differences in heating and circulation changes. In addition, geological and geophysical processes cause vertical land movements and thus affect relative sea levels on local and regional scales. Finally, extreme sea level events – tides, waves and storm surges – could be affected by regional climate changes but are, at present, difficult to predict.

Overall, the basic understanding of climate-sea level relationships has not changed fundamentally since IPCC (1990). The estimates of global sea level rise presented here are lower than those presented in IPCC (1990), due primarily to significantly lower estimates of global *temperature* change which drive the projections of sea level rise. Thus, if global warming were to occur more rapidly than expected, the rate of sea level rise would consequently be higher.

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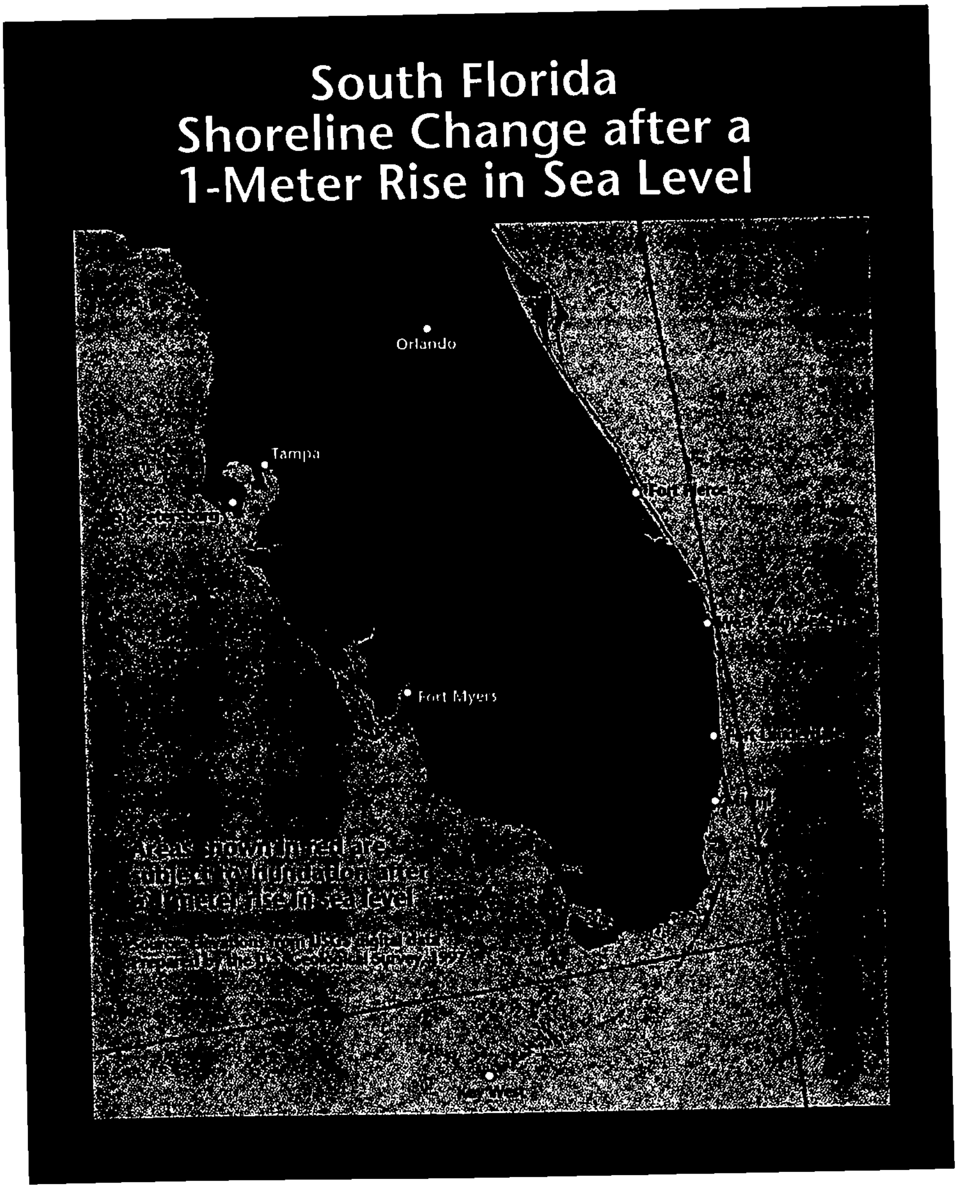

Figure 16. Sea level rise could inundate many low-lying coastal areas in Florida, and will increase the vulnerability of all such areas to storm surges.

By

James G. Titus, Richard A. Park, Stephen P. Leatherman,

J. Richard Weggel, Michael S. Greene, Paul W. Mausel,

Scott Brown, Cary Gaunt, Manjit Trehan, and Gary Yohe

ABSTRACT

Previous studies suggest that the expected global warming from the greenhouse effect could raise sea level 50 to 200 centimeters (2 to 7 feet) in the next century or two. This article presents the first nationwide assessment of the primary impacts of such a rise on the United States: (1) the cost of protecting ocean resort communities by pumping sand onto beaches and gradually raising barrier islands in place; (2) the cost of protecting developed areas along sheltered waters through the use of levees (dikes) and bulkheads; and (3) the loss of coastal wetlands and undeveloped lowlands. The total cost for a one meter rise would be $270-475 billion, ignoring future development.

We estimate that if no measures are taken to hold back the sea, a one meter rise in sea level would inundate 14,000 square miles, with wet and dry land each accounting for about half the loss. The 1500 square kilometers (600-700 square miles) of densely developed coastal lowlands could be protected for approximately one to two thousand dollars per year for a typical coastal lot. Given high coastal property values, holding back the sea would probably be cost-effective.

The environmental consequences of doing so, however, may not be acceptable. Although the most common engineering solution for protecting the ocean coast--pumping sand--would allow us to keep our beaches, levees and bulkheads along sheltered waters would gradually eliminate most of the nation's wetland shorelines. To ensure the long-term survival of coastal wetlands, federal and state environmental agencies should begin to lay the groundwork for a gradual abandonment of coastal lowlands as sea level rises.

INTRODUCTION

At the turn of the century, scientific opinion regarding the practical implications of the greenhouse effect was sharply divided. Since the 1860s, people had known that by absorbing outgoing infrared radiation, atmospheric CO_2 keeps the earth warmer than it would otherwise be (Tyndall, 1863). Svante Arrhenius (1896), who coined the term "greenhouse effect," pointed out that the combustion of fossil fuels might increase the level of CO_2 in the atmosphere, and thereby warm the earth several degrees. Because the 19th century had experienced a cooling trend, however, others speculated that the oceans and plant life might gradually reduce CO_2 levels and cause an ice age (Barrel et al., 1919).

Throughout the first half of the 20th century, scientists generally recognized the significance of the greenhouse effect, but most thought that humanity was unlikely to substantially alter its impact on climate. The oceans contain 50 times as much CO_2 as the atmosphere, and physical laws governing the relationship between the concentrations of CO_2 in the oceans and in the atmosphere seemed to suggest that this ratio would remain fixed, implying that only 2 percent of the CO_2 released by human activities would remain in the atmosphere. This complacency, however, was shattered in 1957 when Revelle and Seuss (1957) demonstrated that the oceans could not absorb CO_2 as rapidly as humanity was releasing it: "Human beings are now carrying out a

THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES

REPORT TO CONGRESS

Editors: Joel B. Smith and Dennis Tirpak

United States Environmental Protection Agency
Office of Policy, Planning and Evaluation
Office of Research and Development

December 1989

Smith/Tirpak

Cost of Raising Barrier Islands

The data provided by Weggel focused only on elevating roads, buildings, and bulkheads. Thus, Titus and Greene do not consider the cost of replacing sewers, water mains, or buried cables. On the other hand, Weggel's cost factors assume that rebuilt roads would be up to engineering standards; it is possible that communities would tolerate substandard roads. In addition, the census data Titus and Greene used were only available for incorporated communities, many of which are part barrier island and part mainland; thus, the data provide only a rough measure of typical road density.

Sensitivity of Sand Costs to Increased Scarcity of Sand

Finally, Titus and Greene made no attempt to determine how realistic their assumption was that sand costs would increase by the same pattern nationwide as they would in Florida.

Results

Loss of Wetlands and Dryland

Table 7-4 illustrates 95% confidence intervals for the nationwide losses of wetlands and dryland. If all shorelines were protected, a 1-meter rise would result in a loss of 50 to 82% of U.S. coastal wetlands, and a 2-meter rise would result in a loss of 66 to 90%. If only the densely developed areas were protected, the losses would be 29 to 69% and 61 to 80% for the 1- and 2-meter scenarios, respectively. Except for the Northeast, no protection results in only slightly lower wetland loss than protecting only densely developed areas. Although the estimates for the Northeast, mid-Atlantic, the gulf regions outside Louisiana, and the Florida peninsula are not statistically significant (at the 95% confidence levels), results suggest that wetlands loss would be least in the Northeast and Northwest.

Table 7-4. Nationwide Loss of Wetlands and Dryland[a] (95% confidence intervals)

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	Square miles[b]			
	Baseline	50-cm rise	100-cm rise	200-cm rise
Wetlands				
Total protection	N.C.	4944-8077 (38-61)	6503-10843 (50-82)	8653-11843 (66-90)
Standard protection	1168-3341 (9-25)	2591-5934 (20-45)	3813-9068 (29-69)	4350-10995 (33-80)
No protection	N.C.	2216-5592 (17-43)	3388-8703 (26-66)	3758-10025 (29-76)
Dryland				
Total protection	0	0	0	0
Standard protection	1906-3510	2180-6147	4136-9186	6438-13496
No protection	N.C.	3315-7311	5123-10330	8791-15394

[a]Wetlands loss refers to vegetative wetlands only.
[b]Numbers in parentheses are percentages.
NC = Not calculated.
Source: Titus and Greene (Volume B).

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which tend to raise sea level. However, the potential future effect on sea level from such sources is probably relatively small, of the order of a few centimetres during the next century.

An exact accounting of the past sea level rise is difficult, particularly in the light of the large uncertainties associated with the mass balances of the ice sheets. However, the observed rise lies well within the combined ranges of uncertainty of the above factors.

Projections of future changes in sea level as a consequence of greenhouse-gas-induced warming were made for each of the six IPCC IS92 emission scenarios, with and without the effect of aerosol changes after 1990, for the period 1990 to 2100. In addition, high, middle and low estimates, using a range of parameter values based on key model uncertainties, were made for IS92a (the emission scenario most comparable to the IPCC (1990) Scenario A, the so-called "Business-as-usual" scenario). The results showed that:

- for Scenario IS92a, sea level is projected to be about 50 cm higher than today by the year 2100, with a range of uncertainty of 20–86 cm;
- for the range of emission scenarios IS92a–f using "best-estimate" model parameters, sea level is projected to be 38–55 cm higher than today by the year 2100;
- the extreme range of projections, taking into account both emission scenarios and model uncertainties, is 13–94 cm;
- most of the projected rise in sea level is due to thermal expansion, followed by increased melting of glaciers and ice caps. On this time-scale, the contributions made by the major ice sheets are relatively minor, but are a major source of uncertainty.

It is evident that the choice of emission scenario makes relatively little difference to the projected rise in sea level, especially for the first half of the next century. This is because much of the rise has already been determined by past changes in radiative forcing, due to lags in the response of the oceans and ice masses. For this same reason, in model simulations sea level continues to rise over many centuries even after concentrations of greenhouse gases are stabilised. In contrast, the scientific uncertainties – as reflected partly in intra-model uncertainties in the choice of individual model parameter values, and partly in inter-model uncertainties in the choice of methods for climate, glacier and ice sheet modelling – make a very large difference in the estimate of future sea level rise.

A major source of uncertainty concerns the polar ice sheets. Not only is there a lack of understanding of the current mass balance, but there is also considerable uncertainty regarding the possible dynamic responses on time-scales of centuries. Concern has been expressed that the West Antarctic Ice Sheet might "surge", causing a rapid rise in sea level. The current lack of knowledge regarding the specific circumstances under which this might occur, either in total or in part, limits the ability to quantify the risk. Nonetheless, the likelihood of a major sea level rise by the year 2100 due to the collapse of the West Antarctic Ice Sheet is considered low.

The changes in future sea level will not occur uniformly around the globe. Recent coupled atmosphere-ocean model experiments suggest that the regional responses could differ significantly, due to regional differences in heating and circulation changes. In addition, geological and geophysical processes cause vertical land movements and thus affect relative sea levels on local and regional scales. Finally, extreme sea level events – tides, waves and storm surges – could be affected by regional climate changes but are, at present, difficult to predict.

Overall, the basic understanding of climate-sea level relationships has not changed fundamentally since IPCC (1990). The estimates of global sea level rise presented here are lower than those presented in IPCC (1990), due primarily to significantly lower estimates of global *temperature* change which drive the projections of sea level rise. Thus, if global warming were to occur more rapidly than expected, the rate of sea level rise would consequently be higher.

scales of the disk correspond to those of the large-scale radio jets and lobes. For example, the kinetic timescale in which the radio jet structures change is about 10^6 yr, while the synchrotron lifetimes of radio regions range from $\sim 10^6$ yr for the hot spots to $\sim 10^8$ yr for the more extended lobes. Similarly, the total 'equipartition' energy in the lobes, $\sim 10^{57}$ erg, corresponds to the mass energy available in the disk: for a dust/gas ratio similar to our Galaxy, the disk mass is about 10^5 solar masses. Converted to energy at an efficiency of 1%, a value often assumed, this mass would yield 10^{57} erg.

These facts, combined with the alignment of the radio axis and disk spin axis, lead us to describe the feature seen in NGC4261 as the 'outer accretion disk' of the central active nucleus. The bright unresolved point at the centre of the disk probably represents thermal optical emission from the hot inner accretion disk. The outer disk supplies fuel by way of the inner disk to the central engine, probably a massive black hole, in quantities that determine the luminosity, size and orientation of the extended radio emission.

Hints of such features have been obtained earlier: a previous ground-based image of NGC4261 showed a small central dust region (~ 3" in diameter), but neither its size nor morphology could be accurately determined. Molecular radio observations[12] of Centaurus A have indicated the presence of rotating cold material in a rather larger region (~ 1 kpc). To our knowledge, however, the image presented here is the first of an accretion disk where size and structure can be directly associated with the results of nuclear activity.

On much larger scales, dust has been seen before in many other elliptical galaxies[9,13], as lanes, disks and filamentary structures. These structures, often assumed to be the remnants of a captured late-type galaxy, are generally 10 to 100 times larger than the disk shown here. Although their presence may be correlated statistically with nuclear activity, their dynamic and decay timescales are much longer than those associated with AGN phenomena.

If the disk is in simple circular rotation, measurements of the rotation curve at HST resolution should lead to an estimate of the central mass that is free from the ambiguities of estimates derived from the orbits of stars. Measurements of the turbulent velocities should help to constrain models of the nature of the angular momentum and mass transport in the disk[11]. □

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Century-scale effects of increased atmospheric CO_2 on the ocean–atmosphere system

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SEVERAL studies have addressed the likely effects of CO_2-induced climate change over the coming decades[1-10], but the longer-term effects have received less attention. Yet these effects could be very significant, as persistent increases in global mean temperatures may ultimately influence the large-scale processes in the coupled ocean–atmosphere system that are thought to play a central part in determining global climate. The thermohaline circulation is one such process — Broecker has argued[11] that it may have undergone abrupt changes in response to rising temperatures and ice-sheet melting at the end of the last glacial period. Here we use a coupled ocean–atmosphere climate model to study the evolution of the world's climate over the next few centuries, driven by doubling and quadrupling of the concentration of atmospheric CO_2. We find that the global mean surface air temperature increases by about 3.5 and 7 °C, respectively, over 500 years, and that sea-level rise owing to thermal expansion alone is about 1 and 2 m respectively (ice-sheet melting could make these values much larger). The thermal and dynamical structure of the oceans changes markedly in the quadrupled-CO_2 climate — in particular, the ocean settles into a new stable state in which the thermohaline circulation has ceased entirely and the thermocline deepens substantially. These changes prevent the ventilation of the deep ocean and could have a profound impact on the carbon cycle and biogeochemistry of the coupled system.

The model used here[8] consists of a general circulation model (GCM) of the atmosphere and oceans, and a simple model of land surfaces that includes the budgets of heat and water. It is a global model with realistic geography. The atmospheric GCM includes the seasonal variation of insolation, and predicted cloud over which depends only on the relative humidity. It has nine vertical finite difference levels. The horizontal distribution of predicted variables is represented by spherical harmonics (15 associated Legendre functions for each of 15 Fourier components) and by corresponding grid-point values. The oceanic GCM uses a finite difference technique with a regular grid system which has horizontal spacing (4.5° latitude) by (3.75° longitude) and 12 vertical levels. This model is similar to that of Bryan and Lewis[12], except that it mimics the effect of mesoscale eddies by the diffusion of potential temperature and salinity on isopycnal surfaces. The atmospheric and oceanic GCMs interact through the exchange of heat, water and momentum.

Assuming the temporal variations of atmospheric CO_2 in Fig. 1*a*, three 500-year integrations of the coupled model are done. One is a standard integration (S) in which the atmospheric CO_2 remains unchanged. In a second integration (4×C), the CO_2 concentration increases by 1% yr^{-1} (compound) (close to the 'business as usual' (BAU) radiative forcing rate obtained by the Intergovernmental Panel on Climate Change[13]; IPCC) until it reaches four times the normal value at about the 140th year and remains unchanged thereafter. In a third integration (2×C), the CO_2 concentration also increases at the rate of 1% yr^{-1} (compound) until it doubles around the 70th year and remains unchanged thereafter. By comparing the three integrations, one can evaluate the long-term impact of the doubling and quadrupling of atmospheric CO_2 on the coupled system.

The initial conditions for these integrations have realistic seasonal and geographical distributions of surface temperature, surface salinity and sea ice; the atmospheric and oceanic components of the model are nearly in equilibrium with these distributions. When the time integration of the model starts from this initial condition, the model climate rapidly drifts towards its own equilibrium state. To minimize the drift, the fluxes of heat and water at the ocean–atmosphere interface are adjusted by amounts that vary seasonally and geographically[8]. These adjustments, applied to all three integrations identified above, are independent of the anomalies of temperature and scales of the disk correspond to those of the large-scale radio jets and lobes. For example, the kinetic timescale in which the radio jet structures change is about 10^6 yr, while the synchrotron lifetimes of radio regions range from ~ 10^6 yr for the hot spots to ~ 10^8 yr for the more extended lobes. Similarly, the total 'equipartition' energy in the lobes, ~ 10^{57} erg, corresponds to the mass energy available in the disk: for a dust/gas ratio similar to our Galaxy, the disk mass is about 10^5 solar masses. Converted to energy at an efficiency of 1%, a value often assumed, this mass would yield 10^{57} erg.

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The initial conditions for these integrations have realistic seasonal and geographical distributions of surface temperature, surface salinity and sea ice; the atmospheric and oceanic components of the model are nearly in equilibrium with these distributions. When the time integration of the model starts from this initial condition, the model climate rapidly drifts towards its own equilibrium state. To minimize the drift, the fluxes of heat and water at the ocean–atmosphere interface are adjusted by amounts that vary seasonally and geographically[8]. These adjustments, applied to all three integrations identified above, are independent of the anomalies of temperature and

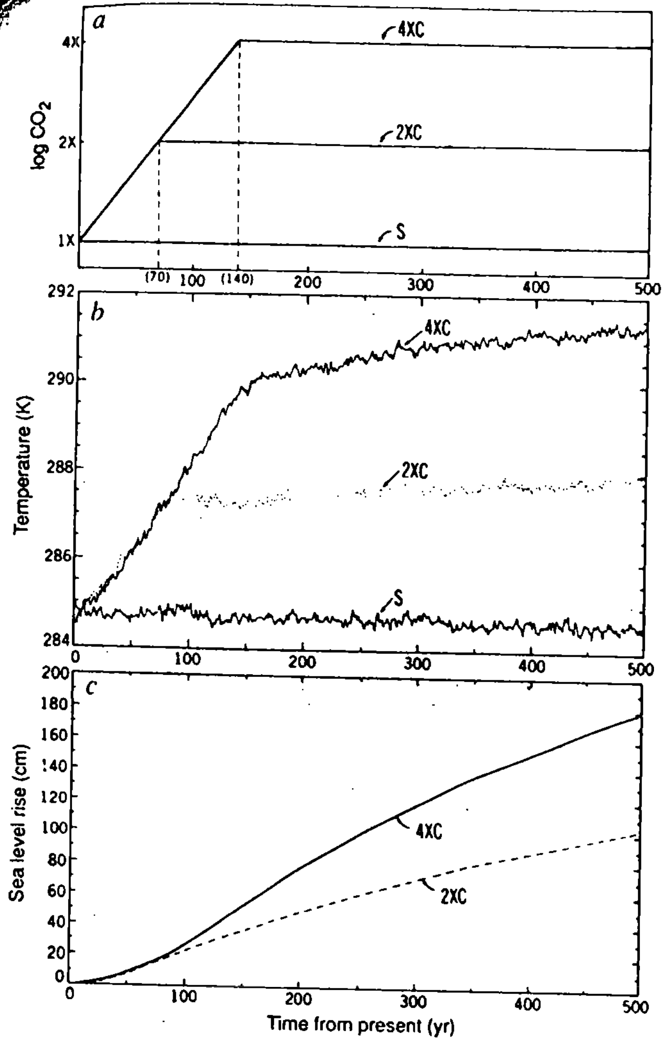

FIG. 1 Temporal variations of: *a*, logarithm of atmospheric CO_2 concentration; *b*, global mean surface air temperature (K); and *c*, global mean increase of sea level (cm) due to thermal expansion, computed as the difference between 4×C and S, and 2×C and S.

salinity at oceanic surface, and so neither damp nor amplify the anomalies.

Figure 1*b* contains the time series of global mean surface air temperature from the 4×C, 2×C, and S integrations. During the first 140 years of the 4×C integration, the global mean surface air temperature increases by 5 °C, at the rate of ~3.5 °C per century. After the 140th year, the global mean surface air temperature increases slowly by an additional 1.5 °C despite the absence of further CO_2 increase in the model atmosphere. The large thermal inertia of the deep ocean is mainly responsible for this residual warming.

A qualitatively similar feature is evident in the time series of the 2×C integration. During the first 70 years, the global mean temperature increases by 2.2 °C, again at the rate of 3.5 °C per century. After atmospheric CO_2 stops increasing at the 70th year, the global mean surface air temperature increases by an additional 1 °C.

The temporal variations of global mean sea level due to thermal expansion of sea water alone are estimated for both the 4×C and 2×C integrations (Fig. 1*c*), although sea level is not explicitly predicted in the present model[12]. During the first few decades of the 4×C experiment, the sea level rises by ~1 cm per decade. The sea level continues to rise long after the 140th year when the atmospheric carbon dioxide stops increasing. A qualitatively similar feature is indicated in the curve of sea-level rise in the 2×C integration. The total sea-level rise over the entire 500-year period of the 4×C amounts to about 1.8 m and is substantially larger than the corresponding rise of about 1 m in the 2×C.

Although the melt water from continental ice sheets is not included in the computation of sea-level rise mentioned above, the rate of melting at the surface of ice sheets has been estimated from the surface heat budget. If the effect of melt water were taken into consideration, the resulting sea-level rise could be much larger.

Figure 2 indicates that, in the 4×C, the thermohaline circulation (THC) almost disappears in most of the model oceans, leaving behind wide-driven cells. For example, the THC nearly vanishes in the North Atlantic during the first 200-yr integration (Fig. 3). In the immediate vicinity of the Antarctic continent, the THC weakens and becomes shallower (Fig. 2), markedly reducing the formation of Antarctic Bottom Water. This in turn weakens the northward flow of bottom water in both Pacific and Atlantic.

The near-extinction of the THC described above is attributable mainly to the capping of oceans by relatively fresh water in high latitudes, where the supply of water to the ocean surface increases markedly. The excess of precipitation over evaporation and runoff from continents increases in high-latitude oceans because of the enhanced poleward transport of water vapour in the warmer model troposphere.

The evolution of the THC in 4×C described above can be

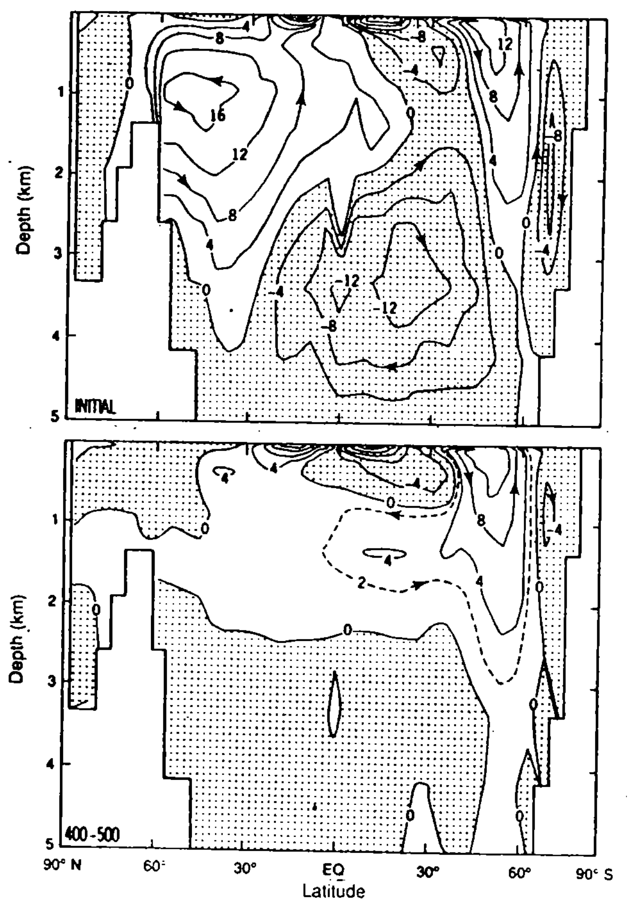

FIG. 2 Stream function of zonal mean meridional circulation in model oceans. Top: initial distribution obtained from the S. Bottom: average over the 400–500th year of the 4×C. Units on contours are in Sverdrups (10^6 m^3 s^{-1}).

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Multiple-Century Response of a Coupled Ocean–Atmosphere Model to an Increase of Atmospheric Carbon Dioxide

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ABSTRACT

To speculate on the future change of climate over several centuries, three 500-year integrations of a coupled ocean–atmosphere model were performed. In addition to the standard integration in which the atmospheric concentration of carbon dioxide remains unchanged, two integrations are conducted. In one integration, the CO_2 concentration increases by 1% yr^{-1} (compounded) until it reaches four times the initial value at the 140th year and remains unchanged thereafter. In another integration, the CO_2 concentration also increases at the rate of 1% yr^{-1} until it reaches twice the initial value at the 70th year and remains unchanged thereafter.

One of the most notable features of the CO_2-quadrupling integration is the gradual disappearance of thermohaline circulations in most of the model oceans during the first 250-year period, leaving behind wind-driven cells. For example, thermohaline circulation nearly vanishes in the North Atlantic during the first 200 years of the integration. In the Weddell and Ross seas, thermohaline circulation becomes weaker and shallower, thereby reducing the rate of bottom water formation and weakening the northward flow of bottom water in the Pacific and Atlantic oceans. The weakening or near disappearance of thermohaline circulation described above is attributable mainly to the capping of the model oceans by relatively fresh water in high latitudes where the excess of precipitation over evaporation increases markedly due to the enhanced poleward moisture transport in the warmer model troposphere.

In the CO_2-doubling integration, the thermohaline circulation weakens by a factor of more than 2 in the North Atlantic during the first 150 years but almost recovers its original intensity by the 500th year. The increase and downward penetration of positive heat and temperature anomaly in low and middle latitudes of the North Atlantic helps to increase the density contrast between the sinking and rising regions, contributing to this slow recovery. The recovery is aided by the gradual increase in surface salinity that accompanies the intensification of the thermohaline circulation.

During the 500-year period of the doubling and quadrupling experiments, the global mean surface air temperature increases by about 3.5°C and 7°C, respectively. The rise of sea level due to the thermal expansion of sea water is about 1 and 1.8 m, respectively, and could be much larger if the contribution of meltwater from continental ice sheets were included. It is speculated that the two experiments described above provide a probable range of future climate change.

1. Introduction

The CO_2-induced change of climate has been the subject of many studies using general circulation models of the coupled ocean–atmosphere system (e.g., Bryan et al. 1982; Spelman and Manabe 1984; Schlesinger et al. 1985; Bryan and Spelman 1985; Bryan et al. 1988; Washington and Meehl 1989; Stouffer et al. 1989; Manabe et al. 1991, 1992; Cubasch et al. 1992). This study, recently summarized by Manabe and Stouffer (1993), is an extension of the earlier studies by Stouffer et al. and Manabe et al., which explored the response of a coupled ocean–atmosphere model to a gradual increase of atmospheric carbon dioxide. (Hereafter, these earlier studies will be referred to as SM for the convenience of identification.) By examining the multiple-century responses of the coupled model to the quadrupling and doubling of atmospheric CO_2, the present study examines the robustness of the results from the earlier work. The study also speculates on the nature of a large change of climate that may occur in the more distant future.

Stouffer and Manabe noted that the CO_2-induced warming of sea surface temperature is delayed markedly in the northern North Atlantic and the Circumpolar Ocean of the Southern Hemisphere due partly to the deep mixing of heat trapped by the increasing greenhouse gas. This study investigates whether such a delay continues when the time integration of the coupled model is extended over several centuries.

Based upon the paleo-oceanographic evidence, Broecker (1987) raised the possibility that the thermohaline circulation in the Atlantic and the rest of the world oceans may undergo an abrupt change in response to the global warming of climate. Using a cou-

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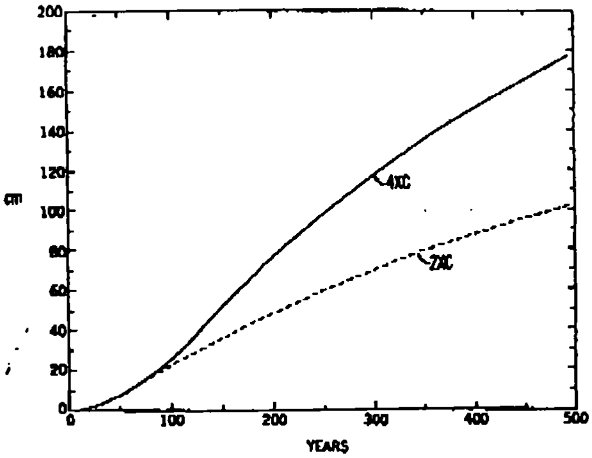

FIG. 3. Temporal variation of the global mean sea level from the 4XC and 2XC experiments. The 4XC and 2XC time series represent the difference between the 4XC and S, and 2XC and S integrations, respectively. Units are in centimeters.

year. Even after the 180th year, the rate of sea level rise is reduced only very gradually. As discussed in section 5, the gradual, downward penetration of positive temperature anomaly in the model oceans is mainly responsible for the continuous sea level rise after the 140th year when the atmospheric CO_2 stops increasing.

In the 2XC experiment, the initial rate of sea level rise is nearly identical to the initial rate in the 4XC experiment. By the 70th year when atmospheric carbon dioxide stops increasing, the rate of sea level rise reaches 3 cm decade^{-1} and stays at this value until about the 110th year when it begins to decrease very gradually. A qualitatively similar feature is indicated in the curve of sea level rise obtained by Warrick and Oerlemans [Fig. 9.8 of IPCC (1990)]. Note, however, that their result includes the contribution of meltwater from ice sheets and mountain glaciers.

Because of the downward penetration of a larger temperature anomaly, the rate of sea level rise is larger in the 4XC than the 2XC experiment even after the atmospheric CO_2 stops increasing in both experiments. Thus, the total sea level rise over the entire 500-year period of the 4XC experiment amounts to about 1.8 m and is substantially larger than the corresponding rise of about 1 m in the 2XC experiment.

Although the meltwater from continental ice sheets is not included in the computation of sea level rise mentioned above, the rate of melting at the surface of ice sheets has been estimated as described in section 2b for the sake of bookkeeping. Assuming that the meltwater does not refreeze at all in the ice sheet, sea level would rise by as much as an additional 7 m during the 500-year period of the 4XC integration, resulting in a total sea level rise of about 9 m. Even if only half of the meltwater were to eventually run off into the oceans, the total sea level rise would be about 5 m. (For the temporal variation of the meltwater from continental ice sheets, see Fig. 14 in section 4b.)

4. Thermohaline circulation

a. Temporal variation

One of the most remarkable aspects of the 4XC integration is the gradual disappearance of the thermohaline circulations in the model oceans. For example, the thermohaline circulation almost vanishes in the North Atlantic Ocean before the end of the 4XC integration (Fig. 4). It weakens rapidly during the first 140 years of the CO_2 increase, and continues to decrease after the 140th year despite the absence of the CO_2 increase until its intensity is reduced to a few Sverdrups (1 Sv ≡ 10^6 m^3 s^{-1}) around the 200th year. During the second half of the integration, very weak overturning is essentially confined equatorward of 45°N with practically no sinking in the northern North Atlantic (Fig. 5c). In the immediate vicinity of the Antarctic continent, the thermohaline overturning not only weakens markedly but also shifts toward the surface during the first 140 years of the 4XC integration (Figs. 5g and 5h). Although the coastal cell of thermohaline circulation reintensifies slightly after the 140th year, it is essentially confined to the top 1.5-km layer of ocean, (Fig. 5i), resulting in a marked reduction of the formation of Antarctic Bottom Water. Thus, the northward flow of the bottom water stops and the deep cell of clockwise circulation disappears in the Pacific Ocean (Fig. 5f). The reduction in the formation of the Antarctic Bottom Water (AABW) also affects deep circulation in the Atlantic sector. Although the clockwise cell of AABW in the Atlantic intensifies during the first 140 years as the upper thermohaline cell becomes shallower, it eventually disappears and the northward flow of the bottom water also stops for all practical purposes toward the end of the 4XC integration (Fig. 5c). In summary, most of the thermohaline circulations disappear in the model oceans toward the end of the 4XC integration, leaving the wind-driven, shallow cells in

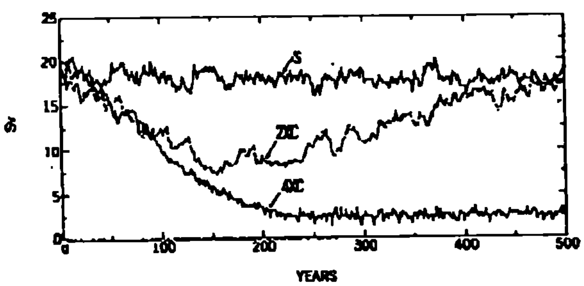

FIG. 4. Temporal variation of the intensity of the thermohaline circulation in the North Atlantic Ocean from the 4XC, 2XC, and S integrations. Here the intensity is defined as the maximum value of the streamfunction representing the meridional circulation in the North Atlantic Ocean (e.g., Fig. 5a). Units are in Sverdrups.

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The effects of the global climate system described above do not include potential non-linearities in the relationships between greenhouse gas concentrations and temperature, between temperature and economic damages, or in the various other complicated relationships governing interactions among greenhouse gas emissions, the climate, and the economy. Three possibilities serve as illustrations. Warming of Northern tundra might release large amounts of methane from the subarctic permafrost, thereby acting as a positive feedback on the climate, leading to potentially devastating acceleration of an otherwise controllable global warming process (Gorham 1991, 1995; Nisbet and Ingham 1995). Second, evidence from the historic record suggests that some types of climate change might lead to abrupt changes in ocean currents, including displacement of the currents that warm Western Europe. Evidence from ocean core samples suggests such changes of ocean currents have occurred in previous ice ages (Broeker 1997). Third, warming might cause accelerated melting of the Antarctic ice sheet causing even more substantial increases in sea levels (Rott et al. 1996; Vaughan and Doake 1996). These potential nonlinearities strengthen the argument for taking prompt, reasonable steps to mitigate climate change.

In: Biotic Feedback in the Global Climatic System. G.M. Woodwell & F.T. Mackenzie, eds. Oxford Univ. Press, NY

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Methane Output from Natural and Quasinatural Sources: A Review of the Potential for Change and for Biotic and Abiotic Feedbacks

E. G. NISBET AND B. INGHAM

Methane output from "natural" sources has changed rapidly in the recent geological past, is changing at present under human influence, and may change further as the earth warms. Unfortunately, the causes, feedback processes, and extent of geological changes are still only poorly understood, the relative strengths of modern sources of CH_4 remain controversial, and prediction is virtually impossible. One of the most difficult problems is in linking accurate but very imprecise, qualitative, and often anecdotal field biogeochemical observations with precise but not necessarily accurate quantitative synthetic models.

This discussion is confined to an analysis of those major "natural" sources and sinks that may have caused the postglacial fluctuations in atmospheric CH_4. The net effect of the latitudinal and seasonal distribution of sources, sinks, and atmospheric transport is shown in Figure 10.1, from Steele et al. (1992). This plot reveals the most important constraint on the global CH_4 budget; the other major constraint is the isotopic finding (e.g., Lowe et al. 1991) that roughly 20% of the atmospheric CH_4 is outut from fossil sources. The present budget is still not well understood (Watson et al. 1990; Tyler 1991), and prediction of future concentrations is difficult.

THE MAJOR SOURCES

Arctic and Sub-Arctic Hydrates

Very large stores of CH_4 exist in permafrost regions, held in soil and in sedimentary rock as gas hydrates (clathrates) (Kvenvolden 1988). Gas hydrates, composed of rigid cages of water molecules that trap molecules of gas (Cox 1983), are potentially stable where

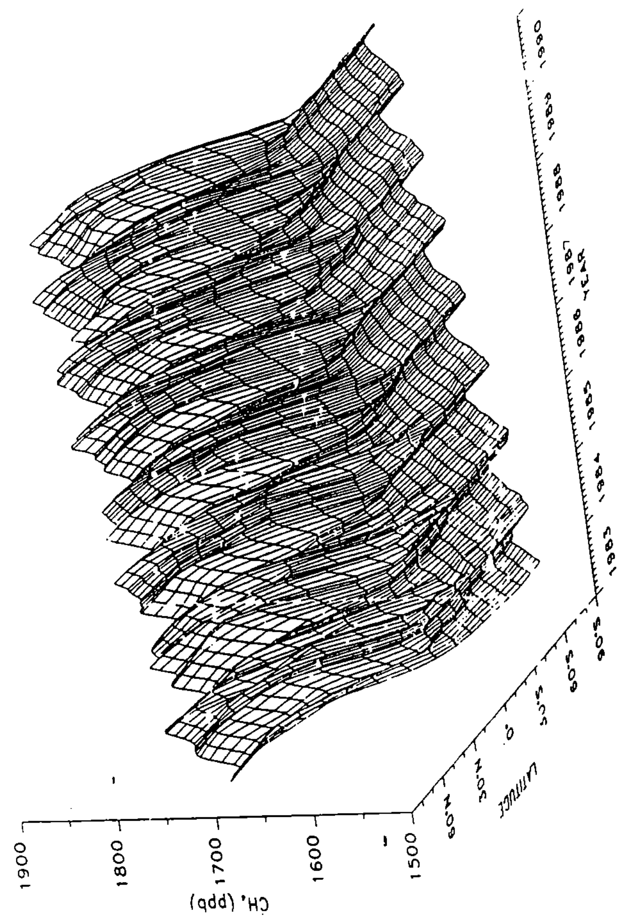

Figure 10.1. Plot of the CH_4 mixing ratio at the marine boundary layer, Pacific and Arctic. Note the seasonality in high latitudes, especially in the Northern Hemisphere. Southern seasonality in part reflects OH seasonality in the tropical upper troposphere, and in part may derive from northern seasonality, blown south over the equator in the midtroposphere by tropospheric circulation cells (From U.S. NOAA data, courtesy of E. Dlugokencky and P. Tans. See also Steele et al. 1992.)

Table 10.1. Global CH_4 Budget

Source	Estimated flux (Tg)	Comment	Possible feedback (change after global warming)
"Quasi-natural"			
CH_4 hydrates	5	Variable	Significant danger
Wetlands			
Northern bogs, tundra	35	Too low ?	May increase or decrease
Swamps/alluvial	80	Too high ?	May increase
Biomass burning	55	Fluctuates	Substantial increase
Termites	20		May decrease
Oceans and freshwater	10		
	205		
Animals	80		May increase
	285		
Anthropogenic			
Rice	100		Will increase
Landfills	40	Too high ?	Decreasing?
Natural gas vents	10		Controllable
Natural gas leaks	30		Controllable
Coal mining	35	Poorly known	Controllable
	215		
Total	500		

Source: Estimates of flux from Fung et al. (1991): scenario 7.

well-studied area, albeit a small one (in global terms) without permafrost, the North Sea seepage losses to the atmosphere have been thought to be small, on the order of a few kilotons (Judd in A. Williams 1993). Globally, however, the flux from shallow marine sediment has been estimated as being as large as 8–65 Tg annually (Hovland et al 1993).

The isotopic data imply that between 80 and 125 Tg of fossil CH_4 are released annually (Table 10.1). Fung et al. (1991) took the lower figure and allocated 35 Tg to loss from coal mining, 40 Tg to loss from the natural gas industry, and 5 Tg to loss from CH_4 hydrates. However, the 5-Tg figure, which is ultimately derived from the estimate of Cicerone and Oremland (1988), is essentially a "placeholder," to use Cicerone and Oremland's term. The true figure may be rather different and is very poorly constrained. The 40-Tg figure for gas industry losses may be a snapshot of a moving figure, roughly correct in the 1970s and too low for the 1980s, but perhaps an attainable target for the 1990s as losses from the huge Russian natural gas industry are reduced. Table 10.2 is a rough estimate of the "fossil" CH_4 burden of the atmosphere.

Subtracting fossil fuel losses from the isotopically derived total of 80–125 Tg of fossil CH_4 emitted annually gives, by difference, the hydrate loss. Tables 10.1 and 10.2 make the assumption that hydrate gas emission at present is roughly 5 Tg annually. This estimate is highly approximate, and within the isotopic constraints it is possible that the hydrate output is either virtually nil or perhaps as high as 10 Tg. The only way to improve the estimate of the hydrate contribution is through steady isotopic monitoring; even then, since the Russian gas is derived partly from hydrate, it may be impossible to quantify hydrate losses until detailed knowledge of Russian gas industry losses is available. Nevertheless, the hope is that hydrate losses are at present fairly small.

Table 10.2. Model of the "Fossil" CH_4 Content of the Atmosphere: Natural Gas and Coal Industry CH_4 Production and Losses, and Contribution from the Oil Industry and Hydrates: A Simple Model to Calculate Atmospheric Burden of "Fossil" Methane

	Natural gas[a]		Coal[b]		Total[c]	
	Production 10^9 m^3	Loss (Tg)	Production (10^9 metric ton)	Loss (Tg)	Annual (Tg)	Cumulative (Tg)
1981	1503	49	3814	27	61	770
1982	1484	49	3930	28	63	776
1983	1490	51	3951	28	66	783
1984	1626	52	4122	29	66	790
1985	1686	55	4345	31	71	803
1986	1738	57	4518	32	74	817
1987	1830	60	4630	33	77	834
1988	1906	63	4730	34	80	853
1989	1975	61	4816	34	77	868
1990	2028	57	4736	34	72	877
1991	2059	52	4566	33	66	881
1992	2066	47	4484	32	60	878

[a] The loss is calculated on the assumption that 95% of natural gas is CH_4 and that in the industry (excluding the territory of the former Soviet Union) the average loss rate is 3%. For the former Soviet Union, a loss rate of 9% is assumed until 1983, 8% from 1984 to 1988, 7% in 1989, 6% in 1990, and 5% from 1991 to 1992. These assumptions are arbitrary but within the range of anecdotal information.

[b] The loss for the global coal industry excluding China is calculated on the basis of 10 m^3 gas per metric ton, using a conversion factor of 714 g/m^3 from United Kingdom sources. Production figures include brown coal with low losses of CH_4, and hard coal with losses on the order of 15 m^3/metric ton. The assumption of a global loss rate of 10 m^3/metric ton falls between estimates of Smith and Sloss (1992) and Beck et al. (1993).

[c] The total figure includes the loss of CH_4 as a by-product of the oil industry, approximately 2 Tg/year, scaled up from United Kingdom industry data to a global figure. It also includes 5 Tg/year from hydrate release. This figure is simply a "placeholder" (Cicerone and Oremland 1988): the true figure is unknown. The cumulative total assumes a pre-1981 content of 820 Tg of fossil-derived CH_4 in the atmosphere and an annual exponential decay of one-tenth of the previous year's value. The cumulative total should be compared with the total CH_4 content of the troposphere from all sources, which is roughly 4000 Tg. This model is very approximate, but it illustrates the scale of "fossil" emissions of CH_4.

Sources: *Encyclopedia Britannica Yearbooks*, 1982–1992; *BP Statistical Review of World Energy, 1993*, and previous years; and *BP Review of World Gas 1993*, British Petroleum Company, London.

Vulnerability of Hydrate to Climatic Change

Any changes that increase temperature or reduce pressure may liberate CH_4 from hydrate (Figure 10.3A). Specific changes that can occur include heating from a rise in atmospheric temperature, heating from a change in surface albedo, and heating because of marine transgression. Pressure release can occur as a result of sea-level drop, either as a global effect or (a more important cause at present) from local uplift as the lithosphere recovers after glacial loading. Pressure release also occurs in slumping. Perhaps the major cause for concern is the risk of a sudden massive release of CH_4 either from a marine slump or from the rupturing of a major pool of Arctic gas. Such massive release would not be directly attributable to modern warming in the past few decades; rather it would be a stochastically timed part of a longer-term process. The largest source would be a major marine slump (Figure 10.3B). Marine slumps are more likely at times of lowered sea-level (i.e., just before the end of the last major glaciation, around 13–15 kaBP), but can occur at any time and release enormous quantities of CH_4 (Paull et al.

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Thermohaline Circulation, the Achilles Heel of Our Climate System: Will Man-Made CO_2 Upset the Current Balance?

Wallace S. Broecker

During the last glacial period, Earth's climate underwent frequent large and abrupt global changes. This behavior appears to reflect the ability of the ocean's thermohaline circulation to assume more than one mode of operation. The record in ancient sedimentary rocks suggests that similar abrupt changes plagued the Earth at other times. The trigger mechanism for these reorganizations may have been the antiphasing of polar insolation associated with orbital cycles. Were the ongoing increase in atmospheric CO_2 levels to trigger another such reorganization, it would be bad news for a world striving to feed 11 to 16 billion people.

One of the major elements of today's ocean system is a conveyor-like circulation that delivers an enormous amount of tropical heat to the northern Atlantic. During winter, this heat is released to the overlying eastward moving air masses, thereby greatly ameliorating winter temperatures in northern Europe. The record contained in ice (*1*) and sediment (*2*) indicates that this current has not run steadily, but jumped from one mode of operation to another. The changes in climate associated with these jumps have now been shown to be large, abrupt, and global (*3–5*). Although the exact linkages that promote such climate changes have yet to be discovered, a case can be made that their roots must lie in the ocean's large-scale thermohaline circulation [see (*2*)]. The results of a wide variety of modeling exercises clearly demonstrate that because waters dense enough to sink to the deep sea can be generated at more than one place on the planet, several quasi-stable patterns of circulation exist (*6*). Variations in the conditions governing the density of high-latitude surface waters can lead to abrupt reorganizations of the ocean's circulation. The surprise revealed to us by the climatic record is the extent, rapidity, and magnitude of these atmospheric changes.

Although to date the documentation of abrupt global climate change is confined to the last 110,000 years, the time interval preserved in the Summit Greenland ice cores (*1*), there is reason to suspect that this phenomenon has operated off and on, throughout the history of the Earth. The evidence comes from the well-documented cyclicity in sedimentary rock sequences. In many of these sedimentary cycles, the boundaries between the individual units are sharp rather than gradational, as might be expected if the sediment composition followed the sinusoidal insolation cycles.

Might the ongoing buildup of greenhouse gases in our atmosphere trigger yet another reorganization of the climate system? Were this to happen a century from now, at a time when we struggle to produce enough food to nourish the projected population of 11 to 16 billion, the consequences could be devastating. Thus, it behooves us to get a better grasp than we now have of this phenomenon.

The author is at The Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA.

How Today's Ocean Functions

A complex of currents collectively known as the Conveyor (*7*) dominates circulation in today's Atlantic Ocean (see Fig. 1). The waters in the upper 1500 m of the Atlantic Ocean carry heat to its northern reaches. Much of this transport is by western boundary currents. During the cold winter months, this heat is transferred to the overlying atmosphere, greatly supplementing that received from the sun (*8*). The primary beneficiary of this extra heat is northern Europe, where winters are far warmer than one would otherwise expect.

Cooling in the North Atlantic increases the density of this upper ocean water to the point where it sinks to the bottom and flows southward, forming the lower limb of the Conveyor. This limb extends all the way to the southern tip of Africa where it joins the raceway, which transports water around the

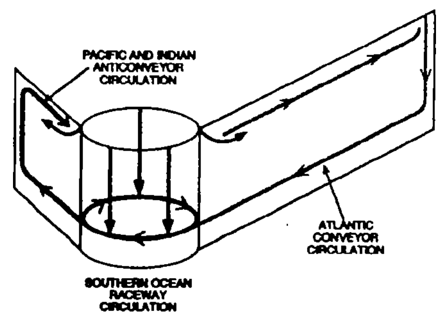
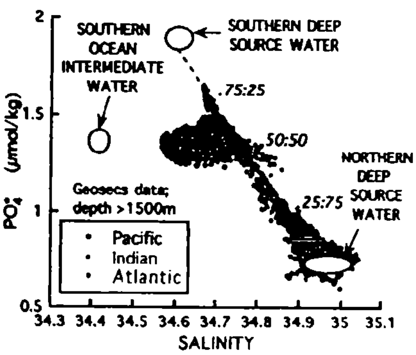
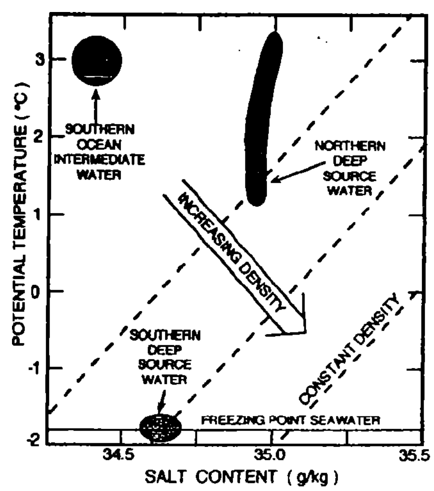


Fig. 1. The present-day large-scale thermohaline circulation pattern of the ocean. (**Top**) Salty upper Atlantic water moves northward into the vicinity of Iceland, where it is cooled through contact with cold winter wind. This thermally densified salty water sinks to the bottom and flows to the south, forming the Conveyor's (orange) lower limb. After passing the tip of Africa, it joins the Southern Ocean raceway, which carries water around the Antarctic continent. Here it is blended with brine-densified winter waters that pour off the shelves surrounding the Antarctic continent into the abyss (blue). The mixture (purple) thus formed enters the Pacific and Indian Oceans as bottom water forming the lower limbs of large anti-Conveyor circulation cells. Penetrating into all three oceans are tongues of intermediate depth water formed along the northern margins of the Southern Ocean (black). This water is mixed downward into the deep ocean, forming the third end member. As can be seen in the PO versus salinity diagram (**below**), its presence is made known by a deviation toward lower salinity. The PO_4^* of these waters is about 1.4 μmol/kg, their salinity about 34.4 g/liter, and their potential temperature about 3°C (**right**).





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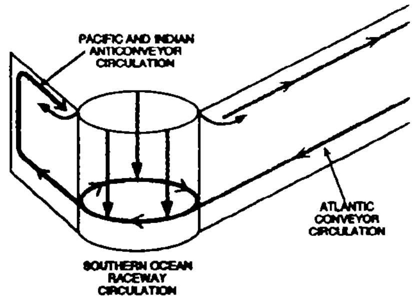

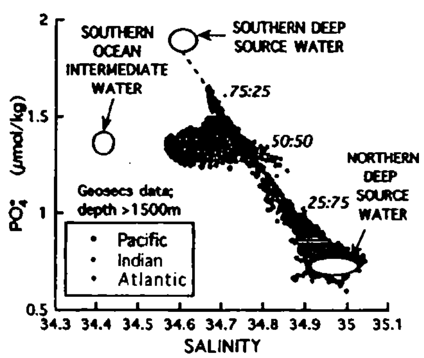

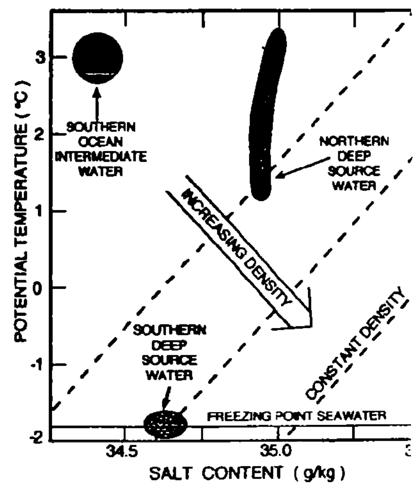

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Summary

Through the record kept in Greenland ice, a disturbing characteristic of the Earth's climate system has been revealed, that is, its capability to undergo abrupt switches to very different states of operation. I say "disturbing" because there is surely a possibility that the ongoing buildup of greenhouse gases might trigger yet another of these ocean reorganizations and thereby the associated large atmospheric changes. Should this occur when 11 to 16 billion people occupy our planet, it could lead to widespread starvation, for in order to feed these masses, it will be necessary to produce two to three times as much food per acre of arable land than we now do. More problematic perhaps than adapting to the new global climate produced by such a reorganization will be the flickers in climate that will likely punctuate the several-decade-long transition period (Fig. 3, right panel).

So what do we do? Everyone would agree that the smaller the CO_2 buildup the less the likelihood of dire impacts. But we are hooked on cheap energy and the demand for it continues to grow. Furthermore, no viable and acceptable option to fossil fuels has yet been devised. Although efforts to bring about more efficient use of energy must be redoubled, it is my feeling that this route is not likely to succeed in bringing about an adequate reduction in CO_2 emissions. Hence, as a backstop, we must strive to develop an energy supply that does not load the atmosphere with CO_2. To this end I see a ray of hope. The idea is to separate the hydrogen atoms contained in fossil fuels by reacting them with steam. The H_2 produced in this way would be used in fuel cells, and the CO_2 would be captured at its source, liquified, and injected either into continental reservoirs or onto the sea floor (54). While perhaps doubling the cost of energy, this is something that could be accomplished. But as such a transition in energy-generation technology would require at least 50 years to implement, we must get off to a running start to put into place this insurance policy.

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13. The Sverdrup (Sv) is a unit of water transport. One Sverdrup is equal to 1 x 10⁶ m³/s. The transport by today's Conveyor is about 15 Sv compared to that of all the world's rivers of about 1 Sv.
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56. My recent ideas about sedimentary cycles in the distant past have been tempered by discussions with A. Fischer, B. Berggren, N. Christie-Blick, D. Kent, P. Olsen, P. Lohmann, L. Hinnov, P. deMenocal, F. Read, J. Banner, and B. Cecil. It was a push by T. Edgar that launched me down this track. Over the years, discussions with M. Bender, G. Denton, J. Jouzel, G. Bond, R. Alley, J. Severinghaus, and J. Imbrie have molded my thinking about the events of the Late Quaternary. In this case, it was ideas about multiple climate states expressed to me by H. Oeschger in 1984 that sparked my thinking. My research on the oceans has benefited from the wisdom of T. Stocker, T. Takahashi, S. Rahmstorf, R. Toggweiler, E. Maier-Reimer, S. Manabe, J. Marotzke, J. McWilliams, U. Mikolajewicz, A. Gordon and P. Schlosser. It was the late H. Stommel who inspired me to a new level of thinking and action (that is the GEOSECS program). S. Peacock has worked with me on the problem of deep water formation in the Southern Ocean. J. Totton and P. Catanzaro transformed my hand scribbles into readable manuscript.

Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula

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In 1978 Mercer[1] discussed the probable effects of climate warming on the Antarctic Ice Sheet, predicting that one sign of a warming trend in this region would be the retreat of ice shelves on the Antarctic Peninsula. Analyses of 50-year meteorological records have since revealed atmospheric warming on the Antarctic Peninsula[2,3], and a number of ice shelves have retreated[4-8]. Here we present time-series of observations of the areal extent of nine ice shelves on the Antarctic Peninsula, showing that five northerly ones have retreated dramatically in the past fifty years, while those further south show no clear trend. Comparison with air-temperature data shows that the pattern and magnitude of ice-shelf retreat is consistent with the existence of an abrupt thermal limit on ice-shelf viability, the isotherm associated with this limit having been driven south by the atmospheric warming. Ice shelves therefore appear to be sensitive indicators of climate change.

Ice shelves fringe most of the Antarctic continent where there are bays or islands to constrain them. Robin and Adie[9], however, noted that a portion of the Antarctic Peninsula was free of ice shelves, despite many glacier-fed bays and offshore islands. The limit of ice shelves apparently corresponded with the 0 °C January isotherm, and they concluded this marked a "limit of viability". Other constraints on ice-shelf viability based on ocean temperature[10] and tidal amplitude[11] have been proposed, but have not been shown to fit the known distribution.

Where there is little summer melting, the yearly surface temperature cycle is attenuated to ∼5% at a depth below the ice surface of 10 m (ref. 12). The 10-m temperature thus provides an estimate of the mean annual air temperature. Mercer[1] suggested that the downward percolation and subsequent refreezing of surface melt could eliminate the cold thermal wave from the previous winter and raise the ice shelf to the pressure melting point throughout. The so-called temperate ice shelf thus created was at that time thought to be inviable. However, it is unlikely that this process would be sufficient to form a temperate ice shelf if percolation is restricted to the near surface layers (∼10 m). Furthermore, there is strong evidence that portions of stable ice shelves can approach the temperate state[13]. Nevertheless, we believe that increased melt could play an important role in providing the reason for a climate-imposed limit.

The duration and extent of the summer melt season has been determined from satellite passive microwave data[14,15]. The threshold for melting in the Antarctic Peninsula region is about −2.5 °C (monthly average) and the area of melt increases rapidly with temperature[14]. Trends are not well established, being masked by the inter-annual variability from 1978 to 1987[14], but the number of days per year with summer melting seems to have increased (one day per year) over the period 1978–91 on four ice shelves on the Antarctic Peninsula[15].

The only climate parameter that is well mapped on the Antarctic Peninsula is the mean annual air temperature[16] (Fig. 1). The distribution of ice shelves indicates that the −5 °C mean annual isotherm in Reynolds' compilation[16] could be taken as proxy for the limit of viability of ice shelves. Although the 0 °C January isotherm is not well mapped, the sparse data available suggest that it coincides with the mean annual −5 °C isotherm[17]. For example, mean January temperatures at Faraday Station are around 0.5 °C, whereas the mean annual temperature is −4.4 °C (ref. 2). We thus adopt mean annual air temperature as the best available indicator of the amount of summer melt.

Meteorological records along the west coast of the Antarctic Peninsula[2,3] show a spatially consistent warming trend. At Faraday Station, a warming of 0.056 °C yr^{-1} has been measured[2] since 1945, a total of ∼2.5 °C. Consistency along the west coast is to be expected, as sea-ice extent in the Bellingshausen Sea strongly modulates the temperature of the entire area[18]. In 1988–91 sea-ice extent in the Bellingshausen Sea reached a minimum, coinciding with the warmest recorded temperatures on the west coast of the Antarctic Peninsula[19]. In contrast, the climate of the east coast is governed by conditions in the Weddell Sea[17] and there is little meteorological evidence that warming has also occurred on the east coast. The temperature record from Marambio Station is short and incomplete[20], and Jones' comparison of a two-year record from Snow Hill Island with spatially smoothed mean temperatures 1957–75 (ref. 21) is untrustworthy, because the area has extremely high spatial gradients of mean annual air temperature.

Figure 2 presents a catalogue of changes in ice-shelf areas on the Antarctic Peninsula since direct observations began, compiled from published sources[4-8,22-27] and recent satellite imagery. How do we distinguish climate-induced retreat from normal calving? We suggest that an ice shelf which is no longer viable will suffer a progressive retreat, via a series of small calming events occurring each year over a period of many years, without substantial readvance. Such behaviour was clearly seen during the disintegration of Wordie Ice Shelf (Fig. 3), and Fig. 2 suggests similar behaviour in three other ice shelves close to the −5 °C isotherm; namely, the ice shelf that occupied Prince Gustav Channel, Larsen Inlet, and the northernmost section of Larsen Ice Shelf (Sobral Peninsula to Robertson Island, hereafter Larsen-A). An order of magnitude smaller and potentially quite different, Müller Ice Shelf has shown a progressive retreat since the 1950s, but without complete disintegration. In summary, each retreat was pro-

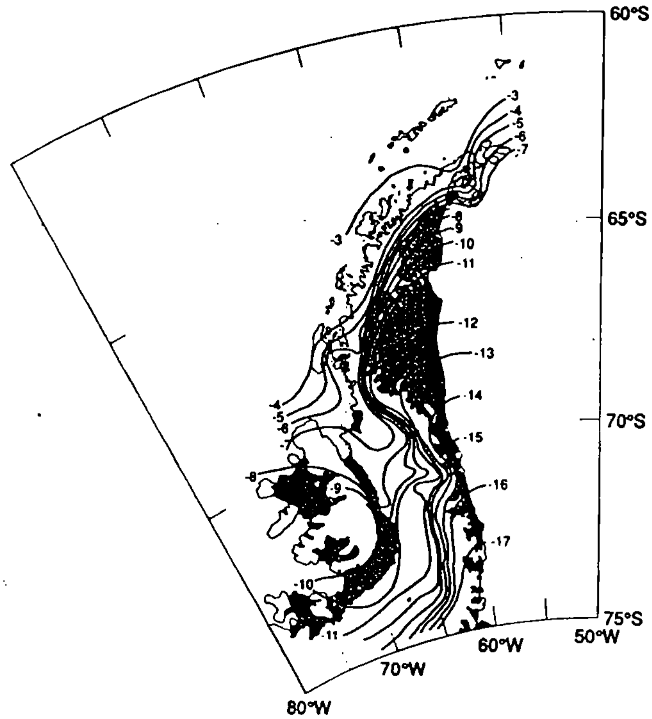

FIG. 1 Map of pre-1981 mean annual air temperatures in °C. Derived from temperatures 10 m below the ice surface, normalized to sea-level by Reynolds[16]. Ice shelves (shaded) are indicated at their mid-1970s extent.

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15. Uncaptured flood runoff provides a variety of human benefits, including support of flood-recession farming, fisheries, and generation of hydroelectricity; however, in these capacities, its use is either insignificant globally or does not involve actual appropriation.
16. Theoretically, a reservoir could be filled and emptied more than once a year, creating a greater effective capacity to regulate runoff than the storage capacity alone would indicate. We know of no estimates of this effective storage capacity other than the statement by K. Mahmood [*Reservoir Sedimentation: Impact, Extent, and Mitigation* (The World Bank, Washington, DC, 1987)] that the usable reservoir storage capacity "is nearly used once every year." We therefore make no adjustments to the estimated 3500 km^3 of capacity usable for runoff storage on an average annual basis.
17. This is a somewhat higher rate than is implied by Shiklomanov's estimates (*4*), which suggest rates of 10,700 to 11,000 m^3/ha. We arrived at our figure after examining data for California that suggest an average water application rate on that state's irrigated area of ~10,300 m^3 ha [*California Water Plan Update* (California Department of Water Resources, Sacramento, CA, 1994), vol. 1]. Because the average irrigation efficiency in California is reported to be 70%, which is substantially higher than the worldwide average [S. Postel, in (*5*), pp. 56–66], we believe that 12,000 m^3/ha is closer to the actual global average application rate. Moreover, the California figures account only for on-farm water applications and do not include the portion of diversions lost to seepage or evaporation between reservoirs and farmers' fields.
18. Evaporative losses from Lake Nassar, for example, have averaged 10 km^3/year, which is equal to 12% of the Nile's average annual flow [J. A. Allan, in *The Nile: Sharing A Scarce Resource*, P. P. Howell and J. A. Allan, Eds. (Cambridge Univ. Press, Cambridge, 1994), pp. 313–320].
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21. Even if wastewater treatment coverage should become nearly universal, substantial instream flows would still be required to maintain fisheries, support recreational demands, and satisfy other instream needs. For example, California's instream environmental water requirements (after omission of the north coast hydrologic region, which contains several wild and scenic rivers and thus may not be indicative of instream needs more narrowly defined) equal 22% of average annual runoff [*California Water Plan Update* (California Department of Water Resources, Sacramento, CA, 1994).
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26. *Status of Dam Construction, 1991* (International Commission on Large Dams, Paris, 1992), suggests that ~300 dams are now commissioned each year, but these data include only 64 countries.
27. A. P. Covich [in (*5*), pp. 40–55] indicates that large dams are currently being completed at an average rate of 500 per year, or 56% of the rate of the period from 1950 to 1986.
28. Because ~85% of existing large dams were built since mid-century (*25*), this calculation assumes that 85% of total existing storage capacity was constructed since then, or 4675 km^3 (5500 km^3 × 0.85). With the assumption that 40% as many dams would be constructed between 1990 and 2025 as between 1950 and 1985, and that capacity per dam remains constant, 1870 km^3 (4675 km^3 × 0.40) of capacity would be added by ca. 2025, of which 1190 km[illegible] would be live storage for water supply.
29. Even as dam construction is adding to the total stable runoff, other human activities are reducing it. Deforestation and the paving over of aquifer recharge areas often reduce rainwater infiltration, thereby reducing base flow and increasing surface flood runoff. More important globally, many reservoirs are losing active storage capacity faster than originally estimated because of rapid siltation from deforestation, soil erosion, and generally poor watershed management. The Nizamsagar reservoir in India, for instance, los[t] more than 60% of its capacity over 40 years [M. Newson, *Land, Water and Development: River Basin Systems and Their Sustainable Management* (Routledge, London, 1992]. Lacking global estimates, we mak[e] no subtraction for these losses.
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Rapid Collapse of Northern Larsen Ice Shelf, Antarctica

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In January 1995, 4200 square kilometers of the northern Larsen Ice Shelf, Antarc[tic] Peninsula, broke away. Radar images from the ERS-1 satellite, complemented by fie[ld] observations, showed that the two northernmost sections of the ice shelf fractured a[nd] disintegrated almost completely within a few days. This breakup followed a period [of] steady retreat that coincided with a regional trend of atmospheric warming. The obse[r]vations imply that after an ice shelf retreats beyond a critical limit, it may collapse rapi[dly] as a result of perturbated mass balance.

Ice shelves cover 11% of the total area of Antarctica (*1*) and play an important role in the mass budget and dynamics of the Antarctic Ice Sheet. Most of the ice that has accumulated over the grounded parts of Antarctica is discharged to ice shelves, where it is lost as icebergs along the seaward edges as well as by basal melting (*2*). Because ice shelves are exposed to both atmosphere and ocean, they are sensitive to changes in the temperature and circulation of either (*3*). The 0°C summer isotherm [has] been taken as the climatic limit for [the] existence of ice shelves along the west co[ast] of the Antarctic Peninsula (*4*). Betw[een] 1966 and 1989, the Wordie Ice Shelf ([Fig.] 1) decreased from ~2000 to 700 km^2, pr[ob]ably as a result of regional atmosph[eric] warming (*5*). Here, we report on the rec[ent] disintegration of the northern Larsen [Ice] Shelf (LIS).

The LIS extends along the eastern [coast] of the Antarctic Peninsula from latit[ude] 64° to 74°S (Fig. 1). The part of the [LIS] north of Robertson Island has retre[ated] slowly but constantly since the 1940s (*6*[)]. The retreat accelerated after 1975 (*8*),

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Our observations suggest that ice shelves close to the climatic limit for existence may disintegrate rapidly. During the next years, increased attention should be paid to the section of the LIS south of Seal Nunataks, which may be subject to major changes if the warming continues. In November 1994, we observed a transverse rift ~50 km in length in section 1, ~30 km inland from the ice front.

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9. The ERS-1 SAR images were acquired at the German receiving station near the Chilean Antarctic Base O'Higgins, operating on a campaign basis. The northern LIS was imaged by ERS-1 SAR in July 1992, between December 1992 and February 1993, in August 1993, and between mid-January and mid-February 1995. For comparison with conditions previous to the accelerated retreat, we analyzed Landsat Multispectral Scanner (MSS) images from 1 March 1986.
10. We obtained the ERS-1 SAR data in Universal Transverse Mercator projection based on the WGS-84 ellipsoid with nominal spatial resolution of 25 m by 25 m and location accuracy of better than 100 m in areas of low relief. We used geodetic field data to control and improve the absolute location accuracy. Geometric accuracy was high only close to sea level, because terrain-induced distortions resulting from radar imaging geometry could not be corrected because of a lack of high-resolution elevation data.
11. Data on ice motion, surface mass balance, and ice thickness were obtained for sections 1, 2, and 3 during field observations beginning in the early 1980s. Mean annual velocities from 1984 to 1994 in the center of the profiles (Fig. 2) were 385 m/year in section 1 and 248 m/year in section 3. Ice thicknesses at the same points were 250 m (section 1) and 220 m (section 3).
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$$\frac{\partial H}{\partial x} = \frac{\tau_s}{\rho g[1 - (\rho/\rho_w)]W}$$

where τ_s is the shear stress at the sidewalls, g is the acceleration of gravity, ρ_i and ρ_w are the density of ice and water, respectively, and W is the width of the ice shelf. When the ice front retreated into the bay west of Sobral Peninsula, W became enlarged suddenly, violating the stability criterion. (ii) The shear strain $(\partial u/\partial y + \partial v/\partial x)$ at a stable ice front is zero, where u is the velocity in direction x of the flow line and v is the velocity in direction y. This essentially means that the front is perpendicular to the flow lines. After 1986, the ice front north of Lindenberg Island differed increasingly from this stable geometry.
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25. A wind velocity of 49 knots results in a surface stres due to wind shear of ~1 N m^{-2}. For an undisturbe ice shelf of the size of the LIS, this force would b ~0.1 to 0.2% of the stress due to shear at the side walls. For the breakup of a heavily disturbed ice shel even these small forces due to wind may play a role as may the effects of wind on ocean circulation. A increased probability of calving events during per ods of persistent offshore winds and air tempera tures above 0°C has been reported for Arctic ic shelves [M. O. Jeffries, *Rev. Geophys.* **30**, 24 (1992)].
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DNA: An Extensible Molecule

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The force-displacement response of a single duplex DNA molecule was measured. The force saturates at a plateau around 70 piconewtons, which ends when the DNA has beer stretched about 1.7 times its contour length. This behavior reveals a highly cooperative transition to a state here termed S-DNA. Addition of an intercalator suppresses this transition. Molecular modeling of the process also yields a force plateau and suggests a structure for the extended form. These results may shed light on biological processes involving DNA extension and open the route for mechanical studies on individual molecules in a previously unexplored range.

Many biologically important processes involving DNA are accompanied by deformations of the double helix, and the ability of DNA to stretch "like a spiral spring in tension" (*1*, p. 739) was recognized long ago (*1–3*). The mechanics of DNA has regained interest in recent years as a result of the possibility of working with individual molecules. The extension of a duplex DNA molecule under the action of an external force was measured by Smith *et al.* (*4*) and compared to predictions of the wormlike chain model (*5*). In good agreement with this theory, these researchers observed that a force of 2 to 3 pN is able to stretch the DNA to 90% of its contour length at rest in the B-form, l_0 and that the force then rises sharply when the extension approaches l_0. This experiment was restricted to forces smaller than 20 to 30 pN, whereas it has been suggested that DNA is able to withstand about 500 pN before breaking (*6*). We present here a study of the force-extension response of a single duplex DNA molecule submitted to forces ranging from 10 to 160 pN, using an apparatus (Fig. 1) that improves on that developed by Kishino and Yanagida to study the actin-myosin interaction (*7*).

We repeated our experiment many times using different fibers and stretching velocities (a few seconds was typically required for stretching). Two types of curves were ob-

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