Appendix H

Global Climate Change

Table of Contents

Page

Page

Appendix H

Global Climate Change

Introduction

Thirty years of scientific research and ten years of intensive analysis and discussion have resulted in the development of a reasonably well accepted description of the global climate change problem. A number of the review boards (see Table 10) and other analysts (for instance, Mahlman, 1997) have reduced this description to a set of conclusions.

Based on the scientific literature, the following can be said:

- greenhouse gases efficiently absorb and reradiate infrared radiation;
- greenhouse gases are accumulating in the atmosphere;
- at current rates of emission, atmospheric levels of CO_2, the principal greenhouse gas, will almost double by 2100; a doubling will be realized by 2075 at current rates of increase in atmospheric concentrations, and about mid-century under business-as-usual evolution of the global energy system;
- if atmospheric concentrations of greenhouse gases are allowed to rise appreciably, climate will warm; the sole question is one of degree. With the sensitivity of climate near the lower end of the recommended range for doubled atmospheric levels of CO_2, it will still warm 1.5 to 2.5 degrees Celsius; if near the top end of this range of climate sensitivity, 5 degrees Celsius. A minimum level of warming is now unavoidable;
- it is warming;
- the warming that is forecast for the next 100 years is larger than anything in the record for periods of similar length;
- once initiated, the warming will persist for many hundreds of years;
- the surface warming is likely to involve large geographical shifts of existing climates and associated vegetation regimes;
- energy production is the principal present-day source of greenhouse gas emissions to the atmosphere;
- and, stabilization of atmospheric CO_2 levels in the atmosphere will require emissions reductions of 50 to 80% from present levels. Many decades of effort will be required to realize this end.

1.0 What Is The Global Climate Change Phenomenon?

Global climate change, as it is referred to today, is the human-induced change in the earth's climate that arises from greenhouse gases being emitted to and accumulating in the atmosphere. Human activities are releasing large new amounts of greenhouse gases into the atmosphere, with

the effect of intensifying the existing background greenhouse effect, raising the surface temperature of the earth, and changing the distribution and nature of regional climates.

The earth has a radiatively active atmosphere. It contains clouds that reflect incoming sunlight, thereby cooling the planet, particles that act to scatter sunlight, also cooling the planet, and infrared-active gases that absorb infrared radiation or heat. The principal infrared-active gases, known as greenhouse gases, include carbon dioxide (CO_2), water vapor (H_2O) and ozone (O_3). Together they create what is known as the background greenhouse of the planet, adding roughly 33 degrees Celsius to the mean surface temperature of the earth – creating the climate we consider "normal" today.

Greenhouse gases derive from a range of activities from energy production to agriculture. The central characteristic of greenhouse gases is the absorption of radiation in the long-wave or infrared part of the electromagnetic spectrum, in the same wavelengths in which the earth is emitting radiation to space. Greenhouse gases act to absorb a part of that emitted radiation, warming the surrounding atmosphere. This causes a large downward thermal emission from the atmosphere to the surface that results in increased surface heating and elevated surface temperatures.

The effect is to intensify the background greenhouse effect by about 10 percent, and to raise surface temperatures 3 to 4 degrees Celsius above background greenhouse gas levels.

Climate, as it is experienced by people, results from both surface heating and the motions of the atmosphere. The motions of the atmosphere fall into fairly recognizable patterns that result principally from the geographical distribution of surface heating. The polar regions are cold, tropical latitudes are warm. Oceans are sometimes warmer than land masses, sometimes cooler. The earth's atmosphere acts like a giant heat engine, moving heat from areas of excess to areas of deficit, and in the process creating what we know as weather and climate.

Global warming is altering the geographical distribution of surface heating, resulting in a broad redistribution of climates in as little as 100 years. Effects are expected to be particularly profound on ecological systems.

1.1 What Are The Principal Greenhouse Gases?

The principal greenhouse gases that are emitted by human activities are:
- carbon dioxide (CO_2),
- methane (CH_4),
- nitrous oxide (N_2O),
- tropospheric ozone (O_3), and
- CFC-12, a synthesized compound that is part of a larger class of compounds called chlorofluorocarbons (CFCs).

Greenhouse gases of lesser significance include:
- Other CFCs (CFC-11, CFC-113),
- HCFC-22,
- HFC-134a,
- carbon tetrachloride (CCl_4),

- methyl chloroform (CH_3CCl_3),
- carbon tetrafluoride (CF_4),
- perfluoroethane (C_2F_6), and
- sulfur hexafluoride (SF_6).

HCFC-22 is of a class of compounds known as hydrochlorofluorocarbons. HFC-134a is of a class of chemical compounds corporately known as hydrofluorocarbons. C_2F_6 and CF_4 are part of a class of compounds known as perfluorocarbons.

As noted above, water vapor is a naturally occurring greenhouse gas.

1.2 Where Do Greenhouse Gases Come From?

The principal anthropogenic or human sources of greenhouse gas emissions are shown in Table 1.

Carbon Dioxide (CO_2)
The principal source of emitted CO_2 is fossil fuel combustion. The clear-cutting of forests and the sustained cultivation of agricultural soils also can contribute to rising atmospheric CO_2 levels. The manufacture of cement using limestone also results in a measurable emission of CO_2 to the atmosphere.

Methane (CH_4)
Methane (CH_4) derives from the anaerobic decay of organic matter in oxygen-deprived reducing environments, and from a number of fossil fuel sources, including underground and surface coal mines, oil and natural gas production, and natural gas transmission and distribution. Anaerobic decay of organic matter leading to the production of CH_4 takes place in swamps, marshes, peat bogs, lake sediments, and, in the case of managed human systems, in mixed municipal solid waste landfills, the digestive tract of ruminant cattle, liquid manure storage ponds and pits, and rice paddies. Biomass burning also can produce CH_4.

Nitrous oxide (N_2O)
Nitrous oxide (N_2O) is produced principally in soils by bacteria. Soil bacteria gain energy by reducing nitrate and nitrite to simpler forms of nitrogen. Depending on soil conditions, the production of N_2O often results. N_2O is also produced during bacterial nitrification activities, from which soil bacteria also gain energy. N_2O production increases linearly with the availability of soil nitrogen. Available nitrogen for bacterial activities derives from the preexisting pool of organic nitrogen found in soils, which upon mineralization is made available to bacteria. Large amounts of available nitrogen also are added to soils through the application of commercial fertilizers and livestock manure used as a soil amendment. Additional sources of added soil nitrogen include leguminous crops, crop residues, and atmospheric deposition.

Non-soil sources of N_2O emissions include biomass burning and coal combustion and emissions from stacked solid livestock manure.

Chlorofluorocarbons (CFCs)
Chlorofluorocarbons (CFCs) are synthetic compounds that do not exist in nature. They are emitted upon the intentional use and leakage or venting of the compounds. In the past, the CFCs were used as solvents in metal cleaning and the cleaning of electronic equipment, as blowing agents in the manufacture of plastic cushioning foams and insulating gases in plastic insulating foams, and as refrigerants in residential and commercial refrigeration and air conditioning equipment. The CFCs are known stratospheric ozone depleters. As such, the production of CFCs in the US was banned as of 1995. Small quantities continue to be emitted from pre-1995 stocks, particularly slow-release insulating foams. In the developing world, production and use of CFCs remains permissible.

Hydrochlorofluorocarbons (HCFCs)
Hydrochlorofluorocarbons (HCFCs) were developed in the 1970s and 1980s as substitutes for the CFCs in industrial, commercial and residential applications. While not as effective as the 'hard' CFCs (CFC-12, CFC-11, CFC-113) in depleting stratospheric ozone, an effect on stratospheric ozone levels has been identified. Under international agreements, the production and use of these compounds in developed economies is to be phased-out by 2030. As in the case of the CFCs, emissions result from intentional use and subsequent leakage or venting to the atmosphere. HCFCs are primarily used as cleaning solvents, insulating gases in plastic foams, and refrigerants. Within this class of compounds, the most important greenhouse gas is HCFC-22. Other HCFCs that may grow slightly in importance include HCFC-142b and HCFC-141b.

Hydrofluorocarbons are another class of substitutes for CFCs. At present, the most important of these is HFC-134a, a substitute for CFC-12 with widespread applications in motor vehicle air conditioning and residential and commercial refrigeration and cooling. Unlike the CFCs and HCFCs, in the atmosphere it does not negatively impact stratospheric ozone. However, like the HCFC-22 and CFC-12, HFC-134a is a potent greenhouse gas.

Chlorocarbons
Carbon tetrachloride and methyl chloroform belong to a class of chemical compounds known as chlorocarbons. These compounds have had primarily industrial applications, notably in metal cleaning. Like the CFCs, they are potent ozone depleters, and like the CFCs, the production and use of these compounds was banned in developed economies under the terms of the Montreal Protocol on Substances that Depleter the Ozone Layer. Use in industrial applications continues in developing economies.

Perfluorocarbons (PFCs)
C_2F_6 and CF_4 belong to a class of synthesized compounds known as perfluorocarbons (PFCs). C_2F_6 and CF_4 are produced principally as byproducts of the refining of aluminum. C_2F_6 also has industrial applications in the etching of semiconductor chips. Sulfur hexafluoride is used in circuit breakers and other electronic equipment. It is released to the atmosphere through inadvertent leakage or purposeful venting during the servicing of equipment.

Nitrogen oxides (NO_x)
Nitrogen oxides (NO_x) are produced during high temperature combustion of fossil fuels. The combustion of petroleum-based fuels in internal combustion is a large emitter of NO_x. Stationary source coal combustion is also a large emitter of NO_x. NO_x is also produced in soils

by facultative soil bacteria following the input to soils of commercial fertilizer and other sources of nitrogen. Biomass burning also contributes to global NO_x emissions.

Ozone (O_3)

Ozone (O_3) in the troposphere is produced from the photochemical interaction of volatile organic compounds (VOCs) with nitrogen oxides (NO_x). Sources of VOCs are more heterogenous. In Minnesota, most VOC emissions result from the combustion of petroleum-based fuels in internal combustion engines and industrial solvent use. Fugitive losses from gasoline service stations and residential wood combustion also contribute.

Water Vapor

Finally, water vapor is naturally occurring. Its tropospheric concentration is largely a function of lower tropospheric and surface heating. In cool climates, its tropospheric concentration is quite low, while in warm tropical climates it can comprise up to 2% of the troposphere by volume. In the stratosphere water vapor is a very potent greenhouse gas. Water vapor accumulates in the stratosphere through the atmospheric build-up of methane and its oxidation at high altitudes.

Table 1. Principal Anthropogenic Sources of Greenhouse Gases

Carbon Dioxide
Fossil Fuel Production and Combustion
Deforestation
Soil Nutrient Management
Cement Manufacture

Methane
Rice Cultivation
Enteric Fermentation in Livestock
Manure Management
MMSW Landfills
Coal Mining
Natural Gas Production and Transmission
Biomass Burning

Chlorofluorocarbons
Cooling and Refrigeration
Plastic Insulating Foams
Manufacture of Plastic Cushioning Foams
Solvent Uses

Ozone Precursors
Fossil fuel combustion
Industrial Processes
Biomass Burning
Soils Nutrient Management

Nitrous Oxide
Soil Nutrient Management
Manure Management
Biomass Burning
Coal Combustion

Perfluorocarbons
Aluminum Manufacture
Semiconductor Manufacture

Hydrofluorocarbons
Cooling and Refrigeration

Hydrochlorofluorocarbons
Cooling and Refrigeration
Solvent Use
Plastic Insulating Foams

Chlorocarbons
Metal Cleaning

Sulfur Hexafluoride
Electrical Equipment

1.3 What Are Atmospheric Concentrations Of Greenhouse Gases?

Water vapor constitutes about 1% of the troposphere by volume. CO_2 constitutes 0.037% of the atmosphere by volume (370 parts per million by volume), or, in terms of atmospheric mass, about 2,750 billion metric tons of CO_2 (750 billion tons of carbon). As noted above, together, these two gases account for the overwhelming bulk of greenhouse gas absorbers in the atmosphere, accounting for most of the natural background greenhouse effect.

CH_4 concentrations are 1,693 parts per billion by volume (ppbv). This represents about 0.00017% of the atmosphere. Atmospheric levels of N_2O are 311 ppbv, which represents 0.00003% of the atmosphere by volume. Atmospheric levels of ozone are about 50 ppbv. Next to CO_2, CH_4, N_2O and ozone are the most important non-water vapor greenhouse gas absorbers in the present atmosphere.

Concentrations of the lesser greenhouse gases like the CFCs, HCFCs, HFCs and PFCs are much smaller, typically measured in parts per trillion. In aggregate they comprise about 0.0000001% of the atmosphere by volume. Concentrations of CFC-12, the most important of these synthetic compounds are about 530 pptv.

1.4 Have Atmospheric Levels Of Greenhouse Gases Been Rising?

Current atmospheric concentrations of the principal greenhouse gases are shown in Table 2. Also shown for each gas is the current annual rate of increase in concentration and the percentage change in concentration since the beginning of the industrial era. Atmospheric levels of greenhouse gases have been monitored for between 10 and 45 years, depending on the compound. Earlier concentrations can be determined from air bubbles trapped in ice and ice sheets in high latitudes.

The present atmospheric concentration of CO_2 is 370 ppmv. CO_2 levels are currently increasing in the atmosphere about 1.5 ppmv per year or 0.4% per year. Since about 1800 AD, atmospheric levels of CO_2 have risen about one-third, from a pre-industrial concentration of 275 ppmv. Over that time, roughly 750 billion metric tons of CO_2 (200 billion tons of carbon) has been added to the atmosphere. Since, next to water vapor, CO_2 is the most important gas contributing to the large background greenhouse effect of the earth, this is significant. The current rate of build-up of CO_2 in the atmosphere continued just ten years is sufficient to warm the earth 0.15 degrees Celsius. This is because, although on a per molecule or per ton basis CO_2 is a weak infrared-absorber in comparison to some of the other greenhouse gases, in practice, due to its large background concentration, almost any measurable increase in concentration is climatically significant.

Less is known about changes in tropospheric water vapor. Systematic measurements have only recently been instituted. Long-term records for precipitation over land suggest a long-term increase in tropospheric water vapor of some level (Dai, *et al*, 1997).

Atmospheric concentrations of CH_4 are increasing about 0.4% per year. Concentrations of CH_4 have increased about 140% since pre-industrial times. Over the same period, levels of N_2O have

risen about 13%, with a recent rate of increase of 0.3% per year. Evidence indicates that tropospheric ozone levels have approximately doubled since pre-industrial times (IPCC, 1994).

For purely synthetic compounds, like the CFCs, HCFCs, HFCs, PFCs, and chlorocarbons, with no pre-industrial concentrations, atmospheric levels have increased to the part per trillion to hundred part per trillion level since pre-industrial times. Atmospheric concentrations of some of these are currently increasing, and some have stabilized or are now slightly decreasing. Particularly rapid growth in concentrations have been noted for substitute compounds for the CFCs, compounds like HFC-134a and HCFC-22. Concentrations of the most important of the CFCs, CFC-12, are increasing about 0.7% per year, while concentrations for the other CFCs are slightly declining.

Table 2. Changes in Greenhouse Gas Concentrations in the Atmosphere Since the Pre-industrial Period

	Current Concentration	% increase from pre-industrial	Current Rate of Increase (%/year) [a]
CO_2	367 ppmv	33	0.4
CH_4	1,693 ppbv	142	0.4
N_2O	311 ppbv	13	0.2
O_3	50 ppbv	100	NA
CFC-11	259 pptv	No preindustrial levels	-0.4
CFC-12	530 pptv	No preindustrial levels	0.7
CFC-113	82 pptv	No preindustrial levels	-1.2
CCl_4	96 pptv	No preindustrial levels	-1
CH_3CCl_3	64 pptv	No preindustrial levels	-12.3
HCFC-22	100 pptv	No preindustrial levels	4
SF_6	32 pptv	No preindustrial levels	6.5
CF_4	70 pptv	No preindustrial levels	NA
C_2F_6	4 pptv	No preindustrial levels	NA

[a] mean annual value for most recent 10-year period for non-ozone depleting compounds

NA=not available

Sources: World Resources Institute (2000), J. Butler, *et al.,* (1999), Sturges, *et al.,* (2000), R. Prinn, *et al*., (2000), IPCC (1996)

1.5 How Long Do Greenhouse Gases Remain In The Atmosphere?

Depending on the gas in question, once emitted to the atmosphere, greenhouse gases persist in the atmosphere for between five years and thousands of years. This depends on removal mechanisms. For a gas like CO_2, multiple removal mechanism are involved, some acting rapidly, and some over periods of hundreds years.

Atmospheric residence times for the most important greenhouse gases are assembled in Table 3. For CO_2, this is an adjustment time, the amount of time for an atmospheric concentration to

decline to about one-third of initial levels. It is dependent on assumed long-term background concentration. At concentrations that are thought likely to prevail in the next century, this adjustment time is long, more than 500 years.

For N_2O, the estimated atmospheric lifetime is 120 years, and for CFC-12, about 100 years. CH_4 remains in the atmosphere for less time, a decade, HFC-134a about double that. SF_6 has an estimated atmospheric lifetime of 3,200 years, and CF_4 an estimated 50,000-year atmospheric lifetime.

Also shown in Table 3 are what are called global warming potentials (GWP). This is a measure of the relative effect of an emission of any of the greenhouse gases, accounting for both the intensity of infrared absorption of each and their respective atmospheric lifetimes. Greenhouse gases differ in their absorption of infrared radiation. Absorption depends on the strength of absorption bands. Infrared absorption also depends on the wavelength of absorption and concentrations of other trace gases that may absorb at the same wavelength. By accounting for the atmospheric lifetimes and infrared absorption characteristics of each of the greenhouse gases, it is possible to develop an index of relative effect of emissions.

The values given in Table 3 are referenced to equivalent emissions of CO_2. Thus, accounting for both radiative absorption and atmospheric lifetime, one ton of emitted methane (CH_4) is said to have roughly the same effect on surface temperature as 21 tons of CO_2. A one ton emission of N_2O would be equivalent to 310 tons of CO_2. For a compound like SF_6, the equivalent of one ton of emissions would be some 23,900 tons of CO2. Other compounds fall intermediate between these two levels of equivalent CO_2-effect.

Table 3. Atmospheric Lifetimes and Global Warming Potentials of Principal Greenhouse Gases

Chemical Compound	Current Atmospheric Lifetime (years)	Global Warming Potential
CO_2[a]	>500	1
CH_4	12	21
N_2O	120	310
CFC-11[b]	50	3,800
CFC-12[b]	102	8,100
CFC-113[b]	85	4,800
HCFC-22[b]	13	1,500
Carbon Tetrachloride	42	1,400
Methyl chloroform	5	100
HFC-134a	14.6	1,300
CF_4	50,000	6,500
C_2F_6	10,000	9,200
SF_6	3,200	23,900

[a] for an atmospheric concentration increase leading to ultimate stabilization at 650 ppmv
[b] direct radiative effects only
Sources: Intergovernmental Panel on Climate Change (1996), Intergovernmental Panel on Climate Change (1994).

1.6 Do Greenhouse Gases Have Effects Other Than Climate Change?

CO_2 is absorbed into the upper layer of the earth's oceans. This acts to raise the acidity of ocean water in the surface layer. Among other systems, coral is sensitive to acidity. Rising levels of acidity in the ocean are suspected as one cause of global coral reef decline. (Kleypas, *et al*., 1999)

On the positive side, elevated atmospheric CO_2 acts to accelerate plant growth and to reduce water stress. This acts to raise agricultural productivity.

As noted above, chlorofluorocarbons, HCFCs and chlorocarbons act catalytically to destroy ozone. This allows the enhanced penetration of ultraviolet radiation through the atmosphere to the surface of the earth. Human exposures to ultraviolet radiation has been linked to elevated rates of skin cancer, including melanoma, which is often lethal, higher rates of cataract formation, and other eye disorders.

N_2O and CH_4 are minor contributors to ozone depletion in the stratosphere.

Ozone is a lung irritant at ground level. Effects of short-term exposure include: inflammation of lung tissue and reduced lung function. Long-term exposure acts to increase susceptibility to respiratory disease and contributes to permanent structural damage to the lungs. NO_x has similar effects on pulmonary function.

1.7 How Sensitive Is Climate To Greenhouse Gases?

The sensitivity of climate to greenhouse gases varies by gas. The sensitivity of climate to CO_2 is normally discussed in relation to doubled atmospheric levels of CO_2 and in relation to change in mean global surface temperature. From a wide variety of numerical models of the climate, the sensitivity of mean global surface temperature to doubled atmospheric levels of CO_2 has been determined to lie in the range of 1.5 to 4.5 degrees Celsius. Upon a doubling of atmospheric levels of CO_2, mean global surface temperature will rise between 1.5 and 4.5 degrees Celsius. The relationship of temperature to concentration is logarithmic; each doubling of concentration will raise mean global surface temperature 1.5 to 4.5 degrees Celsius. Thus a doubling of the pre-industrial concentration of CO_2 to 540 ppmv would result in a 1.5 to 4.5 degrees Celsius warming. A doubling of that to 1,100 ppmv would result in an additional 1.5 to 4.5 degrees Celsius warming.

Early estimates of climate sensitivity were developed using simplified one-dimensional climate models. Developed in the 1970s and early 1980s, these early estimates of climate sensitivity tended to cluster near the lower end of the 1.5 to 4.5 degrees Celsius range found in the literature for doubled CO_2 (MacCracken and Luther, 1985).

Few recent estimates of climate sensitivity, developed using the most advanced models of climate called general circulation models (GCMs), fall below 2 degrees Celsius per doubled atmospheric levels of CO_2. Most recent estimates fall into the range of 2 to 3.5 degrees Celsius for each doubling of atmospheric CO_2 (IPCC, 1996, LeTreut and McAvaney, 2000).

The sensitivity of surface temperature to doubled atmospheric concentrations of CH_4 is estimated to be about 0.2 to 0.6 degrees Celsius. The relationship of mean global surface temperature to methane concentration is near-logarithmic. The same is true for N_2O. The sensitivity of mean global surface temperature to doubled atmospheric level of N_2O is 0.3 to 0.9 degrees Celsius. The sensitivity of mean global surface temperature to each 1 ppbv increase in atmospheric concentration of CFC-12 is 0.1 to 0.3 degrees Celsius. Climate sensitivities for the most important greenhouse gases are shown in Table 4.

Table 4. Climate Sensitivity for Greenhouse Gases

Compound	Increase	Sensitivity of Mean Global Surface Temperature [a] (degrees Celsius)
CO_2	2x	1.5 to 4.5
CH_4	2x	0.2 to 0.6
N_2O	2x	0.3 to 0.9
CFC-11	1 ppbv increase	0.08 to 0.23
CFC-12	1 ppbv increase	0.1 to 0.29
CFC-113	1 ppbv increase	0.1 to 0.29
CCl_4	1 ppbv increase	0.04 to 0.1
CH_3CCl_3	1 ppbv increase	0.02 to 0.05
HCFC-22	1 ppbv increase	0.07 to 0.2
HFC-134a	1 ppbv increase	0.06 to 0.18
CF_4	1 ppbv increase	0.04 to 0.1
C_2F_6	1 ppbv increase	0.08 to 0.24
SF_6	1 ppbv increase	0.02 to 0.07

[a] CFCs, HCFCs, HFC and PFCs calculated from the radiative forcings given in IPCC (1996) at 0.35 to 1°C Wm^{-2}

Source: IPCC (1996), IPCC (1994)

Using these estimated climate sensitivities to changed atmospheric greenhouse gas levels, it is possible, given some scenario of future change in greenhouse gas concentrations, to roughly estimate the level of mean global surface warming that might result. Table 5 gives the results for a condition in which atmospheric CO_2 levels double from current levels and levels of the other greenhouse gases evolve in a manner that is roughly consistent with present trends or recent forecasts.

Table 5. Climate Response to a Hypothetical Rise in Atmospheric Greenhouse Gas Levels

Greenhouse Gas	Increase	Rise in Mean Global Surface Temperature (degrees Celsius) [b]
CO_2	2x[a]	2.5
CH_4	2x[a]	0.3
N_2O	50%[a]	0.2
CFC-11, CFC-12, CFC-113	-75%	-0.1
Chlorocarbons and HCFC-22	-75%	-0.02
HFC-134a	+0.8 ppbv[a]	0.1
PFCs and SF_6	+0.25 pptv (all)	005 to 0.1
Total		**3.1**

[a] approximate level from IPCC case IS92a
[b] calculated at a climate sensitivity of 2.5°C per doubled atmospheric CO_2

2.0 Is There Evidence Of Global Warming?

Numerous indicators provide evidence that global warming is occurring. Instrumental records of surface, oceanic and the lower troposphere temperatures for the past 150 years show a distinct warming trend. Sea levels have risen over the past 100 years and most mid-latitude glaciers are in retreat. Reconstructions of long-term surface temperatures (500 to 100 years) provide evidence of pronounced climate stability over the pre-industrial era, marked by a very compressed range of natural variability, and pre-industrial temperatures substantially lower than modern normals, followed by rapid 20th century warming.

2.1 What Does The Instrumental Temperature Record Tell Us?

Surface temperature is measured using thermometers on land and, for sea surface temperatures, measurements of sea water temperature taken by ocean-going ships or, in less traveled waters, buoys. Satellite remote sensing is also used to derive sea surface temperatures. Temperatures of the free troposphere are measured using balloon-based temperature-sensing instruments that radio readings to the surface or satellite instruments that derive tropospheric temperatures from atmospheric radiances.

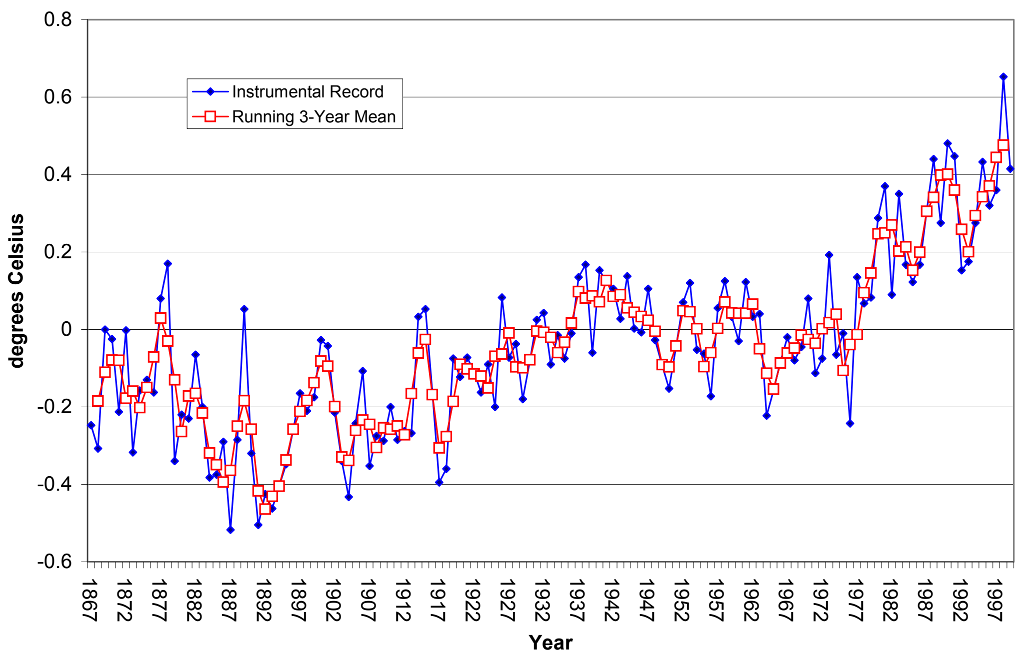
Longer-term pre-industrial records have been developed using proxy indicators of trends in surface temperature. Some of the indicators used to develop these longer-term records include: tree rings, isotopes of various elements incorporated in oceans corals or trapped in air bubbles in ice; pollen preserved in lake and ocean sediments; evidence of glacier advance or retreat; and historical evidence of agricultural crops cultivated, crop yields, and lake freeze and thaw.

Trends in mean global surface temperature are the best evidence of global climatic change. Mean global surface temperature is the temperature of the air at the surface averaged over all locations above the surface. This requires adequate spatial coverage in the measurement network.

Temperature records have been developed for the surface of the earth, a range of depths of the atmosphere, and ground and deep ocean temperatures.

The instrumental record of surface temperature over global land surfaces is shown in Figure 1. A marked warming trend is evident in this 133-year land record. Since 1867, the earliest year in the record, mean surface temperature over global land surfaces has risen about 0.8 degrees Celsius. This has occurred in two distinct phases, an initial warming of about 0.4 degrees Celsius from 1910 to 1940, followed by a second period of warming of a similar amount from 1980 to the present.

Figure 1. Departures of Mean Surface Temperature Over Land from Modern Climatological Normals (GISS, 1999)

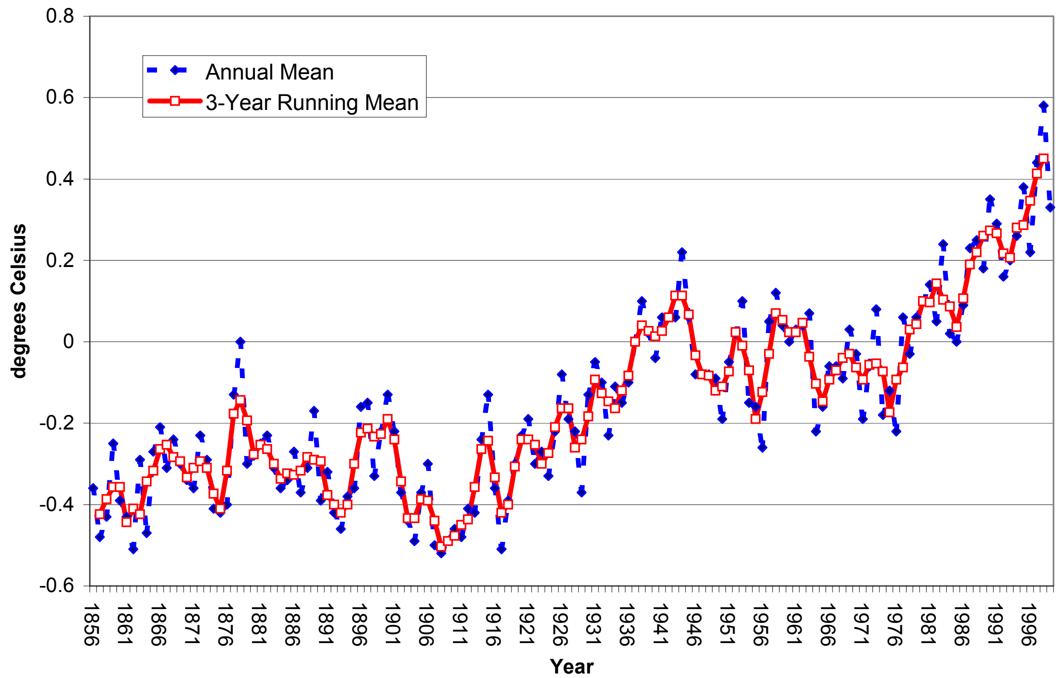


As noted above, it is possible to develop a composite surface temperature record using meteorological station data for surface temperature over land, and, for surface temperature over oceans, historical sea surface temperature records from ships of opportunity and, more recently, satellite data remote sensing.

The combined surface temperature record for land and oceans is shown in Figure 2. This record closely mirrors the record shown in Figure 1 for meteorological stations on land. Since 1856, the earliest year of the record, mean global surface temperature over land masses and oceans has risen 0.8 to 0.9 degrees Celsius, mostly in two phases of warming—0.4 degrees Celsius between 1920 and 1945, and 0.5 degrees Celsius from 1975 to 2000. For the first roughly 65 years of the record, prior to 1920, mean global surface temperature was quite stable. More recently, the rate of global surface warming has averaged about 0.2 degrees Celsius per decade.

The estimated level of uncertainty in this record, it might be noted, is on the order of +/-0.1 degrees Celsius for the last 40 years of data, and +/-0.18 for the 1850 to 1900 component of the record (Jones*, et al.,* 1997, NAS, 2000).

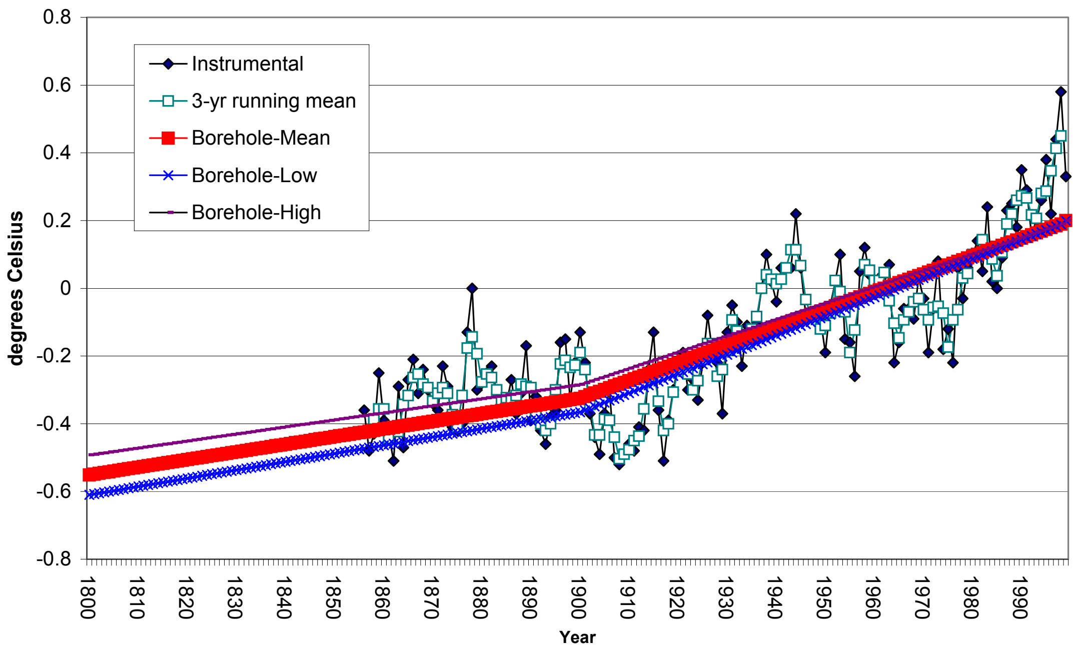
Figure 2. Departures of Mean Global Surface Temperature from 1960-90 Climatological Normals (Jones, et al., 1999)



The principal source of surface inputs of heat to soils and subsurface bedrock is the atmosphere. For this reason, the pattern of ground temperatures with depth often constitutes an excellent natural record of surface air temperature going back even as long as several hundred of years in the past.[1] Figure 3 shows a record of mean surface temperature over land for the last 200 years, as developed from studies of ground temperatures with depth. Also shown is the instrumental record for land and oceans from Jones, *et al*., (1999), as fit to the 'boreholed' data by Pollack, *et al.*, (1999). As is clear from Figure 3, the best available natural records also show global warming well underway.

[1] Borehole studies use the pattern of ground temperature with depth to estimate atmospheric heat input to soils and bedrock. Ground temperature declines with depth. Given a constant surface input of heat, ground temperatures decline linearly with depth. Given a more variable source of heat input across time, the pattern of ground temperatures with depth departs from linearity. Using the measured rate of decline of ground temperature with depth, it is possible to calculate the level of surface heat input to soils and bedrock going back in time hundreds of years. Essentially, levels of heat input are calculated such that, given the equations that govern heat transport, it is possible to replicate the pattern of ground temperature with depth.

Figure 3. Departures of Mean Surface Temperature from Modern Climatological Normals from Borehole Studies (Pollack et al.,, 1998)

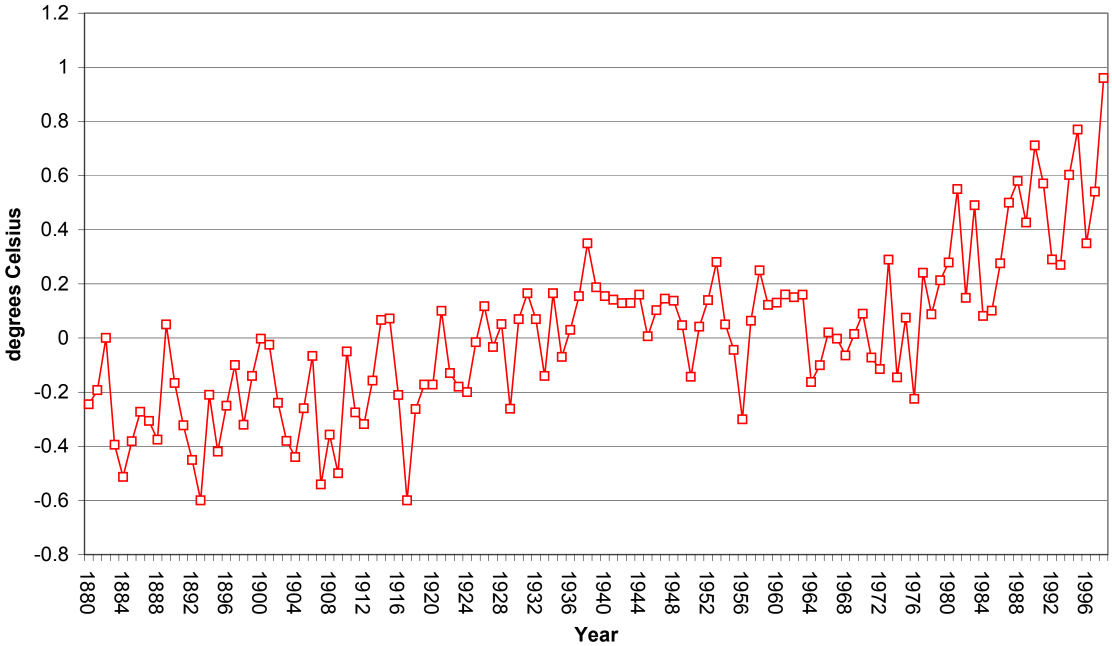


Returning to the instrumental record, Figure 4 shows the instrumental record for surface temperature over land for rural meteorological stations. Mean annual surface temperature at these rural locations has increased about half a degree Celsius, or about the same as in the record for all meteorological stations, rural and urban. This is significant in that these rural stations provide a measure of warming over land surfaces that is largely insulated from the effects of increasing urbanization. It has been suggested by some that the warming trend found in the surface temperature record might be an artifact of the location of meteorological stations in increasingly urban areas (Michaels and Stooksbury, 1992).

Since the atmosphere is the principal source of surface heat inputs to soils and bedrock, this results in a record of heat input across time that can be translated to a record of prevailing surface temperature (see WDC-A, 1999, for more detail).

From these borehole studies, global temperatures have increased in the range of 0.5 to 0.8 degrees Celsius since pre-industrial times. These data, it might be noted, constitute a completely independent verification of the reality of the warming in the instrumental surface record.

Figure 4. Departures of Mean Global Surface Temperatures Over Land from Modern Climatological Normals From Rural Stations (Peterson, *et al*., 1999)



Regarding the geographical component of the warming, the mean annual surface temperature record by hemisphere is shown for Northern Hemisphere in Figure 5 and the Southern Hemisphere in Figure 6. In general, the warming has been slightly weighted toward the Northern Hemisphere, but still is evident in the instrumental record for both Northern and Southern Hemispheres.

Figure 5. Departures of Mean Annual Surface Temperature for the Northern Hemisphere from Modern Climatological Normals (Jones, et al., 2000)

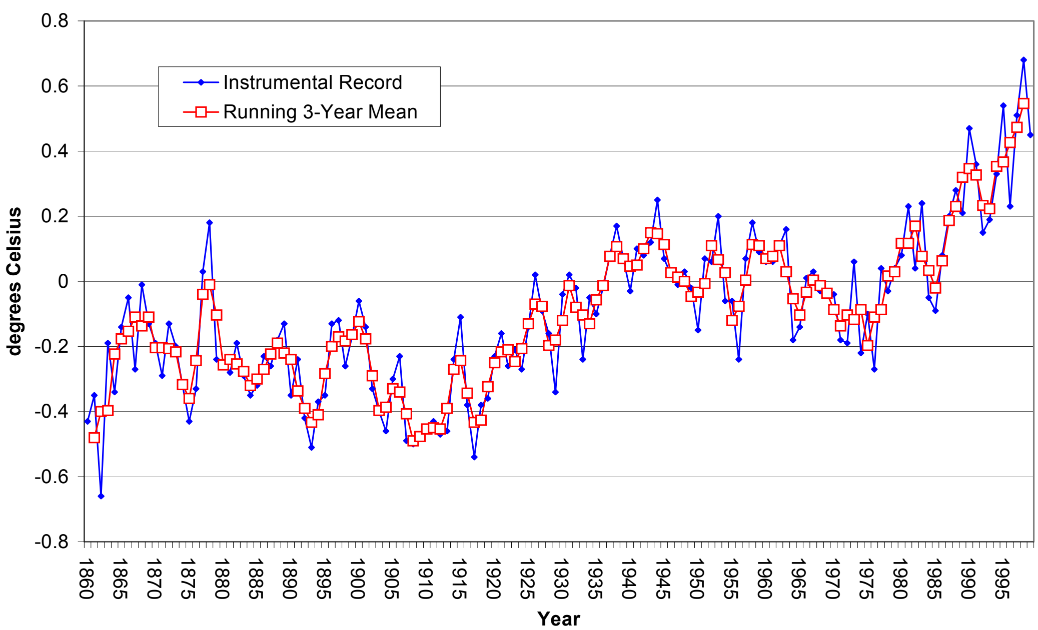
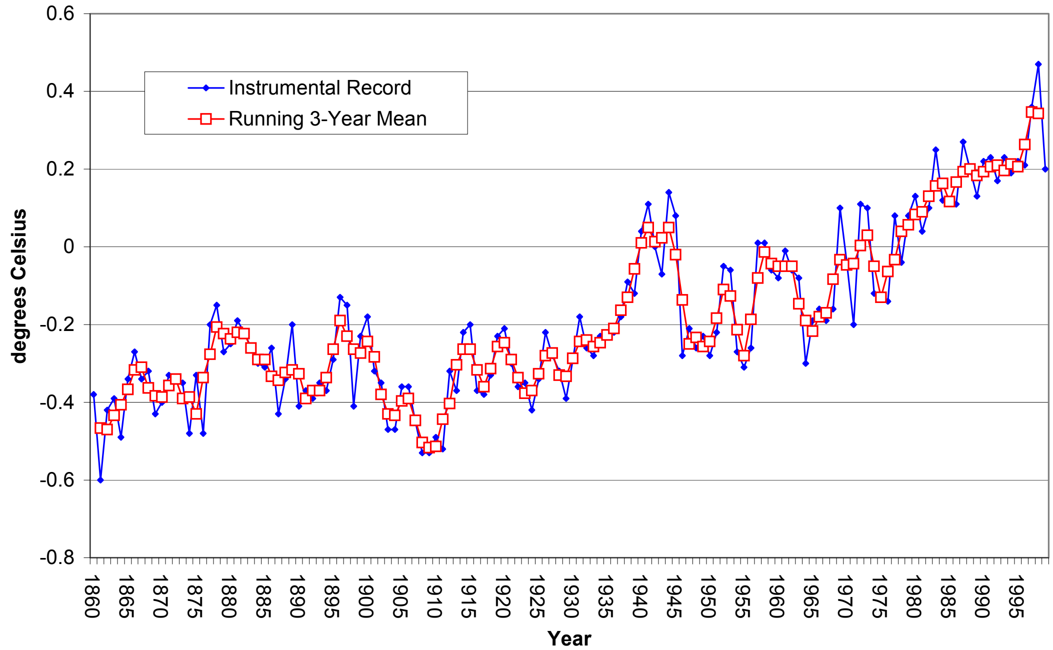
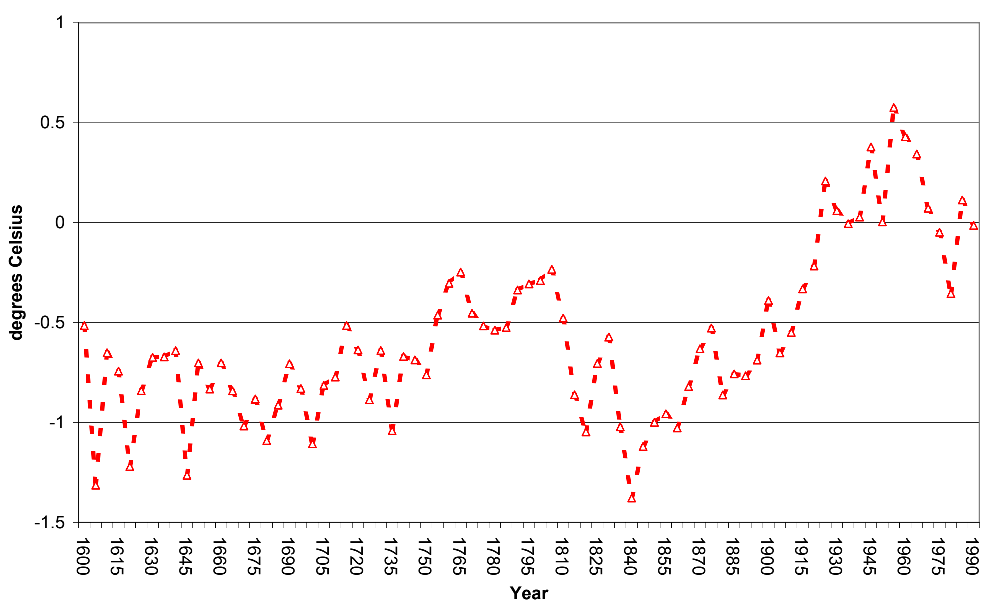


Figure 6. Departures of Mean Annual Surface Temperature for the Southern Hemisphere from Modern Climatological Normals (Jones, et al., 2000)



All latitudes have experienced surface warming. Figure 7 shows a 400-year record of surface temperature for the Arctic basin. From this reconstruction, which was developed both from instrumental records and from a range of proxy indicators of mean annual temperature across the basin, the Arctic has warmed between 1 and 1.5 degrees Celsius since the beginning of industrialization. Of all earth's climates, the climate of the Arctic is thought to be the most sensitive to an intensifying greenhouse effect.

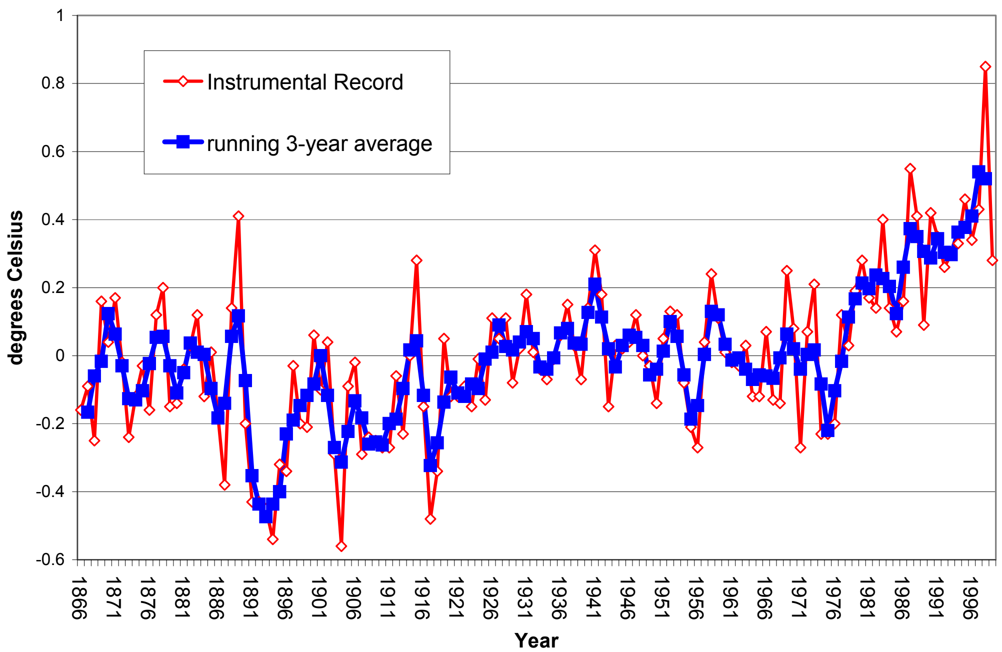
Figure 7. Departures of Mean Annual Arctic Temperature from Modern Climatological Normals (Overpeck, et al., 1997)



Trends in mean annual surface temperature for tropical latitudes 24N to 24S are shown in Figure 8. Since 1867, these latitudes have experienced a warming of more than 0.5 degrees Celsius. In the few proposals in the scientific literature for a naturally dampened greenhouse warming, cooling in tropical latitudes from large-scale upper atmospheric drying is required to offset warming elsewhere (Lindzen, 1990). From Figure 8, no offsetting tropical cooling is evident anywhere in the record.

Due to the large surface area between latitudes 24N and 24S, trends in tropical temperatures necessarily dominate the mean global record.

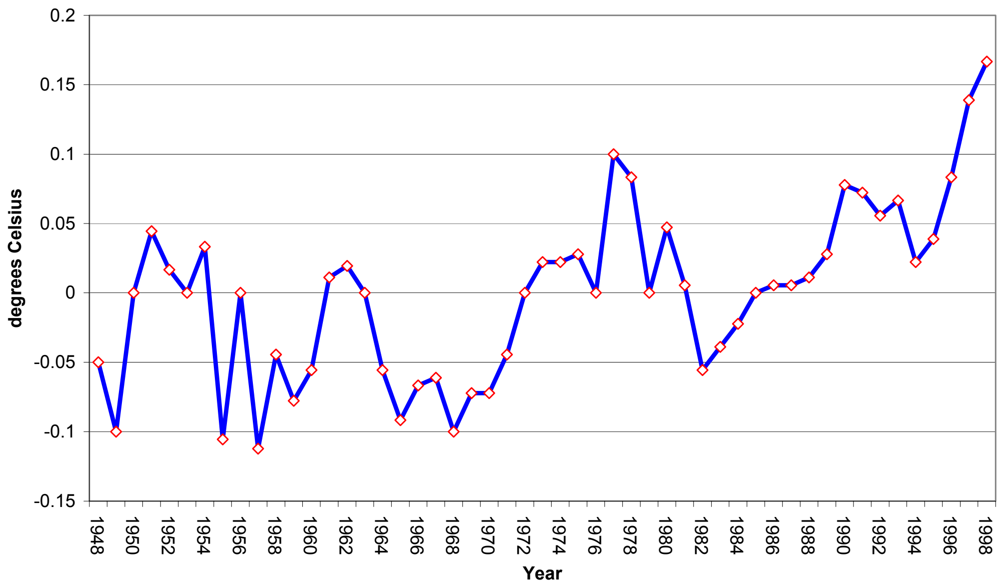
Figure 8. Departures of Mean Annual Tropical (24N to 24S) Land-Ocean Temperatures from 1960-1990 Climatological Normals (GISS, 1999)



Paralleling the surface record is a 50-year record of trends in ocean temperature at depths of 300 meters and two miles (Levitus *et al*., 2000). This shows a warming of 0.2 degrees Celsius in the top 300 meters (see Figure 9), and a 0.03 degrees Celsius warming to 2 miles in depth.

The energy input from the atmosphere required to raise ocean temperatures to this degree is estimated to be some 190,000 quadrillion btus of energy. This represents a substantial drain on the rate of atmospheric heating that otherwise would be expected in absence of oceanic warming. Essentially, heat that is withdrawn into the oceans to raise ocean water temperature is not available to warm the atmosphere. Based on these new data, since1950 an amount of atmospheric heating sufficient to raise mean global air surface temperature on the order of 0.5

Figure 9. Temperature Trend in the mixed Layer of the Atlantic, Pacific and Indian Oceans (Levitus, 2000)



degree Celsius has been drained off into the oceans (Kerr, 2000). With time, this oceanic heat sink will disappear as the oceans come to thermal equilibrium with the atmosphere.

That is the practical significance of these oceanic temperature data. Using these data, it is possible to estimate the degree of thermal disequilibrium between the atmosphere and the oceans, hence the amount of additional atmospheric warming above present levels that will be realized as global oceans reach thermal equilibrium with the atmosphere. From the above, this value is probably near one-half degree Celsius.

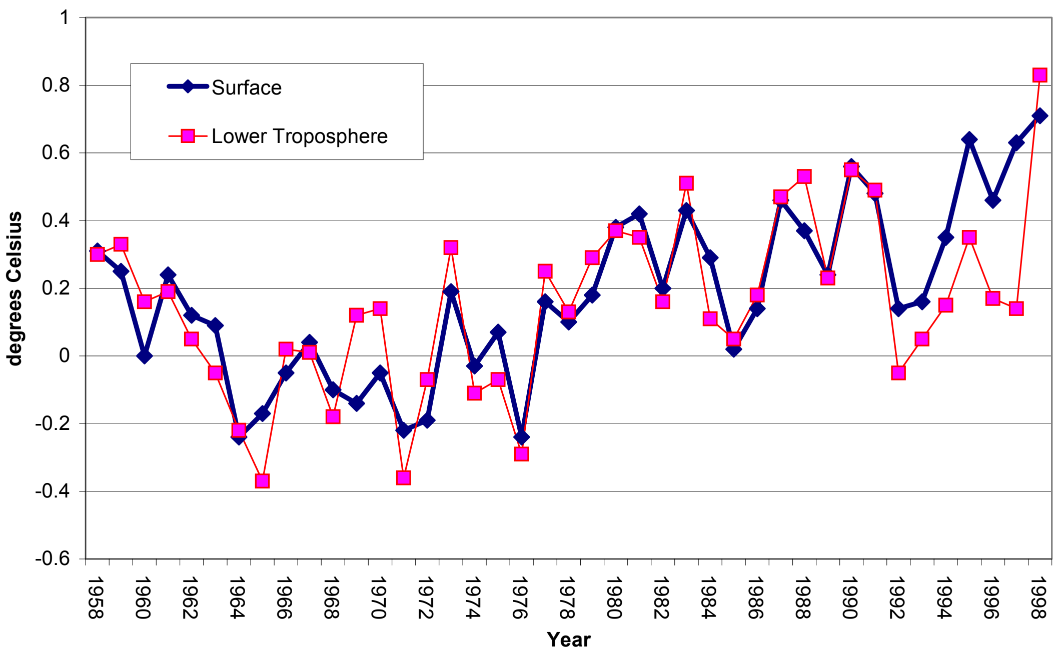
In and of itself, the record of ocean warming provides yet another indicator of systematic long-term warming of the planet. Sea surface temperature has been rising about 0.1 degrees Celsius per decade for about four decades (Lau and Weng, 1998).

To complete the discussion of the instrumental record for the last 150-years, Figure 10 shows a 40-year record of globally-averaged temperatures for the lower troposphere roughly 1 to 3 miles above the surface derived from balloon-based radiosonde instruments (Angell, 1999). As in the case of the surface and oceanic records, a distinct warming trend is evident. Since 1958, this layer of the atmosphere has been warming at an average rate of 0.1 degrees Celsius per decade.[2]

[2] A shorter record for the same thickness of the atmosphere also has been developed using remote sensing of atmospheric radiances by instruments on-board orbiting satellites. The satellite record extends from 1979 to the present, and hence covers only a part of the period covered by the radiosonde record shown in Figure 4. However, for the period of overlap, the two are in close agreement. Over this period, the average rate of warming of the lower troposphere in the satellite record has been less than 0.05 degrees Celsius per decade. It has been suggested by some scientists that the lack of evidence in the satellite-based record of substantial warming indicates a more generalized [2] absence of warming in the available record. However, given the pronounced upward trend in the longer radiosonde record, this is obviously incorrect.

There is now general consensus that a 20-year period of record is of insufficient length to allow the development of useful conclusions about long-term forcing of climate (Jones *et al*., 1999, NAS 2000). Over such a short period, long-term changes may be masked by internal variability of the climate system, or the effects of short-term nongreenhouse external forcings of climate.(NAS 2000) Longer records allow naturally occurring fluctuations to average out, allowing longer-term trends to become obvious. Possibly important short-term forcings in the 20-year record include volcanic aerosol loading or stratospheric ozone depletion (Santer, *et al*., 2000, Stendel, *et al*., 2000).

Figure 10. Departures from Climatological Normals for Different Thicknesses of the Atmosphere, 1958-1998(Angell, 1999)



2.2 What Are The Physical Indicators Of Global Warming?

In addition to the various instrumental records of air and ocean temperature, there is also available a number of physical indicators of substantial warming. A number of these are listed in Table 6. These range from changes in the thickness (-40%, 1958-present) and extent of the floating Arctic ice pack (-7%, 1978-present) to satellite observed lengthening of the period of vegetative growth throughout the Northern Hemisphere at latitudes 45-70N. It is expected that, while the surface of the earth warms as the result of an intensifying greenhouse effect, the stratosphere and middle atmosphere will cool markedly. These is evidence of exactly that type of systematic change in the vertical distribution of temperatures

Sea level has risen roughly about 20 centimeters over the last 100 years (IPCC, 1996). Sea level rise would be expected from any warming due to thermal expansion of the water column and melting of glaciers and at the margins of ice sheet.

Most mid-latitude glaciers are also in retreat. The recent trend in the rate of loss of mass from mid-latitude glaciers is shown in Figures 11 and 12 for Eurasian glaciers and glaciers of the Western Hemisphere, respectively. The figures show change in glacier vertical extent in meters of water-equivalent.

There is a trend in the mid-latitude record to long-term reductions in the seasonal length of lake ice cover, and a shorter-term satellite observation of increased vegetative growth and a lengthening of the growing season throughout the high middle and high latitudes of the Northern Hemisphere. Satellite altimetry, which measures the height of surfaces, reveals that between 1994 and 1999 the ice sheet on Greenland lost approximately 51 cubic kilometer of ice—an amount sufficient to cover the states of Delaware and Maryland with about 1 foot of ice.

Table 6. Indirect Indicators of Global Warming

Indicator	**Source**
Declining Arctic Sea Ice Extent	Johannessen, *et al*., 2000
Declining Arctic Sea Ice Thickness	Rothrock*, et al.,* (1999)
Decline in Antarctic Sea Ice Extent	de la Mare (1997)
Greenland Ice Loss	Krabill, *et al*., (2000)
Middle Latitude Glacier Recession	Oerlemans, (1994)
Global Sea Level Rise	IPCC (1996)
Global Coral Die-back	Goreau and Hayes (1994)
Lengthen Growing Season 45-70N	Myneni, *et al*. (1997)
Reduced Lake Ice Cover in Middle Latitudes	Magnuson, *et al*., (2000)
Changing Vertical Atmospheric Temperature Profile	Santer, *et al*., (1996)

Figure 11. Ice Loss from Retreating Melting Eurasian Glaciers from Mass Balance Analysis, 1978-1999 (World Glacier Monitoring Service, 2000)

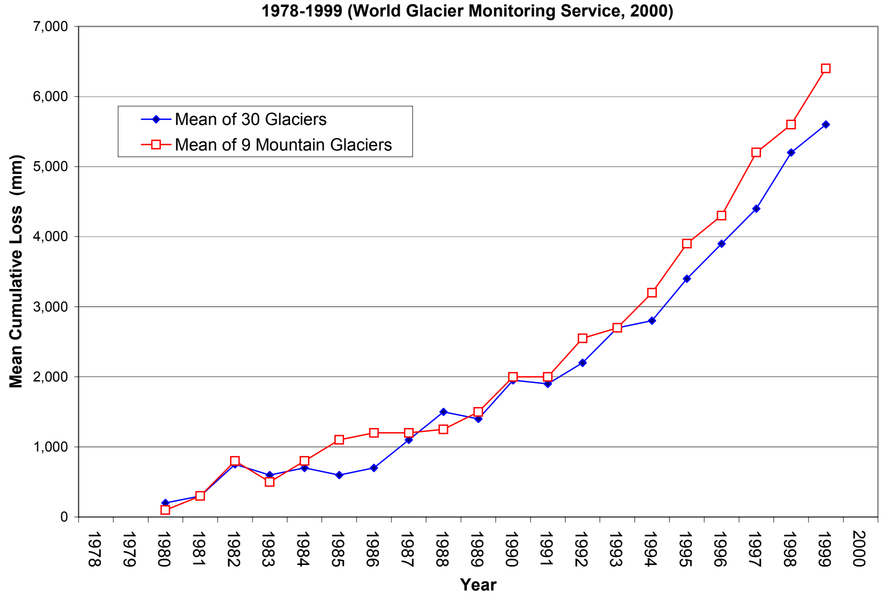


Figure 12. Ice Loss from Retreating Glaciers in North and South America, 1978-1999 (World Glacier Monitoring Service, 2000)

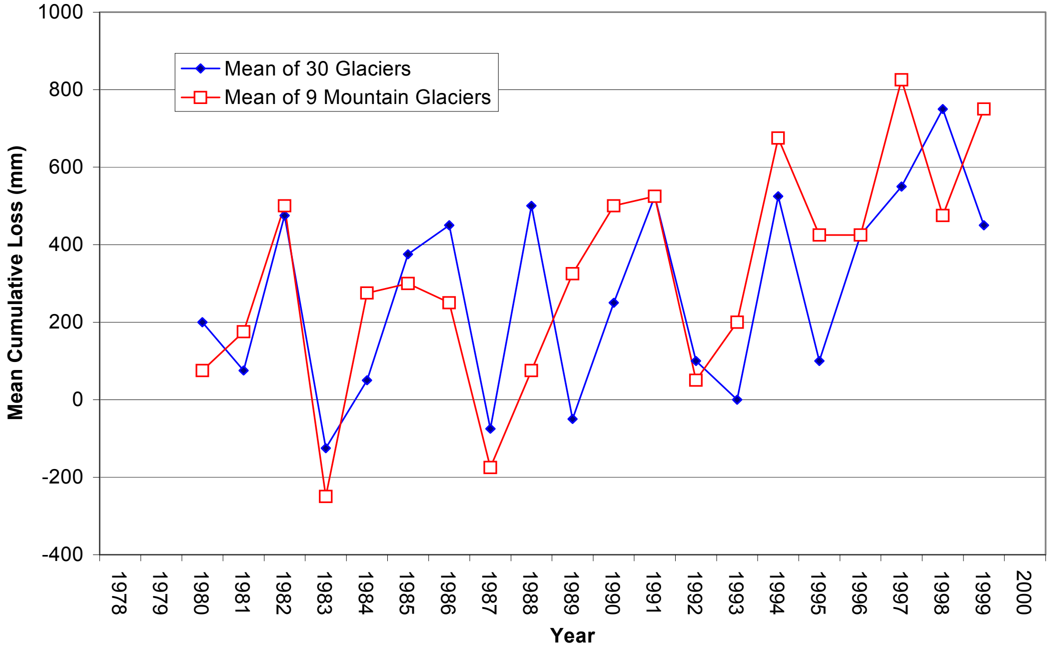
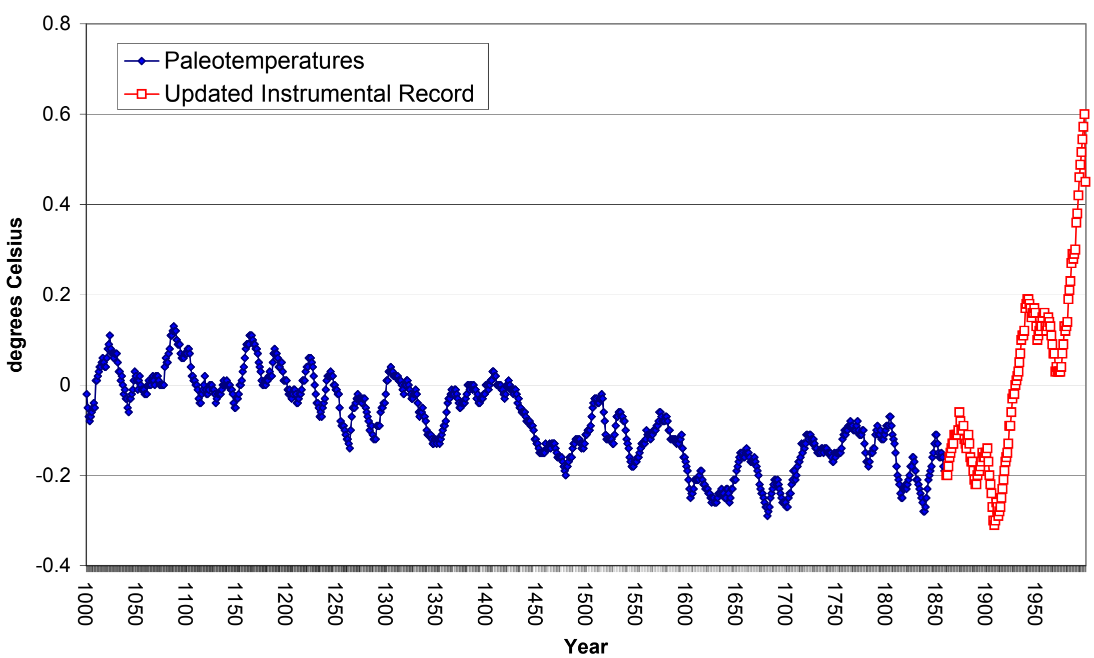


Figure 13. Departures of Mean Northern Hemispheric Surface Temperatures from Modern Climatological Normals (Crowley, 2000)



2.3 Has Mean Global Surface Temperature Moved Outside Of The Range Of Natural Variability?

The range of 100- to 200-year natural variability of unforced mean global surface temperature is about 0.2 to 0.4 degrees Celsius. This is smaller than the 150-year warming in the modern record by a factor of about 2 to 4, which implies that we probably moved outside of the range of natural variability sometime about mid-century (see, for instance, Grassl, 2000 or Crowley, 2000).

The very long-term surface temperature record is shown in Figure 13. This was developed from proxy indicators of surface temperature at a large number of locations widely distributed across the earth's land surface. To this, the instrumental record of surface temperature from Jones *et al*., (1998) has been appended.

The long-term surface record reveals the following:

- pre-industrial temperatures at a generally lower level than modern temperatures;
- a slow 800-year decline of mean annual surface temperature of about 0.05 degrees Celsius over the pre-industrial period;
- a narrow, compressed range of natural variation over periods of 250 to 300 years of 0.25 to 0.4 degrees Celsius and 0.4 to 0.5 degrees Celsius over the entire pre-industrial period;
- late 20th century temperatures far in excess of anything elsewhere in the record, including the 11th and 12th centuries, which even a few years ago were thought to have been characterized by substantial surface warmth (Hughs and Diaz, 1994);
- 20th century warming of 0.9 degrees Celsius that is completely discontinuous with what proceeded and is greater than the range of 1000-year natural variability found in the pre-industrial part of the record by about a factor of two to four.

Other reconstructions of long-term 500- to 1,000-year mean global surface temperature have come to similar conclusions. These are listed in Table 7. The type of proxy data on which these were based include: tree-rings, ice cores, corals, historical records of climatic phenomena like annual freeze and thaw of lakes or of crop yields and distribution, lake and marine sediments, and early modern instrumental records. Often, multiple sources of information were used to insure the absence of bias in the reconstruction. Common to all of these reconstructions is: evidence of very pronounced stability of climate over the pre-industrial era, marked by a very compressed range of natural variability; and pre-industrial temperatures substantially lower than modern normals, followed by rapid 20th century warming.

These conclusions are well established for the period going back to about 1600 A.D. Prior to that, the data are probably less reliable. However, even accounting for possible error in the earliest data still results in a pronounced 20th century warming from pre-industrial conditions. (Mann, *et al*., 1999) Evidence for the existence of an early medieval optimum around 1000 A.D, as warm or warmer than now, has been shown to be illusory (Hughs and Diaz, 1994).

Table 7. Paleoclimatic Reconstructions

Author	Geographical Scope	Length of Record
Jones, *et al*., (1999)	Global	1000 years
Pollack, *et al*., (1998)	Global	500 years
Huang, *et al*., (2000)	Global	500 years
Mann, *et al*., (1998)	Hemispheric (N. Hemisphere)	600 years
Mann, *et al*., (1999)	Hemispheric (N. Hemisphere)	1000 years
Crowley, (2000)	Hemispheric (N. Hemisphere)	1000 years
Bradley and Jones, (1993)	Hemispheric (N. Hemisphere)	600 years
Briffa, *et al*., (1998)	Hemispheric (N. Hemisphere)	600 years
Groveman and Landsberg, (1978)	Hemispheric (N. Hemisphere)	400 years
Overpeck, *et al*., (1997)	Arctic Basin	500 years

3.0 What Is The Forecast?

The Intergovernmental Panel on Climate Change has developed forecasts of future mean global surface warming based on analysis of energy systems, formal energy-economy modeling, trends in the emission of non-CO2 trace gases and other atmospheric constituents, and numerical climate models. The most recent forecast, to be published in 2001 as part of the Third Assessment report, will project a 2.8 degrees Celsius mean global surface warming by 2100. Previous IPCC forecasts projected warming at 2100 from 1990 levels of 3.1 degrees Celsius (4.2 degrees Celsius from 1765) with a range of uncertainty of 1.7 to 5.15 degrees Celsius (IPCC, 1990), and 2 degrees Celsius with a range of uncertainty of 0.8 to 4.5 degrees Celsius (IPCC 1995).

For 2050, the IPCC forecasts a warming from current levels of 1.2 degrees Celsius; earlier IPCC assessments forecast a 1.7 degree Celsius warming and 0.9 degrees Celsius mean global surface warming by 2050 from 1990 levels (IPCC, 1990, IPCC, 1995).

The best guess forecasts assume a 2.5 degrees Celsius climate sensitivity.

For purposes of comparison, forecasts of warming developed by the leading ‘climate skeptics’ are shown in Table 8, along with the implied climate sensitivity of each. In general, these are in good agreement with the consensus IPCC forecast.

Table 8. Forecasted Rise in Mean Global Surface Temperature From Greenhouse Gas Emissions: Estimates of 'Climate Skeptics'

	Forecast	Year	Implied Sensitivity
Michaels	2.3	2100[a]	2[b,c] C
Balling	1	2050	2[b] C
Lindzen	NA	NA	0.5-2 ° C

[a] presumably
[b] approximate
[c] Michaels also offers a 1.5 degree Celsius estimate in Pearce (1997)

Sources: Pearce (1997), Stevens (2000), Balling (1996)

As noted above, there is a substantial lag in the response of mean global surface temperature to rising atmospheric levels of CO_2 and the other greenhouse gases. This results from delays introduced by the large thermal inertia of the earth's oceans. Given this, it is appropriate also to evaluate the total mean global surface warming to which atmospheric greenhouse gas accumulations commit the earth over longer periods of time to 2150 and beyond.

Such an estimate is shown in Table 9. For a rise of atmospheric CO_2 levels to 699 ppmv at 2100 (IPCC, 1992, IPCC, 1995), an equilibrium warming of 3.4 degrees Celsius from pre-industrial levels would result, assuming a mid-range climate sensitivity of 2.5 degrees Celsius. Atmospheric accumulations raise this to 5.1 degrees Celsius. 0.8 degrees Celsius of this has already been observed, and about half of a degree Celsius is thought likely to be offset by the scattering effects on sunlight of sulfate aerosols (see below), leaving a net warming from current levels of about 3.8 degrees Celsius.

Table 9. Estimated Equilibrium Warming from IPCC (1996) Forecast

Compound	Level	Equilibrium Warming from Pre-industrial Levels[a] degrees Celsius
CO_2	698 ppmv[b]	3.4
Other Greenhouse Gases	1/3 of total forcing[b]	1.7
subtotal		5.1
less observed warming		-0.8
less tropospheric aerosols offset		-0.5
Total		**3.8**

[a] Climate sensitivity of 2.5 degrees Celsius
[b] IPCC (1992), IPCC (1996)
[c] range of 1.9 to 5.8 degrees Celsius

3.1 Has The Forecast Changed Markedly Over The Last Few Years Or Decades?

Systematic modeling of possible future surface warming from human activities began in earnest in 1990. Prior to 1990, a few estimates had been developed (see Table 10), but until the early 1990s, it was usually simply assumed that in the 21st Century atmospheric greenhouse gas concentrations would rise to the equivalent of at least a doubling of atmospheric CO_2 levels. With mid-range estimates of climate sensitivity, it was modeled, upon a doubling, mean global surface temperature would rise 2 to 3 degrees Celsius in the climate models (see, for instance, WMO, 1981, Hansen, *et al*, 1981, Ramanathan, *et al*., 1985). Since 1990, a series of forecast estimates have been developed on the basis of more systematic analysis. For a forecast date of 2050, these estimates have converged on a forecast 2 to 3 degrees Celsius warming from pre-industrial levels (or 1 to 2 degrees Celsius from current levels) (see Table 10). There has been little evidence of systematic revisions, upward or downward, in the forecasts.

In general, taking the totality of the description of the problem into account, in its essentials, the problem has not changed almost at all in more than 35 years of research. In terms of the general level of forecasted warming, the problem remains essentially what it was in 1970 or 1975. This appears to be the result of the dominance of the description of the problem by the modern estimate for climate sensitivity and the stability of that estimate over time.

3.2 Is This Newly Developed Scientific Information?

It has long been understood that the global climate change problem, if real, has substantial implications for fossil fuel use and energy policy generally. For this reason, the basic calculation of climate sensitivity has been subject to high level review for almost 25 years. Review boards of the US National Academy of Sciences have reviewed the calculation five times since 1979 to the early 1990s. The World Meteorological Organization of the United Nations has reviewed the matter three times, and the United Nations Intergovernmental Panel on Climate Change has reviewed the calculation five times. Interspersed have been two reviews by the US Department of Energy and two by the German Bundestag, as well as miscellaneous other governmental reviews.

The results of the review boards are summarized in Table 10 for both climate sensitivity and for forecasted levels of mean global surface warming by 2050. Without exception, these formal review bodies have concluded, based on the underlying physics, that the sensitivity of mean global surface temperature to doubled atmospheric levels of CO_2 is somewhere in the range of 1.5 to 4.5 degrees Celsius, or the equivalent in forecasted 21st century surface warming.

Two tests have been established: are the underlying physics correct, and have any important physical mechanisms been ignored or omitted that might erase or substantially reduce the sensitivity of climate to elevated atmospheric greenhouse gas levels. The 1979 conclusion of the US National Academy of Science—affirmative to the first of these tests and negative to the second—still stands fundamentally unchallenged.

The first modern numerical calculations of the effects of doubled atmospheric levels of CO_2 were published in 1967 in the peer-reviewed scientific literature. Since 1967, on the order of 500 to 1,000 numerical modeling studies of the question have been published in the peer-reviewed

literature. In all of that time, there has never been published in the peer-reviewed scientific literature a numerical modeling study of the question (that has not had to be withdrawn) that has shown anything other than a mean surface warming of 1.5 to 4.5 degrees Celsius or near to it from doubled atmospheric levels of CO_2.

The literature itself is built upon, among other thing, an extended sensitivity analysis of the basic calculation of climate sensitivity stretching back almost 30-years. During this period, the sensitivity of the calculation to different assumptions and conditions has been systematically tested, again with the results noted just above.

Finally, this condition has persisted into the last decade, during which the so-called 'climate skeptics' have been given ample opportunity to adduce some physical mechanism of climate that would justify a zero or near-zero value for climate sensitivity. It is instructive that, over this period, other than the single suggestion of Lindzen (1990) for upper tropospheric drying, nothing has been brought forward in the peer-reviewed literature. As regards the Lindzen suggestion—for large-scale drying at the subtropical tropopause—satellite evidence has since shown upper level drying not to be a dominant condition of the atmosphere (Zu, *et al*., 2000, Chen, *et al*., 1999). After reviewing the empirical evidence (Soden and Fu, 1995, Raval and Ramanathan, 1989), the IPCC concluded in 1992 and again in 1996 that the water vapor feedback is likely to be strongly positive. More recent analysis of Lindzen's suggestions have come to similar conclusions (Ramanathan and Inamdar, 1999, Soden, 1999).

In practice, as also noted above, the 'climate skeptics' have pegged climate sensitivity at 2 degrees Celsius, 1.5 Celsius, and 0.5 to 2 degrees Celsius (see Table 8 above). This, it might be noted, is consistent with the lower end of the range of climate sensitivity endorsed by the review boards listed in Table 10.

For all of these reasons, the issue of climate sensitivity, if not a settled matter in the scientific literature, is not nearly as disputed as is sometimes suggested. The dominant question with regard to climate sensitivity remains essentially what it has been for the last 20 years—within the range of 1.5 to 4.5 degrees Celsius, how much the earth's climate will warm, rather than, if it will warm.

Table 10. Results of Scientific Review Boards

Review Body	Climate Sensitivity (degrees C/2x CO_2)	Global Surface Temperature at 2050 (degrees C) [(a)]
US National Academy of Sciences (1979)	1.5-4.5	NA
US National Academy of Sciences (1981)	1.5-4.5	NA
US National Academy of Sciences (1983)	1.5-4.5	NA
US National Academy of Sciences (1987)	1.5-4.5	NA
US National Academy of Sciences (1992)	1-5	NA
World Meteorological Organization/UNEP (1981)	1.5-3.5	NA
World Meteorological Organization/UNEP (1985)	1.5-4.5	NA
World Meteorological Organization/UNEP (1988)	NA	+2.5
U.S. Department of Energy (1985)	1.5-4.5	NA
U.S. Department of Energy/National Laboratories (1990)	NA	
SCOPE 29 (1986)	1.5-5.5	NA
German Bundestag (1989)	1.5-4.5	>+3
German Bundestag (1992)	NA	+2.5 to 3
Government of the Netherlands (1983)	2	+1.75[(b)]
Canadian Climate Planning Board (1981)	2.0-3.0	NA
Australian Academy of Sciences (1981)	1.5-4.5	NA
Joint US/USSR Commission on Protection of the Environment (1990)	NA	+2
Royal Society of New Zealand (1990)	1.5-4.5	NA
Intergovernmental Panel on Climate Change (1990)	1.5-4.5	+3
Intergovernmental Panel on Climate Change (1992)	1.5-4.5	+2.5
Intergovernmental Panel on Climate Change (1994)	1.5-4.5	NA
Intergovernmental Panel on Climate Change (1996)	1.5-4.5	+1.75[(a)]
Intergovernmental Panel on Climate Change (2001)	1.5-4.5[(d)]	+2 [(a,c)]

Sources: See endnotes.
(a) above the preindustrial
(b) CO_2 only, low IIASA energy use scenario.
(c) Approximated based on a 2100 warming of 2.8 degrees Celsius from 2000 levels
(d) As reported in Revkin (2001)

Source: Ciborowski (1995) updated for 1996 and 2001 IPCC citation.

The numerical modeling of the global carbon cycle, which controls the rate of atmospheric accumulation of CO_2, likewise has been underway for decades. The first substantial studies were published in the period between the late 1950s and the early 1970s (for instance, Keeling and Bacastow, 1977, Revelle and Suess, 1957). The work since has been subject to extensive review by the National Academy of Sciences, the IPCC, and the US Department of Energy in its State of the Art review in the mid-1980s (NAS 1983, IPCC 1992, IPCC 1996, Trabalka, *et al*., 1985).

The modeling of removal mechanisms that control rates of accumulation and atmospheric lifetimes of the non-CO_2 greenhouse gases has been underway for more than 20 years (see, for instance, Hameed, *et al*., 1980, D. Ehhalt, 1980).

Finally, energy system modeling has been underway in earnest for almost two decades.

3.3 What Is The Minimum Level It Might Warm Under Business As Usual Conditions?

The lower limit on the sensitivity of climate for a doubling of atmospheric CO_2 levels is estimated to be 1.5 degrees Celsius, and possibly as low as 1 degree Celsius. Given a forecast of future atmospheric concentrations of greenhouse gases, it is possible to calculate amounts of expected equilibrium warming for a 'low-end' climate sensitivity. Results for this condition are shown in Table 11. Low-end climate sensitivities result in an equilibrium mean global surface warming of 1.8 to 2.7 degrees Celsius, which, while substantially less than a mid-range sensitivities, is still impressive. A 1.5 degree Celsius warming would make the planet as warm as any time in the last 3 to 4 million years.

Table 11. Calculated Equilibrium Warming from Pre-industrial Levels Using the IPCC (1996) Forecast and Low-end Climate Sensitivity

Compound	Level	Equilibrium Warming from Pre-industrial Levels[a] (degrees Celsius)
CO_2	698 ppmv[b]	1.3 to 2
Other Greenhouse Gases	1/3 of total forcing[b]	0.4 to 0.7
Total		1.8 to 2.7

[a] calculated at a climate sensitivity of 1 to 1.5 degrees Celsius per doubled atmospheric CO_2 levels
[b] IPCC (1996)

3.4 What Is The Basis For Low-End Climate Sensitivity Estimates?

The lower limit on the sensitivity of climate for a doubling of atmospheric CO_2 levels is estimated to be 1.5 degrees Celsius, and possibly as low as 1 degree Celsius.

The basis for this is essentially as follows. The response of mean global surface temperature to a doubling of atmospheric CO_2 levels can be decomposed into two distinct parts: the change in radiative heating of the atmosphere due to CO_2, leading to a downward thermal emission to the surface that results in a surface warming of about 1.3 degrees Celsius (IPCC, 1990); and a set of feedback effects that amplify or dampen this initial warming. The warming from direct radiative heating by CO_2 is well established. Little evidence has been adduced for a substantially negative overall feedback effect. Most evidence suggests that the likely net effect of all climate feedbacks is likely to be positive, but it is possible that some feedbacks could be negative and offset positive forcing from others. The effect of this would be a low-end sensitivity between 1 and 1.5 degrees Celsius.

Amplifying factors include water vapor, surface reflectivity changes due to changes in snow and ice cover (ice-albedo effect), and cloud feedbacks.

Of these feedbacks, water vapor is the most important. Water vapor is a greenhouse gas. In increased atmospheric concentrations, it acts to warm the surrounding atmosphere and the surface. Its concentration increases in the atmosphere with surface and atmospheric warming. An increase in the atmospheric CO_2 level acts to warm the troposphere, increasing the amount of water vapor in the troposphere, thereby leading to additional warming. Two parts of the

troposphere –the lower troposphere and the upper troposphere—contribute about equally to the feedback (IPCC, 1996). Water vapor in the lower part of the troposphere is controlled by temperature. This is not controversial. The water vapor response of the upper troposphere depends on large-scale motions of the atmosphere.

Most attention has focused on the upper troposphere. Evidence in support of a positive water vapor feedback in the upper troposphere in the tropics using satellite observations has been adduced by Soden and Fu (1995), Soden (1998), Zhu, *et al*, (2000), Rind, *et al*., (1991), Chen, *et al*, and Ramanathan and Inamdar (1999). No evidence of a negative feedback effect involving water vapor has been identified, although some drying in the upper troposphere takes place along with otherwise dominant moistening (IPCC, 1996, Zhu, *et al*., 2000).

As noted above, the water vapor feedback in the lower part of the troposphere is relatively noncontroversial. Taking these two pieces of evidence together—positive water vapor feedback for the lower troposphere and positive water vapor feedback in the upper troposphere of the tropics—most scientists have concluded that the water vapor feedback for the earth as a whole is probably positive, although better resolution of physical processes is needed (IPCC, 1996).

The results from numerical climate models that can closely simulate the distribution of water vapor with height do tend to produce lower climate sensitivities, but still at the 1.5 degree Celsius level or above (Hu, *et al*., 2000).

With respect to surface reflectivity, this is relatively non-controversial, contributing a small positive effect. The effects of possible cloud cover changes in model intercomparisons range from slightly negative (10 to 25% reduction in radiative forcing for models with a negative cloud forcing) to slightly to moderately positive. In general, in the models, different competing changes in cloud characteristics tend to cancel, resulting in a near-neutral effect (Cess, *et al*., 1996). On this basis, in the IPCC analyses, it is concluded that it is unlikely that the effect of cloud changes is very negative or very positive (IPCC, 1996).

Taking all four terms—well-accepted 1.3 degree Celsius direct radiative heating from CO_2, likely positive water vapor feedback, slightly positive ice-albedo feedback, and unknown but possibly limited cloud feedback—it has been concluded that the lower level to climate sensitivity is unlikely to be less than 1 to 1.5 degrees Celsius. The basis for this is probabilistic reasoning based on best scientific judgment and preponderance of evidence. In the last analysis, the judgment resides on the absence of identified mechanism for substantially negative feedback. In absence of this, the feedback component of the warming is concluded to be at least neutral and probably positive. This yields lower end estimates for climate sensitivity in the 1 to 1.5 degrees Celsius range shown in Table 10.

Observational evidence that this level is reasonable is found in the implied climate sensitivity for the Last Glacial Maximum, the Pliocene, (Hoffert and Covey, 1992), and the mean global surface temperature and the record for the last 1,000 years (Crowley, 2000). All require climate sensitivities of at least 1 degree Celsius. Reconstructions of global surface temperatures for the last 150 years require climate sensitivities in the range of about 1 to 5 degrees Celsius (Wigley, 1997).

3.5 Are There Offsetting Factors That May Slow Global Warming?

A number of offsetting factors that influence global climate on time-scales of a few years to decades have been identified, and their likely effect quantified. This is shown graphically in Figure 14 for the period 1860 to 1998. For purposes of comparison, the estimated effects of observed increases in atmospheric levels of greenhouse gases also are shown. The units are watts per square meter, a measure of the extra energy radiated downward from the top of the troposphere toward the surface, for each influence or 'forcing' of the climate.[3]

Aerosols

Aerosols are particles or very small droplets. Aerosols are highly reflective of incoming solar radiation or sunlight. In substantial atmospheric abundances, they act to increase the overall reflectiveness of the atmosphere to sunlight, thereby reducing the amount of sunlight that reaches the lower atmosphere and surface of the earth, cooling it.

Aerosols in the troposphere also can act to modify cloud properties, decreasing cloud droplet size, and effectively increasing the whiteness or reflectivity of clouds to incoming sunlight, again cooling the planet.

Tropospheric aerosols and their precursors derive from natural and anthropogenic sources. Anthropogenic sources are dominated by sulfate aerosols formed from sulfur dioxide (SO_2) emitted during coal and oil combustion. Natural sources include wind-blown soil particles and various sea salt aerosols produced from the evaporation of sea-spray droplets (IPCC 1994). Roughly speaking, about one-half of the scattering effect of aerosols in the troposphere is associated with aerosols of anthropogenic origin. It is thought that aerosols in the troposphere act to offset from one-third to one-half of the climate forcing from elevated atmospheric levels of greenhouse gases (Hansen, *et al*., 1999, IPCC, 1996).

Aerosols in the stratosphere derive principally from explosive volcanic events. Large events are episodic in nature, occurring once every quarter century. The lifetime of aerosols in the stratosphere is short, several years, and so the attendant cooling effect that results from an explosive volcanic event is usually short-lived. Large volcanic events can act to depress mean global surface temperature several tenths of a degree Celsius for up to three or four years (Free and Robock, 1998).

Stratospheric ozone depletion

Stratospheric ozone depletion acts to slightly cool the surface of the earth. Ozone in the stratosphere is a greenhouse gas. In the stratosphere, it acts to absorb infrared radiation, warming the surrounding atmosphere, including the upper troposphere. Large-scale depletion of stratospheric ozone acts to reduce infrared absorption in the lower stratosphere, leading to a cooling that extends into the upper troposphere. The effect at the surface is a slight cooling. (IPPC, 1994) Ozone abundances have been decreasing about 4 to 5% per decade at mid-latitudes.

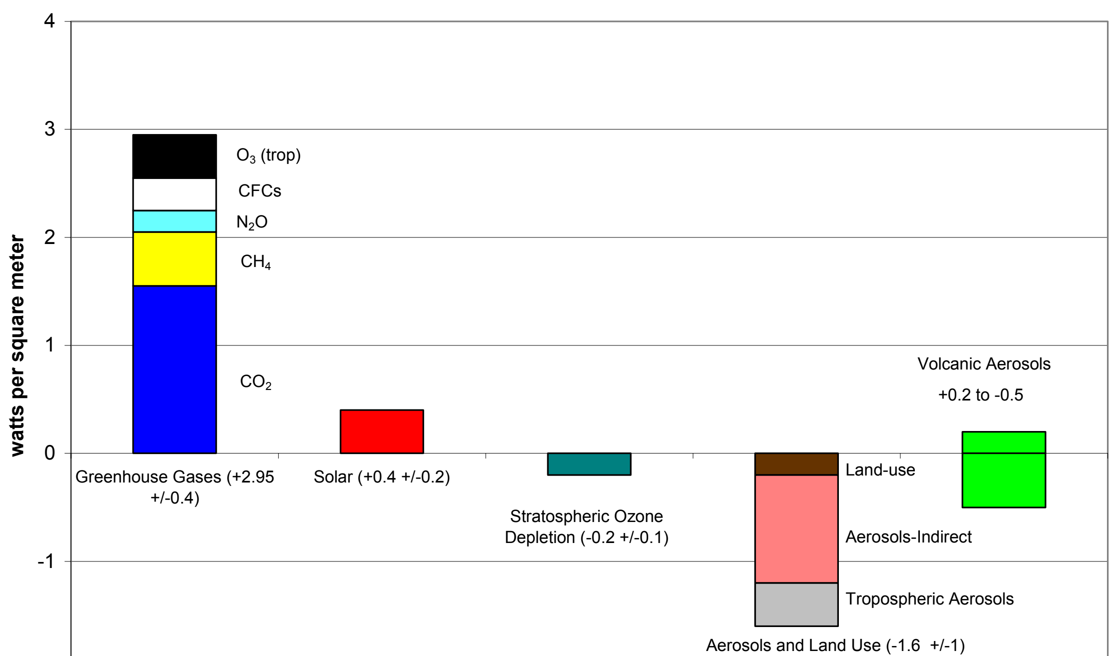
[3] It is a convention to evaluate radiative forcing of climate for direct effects only, omitting feedback from increased levels of atmospheric water vapor, or from elsewhere in the climate system. This is what is represented in Figure 14. In the modeling, feedback acts to amplify the forcing by a factor of 1 to 6, with about 4 for a mid-range climate sensitivity. (Raval and Ramanathan, 1989, Ramanathan, 1981).

Ozone depletion results from the presence in the stratosphere of free chlorine and bromine, which acts to catalyze the destruction of ozone. CFCs and chlorocarbons are the principal sources of free chlorine in the stratosphere.

<u>Solar Radiant Energy Output</u>

Variations in the amount of sunlight reaching the top of the stratosphere have been monitored for more than 23 years. Variations over this period have been small, about 0.1%. Based on this record, relatively little if any of the more recent phase of the warming can be accounted by increasing solar output of radiant energy (Hoffert, *et al*., 1988, IPCC, 1994).

Figure 14. Radiative Forcing of Global Climate, 1860-1998: GISS Modeling of Sources



Longer-term influences are more uncertain. Evidence drawn from isotope studies suggests that variations in the radiant output of the sun may have been more substantial in prior epochs. While some authors find a greater effect, the general sense of the scientific literature is that a variable sun may be able to account for one-quarter to one-third of the observed warming since 1850. (Lean and Rind, 1998, Lean and Rind, 1999, Damen and Peristykh, 1999) The representation shown in Figure 14 assumes a slightly less variable sun.

The apparent long-term stability of climate over periods of 200 to 300 years, it might be noted, may argue for a limited role for a variable sun (see Figure 13).

Soot and Carbon Black Effects
Other factors that are just receiving attention include soot and carbon black effects on cloud cover and stratospheric water vapor forcing (Smith, *et al*., 2001, Lohmann and Feichter, 2001).

In general, it is thought that at present up to one-half of the climate forcing of greenhouse gases might have been offset over the period 1860 to present by effects arising elsewhere. Episodic volcanic events add to the noise of the record.

For the observed assemble of climate forcings on climate shown in Figure 14, net radiative forcing on climate from 1860 to the present would be about 1.5 watts per square meter, omitting feedbacks. Given the amount of observed surface warming in the record, this would be most consistent with climate sensitivity toward the middle of the range of 1.5 to 4.5 degrees Celsius for doubled atmospheric levels of CO_2 (IPCC 1996, Hansen, *et al*., 2000).[4] Allowing for uncertainty broadens this out to 0.7 to 5 degrees Celsius (Forest, *et al*., 2000).

In the long-run, this offset is expected to approximately stabilize in absolute terms near current levels of 1 to 2 watts per square meter as controls on SO_2 emissions from coal and oil combustion are imposed globally. The likelihood of widespread future controls on SO_2 is the basis for much of the upward revision in the latest IPCC forecast from 2 to 2.8 degrees Celsius. (Revkin, 2000) In the latest IPCC forecast, it is assumed that, as the developing economies modernize, for reasons of health effects and acidification, rigorous controls on SO_2 emissions will be instituted. In the earlier 1996 100-year forecast, it had been assumed that offsetting emissions of sulfates would rise proportionally with energy use.

Slight long-term warming from stratospheric ozone recovery will also contribute slightly to this. (Solomon and Daniel, 1996) No estimate has been offered for future solar influences on long-term climate forcing.

In general, the values given in Figure 14 appear to support a climate sensitivity of about 2.5 degrees Celsius, assuming the yet unrealized warming due to delays introduced by the ocean's thermal inertia is about 0.5 degrees Celsius. This would be calculated as:

$$(0.8 + 0.5 + 0.5) * 0.6 * \text{1n}2 * \frac{1}{\frac{370}{275}\,\text{1n}} = 2.5$$

where: the observed warming is 0.8 degrees Celsius
the aerosol offset is 0.5 degrees Celsius (IPCC 1996)
the delayed warming is 0.5 degrees Celsius
CO_2 accounts for 60% of the forcing from elevated levels of greenhouse gases
the pre-industrial level of CO_2 is 275 ppmv
the present level of CO_2 in the atmosphere is 370 ppmv.

[4] Without feedback, the sensitivity of surface temperature to forcing is about 0.3°C per Watt per square meter (Wm^{-2}). (IPCC, 1996) With 1.5 Wm^{-2} forcing, a 0.45 C warming would result. From the record, a 0.8 degree Celsius warming has been observed, plus about 0.5 C has been delayed through the effects of the ocean's thermal inertia, which in total requires a response of about 0.9°C Wm^{-2}.

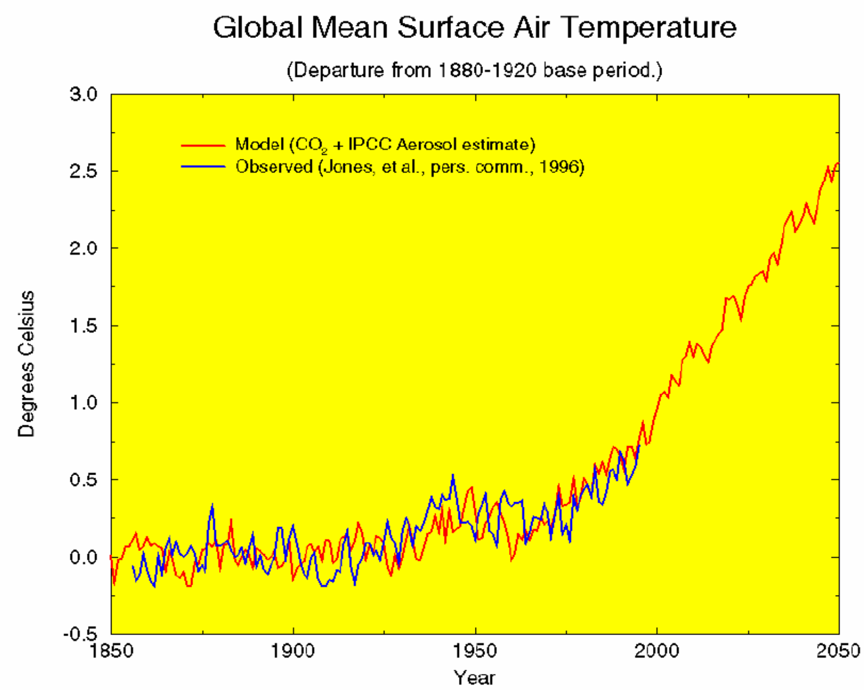
3.6 Have The Numerical Climate Models Been Validated Against Observed Temperature Changes?

Efforts to validate the numerical climate models against observed changes began in earnest in the middle 1990s. Central to the effort was the realization that combustion-derived sulfate aerosols, in substantial concentration in the troposphere, act increase the reflectiveness of the atmosphere to incoming sunlight, and thereby cool the climate (see prior section). Prior to the incorporation of aerosols, the models tended to over-predict the rate of 20^{th} century warming, and were generally unable to reproduce the start-stop pattern of warming.

Figure 15 shows output from a late-1990s model that incorporates the effects of both rising atmospheric levels of CO_2 and reconstructed tropospheric aerosol levels. This model, like most of the models that incorporate realistic distributions of tropospheric aerosols, is now capable is capable of reproducing most aspects of the historical record, including both phases of the 20^{th} century warming (1910-1940 and 1975-2000), and the leveling of the temperatures between the two warming phases (GDFL, 1999, Hadley, 2000, IPCC, 1996).

More generally, the models have been validated against: the climate changes of the middle Holocene (Joussaume, *et al*, 1999), the climate of the Last Glacial Maximum (Joussaume 1993), the response of mean global surface temperature to the short-term effects of explosive volcanism (Hansen, *et al.*, 1992), and the annual climatic cycle (IPCC, 1996).

Figure 15. Numerical Climate Model Simulation of Observed Rise in Mean Global Surface Temperature, 1850-1996



3.7 How Does The Forecast Compare To Changes In Climate In The Historical And Geological Record?

The period of the last 18,000 years since the retreat of the last ice age has been marked by a number of global temperature optima: the modern 20th century optimum; the early medieval optimum discussed above; and an optimum about 6,000 years before the present (YBP), during which temperatures probably were near late-20th century levels. The Roman period also may have experienced warmer temperatures, though lower than those of 1000 AD. Sandwiched between these were colder periods: 20,000 to 18,000 years before the present, the peak of the last ice age, during which global temperatures were probably 4 to 5 degrees Celsius cooler than now; the Little Ice Age 1400 to 1800 AD; and a cool period 600 to 800 AD.

Table 12 shows the estimated difference in mean global surface between these alternating periods of cold and warmth. Additional estimates taken from longer-term change of the very distant geological past are also given. Also shown, for purposes of comparison, is the forecast for the next century.

As is evident from Table 12, the forecasted warming for the next century is a large change in comparison to nearly any change in the record. At the level of average 100-year rate of change in global temperature, the 100-year forecasted warming is larger than others in the record by 1 to 2 orders of magnitude.

In absolute terms, the IPCC base case forecast to 2100 of 3.6 degrees Celsius from pre-industrial levels (2.8 degrees Celsius from the present plus the observed 0.8 degrees Celsius warming) is roughly of the same level of intensity as the largest 10,000-year warming in the record—the warming experienced with the end of the last ice age, from 18,000 YBP to about 6000 YPB.

Table 12. Comparison of Forecasted Warming with Global Climatic Changes of the Past

Period	Change in Average Global Temperature[a] Degrees Celsius	Mean Rate of Change degrees C per century
1000 AD to 1700 AD	(-) 0.4	0.06
4000 BC to present	(-) 1	0.01
18,000 YBP to present	(+) 4 to 5	0.025
3 million YBP to present	(-) 1.75	0.00006
30 million YBP to present	(-) 5 to 6	0.00002
1850 to present	(+) 0.8	0.5
Forecast 2000-2100	(+) 1.5 to 6	1.5 to 6

[a] approximate level of warming or cooling

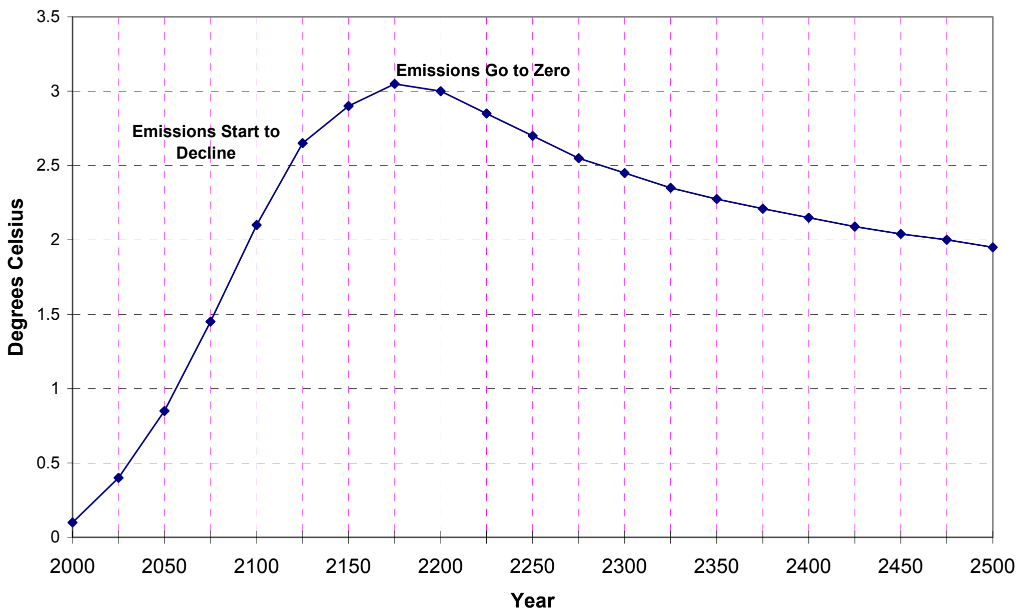
3.8 How Long Will The Warming Persist?

As discussed above, at atmospheric concentrations like are expected under business-as-usual conditions (600 to 700 ppmv, see Table 14 below), the persistence of emitted CO_2 in the atmosphere is long, on the order of 500 years. Thus, once emitted, CO_2 will exert an influence on climate for very long periods of time.

Figure 16 shows the results of an IPCC calculation of the persistence of effect of accumulated CO_2 on the earth's climate. In this particular figure, CO_2 emissions are assumed to follow unrestricted paths of growth for 100 years to 2100, and then to be linearly phased out to zero. Mean global surface temperature peaks at 2175 at 3 degrees Celsius above current levels. After the passage of 300 years, however, global temperatures are still 2 degrees Celsius above present levels (and 3 degrees Celsius above pre-industrial levels), with temperatures on a long-term trajectory of decline that suggests persistence for many more hundreds of years.

So, in answer to the question of how long the warming will persist—at least 500 years and possibly a good deal longer.

Figure 16. Change in Mean Global Surface Temperature for Business as Usual Emissions Until 2100 and Then a Linear 100-Year Phase Out of Emissions, 2100-2200



3.9 Have All Of The Criticisms Of The Climate Skeptics Been Addressed?

The climate skeptics have variously claimed that:

- the global temperature record reveals little warming, either in the free troposphere, for which they use the 1979-present satellite record, or in the surface record, which, it is claimed, is contaminated by the effects of urbanization (Michaels and Stooksbury, 1992);
- if it warming, it must be of natural provenance, and probably solar-inspired (G. Marshall Institute, 1991);
- the lack of warming in the free troposphere over the period covered by the record is inconsistent with greenhouse forcing (Pearce, 1977);
- important negative feedbacks have been omitted from the numerical climate models (Lindzen, 1990);
- and, the numerical climate models over-predict the observed warming, which implies that the climate is much less sensitive to greenhouse gas loading than orthodoxy suggests (Michaels and Stooksbury, 1992).

The temperature records for both the free troposphere and rural meteorological stations were presented above in Figures 4 and 10. Appreciable warming is evident in both records.

The long-term climatic record was presented in Figure 13. From Figure 13, the range of natural variability of climate appears to be quite limited. This would seem to argue against a

predominant role—or possibly even a major role—for natural variability in explaining the large discontinuous warming that began about 1900. This would include variations in the energy output of the sun.

The National Academy of Sciences has addressed the question of the satellite record (NAS, 2000). In its review, it noted that a 20-year record is too short to serve as the basis for conclusions about trends in long-term physical processes.

Regarding omitted negative feedbacks, with the exception of subtropical upper tropospheric drying, none has been proposed in the peer-reviewed scientific literature. As noted above, observational evidence argues against such drying as the physical basis for a negative water vapor feedback effect.

It has been demonstrated that it is possible to adequately account for much of the detail in surface temperature record, even assuming climate sensitivities in the 2.5 to 4 degrees Celsius range (GDFL, 1999, Hadley, 2001). This was not true just five years ago.

It is possible that climate sensitivity is at the low end of the accepted range, but none of the arguments of the 'skeptics' seem to require that to be true or demonstrates that it is true. It long has been an accepted element of the description of the global climate change problem that climate sensitivity could be as low as 1 to 1.5 degrees Celsius per doubled atmospheric levels of CO_2. Reasserting the possibility that climate sensitivity might fall into this range adds nothing new to description of the problem.

Finally, it should be noted that it will never be possible to address all potential objections that are raised to the prevailing scientific description of the problem. There will always be questions, there will always be uncertainties. It will always be possible that some new understanding could undo the present description of climate change problem. However, to date, none appears to have done so.

3.10 What Do We Know About The Long-term Future Rates Of Atmospheric Accumulation Of Greenhouse Gases?

Long-term rates of atmospheric accumulation of greenhouse gases are determined by removal mechanisms and rates of emission. About 45% of emitted CO_2 is removed from the atmosphere to the oceans or the biosphere. The remainder accumulates in the atmosphere. The current annual rate of oceanic removal of CO_2 from the atmosphere is about 2 billion metric tons of carbon (7 billion tons of CO_2). Removals through an expanding land biota are about 0.7 billion metric tons of carbon (Battle, *et al.*, 2000). The annual rate of atmospheric accumulation is about 3.3 billon metric tons of carbon per year (12 billion tons of CO_2), or 1.5 ppmv per year.

Given a stream of emissions from fossil fuel combustion, ocean removal of CO_2 is the controlling influence on the rate at which CO_2 accumulates in the atmosphere.

Oceanic removal of CO_2 from the atmosphere depends on a well-understood carbonate chemistry of the surface layer and less well understood ocean mixing processes. The latter have been constrained using passive oceans tracers like bomb radiocarbon and tritium. Independent

verification of current model-generated estimates of annual oceanic removal of excess atmospheric CO_2 has been developed using isotopic analysis and analysis of N_2/O_2 ratios in the atmosphere (Battle, *et al.*, 2000, Keeling, *et al.*, 1996, Quay, *et al.*, 1992).

Ultimately, oceanic removal of CO_2 from the atmosphere is limited by the solubility of CO_2 in seawater and the slow rate of mixing between the surface and deep-ocean waters.

Oceanic removal mechanisms are not invariant in their ability to remove CO_2 from the atmosphere. From the modeling of the carbonate chemistry of the oceans, it has been determined that the rate of removal of emitted CO_2 should somewhat decline as a percent of fossil fuel-related emissions with rapidly increasing emissions (Trabalka, 1985).

While net removal of atmospheric CO_2 is not insensitive to the response of the biota, the biotic response is less important. Independent verification of the annual rate of removal of excess atmospheric CO_2 through the biota has been developed. This is estimated at about one-quarter of the annual global carbon sink.

It is thought that the present net rate of biospheric removal of CO_2 will increase with a projected increase in net primary biospheric productivity. As noted above, plant productivity increases with CO_2 level independent of climate change. Currently, in order to account for an expanding land biosphere, in forecasting future CO_2 levels, a substantial biotic accumulation is assumed, based on about a 25% enhancement of net primary productivity of the biosphere (IPCC, 1996). Using this rate of enhancement, typical forecasted CO_2 levels at 2100 are about 700 ppmv. Extreme values for this rate of enhancement results in variations in predicted atmospheric CO_2 at 2100 of less than 50 ppmv from forecasted levels (IPPC, 1994).

The sensitivity of forecasted atmospheric CO_2 levels to mid-latitude forest die-back, should this result from rapid warming, is again small, potentially adding on the order of 25 to 50 ppmv to forecasted levels. Potential ocean circulation effects also are small (Joos, *et al.*, 1999).

More generally, the rate of atmospheric removal of emitted CO_2 has been relatively constant for decades at 55 to 60%. This requires that substantial accumulations of CO_2 will result from any prolonged emission of CO_2 to the atmosphere at current or accelerated rates. Table 13 provides estimates of CO_2 accumulation for different levels of cumulative emission.

Table 13. Atmospheric Accumulations of CO_2 at Different Cumulative Emission Amounts

Cumulative Emissions (billion metric tons of Carbon)	Added CO_2 (ppmv)[a]	Atmospheric CO_2 Level at 2100 (ppmv)	Associated Rate of Increase in Emissions (% per year)
700	180	550	0.2
1000	260	630	0.85
1500	390	760	1.5

[a] Calculated at a retention rate of 55%

The principal source of CO_2 emission to the atmosphere is fossil fuel combustion. About 80% of global commercial energy use involves fossil fuel combustion, a level little changed over recent decades. The economics of fossil fuel use depend on production costs of fossil fuels in relation to production costs of alternative energy source, the costs of energy efficiency improvements, and growth in the underlying demand for energy services. Fossil fuel production costs have been declining for a century in real terms. Rogner (1997) suggests that, at the long-term rate of decline in production costs, ultimately as much as 3,500 billion metric tons of carbon will be economically exploitable at current energy prices.

Other factors that contribute to long-term trends in CO_2 emissions include:

- rate of population growth
- rate of income growth
- background rate of improvement in the efficiency and energy use
- energy production costs for non-fossil carbon renewable energy systems
- technology development
- responsiveness of technology development to energy prices
- availability of and access to natural gas
- energy pricing

Atmospheric accumulations of CO_2 for a wide range of different conditions are given in Table 14 from the IPCC analysis. Business-as-usual emissions (approximately triple current levels by 2100) result in an approximate doubling of the current atmospheric CO_2 level. Pre-industrial concentrations increase by 150%. Long-term emission at constant 1990 rates results in atmospheric CO_2 concentrations 50% above current levels and about double the pre-industrial level. A long-term path of decline in emissions, culminating in emissions at 2100 one-half of current levels, results in the modeling in atmospheric levels of CO_2 still 80% above pre-industrial levels, (and 30% above current) but stabilizing near 500 ppmv.

Table 14. Modeled Atmospheric Concentrations of CO_2 for Different Long-term Emissions Paths

	Forecasted Atmospheric Concentration at 2100 (ppmv)	Associated Rise in Mean Global Surface Temperature[a] (degrees Celsius)
Business-as-Usual[b]	700	3.4
Constant Emissions at 1990 Levels	550	2.5
Emissions at one-half 1990 Level by 2100	490	2.1

[a] For a mid-range climate sensitivity of 2.5°C per doubled atmospheric levels of CO_2
[b] Annual CO_2 emissions increasing 0.9% per year and tripling by 2100 to 74 billion metric tons

Source: IPCC, 1996

A large net reduction in emission levels will be necessary to stabilize atmospheric CO_2 levels at or near current levels. From the modeling, a reduction of on the order of 50 to 80% will be necessary (IPCC 1990).

Reduction requirements leading to stabilization are given in Table 15 for the other important greenhouse gases. With the exception of CH_4, large percentage reductions are required. However, with the exception of N_2O, which may be relatively difficult to control, most of the long-lived compounds have purely industrial uses and are emitted in such small quantities that control measures, through the introduction of drop-in chemical substitutes, may be relatively easy to implement. Thus far that has been the experience under the requirements of the Montreal Protocol.

Removal rates of emitted nonCO_2 greenhouse gases can be approximated from the respective atmospheric lifetimes of these gases. Good estimates, either empirical or theoretical, exist for most of these compounds.

Table 15. Percentage Emission Reductions Required to Stabilize Atmospheric Concentrations of Greenhouse Gases at Current Levels

Compound	Reduction Required
CO_2	50 to 80%
CH_4	15 to 20%
N_2O	70 to 80%
CFC-12	75 to 85%
CFC-11	70 to 75%
HCFC-22	40 to 50%

Source: IPCC (1990)

Some important factors that control emissions of the nonCO_2 greenhouse gases include:

- treaty requirements under the Montreal Protocol and its amendments;
- rates of substitution of HFCs for banned CFCs and HCFCs;
- global demand for refrigeration and cooling services;
- technology development for new cooling cycles and alternative non-greenhouse gas refrigerants;
- world food needs;
- rates of income growth in developing nations;
- and, controls on the emission of ozone precursors.

The 1996 IPCC analysis forecast a one-third the contribution of the nonCO_2 greenhouse gases to the overall warming. Reducing this to one-fifth to accommodate would lower the forecast a meager 0.25 degrees Celsius.

3.11 How Will The Distribution Of Climate Change As It Warms?

The geographical distribution of surface warming and climatic change generally is modeled through the use of linked general circulation models of the atmospheric and oceans. These are

numerical models of the climate, developed from well-known physical laws governing the distribution of momentum, heat, and moisture, and, in the case of the oceans, salinity. The models are designed to replicate all know physical processes of climate and atmosphere. Most include realistic geography and orography, realistic distributions of vegetation and vegetation characteristics, a detailed hydrological cycle including land surface processes, an atmosphere divided into 10 to 20 layers, a radiative transfer scheme, and a multi-layer model ocean with sea ice formation. The most recent models have realistic geographical distributions of tropospheric aerosols, and some incorporate carbon cycle dynamics.

The models divide the surface of the earth into a horizontal grid, roughly 2 to 4 degrees in latitude by 2 to 4 degrees in longitude. From the primitive equations for the conservation of heat, mass and momentum, and the ideal gas law, the models calculate values for surface and upper tropospheric temperature, evaporation, humidity, precipitation, surface pressure, soil moisture and surface run-off, latent and sensible heat exchange, wind, ocean circulation, surface fluxes of heat to the oceans and land surfaces, and many other variables for each grid.

Since 1990, the modeling of the geographical component of climate has developed rapidly, and it is now possible to simulate many aspects of the large-scale aspects of current climate (IPCC 1996, Grassl, 2000).

Based on 30-years of modeling the geographical component of global climate change, the following conclusions can be drawn:

- warming is likely to be more intense in the high latitudes;
- warming is likely to be more intense on land and in the winter months;
- warming is likely to be more intense in the Northern Hemisphere than in Southern Hemisphere;
- minimum daily temperatures are likely to increase more than maximum daily temperatures;
- evaporation and precipitation will increase globally;
- precipitation will increase more in the high latitudes than elsewhere;
- the balance of evaporation and precipitation in the interior of mid-latitude continents may favor widespread summer drying;
- heavy daily precipitation events may increase in frequency and severity (Groisman, *et al*, (1999)
- cold winter seasons in the Northern mid-latitudes will shorten in duration by one month or more, and the timing of early spring events like lake ice-out and spring snow-melt will be advanced to March and February;
- the variability of regional climate from one decade to the next will increase until at least 2050 due to progressive and accelerating forcing of surface temperatures.

Figure 17 shows mapped results for a fairly conventional numerical modeling exercise of the effects of elevated atmospheric levels of CO_2 on annual surface temperature. Two conditions are shown: modeled conditions for a doubling of atmospheric levels of CO_2 and conditions for a

quadrupling. Most analysis suggests that, under business-as-usual policies, concentrations of all greenhouse gases will rise to the equivalent of about a tripling of CO_2 levels.

The mean Northern Hemispheric warming over land for the condition roughly halfway between the two cases shown in Figure 17 is about 10 degrees Fahrenheit (5.5 degrees Celsius). In the high latitudes of the Northern Hemisphere, the average annual warming is about 20 degrees Fahrenheit (11 degrees Celsius). Roughly speaking, for each 1 degree Celsius warming, a 100-mile poleward shift of climatic zones results in the model simulations.

The mean annual warming modeled for the Upper Midwest under the conditions of a tripling is about 10 degrees Fahrenheit.

Conclusions also can be drawn about several other components of the climate and related systems, including sea level and sea ice extent in polar regions. Sea level is forecast to rise about 0.5 meters (one and one-half feet) over the next 100-year, and eventually 1 to 2 meters as the oceans slowly response to the extended 500-year warming (IPCC, 1996). Floating pack ice in the Arctic basin will shrink back toward 90 degrees North latitude, creating a partially or completely ice-free Arctic in summer (Hadley, 2000b, GDFL, 1999).

Little can be said now with certainty about changes in regional precipitation. Precipitation changes depend on larger changes in the general circulation of the atmosphere, and these currently cannot be modeled with confidence down to the regional and local level. Other climatic parameters for which this is true at the local level are: drought incidence, probability of extreme precipitation events, storminess, surface run-off, cloudiness, and relative humidity. More certain information here will necessarily await fuller model development.

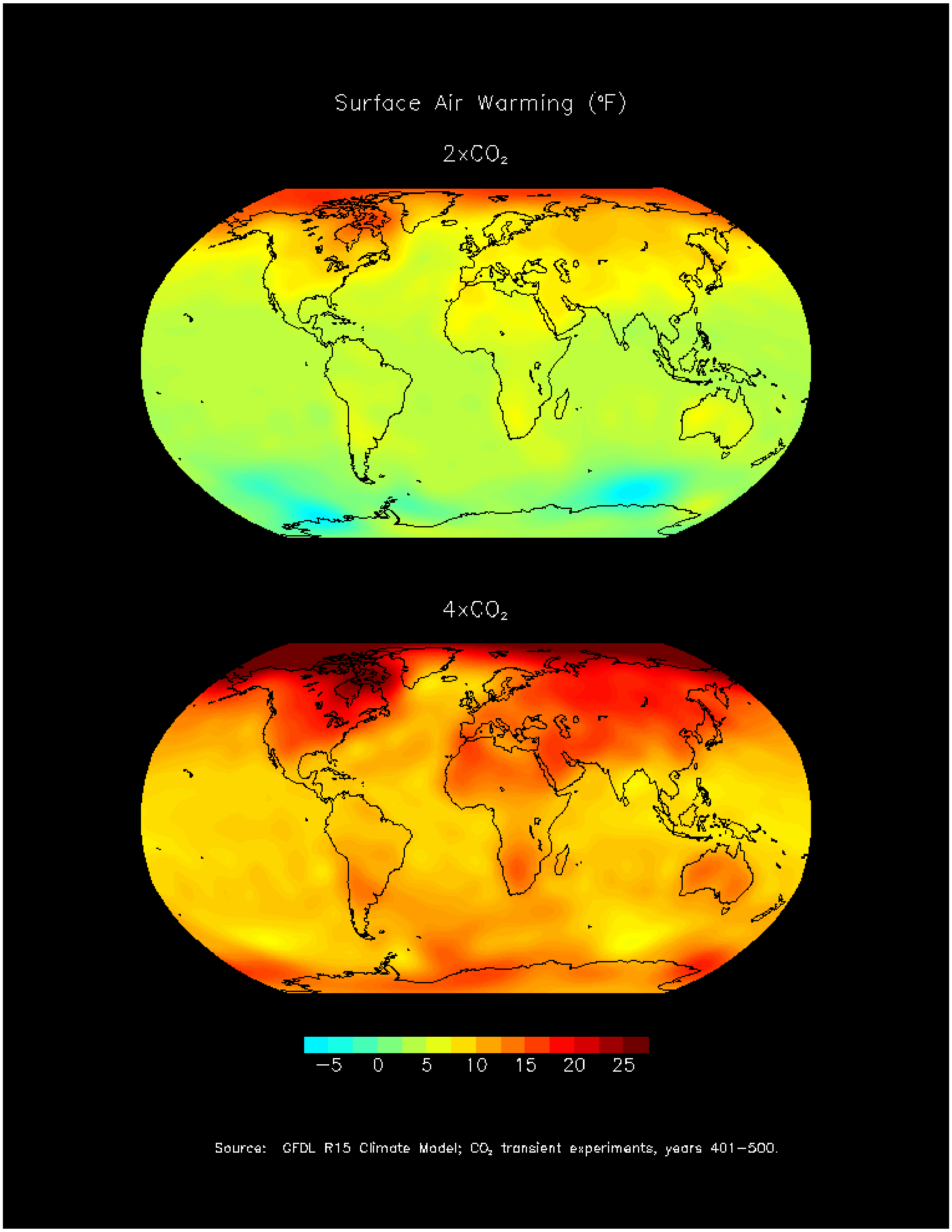
4.0 What Is The Basis For Concern About Global Climate Change?

Concerns about global climate change are many. The four that attract the most attention are:
1. ecological effects,
2. economic effects,
3. the potential for large unpleasant climatic surprises, and
4. irreversibility.

Ecological effects

Significant ecological effects are thought likely to result from global climate change. As noted above, the geographical distribution of climate will change under an intensifying greenhouse effect. The best evidence, drawn from the geological record and from numerical climate modeling, suggests that for each 1 degree Celsius warming, regional climates in the Northern Hemisphere will shift south to north on the order of 100 miles. During periods of climatic change in the past, natural ecosystems have adapted through migration, essentially following regional climates as they have shifted about. The climatic changes of the past, however, have been much slower than what are envisioned for the next century.

Figure 17. Modeled Surface Warming for Conditions of Doubled and Quadrupled Atmospheric Levels of CO_2 (GDFL Model)



Forest systems are the most studied. Forests move by expanding their range at one boundary, and contracting elsewhere, all over very long periods of time. Rates of migration are slow. The principal limits are the life of the tree and the distance of seed dispersal. Inferred from migration rates during the last deglaciation, 17,000 years before the present to about 8,000 years before present, maximum sustainable rates of forest migration appear to be on the order of 1 to 2 kilometers (km) per century (Davis 1989). Under the conditions outlined above, actual forced rates of migration are likely to be at least several hundred km per century, or at least 1 orders of magnitude faster than what long-lived forest systems can sustain.

Based on this reasoning, most ecologists have come to the conclusion that a rapid intensification of the earth's natural greenhouse effect on the scale that is now forecast will likely involve substantial disruption of existing natural systems. Forest die-back is the most frequently cited mechanism getting us from the current condition to the forests and natural landscape of the future, although this is unclear. Whatever the mechanism, species loss, the disruption of established ecosystem relationships, and reduced biodiversity seem to be the inevitable consequences of widespread disruption to natural systems.

Analysis by the IPCC suggests that upwards of one-third of global forests would be effected by global climatic change (IPCC, 1996).

Particularly vulnerable are ecosystems in high northern latitudes, some of which, the evidence suggests, may not survive the warming (IPCC, 1996).

Economic effects

Economic systems will be impacted to a lesser degree. Numerous studies on economic impact suggest aggregate economic losses on an annual basis in the US and globally on the order 0.5 to 1% of gross domestic and gross world production, respectively (Nordhaus, 1991, Cline 1992, Fankhauser and Tol, 1996).

Climatic "Surprises"

The projected 'forcing' of climate by rapidly increasing atmospheric levels of greenhouse gases moves climate outside of the existing boundary conditions on climate. This makes possible the occurrence of what climatologists euphomistically call 'unpleasant surprises' as rapid warming unfolds. This simply reflects the limits of our experience; we are not acquainted with the behavior of natural systems under conditions that radically diverge from present conditions. We are continuously being surprised by nature; the suggestion is that we prepare for a century of surprises, some of them quite unpleasant.

The particular system that has prompted this concern is oceanic circulation, which has been shown in the past to evidence signs of high non-linear behavior during periods of climatic change. There appear to be multiple equilibrium states for ocean circulation under roughly the same climatic conditions. There is evidence in the geological record for rapid movement between such different equilibrium states during which the thermohaline circulation of the oceans collapsed, and the large-scale circulation of the oceans 'reorganized' itself. A similar collapse or partial collapse is a commonly calculated in numerical climate simulations under conditions of rapid warming (Rahmstorf, 1999). It is not now known how many equilibrium conditions there might be or the ways in which the climate moves from one to another.

Others systems for which nonlinear behavior might be a concern that are discussed in the literature include: the West Antarctic ice sheet, and methane hydrate deposits in ocean sediments. There is a large amount of methane tied up in a frozen form off-shore as hydrates. It has been theorized that warming of ocean bottom waters could result in the release of this CH_4 in a pulse, thereby exacerbating the warming.(Blunier, 2000) It has been speculated by some that the West Antarctic Ice Sheet may be unstable, and that warming might trigger a catastrophic collapse, raising sea level 15 to 20 feet. While most analysts have concluded that this is unlikely to occur over the next century (Oppenheimer, 1998), this catastrophic collapse has yet to be conclusively ruled out as a possibility.

Irreversibility

Finally, as noted above, once underway, global warming is essentially irreversible. In decision rules, the irreversibility of condition, especially in the face of large uncertainty and large potentially negative effects, is often the triggering condition for the application of the precautionary principle. This is essentially a concern for what we do not know and for conditions that, once set into motion, cannot be reversed. Traditionally, this is the basis for what is known as a 'safety-first' policy response—for policies that maintain options in the face of unknown and potentially undesirable future conditions.

4.1 What Are The Domestic Impacts Of Global Climate Change?

Assessment of the impacts of global climate change in the US is just beginning. Relatively little is known about impacts beyond general effects arising from forecasted changes in average annual surface temperature. These results are of limited use, considering that most climate-related effects probably derive from the occurrence of extreme events, like flooding, storm surge, or extreme extended drought. Absent a realistic forecast of the incidence of extreme events by type and severity, and period of occurrence, it is difficult to provide a realistic picture of the effects of global warming.

General patterns of impacts, however, can be discerned. These are evident in the results of the recently completed National Assessment of the impacts of global climate change in the United States (GCRP, 2000).

Four broad regions of impact have been identified: the coasts; the extreme northern tier of states, where existing ecosystems depend on the persistence of cold winter, cool summer climate conditions; the extreme southern tier of states, where agriculture and other systems are near to their extreme southern limit with regard to summer heat tolerance; and the semi-arid western states.

Coastal effects arise from rising sea level. Effects include coastal flooding and land abandonment, salt-water intrusion into estuaries and ground water, coastal wetland loss, and increased economic losses due to potentially increased severity of coastal storms. The decline of Florida and Hawaiian coral reefs is also projected.

In the western one-third of the nation, water availability is the issue most widely identified. Water supplies in the western states depend on natural stream flow. Water is withdrawn from

large western rivers and moved over long distances to population centers. The availability of stream flow is determined by spring snowmelt. Low-flows are experienced in summer months as seasonal snow-melt comes to an end. Under conditions of rapid surface warming, seasonal snowmelt comes much earlier in the year and the period of first snows comes later, substantially extending the period of low-flow in western rivers, and leading to longer periods of reduced water availability for human uses. Large new public expenditures will be necessary to accommodate these changes in the timing of water availability through the construction of increased reservoir water storage capacity.

At the northern extreme of the US, natural systems are adapted to cool summer and cold winter conditions. Some are at the current extreme southerly limit of their ranges, and hence are very susceptible to almost any surface warming. The cool conditions that favor the persistence of these systems disappears in the next century. For this reason, some of the most intense negative impacts on natural systems are likely to be concentrated in the far northern tier of states. Effects include: loss of existing forest-types and associated habitat, out-migration of cool climate animal species, and reduced habitat for cold water fishes.

Mapping of forced changes in forest type suggests substantial changes in the forests of this northern tier of states, with the now dominant aspen-birch, spruce-fir and maple-beech forest-types forced far to the north, to be replaced, eventually, by more southern hardwood forest types or savannah. Exactly how this change is effected is unknown. Peteet (2000) has shown that change can be rapid at the boundaries between biomes.

By contrast, agricultural systems in these states, which are now near their northern limit, flourish in the northern tier of states as climatic constraints on plant growth are relaxed. This is particularly true for crops adapted to warm, humid conditions, like corn, soybeans, and sugar beets. Cool season crops like oats or potatoes do less well, or decline.

Natural systems do better in the southern states. The obvious exception are freshwater lakes, in which dissolved oxygen is more readily depleted in warm months, leading to loss of fish habitat. The agricultural system in these southerly states, which is near its extreme southerly limit with regard to the effects of peak summer heat on agricultural productivity, does less well. Effects include the out-migration out of regional soybean and corn production to areas to the north with newly relaxed climatic constraints of production.

Outside of the coterminous US, the national assessment also foresees largely negative impacts to cold high latitude environments, including loss of glaciers, and negative impacts to polar animal species.

All of this, it might be noted, assumes a largely positive change in precipitation, which acts to offset many of the effects of higher surface temperature in the US forecast. Thus this is essentially the best-case scenario. Should the large-scale motions of the atmosphere under a warming favor the development of an extended period of drought, intermittent periods of drought during the warming, or increased frequency of short-duration extreme intensity droughts, this assessment would turn more negative. It might be noted that, at this point, there is little basis to conclude that either of these conditions is inherently more likely than the other. We simply do not know.

What we do know is that drought has been a normal condition in the center of North America for a very long period of time. From a review of the drought history of the Great Plains, it is clear that, over the last millennium, there have been numerous extended periods of extreme drought in the Great Plains lasting upwards of several hundred years, during periods of both relative coolness and warmth (NOAA, 2000). The primary task before climatologists is resolution of this basic question—how does this change under rapid global warming? Some time may pass before a satisfactory answer is available.

4.2 What Conclusions Can Be Drawn From The National Assessment For Minnesota?

The same constraints that limit discussion of domestic US impacts hold sway in discussing impacts in the upper Midwest. It is also difficult to generalize from conclusions drawn broadly from the average response of a very large geographical area to any specific locality. However, in as much as surface warming is forecast to be fairly homogenous across the continental US, some broad conclusions can be gleaned from the National Assessment (GCRP, 2000).

First, the boreal spruce-fir forest that now dominates the landscape of extreme northern Minnesota in the Boundary Waters Canoe Area will not survive rapid surface warming. Rapid warming will reduce stands of Aspen, particularly near the southern edge of the present forested part of Minnesota. The existing northern hardwood forest, as a whole, will give way to temperate deciduous forest and deciduous savannah. In general, the conditions suited for persistence of spruce-fir and Aspen-Birch forest types shifts well into Canada. Associated mammalian habitats shift northward out of the state. With time, cold and cool climate species are replaced by hemophilic species now found in states to the south of Minnesota.

Second, the habitat of cold water fish is negatively impacted. In shallow lakes, under conditions of rapid warming, habitat for cold water fish is eliminated; cold water fish habitat is unaffected in deep lakes (Stefan, 1999). Stream habitat for cold water fish declines by 50 to 100%. Shallow lakes and streams and streams become increasingly dominated by cool and warm water species of fish.

Third, water levels in Lake Superior fall by several feet. Inland lake levels also decline. Great Lakes shipping is effected by lower lake levels, requiring expensive new investments in harbor and lock and dam infrastructure throughout the Great Lakes basin, as well as increased dredging. This effects the competitiveness of the Great Lakes shipping business and the port of Duluth-Superior.

Fourth, the influx of invasive species into Minnesota waterways and lakes intensifies.

Fifth, insect populations expand with a longer warm season, requiring more intensive public health measures to control associated human health effects. In agriculture, increased insect crop losses require greater use of insecticides, potentially increasing the contamination of surface and ground water.

Sixth, reduced snow season and the shortening of the duration of ice cover on lakes by 1 to 2 months results in the curtailment or shortened season of winter recreation activities. These are replaced with warmer season activities.

Seventh, summer cooling costs rise and winter heating costs fall. The position of agriculture improves as the center of agricultural productivity in the US shifts northward. But this comes at the price of environmental effects associated with more intensive agricultural practices. The forest industry converts from reliance on Aspen to other species and products.

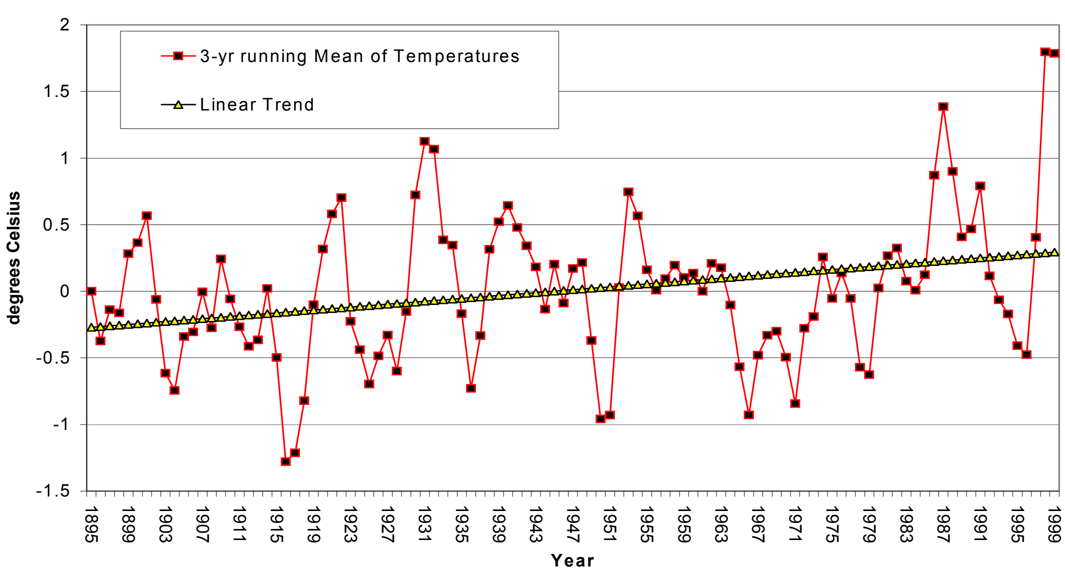
And last, general uncertainty about long-term future climatic conditions results in the necessity for new large public expenditures to broaden the design and operating parameters of sewage and water treatment facilities, the in-land barge system, and the flood control infrastructure. Uncertainties about short- and long-term precipitation and run-off changes, and uncertainties about changes in the frequency and intensity of extreme events like drought and flood are the principal concern here.

4.3 Is Climate Warming In Minnesota?

A monthly surface temperature record for nine state climatic divisions has been developed for Minnesota by the National Climate Data Center. This record is shown in Figure 18, converted to an annual basis and a statewide average. Evident in the record is a surface warming of about 0.5 degrees Celsius.

The warming is primarily a winter and spring warming, with summer temperatures rising dramatically from 1900 to 1940 and thereafter leveling out. From 1960, there also has been a trend toward autumn cooling. Geographically, the warming has been most intense in the northwest, north central and west central parts of the state. The southwest and south central sections have witnessed a slight cooling.

Figure 18. Trends in Mean Annual Surface Temperature for Minnesota: Average for Nine State Climatic Divisions



5.0 Is Global Climate Change Covered By An International Convention?

Global climate change is the subject of an international convention, developed in 1992, known as the United Nations Framework Convention on Climate Change (UNFCCC). 186 nations are parties to the UNFCCC, including the US, which became a party in 1992 upon Senate ratification of the convention. The UNFCCC explicitly recognizes that human activities are altering the global atmosphere and climate. It is the stated desire of the framers of the convention that dangerous human interference in the global climate be avoided. The UNFCCC was developed around this larger purpose.

The specific provisions of the UNFCCC require its parties to implement policies that return anthropogenic greenhouse gas emissions to 1990 levels by 2000. In doing so, the convention implicitly recognizes that the long-term accumulation of greenhouse gases in the atmosphere may represent a dangerous human interference in global climate.

The underlying reasoning of the treaty is precautionary in nature. It is possible that human releases of greenhouse gases to the atmosphere may result in dangerous interference in global climate. The science is still developing. Until it can be conclusively shown that global climate change poses no large-scale risks to society, the reasoning goes, society should seek to avoid any increase in the rate of forcing on climate, essentially as a precaution against what we do not know.

The greenhouse gases that are named in the UNFCCC include: CO_2, CH_4, N_2O, the HFCs, PFCs, and SF_6. The CFCs, HCFCs and chlorocarbons are not included under the terms of the accord. The production and use of these compounds is covered under the terms of an earlier international convention, the Montreal Protocol on Substances that Deplete the Ozone Layer and its amendments

Under the terms of the UNFCCC, the US is bound to implement policies to reduce domestic emissions to 1990 levels. The US is required under the UNFCCC to prepare and submit annual greenhouse gas emission inventories to the secretariat of the Conference of the Parties to the convention. In addition, it is required to prepare and submit to the secretariat a summary and analysis of the policies it has implemented under the terms of the UNFCCC to meet its obligations under the convention. Both submissions are reviewed by the secretariat of the Conference of Parties to the convention. Scientific expertise is provided to the secretariat by the Intergovernmental Panel on Climate Change.

5.1 What Is The Kyoto Protocol?

Built into the UNFCCC is provision for extended evaluation of the underlying science of global climate change, the need for targets and timetables, and the general effectiveness and adequacy of treaty provisions. Within a few years of the UNFCCC having come into effect, review determined its provisions were probably inadequate to its purpose of preventing dangerous human interference in the global climate. In part, there developed a recognition that, even if enforced, the requirements made of the parties to the UNFCCC would still result in substantial global surface warming. By 1996 or 1997 it also had become clear that at least 50 years and probably more would be required to wean the global commercial energy system from its

dependence on fossil fuels. This seemed to require an early start date to actions to begin to reduce that fossil fuel dependence.

Finally, by 1997 it had become clear that the lack of language in the UNFCCC mandating specific levels of emission reduction was hindering the effectiveness of the convention. By 1997, with the exception of Russia, Germany, the United Kingdom, few signatories from the developed industrial economies had made much progress toward achievement of the goals specified in the UNFCCC for 2000. By 1998, US emissions of greenhouse gases were about 12% above 1990 levels.

In response, in 1997 the parties to the UNFCCC developed the Kyoto Protocol to the UNFCCC that included language requiring legally binding emission reductions. Under the Kyoto Protocol, the developed economies of Europe, North America, Russia, Japan and Australia and New Zealand, otherwise known as Annex 1 countries, in aggregate are required by 2008 to 2012 to reduce their emissions to a level that is 5% below 1990 levels. Reductions were apportioned among the developed economies, depending on the unique conditions of each developed economy. Under the terms of the Protocol, the US would need to reduce its emissions of CO_2 and other greenhouse gases to a level that is 7% below 1990 levels, the European Union by 8% below 1990 levels, and Japan and Russia by 6% and 0%, respectively, below 1990 levels.

In aggregate, the Annex 1 economies account for more than half of global anthropogenic emissions of greenhouse gases, so the effect would be to stabilize global emissions near 1990s levels for a few years.

The Protocol specifies successive budget period for purposes of emissions control. The initial budget period would be 2008 to 2012. The developed economies would have to reduce their emissions in aggregate an average of 5% across all years of that budget period. The second budget period would be 2013 to 2018, with targets and timetables for that budget period to be set in the mid-2000s.

The same greenhouse gases as are named in the UNFCCC are named in the Kyoto Protocol. 1990 is set as the baseline year for the most important greenhouse gases.[5] For purposes of calculating emissions during the 2008 to 2012 budget period, according to the Protocol a nation counts gross emissions less any carbon dioxide removed from the atmosphere during the period 2008-2012 through land reforestation or afforestation activities. As discussed above, during photosynthesis, CO_2 is removed from the atmosphere and incorporated into the growing stock of trees and other components of the forest. With reforestation of previously cleared land, substantial amounts of carbon dioxide can be removed from the atmosphere, essentially offsetting a part of emissions resulting from fossil fuel combustion.

Two trading blocks are enumerated in the Protocol: a European bloc comprised of the economies of western and eastern Europe; and a second trading bloc comprised of the US, Canada, Russia, Japan, Australia and New Zealand. Under the terms of the Kyoto Protocol, the trading of emission allowances within trading blocs is permitted. Thus a nation that in 2008 finds that it

[5] 1995 is set as the baseline for the PFCs, HFCs and SF_6.

cannot meet its treaty obligations through domestic actions may purchase excess emission allowances generated by other nations within its trading bloc.

Emission reductions also may be realized by Annex 1 economies within developing economies through the Clean Development Mechanism (CDM). Through the CDM, emissions reductions that are realized in a developing nation as a result of expenditure by an entity from an Annex 1 nation are credited against the treaty obligations of that Annex 1 country.

The Kyoto Protocol does not specify policy measures that must be implemented domestically in Annex 1 economies. Each Annex 1 country is free to develop national policies along whatever lines it chooses, subject to the constraint that it not exceed its greenhouse gas emission allowance under the Protocol. In practice, for a state like Minnesota, this means that likely future regulatory obligations cannot be predicted on the basis of national treaty obligations, proposed or otherwise. Regulatory obligations will depend on the shape of the national regulatory structure put into place by Congress.

Of the provisions of the Kyoto Protocol, the emission trading regime, the compliance regime, the CDM, and the treatment of carbon sinks are most controversial. On trading, it is the US position that few or no limitations be imposed on the ability of a country to meet its treaty requirements through cross-border trading of emissions rights or allocations. In this, the US is supported by Canada, Australia, and Russia. The European countries have steadfastly maintained that a country could use cross-border trading to satisfy only a small portion of its required emission reduction.

On carbon sinks, over the last year, the US has adopted a position that any increased carbon storage in soils and on forestland, regardless of whether new land is put into trees or not, should be treated as a CO_2-offset, or a negative emission. Essentially, the US argument runs, since carbon is stored terrestrially through photosynthetic activity, and since the carbon source for the underlying photosynthetic activity is atmospheric in nature, any increase in terrestrial carbon storage would accompany a parallel removal of carbon from the atmosphere. The US has a large land base with a forest that is slowly regrowing and storing carbon, and agricultural lands that, due to increasing plant productivity, probably are building carbon reserves. Based on recent emission and sink inventories, this sink might be equal to 5 to 10% of gross emissions. The US position is that any and all terrestrial carbon storage ought to count against a county's cap obligations.

By contrast, the Europeans are much less sanguine about the wisdom of allowing emission caps to be met all or in part through the use of terrestrial carbon sequestration. They point to the difficulty encountered in measuring terrestrial carbon storage, particularly on an annual basis,

and the wisdom in granting credits for carbon storage that may be only temporary in nature.[6]

On compliance regimes, the discussion centers on the nature of any sanctions imposed upon countries not meeting their mandated caps.

On the CDM, the question centers on the types of activities that should be creditable under the Protocol. For instance, some parties to the negotiations have objected to credits being provided for emission reductions realized in developing economies through the extension of civilian nuclear power to these economies.

Much of the work of the Conference of Parties takes place during the sessions of the subsidiary bodies. These bodies develop the necessary analyses, frame questions, and present recommendations to the larger conference of the parties for ratification.

The parties of the UNFCCC have met in three extended negotiating sessions since meeting in 1997 in Kyoto. Many parts of the Protocol remain yet to be developed, including sections trading, sinks and compliance. The most recent negotiating session, at the sixth meeting of the Conference of the Parties (COP-6) ended in failure to resolve differences over the role of carbon sequestration in the Protocol. In 1999 the parties to the UNFCCC set 2000/2001 as the period for final development of the Protocol, and 2002 as the year the Protocol would enter into force.

Roughly 85 countries or political unions have signed the Protocol and about 25 have legislatively ratified it.

5.2 What Does The Modeling Show About The Effectiveness Of The Kyoto Protocol?

The effectiveness of the Kyoto Protocol in limiting the forecasted rate of surface warming has be evaluated by Wigley (1998). The results are shown graphically in Figure 19. Two warming trends are shown: the surface warming calculated at a climate sensitivity of 2.5 degrees Celsius per doubled atmospheric levels of CO_2 under forecasted business-as-usual conditions; and the surface warming expected at the same climate sensitivity with full implementation of the provisions of the Kyoto Protocol. At 2100, the difference in mean global surface temperature between the two is about 0.15 degrees Celsius.

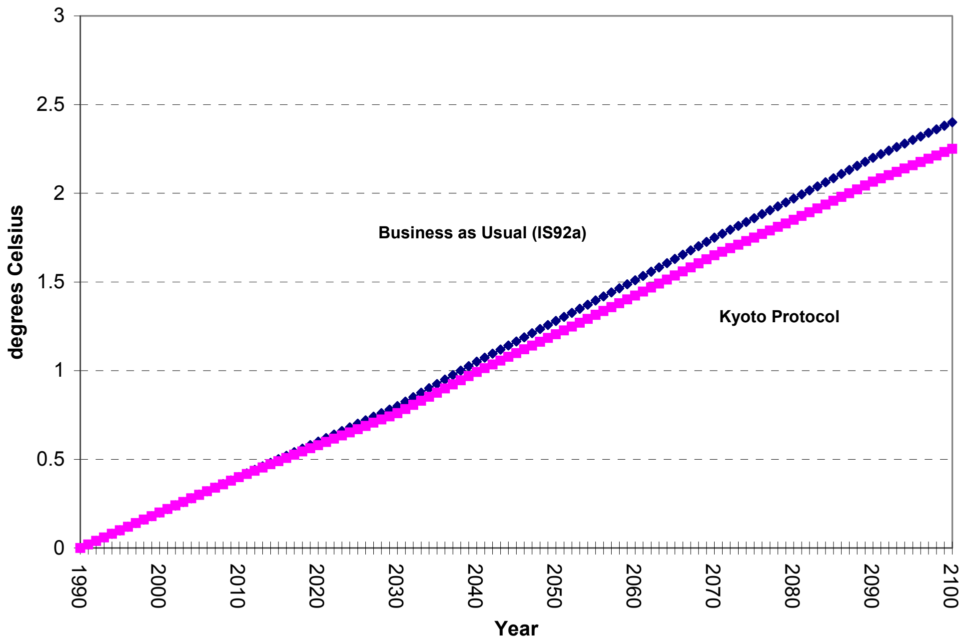
The principal reason for the lack of responsiveness of forecasted mean global surface temperature to the implementation of the Protocol is the low level of required emission reduction under the Protocol. As noted earlier, under the conditions of constant 1990 emissions globally,

[6] The contribution of terrestrial carbon storage has been controversial, at least in part due to uncertainties in he underlying science. Once emitted to the atmosphere, about 40 percent of all carbon emitted during fossil fuel combustion and forest-clearing remains in the atmosphere. The remainder is absorbed in the biosphere or oceans. We can account for the withdrawal into oceanic systems. (Kheshgi, *et al*. 1999) This amounts to about 60 percent of the carbon withdrawn into the ocean-biosphere system. The fate of remainder of emitted remains uncertain. It is likely to be terrestrial in nature. Evidence drawn from the spatial distribution of atmospheric CO_2 concentrations suggests that large-scale regrowth of forests in the northern hemisphere may account for much of this carbon withdrawal. (Battle, *et al*., 2000) However, detailed forest inventories, land-use records, and vegetation modeling yield very different estimates of this sink for specific geographical areas. (Schimel *et al*., 2000, Houghton, *et al*., 1999) Our inability to account for this 'missing sink' troubles the debate on the use of carbon sequestration to meet treaty obligations.

mean global surface temperature still rises 1 degree Celsius by 2050 from 1990 levels and under 2 degrees Celsius by 2100. This is not too different from the forecast developed under the conditions of full implementation of the terms of the Protocol, which requires controls at more or less constant 1990 levels (less 5%), but only of the developing economies.

The absence of developing country participation also acts to erode the forecasted effectiveness of the Protocol.

Figure 19. Forecasted Effects of the Implementation of the Kyoto Protocol by Annex B Countries on Changes in Mean Global Surface Temperature: Mid-range Climate Sensitivity (Wigley, 1998)



5.3 What Is The Outlook For The Kyoto Protocol?

The Kyoto Protocol has been controversial in the US. Environmentalists have criticized it as ineffective and riddled with loopholes. Industry, for its part, has criticized the treaty on the grounds of cost and need. As far as need, it is the position of industry that the science of global climate change remains far too uncertain to justify the formulation of policy now. Regarding cost, it is noted that, in the case like an economy like that of the US, the terms of the Kyoto Protocol, as currently written, would require a 20 to 25% emission reduction from expected 2008 to 2012 levels (US DOE, 2000), or 360 to 400 MMTCE tons at $100 to 300 per ton. They further note that many of these reductions could be met only at the expense of the closure of many energy-intensive basic industries.

A far cheaper path to control, it is suggested, is to implement a control program over a more extended period that allows for the deployment of advanced energy conversion and manufacturing technology and the orderly retirement of existing capital stocks (Wigley, *et al.*, 1996).

The Protocol has been signed, but remains unratified by the US Senate. In 1997, the Senate resolved 99 to 1 that the US should not become a party to any agreement that does not include developing country participation or that threatens the economic well-being of the country.

The attitude of the incoming Bush Administration is unclear. It seems unlikely that it will allow the Kyoto/UNFCCC process to collapse, but also seems unlikely to go along with the Protocol in its present form. During the campaign, then candidate Bush voiced his opposition to the Kyoto Protocol as written, particularly its lack of developing country participation. Then candidate Bush also expressed the opinion that the science was yet uncertain. At the least, it is unlikely that the Kyoto negotiations will be a very high priority of this Administration.

Given this, the outlook for the Protocol in the US seems dim.

One possibility that has been suggested is the redesign of the Protocol along completely new lines, possibly a long-term CO_2 concentration cap, with actual emission reductions put off until the out-years a decade or more into the future. This would allow for a more orderly transition to an international control regime, while maintaining a long-term commitment to control emissions. This is likely to be rejected by the environmental community.

The Kyoto Protocol enters into force with ratification by at least 55% of the UNFCCC members responsible for at least 55% of 1990 global anthropogenic greenhouse gas emissions. With ratification by the countries of the European Union, Russia and Japan, it is possible for the Protocol to take effect without US ratification. The prospects for such an outcome are uncertain. This, however, will require that the yet unfinished sections of the Protocol be completed.

The Conference of the Parties to the UNFCCC is scheduled to meet in November to resume negotiations on the terms of the Protocol. More will be known by then.

5.4 What Is Being Done Nationally?

The United States is a party to the UNFCCC, which the US Senate ratified in 1992. As noted above, the UNFCCC requires the parties to the convention to implement policies designed to return greenhouse gas emissions to 1990 levels by 2000.

To implement the UNFCCC, the US has adopted a voluntary program of emission reductions. No mandatory reductions have been instituted. The programs were designed on the assumption that large voluntary emission reductions on the part of industry could be leveraged through the provision of Federal technical assistance to industry and the owners of commercial buildings, product labeling, voluntary agreements, and Federal research and development spending. Instituted under the Climate Change Action Plan were: the Greenlights Program, Energy Star, the Climate Challenge, Motor Challenge, the AgStar program, the Ruminant Methane program, and similar technical assistance and research and development programs.

During the development of the Climate Change Action Plan, it was projected that full implementation of the program would result in attainment by the US of the UNFCCC goals. In practice, the programs have not been able to realize emissions control at 1990 levels. As of the

end of calendar year 1998, US emissions of CO_2 and the other greenhouse gases were roughly 12 percent in excess of 1990 levels, rising roughly 1.3% per year.

The fate of the existing technical assistance programs is uncertain, as is the larger direction of US domestic and international policy on global climate change. As noted above, the policy of the incoming Administration on global climate change has yet to be worked out. It is possible that the global climate change programs initiated by the last Administration could be wound down and allowed to lapse. It is likely that the incoming Administration will develop a new overarching strategy for dealing with global climate change. More will be known by spring, when the US position going into COP-7 will have to be developed, and future funding levels for global climate change programs will be announced.

6.0 What Are Minnesota's Annual Greenhouse Gas Emissions?

The Minnesota Pollution Control Agency has developed an annual emission inventory for greenhouse gases. Emissions are inventoried for CO_2, CH_4, N_2O, and HFC-134a.[7] Since the production of CFC-11, CFC-12, CFC-113 and CCl_4 and CH_3CCl_3 is banned by law, emissions of these compounds are not inventoried. Of the greenhouse gases of secondary importance, HCFCs and recently developed substitutes for the CFCs, HCFCs and chlorocarbons are not inventoried due to lack of adequate reporting on industrial and commercial uses. It is unlikely that Minnesota industry emits substantial quantities of perfluorocarbons; those tend to be associated with aluminum manufacture or with etching activities in the semiconductor industry. Hence, no inventory estimate is developed for PFCs. Emissions of SF_6 also are probably small, and hence are not inventoried.

Emissions are inventoried for six economic sectors: transportation, electricity generation, agriculture, and the commercial, industrial and residential sectors.

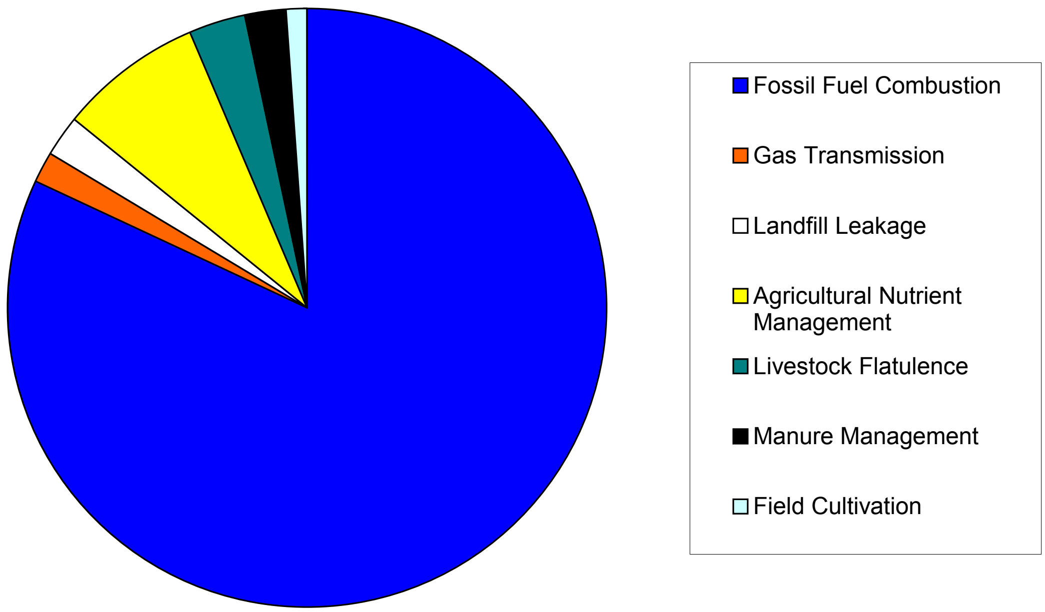
1997 greenhouse gas emissions from Minnesota totaled an estimated 140 million CO_2-equivalent tons.

6.1 What Are Sources Of Greenhouse Gases In Minnesota?

The sources of Minnesota 1997 greenhouse gas emissions are shown in Figure 20. In 1997, about 80% of Minnesota emissions derived from fossil fuel combustion. Another roughly 10% was associated with agricultural nutrient management, and about 7% is estimated to have derived from livestock production. Emission from natural gas transmission and distribution and landfill leakage account for the remainder of estimated 1997 Minnesota greenhouse gas emissions.

[7] A number of minor emission sources have yet to be inventoried. These include: wastewater treatment, prescribed burning, septic systems, agricultural liming of fields, biosolids land application, MMSW and grass composting, and commercial space cooling. It is not thought that these sources emit substantial quantities of greenhouse gases to the atmosphere.

Figure 20. Distribution of Greenhouse Gas Emissions from Minnesota for 1997 by Emission Source



6.2 What Are Trends Of Greenhouse Gas Emissions In Minnesota?

Trends in greenhouse gas emissions from Minnesota are shown in Figure 21 for the period 1970 to 1997. Three distinct phases are evident in the emissions data: a period of rapid growth in emissions from 1970 to 1979, a period of contraction from 1980 through 1987, and a resumption of rapid growth in emissions, 1988 to 1997. The first of these periods coincided with a decade of robust economic expansion, both nationally and statewide, that ended with the deep 1981-2 recession; the second, with a period of de-industrialization and fuel-switching from coal to natural gas throughout Minnesota industry. Also important in the contraction of emissions in the mid-1980s was the large-scale substitution of in-state electricity generation by electricity purchases from out-of-state sources. The period since 1988 has been characterized by a return to greater reliance on in-state generation sources, rapid growth in emissions from transportation sources, and, in the middle and late1990s, robust economic growth.

The ten-year average annual rate of growth in emissions from 1988 to 1997 is about 2 percent per year. Since 1988, emissions have increased about 20%. As of the end of 1997, emissions were roughly 25% above the Kyoto targets.

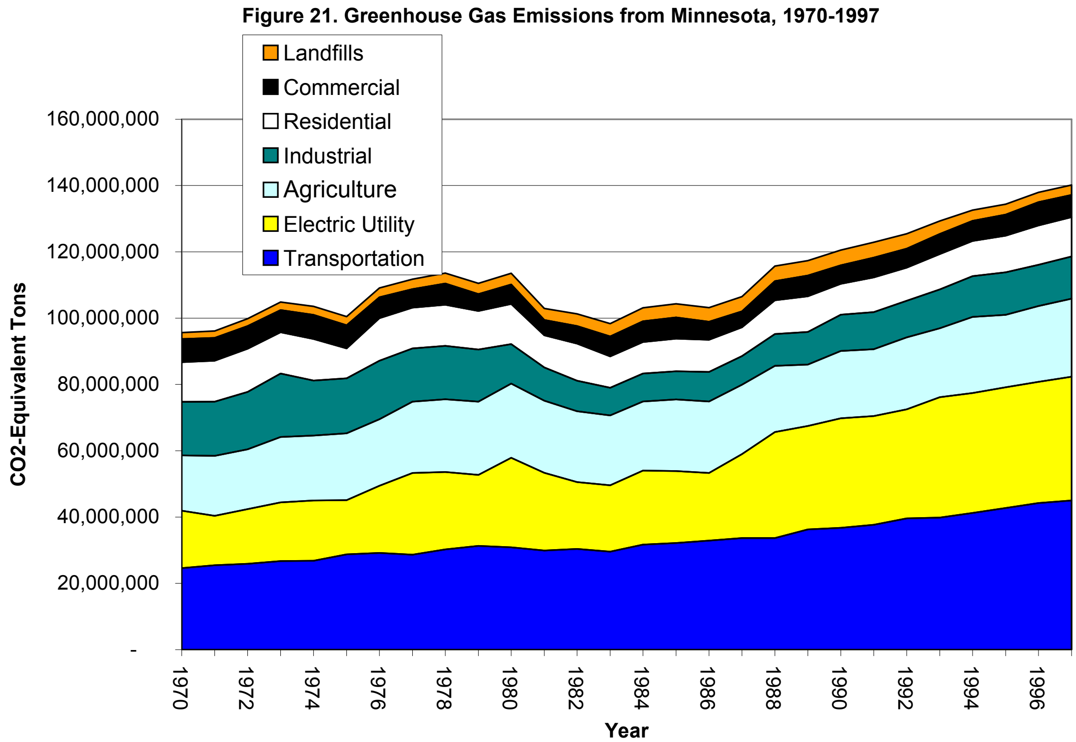
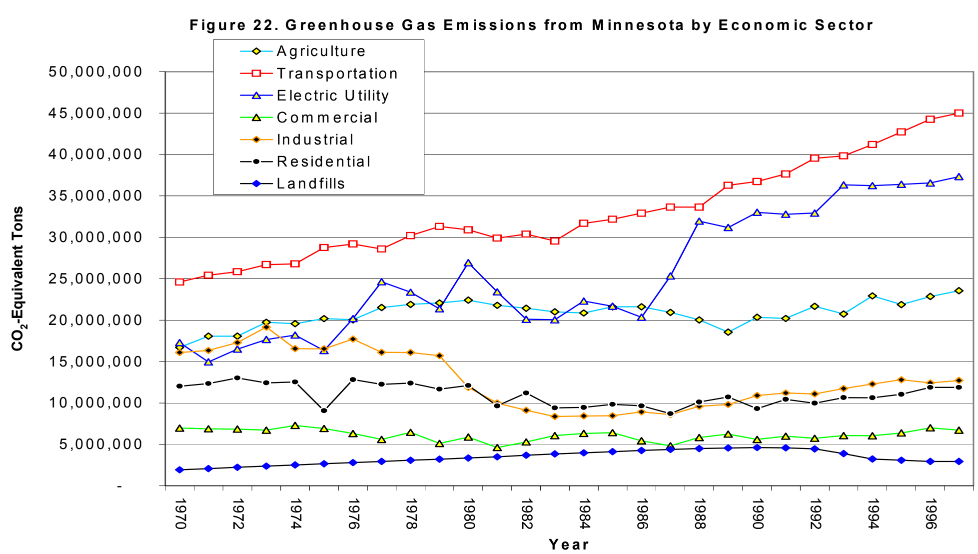


Figure 22 presents the same trend information without stacking sectoral emission totals. This reveals the electric utility and transportation sectors to be source of the long-term increase in greenhouse emissions from Minnesota. Together, in 1960 these two sectors accounted for about 40% of all emissions from the state. By 1997, their contribution had risen to 60%. Simple linear extrapolation of historic trends suggests that, within a decade, these two sectors will account for two-thirds of all greenhouse emissions from Minnesota.



Figures 23 and 24 show trends in greenhouse gas emissions for the same period of time broken down by gas and by major emitting activity.

Figure 23. Greenhouse Gas Emissions from Minnesota by Gas

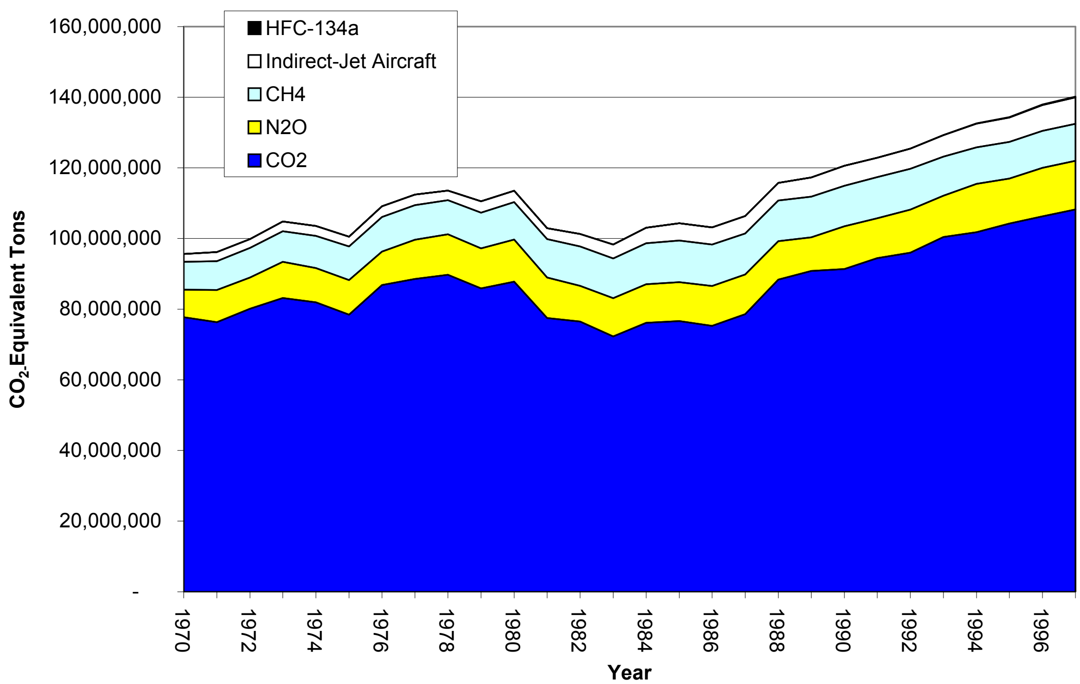
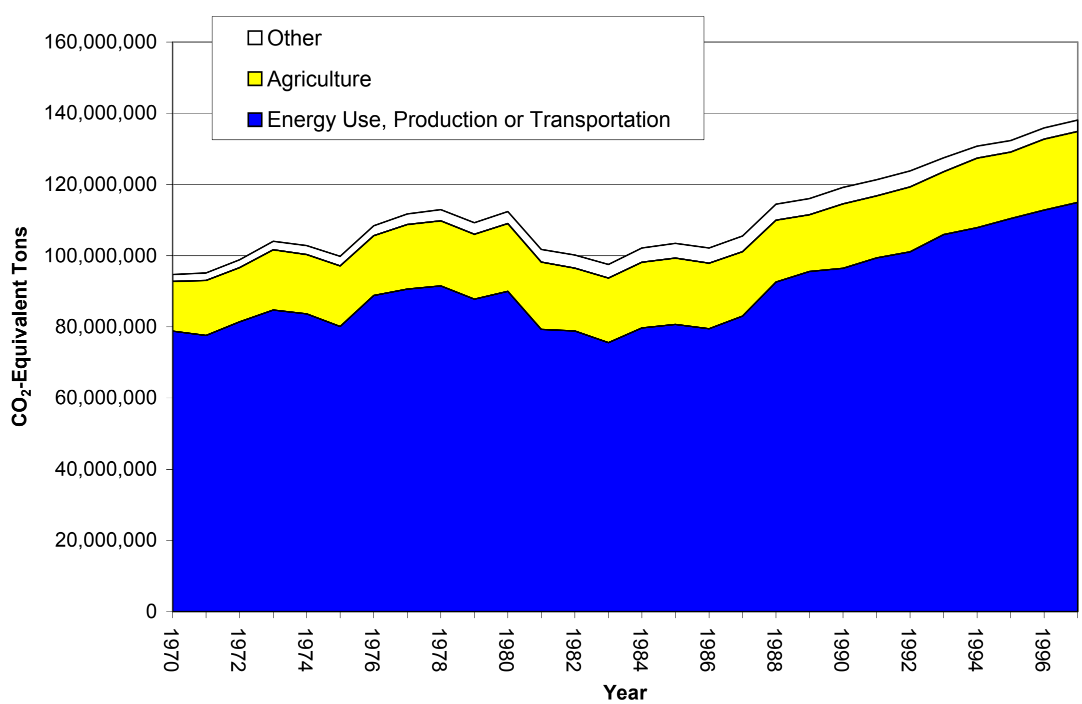


Figure 24. Greenhouse Gas Emissions from Minnesota, 1970-1997



Figures 25, 26 and 27 show trends in greenhouse emissions since 1970 for each of the principal greenhouse gases emitted in Minnesota by major emitting activity. Figure 25 shows trends in CO_2 emissions. Trends in emissions of CH_4 and N_2O are shown in Figures 26 and 27, respectively. Emissions of CO_2 from fossil fuel combustion are broken out by emitting sector. Calculated emissions of CO_2 from the cultivation of agricultural soils are shown separately from emissions from fossil fuel combustion in agriculture. Emissions of CO_2 increase rapidly to 1980, stabilize or decline to the late 1980s, when rapid growth recommences.

Estimated emissions of CH_4 rise rapidly until about 1984, stabilize until 1991, and then decline. Much of the decline stems from reductions in the number of cattle on Minnesota farms, and from reductions in the amount and composition of mixed municipal solid waste landfilled in Minnesota. Emissions of N_2O follow are pattern similar to that of CO_2.

Figure 25. CO_2 Emissions from Minnesota, 1970-1997

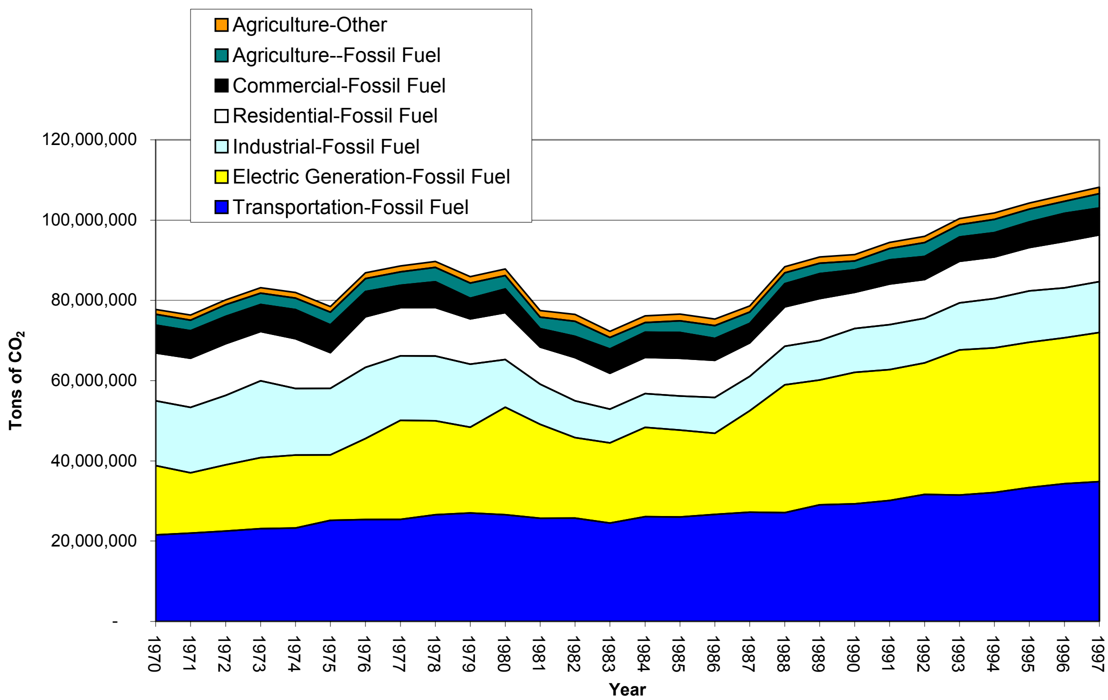


Figure 26. Methane Emissions from Minnesota

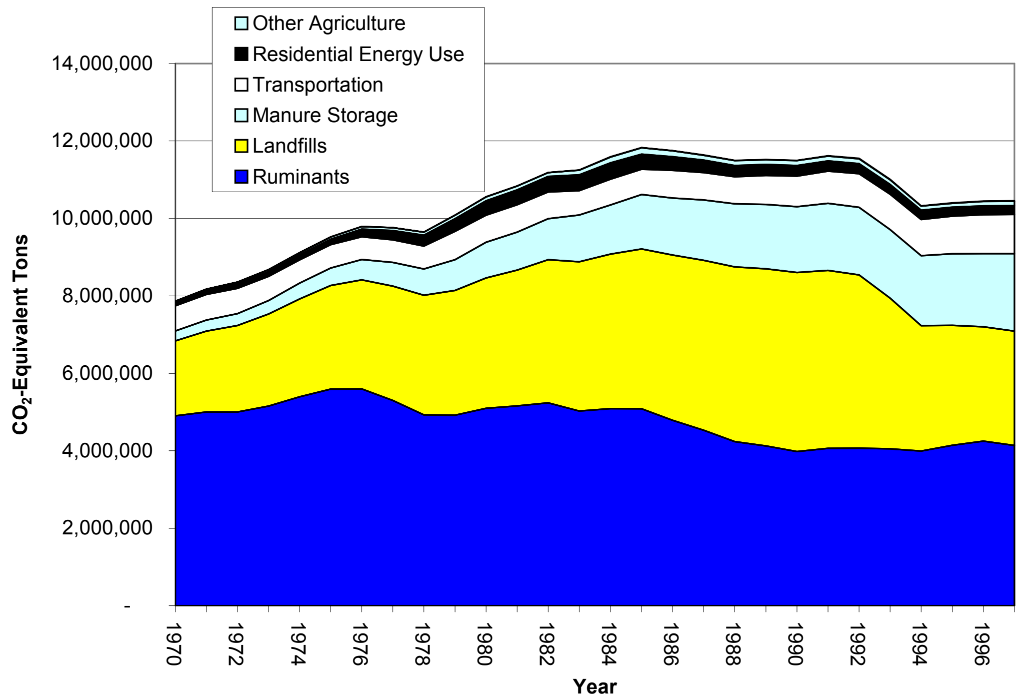
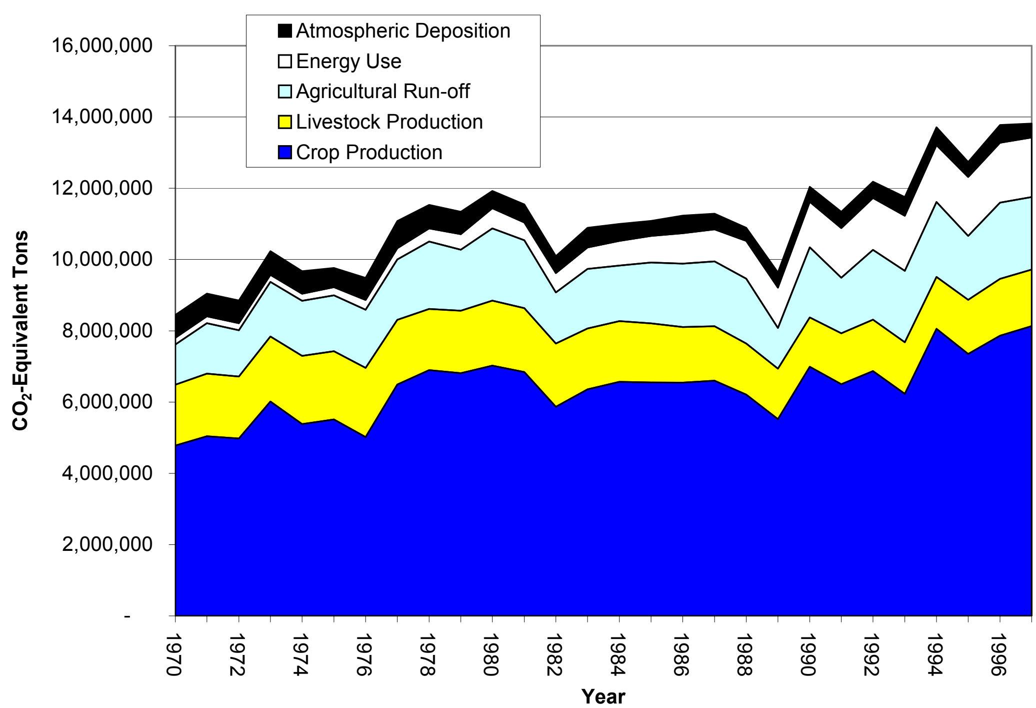


Figure 27. Nitrous Oxide Emissions from Minnesota Sources, 1970-1997



Figures 28 and 29 show a longer record for just CO_2 emissions associated solely with fossil fuel combustion in Minnesota by fuel combusted and by economic sector. Emissions of CO_2 increased steadily over this period, approximately doubling over the roughly four decades since 1960. The long-term average annual rate of increase during this period was about 1.8% per year. Two sectors – transportation and electric utilities – dominate the CO_2 totals throughout the record. In 1960 these two sectors accounted for about 40% of all CO_2 emissions from the state. By 1997, their contribution had risen to 66%.

Figure 30 presents the same trend information as in Figure 29 for CO_2 emissions without stacking fuel-related totals. This reveals coal combustion to be the source of the long-term increase in CO_2 emissions from Minnesota.

Finally, while CO_2 is emitted to the atmosphere through combustion activities, it is also removed from the atmosphere through photosynthesis and plant growth. As discussed above, over the lifetime of a large, long-lived plant like a tree, substantial amounts of carbon can be removed from the atmosphere and incorporated into above- and below-ground plant biomass or into the forest floor. After harvest, a part of this goes into semi-permanent storage as the structural components of housing or into landfills in the case of paper uses of forest biomass. About 65% of all biogenic carbon that is landfilled remains sequestered in the landfill for long periods of time.

Figure 28. CO_2 Emissions from Fossil Fuel Combustion in Minnesota by Fuel Type

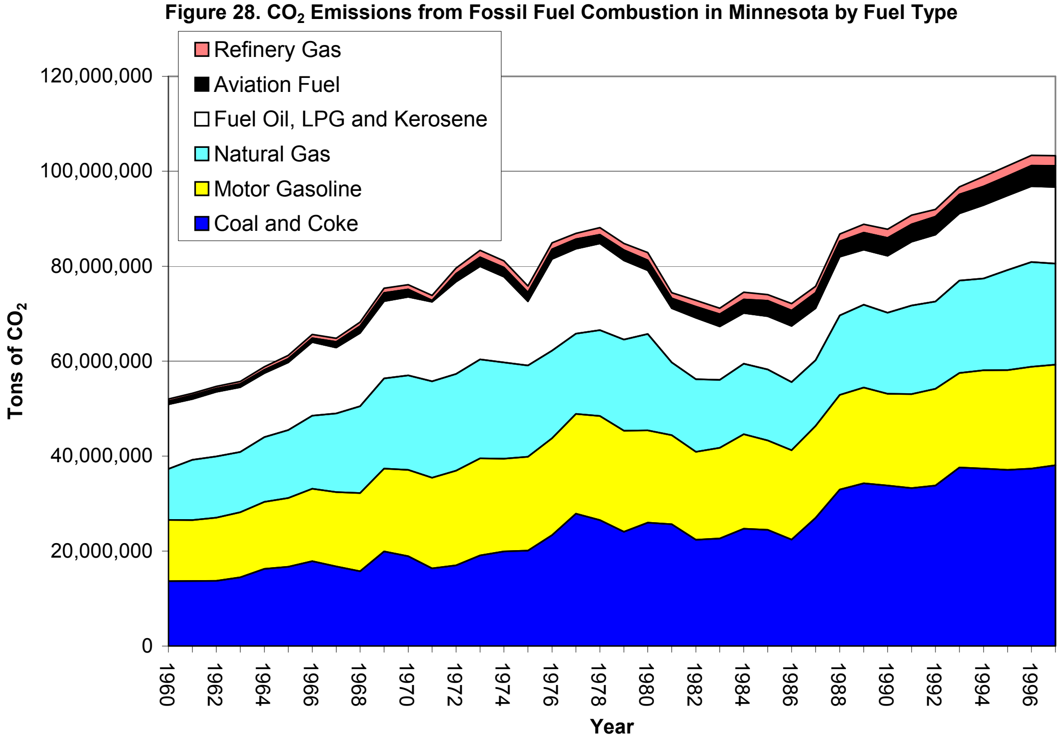


Figure 29. Carbon Dioxide Emissions from Fossil Fuel Combustion in Minnesota

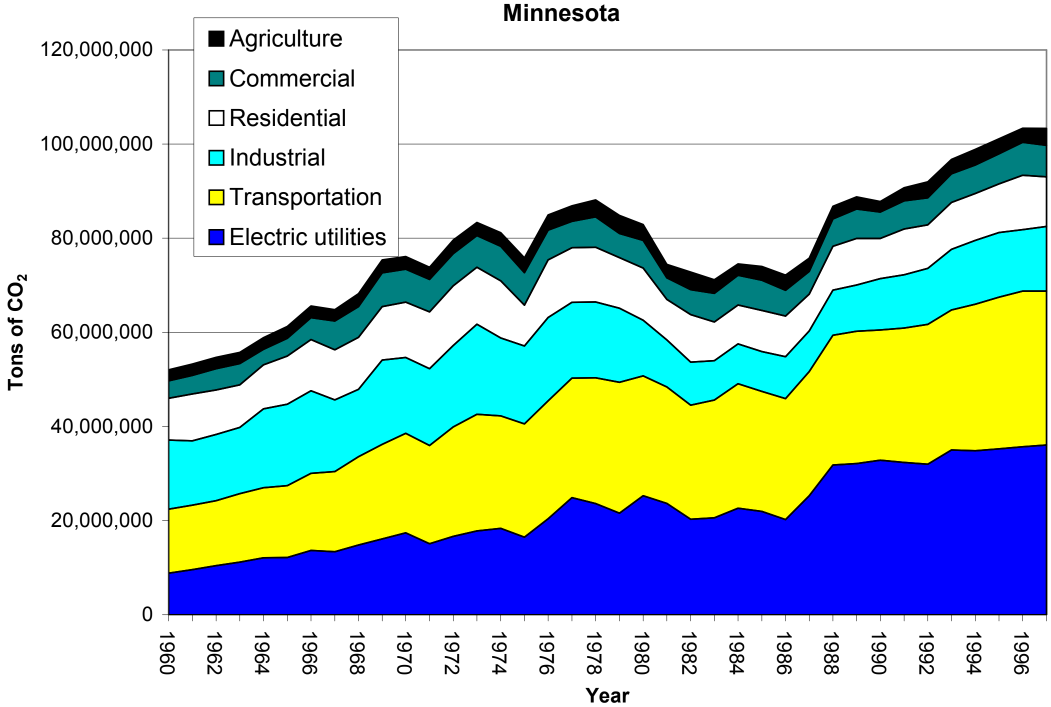


Figure 30. CO_2 Emissions from Fossil Fuel Combustion in Minnesota by Fuel Type

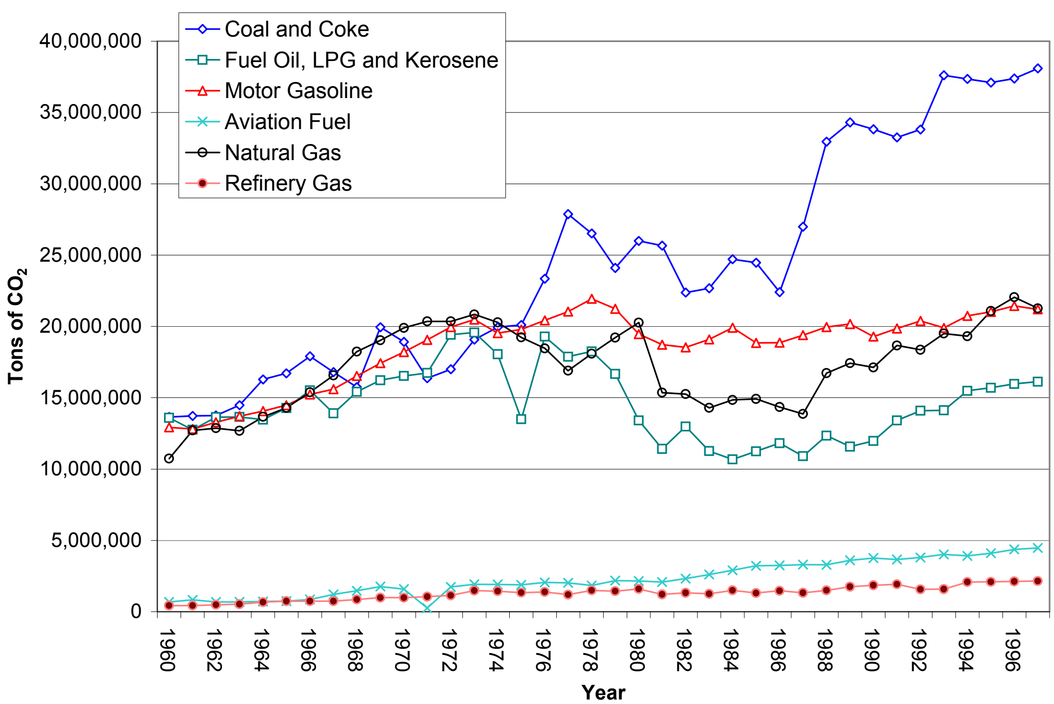
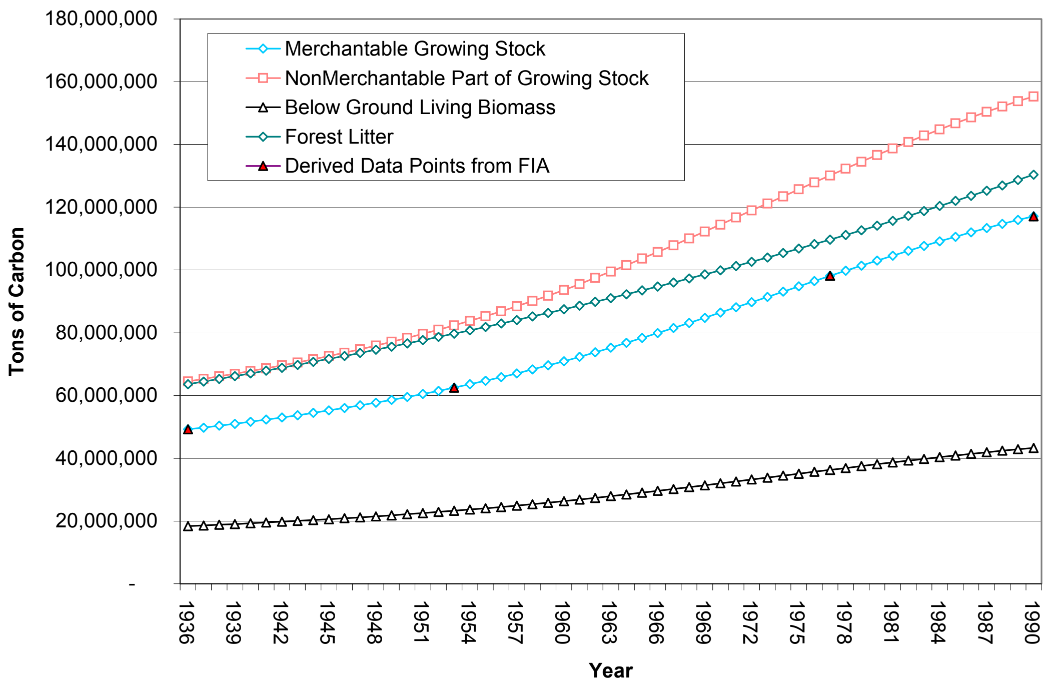


Figure 31 plots trends in carbon storage on Minnesota timberlands for different forest components from 1936 to 1990 developed from US Forest Service Forest Inventory Assessment (FIA) data and characteristic relationships between the merchantable and non-merchantable parts of growing stock and below ground living biomass and the forest floor. Totaling all forest components, as of 1990, about 450 million tons of carbon were stored on Minnesota timberlands, up from about 330 million tons in 1977. This is shown in a stacked representation in Figure 32. The mean annual rate of carbon storage in 1990 was probably near 5 million tons of carbon, or the equivalent of about 18 million tons of CO_2.

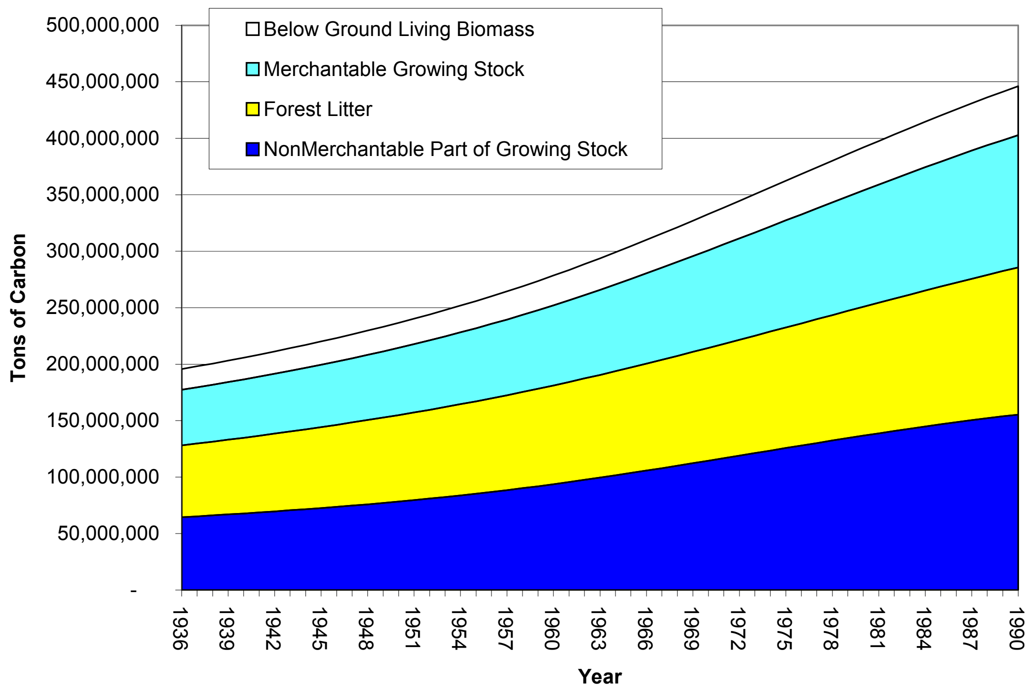
Figure 31. Carbon Storage on Minnesota Timberlands



Parallel storage of carbon in structures is shown in Figure 33. This was based on analysis of total structures in place, their size, and the intensity of wood use per square foot of floor space. On a decadal basis, about 200,000 tons of carbon are stored in structures, or about 20,000 tons per year, the equivalent of about 73,000 tons of CO_2.

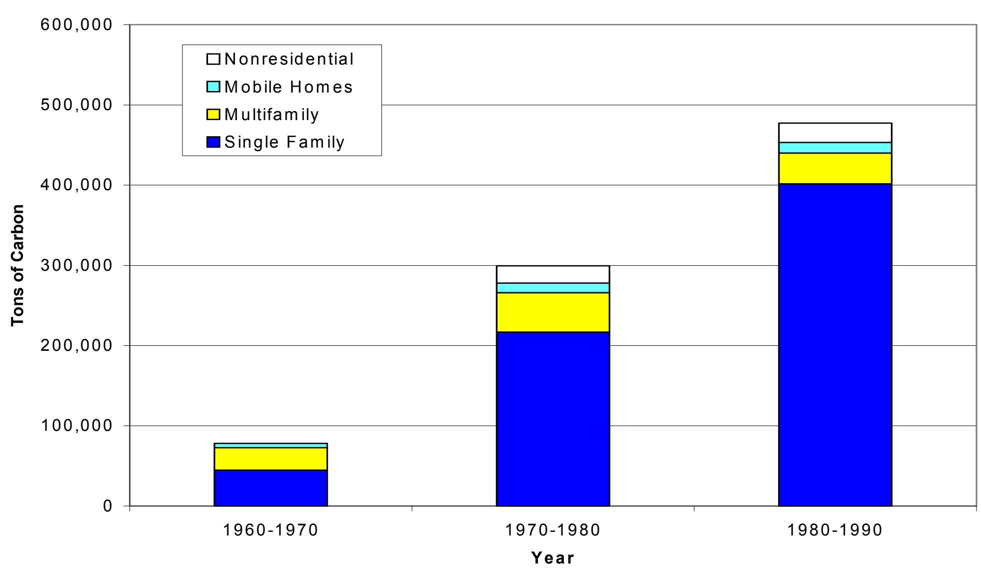
Annual landfill storage of carbon in the early 1990s is estimated to have been about 1 million tons of carbon, or about 3.7 million tons of CO_2. However, landfill dynamics are complex. Modeling suggests that, given current levels of receipts of MMSW into Minnesota landfills, present annual rates of storage may be substantially lower than rates for the early 1990s.

Figure 32. Carbon Storage on Minnesota Timberlands



Total carbon storage in 1990 in Minnesota forests, landfills and structures is estimated to have been 6 to 7 million tons of carbon (22 to 25 million tons of CO_2), offsetting in Minnesota on the order of 20% of gross emissions of all greenhouse gases. Current annual rates of storage are probably of roughly the same order.

Figure 33. Storage of Carbon in Structures in Minnesota



7.0 What Are Technical Measures For Controlling Emissions Of Greenhouse Gases?

CO_2 is the principal greenhouse gas emitted in Minnesota. It is technically feasible to remove CO_2 chemically from the flue gases of fossil fuel-fired power plants and industrial boilers using adsorption with various amine solutions. Other advanced concepts for removal are also under development (Simbeck, 1999). The principal constraint to CO_2 capture and disposal is one of permanent storage of such large amounts of carbon dioxide. Injection in the deep ocean has been suggested. Once captured at the plant and liquified, under this suggestion, the CO_2 would be moved by pipeline to the coasts, then off-shore, where it would be injected into deep ocean waters. There, it is hoped, it will permanently remain. Another possibility that has been suggested is injection in depleted oil and gas wells (Socolow, 1997).

These concepts are being investigated. Preliminary estimates suggest control costs at about $0.02/kwh for new generation sources (Williams, 2000).

Land sequestration of Atmospheric carbon through expanded global forests and increased storage in soils is a different type of response. It has been suggested that upwards of 0.3 billion metric tons of carbon could be stored annually in forests and soils of Kyoto Annex I countries, enough to satisfy Kyoto treaty requirements for the Annex 1 bloc of economies (IPCC, 2000). The cost of sequestration in the US is an estimated $20 to40 per metric ton of carbon equivalent sequestered (Adams, *et al*., 1999, McCarl and Schneider, 1999, IPCC, 1996). At least part of the offset realized through land storage of carbon activities would be offset by surface warming from increased as surface absorption of incident sunlight by a now darker, greener forested landscape (Hadley, 2001).

Various geoengineering proposals have been made. It has been suggested that we counter greenhouse warming with lower stratospheric aerosol injection, which should act to cool the atmosphere, thereby offsetting some of the warming. Alternatively, it has been suggested that nutrient constraints to biological oceanic uptake of CO_2 be relaxed through intentional loading of the ocean's surface layers with nitrogen or iron. These have yet to be systematically evaluated for feasibility and environmental acceptability (Schneider, 1996).

With regard to the energy system proper, technical measures of control include: fuel switching at existing facilities and in transportation; co-firing coal with gas or biomass; power plant repowering; enhanced plant efficiency though cogeneration; energy end-use efficiency improvement, and the deployment of advanced energy conversion technology in place of existing plant or to meet new demand.

Per million btu (mmbtu) of energy produced, the combustion of coal produces roughly twice as much CO_2 as does the combustion of natural gas, and about 1.5 times what is produced during the combustion of oil or refined petroleum products.

Co-firing coal with up to 20% natural gas or wood can reduce CO_2 emissions per mmbtu of energy produced by 10 and 20%, respectively.

Power plants can be re-powered by adding a bottoming or topping cycle to boost plant efficiency.

Cogeneration can take new plant efficiency of energy use from the 40% range to 80% through the use of low temperature waste heat for industrial processes or space heating following power generation.

End-use efficiency can be improved at least 10% through cost-effective investments, and possibly as much as 30% (NAS, 1992).

Finally, advanced energy conversion technology is substantially more efficient in converting fuel to usable energy, particularly in electricity generation. Estimated CO_2 emissions per kilowatt-hour (kwh) of electricity generated are shown in Table 16 for advanced conversion technology.

Table 16. CO_2 Emissions per Unit Net Electricity Produced from New Power Generation Technology

	Lb. CO_2/kwh
New Coal Pulverized Coal with Scrubber	1.92
New Coal-Atmospheric Fluidized Bed	2.05
New Coal-Pressurized Fluidized Bed	1.95
New Coal-Integrated Gasification Combined Cycle	1.7
New Oil-Gas Turbine, Simple Cycle	1.65
New Oil-Gas Turbine, Combined Cycle	1.13
New Gas-Combustion Turbine-Simple Cycle	1.25
New Gas-Combined Cycle Combustion Turbine	0.79
New Gas-Molten Carbonate Fuel Cell	0.75
New Coal-Integrated Coal Gasification Fuel Cell	1.28
Whole tree burner	0
Biomass Integrated Combined Cycle Gasification	0
Waste Wood	0
Alfalfa Gasification	0
Turkey Manure	0
RDF	1.85
Current Pulverized Coal	2.1

Sources: RDF calculated from MN Utility Data Book fuel throughput and MWh generation for NSP plants
Biomass-based systems are assumed to have zero emissions, since that CO_2 emitted is otherwise part of fast-cycling natural carbon cycle and would have been emitted to the atmosphere through natural oxidation processes anyway
Natural Gas Combined Cycle (air cooled) and Coal Integrated Combined Cycle (air cooled), R. Williams, "Advanced Energy Supply Technologies," *in World Energy Assessment*, UN Development Program, 2000.
Other: I. Torrens, "The Greenhouse Gas Performance of Power Sector Utilization Technologies," in *Proceedings of the International Conference on Coal, the Environment and Development: Technologies to Reduce Greenhouse Gas Emissions*, 18-21, Sydney, Australia, OECD, 1992, pp. 131-148.

About a factor of four separates the best conversion technology form the worst in terms of per kwh emissions of CO_2. On a per kwh basis, the most advanced coal-based power generation technology emits about 30% less CO_2 than the typical pulverized coal technology currently in use. For a 3,000 $MW_{(e)}$ increase in baseload generation capacity, which is what the Minnesota Department of Commerce is suggesting may be needed in Minnesota, and should be built by

2005, the difference between the worst and best fossil fuel conversion technologies is about 15 million tons of CO_2 annually (23 million tons for new pulverized coal technology and 8 million tons for new natural gas combined-cycle turbine technology, respectively). The difference between best coal conversion technology and the worst is about 5 million tons annually (23 million tons for new pulverized coal and 18 million tons for integrated gasification combined-cycle).

For biomass-based systems or wind, the difference is 23 million tons, since these systems emit no fossil CO_2.

For HFCs and CFCs, substitutes with lower per ton effects on the climate are available. Potential substitutes and their global warming potentials per ton of emission are shown in Table 17.

Table 17. Global Warming Potentials of HFCs, HCFCs and PFCs

Compound	Chemical Formula	Global Warming Potential
HCFC-22	CF_2HCl	1,700
HCFC-141b	$C_2FH_3Cl_2$	630
HCFC-142b	$C_2F_2H_3Cl$	2,000
HCFC-123	$C_2F_3HCl_2$	93
HCFC-124	C_2F_4HCl	480
HCFC-225ca	$C_3F_5HCl_2$	170
HCFC-225cb	$C_3F_5HCl_2$	530
HFC-23	CHF_3	12,100
HFC-32	CH_2F_2	580
HFC-43-10mee	$C_5H_2F_{10}$	1,600
HFC-125	C_2HF_5	3,200
HFC-134	CHF_2CHF_2	1,200
HFC-134a	CH_2FCF_3	1,300
HFC-152a	$C_2H_4F_2$	140
HFC-143	CHF_2CH_2F	290
HFC-143a	CF_3CH_3	4.400
HFC-227ea	C_3HF_7	3,300
HFC-236fa	$C_3H_2F_6$	8,000
HFC-245ca	$C_3H_3F_5$	610
Perfluoroethane	C_2F_6	12,500
Perfluorcyclobutane	c-C_4F_8	9,100
Perfluorohexane	C_6F_{14}	6,800
Trifluoroiodomethane	CF_3I	<1

Source: IPCC, 1994

A listing of potential technical measures for control across all sectors is given in Table 18. These range from land retirements and anaerobic digestion to old coal-plant retirements, landfill gas capture, and alternative fuels use in transportation.

Table 18. Technical Measures for Greenhouse Gas Control

Agriculture

Manure Storage
Anaerobic digestion
Conversion to solid manure storage
Storage covers for NH_4 control
Dietary changes for reduced manure nitrogen content

Soil Nutrient Management
Precision farming
Wet soils retirement
Use of nitrification inhibitors
Injection application of nutrients

Tillage
Expanded use of conservation tillage practice
Expanded use of no-till tillage practice
Land retirements to grasses and trees
Conversion from row crops to close sown crops or perennial forages
Enhanced tractor efficiency

Waste Management
Enhanced materials recycling
Active gas capture at existing landfills
Anaerobic digestion wastewater treatment facilities
Reduced nitrogen discharge to surface waters from wastewater facilities

Forestry
Reduced harvest
Increased stocking levels on poorly stocked acres
Increased amount of debris required to be left on harvested timberland
Conversion to structural timbers type of forest products industry

Electric Utilities

Existing and New Plants
Coal-to-gas conversions
Co-firing with gas or wood
Improved plant efficiency through enhanced O&M
Old plant retirements
Low carbon energy systems for all new generation
Cogeneration
CO_2 capture and permanent disposal
SF_6 capture and recycle
Permanent landfill disposal of ash carbon
Tree planting to offset emissions
Green pricing to influence plant time on-line

Table 18. Technical Measures for Greenhouse Gas Control (Cont.)

Electric Demand
Enhanced spending on energy conservation through DSM programs
Marginal and real-time pricing of electricity
Externalities pricing of electricity

Transportation

Light-Duty Vehicles
Improved vehicle fuel economy through CAFÉ or hybrids penetration
Shift in LDV fleet composition
Higher ethanol fuel fraction
Greater use of alternative fuel vehicles
Reduced highway speeds
Improved traffic flow
Densification of settled urban areas
Improved opportunities for travel using mass transit
Increased state fuel taxation
State gas guzzler taxation
Reduced rate of emission per mile traveled for new vehicles through state tailpipe standards for CO_2, CH_4 and N_2O.

Other (Transportation)
Conversion of reciprocating engines to turbines in gas transmission
Reduced highway speeds for heavy-duty trucks

Residential

Retrofits of existing structures with high efficiency furnaces and water heating
High efficiency furnaces and water heat in all new construction
Shell retrofits for existing structures
Reduced shell size for new construction
Smart building controls in new structures
Enhanced tree shading of residences
Expansion of gas distribution systems to outstate areas lacking gas service

Commercial/Industrial

Coal-to-gas conversions
Expanded cogeneration in commercial sector
Co-firing with wood or natural gas
Enhanced efficiency of motor drive, facility lighting, and facility HVAC
Capture and reuse of high GWP etching chemicals in electronic manufacture

8.0 What Is The MPCA Doing?

In the MPCA's five year strategic plan, global climate change is identified as one of the emerging environmental issues of the 21st century. The plan calls upon the MPCA to develop a strategy for responding to global climate change. Specific pieces of work to be developed under the global climate change component of the strategic plan include: an assessment of likely

impacts of global climate change on Minnesota resources; an analysis of strategic directions for policy; an assessment of technical options for the control of greenhouse gas emissions; policy recommendations; and a communications strategy. The intention is to have developed by 2003 a strategy for responding to global climate change.

Ongoing efforts that will continue under this initiative include: the annual greenhouse gas inventory and a greenhouse gas emissions forecasting activity. The development of an annual emission inventory for greenhouse gases provides the PCA staff with baseline information on trends necessary for the development of emission control strategies. The forecasting of emissions into the future enables the staff to take a long-term view of strategies of response to what is a long-term problem.

Finally, it has been agreed that MPCA staff will help the Department of Commerce develop the environmental component of the state energy plan. Global climate change must be a consideration in the design of any long-term energy plan for the state. This may include the development of long-term environmental targets for the electricity generation sector and analysis of the environmental consequences of alternative state energy strategies.

References

D. Adams, *et al*., "Minimum Cost Strategies for Sequestering Carbon in Forests," *Land Economics, no.3* (August 1999): 360-374.

J. Angell, "Comparison of Surface and Tropospheric Temperature Trends Estimates from a 63-Station Radiosonde Network, 1958-1998," *Geophysical Research Letters, 26,* (1999): 2,761-2,764.

Australian Academy of Sciences, *The CO_2-Climate Connection*, (Canberra: 1981).

R. Balling, oral testimony, May 1995, in Contested Case on the Establishment of Externality Values for Use in Electricity Planning, OAH Docket no.6-2500-8632-2 and MPUC Docket no. E-999/CI-93-583 .

M. Battle, *et al.,* "Global Carbon Sinks and Their Variability Inferred from Atmospheric O_2 and $d^{13}C$," *Science, 287,* (2000): 2,467-2,470.

T. Blunier, "'Frozen Methane Escapes from the Sea Floor," *Science, 288* (2000): 68-69.

B. Bolin, *et al*., *The Greenhouse Effect, Climatic Change, and Ecosystems*, SCOPE 29 (Chicester, UK: John Wiley and Sons, 1986).

R. Bradley and P. Jones, "'Little Ice Age' Summer Temperature Variations: Their Nature and Relevance to Recent Warming Trends," *The Holocene, 3* (1993): 387-396.

K. Briffa, *et al*., "Influence of Volcanic Eruption on Northern Hemispheric Surface Temperature over the Last 600 Years," *Nature, 293* (1998): 450-455.

J. Butler, *et al.,* "A Record of Atmospheric Halocarbons During the Twentieth Century from Polar Firn Air," *Nature, 399* (1999): 749-755.

R. Cess, *et al*., "Cloud Feedback in Atmospheric General Circulation Models-An Update," *Journal of Geophysical Research, 101* (1996): 12,791-12,794.

M. Chen, *et al.*, "Seasonal Variations of Upper Tropospheric Water Vapor and High Clouds Observed from Satellites," *Journal of Geophysical Research, 104* (1999): 6,193-6,197.

P. Ciborowski, Minnesota Pollution Control Agency, Pre-filed Surrebutal Testimony, April 1995, in Contested Case on the Establishment of Externality Values for Use in Electricity Planning, OAH Docket no.6-2500-8632-2 and MPUC Docket no. E-999/CI-93-583 (updated for 1996 and 2001 IPCC citation).

Climate Planning Board, *The Carbon Dioxide Question: Canadian Perspectives,* (Toronto, Canada: 1981).

W. Cline*, The Economics of Global Warming*, (Washington, D.C.: Institute for International Economics, 1992).

T. Crowley, "Causes of Climate Change Over the Past 1000 Years," *Science, 289* (2000): 270-277.

A. Dai, *et al*., "Clouds, Precipitation and Temperature Range," *Nature, 386* (1997): 665-666.

P. Damon and A. Peristykh, "Solar Cycle Length and the 20th Century Northern Hemispheric Warming Revisited," *Journal of Geophysical Research, 26* (1999): 2,469-2,472.

M. Davis, "Lags in Vegetation Response to Greenhouse Warming," *Climatic Change, 15* (1989): 550-563.

Department of Energy, *Energy and Climate Change: Report of the DOE Multi-Laboratory Climate Change Committee,* (Chelsea, MI: Lewis Publ., 1990).

Department of Energy, *Annual Energy Outlook 2001*, DOE/EIA-0383(2001), (Washington, D.C.: 2000)

D. Ehhalt, "The Effects of Chlorofluorocarbons on Climate," in W. Bach., *et al*., eds*., Interactions of Energy and Climate*, (Dordrecht, Netherlands: D. Reidel Publishing Co, 1980).

S. Fankhauser and R. Tol, "Climate Change Costs: Recent Advancements in the Economic Assessment*," Energy Policy, 24* (1996): 665-673.

C. Forest, *et al.,* "Constraining Uncertainties in Climate Models Using Climate Change Detection Techniques," *Geophysical Research Letters, 27* (2000): 569-572.

M. Free and A. Robock, "Global Warming in the Context of the Little Ice Age*," Journal of Geophysical Research, 104,* (1999): 19,057-19,070.

George Marshall Institute, *Scientific Perspectives on the Greenhouse Problem*, (Washington, D.C.: 1989).

German Bundestag, *Climate Change - A Threat to Global Development. First Report of the 12th German Bundestag's Enquete Commission 'Protecting the Earth's Atmosphere'*, (Bonn: Economica Verlag, 1992).

German Bundestag, *Protecting the Earth's Atmosphere: Interim Report of the Study Commission of the 11th Bundestag 'Preventive Measures to Protect the Earth's Atmosphere'*, (Bonn: 1989).

GDFL, "A Retrospective Integration of GDFLs Climate Model 1850 to Present," http://www.gfdl.noaa. gov/~rjs/stouffer_MBO.html

Global Change Research Program, *Climate Change Impacts in the United States: The Potential Consequences of Climatic Variability and Change,* Report of the National Assessment Synthesis Team, (Washington, D.C.: 2000).

Goddard Institute for Space Studies/NASA, (1999), web site, http://www.giss.nasa.gov/ data/update/gistemp/

T. Goreau and R. Hayes, "Coral Bleaching and Ocean 'Hot Spots'," *Ambio, 73* (1994): 176-180.

H. Grassl, "Status and Improvement of Coupled General Circulation Models," *Science, 288,* (2000): 1,991-1,997.

P. Groisman, *et al*., "Changes in the Probability of Heavy Precipitation: Important Indicators of Climatic Change," *Climatic Change, 42* (1999): 243-283.

B. Groveman and H, Landsberg, "Simulated Northern Hemisphere Temperature Departures 1579-1880," *Geophysical Research Letters, 6* (1979): 767-769.

Hadley Center, *An Update of Recent Research from the Hadley Center*, (Bracknell, UK: November 2000a), website, www.metoffice.gov.uk.

Hadley Center, Climate Change Projections from the Hadley Center, (Bracknell, US, 2000b), website, http://www.meto.govt.uk/research/hadleycentre/models/modeldata.html

W. Haeberli, *et al*., ed., *Glacier Mass Balance Bulletin no. 4 1994-5*, World Glacier Monitoring Service for the Global Environmental Monitoring System (GEMS) and the International Hydrological Program, IAHS (ICSI)-UNEP-UNESCO, Zurich, Switzerland, 1996.

S. Hameed, *et al*., "Response of the Global Climateto Changes in Atmospheric Composition Due to Fossil Fuel Burning," *Journal of Geophysical Research, 85* (1980): 7,537-7,548.

J. Hansen, *et al*., "Climate Impact of Increasing Atmospheric Carbon Dioxide," *Science, 213* (1981): 957-966.

J. Hansen, *et al*., "Potential Climatic Impact of Mount Pinatubo Eruption," *Geophysical Research Letters, 19* (1992): 215-218.

J. Hansen *et al*., "Climate Forcings in the Industrial Era," *Proc. National Academy of Science. 95* (1998): 12,753-12,758.

J. Hansen, *et al*., "Global Warming in the Twenty-First Century: An Alternative Scenario," *Proc. National Academy of Science*, 97 (2000): 9,875-9,880.

D. Harvey, "An Assessment of the Potential Impact of a Downward Shift of Tropospheric Water Vapor on Climate Sensitivity," *Climate Dynamics, 16*, (2000): 491-500.

A. Haywood, *et al*., "Global Scale Paleoclimate Reconstruction of the Middle Pliocene Climate Using the UKMO GCM: Initial Results," *Global and Planetary Change, 25,* (2000): 239-256.

Health Council of the Netherlands, *Part One: Report on CO_2 Problem*, (The Hague: Committee of the Health Council of the Netherlands, 1983).

M. Hoffert, *et al*., "Application of Solar Max ACRIM data to analysis of Solar-Driven Climatic Variability on Earth," *Climatic Change, 13* (1988): 267-285.

M. Hoffert and C. Covey, "Deriving Global Climate Sensitivity from Paleoclimate Reconstructions," *Nature, 360* (1992): 573-576.

R. Houghton, *et al*., "The US Carbon Budget: Contributions from Land-use Change," *Science, 285* (1999): 574-578.

S. Huang, *et al*., "Temperature Trends Over the Past Five Centuries from Reconstructed Borehole Temperatures," *Nature, 403* (2000): 756-758.

H. Hu, *et al*., "The Relationship between Atmospheric Water Vapor and Temperature in Simulations of Climate Change," *Geophysical Research Letters, 27* (2000): 3,513-3,516.

M. Hughs and H. Diaz, "Was There a 'Medieval Warm Period' and If So When and Where*,"* *Climatic Change, 26* (1994): 109-124.

Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Scientific Assessment*, (New York: Cambridge University Press, 1990).

Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment,* (Cambridge: University of Cambridge Press, 1992).

Intergovernmental Panel on Climate Change, *Climate Change 1994: Radiatove Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios*, (Cambridge: Cambridge University Press, 1995).

Intergovernmental Panel on Climate Change, *Climate Change 1995: the Science of Climate Change*, (Cambridge: Cambridge University Press, 1996).

Intergovernmental Panel on Climate Change, *Climate Change 1995: Impacts, Adaptation, and Climate Change,* vol. 2, (Cambridge: Cambridge University Press, 1996).

Intergovernmental Panel on Climate Change, *Climate Change 1995: Economic and Social Dimensions of Climate Change,* vol. 3, (Cambridge: Cambridge University Press, 1996).

Intergovernmental Panel on Climate Change, *Special Report on Land Use, Land use Change and Forestry*, web site, www.grida.no/climate/ipcc/land_use.html.

O. Johannesson, *et al*., "Satellite Evidence for an Arctic Sea Ice Cover in Transformation," *Science, 28,6* (1999): 1,937-1,939.

Joint US/USSR Commission on Protection of the Environment, *Prospects for Future Climate: A Special US/USSR Report on Climate and Climate Change*, (Chelsea, MI: Lewis Publishers, Inc., 1990).

P. Jones, *et al*., "Estimating Sampling Errors in Large-scale Temperature Averages*," Journal of Climate*
10 (1997): 2,548-2,568.

P. Jones, *et al*., "High Resolution Paleoclimatic Records for the Last Millennium: Interpretation, Integration, and Comparison to General Circulation Model Control Run Temperature," *The Holocene, 8* (1998): 455-471.

P. Jones, *et al*., "Surface Air Temperature and Its Changes Over the Past 150 years*," Reviews of Geophysics, 37* (1999): 173-199.

P. Jones, *et al*., "Global and Hemispheric Temperature Anomalies-Land and Marine Instrumental Records," in *Trends: A Compendium of Data on Global Change*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, 2000.

F. Joos, *et al*., "Global Warming and Marine Carbon Cycle Feedbacks on Future Atmospheric CO_2," *Science, 284* (1999): 464-467.

S. Joussaume, "Paleoclimatic Tracers: An Investigation Using an Atmospheric General Circulation Model Under Ice Age Conditions," *Journal of Geophysical Research, 98* (1993): 2,767-2,805.

S. Joussaume, *et al*., "Monsoon Changes from 6,000 Years Ago: Results from 18 Simulations from the Paleoclimate Modeling Intercomparison Project (PMIC)," *Geophysical Research Letters, 26* (1999): 859-862.

C. Keeling and R. Bacastow, "Impact of Industrial Gases on Climate," in NRC Geophysics Study Committee, *Energy and Climate*, (Washington, D.C., National Academy of Sciences, 1977.)

C. Keeling, *et al*., "Global and hemispheric CO_2 Sinks Deduced from Changes in Atmospheric O_2 Concentrations," *Nature, 381* (1996): 218-221.

R. Kerr, "Globe's 'Missing Warming Found in the Ocean," *Science, 287* (2000): 2,126-2,127.

H. Kheshgi, *et al*., "Model-based Estimation of the Global Carbon Budget and its Uncertainty from Carbon Dioxide and Carbon Isotope Records," *Journal of Geophysical Research, 104* (1999): 31,127-31,144.

G. Kohlmeier, *et al*., "The Role of the biosphere in the Carbon Cycle and Biota Models," in W. Bach, *et al*., eds*., Carbon Dioxide: Current Views and Developments in Energy/Climate Research,* (Dordrecht, Netherlands: D. Reidel Publishing Co., 1983.

J. Kleypas, *et al*., "Geochemical Consequences of Increased Atmospheric Carbon Dioxide on Coral Reefs," *Science, 284* (1999): 118-120.

W. Krabill, *et al*., "Greenland Ice Sheet: High Elevation Balance and Peripheral Thinning," *Science, 289,* (2000): 428-430.

K. Lau and H. Weng, "Interannual, Decadal-Interdecadal and Global Warming Signals in Sea Surface Temperatures During 1955 to 1997," *Journal of Climate, 12* (1998): 1,257-1,267.

H. Le Treut and B. McAvaney, 2000, reported in Grassl (2000), *supra*.

J. Lean and D. Rind, Climate Forcing by Changing Solar Radiation," *Journal of Climate, 11* (1998): 3,069-3,094.

J. Lean and D. Rind, "Evaluating Sun-Climate Relationships Since the Little Ice Age*," Journal of Atmosphere Solar terrestrial Physics, 61* (1999): 25-36.

S. Levitus, *et al*., "Warming of the World Ocean," *Science, 287* (2000): 2,225-2,228.

R. Lindzen, "Some Coolness Concerning Global Warming," *Bulletin American Meteorological Society, 71* (1990): 288-299.

U. Lohmann and J. Feichter, "Can the Indirect and Semi-direct Aerosol Effect Compete with the Indirect Effect on a Global Scale," *Geophysical Research Letters, 28* (2001): 159-161.

M. MacCracken and F. Luther, eds., *Projecting the Climatic Effects of Increasing Carbon Dioxide*, DOE/ER-0237 (State of the Art Report) (Washington, D.C.: U.S. Department of Energy, 1985).

J. Magnuson, *et al*., "Historic Trends in Lake and River Ice Cover in the Northern Hemisphere*," Science, 289* (2000): 1,743-1,746.

J. Mahlman, "Uncertainties in Projections of Human-Caused Climate Warming," *Science, 278* (1997): 1,416-1,417.

M. Mann, "Global Scale Temperature Patterns and Climate Forcing Over the Past Six Centuries*," Nature, 392* (1998): 779-787.

M. Mann, *et al*., Northern Hemispheric Temperatures During the Past Millennium: Inference, Uncertainties, Limitations," *Geophysical Research Letters, 26* (1999): 759-762.

W. de la Mare, "Abrupt Mid-Twentieth Century Decline in Antarctic Sea-Ice Extent from Whaling Record," *Nature, 389* (1997): 57-59.

B. McCarl and U. Schneider, “US Agriculture’s Role in a Greenhouse Gas Emission Mitigation World: An Economic Perspective,” Department of Agricultural Economics, Texas A&M, 1999.

P. Michaels and D. Stooksbury, “Global Warming: A Reduced Threat,” *Bulletin American Meteorological Society, 10* (1992): 1,563-1,577.

J. Mitchell, *et al*., “Transient Climate Response to Increasing Sulfate Aerosols and Greenhouse Gases,” *Nature, 376* (1995): 501-4.

R. Myneni, *et al*., “Increased Plant Growth in the Northern Latitudes from 1981 to 1991,” *Nature, 386* (1997): 698-702.

National Academy of Science, *Carbon Dioxide and Climate: A Scientific Assessment. Report of the Ad hoc Study Group on Carbon Dioxide and Climate,* (Washington, D.C.: 1979).

National Academy of Sciences, *Carbon Dioxide and Climate: A Second Assessment. Report of the CO_2/Climate Review Panel*, (Washington, D.C.: National Academy Press, 1982).

National Academy of Sciences, Board on Atmospheric Sciences and Climate, *Changing Climate: Report of the Carbon Dioxide Assessment Committee,* (Washington, D.C.: National Academy Press, 1983).

National Academy of Sciences, *Current Issues in Atmospheric Change,* (Washington, D.C.: National Academy Press, 1987).

National Academy of Sciences, *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*,(Washington, D.C.: National Academy Press, 1992).

National Academy of Sciences, Panel on Reconciling Temperature Observations*, Reconciling Observations of Global Temperature Change*, (Washington, D.C.: National Academy Press, 2000.

NCDC, *CLIMVIS*, website, http://www.ncdc.noaa.gov/onlineprod/drought/xmgrg1.html

NOAA Paleoclimatology Program, web site http://www.ngdc.noaa.gov/paleo/drought/drght_home.html

W. Nordhaus, “To Slow or Not to Slow: The Economics of the Greenhouse Effect,” *The Economic Journal, 101* (1991): 920-937.

J. Oerlemans, ‘Quantifying Global Warming from the Retreat of Glaciers,” *Science, 264* (1994): 243-245.

M. Oppenheimer, "Global Warming and the Stability of the West Antarctic Ice Sheet," Nature, 393 (1998), 502.

J. Overpeck, *et al*., "Arctic Environmental Change of the Last Four Centuries," *Science, 278* (1997): 1,251-1,256.

D. Parker, *et al*., "Marine Surface Temperature: Observed Variations and Data Requirements," *Climatic Change 31* (1995):559-600.

F. Pearce, "Greenhouse Wars," *New Scientist*, 19 July, 1997.

D. Peteet, "Sensitivity and Rapidity of Vegetation Response to Climate Change*," Proc. National Academy of Sciences, 97* (2000): 1,359-1,361.

T. Peterson, *et al*., "Global Rural Trends," *Geophysical Research Letters*, 26 (1999): 329-332.

H. Pollack, *et al*., "Climate Change Record in Subsurface Temperatures: A Global Perspective*," Science, 282* (1998): 279-281.

R. Prinn, *et al*., "A History of Chemically and Radiatively Important Gases in the Atmosphere Deduced from ALE/GAGE/AGAGE," *Journal of Geophysical Research, 105 (D4)* (2000): 17,751-17,792.

P. Quay, *et al*., "Oceanic Uptake of Fossil Fuel CO_2: Carbon 13-Evidence," *Science, 256* (1992): 74-79.

V. Ramanathan, "The Role of Ocean-Atmosphere Interactions in the CO_2 Climate Problem*," Journal of the Atmospheric Sciences, 38* (1981): 918-930.

V. Ramanathan, *et al*., "Trace Gas Trends and Their Potential Role in Climate Change*," Journal of Geophysical Research, 90* (1985): 5,547-5,566.

V. Ramanathan and A. Inamdar, "Water Vapor Feedback in the Tropics," paper presented at the 23rd Conference on Hurricanes and Tropical Meteorology, 1999.

A. Raval and V. Ramanathan, "Observational Determination of the Greenhouse Effect," *Nature, 342*, (1989): 758-761.

S. Ramstorf, "Shifting Seas in the Greenhouse," *Nature, 399*, (1999): 523-524.

R. Revelle and H. Suess, "Carbon Dioxide Exchange Between Atmosphere and Oceans and the Question of an Increase of Atmospheric CO_2 During the Past Decades," *Tellus, 9* (1957): 18-27.

A. Revkin, "Scientists Now Acknowledge Role of Humans in Climate Change," *New York Times,* October 26, 2000.

D. Rind, "Positive Water Vapor Feedback in the Climate Models Confirmed by Satellite Data," *Nature, 349* (1991): 500-503.

H. Rogner, "An Assessment of World Hydrocarbon Resources," *Annual Review of Energy and Environment, 22* (1997): 217-262.

D. Rothrock. *et al*., "Thinning of the Arctic Sea-Ice Cover," *Geophysical Research Letters, 26* (1999): 452-455.

Royal Society of New Zealand, *New Zealand Climate Report 1990: A report prepared by the New Zealand Climate Committee of he Royal Society of New Zealand*, (Wellington, NZ: 1990).

G. Russell, *et al*., "Comparison of Model and Observed Regional Temperature Changes During the Past 40 Years," *Journal of Geophysical research, 105* (2000): 14,891-14,898.

B. Santer, *et al*., "A Search for Human Influences on the Thermal Structure of the Atmosphere," *Nature, 382* (1996): 39-46.

B. Santer, *et al*., "Interpreting Differential Temperature Trends at the Surface and in the Lower Troposphere," *Science, 287* (2000): 1,227-1,232.

D. Shimel, *et al*., "Contribution of Increasing CO_2 to Carbon Storage by Ecosystems in the United States, *Science, 287* (2000): 2,004-2,006.

S. Schnieder, "Geoengineering: Could-Or Should-We Do It," *Climatic Change, 33* (1996): 291-302.

D.Simbeck, *et al*., Portfolio Selection Approach for Power Plant CO_2 Capture, Separation, and R&D Options," in B. Eliasson, *et al*., eds., *Greenhouse Gas Control Technologies: Proc. 4th International Conference on GHG Control Technologies*, (Amsterdam: Pergamon, 1999)

C. Smith, *et al*., "Radiative Forcing Due to Trends in Stratospheric Water Vapor," *Geophysical Research Letters, 28* (2001): 179-182.

R. Socolow, ed., "Fuels Decarbonization and Carbon Sequestration: Report of a Workshop by the Members of the Report Committee," PU/CEES Report 302, Center for Energy and Environment Studies, Princeton, University, Princeton, NJ.

B. Soden, "Variations in the Tropical Greenhouse Effect During El Nino," *Journal of Climate, 10* (1997): 1,050-1,055.

B. Soden and R. Fu, "A Satellite Analysis of Deep Convection, Upper Tropospheric Humidity and the Greenhouse Effect," *Journal of Climate, 8* (1995): 2,333-2,351.

S. Solomon and J. Daniel, "Impact of the Montreal Protocol and its Amendments on the Rate of Change of Global Radiative Forcing," *Climatic Change, 32* (1996): 7-17.

H, Stefan, "Alterations of Water Availability, Water Quality and Fish Habitat in Cold Regions by Climate Change," final technical report to USEPA, St. Anthony Falls Laboratory, University of Minnesota, Minneapolis, 1999.

M. Stendel, *et al*., "Assessing Levels of Uncertainty in Recent Temperature Time Series*,"* *Climate Dynamics, 16* (2000): 587-601.

W. Stevens, "Global Warming: The Contrarian View," *New York Times*, February 29, 2000.

W. Sturges, *et al.,* "Trifluoromethyl Sulfur Pentafluoride (SF_3CF_3) and Sulfur Hexafluoride (SF_6) from Dome Concordia," in *Trends: A Compendium of Data on Global Change*, (Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, 2000).

I. Torrens, "The Greenhouse Gas Performance of Power Sector Utilization Technologies," in *Proceedings of the International Conference on Coal, the Environment and Development: Technologies to Reduce Greenhouse Gas Emissions*, 18-21, Sydney, Australia, OECD, 1992, pp. 131-148.

J. Trabalka, *et al*., *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, DOE/ER-0237 (State of the Art Report) (Washington, D.C.: U.S. Department of Energy, 1985).

VEMAP, web site for data on forest type, http://www.fs.fed.us/ne/delaware/atlas/s318f.html

T. Wigley, *et al*., "Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations," *Nature, 379* (1996): 240-24.

T. Wigley, *et al*., "The Observed Global Warming record: What Does it Tell Us*,*" *Proc. National Academy of Sciences, 94* (1997): 8,314-8,320.

T. Wigley. "The Kyoto Protocol: CO_2, CH_4 and Climate Implications," *Geophysical Research Letters, 25* (1998): 2,285-2,288.

R. Williams, "Advanced Energy Supply Technologies," *in World Energy Assessment*, (New York:
UN Development Program, 2000), pp. 273-325.

World Data Center-A (WDC-A), Boulder CO, website,
http://www.ngdc.noaa.gov/paleo/borehole/ borehole.html

World Glacier Monitoring Service, *Glacier Mass Balance Data, 1998-9*, Zurich, Switzerland, 2000.

World Meteorological Organization/United National Environmental Programme, International Council of Scientific Unions*, Assessment of the Role of CO_2 on Climate Variations and Their Impact*, (Geneva: World Meteorological Organization: 1981).

World Meteorological Organization (ozone depletion)

World Meteorological Organization, *Report of the International Conference on the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts,*

Villach, Austria, 9-15 October, 1985, World Climate Programme Report no. 661, (Geneva: World Meteorological organization, 1986).

World Meteorological Organization/United Nations Environmental Programme/ International Council of Scientific Unions, *Developing Policies for Responding to Climate Change: A Summary of Discussions and Recommendations of the Workshops Held in Villach (28 September-2 October,1987) and Bellagio (9-13 November, 1987*), WMO/TD-no. 225, (Geneva: 1988).

World Resources Institute, *World Resources 2000-2001,* (Washington, D.C.: 2000).

Y. Zhu, *et al*., "Factors Controlling Upper-Tropospheric Water Vapor," *Journal of Climate, 13* (2000): 836-848.