150 *CLEAN TECHNOLOGY*, DECEMBER, 1996, 2(2) pp 150-164

GREENHOUSE WARMING: THE UNCERTIFICATIES AND THE MITIGATION CHALLENGE

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When considering the issues of greenhouse warming, one must deal with many questions for which there are high levels of uncertainty. However, there is close to a consensus in the significant driving force for warming over pre-industrial temperature levels.

Such human activity has led to an increased atmospheric concentration of carbon dioxide(CO_2), methane (CH_4), and chlorofluorocarbons (CFCs), which resist the outward flow of infrared radiation more effectively than they impede incoming solar radiation. This imbalance yields the potential for global warming as the atmospheric concentration of CO_2 in the atmosphere was about 280ppm, and it is now about 360ppm. Similarly, CH_4 atmospheric concentration have increased substantially, and they are now more than twice what they were before the industrial revolution, currently about 1.80ppm. The impact of human activities is more dramatic with regard to CFCs. These compounds do not occur naturally; they were not found in the atmosphere until their initial production several decades ago. Recent data also suggest that airborne particulates have increased significantly in the post-industrial period and have contributed to a counteracting cooling impact.

We will attempts to shed light on several of the key issues associated with greenhouse warming. Using a relatively simple, but instructive, model, and information from a variety of credible sources, the following issues will discussed:

-What uncertainties are most critical in allowing us to confidently project the degree of warming expected over the next century?

-Given these uncertainties, what are the range of warming that appear reasonable?

-Which countries and what sectors are most important regarding greenhouse gas emissions?

-Which gases contribute to warming? What is their projected share of such warming? What is the relative confidence in such impacts?

-How effective are various mitigation strategies; what levels of mitigation are achievable for strategies capping emissions versus a more stringent approach calling for annual reduction by a given percentage after a certain year? How important is control of CH_4 and of CFC replacements?

The model (Glowarm 3.0) that the author has developed to help evaluate these questions is a spreadsheet (Lotus 1-2-3) model which calculates global concentrations and their associated global warming contributions for all the major greenhouse gases: CO_2, CH_4, ozone precursors, nitrous oxide (N_2O), CFCs, and their substitutes. The model calculates atmospheric concentrations of greenhouse gases based on projected emissions in 10-year increments. For CO_2, look-up tables are used to relate the fraction of CO_2 remaining in the atmosphere as a function of time after emission for two alternative CO_2 life cycles. For the other gases, an inputted lifetime value is used. Average global equilibrium temperatures are calculated using lifetimes and radiative forcing functions described in Intergovernmental Panel on Climate Change (IPCC), 1990. Realized (or actual) temperature is estimated using an empirical correlation algorithm we developed based on general-circulation model (GCM) results presented in IPCC, 1922. This approach uses a correlation which relates the rate of equilibrium warming over the period between the target year and 1980 to the ratio of actual to equilibrium warming. The greater the rate of equilibrium warming, the smaller is the ratio of the actual to equilibrium ratio. Note that it is much easier to calculate average global warming than it is to estimate warming on a geographical and seasonal basis, such calculations requires much more complex models and are subject to a much greater degree of uncertainty.

Figure 1 shows input and output fields for the model. Note that equilibrium and transient (realized or actual) warming can be calculated for any year (to 2100) for a variety of emission and control scenarios, two CO_2 life cycles, an assumed atmospheric sensitivity to a doubling of CO_2 concentration, CH_4 lifetime, and both sulfate cooling and CFC phaseout assumptions. Under the same assumptions, the model output temperatures fall generally within 10% of values calculated by other models (IPCC, 1992; NAS, 1991; Krause, 1989).

UNCERTAINTIES IMPACTING DEGREE OF WARMING EXPECTED

There are many uncertainties associated with the expected magnitude of global warming. The following are major uncertainties which will be considered and quantified:

1. Atmospheric Sensitivity. This critical variable is generally defined as the equilibrium temperature rise associated with a doubling of CO_2 concentrations. GCMs are utilized by climate modelers to forecast the impact of CO_2 warming. Unfortunately, the range of their results is wide and not converging (Dornbusch and Poterba, 1991). The IPCC (IPCC, 1992) has concluded this range to be between 1.5and 4.5℃.

2. CO_2 Life Cycle. The Earth's carbon cycle (which involves atmospheric, terrestrial, and oceanic mechanisms), is complex and not completely understood. Yet, in order to estimate CO_2 atmospheric concentrations and subsequent warming, it is necessary to assume a relationship between CO_2 remaining in the atmosphere and time after emission. For this analysis, two CO_2 life cycles were utilized, one based in IPCC (1992) and the other described by Walker and Kasting (1991). The Walker model yields longer atmospheric lifetimes leading to higher CO_2 concentrations.

3. Projected Growth of CO_2 Emissions Over Time for a "Business as Usual" Case. Attempting to predict the future is a risky business, at best. Yet, to scope the magnitude of the warming issue, it is necessary to estimate emissions of greenhouse gases as far in the future as one wishes to project warming. As we discussed and quantified in a previous paper (Princiotta, 1994), the following are key factors which will determine a given country's emissions of CO_2, the most important greenhouse gas:

-current emission rate
-population growth
-growth of economy per capita
-growth rate: energy use per economic output
-growth rate: carbon emissions per energy use unit

Since future global CO_2 emissions will be the sum of an individual country's emissions, all subject to varying factors, listed above, it is clear that even for a "business-as-usual" or base case there is a large band of uncertainty.

4. Methane Lifetime. A variety of investigators have provided a range of estimates for the atmospheric lifetime of CH_4. Recent atmospheric data (IPCC, 1992) have indicated an unexpected deceleration of the increase of CH_4 concentration in the atmosphere. We have analyzed the data and concluded that such behavior seems consistent with a possible recent decrease in CH_4 lifetime (possibly due to an increase in atmospheric hydroxyl (CH) concentrations, the primary mechanism for CH_4 degradation) and/or a

recent significant slowdown in the increase in CH_4 global emissions. The longer the lifetime, the greater is CH_4's contribution to global warming.

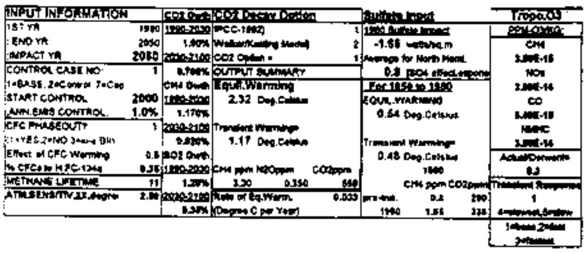
INPUT INFORMATION
1ST YR 1990
END YR 2050
IMPACT YR 2050
CONTROL CASE NO 1
START CONTROL 2000
ANN.EMIS CONTROL 1.0%
METHANE LIFETIME 11
CO2 Decay Option
OUTPUT SUMMARY
Equil.Warming 2.32 Deg.Celsius
Transient Warming 1.17 Deg.Celsius
Sulfate Input
-1.66 watts/sq.m
EQUIL.WARMING 0.64 Deg.Celsius
Transient Warming 0.48 Deg.Celsius
Tropo.O3

Figure 1: Glowarm Model Input and Output Screen

5. Projected Growth of Methane Emissions. There is an incomplete understanding of the current contributions of the major anthropogenic source of CH_4. They include: landfills, rice production, coal mines, natural gas production and distribution systems, and the production of cattle. There is even more uncertainty regarding the likely growth of such emissions over time as population grows, industrialization accelerates in undeveloped countries, and agricultural practice change.

6. Use of High Global Warming Potential Compounds (e.g. HFC-134a) to Replace CFCs. As the International community phases out of CFC production, due to concerns associated with stratospheric ozone depletion, hydrofulorocarbon (HFC-134a) and other compounds with significant greenhouse warming potential are being utilized as replacements. The importance of the extent to which compounds such as these are utilized will be evaluated.

7. Actual Temperature Response Versus Calculated Equilibrium Warming. GCMs often calculate projected equilibrium warming rather than transient or actual warming. Equilibrium warming can be defined as the temperature the Earth would approach if it were held at a given mix of greenhouse gas concentrations over a long period of time. Transient (also called realized or actual) temperatures are those that would actually be experienced at a given point in time, taking into account the thermal inertia of the Earth, especially its oceans. There is only an incomplete understanding of this thermal inertia effect and its quantitative impact on actual warming.

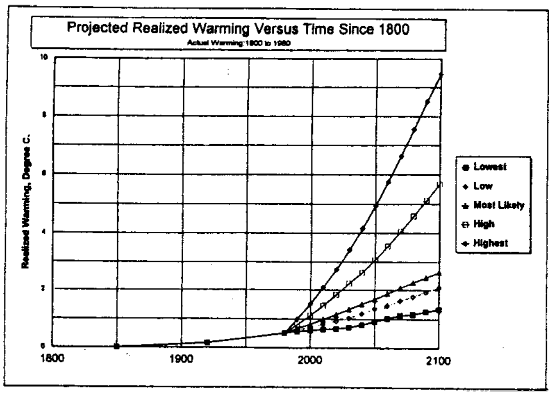

Figure 2: Projected Realized Warming Versus Time Since 1800

8. Aerosol (Sulfate) Cooling. A recent development (IPCC, 1992) has been the availability of evidence that emissions of sulfur dioxide (SO_2), other gases, and aerosol have contributed to a significant cooling impact, counteracting greenhouse gas warming. There is significant uncertainty over the magnitude of the direct impact of such fine particles and even more uncertainty over their secondary impact on clouds (generally thought to be significant and in the cooling direction). A related uncertainty is the relationship of atmospheric particles to their anthropogenic precursor emissions of SO_2 and other substances. Yet another aspect of uncertainty is the fact that the atmospheric lifetime of such particles is quiet short, so that, unlike CO_2, atmospheric concentrations are much higher over highly industrialized areas compared to concentrations above

the oceans.

In order to attempt to understand the impact of these variables, we have estimated warming for five scenarios spanning what we believe are reasonable ranges of values for these variables. For certain factors, such as atmospheric sensitivity, there is a reasonable consensus regarding the possible range of values. For other factors, there is no such conseneus. It shoud be recognized that credibility of this uncertainty analysis is only as good as the variable ranges assumed. Table 1 shows the assumed range of values from the "lowest" scenario which assumes that all of these variables are at values which will yield the lowest degree of warming to the "highest"case which assumes those values which will yield the highest projected warming. These can be characterized as representing best versus worst case scenarios, respectively. In the middle is the base case which is generally consistent with IPCC(1992)[1] and represents current conventional wisdom regarding the most likely scenario.

Table 1

Five Scenarios Impacting Degree of Global Warming					
Variables Impacts on predicted warming	Range of Impacts--------> Greater Warming				
	Lowest	Low	Base Case	High	Highest
Atmospheric Sensitivity	1.5	2	2.5	35.	4.54
CO2 Life Cycle Model	IPCC	IPCC	IPCC	Walker	Walker
CO2 Growth Rate: 1990-2030	1.0%	1.4%	1.85%	2.00%	2.2%
CO2 Growth Rate :2030-2100	0.5%	0.65%	0.78%	1.85%	2.2%
Methane Lifetime, yrs.	7	8	11	12	13
CH4 growth Rate : 1990-2030/2030-2100	0.67%/.32%	0.77%/.52%	1.17%/.82%	1.27%/.92%	1.37%/1.02%
Penetration so HFC-134a	15%	25%	35%	45%	55%
Actual/Equil. Temp. Ratio @ 0.35C deg/yr	0.3	0.4	0.505	0.6	0.7
Current Sulfate Cooling, Deg. C	-2.5	-2	-1.65	-1	-0.1
Sulfate Cooling Emission Ratio Exponent	1	0.9	0.8	0.7	0.6
Warming from 1980, Deg. C. (For warming from pre-industrial period about 0.5℃, should be added)					
Equilibrium Temperature @ 2050	0.4	1.1	2.3	5.1	7.8
Realized Temperature @ 2050	0.4	0.9	1.2	2.6	4.4
Equilibrium Temperature @ 2100	0.9	2.2	4.3	10.3	15.9
Realized Temperature @ 2100	0.8	1.6	2.2	5.2	9.1

Figure 2 graphically summarizes the results of Glowarm model calculations for the five scenarios examined.

Also included in this figure is the actual warming estimated in 1980 relative to the pipe-industrial era (NAS, 1991). As indicated, the range of projected global warming varies from significant to catastropic. We believe a more likely range of uncertainty is represented between the low and high scenarios. The predicted warming at 2100 for these cases is 2.1 and 5.7℃, respectively. The magnitude of these values and the difference between them support the contention that we are dealing with an issue not only of unprecedented potential impact, but also of monumental uncertainty. It is noteworthy that, even for the "low" scenario, temperature increases of 2.1℃ over pre-industrial values (1.6℃ over 1980 levels) are projected by 2100. According to Vostock ice core measurements

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[1] Note that, although the IPCC discussed sulfate cooling as a credible phenomenon, they did not factor this into their projections of greenhouse warming over time. Also, the current analysis assumes CO2 emissions consistent with IPCC's model IS92f, which assumes emissions somewhat higher than their base case, IS92a.

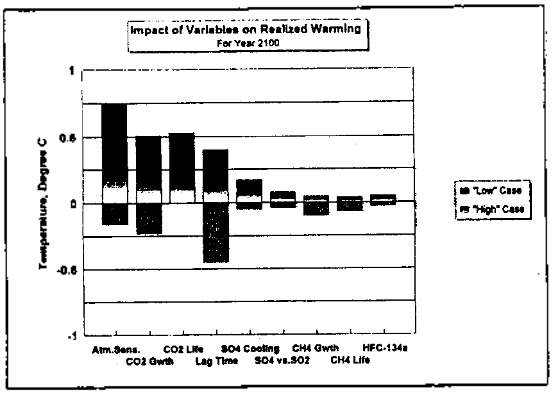

Figure 3: Impact of Each Variable on Base Case Realized Warming

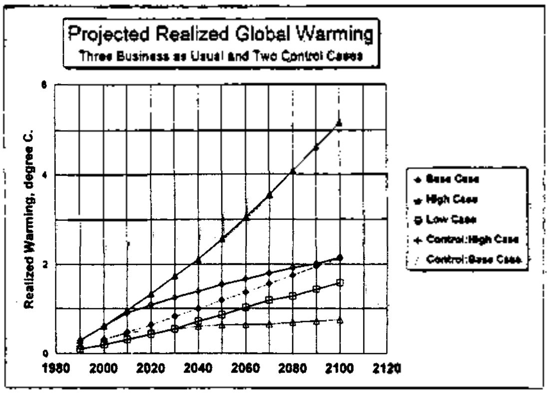

Figure 4: Projected Realized Global Warming for Three Business as Usual and Two Control Cases

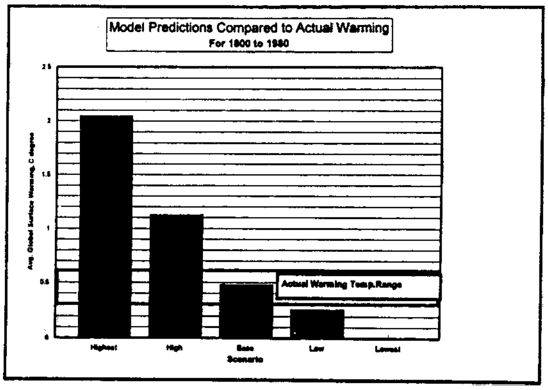

Figure 5: Model Predictions Compared to Actual Warming from 1800 to 1980

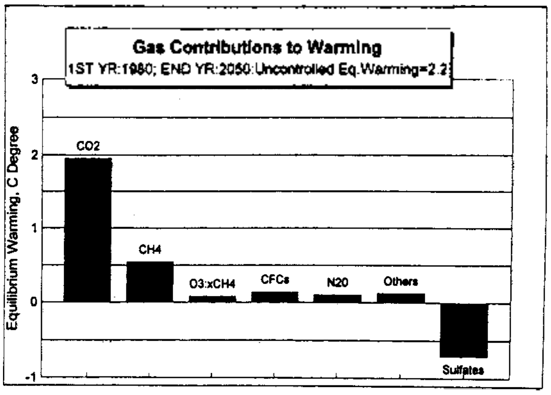

Figure 6: Gas Contrubutions to Warming

(Dornbusch and Poterba, 1991), the last time the Earth experienced such an average temperature was 125,000 years ago.

In order to elucidate the impact of specific variables on warming, additional model runs were made which evaluated each variable's influence on warming when its value for the "low" and "high" scenarios was input with all other variables set at their base level. Figure 3 shows the influence of each variable on realized warming at 2100. As can be seen, atmospheric sensitivity, CO_2 emission growth and atmospheric life, and lag time associated with the Earth's thermal inertia yielded the largest uncertainties. However, other factors, especially sulfate cooling, were important contributors to uncertainty as well.

It is important to note that uncertainty influences not only the predicted degree of future warming, but also the effectiveness of a given mitigation strategy. Figure 4 illustrates this point. Realized warming versus time is plotted for the "low," "high," and base scenarios. In addition, two stringent mitigation cases are included. Both assume that, by the year 2000, worldwide mitigation is imposed to decrease emissions of all greenhouse gases by 1% annually. However, the first mitigation case assumes all of the "high" variables summarized in Table 1. The second, imposes a mitigation program assuming base (or "most likely")variables. The results are dramatic. They show summarized in Table 1. They show that, even with a stringent emission reduction program, if the "high" case values are assumed, warming will be greater for all years before 2100 than for the uncontrolled base case!

Another series of calculations can shed light on the reasonableness of the five warming scenarios. By using the model to back-calculate(i.e., to calculate warming which would be expected from the pre-industrialized period to 1980), some indication of scenario credibility can be deduced. Figure 5 shows calculated warming for the five scenarios. Note that actual atmospheric concentrations were utilized for this time period, since they are available, so that atmospheric lifetimes and emission rates are not used by the model. As can be seen, the base case appears most consistent with the actual warming estimated for the 1800-1980 period.In fact, the calculated base case warming of about 0.5℃ falls right in the middle of the actual warming of 0.3 to 0.6℃ (IPCC, 1992) experienced. However, even on this issue, uncertainty is a factor. Although most experts agree that such warming has taken place, some argue that causes other than greenhouse warming (e.g., natural climate variability) are responsible.

WHICH GASES ARE IMPORTANT?

Let us now examine the important greenhouse gases and their potential warming contributions. Figure 6 shows the projected contribution by greenhouse gas over the period 1980-2050 for the base scenario. CO_2 and CH_4 are clearly the most important contributors to warming, with CFCs and their substitutes, N_2O, and tropospheric ozone[2] playing small but significant roles. Noteworthy, is the projected cooling impact of aerosol sulfates.

However, again, uncertainty is significant, this time in determining the relative contributions of the greenhouse gases. Such uncertainties are considered in Table 2. For each greenhouse gas, Table 2 summarizes: atmospheric lifetime, the ratio of current to pre-industrial atmospheric concentrations, projected contributions to realized warming, and the projected impact of mitigating emissions. Also included is a judgement regarding the relative confidence of the predicted warming impacts, along with major uncertainties and the major human sources. Uncertainty is important for all gases, but especially for aerosols and tropospheric ozone.

When one considers the importance of a given greenhouse gas, it is informative to evaluate warming prevented for a given mitigation scenario. Figure 7 shows result of model calculations for the period 1980-2050 comparing equilibrium base scenario warming to warming prevented assuming a stringent mitigation program. In this case, a 1% annual reduction in emissions is assumed for each gas (or its precursor) starting in the year 2000. The main result here is that short-lived gases such as CH_4 and ozone can mitigate a higher fraction of their base warming. for example, whereas less than half of CO_2's base warming is mitigated in this case, about three-quarters of CH_4's base warming is mitigated. When viewed from a mitigation (or warming prevented) viewpoint, CH_4 is about half as important as CO_2; whereas, from an emission viewpoint, it is less than a third as important.

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2. This values assumes volatile organic compound (VOC), nitrogen oxide(NO_x), and carbon monoxide(CO) precursors contribute to ozone(O_3) formation. However, the small component of O_3 warming associated with CH_4 emissions is included in the CH_4 value.

Figure 8 shows additional model results to help shed light on this point. In this case, the effect of annual mitigation rate (starting in 2000) on warming mitigated by gas is illustrated. An interesting observation that can be made is that a stringent 2% per year mitigation program for CH_4 could have almost as much benefit by the year 2050 as capping (0% growth) CO_2 emmisions. Of course, such conclusions are subject to the uncertainties previously discussed. Such calculations are only as good as the underlying assumptions; they include atmospheric lifetime and projected emission growth over the period examined.

A closer look at the contributions of chlorofluorocarbons (CFCs), and related compounds and their substitutes is also informative. Figure 9 shows equilibrium model results for these compounds for both phaseout and no phaseout cases. It should be noted that, for the CFCs and carbon tetrachloride (CCl_4), the model assumed that half of the projected warming would be counteracted by the cooling associated with the decrease of lower stratospheric ozone associated with these compounds. As can be seen, the international CFC phaseout program is projected to essentially eliminate greenhouse warming associated with CFCs by the year 2050.

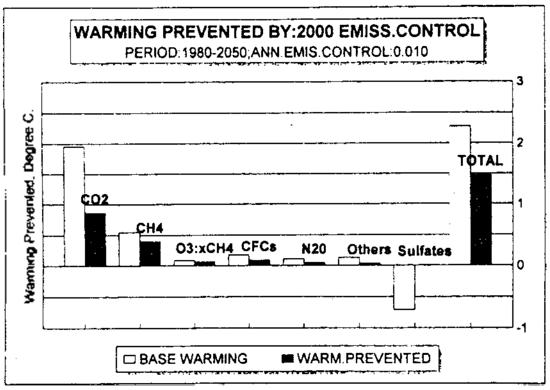

Figure 7: Warming Prevented by 2000 Emission Control

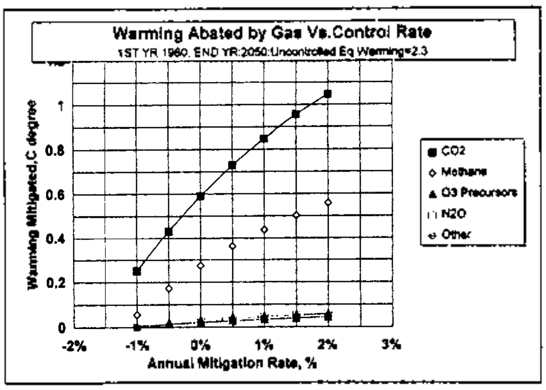

Figure 8: Warming Abated by Gas Vs. Mitigation Rate

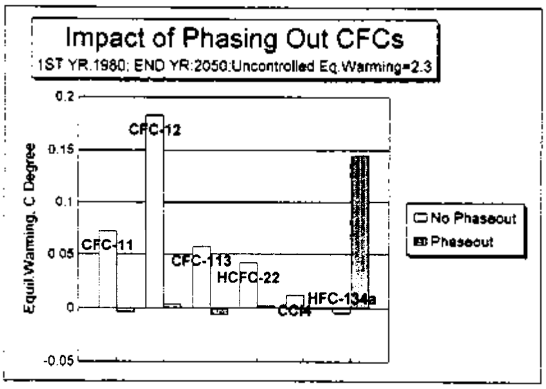

Figure 9: Impact of Phasing Out CFCs

However, Figure 9 also shows that CFC substitutes such as HFC-134a, a potent greenhouse gas, can be significant contributors to greenhouse warming, depending, of course, on the degree to which they are utilized. This particular analysis assumes that 35% of all projected uses of CFC-11, CFC-12, and CFC-13 in a non-phaseout scenario, would be substituted for by HFC-134a.

Table 2. GREENHOUSE GASES-WHAT IS KNOWN AND WHAT ISN'T

CHARACTERISTIC	CARBON DIOXIDE	METHANE	AEROSOLS
1.Atmospheric Lifetime(Yrs)	50-100	10-12.5	<<1
2.Current Concentration/ Pre-Industrial Concentration	1.26	2.15	Uncertain
3. Projected Realized Warming/			
By Gas at the year 2100	+1.8	+0.5	-1.5
Most Likely Case Total Warming=2.2		Incl Indirect Effects	
4. Impact of 1% /Yr Mitigation	60%	31%	-
Control starts 2000, the impact at 2050			
Calculated as % of total mitigation			
5. Confidence in Warming Calculations	Fair/Good	Fair	Poor
6. Major Uncertainties	Carbon Cycle Influence on CO2 Atmospheric Lifetime	1. Quantification of Natural and Human Sources and Sinks 2. Explanation needed for deceleration growth in Atm. Concentrations	1. Current extent of Cooling 2. Relationship of Emissions to Atm. Aerosols 3. Impact on Cloud Formation
7. Major Human Sources	Fuel Combustion	Coal Mining	Fossil Fuel Combustion
	-Electric Power	Natural Gas and Oil Production and	Biomass Combustion
	-Mobile Sources		
	-Industrial Deforestation	Landfills	
		Rice Paddies	
		Ruminants	
		Biomass Burning &	

WHICH COUNTRIES ARE MAJOR CONTRIBUTORS TO EMISSION OF GREENHOUSE GASES? WHAT ARE LIKELY TRENDS?

It is useful to look at recent histories of CO_2 emissions for key countries. Figure 10 derived from NAS, 1991, illustrates growth in CO_2 emissions from 12 key countries between 1960 and 1988. As indicated the U.S., USSR (now Russia, Ukraine, and other independent countries), and China are by far the major sources of CO_2. However, when one considers the recent (1980-1988) growth rate, China and India are especially significant since this portends future contributions to CO_2 emissions. Table 3 summarizes 1988 CO_2 data (NAS, 1991) for key countries listed in order of overall emissions, per capita emissions, and per gross national product(GNP) emissions. Although, the U.S. leads the world in overall and per capita emissions, China easily has the largest per GNP emissions. In order to provide insight into the various sectors contributing to 1990 CO_2 emissions for key countries, Figure 11 was generated based on Oak Ridge National Laboratory (ORNL) calculated data (Bowdenm et al., 1993).

Table 2. GREENHOUSE GASES-WHAT IS KNOWN AND WHAT ISN'T (continued)

CHARACTERISTIC	HFC-134a	TROPO, OZONE	N_2O
1.Atmospheric Lifetime(Yrs)	16	<<1	150
2.Current Concentration/ Pre-Industrial Concentration	New CFC Substitutes	>1, But Poor Data	1.08
3. Projected Realized Warming/			
By Gas at the year 2100	+0.2	+0.1	+0.1
Most Likely Case Total Warming=2.2		(Excludes CH_4 source)	
4. Impact of 1% /Yr Mitigation	-	4%	4%
Control starts 2000, the impact at 2050			
Calculated as % of total mitigation			
5. Confidence in Warming Calculations for items 3 and 4 Above	Good	Poor	Fair
6. Major Uncertainties	Extent to which will substitute for CFCs	1. Atmospheric Chemistry Models insufficient	Atmospheric Concentration
			Rising Faster Than Known
		2. Data on Tropo. Ozone Trends Poor	Sources/Sinks Predict
		3. Emission data for NOx, Hydrocarbons and CO, Precursors poor	
7. Major Human Sources	Refrigeration Cycles	Mobile Sources VOCs, NOx and CO	Biomass Burning
			Adipic Acid and HNO_3 Prod
		Stationary Combustion: NOx and CO	Mobile Sources
			Farming
		Biomass Burning CO and VOCs	Stationary Source Combustion

This figure illustrates that each country has a distinctive mix of activities yielding CO_2 emissions. In the case of the U.S., coal combustion (for electricity and steam), petroleum for transportation, and natural gas combustion (primarily for power generation and space heating) are the three most critical contributors. The pattern is similar in the former Soviet Union with the major difference in the automobile sector; much less CO_2 is generated by a much smaller fleet of vehicles. In China, coal combustion is the dominant source of CO_2 emissions, helping to explain why China's CO_2 unit of GNP is so high; coal is by far the most CO_2-rich fuel source per unit of useful output energy. Germany, the fourth most important source of CO2, is also dominated by coal use: in their case, brown coal (lignite) is indigenous to their country.

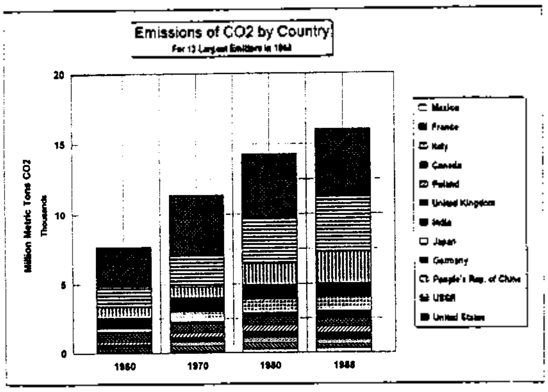

Figure 10: Historical Emissions of CO_2 by Country

Table 3

CO_2 Emissions-1988 (Million of Tons)		CO_2 per capita (tons per person)		CO_2 per GNP (Mt CO_2 per $1000 GNP)	
United States	4804	United States	19	China	6.0
USSR	3982	Canada	17	South Africa	3.6
China	2236	Czechoslovakia	15	Romania	2.8
Germany	997	Australia	15	Poland	2.7
Japan	989	USSR	14	India	2.5
India	601	Germany	13	Czechoslovakia	1.9
United Kingdom	559	Poland	12	Mexico	1.7
Poland	459	United Kingdom	10	USSR	1.5
Canada	438	Romania	10	Korea	1.2
Italy	360	South Africa	8	Canada	1.0
France	320	Japan	8	United States	1.0
Mexico	307	Italy	6	Australia	1.0
South Africa	284	France	6	United Kingdom	0.8
Australia	241	Korea	5	Germany	0.7
Czechoslovakia	234	Spain	5	Brazil	0.6
Romania	221	Mexico	4	Spain	0.6
Korea	205	China	2	Italy	0.4
Brazil	202	Brazil	2	Japan	0.3
Spain	188	India	1	France	0.3

Table 4 ASSUMED ANNUAL GROWTH FACTORS INFLUENCING CO_2 EMISSIONS (1990-2025) (Derived from IPCC, 1992)

FACTOR	OECD	ASIA
Growth of Economy Per Capita	2.2%	3.5%
Population Growth Rate	0.3%	1.5%
Growth Rate : Energy Use Per Economic Output	-1.1%	-0.8%
Growth Rate : Carbon Emissions Per Energy Use Unit	-0.7%	-0.3%
Annual CO_2 Growth Rate (Sum of above factors)	+0.7%	+3.9%

Japan, with few indigenous fossil fuel resources, is heavily dependent on imported coal and residual oil for power generation. It is interesting to note that India, the second most populous country in the world and likely a major future contributor, has a pattern similar to China, with steam coal the dominant source.

We have already discussed the uncertainties associated with future emissions of CO_2. Such emissions will depend on country-specific factors: population growth, rate of industrialization, energy use per economic output, and carbon use per energy utilized. Table 4 (Princiotta, 1994) shows a projection of growth of these factors for the developed (Organization for Economic Cooperation and Development-OECD) and relatively undeveloped Asian countries for the period 1990-2025. This projection is derived from information presented in IPCC, 1992. For the OECD countries, the key driver yielding increased CO_2 emissions is expected to be economic growth, whereas population growth is projected to be quite modest. For the Asian countries, the key driver is likely to be economic growth, with population growth also significant. For both regions, in the absence of a CO_2 mitigation program, energy efficiency gains and a decrease in carbon-intensive energy use are projected to be modest over this time period.

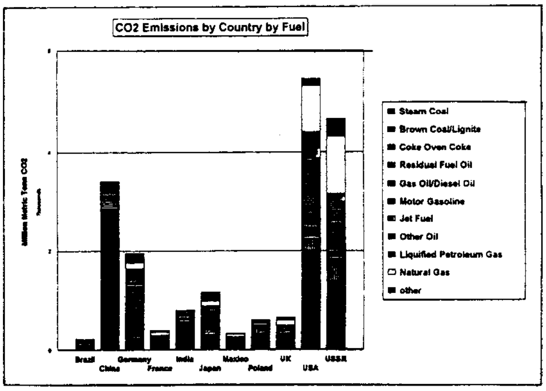

Figure 11: Recent CO_2 Emissions by Country by Fuel

It is useful to examine the likely results of these drivers on projected emissions of CO_2 from selected countries. Figures 12 and 13 show such a projection assuming economic, population, and energy use trends summarized in IPCC, 1992.

Projections for the years 2030 and 2100 are combined with actual CO_2 emission data (NAS, 1991)from the 1960-1988 time period.

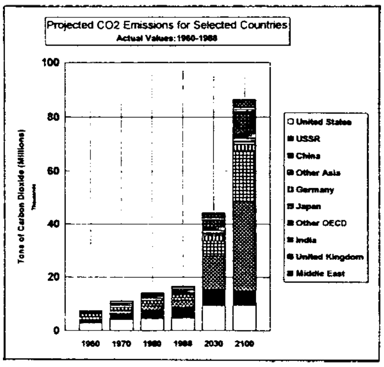

Figure 12: Projected CO_2 Emissions for Selected Countries (cumulative bar chart)

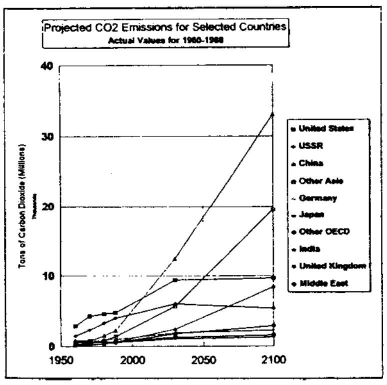

Figure 13: Projected CO_2 Emissions for Selected Countries (line chart)

These graphics show that the Asian countries, especially China and India, driven by high projected economic and population growth, will be the dominant CO_2 emitters by the middle of the next century.

Finally, it is instructive to examine CH_4 emissions from the important anthoropogenic sources for key countries.

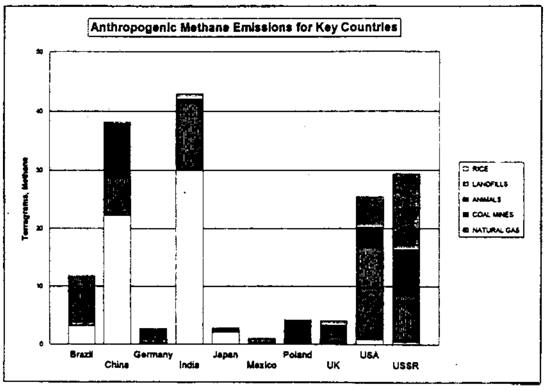

Figure 14: Antropogenic Methane Emissions for Key Countries

Figure 14 summarizes preliminary information from a variety of sources (Thorneloe, et al., 1993; Lerner, et al., 1988; Safley, et al., 1992; Kirchgessner, et al., 1993; and Barnes and Edmonds, 1990). Again, each key country has a unique signature dependent on the size of the economy and the relative importance of: rice production; coal mining; natural gas extraction, transmission, and distribution; beef production; and the amount of garbage generated and landfilled. Since rice production is a major CH_4 source and China and India are world's largest rice producers, this is the major source for these countries. For the U.S., which leads the world in garbage produced and landfilled, landfill CH_4 is the largest source; beef production, natural gas infrastructure, and coal mines are also significant.

WHAT IS AN APPROPRIATE MITIGATION TARGET? HOW MUCH WARMING IS ACCEPTABLE?

What targets should guide any greenhouse warming mitigation program? In order to answer this critical question, it is highly desirable to have a good understanding of the effects of various levels of greenhouse warming on the environment, the economy, and human settlements. Unfortunately, again, uncertainty prevails. Unfortunately, our understanding of such potential impacts ranges from fair (e.g., sea level rise) to poor (e.g., geographical change of rainfall/evaporation patterns). Therefore, it is exceedingly difficult to set such a target based on available effects information.

In the absence of definitive effects information, one approach involves selecting an allowable global temperature increase consistent with our understanding of Earth's climate history. Krause (1989) summarizes this as:

-A 1-1.5℃ global average warming would represent a climate not experienced since the beginning of agricultural civilization(6000 years ago).

-A 2-2.5℃ warming represents a climate not experienced since 125,000 years ago when small human communities existed. Such a climate seemed to partially disintegrate the West Antarctic shields, raising sea levels 5-7m.

-A 3-4℃ warming has not been experienced since humans appeared on the Earth (2 million years ago). The last time Earth experienced such a climate was about 3-5 million years ago.

Available limited effects information suggests that climate change to the degree projected by the base case (2.7℃, from pre-industrial to 2100), could have the following impacts (Krause, 1989; IPCC, 1990; Stone, 1995);

-increased mortality due to spread of infectious disease; e.g., malaria and summer heat stress.

-sea levels rising by at least 0.5 to 1.5 m over the next few decades, several meters in the long term.

-Changing ocean currents and precipitation patterns.

-More frequent occurrences of weather conditions considered extreme, producing floods, avalanches, and changes in the availability of run-off water.

-Loss of soil moisture due to increased evaporation, with an increase in duration and frequency of heat waves and droughts.

-Reduced precipitation in the mid-latitude continental regions of North America and Eurasia.

-More stagnant air masses for longer time periods.

-Potential severe impact on agricultural productivity.

-Die-back of unmanaged forests since they cannot migrate fast enough to keep up with the warming trends; this could exacerbate loss of species diversity.

-Reduction in stream flows yielding increased pressure on groundwater supplies.

MITIGATION: HOW MUCH AND WHEN TO START?

Figure 15 illustrates the projected results of two hypothetical mitigation scenarios assuming base case values. If emissions were held constant at year 2000 levels, the rate of projected warming could be slowed substantially; although significant warming would continue for the foreseeable future. However, if emissions for all greenhouse gases were reduced 1% annually, post-1980 warming could be stabilized below about 1℃ by he year 2100.

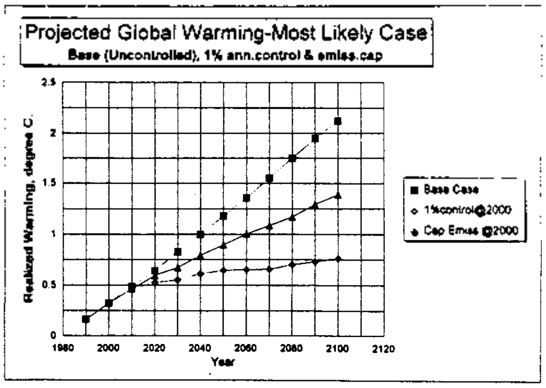

Figure 15: Projected Global Warming for the Base Case and Two Mitigation Scenarios

Figure 16 illustrates the impact of the year control starts on realized warming projected in 2050 for two mitigation scenarios (1% of annual control and emission cap). As indicated, early emission control allows for a much larger degree of climate stabilization. These results suggest that a mitigation program which caps emissions can be equally effective as a more stringent, and expensive, emission reduction program initiated 10 years later.

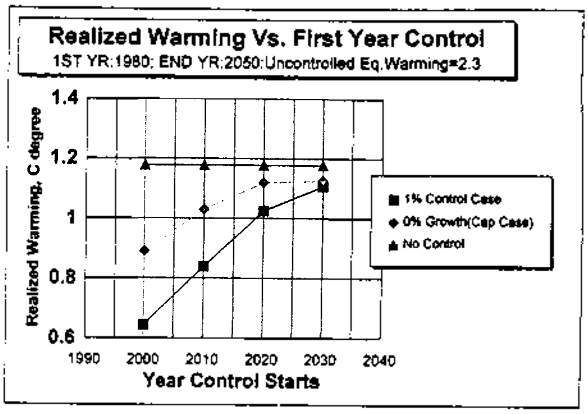

Figure 16: Projected Realized Warming vs. First Year Control

SUMMARY AND CONCLUSIONS

-A spreadsheet model has been developed to allow for calculations of both equilibrium and realized greenhouse warming as a function of key variables including: greenhouse gas emission growth rates, CO_2 life cycles, CH_4 lifetime, current aerosol cooling, and CFC phaseout assumptions.

-Model calculations for the three most credible cases, assuming a varying range of assumptions, yield projected warming at 2100 from a substantial 2.1℃ to a potentially catastrophic 5.7℃. The most likely case yields 2.7℃ projected warming from pre-industrial values. Such uncertainty also impacts the estimates of the effectiveness of a mitigation program. Model results suggest that, even assuming a stringent mitigation program, if key uncertainties all align toward maximum greenhouse warming, warming will be greater than it would be for a business-as-usual case assuming the mid-range of the key variables contributing to uncertainty.

-Factors contributing most to this uncertainty are: atmospheric sensitivity to a doubling of CO_2, CO_2 emission projections, the CO_2 life cycle model assumed, and the Earth's transient response to warming.

-Utilizing available atmospheric concentrations of the greenhouse gases from the pre-industrial era to 1980 yields, the model predicts 0.5℃ warming, assuming "most likely" values for the key variables. This agrees well with he range of warming observed for this period.

-Aerosol/sulfate cooling is an important phenomenon, with recent data suggesting cooling comparable to the warming associated with CH_4, the second most important greenhouse gas. Again, uncertainty in current and projected cooling is substantial.

-CO_2 is the largest potential contributors of the greenhouse gases, with CH_4 the second most important contributor. Warming associated with tropospheric ozone could be important , but the underlying science allowing a quantitative judgement is weak.

-Mitigating CH_4 emissions can achieve substantial benefits, in the near term, in light of its relatively short atmospheric lifetime. In fact, a 2% per year CH_4 mitigation program can be almost as effective as placing a cap on CO_2 emissions, assuming mitigation started in 2000 and the target year is 2050.

-Although the international phaseout will essentially mitigate greenhouse warming from CFCs and related compounds by 2050, replacement chemicals such as HFC-134a could be significant greenhouse gases in this time frame, depending on the extent of use.

-The United States, the former Soviet Union, China, Germany, and Japan are the largest emitters of CO_2 (in rank order). Each has a distinctive profile with regard to contributions per fuel-use sector. Developing countries in Asia such as China and India are expected to have exponential growth in greenhouse gas emissions, driven primarily by projected economic growth and dependence on coal as a major fossil fuel.

-To select a mitigation target, it would be desirable to have a solid understanding of the likely environmental, economic, and human settlement impacts associated with various levels of greenhouse warming. Since such information is not available, an alternative approach is to compare projections of greenhouse warming to geologic histories with comparable warming and, where possible, deduce possible impacts. Such an analysis suggests that projected greenhouse warming by (assuming base case variables) 2100 would lead to mean global temperature not experienced by the Earth in the last 125,000 years. Possible impacts include: seawater rise, changing precipitation patterns, die-back of indigenous forests, and potential loss of agricultural productivity.

-Model analysis shows that the time mitigation is initiated has an important impact on the degree of mitigation achievable. For example, a program to cap (hold constant) greenhouse gas emissions can be equally effective as a more stringent mitigation program initiated 10 years later.

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