The Net Environmental Effects of Carbon Dioxide Reduction Policies

by

Leslie A. Liu

B.S. in Physics
Massachusetts Institute of Technology, 1989

M.S. in Applied Physics
Harvard University, 1990

Submitted to the Department of Electrical Engineering and
Computer Science in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
in Technology and Policy

at the

Massachusetts Institute of Technology

May, 1994

Signature of Author ....
Technology and Policy Program
May 10, 1994

Certified by..
Henry Jacoby
William F. Pounds Professor of Management
Thesis Supervisor

Accepted by ....
Richard de Neufville
Chairman, Technology and Policy Program

The Net Environmental Effects of Carbon Dioxide Reduction Policies

by

Leslie A. Liu

Submitted to the Department of Electrical Engineering and Computer Science on May 10, 1994 in partial fulfillment of the requirements for the Degree of Master of Science in Technology and Policy

Abstract

In response to the threat of global warming a variety of policy measures have been proposed to reduce the emissions of carbon dioxide (CO_2). However, policies which reduce CO_2 emissions will also decrease the emissions of greenhouse-relevant gases methane, nitrous oxide, nitrogen oxides, carbon monoxide, and sulfur oxides. When these additional effects are overlooked the net effect of CO_2 reduction policies on global warming is understated. Thus, emissions of all greenhouse-relevant gases should be included when evaluating CO_2 reduction policies.

Other proposals which recognize the need to reduce emissions of all greenhouse gases have called for the reduction of a "CO_2-equivalent" amount. Policymakers evaluate these policies by using a Global Warming Potential (GWP) which is an index that supposedly indicates the relative radiative power of a greenhouse gas with respect to CO_2. This method, however, is flawed, as calculation of the GWP depends critically on the lifetime of the gas as well as the radiative effect of CO_2 which can change depending on the composition of the atmosphere. When analyzing the effect of gases on global warming, an atmospheric chemistry model which describes the interactions of all the gases should be used in place of the GWP. In this case, specification of future emissions of all greenhouse-relevant gases is also required.

This thesis addresses these two problems by developing a model which forecasts emissions of all greenhouse-relevant gases. This emissions model uses the GREEN model as the underlying economic model and incorporates the emissions of greenhouse-relevant gases from activities in energy, agriculture, industry, and land use. The results of the model are then fed into an atmospheric chemistry model to evaluate the effect on warming.

The atmospheric chemistry model is used to compare the results of a reference case with a Toronto-type agreement. The thesis finds that including other greenhouse-relevant gases results in an additional decrease of 40% in warming as compared to when only CO_2 is specified. Additional analyses are performed to illustrate the interaction between chemical species and the importance of including all greenhouse-relevant gases when evaluating global warming policies.

Thesis Supervisor: Prof. Henry Jacoby
Title: Willam F. Pounds Professor of Management

Acknowledgements

I would like to thank Prof. Henry Jacoby for his continual guidance throughout the undertaking of this thesis. Without his insight, direction, and timely comments, this thesis would have never reached its current state. He has been a excellent role model not only as a successful professor and researcher but also as a conscientious manager and mentor.

I would also like to thank the Joint Program on the Science and Policy of Global Change for providing the means necessary to complete this research. A special thanks goes to Jean Fitzmaurice for patiently running the atmospheric composition model many times. In addition, I thank those who helped me by providing helpful discussions, explanations, and other essential ingredients for this thesis, including Prof. Dick Eckaus, Denny Ellerman, N'gai Merrill, and Therese Henderson.

Finally, I am indebted to my husband Ling Yi for his constant encouragement and support at all times — especially from 8,000 miles across the Pacific. The ways in which I am thankful for him are beyond count. This thesis is dedicated to him.

Table of Contents

List of Tables

List of Figures

1. Introduction

In response to the threat of global warming a variety of policy measures have been proposed to reduce the emissions of carbon dioxide (CO_2), the most important greenhouse gas under the control of human activity. Carbon dioxide, which has been estimated to have contributed 50-60% of the warming in the last century, is released during fossil fuel combustion and deforestation. Proposed national policies and global agreements have focused on reducing carbon emissions from these sources.

One example is the so-called Toronto-type agreement in which OECD[1] countries would reduce CO_2 emissions to 80% of their 1990 levels by 2010, and non-OECD countries would emit no more than 50% above their 1990 levels by 2010. Emissions from all countries would be stabilized thereafter (Martin *et al.*, 1992).

However, other gases also play an important role in global warming. Concentrations of gases with radiative properties such as methane, nitrous oxide, and halocarbons have been increasing since pre-industrial levels due to anthropogenic activities. In addition, emissions of trace gases which affect climate indirectly, such as nitrogen oxides, sulfur oxides, and carbon monoxide, have also been increasing due to energy use and burning of the world's forests and grasslands.[2] Policies which reduce CO_2

---

[1] Organization for Economic Cooperation and Development; it includes Western Europe, U.S., Canada, Japan, Australia, New Zealand, and Turkey.

[2] Here we refer to all these gases as "greenhouse-relevant gases."

emissions will also decrease the emissions of these other greenhouse-relevant gases. When these effects are overlooked the net effect of CO_2 reduction policies on global warming may be understated.

The policy implications could be significant. Since greenhouse gases remain in the atmosphere for decades, concentrations would continue to grow over the next century even if emissions leveled off. Drastic cuts are required world-wide to stabilize atmospheric concentrations. There is a wide range of policy options to reduce emissions that may also be consistent with other economic, environmental, and social goals. In light of the uncertainties about global warming as well as uncertainties of the costs and benefits of taking action, policymakers are seeking least-cost and no-regret options that provide a maximum of benefits. By not accounting for the effect of CO_2 reduction policies on the emissions of other greenhouse-relevant gases, the costs and benefits of various options may be miscalculated. In addition, other least-cost alternatives for reducing emissions may be overlooked entirely. Thus, policies should be evaluated by considering the net effect on emissions of all greenhouse-relevant gases.

Other proposals which recognize the need to reduce emissions of all greenhouse gases have called for the reduction of a "CO_2-equivalent" amount. This phrase reflects the idea that each greenhouse gas differs in its radiative ability, so a certain emission of a greenhouse gas can be converted to the equivalent amount of CO_2 through the use of a "Global Warming Potential" (GWP). The GWP is an index that supposedly indicates the relative radiative power of a greenhouse gas with respect to CO_2.

This method, however, is flawed, as calculation of the GWP depends critically on the lifetime of the gas as well as the radiative effect of CO_2 which can change depending on the composition of the atmosphere. The radiative effect of greenhouse gases is determined by a complex set of chemical interactions which cannot simply be added in a linear fashion.

The shortcomings of these current methods for policy evaluation reveal the need for a way the measure the effect of CO_2 reduction on emissions of other greenhouse-relevant gases and the resulting effecting on climate. What is needed is a new generation of models which describe future emissions of all greenhouse-relevant gases. Since the majority of CO_2 emissions comes from fossil fuel sources, most CO_2 emissions models are based on models which were used in the past to forecast the evolution of energy markets. The other greenhouse-relevant gases, however, are emitted from agricultural and industrial sources and land-use changes, so they are outside the scope of present CO_2 emission models.

In this thesis I present a vehicle for evaluating CO_2 reduction policies, *i.e.* a model that forecasts emissions of all greenhouse-relevant gases. This new model builds upon a current energy-economic model called GREEN (GeneRal Equilibrium ENvironmental Model), developed by the OECD to examine the effects of CO_2 reduction policies. The emissions model, called GEMS (Green EMissions Submodel), incorporates the emissions of greenhouse-relevant gases from activities in energy, agriculture, industry, and land use using the output from GREEN as drivers of the emissions. Since GEMS forecasts emissions of all greenhouse-relevant gases, these emission forecasts can be fed into an atmospheric chemistry model to evaluate the effect on climate, bypassing the problem of using GWP's. The thesis uses this method to analyze the effect of CO_2 reduction policies on the emissions of other greenhouse-relevant gases and the net contribution to global warming.

1.1. Overview of the Thesis

I start in chapter two with a description of the greenhouse effect and the chemistry of the troposphere, *i.e.* the lower atmosphere where warming takes place. This elementary description of atmospheric chemistry examines the interdependent set of reactions among greenhouse-relevant gases and reveals the shortcomings of the method of Global Warming Potentials. I also discuss the requirements for an emissions model that would be useful for evaluating CO_2 reduction policies. Subsequently, I take a look at various models that forecast emissions of greenhouse-relevant gases. Finally, I describe the GREEN model and the objectives considered in designing GEMS.

Chapter three begins the description of the emissions model. First, the sources of methane are described in detail. For each source, I calculate a global budget distribution for the initial year and describe which output vector from GREEN drives the future emissions for that source. In subsequent chapters, I describe the model for nitrous oxide, nitrogen oxides, carbon monoxide, and sulfur oxides.

Chapter six describes the results of the GEMS model from a reference case and a Toronto-type agreement. This analysis investigates the non-carbon effects of commitments to stabilize carbon emissions with respect to 1990 levels. The emissions profile is then is fed into an atmospheric composition model to determine the rise in temperature and radiative forcing. Several analyses are performed with the atmospheric composition model to illustrate the interaction between chemical species and the importance of including all greenhouse-relevant gases when evaluating global warming policies.

A final thought is given. The objective of this thesis is not to determine the absolute magnitude of global warming. There is no expectation that emissions of greenhouse-relevant gases will actually grow as predicted by the model, although reasonable assumptions are made whenever possible. Conventional wisdom has it that most of the time forecasts will be incorrect as unpredictable turns of events cannot be foreseen. The important question to ask is not "What is the absolute magnitude of global warming when all greenhouse-relevant gases are included?" but "What is the change in warming when all greenhouse-relevant gases are included?" By understanding the importance of including all greenhouse-relevant gases in their analyses, policymakers will have a better chance of choosing the most optimal policy solution.

2. Forecasting Greenhouse Gas Emissions

2.1. The Greenhouse Effect

The natural greenhouse effect is a scientifically accepted fact. Without the presence of radiative trace gases in the atmosphere, the earth would be approximately 60° F colder than it is currently is, *i.e.* about 0° F. These radiatively active gases are transparent to incoming short-wave solar radiation, but they absorb and re-radiate outgoing long-wave terrestrial radiation, thus heating the atmosphere. This energy absorption is measured in Watts/m^2 and is called "radiative forcing." Gases which exhibit this property are called "greenhouse gases" and include tropospheric water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), tropospheric ozone (O_3), and halocarbons (CFC's).

However, atmospheric concentrations of these greenhouse gases have increased dramatically since pre-industrial times due to human activities such as fossil fuel combustion, agriculture, and deforestation. These increased levels may lead to additional warming of the earth's atmosphere or an enhanced greenhouse effect, otherwise known as "global warming." This rise in temperature may have potentially disastrous physical and economic consequences for the earth's inhabitants.

Data from air bubbles trapped in ice cores show that for a thousand years prior to Industrial Revolution, concentrations of greenhouse gases were relatively constant. In the last 100-200 years, the atmospheric levels of the greenhouse gases have increased significantly. Carbon dioxide has increased from a pre-industrial atmospheric concentration of 280 ppm[3] to a current-day level of 355 ppm and continues to rise at a rate of 0.5% per year. Methane has more than doubled its pre-industrial level of 0.8 ppm to 1.72 ppm today and is accumulating at 0.6% per year. Nitrous oxide has increased from 288 ppb to 310 ppb and its accumulation rate is 0.2 to 0.3% per year. Since CFC's are not produced in nature, they were not present in the atmosphere during pre-industrial times. CFC-11 has a current concentration of 280 ppt and CFC-12 has a concentration of 484 ppt (IPCC, 1992). Consistent trend data for tropospheric ozone is not available, since its concentration is dependent on latitude, longitude, altitude, and season.[4]

Although all of the sources and sinks of greenhouse gases have not been completely quantified, the increase in atmospheric levels of greenhouse gases has been attributed an increase in human activities producing greenhouse gases. The growth in global energy use has been a main contributor to the growth in emissions of greenhouse gases. Energy use, in particular combustion of fossil fuels, accounts for possibly 75% of the annual global carbon dioxide emission from anthropogenic activities (IPCC, 1992). CO_2 emissions from fossil fuel combustion increased at 4% per year after 1860, slowed to 2% after the oil crisis of 1973, and is currently increasing at 6% per year for developing countries and less than 1% in developed countries (IPCC, 1990). Changes in land-use arising from deforestation is the other large source of CO_2 emissions.

Atmospheric methane has been increasing at about 1% per year which corresponds well to the growth rate of human population (Bouwman, 1990). In 1989 this rate slowed to 0.6% per year, although the reason is still unknown (Steele *et al.*, 1992). Anthropogenic sources of methane emissions include coal mining and natural gas production, rice cultivation, enteric fermentation, wastes from animals, landfills, domestic

---

[3] ppm = parts per million by volume, ppb = parts per billion by volume, ppt = parts per trillion by volume

[4] Trend rates for Europe and North America comparing current-day levels with 100 years ago show an increase by a factor of 2-3 on average. Data for remote sites such as Alaska and Hawaii show an increase of 0.8% per year but a decrease of 0.5% per year at the South Pole. No data is available for tropical regions (IPCC, 1990).

sewage treatment, and biomass burning. Anthropogenic sources of nitrous oxide include emissions from fertilizer use and production, conversion of forests to agricultural lands, nylon production, and biomass burning. CFC's are produced for industrial uses such as aerosol propellants, refrigerants, and solvents.

Greenhouse gases vary in their influence depending on their atmospheric concentration and their ability to absorb terrestrial radiation. Tropospheric water vapor has the largest greenhouse effect, but its concentration is determined internally and is not influenced directly by human sources and sinks. CO_2 is the least effective greenhouse gas considering only heat-absorbing potential on a molecule-by-molecule basis. A molecule of methane is about 21 times more effective than CO_2 and CFC-11 is about 12,000 more effective (IPCC, 1990). However, due to the enormous amount of annual CO_2 emission, CO_2 is the most significant greenhouse gas. The U.S. Environmental Protection Agency has estimated using the method of Global Warming Potentials[5] that over the last 100 years, carbon dioxide has contributed about 60% of the radiative forcing, methane about 20%, CFC's about 10%, and all other gases about 10% (EPA, 1990).

Other greenhouse-relevant gases such as nitrogen oxides (NO_X) and carbon monoxide (CO) contribute indirectly to the climate process by affecting the lifetime of methane and tropospheric ozone. Both NO_X and CO act as precursors to tropospheric ozone along with methane and non-methane hydrocarbons (NMHC) by affecting the concentration of the hydroxyl radical (OH). At low NO_X concentrations, increases in CO, CH_4, and NMHC lead to a decrease in O_3 whereas the opposite occurs at high NO_X concentrations. Since anthropogenic emission of NO_X and CO have been increasing, they have influenced the radiative effect of CH_4 and O_3.

Finally, sulfate aerosols, which are formed from oxides of sulfur (SO_X), have been discovered to play an important role in climate. Backscattering by white sulfate aerosols can have a negative radiative effect by reflecting solar radiation away from the earth (Charlson *et al.*, 1990, 1991, 1992). Since emissions of SO_X from fossil fuel and industrial sources have also followed an increasing trend, this cooling effect may diminish the effect

---

[5] The Global Warming Potential is defined as the time integrated warming effect from the instaneous release of 1 kilogram of a trace gas, relative that of 1 kilogram of CO_2 (see IPCC, 1990, 1992).

of global warming. In addition, sulfur compounds can alter the reflective properties of clouds by providing additional particles which act as cloud condensation nuclei (IPCC, 1992). Although there is uncertainty about the magnitude of these cooling effects, there is no doubt they must be taken into consideration (Prinn, 1994).

2.2. Chemistry of the Troposphere

The magnitude of global warming is determined in part by the atmospheric concentrations of greenhouse gases. These equilibrium concentrations are governed by a complex set of chemical reactions involving CO_2, CH_4, NO_X, and CO. The chemistry of the troposphere is driven by the hydroxyl radical (OH) which is known as the "detergent" of the troposphere since it removes almost all of the gases generated by human activities (Prinn, 1994; Logan *et al.*, 1981).

The primary source of OH is reaction of a singlet oxygen atom $O(^1D)$ with water vapor, where $O(^1D)$ is produced by the photolysis of ozone (O_3):

$$\begin{gathered} O_3 + \text{ultraviolet} \rightarrow O_2 + O(^1D) \\ O(^1D) + H_2O \rightarrow OH + OH. \end{gathered} \tag{1}$$

The sinks of OH include reactions with CH_4, CO, NO_X, and SO_X. CH_4 is oxidized in a series of steps to produce CO as a by-product:

$$CH_4 + OH \rightarrow CH_3 + H_2O \rightarrow \text{multiple steps} \rightarrow CO. \tag{2}$$

CO, in turn, is oxidized by OH to produce CO_2 and a free hydrogen atom which quickly attaches to oxygen to form a hydroperoxy radical (HO_2):

$$\begin{gathered} CO + OH \rightarrow CO_2 + H \\ H + O_2 \rightarrow HO_2. \end{gathered} \tag{3}$$

This hydroperoxy radical is relatively unreactive, so OH radicals are depleted unless NO_X ($NO + NO_2$) is available. When NO_X is present, HO_2 radicals are recycled back into OH radicals through the following process:

$$\begin{gathered} HO_2 + NO \rightarrow OH + NO_2 \\ NO_2 + \text{ultraviolet} \rightarrow NO + O. \end{gathered} \tag{4}$$

Note that NO_X is not consumed and therefore acts as a pump for recycling of OH radicals.

Finally, the other sinks of OH include NO_2, which is oxidized to produce nitric acid (HNO_3):

$$NO_2 + OH \rightarrow HNO_3, \tag{5}$$

and SO_2, which is oxidized to produce sulfuric acid (H_2SO_4):

$$\begin{aligned} &SO_2 + OH \rightarrow HSO_3 \\ &HSO_3 + O_3 \rightarrow HO_2 + SO_3 \\ &SO_3 + H_2O \rightarrow H_2SO_4. \end{aligned} \tag{6}$$

Nitric acid and sulfuric acid are deposited back on the surface in the form of acid precipitation.

These reactions show how the concentration of the OH radical is a critical element in determining the chemical composition of the troposphere and hence radiative forcing. As CH_4 and CO emissions increase, we expect that they would eat up OH and the concentration of OH would fall. However, the presence of NO_X changes the situation by inducing the recycling of OH. The lifetime of CH_4 in the atmosphere is determined by the concentration of OH because if OH increases, CH_4 is destroyed more quickly and its lifetime decreases.

The level of NO_X also influences the concentration of O_3. When NO_X levels are above a critical value, ozone is produced by the series of reactions (3), (4), and the following:

$$O + O_2 \rightarrow O_3. \tag{7}$$

However, if NO_X concentrations are low, O_3 is destroyed by reaction (3) and the following:

$$HO_2 + O_3 \rightarrow OH + 2O_2. \tag{8}$$

The critical value of NO_X is 20-30 ppt. Thus, CH_4 is oxidized to CO which in turn is oxidized by OH to produce CO_2 and O_3 when NO_X concentrations are high. As a result, rising emission levels of CH_4, CO, and NO_X are contributing to the increase of greenhouse gases CO_2 and O_3 in the atmosphere.

Stratospheric ozone, which is depleted by the presence of CH_4, N_2O, and halocarbons, can also affect the levels of tropospheric OH. As stratospheric ozone, which absorbs ultraviolet rays, becomes depleted, more ultraviolet is able to penetrate through to the troposphere. An increase in ultraviolet in the troposphere leads to the production of $O(^1D)$ which is the source of OH and the destruction of tropospheric O_3 (equation 1).

Finally, OH also affects the climatic influence of sulfate aerosols. When sulfate aerosols are emitted they gradually spread out over the atmosphere to reflect solar radiation. An increase in OH would lead to a more rapid oxidation of sulfate aerosols, thus limiting their area of influence on climate.

This elementary description of atmospheric chemistry gives a glimpse into the complexity of interactions between various species in the atmosphere. One cannot easily predict whether levels of trace gases will increase or decrease due to an increase in emissions or how their atmospheric lifetimes will change. Global Warming Potentials which attempt to capture the radiative effect of a greenhouse gas in a single number are inadequate for use as a policy evaluation tool. The magnitude of the GWP depends critically on the lifetime of greenhouse gases which may vary over time depending on the concentration of the OH radical. Thus, there is a need for models which capture all of the chemical interactions occurring in the atmosphere. In order to use such an atmospheric chemistry model, emissions of all greenhouse-relevant gases must be specified.

2.3. Greenhouse Gas Emissions Models

In order to evaluate the effect of policies to stabilize emissions, emissions models are needed to study possible future paths of emissions growth. From the previous section we see the need for these models to specify emissions of all greenhouse-relevant gases. Another important feature of a desired emission model is that the drivers of emissions sources should be endogenous to the model. If emission profiles of greenhouse-relevant gases are specified externally, as in a series of "emission scenarios," changes to model parameters will not result in changes to emissions of gases which are specified exogenously. A third requirement is that the emission model should be global in scope. Gases in the atmosphere have no identity of origin, so only global models will be able to evaluate the complete effect of emissions on global warming.

A review of current emissions models reveals that many of them either do not include greenhouse-relevant gases other than CO_2 or if they are included, they are determined exogenously to the model. This deficiency is revealed by the history of greenhouse gas emissions modelling. Most of these models were constructed from energy models of the past because the majority of CO_2 emissions is from energy sources. Other greenhouse-relevant gases were usually added later. Since the other greenhouse-relevant gases have sources from agriculture, industry, and land use, they were either excluded from CO_2 emission models or determined exogenously by a set of scenarios.

Some of the recent emissions models include Carbon Emissions Trajectory Assessment or CETA (Teisberg, 1993), Edmonds-Reilly, IDEAS (AES Corp., 1993), GEMINI (Cohan, 1993), Global 2100, Global Macro-Energy (Pepper, 1993), and Goulder (see Beaver, 1993, for a description of models). Several of these models focus only on national issues, including Goulder, Global 2100, GEMINI, and IDEAS (Weyant, 1993). GEMINI and IDEAS were both used in formulating U.S. energy policy. Although these models do contain emissions of greenhouse gases other than CO_2, only energy-related emissions are included. All non-energy sources of greenhouse gases are specified exogenously. The global models include CETA, Edmonds-Reilly, and Global 2100. However, they either did not include all greenhouse-relevant gases or the emissions of those gases were specified exogenously.

Only a handful of models exist that address emissions of all greenhouse-relevant gases on a global basis. These models include the Atmospheric Stabilization Framework (ASF), the Integrated Model to Assess the Greenhouse Effect (IMAGE), the Integrated Climate Assessment Model (ICAM), and the Second Generation Model (SGM). These models integrate energy, agriculture, land-use, and industrial activities to determine greenhouse gas emissions from all anthropogenic sources.

We examine these models here, as these models guided the design of GEMS with respect to determining which factors drive emissions of greenhouse-relevant gases. In particular, the ASF incorporated several of the new anthropogenic sources of greenhouse-relevant gases which were introduced in IPCC (1992). The ASF, which is based on the Edmonds-Reilly energy model, is the most complete model at this point in time. The others have potential but are as yet still uncompleted.

2.3.1. The Atmospheric Stabilization Framework (ASF)

The Atmospheric Stabilization Framework is a model used by the U.S. Environmental Protection Agency to analyze policy options for global change and create scenarios for the first IPCC assessment. The details of the ASF are described in EPA (1990). Recently, the ASF was modified to reflect new findings (Pepper, 1992). The ASF contains four modules: energy, agriculture, industry, and land-use. The model runs from 1985 to 2100 and specifies emissions of CO_2, CH_4, N_2O, NO_X, SO_X, and CO.

The energy module of the ASF is the Global Macro-Energy model developed by ICF. It consists of a modified version of the Edmonds-Reilly model with emissions of CH_4, N_2O, NO_X, SO_X, and CO added and detailed end-use models developed at the World Resources Institute (Mintzer, 1988) and Lawrence Berkeley Laboratory (Sathaye *et al.*, 1988). The model divides the world into nine regions and calculates the fossil fuel and biomass energy consumed and produced.

The agricultural module consists of two components: an agricultural activities model and an emissions model. The agricultural activities model is based on Iowa State University's Basic Linked System (Frohberg *et al.*, 1988) and is a regional model of agricultural production and consumption and inputs used in agriculture. Twenty national agricultural models are incorporated, representing 80% of the world's population and agriculture production. The rest of the world is aggregated into fourteen regional models. Countries with similar income levels and import/export characteristics are grouped into regions. The agricultural model estimates regional prices for different agricultural products and makes decisions about the allocation of capital and labor. At the end of each period, prices, consumption, and the level of trade are determined by the model.

The agricultural model is divided into nine commodity classes: rice, coarse grains, bovine and ovine meat, dairy products, other animal products, protein feed, other food, and non-food agriculture. The model runs through 2050, and a simplified method for extrapolating results from 2050 to 2100 is used.

The agricultural emissions model uses outputs related to changes in nitrogenous fertilizer, ruminants, rice production, and burning of agricultural wastes to estimate future emissions resulting from agricultural activities. These emissions include release of CH_4

from rice cultivation, CH_4 from ruminants, N_2O from nitrogenous fertilizer use, and CH_4, N_2O, NO_X, and CO from burning of agricultural wastes. CO_2 emissions from burning of agricultural wastes are assumed to net to zero due to recycling during plant growth.

The industrial emissions module of the ASF forecasts changes in the use of halocarbons and calculates the resulting emissions.

The land-use and deforestation module calculates emissions of CH_4, N_2O, NO_X, and CO from deforestation and biomass burning. Only flux from tropical regions is considered. The model allocates cleared land into three categories: land cleared for fuelwood, crops or pasture, and harvest or industrial uses. For each category, the model has a response curve which determines the change in emissions of carbon over time, allowing for abandonment and regrowth. Emissions of other gases are calculated as a ratio to carbon released.

2.3.2. The Integrated Model to Assess the Greenhouse Effect (IMAGE)

The Integrated Model to Assess the Greenhouse Effect was developed by Jan Rotmans at the National Institute of Public Health and Environment Protection (RIVM) in the Netherlands (Rotmans, 1990). The first version came out in 1990 and a new version is forthcoming.

IMAGE v. 1.0 consists of five modules which run sequentially: emissions, concentrations, climate, sea level rise, and socio-economic impact modules. The greenhouse gases studied in this model include CO_2, CH_4, N_2O, CFC's, and CO. The emissions of these gases from energy, industry, agriculture, and natural sources are considered. The model runs from 1985 to 2100.

Four scenarios labeled unrestricted trends, reduced trends, changed trends, and forced trends drive the growth of emissions over time. The scenarios outline certain assumptions about trends in population growth, energy use, use of agricultural inputs, increase in consumption of meat, dairy products, and rice, and deforestation.

The energy module of IMAGE uses the Edmonds-Reilly model to forecast emissions due to coal, oil, and gas production and use. Unfortunately, the industrial, agricultural, and natural sources of greenhouse-relevant gases are not driven by the model. For example, estimated growth in rice paddies and ruminant animals follows a predetermined pattern from the scenario being run. The area of rice production grows by a constant factor which represents the consequence of human population growth, and cattle production grows according to a logistic function with the coefficients exogenously specified. A feedback factor of temperature rise on emissions of methane from rice production is included. Natural sources are assumed to remain constant over time, although a feedback factor of temperature rise on emissions of methane from wetlands is included in the model.

2.3.3. Integrated Climate Assessment Model (ICAM)

The Integrated Climate Assessment Model is currently being developed at Carnegie Mellon University (Dowlatabadi *et al.*, 1993). The ICAM framework is designed to simulate economic and climate change for two global regions (high latitude/developed and low latitude/developing) in 25-year intervals from 1975 to 2100. The model will include all greenhouse gases as well as a deforestation module but is still in the working stages.

2.3.4. The Second Generation Model (SGM)

The Second Generation Model is currently being developed at Pacific Northwest Laboratories. It is an overhaul of the Edmonds-Reilly model, with two other sectors being added which model the production and consumption of agriculture and other products (Edmonds *et al.*, 1991; Fisher-Vanden *et al.*, 1993).

The preliminary version, SGM v. 0.0, consists of eight energy sectors, one agriculture sector, and an “other products” sector. In version 0.0, there is only a single aggregate agricultural commodity, and the principal inputs are land, labor, and energy. SGM v. 0.0 has 11 regions and runs from 1985 to 2100 in five-year steps.

In version 1.0, there will be nine outputs for the agriculture sector: rice and other grains, ruminant livestock, other livestock, other food, fiber, forests, pulp and paper, wood and wood products, and processed foods. There will be additional inputs of fertilizer, materials, and disaggregation of land by soil type and climate. Changes in land use will also be modeled. Emissions will be determined from the sector breakdowns in rice, ruminants, and forestry. In addition, N_2O emissions will be calculated from the application of fertilizer in all sectors. SGM v. 1.0 will be expanded to 20 regions.

In v. 1.0 the other products sector will be broken down into manufacturing, passenger transport, freight transport, and services. The sectors will then be disaggregated into subsectors which represent sources or sinks of greenhouse gases or major energy users.

2.3.5. The General Equilibrium Environmental Model (GREEN) and the GREEN Emissions Submodel (GEMS)

The GREEN model specifies economic output and CO_2 emissions for twelve regions of the world from the year 1985 to the year 2050. GREEN has several advantages over previous global models used to analyze the global warming. It incorporates full trade linkages between regions and models distortions such as taxes and subsidies affecting the prices of energy across countries.

GREEN is divided into twelve regions, 11 producer sectors, and 4 consumer sectors. The sectors which are relevant to the development of GEMS are the energy sectors (coal, crude oil, natural gas, refined oil), the agricultural sector, and the industrial sector (energy-intensive industries, other industries).

Table 1: Key dimensions of the GREEN model (see Burniaux *et al.*, 1992)

Regions
1. United States (USA)
2. Japan (JPN)
3. European Community (EEC)
4. Other OECD (OOE)
5. European Economies in Transition (EET)
6. Former Soviet Union (FSU)
7. Energy-exporting Countries (EEX)
8. China (CHN)
9. India (IND)
10. Dynamic Asian Economies (DAE)
11. Brazil (BRA)
12. Rest of the World (ROW)

Producer Sectors
1. Agriculture
2. Coal mining
3. Crude oil
4. Natural gas
5. Refined oil
6. Electricity, water, and gas distribution
7. Energy-intensive industries
8. Other industries
9. Carbon based back-stop
10. Carbon-free back-stop
11. Carbon-free electric back-stop

Consumer Sectors
1. Food, beverages, and tobacco
2. Fuel and power
3. Transport and communication
4. Other goods and services

Energy-intensive industries include transportation. GREEN specifies output for five-year periods 1985 to 2010 and for twenty-year periods from 2010 to 2050.

GREEN is calibrated with three parameters specified exogenously: the growth rate of GDP, population, and the AEEI (autonomous energy efficiency improvement) which specifies the rate of technical change. Population projections follow World Bank projections, and world population rises from 5 in 1985 to 10 billion in 2050. AEEI is set to 1.0% per year, and GDP rates vary between regions (see Dean and Hoeller, 1992). This set of assumptions is known as the "Reference Scenario." In this scenario, carbon emission rise from 5 billion tons in 1985 to 17 billion tons in 2050. Carbon dioxide reduction policies are accomplished in GREEN through the implementation of a carbon tax. The existence of trade flows in GREEN also allows for the analysis of tradeable permit policies.

GEMS builds upon GREEN by specifying the emissions of the other greenhouse-relevant gases CH_4, N_2O, NO_X, SO_X, and CO. Since GEMS is a first-pass attempt at forecasting emissions of all greenhouse-relevant gases, several objectives were pursued in designing the model:

1. The model should include all greenhouse-relevant gases of primary importance.
2. The model should be global in scope.
3. The model should attempt to drive future emissions endogenously whenever possible.

Considering these objectives, some items were excluded. First, CFC's are not modeled in GEMS, since their path of future emissions is assumed to follow the schedule specified by the London Amendments to the Montreal Protocol on Substances that Deplete the Ozone Layer (UNEP, 1987).[6] Land-use changes from deforestation are also not included in the model. The extent of deforestation depends on complex interactions of political and economic factors and requires further research in order to come up with an appropriate model. As such a model is not available at this time, the component of deforestation in emissions of CH_4, N_2O, NO_X, SO_X, and CO from biomass burning is

---

[6] Developed countries are to freeze emission levels of CFC's at 1986 levels in 1990, reduce 50% of 1990 levels by 1995, reduce 85% by 1997, and reduce 100% by 2000. Developing countries with less than 0.3 kg per capita may increase up to this limit and are allowed to delay compliance by 10 years.

controlled by an exogenous variable rate of growth. CO_2 emissions from deforestation are not included, since we are not concerned about the absolute magnitude of warming but the change in warming. The addition of CO_2 from deforestation would shift the warming curve but not affect relative changes. Finally, non-methane hydrocarbons (NMHC) are not included in GEMS, since their role in global warming is a second-order effect, *i.e.* as one of the sources of CO through oxidation by OH.

In constructing GEMS, a global budget for each gas is determined for the starting year 1985. These budgets are either taken from existing emission inventories or calculated using coefficients from the literature. A comprehensive summary of existing emission inventories provided a good starting point (Graedel *et al.*, 1993). Since one of the objectives is to model future emissions endogenously, each emission source is disaggregated among the twelve GREEN region so that emissions from each region can evolve independently. The evolution of future emissions, however, is driven by the GREEN model by using the vector of outputs from GREEN. The appropriate output variable is chosen, although in some cases, the disaggregation is not sufficient and can only be roughly approximated. In all cases, the growth rate of emission is assumed to be proportional to the growth rate of the economic sector.

A proportionality constant is usually specified. This proportionality constant acts as an elasticity coefficient, since it relates the percentage change of an emission to the percentage change of a GREEN output variable. For example, in the case of methane emissions from coal mining, I initially chose this elasticity to be equal to one:

$$\frac{\Delta E}{E} = \alpha \frac{\Delta C}{C},$$

where E is the emission of methane from coal mining, C is coal output from GREEN, and $\alpha=1$. By allowing this elasticity to vary, we are able to capture several pieces of information which may be missing from the model otherwise: any technological improvements over time, policy factors, and changes in the relationship between the economic driver and the emission.

Finally, we note that although SO_X is not explicitly involved in the chemistry of the troposphere that determines warming, we include it in the model. The atmospheric composition model does not incorporate the ability of aerosols to cool the troposphere and affect cloud radiative properties, since these climatic effects are still being studied at this time. However, it is useful to examine the emissions profile of SO_X, since it has significant climate implications and plays an important role in local environmental conditions with regard to acid precipitation.

3. Methane

Methane is the most abundant of the atmospheric hydrocarbons and is important in its role as a greenhouse gas. It is estimated to have contributed about 20% of global warming in the last 100 years (EPA, 1990). Methane has a relatively short atmospheric lifetime, about 11 years. The atmospheric concentration of methane has been increasing at about 1% per year with a current value of 0.6% per year and has more than doubled over the last two centuries.

Methane is emitted by a number of biogenic sources (wetlands, termites, oceans, lakes, tundra) as well as anthropogenic sources. The rise in methane is believed to have been caused by an increase in anthropogenic activities which produce methane emissions. These anthropogenic sources include rice paddies, enteric fermentation and wastes by animals, landfills, coal mining, natural gas, and biomass burning. The total global emission of methane is estimated to be 400 to 600 Tg per year[7] (Cicerone and Oremland, 1988), of which approximately one-third comes from natural sources and two-thirds comes from anthropogenic sources, although uncertainties exist in estimations of source strengths.

In this chapter I discuss the anthropogenic sources of methane, the drivers, source strengths, and how these sources of methane emissions are modeled in GEMS. Consideration of driving factors and uncertainties guides the design of the model.

---

[7] 1 Tg = 10^{12} g

3.1. Paddy Rice

Methane is emitted from flooded paddy rice fields as a result of anaerobic decomposition of organic matter. Dryland rice (also known as upland rice), which is not flooded, does not emit methane in significant quantities. Methane is produced from three primary sources in rice paddies: (1) root exudates and sloughed-off root cells from rice plants, (2) organic material such as rice straw introduced during field preparation, and (3) floodwater biomass such as algae (OECD, 1991). The gas escapes into the atmosphere by diffusion through the floodwater and the rice plant itself (Cicerone and Shetter, 1981).

The amount of methane emitted is highly dependent on growing conditions such as soil type, temperature, moisture, redox potential, pH, application of fertilizer, and water management technique (OECD, 1991). There is a huge variation in emissions on an hourly, daily, seasonal basis. Measured methane fluxes have ranged from 5-54 g CH_4/m^2 per harvest cycle in mid-latitude regions (Cicerone and Shetter, 1981; Cicerone *et al.*, 1983; Holzapfel-Pschorn and Seiler, 1986; Schutz *et al.*, 1989; Sass *et al.*, 1990) to 90 g/m^2 (Schutz and Seiler, 1989, Schutz *et al.*, 1990) in a Chinese rice paddy. Over 90% of the global wetland rice area is found in Asia (Neue *et al.*, 1990). Global emissions are calculated by multiplying an average daily flux rate by the harvest area, length of the growing season, and number of cropping cycles. Various estimates for the global emissions of methane from rice paddies are listed in Table 2 below.

Table 2: Estimates of global methane emissions from paddy rice

Source	*Tg CH_4 per year*
Ehhalt and Schmidt, 1978	280
Cicerone and Shetter, 1981	59
Khalil and Rasmussen, 1983a	95
Seiler *et al.*, 1984	35-59
Holzapfel-Pschorn & Seiler, 1986	67-166
Cicerone and Oremland, 1988	60-170
Aselmann and Crutzen, 1989	60-140
Schutz *et al.*, 1989	50-150
Schutz *et al.*, 1990	69-111
Neue *et al.*, 1990	25-60
Matthews *et al.*, 1991	100

The high estimate of Ehhalt and Schmidt (1987) was based on laboratory measurements of methane emission flux using samples of Japanese paddy soils without rice plants present. The first in-situ measurements were done by Cicerone and Shetter (1981) in a California rice paddy. Many of the subsequent global estimates were based on measurements from mid-latitude sites. Seiler *et al.* (1984) used field measurements from Spain, and Holzapfel-Pschorn and Seiler (1986) used data from Italian rice paddies, as did Schutz *et al.* (1989). Some of the more recent estimates including Aselmann and Crutzen (1989), Schutz *et al.* (1990), and Neue *et al.* (1990) have incorporated field measurements from Asia.

From 1940 to 1980 the global methane emission from paddy rice may have increased from 55 Tg to 100 Tg (Schutz *et al.*, 1989), or about 1.6% per year (Holzapfel-Pschorn and Seiler, 1986). Grist (1986) predicts that the harvested paddy rice area in Asia will increase by 25% by 2000. In addition, the percentage of irrigated paddy rice may increase from 32% in 1975 to 52% in 2000 (Dudal *et al.*, 1981) which would also serve to increase methane emissions.

Due to the large uncertainties in methane fluxes and emissions, I decided to choose a number from the middle of the range of estimates and distribute the emission according to rice production in each region. Choosing 100 Tg as an approximate number, I used rice production data from FAO (FAO, 1993) to determine the share of methane emissions from each GREEN region.

Future methane emissions are dependent on amount of rice harvested. We might think of rice production as a function of several economic and physical factors such as price, land area, rice yield, weather, etc. Thus, future methane emissions would depend on the form of a function f:

$$\text{Methane emissions}_{\text{rice}} = f(\text{price of rice, area, yield, weather})$$

Without a model to determine equilibrium prices and land areas, we can only make a first approximation at this point by assuming that methane emissions will grow with agricultural output since rice production is a component of agricultural output. In the future, the amount of land that can be acquired for cultivation will become limited, and harvest yields will probably not grow as quickly as they did during the Green Revolution. In addition, the share of rice production in total agricultural output might be expected to decrease as income rises and consumption of non-staples rises. Therefore, we would expect the growth of rice production to be slower than the growth of total agricultural output.

Using the forecast from Grist (1986) as a guideline, I chose a growth rate for methane emissions from rice production at 40% the growth rate of agriculture. The results show that methane emissions from paddy rice grow from 100 Tg in 1985 to 270 Tg in 2050 (see Table A.1 and Table A.2). These numbers are for the reference case.

3.2. Enteric Fermentation

Methane is produced as a by-product of enteric fermentation of organic matter in domestic animals. Although both ruminants and non-ruminants produce methane, ruminants are a much more significant source. Methane-producing bacteria (methanogens) residing in the digestive tracts of ruminant animals break down the cellulose present in animal feed, and approximately 4-9% of the gross feed energy is transformed into methane. Non-ruminants also produce methane, although this percentage is much lower, less than 1% for pigs and about 3–4% for horses (Crutzen *et al.*, 1986). The amount of methane produced is dependent on the quality and type of feed, amount of feed intake, as well as the size and age of the animal.

Cattle, buffaloes, sheep, and goats account for about 95% of the total methane emitted by animals. Non-ruminants and wild ruminants comprise the other 5% (Crutzen *et al.*, 1986). In general, ruminants from developed countries tend to have higher methane emissions per head than those from developing countries due to differences in feeding practices. Global estimates for methane due to enteric fermentation have been in the range of 80 Tg per year: 86 Tg (Seiler, 1984), 78 Tg (Crutzen *et al.*, 1986), 76 Tg (Lerner *et al.*, 1988), and 78 Tg (Fung *et al.*, 1991). Cicerone and Oremland (1988) give a range of 65-100 Tg from animals. The methane yields in Crutzen *et al.* have an uncertainty of 15% and global population estimates from have a 3% uncertainty.

Table 3: Emission coefficients for cattle, buffalo, sheep, and goats. From Crutzen *et al.* (1986).

Animal type		*CH_4 per head (kg/year)*
Cattle:	Developed countries, Brazil, Argentina	55
	Developing countries	35
Buffalos		50
Sheep:	Developed countries	8
	Developing countries, Australia	5
Goats		5

Using emission coefficients from Crutzen *et al.* (1986) (see Table 3) and data from FAO (FAO, 1993) on animal populations, I calculated the methane emissions from cattle, buffaloes, sheep, and goats for each GREEN region. The emissions estimates were increased by 5% to account for remaining emissions from non-ruminants and wild animals (see Table A.3). The total was 75 Tg for 1985 which falls in the range of previous estimates.

The population of cattle has increased by 2% per year since 1940 (Seiler, 1984) and is mainly driven by the demand for meat and dairy products. The same type of reasoning used in determining future emissions due to rice production can be applied to emissions from enteric fermentation. As agricultural output grows, methane emissions from enteric fermentation can be expected to grow as well. Without additional data and disaggregation of GREEN's agricultural sector, we cannot know for certain the exact value of the elasticity. Here, future emissions are tied to the agricultural sector output from GREEN but grow at only 60% of the agricultural growth rate. Emissions in the reference case increased to 240 Tg in 2050 (see Table A.4).

3.3. Animal Wastes

Under anaerobic conditions, methanogens decompose undigested organic material in livestock manure to produce methane. The composition of the waste, which depends on the animal's diet, is a factor in determining the amount of methane produced. In addition, the waste management system and climate conditions also affect the production of methane. Factors such as contact with oxygen, moisture, pH, temperature, and availability of nutrients all play a role in determining the amount of methane emissions (Safley *et al.*, 1992).

Safley *et al.* (1992) collected information on waste characteristics and rates of production, waste management systems, and animal diets for countries around the world to arrive at a world emission of 28 Tg. Given uncertainty in data on waste systems in certain parts of the world and amount of methane produced by waste systems, they were unable to provide a confidence interval but gave low and high estimates of 21 and 36 Tg, respectively.

Since Safley *et al.* listed emissions by country, I aggregated their figures into the GREEN regions to determine the distribution for 1985. The forecast of these emissions followed the forecast of emissions from enteric fermentation. Emissions from animal wastes grow from 28 Tg in 1985 to 79 Tg in 2050 (see Table A.5).

3.4. Landfills

Methane is also produced in landfills by methanogens decomposing organic waste under anaerobic conditions. Factors that affect the amount of methane produced include waste composition, moisture content, pH, available nutrients, landfill temperature, and waste management practices such as landfill type, density and particle size of the refuse (OECD, 1991).

The generation of municipal solid waste has increased rapidly in industrialized nations in the past, 5% annually in the 1960's and 2% annually in the 1970's (Council on Environmental Quality, 1982). However, waste dumping rates in the industrialized world are stagnating while dumping rates are increasing in developing world due to population growth and increasing urbanization. The projection for developing countries is a doubling of waste generation by the year 2000 (Kresse and Ringeltaube, 1982). Currently the per capita waste generation rate is much lower in developing nations than in industrialized nations, although the waste from developing nations tends to have a higher organic content (Sheppard *et al.*, 1982).

Landfill gas recovery can be an important factor in reducing the amount of methane emitted. Currently there are 242 sites in 20 nations where landfill gas is captured (Richards, 1990). The maximum recovery is about 40% of the gas if the landfill is equipped with gas recovery wells; however, if the gas is flared, only 20% can be recovered.

Bingemer and Crutzen (1987) estimate a global emission of 30-70 Tg methane from landfills, and Orlich (1990) estimate 31.5 Tg. Sheppard *et al.* (1982) give a rough figure of 50 Tg. In estimating methane emissions from landfills, Bingemer and Crutzen calculate the methane released as a product of total waste generated, percentage landfilled, degradable organic carbon content, amount recovered, and several conversion factors. To simplify the calculation, they assume that the methane release is instantaneous, taking place within the same year that the dumping occurs. In reality, food and garden wastes may take 1-5 years to decompose, paper 5-20 years, and wood 20-100 years, although faster rates have been reported (Bingemer and Crutzen, 1987). In developing countries where data is generally lacking, only urban populations are considered, since rural areas reuse organic wastes or practice open dumping which produces very little methane. Orlich's approach is very similar to Bingemer and Crutzen's.

Richards (1990) uses an entirely different approach, using GDP as a basis for methane emissions, assuming that economic prosperity is linked to waste generation. Richards estimates an annual emission of 39-73 Tg but then introduces a time lag by assuming only 25% of the methane is emitted in a given year, thus giving an estimate of 9.8–18.3 Tg for the first year of dumping. This figure is quite low since the 75% of emission from previous years is not added.

Bingemer and Crutzen give an uncertainty of ±30%. In addition to uncertainty of methane emission factors as a function of waste management practices, no data is available for the former Soviet Union, Eastern Europe and some developing countries. OECD (1991) demonstrates how a calculation can be extremely sensitive to whether country-specific or regional data is used by showing that emissions estimates for India increase by a factor of 2.5 when using country-specific data rather than regional data.

Recently Whalen *et al.* (1990) observed high CH_4 oxidation rates in landfill cover soils. This finding led the IPCC to adopt a lower estimate of 30 Tg per year (IPCC, 1992). Thus, assuming a global budget of 30 Tg, I distributed it among regions by GDP share. As GDP per capital grows, waste per capita can be expected to grow as well. However, due to land constraints in OECD countries, landfill growth rates are stagnating and not expected to grow much in the future. In order to keep methane emissions from landfills in OECD countries close to a constant level, the elasticity was set at 5% of the growth rate of GDP per capita. The elasticity for non-OECD countries was set at 50% of the growth rate. Emissions more than double from 30 Tg in 1985 to 64 Tg in 2050 (see Table A.6 and Table A.7).

3.5. Domestic Sewage Treatment

Domestic sewage treatment is a recently discovered source of methane emissions, and the annual emission is estimated at 25 Tg (IPCC, 1992). One would expect domestic sewage to be concentrated in areas of higher population, so I distributed the emissions among the GREEN regions according to population. The forecast of emissions from domestic sewage follows the forecast of population and grows to 52 Tg in 2050 (see Table A.8 and Table A.9).

3.6. Coal Mining

Methane is formed during coal formation process, known as "coalification," and it is stored in the coal seams and surrounding rock strata. The degree of coalification determines the rank of the coal bed. Higher rank coals, such as anthracite, contain more methane than lower rank coals such as lignite. In addition, given the same rank coal, the storage capacity for methane increases almost linearly with increasing pressure or depth. Thus, most methane emissions are generated by underground mines rather than surface mines. Since methane is explosive at low concentrations, it is hazardous in underground mines and is vented to the atmosphere via mine degasification systems.

As pressure within a coal bed is reduced through mining or natural erosion, the gas escapes from the coal and surrounding strata through fractures and other pathways. The type and rate of mining determines how much methane is released during the mining process. Long-wall mines which are bigger and deeper than room-and-pillar mines tend to have greater emissions (EPA, 1993a). Additional methane may also be released during post-mining activities such as processing, transportation and storage.

There is significant uncertainty in emission factors for coal mining. Barns and Edmonds (1990) calculated average emission factors for methane released per short ton of coal mined in the US. They found 779 ft^3/st (24 m^3/mt) for anthracite, 252 ft^3/st (7.8 m^3/mt) for bituminous, and 10 ft^3/st (0.3 m^3/mt) for lignite. The weighted average for all coal types was 233 ft^3/ton (7.3 m^3/mt). Extrapolating to the entire world, Barns and Edmonds estimated a global average emission factor of 269 ft^3/st (8.4 m^3/mt) in 1986. For future calculations, they suggest using 250 ft^3/st (7.8 m^3/mt) as a global emission factor from a range of 200 ft^3/st (6.2 m^3/mt) to 400 ft^3/st (12.5 m^3/mt).

These emission factors appear to be much lower than the ones listed in OECD (1991) although the reason for the differences is not clear. The list in OECD (1991) shows that Selzer (1990) gives a high of 24 m^3/mt for deep mines and ICF Resources (1990) gives 27.1 m^3/mt for underground mines which is comparable to Barns and Edmonds' estimate for anthracite coal. However, Selzer (1990) gives an average of 14 m^3/mt, and Seeliger and Zimmermeyer (1989) give a range of 14-24 m^3/mt, both of which are much higher than Barns and Edmonds' global average of 8.4 m^3/mt. Fung's estimate (Fung *et al.*, 1991) of 15 m^3/mt is also higher than Barns and Edmonds'.

Thus, it is not surprising that Barns and Edmonds' calculation of 25 Tg CH_4 emitted globally from coal mining is low compared to other estimates. Other global estimates show emissions of 30 Tg (Fung *et al.*, 1991), 30 Tg (Seiler, 1984), 34 Tg (Crutzen, 1987), 25-45 Tg (Cicerone and Oremland, 1988), 29 Tg (Selzer, 1990), and 33-64 Tg (ICF Resources, 1990).

For comparison, I took 1985 data for global coal production from the Energy Information Administration (EIA, 1988) and calculated emissions using coefficients of 7.8 m^3/mt (Barns and Edmonds, 1990) and 15 m^3/mt (Selzer, 1990; Fung *et al.*, 1991).

4,396 million metric tons of coal produced in 1985 (EIA, 1988) is equivalent to 25 Tg and 50 Tg.[8] These emissions factors give a range which is comparable to Cicerone and Oremland's.

The EIA data of 4,396 million metric tons is equivalent to 110 EJ[9]. GREEN's global coal output is 140 EJ which is higher than the 110 EJ calculated from EIA data.[10] I used Barns and Edmonds' coefficient of 7.8 m³/mt with the GREEN output to arrive at 31 Tg CH_4 emissions.[11] Future emissions follow the path of coal production from GREEN, so global emissions almost double to 57 Tg in 2050 (see Table A.10 and Table A.11).

3.7. Natural Gas Production

3.7.1. *Venting and Flaring*

Natural gas is released into the atmosphere by flaring and venting operations at crude oil and natural gas production wells. Gas is flared at oil wells when there are no markets to sell the gas or the market value is too low to warrant development and transport of the gas. Venting of natural gas occurs during natural gas well drilling and well maintenance.

The percentage of natural gas production that is vented or flared has fluctuated in the past. The global percentage has varied from 12% in the early 1970's to 5% in the 1980's (Barns and Edmonds, 1990). In 1984 the percentage was as low as 1% for North America and as high as 61% for the Middle East (Fung *et al.*, 1991). Currently the world average is approximately 5-6%.

Estimates of global methane emissions from venting and flaring operations during the 1980's have been within the range of 15 Tg: 13-16 Tg (Barns and Edmonds, 1990),

---

[8] A mass density for methane of 1400 m³/mt was used.

[9] 1 exajoule = 10^{18} joules. An average heating value of 10,800 Btu/lb was used.

[10] GREEN's coal output is calculated by taking coal output in millions of dollars and dividing by price per terajoule. It is not clear why GREEN has been calibrated to be much higher than the figure from EIA.

[11] The actual coefficient used was 0.222 Tg/EJ which incorporates the 7.8 m³/mt CH_4 released during coal mining, heating value 10,800 Btu/lb, and mass density 1400 m³/mt.

14 Tg (Cicerone and Oremland, 1988), 15 Tg (Darmstadter *et al.*, 1987). The close range of these estimates may be misleading, since knowledge of venting and flaring losses for developing and undeveloped countries is incomplete or unavailable (Simpson and Anastasi, 1993).

To calculate emissions from venting and flaring, 20% is assumed as the fraction of uncombusted vented and flared gas which escapes to the atmosphere as methane (Barns and Edmonds, 1990; Darmstadter *et al.*, 1987) which is slightly lower than the 25% given by Sheppard *et al.* (1990). Natural gas can be from 90-98% methane (Barns and Edmonds, 1990), although Cicerone and Oremland (1988) give a range of 89-93%. The use of this percentage varies from source to source, however, as some include it in their calculations and others do not.

As with the coal production data, the natural gas production data from GREEN seems to be high for 1985. GREEN gives world output of 130 EJ in 1985, compared to 82 EJ from EIA data (EIA, 1988).[12] I used Barns and Edmonds' emission coefficient of 0.172 Tg CH_4 per EJ of gross production with the GREEN data.[13] Assuming a 90% methane content, the global estimate of methane emissions from venting and flaring is 20 Tg. Future emissions decrease to 17 Tg in 2050 (see Table A.12 and Table A.13).

Historically, the percentage of natural gas vented or flared decreases as markets and distribution networks develop. Thus, future emissions are expected to increase more slowly than the gas consumption rate (EPA, 1993a). However, given the relatively small contribution of venting and flaring to the overall methane budget, especially in 2050, we do not consider this second-order effect.

3.7.2. Transmission and Distribution

Natural gas can also escape during the transmission and distribution of gas along pipelines. Estimates of these losses are made by computing "unaccounted for" gas, *i.e.* the difference between supply and delivery. The majority of the losses are due to leaks in

---

[12] The EIA figure was calculated by multiplying global gross production of 76×10^{12} ft^3 by a heating value of 1.08 GJ per 1,000 ft^3 natural gas.

[13] This coefficient assumes 5% of production is vented and flared, 20% of vented and flared gas escapes to the atmosphere, 39,021 kJ/m^3 heating value, and 1485 m^3/mt mass density.

pipework, equipment exhausts, routine maintenance, and system upsets, although the unaccounted for gas could also be due to inaccuracies of measurement, differences in accounting and billing practices and cycles, flow volume correction calculations, and non-efficient end applications (Barns and Edmonds, 1990).

In the Western world, loss rates generally vary from 1-3% of natural gas production (Simpson and Anastasi, 1993). Estimates of global methane emissions from transmission and distribution of natural gas vary from 10-35 Tg. Fung *et al.* (1991) extrapolated a 1% loss rate for Canada and 2.5% for the US to the whole world to obtain a value of 10-36 Tg. Sheppard *et al.* (1982) applied a 2% loss rate to get 20 Tg (1976 data). Seiler (1984) obtained an estimate of 19-29 Tg using a 2-3% loss rate. Barns and Edmonds (1990) applied a 1.5% rate to dry production only (net production after reinjection into reservoirs, venting and flaring and LNG extraction) to obtain 16 Tg. Cicerone and Oremland (1988) estimated 31 Tg using a 2.5% loss rate.

I applied coefficients of 1.5% loss rate and 90% methane content to the natural gas production data from GREEN to obtain 30 Tg CH_4 emitted from transmission and distribution of natural gas. As expected, this estimate is higher than the Barns and Edmonds' estimate which used the same loss rate, since I used gross production rather than net production. In addition, the GREEN data for 1985 is on the high side. Future emissions are tied to natural gas output, so the global emission decreases to 25 Tg CH_4 in 2050 (see Table A.14).

3.8. Biomass Burning

Biomass burning includes the burning of the world's forests for land clearing and agricultural use, the annual burning of savannas to control pests and weeds and prevent brush and litter accumulation, the annual burning of agricultural stubble and waste after harvest, and the burning of wood for energy production. With the exception of prescribed fires in temperate forests, biomass burning takes place almost exclusively in the tropical and subtropical regions of the world. In the developing world, burning is concentrated to limited regions such as the African savannas and the Amazon rainforest and occurs mostly during the dry season. During these times, biomass burning results in levels of pollution comparable to the industrial areas of developed nations (Crutzen and Andreae, 1990; Andreae, 1991).

The burning of organic material produces water vapor and CO_2, since dry biomass is approximately 45% carbon by weight. Other gases and particles are emitted during incomplete combustion of carbon compounds. Biomass burning is a significant source of greenhouse gases including CO_2, CH_4, N_2O, NO_X, SO_X, and CO as well other chemically active gases and aerosol particles. Emissions resulting from biomass burning are to be distinguished from emissions due to soil disturbance as a result of deforestation. In particular, emissions of N_2O from cleared soils are enhanced when forests are disturbed through deforestation or logging. This source of emissions is discussed in the following chapter on N_2O.

In the case of CO_2, annual burning of savannas, brushland, and agricultural wastes do not contribute a net emissions into the atmosphere, since the CO_2 released is re-absorbed by regrowth the following year. For CO_2, only deforestation represents a significant net emissions into the atmosphere, as long-term stores of carbon are released with no possibility for re-absorption in the short term. However, for all other greenhouse-relevant gases, all types of biomass burning represent net releases of these gases into the atmosphere since they are not re-absorbed by plant growth. Any activity which includes burning, whether deforestation or incineration of agricultural wastes should be included in the emission budgets of CH_4, N_2O, NO_X, SO_X, and CO.

Emissions from biomass burning are calculated by multiplying the area cleared and burned by the organic matter per area, the percentage of biomass above ground and the burning efficiency (percentage of dry matter combusted). About 90% of the carbon emitted during burning is in the form of CO_2. Emissions of other gases are calculated by taking a constant molar ratio to CO_2. The uncertainty in the emissions factors of these other gases is about a factor of two. In addition, data on deforestation rates and fuel wood use are unclear or incomplete and have tended to be underestimated in the past (Crutzen and Andreae, 1990; Andreae, 1991).

In the following sections I discuss estimates of the amount of carbon released due to clearing of forests, savanna burning, prescribed fires, fuel wood burning, and burning of agricultural wastes. Then I present emission coefficients from the literature and estimates of methane emissions from biomass burning.

3.8.1. Clearing of forests and brush land for agricultural use

In developing countries forests and brush land are cleared for agricultural or pastoral use. Two types of clearing are practiced: shifting agriculture, also known as slash-and-burn agriculture, and permanent conversion of forests to grazing or crop lands (permanent agriculture). These practices are concentrated mainly in the tropical and subtropical regions of the world.

In shifting agriculture, the undergrowth and trees are cut, left to dry and then burned. After a few years of planting, the land is left fallow and allowed to return to forest vegetation in order to increase soil fertility. The cycle of cutting, planting and regrowth continues until the land is converted to permanent agriculture or is no longer fit for agricultural use. Shifting agriculture is practiced by 20% of the rural population in Latin America and by 30% in Africa (Seiler and Crutzen, 1980). These percentages are not expected to grow much since virgin forest lands which could be converted to this type of cultivation are growing scarce (Andreae, 1991). Seiler and Crutzen (1980) estimate that 400-1125 Tg C is released annually from shifting agriculture. Crutzen and Andreae (1990) estimate 500-1000 Tg C per year.

In contrast, the permanent removal of rainforests is increasing due to population pressures and additional demand for food. Cultivation area is being extended for agriculture as well as cattle grazing. In the Amazon, virgin forests are cleared for colonization purposes as migration programs are moving people from more densely populated areas (Seiler and Crutzen, 1980). A portion of the cleared biomass is marketed as firewood, and the rest is burned and left to decay on the ground. Seiler and Crutzen estimate a release of 250-400 Tg C from burning due to permanent deforestation and Crutzen and Andreae estimate a release of 200-700 Tg. Hao *et al.* (1990) gives a combined estimate of 570 Tg from shifting and permanent agriculture.

3.8.2. Burning in bushlands and savannas

Large parts of dry savannas are burned annually by fires, with 65% of the burning occurring in Africa (Andreae, 1991). Although some of the fires are started by lightning, most are started by humans. Savanna burning is practiced to control weeds, shrubs and litter accumulation, control pests, and drive out game for hunting. Seiler and Crutzen estimate emissions of 200-850 Tg C and Crutzen and Andreae give an estimate of 300-1600 Tg. Hao estimates 1660 Tg C.

3.8.3. Prescribed burning and forest wildfires

Prescribed burning is practiced in the temperate and boreal forests of the North American and Asian continent. It is used for forest management in order to remove forest debris and dry vegetation which could cause destructive wildfires. It also eliminates shrubby vegetation which competes with tree crops for nutrients. Wildfires are also common in these forests and are usually the result of human activities rather than lightning (Andreae, 1991). The area subject to wildfires and prescribed fires is rather small compared to the are of tropical forests and savannas burned. Seiler and Crutzen estimate emissions of 90-150 Tg C, and Crutzen and Andreae estimate 150-300 Tg.

3.8.4. Burning of fuel wood and charcoal production

In developing countries biomass is the dominant energy source for cooking, heating, and some industrial activities. Fuel wood represents 2/3 of all consumed energy in Africa, 1/3 in Latin America and 1/5 in Asia (Seiler and Crutzen, 1980). About 50% of fuel wood is used for cooking, 30% for domestic heating, and 20% for other purposes (Seiler and Crutzen, 1980; Andreae, 1991). Wood is also used in charcoal production, as charcoal has a higher energy density and is easier to transport. In recent years, large charcoal production plants have been established to supply charcoal for industrial uses such as pig-iron smelting (Andreae, 1991).

In the developed nations, 60% of industrial wood goes into construction, 30% into paper and paperboard, and 10% is used for other purposes. The biomass used to produce paper is generally burned within a short time after production whereas the wood used in construction usually goes into long-term storage. Seiler and Crutzen estimate a total release of 450-500 Tg C, Crutzen and Andreae estimate 300-600 Tg, Andreae (1991) estimates 650 Tg, and Hao *et al.* (1990) estimates 280 Tg.

3.8.5. Burning of agricultural wastes

This category includes the burning of agricultural wastes in fields, *e.g.* sugar cane, rice straw, and stalks from grain crops. Two-thirds of rural energy use in China comes from agricultural wastes and altogether, biomass fuels (including fuel wood and charcoal) constitute 35% of the consumed energy in developing countries (Crutzen and Andreae, 1990). In developing countries, about 80% of agricultural waste is burned, and in the U.S., 50% is burned (Seiler and Crutzen, 1980). Seiler and Crutzen estimate 770-950 Tg from the burning of agricultural wastes, Crutzen and Andreae estimate 500-800 Tg, Andreae estimates 910 Tg, and Hao estimates 300 Tg.

3.8.6. Estimates of Emissions

Estimates from the literature of the total amount of carbon released from biomass burning are summarized in Table 4. Emissions are usually reported in terms of total carbon released which may take the form of CO_2, CO, or CH_4. To calculate the emission of CO_2, an emission ratio of 88% is used.

The four sources listed give fairly similar estimates for total carbon emissions, with Crutzen and Andreae's estimate falling near the middle of the estimates. The distribution of emissions, however, is quite different, as Hao *et al.* show a large increase in emissions from savanna burning and decrease from land clearing compared to Seiler and Crutzen's 1980 estimates. Additional estimates without breakdowns include 2730 Tg C (Dignon and Penner, 1991), 2000 Tg CO_2-C (Crutzen *et al.*, 1989), and 3140 Tg CO_2-C (Mueller, 1992).

Emissions for CH_4, N_2O, NO_x, SO_x, and CO are calculated by using a molar ratio to carbon dioxide released during burning. The emission factors and emission estimates for CH_4 found in the literature are listed in Table 5. The uncertainty in the emission ratios are about a factor of two (Andreae, 1991), although it is clear from examining the coefficients that the uncertainty may be even larger. For the model I used a global estimate of 48 Tg CH_4.

Table 4: Estimates of global carbon released annually from biomass burning (Tg C)

Source of burning	*Seiler & Crutzen (1980)*	*Crutzen & Andreae (1990)*	*Hao et al. (1990)*	*Andreae (1991)*[a]
Shifting agriculture	400-1125	500-1000		
Permanent deforestation	250-400	200-700	570	570
Savannas	200-850	300-1600	1660	1660
Prescribed burning, wildfires	90-150	150-300	—	130
Fuelwood, charcoal	450-500	300-600	280	670
Agricultural waste	770-950	500-800	300	910
Total	2160-3960 (3060)	1950-5000 (3475)	2810	3940

Note: totals may not be the sum of individual items due to rounding. Average value given in parentheses.

a. Number for permanent deforestation taken from Hao et al. (1990), number for prescribed burning and wildfires taken from Seiler and Crutzen (1980).

Table 5: Estimates of global CH_4 emissions from biomass burning.

Source	*Estimate (Tg CH_4)*	*Emission Coefficient*[a]
Crutzen *et al.*, 1979	25-110	1.0-2.2 (1.6)
Khalil and Rasmussen, 1983a	25	N/A
Seiler, 1984	53-97	1.9
Crutzen *et al.*, 1985	20-70	1.6
Bolle *et al.*, 1986	55-100	N/A
Craig *et al.*, 1988	52	based on $^{13}C/^{12}C$ ratio
Cicerone and Oremland, 1988	50-100 (55)	N/A
Crutzen and Andreae, 1990	16-79 (51)[b]	0.4-1.6 (1.0)
Andreae, 1991	48	0.6-1.6 (1.1)

a. Units are moles CH_4-C per 100 moles CO_2-C released by biomass burning.

b. Crutzen and Andreae did not include emissions from prescribed burning and wildfires in their calculations because they were calculating carbon released from burning in the tropics. The emissions estimates listed in their paper were increased to account for the additional emissions from prescribed burning and wildfires

Future estimates of emissions are obtained in the following way. Emissions from clearing due to shifting agriculture and permanent deforestation, savanna burning, and prescribed and wild fires are assumed to remain constant. Data on the rate of permanent deforestation is unclear (Andreae, 1991; IPCC, 1992). There was some indication that the deforestation rate in 1990 was 50% higher than the rate in 1980, but it may have been due to underestimates of 1980 data (IPCC, 1922). For the purpose of this analysis, I chose a growth rate which could be varied to conduct sensitivity tests. Initially this rate is set at 0.3% annually (Bolle *et al.*, 1986). Since fuel wood harvesting is related to deforestation, it grows at the same rate. Emissions from burning of agricultural waste follow the growth of agricultural output with a 0.75 elasticity (see Table A.15).

Although a better approximation of future deforestation might be a logistic curve which flattens out rather than a constant growth rate, at this time the constant growth rate is used because the deforestation rate does not turn out to be the dominating factor in determining emissions from biomass burning. Instead, the growth of the agricultural sector is more important for determining future emissions.

3.9. Global Methane Emissions

The total amount of methane emitted from all sources used in this analysis is listed in Table 6. A source strength of 155 Tg per year (IPCC, 1992) is used for natural sources of methane emission for a total of 543 Tg CH_4. This estimate is consistent with estimates in the literature of 400-640 Tg (Cicerone and Oremland, 1988), 300-560 Tg (Seiler and Conrad, 1987; Bolle *et al.*, 1986), and 320-670 (Schutz *et al.*, 1989). The growth of methane emissions as predicted by GEMS is shown in Table 7.

Table 6: Estimate of global methane emissions from all sources

Source	*Tg CH_4*	*Anthropogenic share*
Paddy rice	100	26%
Enteric fermentation	75	19%
Animal wastes	28	7%
Landfills	30	8%
Domestic sewage treatment	25	6%
Coal mining	31	8%
Natural gas	51	13%
Biomass burning	48	12%
Anthropogenic subtotal	388	100%
Natural sources	155	
Total	543	

Table 7: Forecast of methane emissions from GEMS (Tg)

Source	1985	1990	1995	2000	2005	2010	2030	2050
Rice	100	105	115	125	135	145	205	272
Ruminants	75	80	89	99	109	120	177	240
Animal wastes	28	30	33	37	40	43	60	79
Landfills	30	32	34	37	39	41	53	64
Domestic sewage	25	27	30	32	34	37	45	52
Coal mining	31	35	32	30	29	29	41	57
Natural gas	51	53	34	30	28	27	30	42
Biomass burning	48	49	51	52	54	56	66	79
Anthrop. total	388	412	418	443	468	499	676	885
Natural	155	155	155	155	155	155	155	155
Total	543	567	573	598	623	654	831	1040

4. Nitrous Oxide

The current atmospheric concentration of nitrous oxide is 310 ppb, about 8% greater than the pre-industrial level. It has been increasing at about a rate of .2 to .3% per year which represents an annual accumulation of 3 to 4.5 Tg (IPCC, 1992). Nitrous oxide has a long atmospheric lifetime, between 100 to 200 years.

The total annual emission for N_2O has been estimated to be from 7-21 Tg N (Seiler and Conrad, 1987), 12-15 Tg (Bolle *et al.*, 1986) and 20 Tg (Prinn *et al.*, 1990), with 60-80% of the emissions coming from biogenic sources. The largest natural source of N_2O is emission from natural, undisturbed soils. N_2O is produced by microbial processes in soils during denitrification (reduction of NO_3^- to N_2) and nitrification (oxidation of NH_4^+ to NO_3^-). This source strength has been estimated to range from 2.75-7.7 Tg (IPCC, 1992), 3-9 Tg (Bolle *et al.*, 1986). Oceans contribute about 1-3 Tg (Bouwman, 1990) with anthropogenic sources making up the remainder 4 Tg.

This chapter presents the estimates of emissions from anthropogenic sources of N_2O and how these sources are modeled in GEMS.

4.1. Fertilizer Use and Nutrient Runoff

Commercial nitrogen fertilizers enhance the emissions of N_2O from soils by providing an additional source of nitrogen. Numerous factors affect the amount of N_2O

emitted from fertilized soils including temperature, precipitation, soil moisture, pH, fertilizer type, crop type, application rate and timing, irrigation (Eichner, 1990).

Additional N_2O may be emitted when mineral fertilizers run off into groundwater or surface freshwater ecosystems (Conrad *et al.*, 1983). Approximately 5-30% of applied fertilizer nitrogen leaches or runs off (Breitenbeck, 1988). Ronen *et al.* (1988) reports an emission of 0.8-1.7 Tg N per year from fertilizer leaching and Conrad *et al.* (1983) estimates the amount emitted from leaching to be the same as the amount from fertilized soils.

Application of organic fertilizers and cultivation of leguminous, nitrogen-fixing crops may also enhance levels of N_2O (OECD, 1991). Due to magnitude of the uncertainties and the small amount estimated from this source (Eichner, 1990), emissions from leguminous crops are not included in this analysis.

Data on the percentage of applied fertilizer released as N_2O vary considerably due to differences in physical conditions and fertilizer management. A sample of the data is given in Table 8.

Table 8: Emission coefficients from fertilizer use (does not include nutrient run-off).

	Percentages of applied fertilizer released as N_2O			
Type of fertilizer	*Galbally, 1985*	*Bolle et al., 1986*	*OECD, 1991 (mostly from Eichner, 1990)*	*Range (OECD, 1991)*
Ammonium and urea		0.15-0.19		
Ammonium type			0.12	0.02-1.5
Urea	0.5		0.11	0.07-1.5
Anhydrous ammonia	0.5	5	1.63	0.86-6.84
Ammonium nitrate	0.1		0.26	0.04-1.71
Nitrate	0.05	0.04	0.03	0.001-0.5
Other nitrogenous fertilizers	1.0		0.11	0.001-6.84
Other complex fertilizers	1.5		0.11	0.001-6.84

Emissions from fertilizer use are calculated by applying the emissions coefficients for each type of mineral fertilizer to the amount of fertilizer consumed. Global estimates of emissions from fertilizer use and nutrient runoff show a wide range of uncertainty, not surprising given the uncertainty in emission coefficients (Table 9).

Table 9: Estimates of global annual N_2O emissions from fertilizer use.

Source	*Tg N*
Crutzen, 1983	<3
Conrad *et al.*, 1983	0.005-2.2
McElroy and Woofsy, 1985	0.2-0.6
Bolle *et al.*, 1986	0.6-2.3
Seiler and Conrad, 1987	0.5-2.0
Bouwman, 1990	1.5-3.0
EPA, 1990	0.2-2.4
Eichner, 1990	0.2-2.1

Bolle *et al.* and Conrad *et al.* used fertilizer consumption data for (55-60 Tg N of fertilizer) whereas Eichner used consumption data for 1984 (70.5 Tg N fertilizer). Bouwman included background emissions from cultivated soils but did not include emissions from leaching. Most of the above sources assumed a doubling of the emission factors due to leaching into ground and surface water with the exception of EPA (1990) which assumed a 2.0% emission rate across the board.

Conrad *et al.* (1983) notes that the estimates are based on data from experiments which were limited to developed and industrialized countries in higher latitudes. Indeed, a scan of the regions listed in Eichner (1990) reveals that all the experiments were performed in the United States and Western Europe. In the future the share of fertilizer use in developing countries is expected to grow, and these countries tend to be located in warmer climates which might affect the emission rates of nitrous oxide.

To calculate global N_2O emissions, I used FAO data on nitrogenous fertilizer consumption for the year 1985-86 (FAO, 1990). One problem arising from the use of the FAO data was that the breakdown did not correspond to the data on emission factors.[14] Most notably anhydrous ammonium, which has the largest emission rate, was missing from

---

[14] The FAO data was subdivided into the following fertilizer types: ammonium sulfate, ammonium phosphate, ammonium nitrate, ammonium sulfate nitrate, calcium nitrate, sodium nitrate, calcium cyanamide, urea, other nitrogen fertilizers and other complex fertilizers. Ammonium sulfate and ammonium phosphate were categorized as "ammonium type," ammonium sulfate nitrate was categorized with "ammonium nitrate," calcium nitrate and sodium nitrate were included under "nitrates" and calcium cyanamide was included in "other complex fertilizers."

the FAO categories. With a global fertilizer consumption of 69.9 Tg N in 1985, emission factors from OECD (1991) resulted in N_2O emissions of 0.2 Tg N whereas emission factors from Galbally (1985) gave 1.2 Tg N. These calculations do not include additional emissions from fertilizer leaching. In order to simplify the calculation and account for leaching, I used an emission factor of 2.5% for all fertilizer types. This method resulted in a global emissions estimate of 1.75 Tg N for 1985.

In the future this source of N_2O emission may become more important relative to other anthropogenic sources, since the World Bank estimates that nitrogen fertilizer use is increasing at a rate of 1.3 % in industrial countries and 4.1% in developing countries. (World Bank, 1988). According to World Bank estimates, fertilizer use will grow 34% from 70 Tg in 1985 to 93.5 Tg in 1996 (see reference in Eichner, 1990). This growth rate corresponds to 100 Tg fertilizer in the year 2000 or 2.5 Tg N emissions in 2000, or a growth rate for fertilizer use at 80% the agricultural output growth rate. Emissions in 2050 increase to 7.5 Tg N (see Table A.16).

4.2. Nitric Acid Production

The production of nitric acid, occurring during fertilizer production, was found to be an additional source of N_2O emissions (IPCC, 1992). The global emissions are estimated to be between 0.1 and 0.3 Tg N. Using an average value of 0.2 Tg, I distributed emissions from nitric acid production by share of fertilizer production among the GREEN regions. Future emissions from nitric acid production grow at the same rate as emissions from fertilizer use in the previous section resulting in a global estimate of 0.9 Tg in 2050.

4.3. Gain of Cultivated Land

Soil disturbance which takes place during forest clearing and clearcutting is believed to stimulate the loss of soil nitrogen, although the amount lost as N_2O is uncertain (OECD, 1991). An experiment in Brazil found that N_2O emissions for a newly clearcut forest were three times greater than adjacent undisturbed forest soils (Keller *et al.*, 1986). Conversion of tropical forests to pastureland has also been found to enhance the emissions of N_2O relative to uncut forests (Luizão *et al.*, 1989). The most recent estimate of N_2O released from the increase in cultivated land area is 0.2-0.6 Tg N (Bolle *et al.*, 1986). Earlier estimates include 6.6 Tg N (Khalil and Rasmussen, 1983b) and 1-3 Tg N (Crutzen, 1983). For this analysis, I used Bolle's estimate of 0.4 Tg N. Future emissions follow the rate of deforestation and increase to 0.5 Tg N (see Table A.15).

4.4. Biomass Burning

Estimates of global emissions of N_2O from biomass burning as discussed in the previous chapter include the following: 0.1-0.4 Tg N (Crutzen and Andreae, 1990), 0.16-0.50 Tg (Lobert *et al.*, 1990), and 0.81 Tg (Andreae, 1991). The emission ratios used by these studies fall in the range of 0.01% of CO_2. Newer data from Cofer *et al.* (1991) shows a higher emission ratio of 0.02%. Using this coefficient with estimates of carbon released from biomass burning (Table 4) gives 0.6 Tg N released in 1985. Future emissions of N_2O evolve according to the method discussed in the previous chapter (see Table A.15).

4.5. Adipic Acid Production

The production of adipic acid in the manufacture of nylon was a previously unknown source of nitrous oxide emission. Thiemens and Trogler (1991) estimate a yearly emission of 1.5×10^{10} moles of N_2O as a by-product of adipic acid production. 1.5×10^{10} moles of N_2O corresponds to 3.0×10^{10} moles of N, or 0.4 Tg N. Regions producing adipic acid include the OECD, China, the former Soviet Union, and Eastern Europe (Thiemens and Trogler, 1991), so emissions were distributed among those regions. Future emissions of N_2O from nylon production follow the growth of industrial output and increase to 0.8 Tg N in 2050 (see Table A.17 and Table A.18).

4.6. Fossil Fuel Burning

Fossil fuel combustion was once thought to be an important source of N_2O until it was discovered that N_2O was being artificially produced in sampling flasks used to collect the gas (Muzio and Kramlich, 1988). Annual emissions from stationary combustion sources are estimated to be very low (IPCC, 1992), so they were not included in this analysis. Emissions due to mobile sources are estimated to vary from 0.2-0.6 Tg N, and a global strength of 0.4 Tg N was used in the model. Future emissions grow with the transportation sector from GREEN to 2.8 Tg in 2050 (Table A.19 and Table A.20).

4.7. Global Nitrous Oxide Emissions

The estimates of N_2O emissions from all sources used in GEMS are listed below (Table 10). The growth of emissions in the future is shown in Table 11. An average value of 8.3 Tg from biogenic sources was chosen. The largest anthropogenic source is from fertilized soils and this share may be expected to increase in the future. Biomass burning and gain of cultivated land, both of which are linked to deforestation, may also become significant in the future if deforestation rates continue as they have in the past decade. Emissions from fossil fuels are derived mainly from mobile sources, and this source will probably not grow too much in the industrialized countries as exhaust emission controls are becoming more stringent. It is not clear what factors might influence the growth of adipic acid production, so more study is needed in this area.

Table 10: Estimate of global nitrous oxide emissions from all sources

Source	*Tg N*	*Anthropogenic share*
Fertilized soils and nutrient run-off	1.8	47%
Nitric acid production	0.2	5%
Gain of cultivated land	0.4	11%
Biomass burning	0.6	16%
Adipic acid production	0.4	11%
Fossil fuels	0.4	11%
Anthropogenic subtotal	3.8	100%
Natural sources	6-14 (8.3)	
Total	12.1	

Table 11: Forecast of nitrous oxide emissions from GEMS (Tg)

Source	1985	1990	1995	2000	2005	2010	2030	2050
Fertilizer	1.7	1.9	2.2	2.5	2.8	3.1	5.0	7.5
Land clearing	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5
Biomass burning	0.6	0.6	0.6	0.7	0.7	0.7	0.8	1.0
Fossil fuels	0.5	0.6	0.7	0.8	0.9	1.0	1.8	2.8
Nylon production	0.4	0.4	0.5	0.6	0.6	0.7	0.8	1.0
Nitric acid prod	0.2	0.2	0.3	0.3	0.3	0.4	0.6	0.9
Anthrop. total	3.8	4.2	4.7	5.2	5.8	6.3	9.5	13.7
Natural	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Total	12.1	12.5	13.0	13.5	14.1	14.6	17.8	22.0

5. NO_X, CO, SO_X

The anthropogenic sources of emissions of NO_X, CO, and SO_X include fossil fuel combustion, certain industrial processes, and biomass burning. This chapter describes the anthropogenic sources and drivers of emissions of all three gases and how they are modeled in GEMS.

5.1. Nitrogen Oxides

The reactive oxides of nitrogen (NO_X) consist of nitric oxide (NO) and nitrogen dioxide (NO_2). NO_X influences the concentration of tropospheric OH and ozone, and OH serves as the dominant path for removal of CO and CH_4. NO_2 reacts with OH radicals to form nitric acid which is a component of acid precipitation (Logan, 1983). The lifetime of NO_X is approximately one day.

The global budget for NO_X is estimated to be between 25 and 99 Tg N per year (Logan, 1983). Natural sources of NO_X include lightning, soils, oxidation of ammonia and input from the stratosphere. Ammonia is oxidized by OH radicals and transformed through a series of chemical reactions to produce NO and NO_2. NO is formed in the heated air surrounding lightning discharges and is then converted to -NO_2 by reaction with ozone (Logan, 1983). NO_X is also produced in the stratosphere from reaction with free atomic oxygen and is then transported to the troposphere. The total amount from the natural sources is estimated to be between 8 and 40 Tg N per year.

Anthropogenic sources of NO_X include combustion from fossil fuels and biomass burning. Logan (1983) estimates the source strength to be 16-52 Tg N, and the IPCC (1992) estimates 27-37 Tg. The latitudinal distribution of NO_X is important for use in the atmospheric chemistry model which distinguishes between Northern Hemisphere and Southern Hemisphere NO_X emissions. Dignon (1992) found that 95% of NO_X emissions from fossil fuel combustion are emitted in the Northern Hemisphere.

5.1.1. Fossil Fuel and Industrial Sources

NO_X is emitted during fossil fuel combustion from stationary and mobile sources as well as during industrial processes such as petroleum refining, cement manufacture, and nitric acid production. In the U.S., the emissions are almost equally divided between stationary sources and motor vehicles (EPA, 1993b). Estimates of global NO_X emissions include the following: 21 Tg N (Logan, 1983), 22 Tg (Dignon, 1992), 23 Tg (Müller, 1992), and 24 Tg (Hameed and Dignon, 1992). All the estimates are for the year 1980 except for Hameed and Dignon (1992) who calculated emissions for 1986.

Logan (1983) used emission factors derived from the U.S. and West Germany along with coal, natural gas, and oil data to obtain an estimate of 21 Tg N for the year 1980. This figure included emissions from industrial sources which only came out to 1.2 Tg. Müller (1992) used the same emission factors from Logan (1983) and computed 20 Tg N from fossil fuel sources and 2.5 Tg from industrial sources.

Dignon (1992) used a statistical method described in Hameed and Dignon (1988) to compute emissions. They assumed a linear relationship between fuel consumption and emissions. This relation is:

$$y = 0.0059x; \quad y = 0.0095x$$

for OECD countries and non-OECD countries respectively; x is total fuel consumed in million tons of coal equivalent and y is Tg NO_2 emission. When I used fuel consumption data for 1985 (UN, 1989), total NO_X emissions for the world came out to 21.2 Tg N. This relationship is convenient for estimating emissions from countries for which no data is available. However, this method produces regional results which differ quite a bit from existing inventories since it does not account for differences in emission factors across countries.

EPA (1993b) reports an emission for the U.S. of 5.9 Tg N in 1985 from fuel combustion and transportation sources.[15] This figure is higher than the 4.1 Tg calculated using the method from Hameed and Dignon (1988). OECD (1989) reports NO_X emissions for Japan, European Community, and other OECD (as defined in GREEN) in 1985 of 0.4 Tg, 3.4 Tg, and 1.3 Tg respectively, compared to emissions of 0.8 Tg, 2.7 Tg, and 1.0 Tg using Hameed and Dignon's method. I used data from these inventories and for Eastern Europe (WRI, 1993) and calculated emissions for all other countries using Hameed and Dignon's method to obtain a global emission of 24 Tg in 1985.

From the period 1940-1980, NO_X emissions increased with fuel consumption. In the future, however, NO_X emissions in OECD countries should be expected to grow slower than the growth of fuel consumption due to emission controls and regulations. In the U.S., for example, during the period 1985-1990 NO_X emissions increased only 5% from 22.4 million short tons of NO_2 to 23.6 million short tons, and between 1990 and 1992 NO_X emissions actually decreased (EPA, 1993b). In order to make the emissions model consistent with 1985 and 1990 U.S. data, future emissions for the U.S. grow at 30% of the growth rate primary energy consumption, which includes coal, oil, and natural gas consumption. Emissions in the other OECD countries increase slightly faster, at 50% the growth rate of primary energy. For the rest of the world, future emissions increase linearly with primary energy consumption (see Table A.21). Future emissions grow to 58.9 Tg in 2050 (see Table A.22).

By the year 2050 other regions dominate the NO_X emission budget. China is the biggest producer at 10.2 Tg, followed by energy-exporting countries at 9.2 Tg and the former Soviet Union with 8.6 Tg. Together these three regions account for almost 50% of the emissions. By comparison, NO_X emissions from China were only 2.1 Tg and 2.0 Tg from the energy-exporting countries in 1985.

---

[15] The actual figure was 21.5 million short tons of NO_X (NO_2).

5.1.2. Biomass Burning

Estimates of global emissions of NO_X from biomass range from 2.5 Tg to 24 Tg. The large uncertainty in these estimates is due to uncertainty in estimating amount of biomass burned globally as well as differences in methodologies in NO_X emissions. The uncertainty in these estimates is about a factor of 2 or 3 (Andreae, 1991; Crutzen *et al.*, 1989).

Table 12: Estimates of global NO_X emissions from biomass burning.

Source	*Emission (Tg N)*	*Emission Coefficient*	*Normalized Coefficient*[e]
Crutzen and Andreae, 1990	2.5-6.4 (4.6)[a]	12.1% of total N content	0.15%
Crutzen *et al.*, 1989	5.2	0.2% of CO_2-C	0.2%
Müller, 1992	5.5	0.175% of CO_2-C [c]	0.175%
Lobert *et al.*, 1990	2.5-8.7 (5.6)	12.7% of N content	0.18%
Hao *et al.*, 1990	3-9 (6)[b]	N/A	N/A
Andreae, 1991	8.5	2.1 mol N/100 mol CO_2-C	0.25%
Logan, 1983	4-24 (12)	Various	0.44%
Dignon and Penner (1991)	12.5	2.1 g N/kg fuel[d]	0.51%
Hegg *et al.*, 1990	19	N/A	N/A

Notes: Average values or best guesses are given in parentheses.

a. Crutzen and Andreae did not include emissions from prescribed burning and wildfires in their calculations because they were calculating carbon released from burning in the tropics. The emissions estimates listed in their paper were increased to account for the additional emissions from prescribed burning and wildfires

b. This calculation is for the tropics only.

c. Müller uses coefficients of 0.25% and 0.1% for forests and other environments, respectively. The average value is 0.175%.

d. Their paper lists emission coefficients for five different vegetation types. The average coefficient is 2.1.

e. Normalized coefficients were calculated by taking a ratio of NO_X-N to CO_2-C listed in the sources. Lobert *et al.* (1990) used carbon estimates from Crutzen and Andreae (1990). Logan (1983) used carbon estimates from Seiler and Crutzen (1980).

Some sources calculate NO_X emissions by using a constant ratio of NO_X-N released to CO_2 released during burning. However, NO_X emission from biomass burning is directly related to the nitrogen content of the fuel (Clements and MacMahon, 1980). Biomass is 0.3-3.8% nitrogen by weight, depending on the type of fuel (Andreae, 1991). Thus, more accurate estimates can obtained by disaggregating biomass burned, calculating the nitrogen content for each type of fuel, then using an emission ratio for NO_X of total nitrogen content. Estimates and emission coefficients are summarized in Table 12. For comparison, I have calculated a normalized coefficient which is a ratio of NO_X-N to

CO_2-C released during biomass burning. Here we use a global estimate of 12 Tg. Future emissions of NO_X evolve according to the method discussed previously and grow to 19.8 Tg in 2050 (see Table A.15).

5.1.3. Global NO_X emissions

An average value of 24 Tg was used for NO_X emissions from natural sources (Logan, 1983). The growth of NO_X emissions as predicted by GEMS is shown in Table 13.

Table 13: Forecast of NO_X emissions from GEMS (Tg)

Source	1985	1990	1995	2000	2005	2010	2030	2050
Fossil fuels	23.2	25.5	26.7	28.0	29.0	30.7	40.6	58.9
Biomass burning	12.0	12.3	12.7	13.1	13.5	14.0	16.5	19.8
Anthrop. total	35.2	37.8	39.4	41.2	42.5	44.7	57.2	78.7
Natural	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
Total	59.2	61.8	63.4	65.2	66.5	68.7	81.2	102.7

5.2. Carbon Monoxide

The atmospheric concentration of CO is increasing in the Northern Hemisphere at a rate of 1% per year (Khalil and Rasmussen, 1990). About 60% of CO emissions come from human activities and 40% come from biogenic sources. CO has a short lifetime of about two months and is removed by reaction with the OH radical, soils and diffusion into the stratosphere. Increases in CO deplete OH radicals which is a sink for methane, thus causing methane concentrations to increase further.

CO is also derived from the oxidation of methane and NMHC. These sources are not included in the emissions model since they are calculated by the atmospheric chemistry model.

5.2.1. Fossil Fuel and Industrial Processes

Carbon monoxide is released from the combustion of fossil fuels in energy production, from the production of steel, pig iron, ammonia, and from the burning of refuse, agricultural waste, and sewage. The earliest inventories of CO emissions are those of Cullis and Hirschler 1989) and Logan *et al.* (1981) who calculated emissions for 1979 and 1976, respectively, by applying emission factors for each type of fuel/process to energy and industrial data. Logan *et al.* (1981) and Cullis and Hirschler 1989) used emission factors from the U.S. and Western Europe, but the computation procedure differed. The emission factors from Logan *et al.* (1981) were subdivided by fuel technology whereas the emission factors used by Cullis and Hirschler 1989) were by fuel type and sector. Consequently, their results were quite different. Logan *et al.* calculated 295 Tg CO from fossil fuels with about 80% from transportation and 20% from stationary combustion. Cullis and Hirschler calculated 742 Tg CO with 98% from petroleum and 2% from coal. Of the total, 60% was from mobile sources. Both Logan *et al.* and Cullis and Hirschler calculated 150 Tg CO from industrial sources. Combined with emissions from fossil fuels, the total emissions were 445 Tg CO and 890 Tg CO respectively.

Later estimates of global CO emissions are all based on the work of these two papers (Khalil and Rasmussen, 1990; Crutzen and Zimmerman, 1991). Müller (1992) estimated 275 Tg CO from fossil fuel sources and 108 Tg from industrial sources for a total of 383 Tg in 1980. He used emission factors from Logan *et al.* (1981) and Cullis and Hirschler 1989). Subak *et al.* (1992) calculated approximately 500 Tg CO from energy uses of which 400 Tg was from fossil fuel combustion. The other portion was from wood combustion which is included under biomass burning.

To obtain a global budget for 1985, I used CO emission data from EPA (1993b) and OECD (1989) for the OECD countries. For the rest of the world I used data from Subak *et al.* (1992), decreasing the totals proportionally to capture only the emissions from fossil fuels. This method resulted in a global emission of 450 Tg which is the same as the Logan *et al.* (1981) result. The growth of future emissions is a weighted average of the coal and transportation sector, with coal contributing 20% and transportation contributing 80%.

According to EPA (1993b), emissions in 1990 actually decreased slightly. Due to regulations on exhaust emissions, CO emissions in the OECD can be expected to remain constant or increase very slowly even as the transportation and coal sectors grow which is what actually occurred during the 1980's (OECD, 1989). Thus, I used an elasticity of 5% and 15% for the U.S. and rest of the OECD.

In GREEN, the transportation sector booms, with world demand increasing six-fold from 1985 to 2050. This tremendous growth causes the forecast of CO emissions to explode if we assume that emissions in the rest of the world grow linearly with transportation and coal. Realistically, we might expect that the trend in development of low-emissions technologies for transportation will continue, so emissions from mobile sources would not grow linearly with demand. The elasticity for the rest of the world is set at 50%. Global emissions grow to 1600 Tg CO in 2050 (see Table A.23).

5.2.2. Biomass Burning

Estimates of CO emissions from global biomass burning are presented in Table 14. The wide range of estimates is due to the uncertainty in the amount of global biomass burned. The emission factor for carbon monoxide used in most sources is 10-15% molar ratio of CO-C to CO_2-C released from burning. I chose a value of 800 Tg CO for 1985. Future emissions grow to 1300 Tg in 2050 (see Table A.15).

Table 14: Estimates of global CO emissions from biomass burning.

Source	*Emission (Tg CO)*
Logan *et al.*, 1981	350-1400 (660)
Crutzen, 1983	400-1600 (800)
Crutzen, 1987	500-1000
Crutzen and Andreae, 1990	820[a]
Andreae, 1991	820
Müller, 1992	730

a. The emissions estimates listed in their paper were increased to account for the additional emissions from prescribed burning and wildfires

5.2.3. Global CO emissions

An annual source strength of 175 Tg CO was used for emissions from natural sources. This value was a middle-of-the range number from the estimates in IPCC (1992). The forecast of CO emissions as predicted by GEMS is shown in Table 15.

Table 15: Forecast of CO emissions from GEMS (Tg)

Source	1985	1990	1995	2000	2005	2010	2030	2050
Fossil fuels	447	481	530	585	635	701	1065	1607
Industrial sources	150	162	175	189	201	213	255	295
Biomass burning	800	817	844	874	902	932	1102	1322
Anthrop. total	1397	1460	1549	1648	1739	1846	2423	3224
Natural	175	175	175	175	175	175	175	175
Total	1572	1635	1724	1823	1914	2021	2598	3399

5.3. Sulfur Oxides

SO_X includes SO_2 along with sulfur trioxide and sulfate aerosols (SO_4^{2-}). Sulfate is produced by oxidation of sulfur gases and is removed by deposition. Sulfate aerosols are thought to be a major source of cloud condensation nuclei, so they can affect the radiative properties of clouds. Sulfate aerosols may also directly affect warming by reflecting short-wave solar radiation, thus cooling the earth. Removal of sulfur takes place by precipitation processes and dry deposition.

Natural emissions occur as DMS (dimethyl sulfide) and hydrogen sulfide (H_2S). DMS and H_2S are oxidized in the atmosphere into SO_2 which is then oxidized to sulfate. The time scale for this process ranges from hours to a few weeks.

5.3.1. Fossil Fuels

Coal and petroleum combustion and petroleum refining are the main sources of sulfur emissions from fossil fuels. Emissions are calculated by multiplying the amount of fuel used by the sulfur content of the fuel and an emission factor for amount of sulfur released. Estimates for global emissions are shown in Table 16.

Cullis and Hirschler (1980) used emission factors for coal and petroleum from Europe and the U.S. However, emission factors for the U.S. were from the period of time before the Clean Air Act of 1970 went into effect. They estimated 62 Tg from the coal industry and 29 Tg from the petroleum industry.

Table 16: Estimates of global SO_X emissions from fossil fuels.

Source	*Estimate (Tg S)*
Cullis and Hirschler, 1980	91
Möller, 1984[a]	80
Varhelyi, 1985	63
Langner and Rodhe, 1991[a]	70
Dignon, 1992	62
Spiro *et al.*, 1992	71
Müller, 1992	78
Hameed and Dignon, 1992	64

Note: Year of estimate is 1980 except for Cullis and Hirschler (1980) who estimated emissions for 1976, Varhelyi (1985) who estimated emissions for 1979, and Hameed and Dignon (1992) who estimated for 1986.

a. Emissions from industrial sources included.

Varhelyi (1985) took his emission factors from previous sources including Cullis and Hirschler (1980) and Möller (1984). However, he accounted for varying sulfur contents from other parts of the world. In particular, he found that the sulfur content of fuel mind in the Southern Hemisphere was considerably lower than that from the Northern Hemisphere. He calculated a total of 43.6 Tg from coal and 19.7 Tg from petroleum which is much lower than the previous two estimates.

The most complete inventory comes from Spiro *et al.* (1992) who created a global inventory with 1°x1° resolution. They calculated SO_X emissions by using emission factors from the U.S. and fuel sulfur contents from different countries. They also took into account imports and exports of fuel, non-energy uses, and recovery. This procedure resulted in a global emission of 88.4 Tg S from fuel use and industrial activities, of which 55.7 came from coal, 25.9 Tg came from petroleum, and 6.8 Tg came from the smelting of non-ferrous ores. Then, they replaced estimates for Europe, the former Soviet Union, North America, and Japan with data from existing inventories. The global estimate then decreased to 77.6 Tg of which 70.8 Tg comes from fossil fuels,

Müller (1992) used emission factors from Cullis and Hirschler (1980) along with data from inventories published by the OECD. Thus, his estimates are higher than those of Varhelyi (1985) and Spiro *et al.* (1992).For GEMS, I used existing emission data for the U.S., OECD, and Eastern Europe (EPA, 1993b; OECD, 1989; WRI, 1993). Emissions for Japan and China were taken from Fujita *et al.* (1991). Figures for the rest of the world were calculated by the method from Hameed and Dignon (1988) using energy data from U.N. (1989), with the exception of emissions from Eastern Europe which were taken from Spiro *et al.* (1992). Total world SO_X emissions came to 60 Tg S. This figure is lower than the above estimates for 1980 or earlier due to increasing controls on SO_2 emissions, especially in OECD countries. For example, from 1980 to 1985, SO_X estimates decreased 10-15% in the U.S. Between 1980 and 1990 SO_2 emissions in Europe and North America decreased by 28% and 15% (EMEP, 1993, NAPAP, 1990)

Also, from 1980 to 1989, sulfur emissions decreased in the Soviet Union due to increased recovery (Spiro *et al.*, 1992). Future emissions in the OECD grow slower than the growth of the coal and petroleum industries, with the growth parameter for the U.S. and rest of the OECD set at 30% and 50%. For the rest of the world, SO_X emissions grow at a rate that is the weighted average of the coal and petroleum industry growth rates (2/3 and 1/3), consistent with the amount that each sector contributes to SO_X emissions. Future emissions grow to 216 Tg in 2050 (see Table A.24).

5.3.2. Industrial Sources

SO_X is produced during industrial processes, mostly during the smelting of non-ferrous ores such as copper, lead, and zinc as well as during the production of sulfuric acid, paper, and incineration of wastes. Cullis and Hirschler (1980) estimate a global source of 12.6 Tg S in 1976, Varhelyi (1985) estimates 15.1 Tg in 1980, Müller (1992) estimates 15 Tg, and Spiro *et al.* (1992) estimates 6.8 Tg. Varhelyi and Müller both used emission factors derived from Cullis and Hirschler. Spiro *et al.* (1992) used emission factors for the U.S. but reduced the total by the amount of sulfur recovered globally during smelting operations (36%).

I used data on copper, lead, and zinc operations from U.N. (1993) with emission factors from Müller (1992) and Spiro *et al.* (1992) to calculate 12.8 Tg globally. This amount was decreased by 36% to account for sulfur recovered and 1.7 Tg was added for the contribution from other. industrial processes. The total global emission for 1985 was

10 Tg. Future emissions grow at 50% the rate of industrial growth to 21 Tg in 2050 (see Table A.25).

5.3.3. Biomass Burning

Estimates of sulfur emission from global biomass burning are listed in Table 17. Although the range of estimates is very close, Bates *et al.* (1992) caution that burning area estimates are known to no better than ±50% and there are few emission measurements for sulfur. For GEMS I used a value of 2.5 Tg S for 1985 sulfur emissions, and future emissions grow to 4.1 Tg in 2050 (see Table A.15).

Table 17: Estimates of global SO_X emissions from biomass burning.

Source	*Estimate (Tg S)*	*Emission Coefficient*[b]
Bates *et al.*, 1992	1.4-2.9 (2.2)	0.21-0.32
Spiro *et al.*, 1992	2.3	0.32
Langner and Rodhe, 1991	2.5	0.32
Crutzen and Andreae, 1990	1.1-4.3 (2.7)[a]	0.15-0.45
Andreae, 1991	2.8	0.3

a. The emissions estimates listed in their paper were increased to account for the additional emissions from prescribed burning and wildfires

b. Units are moles S per 1000 moles CO_2-C.

5.3.4. Global SO_X emissions

Global emissions of SO_X as predicted by GEMS is shown in Table 18. An estimate of 22 Tg for natural sources was taken from Spiro *et al.* (1992).

Table 18: Forecast of SO_X emissions from GEMS (Tg)

Source	1985	1990	1995	2000	2005	2010	2030	2050
Fossil fuels	60.4	68.1	75.3	82.7	88.3	97.1	143.9	216.3
Industrial sources	10.0	13.4	18.4	25.0	32.5	41.4	81.2	144.8
Biomass burning	2.5	2.6	2.6	2.7	2.8	2.9	3.4	4.1
Anthrop. total	72.9	84.0	96.4	110.5	123.6	141.4	228.5	365.3
Natural	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0
Total	94.9	106.0	118.4	132.5	145.6	163.4	250.5	387.3

6. Results of the Green Emissions Submodel

6.1. The Reference Scenario and a Toronto-type Agreement

GREEN's Reference Scenario was used to produce an emission profile for the years 1985-2050 from GEMS. The assumptions about population, GDP, and technical change growth rates used for the GREEN run are described in Dean and Hoeller (1992). The Reference Scenario is a picture of the world in which CO_2 emissions are allowed to grow in an unconstrained way. Carbon emissions rise from 5 billion tons in 1985 to 17 billion tons in 2050 (see Table A.26). The forecast of emissions for CH_4, N_2O, NO_X, SO_X, and CO was given in Chapters 3–5.

The CO_2 reduction policy that we use here to analyze GEMS is the Toronto-type agreement. In this type of agreement, only CO_2 emissions are lowered. OECD countries reduce CO_2 emissions to 80% of their 1990 levels in 2010 and stabilize thereafter. Non-OECD countries emit no more than 50% above their 1990 levels by 2010 and stabilize thereafter (Martin *et al.*, 1992). CO_2 reduction is implemented in GREEN by the phasing in of a carbon tax. The net result is that global carbon emissions rise to only 8 billion tons in 2050, less than 50% of the Reference Scenario level (see Figure 1). The corresponding rise in emissions for CH_4, N_2O, NO_X, SO_X, and CO is shown in Table 19 to Table 23.

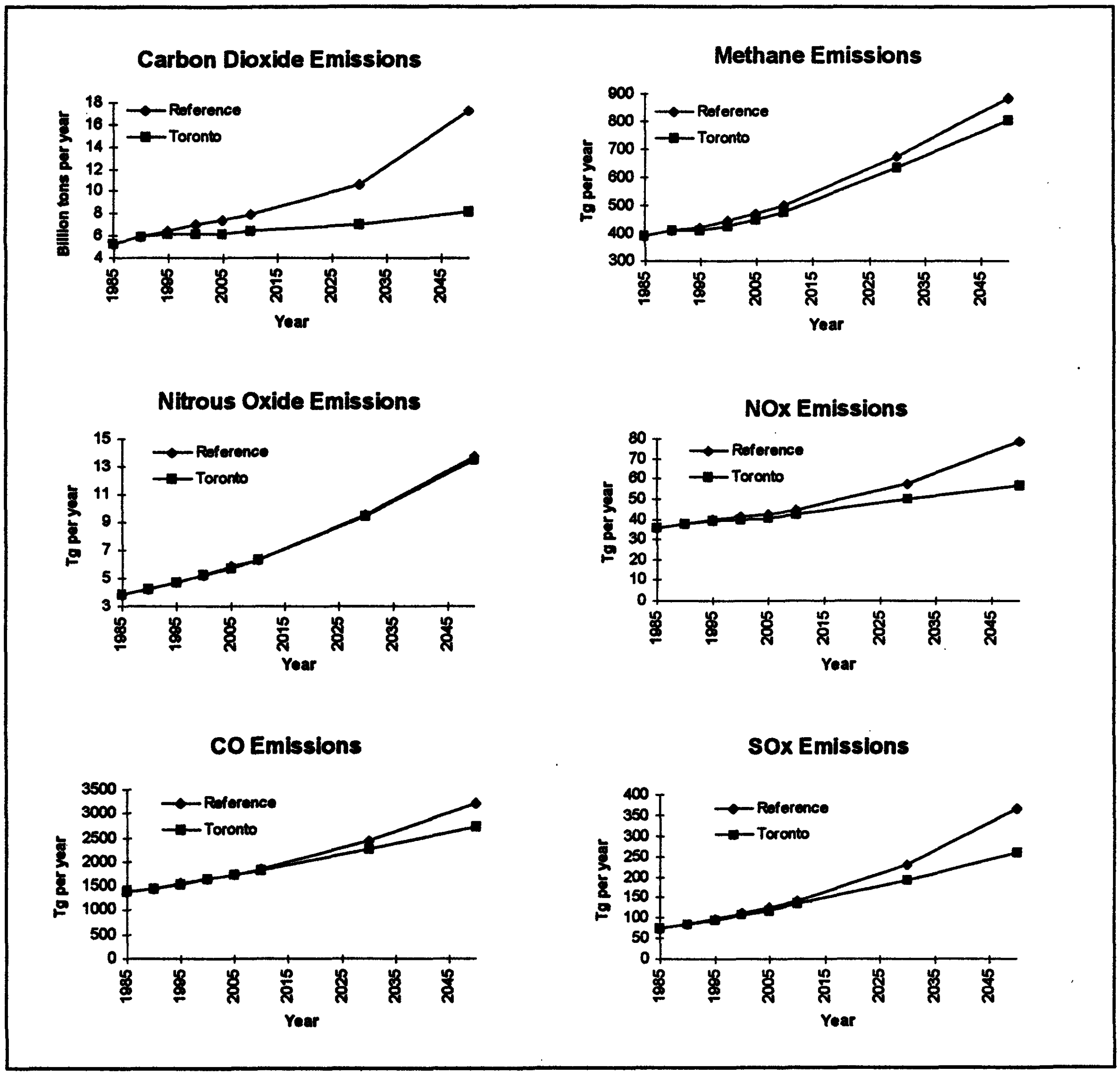


Figure 1: GEMS output for Reference and Toronto Scenarios for CO_2, CH_4, N_2O, NO_X, CO, and SO_X.

As a result of the Toronto-type agreement, emissions of CH_4, N_2O, NO_X, SO_X, and CO are diminished in comparison to the Reference Scenario. N_2O emissions in 2050 are diminished the least, only 2.5%, since many of the sources of N_2O are from agriculture and industry rather than energy. This 2.5% decrease corresponds to the decrease in demand for transportation (energy-intensive industry sector in GREEN) in the year 2050 compared to the reference case.

Table 19: Forecast of CH_4 emissions in the Toronto scenario.

Source	1985	1990	1995	2000	2005	2010	2030	2050
Rice	100	105	115	125	135	145	205	270
Ruminants	75	80	89	99	108	119	176	238
Animal wastes	28	30	33	36	39	42	59	78
Landfills	30	32	34	37	39	41	52	64
Domestic sewage	25	27	30	32	34	37	45	52
Coal mining	31	35	27	21	19	18	12	5
Natural gas	51	53	32	24	20	18	21	21
Biomass burning	48	49	51	52	54	56	66	79
Anthrop. total	388	412	411	426	448	476	637	807
Natural	155	155	155	155	155	155	155	155
Total	543	567	566	581	603	631	792	962
Non-atmos. sinks	30	30	30	30	30	30	30	30
Net emission	513	537	536	551	573	601	762	932

Table 20: Forecast of N_2O emissions in the Toronto scenario.

Source	1985	1990	1995	2000	2005	2010	2030	2050
Fertilizer	1.7	1.9	2.2	2.5	2.8	3.1	5.0	7.5
Land clearing	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5
Biomass burning	0.6	0.6	0.6	0.7	0.7	0.7	0.8	1.0
Fossil fuels	0.5	0.6	0.7	0.8	0.9	1.0	1.7	2.8
Nylon production	0.4	0.4	0.5	0.6	0.6	0.7	0.8	1.0
Nitric acid prod	0.2	0.2	0.3	0.3	0.3	0.4	0.6	0.9
Anthrop. total	3.8	4.2	4.7	5.2	5.7	6.3	9.4	13.5
Natural	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Total	12.1	12.5	13.0	13.5	14.0	14.6	17.7	21.8
Non-atmos. sinks	0	0	0	0	0	0	0	0
Net emission	12.1	12.5	13.0	13.5	14.0	14.6	17.7	21.8

Table 21: Forecast of NO_X emissions in the Toronto scenario.

Source	1985	1990	1995	2000	2005	2010	2030	2050
Fossil fuels	23.2	25.5	26.2	26.7	27.1	28.5	33.2	37.0
Biomass burning	12.0	12.3	12.7	13.1	13.5	13.9	16.5	19.7
Anthrop. total	35.2	37.8	38.9	39.8	40.6	42.5	49.7	56.7
Natural	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
Total	59.2	61.8	62.9	63.8	64.6	66.5	73.7	80.7
Non-atmos. sinks	0	0	0	0	0	0	0	0
Net emission	59.2	61.8	62.9	63.8	64.6	66.5	73.7	80.7
N. Hemis. fraction	0.8							
S. Hemis. fraction	0.2							
NOx - NH	47.4	49.4	50.3	51.0	51.7	53.2	59.0	64.6
NOx - SH	11.8	12.4	12.6	12.8	12.9	13.3	14.7	16.1

Table 22: Forecast of CO emissions in the Toronto scenario.

Source	1985	1990	1995	2000	2005	2010	2030	2050
Fossil fuels	447	481	526	576	621	681	913	1102
Industrial sources	150	162	175	189	200	211	253	292
Biomass burning	800	817	844	872	900	929	1098	1315
Anthrop. total	1397	1460	1544	1637	1721	1822	2264	2709
Natural	175	175	175	175	175	175	175	175
Total	1572	1635	1719	1812	1896	1997	2439	2884
N. Hemi. fraction	0.67							
S. Hemi. fraction	0.33							
NH source	1053	1096	1152	1214	1270	1338	1634	1932
SH source	519	540	567	598	626	659	805	952
NH sink	235	235	235	235	235	235	235	235
SH sink	45	45	45	45	45	45	45	45
NH net emission	818	861	917	979	1035	1103	1399	1697
SH net emission	474	495	522	553	581	614	760	907

Table 23: Forecast of SO_X emissions in the Toronto scenario.

Source	1985	1990	1995	2000	2005	2010	2030	2050
Fossil fuels	60.4	68.1	73.8	79.5	83.5	90.5	110.0	115.3
Industrial output	10.0	10.8	11.8	12.8	13.7	14.6	17.9	20.9
Biomass burning	2.5	2.6	2.6	2.7	2.8	2.9	3.4	4.1
Anthrop. total	72.9	81.4	88.3	95.1	100.0	108.0	131.3	140.3
Natural	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0
Total	94.9	103.4	110.3	117.1	122.0	130.0	153.3	162.3

In the Toronto scenario, output from primary energy sources (coal, oil, and natural gas) is decreased 40% in 2050 compared to the reference case. However, global transportation demand, agriculture output, and industrial output are not severely affected for two reasons. The first is that back-stop technologies come into use which limits the rise of energy costs. The second reason is that since GREEN allows trade flows between regions, there are winners and losers in terms of regional GDP, but global GDP is only reduced 1% in 2050 from the reference case. Thus, greenhouse-relevant gases such as N_2O and CH_4 which are emitted mostly from activities in agriculture, industry, and transportation exhibit less of a decrease in the Toronto case. NO_X, CO, and SO_X, which derive a greater portion of their emissions from primary energy, are significantly decreased in the Toronto case.

Although SO_X is not included in following calculation of radiative effects, we note that SO_X emissions decrease by 40% in the Toronto case. The decrease of SO_X not only has implications for warming but results in the reduction of local environmental problems such as acid precipitation.

6.2. An Assessment Model for Atmospheric Composition (ATCOMP)

The results of GEMS are fed into the Assessment Model for Atmospheric Composition, ATCOMP.[16] ATCOMP takes as input the emissions of CO_2, CH_4, N_2O, NO_X, CO, halocarbons, and non-methane hydrocarbons (NMHC). The relevant output variables include the atmospheric concentrations of the above gases (except for NO_X, which is not given as output), the percentage change in OH and O_3, net radiative forcing, and tropospheric temperature. The initial parameters and units of the output of ATCOMP are given in Table 24.

Table 24: Initial parameters and units of ATCOMP.

Species	*Specification*
CO_2	345 ppm in 1985
CH_4	1600 ppb in 1985
N_2O	300 ppb in 1985
CO	Output in ppb
OH	Output in % change [a]
O_3	Output in % change [a]
Radiative forcing	Output in Watts/m^2 [a]
Tropospheric temperature	Output in °C [b]

a. A value of 0.00 refers to the reference state (1985) using default parameters.
b. A value of 0.00 refers to the pre-industrial state.

---

[16] This model was originally developed by NASA-GISS (NASA, 1989) and was used by the EPA in work done for the IPCC assessments. It has been subsequently revised for use by the M.I.T. Joint Program on the Science and Policy of Global Change (Liu, 1992). The revised model is used in the calculations.

NO_X and CO inputs and outputs are disaggregated into Northern/Southern Hemisphere quantities. Global NO_X emissions are divided between the Northern and Southern Hemispheres at a 80:20 ratio. The assumption is that fossil fuel sources are divided between North and South at a ratio of 95% and 5% (Dignon, 1992). NO_X emissions from biomass burning and natural sources are distributed more evenly between the hemispheres, so the net result is approximately 80% and 20%. CO emissions are divided between North and South at a ratio of 2/3 to 1/3 (Logan *et al.*, 1981). The distribution of CO sinks is also taken from Logan *et al.* (1981) with 235 Tg CO emitted in the Northern Hemisphere and 45 Tg in the South.

Net emissions are specified as input to ATCOMP, where net emissions are equal to anthropogenic emissions plus natural emissions minus any non-atmospheric sinks. For example, in the case of CO, natural sources of emissions include oceans, plants, oxidation of CH_4, and oxidation of NMHC. The sinks of CO include soil uptake, oxidation by OH, and oxidation in the stratosphere. Thus, the net emission used as input to ATCOMP includes only anthropogenic sources plus the emissions from oceans and plants minus the sink from soil uptake. CO from oxidation of CH_4 and NMHC are implicitly solved by the model, as is the removal of CO by OH and stratospheric oxidation.

Note, however, that the emission profiles for halocarbons remain unchanged in all analyses. Halocarbon emissions were not included in GEMS because they are assumed to follow the phase-out schedule as specified by the London Amendments to the Montreal Protocol.

ATCOMP takes the yearly net emission for each greenhouse-relevant gas as input and calculates the resulting values of the outputs. Since GEMS only gives estimates for the years 1985, 1990, 1995, 2000, 2005, 2010, 2030, and 2050, the annual growth between the specified years is extrapolated in a linear fashion.

ATCOMP also evaluates the uncertainty of six climate variables by performing 64 runs and reporting the high, low, and average values of the outputs. The model contains only a simple temperature generator which is a reduced-form equation used to convert atmospheric concentrations to temperature for internal use by the model.[17]

---

[17] In the M.I.T. Joint Program's integrated framework, this temperature will be calculated using a 2D-climate model.

6.2.1. Stabilization of emissions

The first analysis using ATCOMP is to examine the effect of emissions stabilization on the atmospheric concentrations of greenhouse-relevant gases. This analysis is insightful because many policies focus on stabilizing greenhouse gas emissions which may give the impression that stabilization of emissions will forestall global warming. However, given the long lifetimes of greenhouse gases, atmospheric concentrations will continue to rise even if emissions level off.

For this analysis I ran ATCOMP using emission profiles from the Reference Scenario. Then I ran ATCOMP setting emissions of CO_2, CH_4, N_2O, NO_X, and CO constant at 1985 levels from 1985-2050 (halocarbon emissions follow the schedule specified by the London Amendments). The results of this analysis show that for long-lived trace gases such as CO_2 and N_2O, concentrations continue to rise even though emissions are stabilized (Figures 2 and 3). For short-lived gases such as O_3, and CO, atmospheric levels stabilize rather quickly (Figures 4 and 5). The concentration of CH_4 (Figure 6), which has a lifetime of 11 years, also stabilizes since it depends on the concentrations of NO_X and CO. These results are consistent with the concentration of OH which remains fairly flat (Figure 7). Tropospheric temperature, however, continues to rise (Figure 8).

Figure 2: Concentration of CO_2 when emissions are stabilized

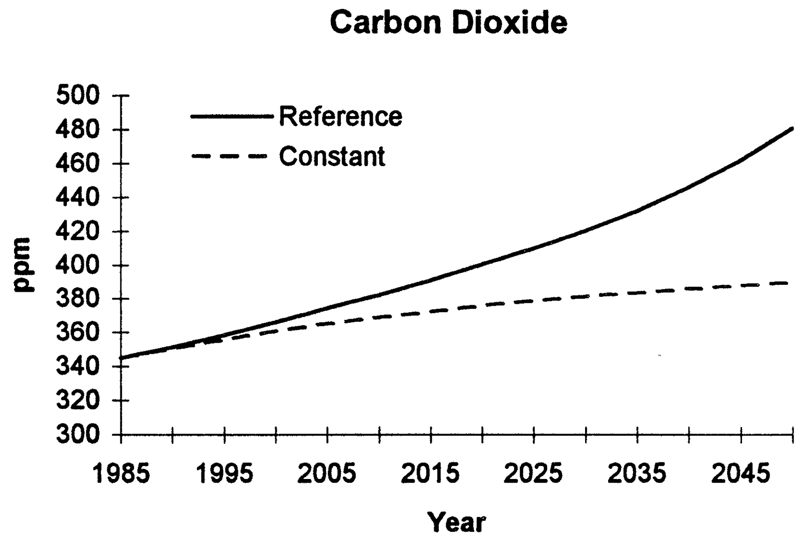


Figure 3: Concentration of N_2O when emissions are stabilized.

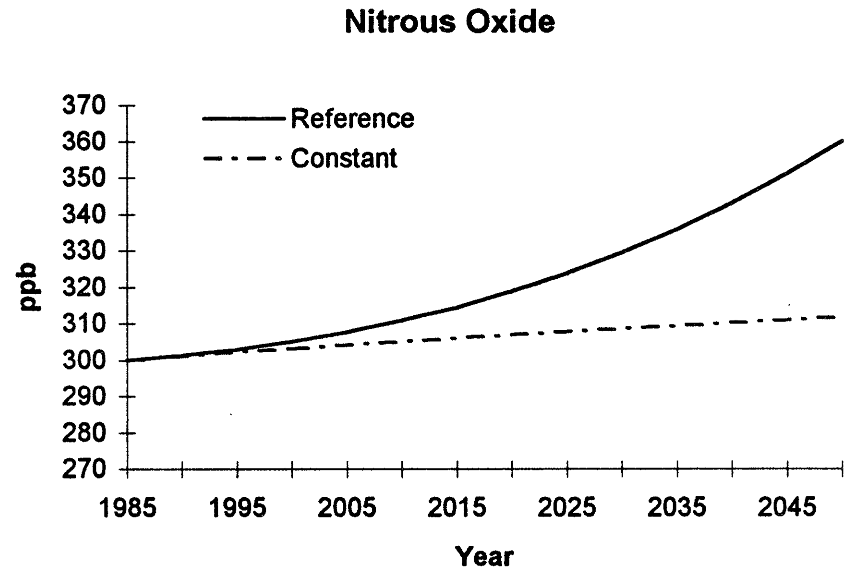
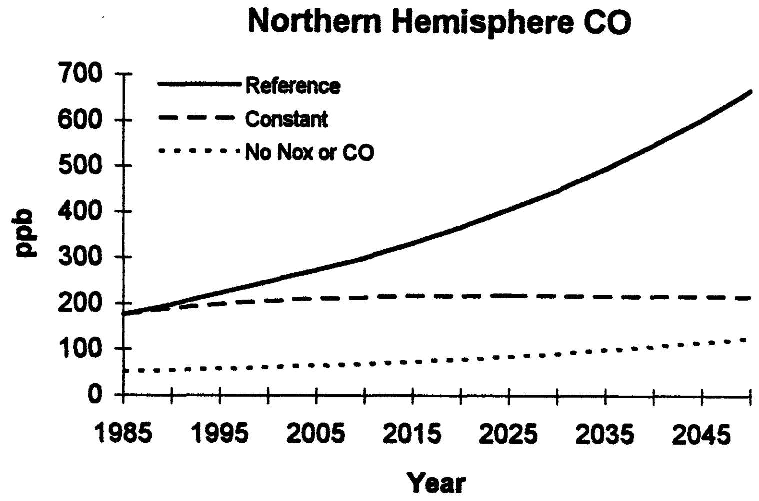


Figure 4: Concentrations of NH-CO and SH-CO with constant emissions and no NO_X and CO.



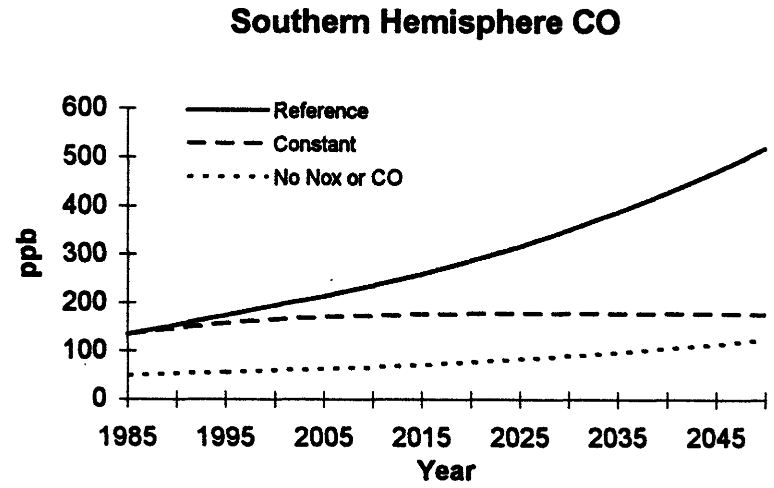
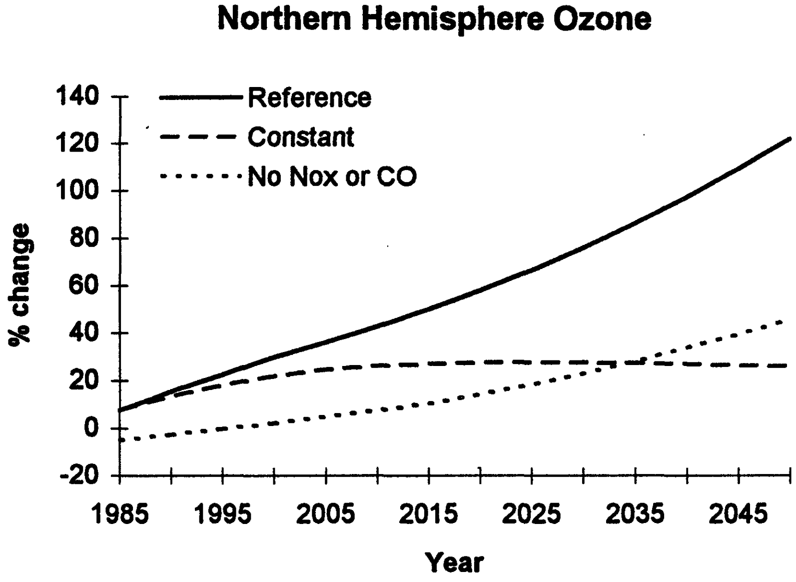


Figure 5: Percentage change in NH and SH-O_3 with constant emissions and no NO_X and CO.



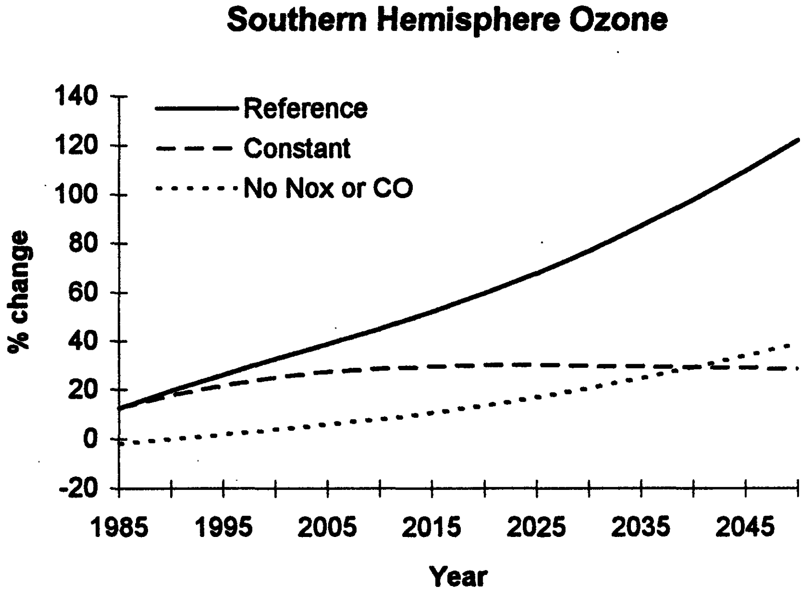


Figure 6: Concentration of CH_4 with constant emissions and no NO_X and CO.

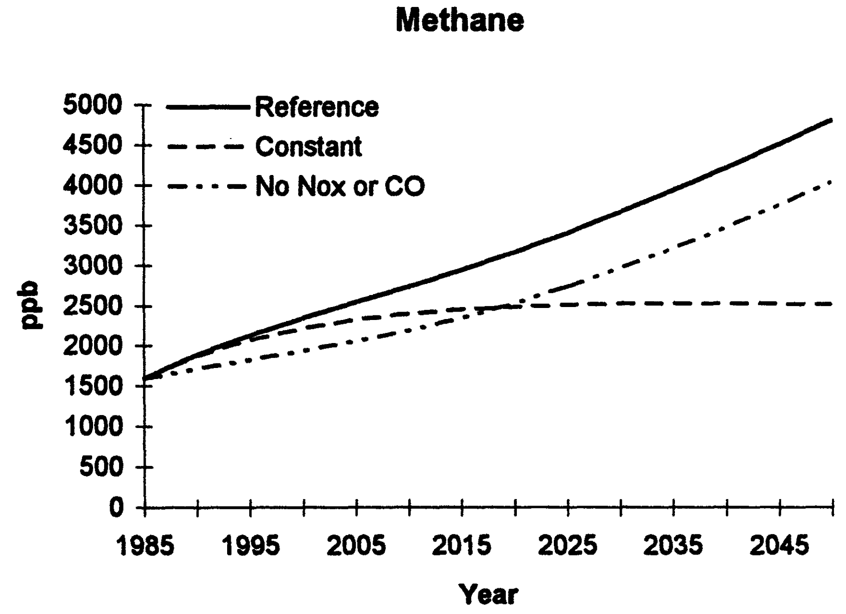


Figure 7: Percentage change in OH with constant emissions and no NO_X and CO

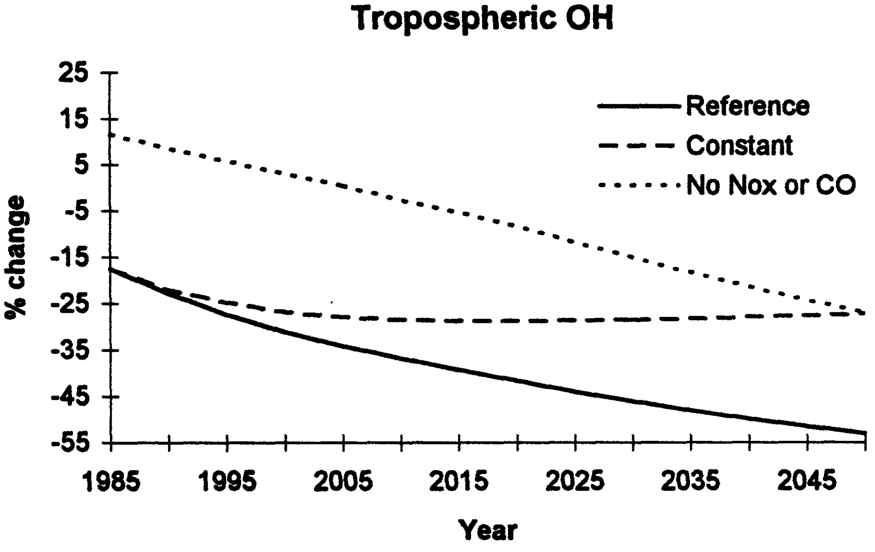


Figure 8: Tropospheric temperature with constant emissions and no NO_X and CO.

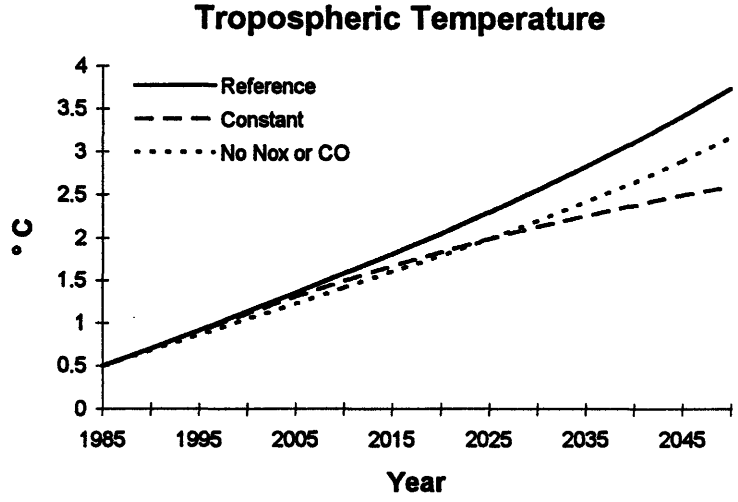
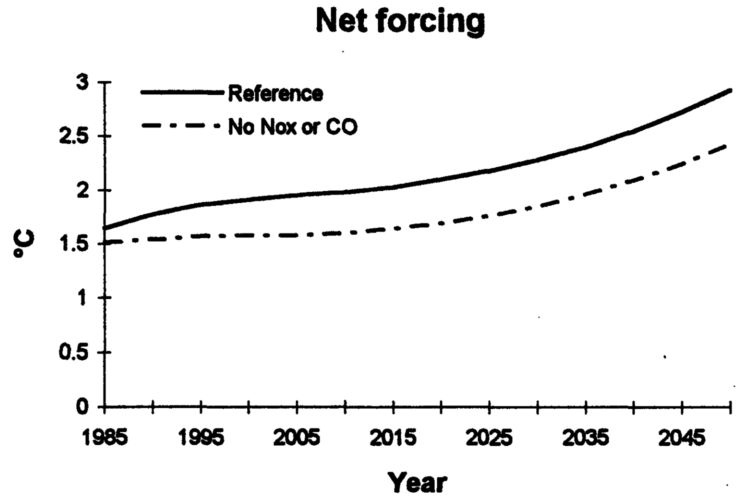


Figure 9: Net forcing with constant emissions and no NO_X and CO.



6.2.2. *Effect of including NO_X and CO*

The next analysis is to evaluate the effect of including NO_X and CO emissions. As discussed in section 2.2, the concentration of CH_4 is dependent on the concentration of the OH radical which is critically determined by NO_X and CO. The effect of NO_X and CO on the OH radical is not clearly predictable, since CO drives the concentration of OH down and NO_X drives the concentration up. Whether the concentration of OH goes up or down will significantly affect the concentration of CH_4, since OH is the main sink of CH_4.

Here I ran the atmospheric composition model for an emissions profile which "zeroed-out" NO_X and CO by setting their emission level at 1 Tg per year (a value of zero would have produced an error in the program). When compared to the reference case, the results show that the concentration of OH exhibits a shift upward (Figure 7), *i.e.*, it is not depleted as much as when NO_X and CO are specified in the emissions profile. CH_4 levels (Figure 6) also exhibit a reduction in growth and do not increase as much as the reference case. CO, however, continues to increase slightly (Figure 4), since it is produced by the oxidation of CH_4 and NMHC. As a result, O_3 also increases slightly due to the increase and CO (Figure 5). However, as its lifetime is relatively short, O_3 concentrations level off. CO_2 and N_2O remain unchanged from the reference case. The net result on radiative forcing and temperature is that without NO_X and CO emissions specified, they show a smaller rise than if NO_X and CO were specified (Figure 8 and Figure 9).

We find that with the inclusion of NO_X and CO, the CO dominates the picture by driving down concentrations of OH. This result can be explained by the fact that the CO lifetime (months) is much longer than the lifetime of NO_X (days).

6.2.3. The Toronto Scenario

Finally, we examine the effect of a CO_2 reduction policy on climate and the additional contribution from specifying emissions of other greenhouse-relevant gases. First, I ran ATCOMP with the emissions of greenhouse-relevant gases at reference levels, with the exception of CO_2, which was reduced to the Toronto-type agreement levels. This case typifies the current method of analysis in which only the effect of reductions in CO_2 is considered. This case is labeled "CO_2 at Toronto level" on Figures 15 and 16. Then, I ran ATCOMP using the results of GEMS where emissions of all other gases are also reduced as a result of policies to reduce CO_2. This case is labeled "Toronto" on Figure 10 through Figure 16.

We see in this case that there is indeed an additional contribution from including the emissions of other greenhouse-relevant gases. Both radiative forcing and tropospheric temperature are slightly lower than they would have been if the other greenhouse-relevant gases had not been included in the model. Radiative forcing is 2.93 W/m^2 in the reference case, 2.30 in the "CO_2 only" case, and 2.08 in the Toronto case. The additional decrease in net forcing by including the other greenhouse-relevant gases is 0.22 W/m^2, representing an additional 35% decrease from the case in which only CO_2 is considered.

The results for temperature also show the same effect. Tropospheric temperature is 3.74° in the reference case, 3.47° in the "CO_2 only" case (a decrease of 0.27°), and 3.36° when all gases are included. This additional 0.11° decrease represents an additional 40% decrease from the case in which only CO_2 is considered.

Figure 10: Concentration of CO_2 in Toronto scenario

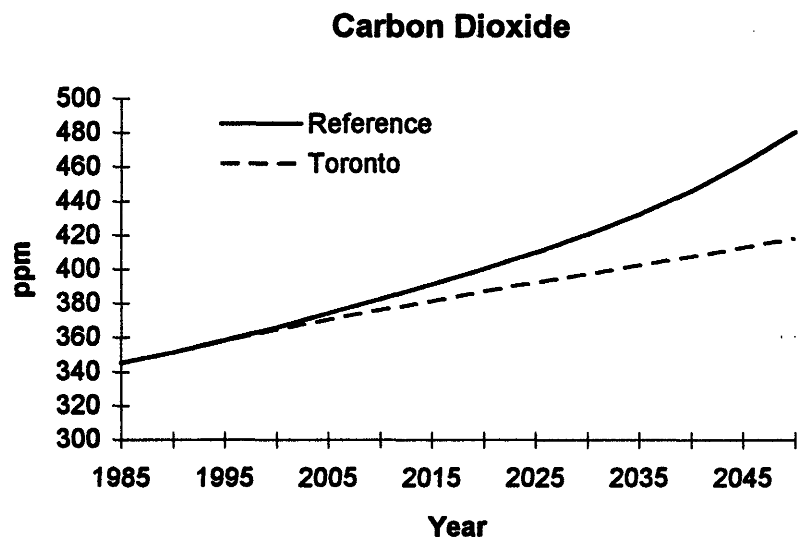


Figure 11: Concentration of N_2O in Toronto scenario

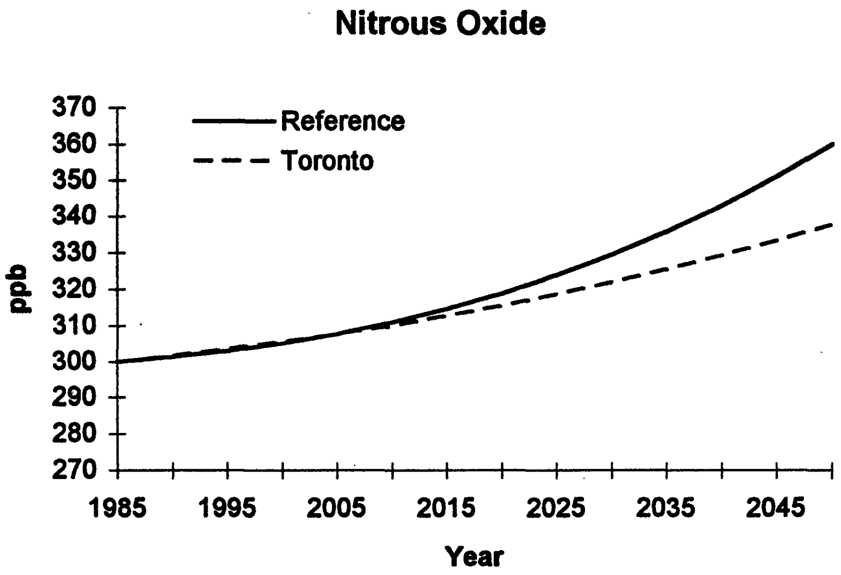


Figure 12: Concentration of NH and SH-CO in Toronto scenario

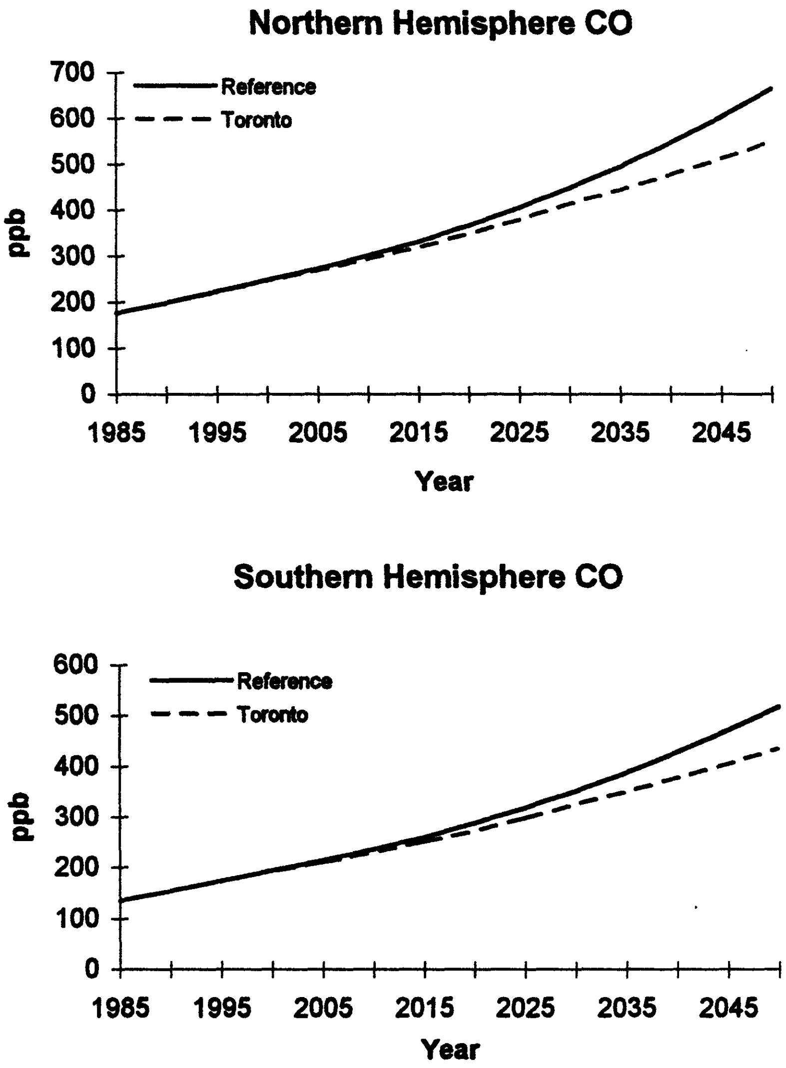


Figure 13: Percentage change in NH and SH-O_3 in Toronto scenario

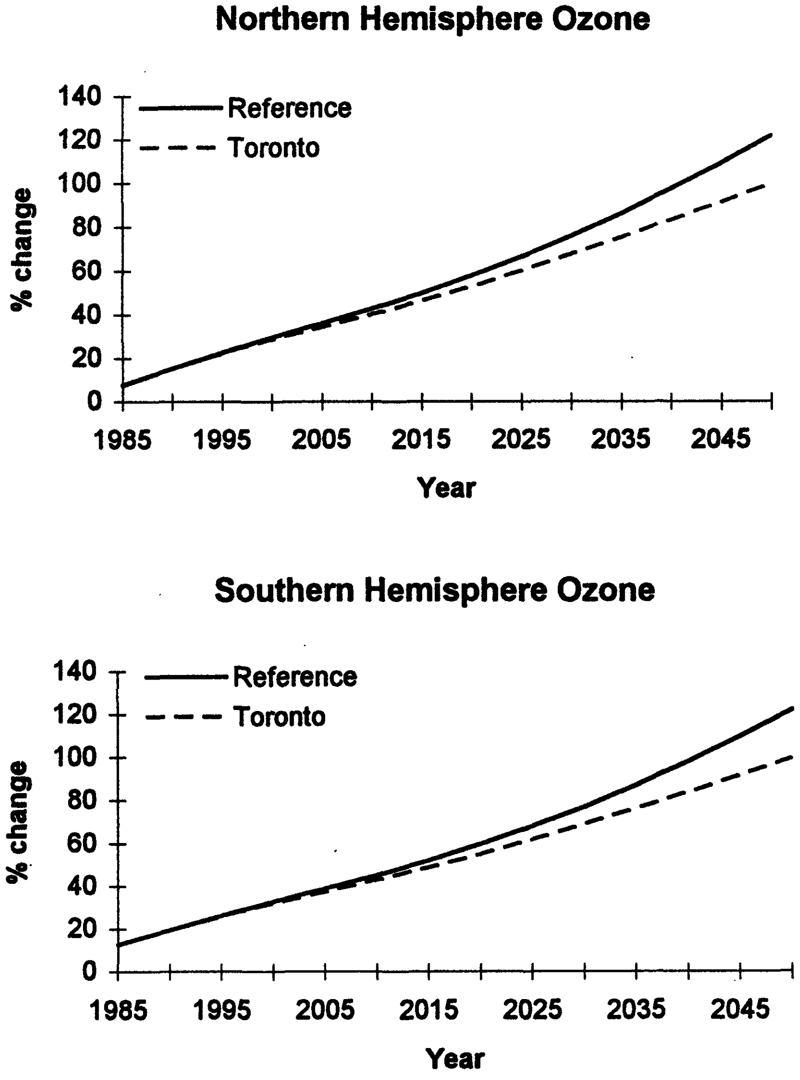


Figure 14: Concentration of CH_4 in Toronto scenario

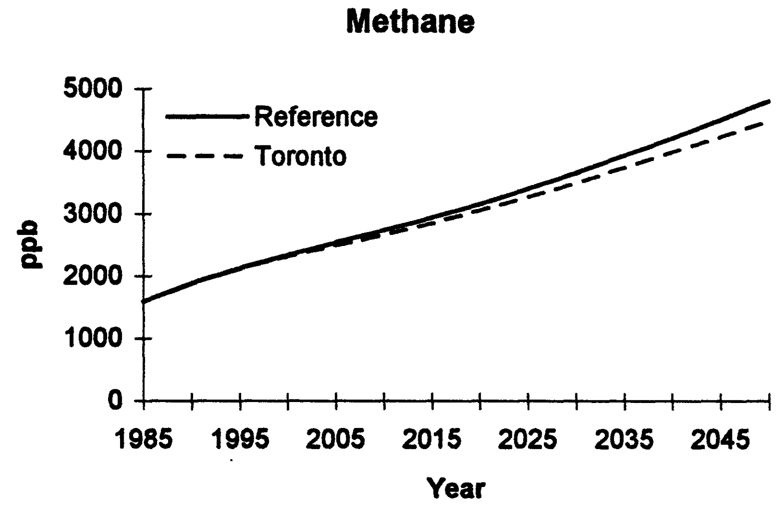


Figure 15: Net forcing in Toronto scenario

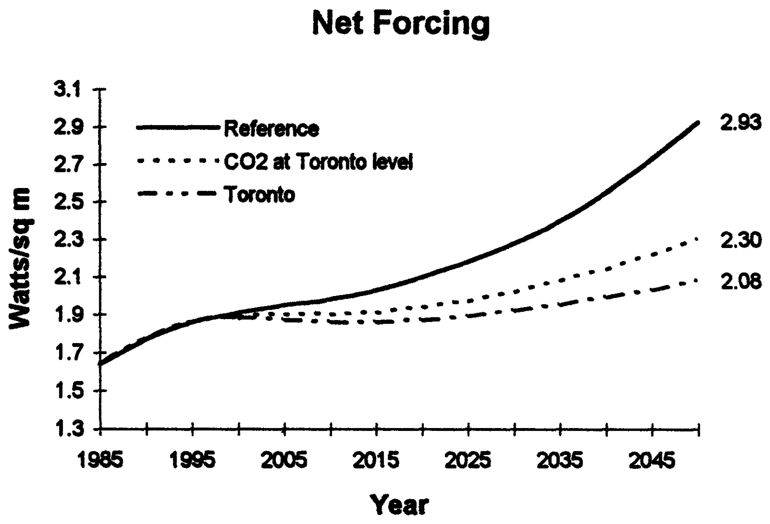
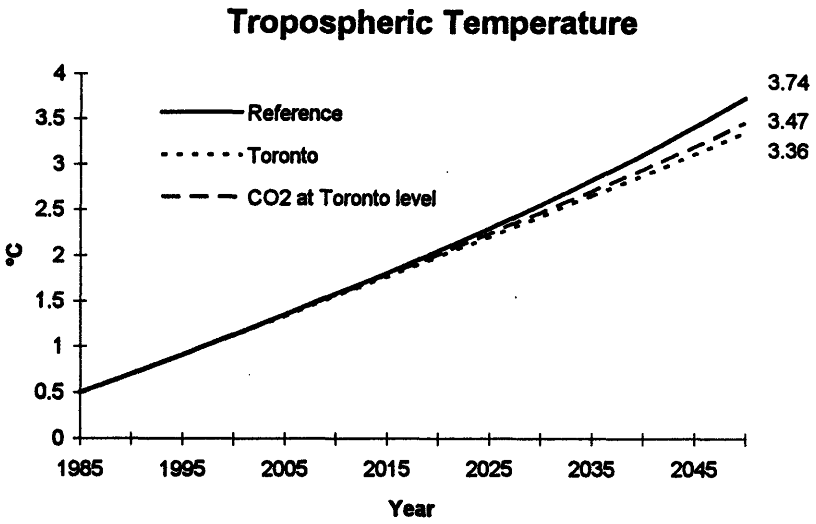


Figure 16: Tropospheric temperature in Toronto scenario



7. Conclusion

The results of this thesis reveal the importance of including emissions of all greenhouse-relevant gases when evaluating CO_2 reduction policies. The chemistry of the troposphere is complex, and one cannot easily predict how changing the emissions of certain species will affect the concentrations of other species. When CO_2 reduction policies are implemented, these policies will affect the emissions of other greenhouse-relevant gases, and the changes in these emissions results in a net contribution to global warming. In the case of a Toronto-type agreement, inclusion of the other greenhouse-relevant gases in the analysis results in an additional reduction of 35-40% in global temperature and radiative forcing when compared to the case where the other gases are not included.

An important policy implication is that policymakers need to include all greenhouse-relevant gases when calculating the cost of various policies. For example, carbon taxes have been proposed to reduce carbon emissions to a desired level which would mitigate the effect of warming. The correct pricing of a carbon tax requires knowledge of the cost of reducing emissions to the desired level. However, the implementation of a carbon tax also reduces emissions of greenhouse-relevant gases other than CO_2, and if this effect is ignored the tax will be priced incorrectly.

Policymakers also need to include all greenhouse-relevant gases when calculating benefits of policies. When greenhouse-relevant gases other than CO_2 were included in the analysis, additional benefit from reduced warming was achieved. There are likely other benefits in the area of energy efficiency, reduced pollution, or forest conservation which may be overlooked if the other greenhouse-relevant gases are not considered. The big picture of benefits obtained by emissions reduction policies cannot be seen unless the effect on all greenhouse-relevant gases is included.

These points lead us to the question of what is an the most appropriate option for achieving policy goals. Carbon taxes have been the focus of attention as a means to mitigate global warming, but what about a "methane tax" or "nitrous oxide tax" or, for that matter, a "greenhouse-relevant gas tax"? Since emissions of other greenhouse-relevant gases are significant in determining warming, there may be other least-cost or no-regret options for reducing emissions from the agricultural and industrial sources of these gases.

Finally, we conclude that the GWP which is being widely used in evaluating the effects of other greenhouse-relevant gases is an inadequate tool for policy evaluation. A mere glimpse into the workings of atmospheric chemistry showed that the GWP for methane would not be correct because its lifetime varied as the hydroxyl radical was depleted. This concentration was determined by interactions between NO_X, CO and other gases. A GWP for gases such as sulfate aerosols cannot possibly be calculated, since their radiative effect depends not only on OH concentration but on geographical distribution. To replace the GWP, a model determining atmospheric composition should be used, which requires the specification of emissions of all greenhouse-relevant gases.

Given the long time scale of global warming, policymakers are seeking solutions which will provide a maximum of benefits both in the long and short term at a minimum of cost to society. The current approach of focusing on carbon emissions and using GWP's for all other gases will not result in an accurate analysis. The method presented in this thesis provides a start towards more complete evaluation of global warming policies.

8. Recommendations for Future Research

The analysis performed in this thesis is a first step towards a new approach in looking at global warming policies. There are many areas in which the analysis could be further improved and refined in the future. Since GEMS is a link between the GREEN model and the ATCOMP model, improvements in all three models are needed.

In GREEN, several major changes would improve the results of GEMS. Disaggregation of the agricultural sector would provide a better estimate of growth in methane and nitrous oxide emissions. Disaggregation of the transportation sector from energy-intensive industries would also refine emission estimates of N_2O, CO, and SO_X. Finally, the addition of a land-use module and inclusion of CO_2 emissions from deforestation would enable one to study the effects of changes in land use on emissions from biomass burning.

There are also several areas for improvement in GEMS. First, estimates and distribution of emissions in the base year can be refined by obtaining more detailed emission inventories. Additional sources of emissions which were not included in this first version of GEMS can be added as more information is made available. For example, some studies have found that additional N_2O and NO_X is emitted by soils after burning occurs (Levine *et al.*, 1988). A further improvement in GEMS would be the addition of non-methane hydrocarbon emissions. Also, more research is required in determining the proper functions for growth in emissions. In certain cases, logistic functions might be used in place of a linear relationship. The estimation of the elasticity values is also crucial in determining future emissions.

As discussed in the thesis, the estimates of emissions from individual sources show a large range of uncertainty. Uncertainty analysis and sensitivity testing would give an idea of the uncertainty of the results and what are key parameters for the model.

Finally, modifications in ATCOMP could provide a more complete picture of the results. The oxidation of CH_4 and CO ultimately produces CO_2, but this source of CO_2 is not included in ATCOMP. The amount of CO_2 produced from the oxidation of CH_4 and CO is dependent on the values of certain rate constants, but given that the carbon in CH_4 and CO_2 emissions is 10-20% the amount in CO_2 emissions, this source could be significant. The addition of sulfate aerosols to the atmospheric composition model would provide additional insight into the effect of SO_X on global warming.

9. Bibliography

AES Corporation (1993). *An Overview of the IDEAS Model.* The AES Corporation, Arlington, Virginia.

Andreae, Meinrat O. (1991). "Biomass burning: Its history, use, and distribution and its impact on environmental quality and global climate." In *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, J. S. Levine, ed. MIT Press, Cambridge, Massachusetts, 3-21.

Aselmann, I. and P. Crutzen (1989). "Global distribution of natural freshwater wetalands and rice paddies: Their net primary productivity, seasonality and possible methane emissions." *Journal of Atmospheric Chemistry* **8**: 307-358.

Barns, David W. and J. A. Edmonds (1990). *An Evaluation of the Relationship Between the Production and Use of Energy and Atmospheric Methane Emissions.* DOE/NBB-0088P, U. S. Department of Energy, Washington D.C.

Bates, T. S., B. K. Lamb, A. Guenther, J. Dignon and R. E. Stoiber (1992). "Sulfur emissions to the atmosphere from natural sources." *Journal of Atmospheric Chemistry* **14**: 315-337.

Beaver, Ron (1993). "Structural comparison of the models in EMF12." *Energy Policy* **21(3)**: 238-241.

Bingemer, H. G. and P. J. Crutzen (1987). "The production of methane from solid wastes." *Journal of Geophysical Research* **492**: 2182-2187.

Bolle, H. J., W. Seiler and B. Bolin (1986). "Other greenhouse gases and aerosols: Assessing their role for atmospheric radiative transfer." In *The Greenhouse Effect, Climatic Change, and Ecosystems*, B. Bolin, B. R. Doos, J. Jager and R. A. Warrick, ed. John Wiley & Sons, New York, 157-203.

Bouwman, A. F. (1990). "Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere." In *Soils and the Greenhouse Effect,* A. F. Bouwman, ed. John Wiley and Sons, New York, 61-127.

Breitenbeck, G. A. (1988). Presentation at U.S. EPA Workshop on Agriculture and Climate Change, Washington, D.C., February 29 to March 1, 1988.

Burniaux, Jean-Marc, Giuseppe Nicoletti and Joaquim Oliveira-Martins (1992). "GREEN: A global model for quantifying the costs of policies to curb CO_2 emissions." *OECD Economic Studies* **19**: 49-92.

Charlson, R. J., J. Langner and H. Rodhe (1990). "Sulfate aerosols and climate." *Nature* **348**: 22-26.

Charlson, R. J., J. Langner, H. Rodhe, C. B. Leovy and S. G. Warren (1991). "Perturbation of the Northern Hemisphere radiative balance by backscattering from anthropogenic sulfate aerosols." *Tellus* **43A-B**(4): 152-163.

Charlson, R. J., S. E. Schwartz, J. M. Hales, R. D. Cess, J. A. Coakley Jr., J. E. Hansen and D. J. Hofmann (1992). "Climate forcing by anthropogenic aerosols." *Science* **255**: 423-430.

Cicerone, F. J. and R. S. Oremland (1988). "Biogeochemical aspects of atmospheric methane." *Global Biogeochemical Cycles* **2**(4): 299-327.

Cicerone, R. J. and J. D. Shetter (1981). "Sources of atmospheric methane: Measurements in rice paddies and a discussion." *Journal of Geophysical Research* **86**: 7203-7209.

Cicerone, R. J., J. D. Shetter and C. Delwiche (1983). "Seasonal variation of methane flux from a California rice paddy." *Journal of Geophysical Research* **88**: 11022-11024.

Clements, H. B. and C. K. McMahon (1980). "Nitrogen oxides from burning forest fuels examined by thermogravimetry and evolved gas analysis." *Thermochemica Acta* **35**: 133-139.

Cohan, David (1993). Personal communication.

Conrad, R., Wolfgang Seiler and G. Bunse (1983). "Factors influencing the loss of fertilizer nitrogen into the atmosphere as N_2O." *Journal of Geophysical Research* **88**(C11): 6709-6718.

Council on Environmental Quality (1982). *Environmental Quality 1981, 12th Annual Report,* CEQ, Washington, D.C.

Craig, H., C. C. Chou, J. A. Welhan, C. M. Stevens and A. Engelkemeir (1988). "The isotopic composition of methane in polar ice cores." *Science* **242**: 1535-1539.

Crutzen, P. and P. H. Zimmermann (1991). "The changing photochemistry of the troposphere." *Tellus* **43**: 136-151.

Crutzen, Paul J. (1983). "Atmospheric interactions in homogeneous gas reactions of C, N, and S containing compounds." In *The Major Biogeochemical Cycles and Their Interactions*, B. Bolin and R. B. Cook, ed. SCOPE 21, John Wiley and Sons, New York, 67-112.

Crutzen, Paul J. (1987). "Role of the tropics in atmospheric chemistry." In *Geophysiology of Amazonia*, R. Dickinson, ed. John Wiley & Sons, New York, 107-132.

Crutzen, Paul J. and Meinrat O. Andreae (1990). "Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles." *Science* **250**: 1669-1678.

Crutzen, Paul J., Ingo Aselmann and Wolfgang Seiler (1986). "Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans." *Tellus* **38B**: 271-284.

Crutzen, P. J., A. C. Delany, J. Greenberg, P. Haagenson, L. Heidt, R. Lueb, W. Pollock, W. A. Seiler, A. Wartburg and P. Zimmerman (1985). "Tropospheric chemical composition measurements in Brazil during the dry season." *Journal of Atmospheric Chemistry* **2**: 287-306.

Crutzen, P.J., W. M. Hao, M. H. Liu, J. M. Lobert and D. Scharffe (1989). "Emissions of CO_2 and other trace gases to the atmosphere from fires in the tropics." 28th Liege International Astrophysical Colloquium on Our Changing Atmosphere, University of Liege, Belgium, June 26-30, 1989.

Crutzen, P. J., L. E. Heidt, J. P. Krasnec, W. H. Pollock and W. Seiler (1979). "Biomass burning as a source of atmospheric gases CO, H_2, N_2O, NO, CH_3Cl and COS." *Nature* **282**: 253-256.

Cullis, C. F. and M. M. Hirschler (1980). "Atmospheric sulphur: Natural and man-made sources." *Atmospheric Environment* **14**: 1263-1278.

Cullis, C. F. and M. M. Hirschler (1989). "Man's emissions of carbon monoxide and hydrocarbons into the atmosphere." *Atmospheric Environment* **23**(6): 1195-1203.

Darmstadter, J., L. Ayres, R. Ayres, W. Clark, P. Crosson, P. Crutzen, T. Graedel, R. McGill, J. Richards and J. Tarr (1987). *Impacts of World Development on Selected Characteristics of the Atmosphere: An Integrative Approach.* ORNL/Sub/86-22033, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Dean, Andrew and Peter Hoeller (1992). "Costs of reducing CO_2 emissions: Evidence from six global models." *OECD Economic Studies* **19**: 15-47.

Dignon, Jane (1992). "NO_x and SO_x emissions from fossil fuels: a global distribution." *Atmospheric Environment* **26A**(6): 1157-1163.

Dignon, Jane and Joyce E. Penner (1991). "Biomass burning: A source of nitrogen oxides in the atmosphere." In *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications,* J. S. Levine, ed. MIT Press, Cambridge, Massachusetts, 370-375.

Dowlatabadi, Hadi and M. Granger Morgan (1993). "A model framework for integrated studies of the climate problem." *Energy Policy* **21**(3): 209-221.

Dudal, R., J. Hrabovsky and A. Pecrot (1981). "Rice soils for food production." In *Proceedings of Symposium on Paddy Soil,* A. S. Institute of Soil Science, ed. Springer-Verlag, New York,

Edmonds, Jae, Hugh Pitcher, Dave Barns, Richard Baron and Marshall Wise (1991). "Modeling future greenhouse gas emissions: The second generation model description." Presented at the United Nations University Conference on Global Change and Modeling, Tokyo, Japan, October, 1991.

Ehhalt, D. H. and U. Schmidt (1978). "Sources and sinks of atmospheric methane." *Pure and Applied Geophysics* **116**: 452-464.

EIA (Energy Information Administration) (1988). *International Energy Annual, 1987.* DOE/EIA-0219(87), EIA, U.S. Department of Energy, Washington, D.C.

Eichner, Melissa J. (1990). "Nitrous oxide emissions from fertilized soils: Summary of available data." *Journal of Environmental Quality* **19**: 272-280.

EPA (U. S. Environmental Protection Agency) (1990). *Policy Options for Stabilizing Global Climate - Report to Congress: Technical Appendices.* 21P-2003.3, US EPA, Washington, D.C.

EPA (U. S. Environmental Protection Agency) (1993a). *Anthropogenic Methane Emissions in the United States: Estimates for 1990,* K. Hogan, ed. EPA-430/R-93-003, US EPA, Washington, D.C.

EPA (U. S. Environmental Protection Agency) (1993b). *National Air Pollutant Emission Trends, 1900-1992.* EPA-454/R-93-032, U.S. EPA, Washington, D.C.

FAO (Food and Agriculture Organization of the United Nations) (1990). *1989 FAO Fertilizer Yearbook.* FAO, Rome.

FAO (Food and Agriculture Organization) (1993). *FAO AGROSTAT PC*. FAO Statistics Division, FAO, Rome.

Fisher-Vanden, Karen, Jae Edmonds, Hugh Pitcher, Dave Barns, Richard Baron, Sonny Kim, Chris MacCracken, Elizabeth L. Malone, Ronald D. Sands and Marshall Wise (1993). "The second generation model of energy use, the economy, and greenhouse gas emissions." Presented to the Sixth Annual Federal Forecasters Conference, Crystal City, Virginia, September 3, 1993.

Frohberg, K. K. and P. R. Van de Kamp (1988). *Results of Eight Agricultural Policy Scenarios for Reducing Agricultural Sources of Trace Gas Emissions*. Center for Agricultural and Rural Development, Iowa State University.

Fujita, Shin-Ichi, Yoichi Ichikawa, Robert K. Kawaratani and Yutaka Tonooka (1991). "Preliminary inventory of sulfur dioxide emissions in East Asia." *Atmospheric Environment* **25A**(7): 1409-1411.

Fung, Inez, J. John, Jean Lerner, Elaine Matthews, M. Prather, L.P. Steele and P.J. Fraser (1991). "Three-dimensional model synthesis of the global methane cycle." *Journal of Geophysical Research* **96**(D7): 13,033-13,065.

Galbally, Ian (1985). "The emission of nitrogen to the remote atmosphere: Background paper." In *The Biogeochemical Cycling of Sulfur and Nitrogen in the Remote Atmosphere,* J. N. Galloway, R. J. Charlson, M. O. Andreae and H. Rodhe, ed. D. Reidel Publishing Company, Boston, 27-53.

Graedel, T. E., T. S. Bates, A. F. Bouwman, D. Cunnold, J. Dignon, I. Fung, D. J. Jacob, B. K. Lamb, J. A. Logan, G. Marland, P. Middleton, J. M. Pacyna, M. Placet and C. Veldt (1993). "A compilation of inventories of emissions to the atmosphere." *Global Biogeochemical Cycles* **7**(1): 1-26.

Grist, D. (1986). *Rice*. Longman, New York.

Hameed, Sultan and Jane Dignon (1988). "Changes in the geographical distributions of global emissions of NO_X and SO_X from fossil-fuel combustion between 1966 and 1980." *Atmospheric Environment* **22**(3): 441-449.

Hameed, Sultan and Jane Dignon (1992). "Global emissions of nitrogen and sulfur oxides in fossil fuel combustion, 1970-1986." *Journal of Air and Waste Management Association* **42**(159-163):

Hao, W. M., M. H. Liu and P. J. Crutzen (1990). "Estimates of annual and regional release of CO_2 and other trace gases to the atmosphere from fires in the tropics, based on FAO statistics for the period 1975-1980." In *Fire in the Tropical Biota: Ecosystem Processes and Global Challenges,* J. G. Goldammer, ed. Ecological Studies, 84, Springer-Verlag, Berlin-Heidelberg, 440-462.

Hegg, D. A., L. F. Radke, P. V. Hobbs, R. A. Rasmussen and P. J. Riggan (1990). "Emissions of some trace gases from biomass fires." *Journal of Geophysical Research* **95**(5669-5675):

Holzapfel-Pschorn, A. and W. Seiler (1986). "Methane emissions during a cultivation period from an Italian rice paddy." *Journal of Geophysical Research* **91**: 11803-11814.

ICF Resources (1990). *Methane Emissions from Coal Mining: Issues and Opportunities for Reduction*. ICF Resources, Fairfax, Virginia.

IPCC (Intergovernmental Panel on Climate Change) (1990). *Climate Change: The IPCC Scientific Assessment*, J. T. Houghton, G. J. Jenkins and J. J. Ephraums, ed. Cambridge University Press, Cambridge.

IPCC (Intergovernmental Panel on Climate Change) (1992). *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, J. T. Houghton, B. A. Callander and S. K. Varney, ed. Cambridge University Press, Cambridge.

Keller, M., W. A. Kaplan and S. C. Wofsy (1986). "Emissions of N_2O, CH_4 and CO from tropical forest soils." *Journal of Geophysical Research* **91**: 11791-11802.

Khalil, M. A. K. and R. A. Rasmussen (1983a). "Sources, sinks, and seasonal cycles of atmospheric methane." *Journal of Geophysical Research* **88**: 5131-5144.

Khalil, M. A. K. and R. A. Rasmussen (1983b). "Increase and seasonal cycles of nitrous oxides in the earth's atmosphere." *Tellus* **35B**: 161-169.

Khalil, M. A. K. and R. A. Rasmussen (1990). "The global cycle of carbon monoxide: trends and mass balance." *Chemosphere* **20**: 227-242.

Khalil, M. A. K., R. A. Rasmussen, Ming-Xing Wang and Lixin Ren (1991). "Methane emissions from rice fields in China." *Environmental Science and Technology* **25**(5): 979-981.

Kresse, K. and J. Ringeltaube (1982). "How resources recovery and appropriate technologies can cut costs at waste management in developing countries." In *Recycling in Developing Countries*, K. J. Thome-Kozmiensky, ed. E. Freitag, Berlin,

Langner, J. and H. Rodhe (1991). "A global three-dimensional model of the tropospheric sulfur cycle." *Journal of Atmospheric Chemistry* **13**: 225-263.

Lerner, Jean, Elaine Matthews and Inez Fung (1988). "Methane emission from animals: A global high-resolution database." *Global Biogeochemical Cycles* **2**: 139-156.

Levine, Joel S., Wesley R. Cofer III, Daniel I. Sebacher, Edward L. Winstead, Shirley Sebacher and Penelope J. Boston (1988). "The effects of fire on biogenic soil emissions of nitric oxide and nitrous oxide." *Global Biogeochemical Cycles* **2**(4): 445-449.

Liu, Yuexin (1992). "An Update Assessment Model for Atmospheric Composition and Climate Response." M.I.T. internal paper, Cambridge, Mass.

Lobert, Jurgen M., Dieter H. Scharffe, Wei M. Hao and Paul J. Crutzen (1990). "Importance of biomass burning in the atmospheric budgets of nitrogen-containing gases." *Nature* **346**: 552-554.

Logan, Jennifer A. (1983). "Nitrogen oxides in the troposphere: Global and regional budgets." *Journal of Geophysical Research* **88**(C15): 10785-10807.

Logan, Jennifer A., Michael J. Prather, Steven C. Wofsy and Michael B. McElroy (1981). "Tropospheric chemistry: A global perspective." *Journal of Geophysical Research* **86**(C8): 7210-7254.

Luizão, F., P. Matson, G. Livingston, R. Luizão and P. Vitousek (1989). "Nitrous oxide flux following tropical land clearing." *Global Biogeochemical Cycles* **3**: 281-285.

Martin, John P., Jean-Marc Burniaux, Giuseppe Nicoletti and Joaquim Oliveira-Martins (1992). "The costs of international agreements to reduce CO_2 emissions: Evidence from GREEN." *OECD Economic Studies* **19**: 93-121.

Matthews, Elaine, Inez Fung and Jean Lerner (1991). "Methane emission from rice cultivation: geographic and seasonal distribution of cultivated areas and emissions." *Global Biogeochemical Cycles* **5**(1): 3-24.

McElroy, Michael B. and Steven C. Woofsy (1985). "Nitrous oxide sources and sinks." In *Atmospheric Ozone, 1985, Vol. 1,* National Aeronautics and Space Administration, Washington, D.C., 81.

Mintzer, Irving (1988). *Projecting Future Energy Demand in Industrialized Countries: An End-Use Oriented Approach.* World Resources Institute, Washington D.C.

Möller, D. (1984). "Estimation of the global man-made sulfur emission." *Atmospheric Environment* **18**: 19-27.

Müller, Jean-Francois (1992). "Geographical distribution and seasonal variation of surface emissions and deposition velocities of atmospheric trace gases." *Journal of Geophysical Research* **97**(D4): 3787-3804.

Muzio, L. J. and J. C. Kramlich (1988). "An artifact in the measurement of N_2O from combustion sources." *Geophysical Research Letters* **15**(12): 1369-1372.

NASA (National Aeronautics and Space Administration) (1989). *An Assessment Model for Atmospheric Composition*, M. J. Prather, ed. NASA Conference Publication 3023, NASA, Washington D.C.

Neue, H. U., P. Becker-Heidmann and H. W. Scharpenseel (1990). "Organic matter dynamics, soil properties and cultural practices in rice lands and their relationship to methane production." In *Soils and the Greenhouse Effect*, A. F. Bouwman, ed. John Wiley & Sons, New York, 457-466.

OECD (Organization for Economic Cooperation and Development) (1989). *OECD Environmental Data Compendium 1989*. OECD, Paris.

OECD (Organization for Economic Cooperation and Development) (1991). *Estimation of Greenhouse Gas Emissions and Sinks*. Final Report from the OECD Experts Meeting, Paris, February 18-21, 1991.

Orlich, J. (1990). "Methane emissions from landfill sites and waste water lagoons." International Workshop on Methane Emissions from Natural Gas Systems, Coal Mining, and Waste Management Systems, Washington, D.C., April 9-13, 1990.

Pepper, William (1993). Personal communication.

Pepper, William, Jane Leggett, Rob Swart, John Wasson, Jae Edmonds and Irving Mintzer (1992). *Emissions Scenarios for the IPCC: An Update. Assumptions, Methodology, and Results*. ICF Resources, Fairfax, Virginia.

Prinn, R., D. Cunnold, R. Rasmussen, P. Simmonds, F. Alyea, A. Crawford, P. Fraser and R. Rosen (1990). "Atmospheric emissions and trends of nitrous oxide deduced from ten years of ALE/GAGE data." *Journal of Geophysical Research* **95**: 18369-18385.

Prinn, Ronald G. (1994). "The interactive atmosphere: Global atmospheric-biospheric chemistry." *Ambio* **23**(1): 50-61.

Richards, K. M. (1990). "Landfill gas: Working with Gaia." International Workshop on Methane Emissions from Natural Gas Systems, Coal Mining, and Waste Management Systems, Washington, D.C., April 9-13, 1990.

Ronen, Daniel, Mordeckai Magaritz and Ehud Almon (1988). "Contaminated aquifers are a forgotten component of the global N_2O budget." *Nature* **335**: 57-59.

Rotmans, J. (1990). *IMAGE: An Integrated Model to Assess the Greenhouse Effect*. Kluwer Academic Publishers, Boston.

Safley, L. M., M. E. Casada, Jonathan W. Woodbury and Kurt F. Roos (1992). *Global Methane Emissions from Livestock and Poultry Manure*. EPA 400/1-91/048, U.S. Environmental Protection Agency, Washington, D.C.

Sass, R. L., F. M. Fisher, P. A. Harcombe and F. T. Turner (1990). "Methane production and emission in a Texas rice field." *Global Biogeochemical Cycles* 4: 47-68.

Sathaye, J. A., A. N. Ketoff, L. J. Schipper and S. M. Lele (1988). *An End-Use Approach to Development of Long-Term Energy Demand Scenarios for Developing Countries.* International Energy Studies Group, Energy Analysis Program, Lawrence Berkeley Laboratory, Berkeley.

Schutz, H., A. Holzapfel-Pschorn, R. Conrad, H. Rennenberg and W. Seiler (1989). "A three-year continuous record on the influence of daytime, season, and fertilizer treatment on methane emission rates from an Italian rice paddy." *Journal of Geophysical Research* 94(D13): 16,405-16,416.

Schutz, H. and W. Seiler (1989). "Methane flux measurements: Methods and results." In *Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere,* M. O. Andreae and D. S. Schimel, ed. John Wiley and Sons, New York, 209-228.

Schutz, H., W. Seiler and H. Rennenberg (1990). "Soil and land use related sources and sinks of methane (CH_4) in the context of the global methane budget." In *Soils and the Greenhouse Effect,* A. F. Bouwman, ed. John Wiley and Sons, New York, 269-285.

Seeliger, W. and G. Zimmermeyer (1989). Private correspondence in ICF Resources (1990).

Seiler, W. (1984). "Contribution of biological processes to the global budget of CH_4 in the atmosphere." In *Current Perspectives in Microbial Ecology,* M. J. Klug and C. A. Reddy, ed. American Society for Microbiology, Washington, D.C., 468-477.

Seiler, Wolfgang and Ralf Conrad (1987). "Contribution of tropical ecosystems to the global budgets of trace gases, especially CH_4, H_2, CO, and N_2O." In *Geophysiology of Amazonia,* R. E. Dickinson, ed. John Wiley and Sons, New York, 133-162.

Seiler, Wolfgang and Paul J. Crutzen (1980). "Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning." *Climatic Change* 2: 207-247.

Seiler, W., A. Holzapfel-Pschorn, R. Conrad and D. Scharffe (1984). "Methane emission from rice paddies." *Journal of Atmospheric Chemistry* 1: 241-268.

Selzer, H. (1990). "Anthropogenic methane emissions." International Workshop on Methane Emissions from Natural Gas Systems, Coal Mining, and Waste Management Systems, Washington, D.C., April 9-13, 1990.

Sheppard, J. C., H. Westberg, J. F. Hopper, K. Ganesan and P. Zimmerman (1982). "Inventory of global methane sources and their production rates." *Journal of Geophysical Research* **87**(C2): 1305-1312.

Simpson, V. J. and C. Anastasi (1993). "Future emissions of CH_4 from the natural gas and coal industries." *Energy Policy* **21**(8): 827-830.

Spiro, Peter A., Daniel J. Jacob and Jennifer A. Logan (1992). "Global inventory of sulfur emissions with 1°x1° resolution." *Journal of Geophysical Research* **97**(D5): 6023-6036.

Steele, L. P., E. J. Dlugokencky, P. M. Lang, P. P. Tans, R. C. Martin and K. A. Masarie (1992). "Slowing down of the global accumulation of atmospheric methane during the 1980's." *Nature* **358**: 313-316.

Subak, Susan, Paul Raskin and David Von Hippel (1992). *National Greenhouse Gas Accounts: Current Anthropogenic Sources and Sinks.* Stockholm Environmental Institute, Boston.

Teisberg, Tom (1993). Personal communication.

Thiemens, Mark H. and William Trogler (1991). "Nylon production: an unknown source of atmospheric nitrous oxide." *Science* **251**: 932-934.

UNEP (United Nations Environment Programme) (1987). *Montreal Protocol on Substances that Deplete the Ozone Layer, Final Act.* No. 87-6106, UNEP, Nairobi, Kenya.

United Nations (1989). *1987 Energy Statistics Yearbook.* United Nations, New York.

United Nations (1993). *Statistical Yearbook 1990/91.* United Nations, New York.

Varhelyi, G. (1985). "Continental and global sulfur budgets—1. Anthropogenic SO_2 emissions." *Atmospheric Environment* **19**(7): 1029-1040.

Weyant, John (1993). Personal communication.

Whalen, M., W. Reeburg and K. Sandbeck (1990). "Rapid methane oxidation in a landfill cover soil." *Applied Environmental Microbiology* **56**: 3045-3411.

World Bank (1988). *World Bank, FAO, UNIDO Fertilizer Working Group Nitrogen Supply, Demand and Balances for 1986/87 to 1992/93.* World Bank, Washington, D.C.

WRI (World Resources Institute) (1992). *World Resources, 1992-93.* Oxford University Press, New York.

Appendix A

Table A.1: Agricultural output from GREEN (millions of $)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	196,596	226,266	260,935	299,688	335,259	373,117	547,660	712,671
JPN	72,831	80,018	94,798	112,333	126,666	138,344	203,979	295,007
EEC	200,860	218,232	240,683	264,457	283,537	301,503	371,698	426,177
OOE	83,916	88,564	97,017	106,139	113,389	121,136	152,616	175,816
EET	66,126	68,481	77,667	88,401	98,227	108,084	161,904	218,644
FSU	148,122	165,034	194,207	224,446	253,441	280,482	429,007	587,837
EEX	187,495	212,503	252,475	290,955	327,726	365,164	666,299	1,192,625
CHN	210,621	236,494	298,738	376,641	462,387	565,047	1,241,456	2,428,043
IND	90,381	110,316	137,776	171,624	208,183	251,528	531,249	1,012,792
DAE	45,492	44,788	53,860	65,186	77,328	91,912	178,190	315,365
BRA	35,059	39,793	49,183	60,988	73,956	90,257	184,892	328,485
ROW	123,114	133,628	157,479	190,544	226,386	267,993	492,306	729,795
Total	1,460,611	1,624,117	1,914,817	2,251,404	2,586,485	2,954,568	5,161,255	8,423,257

Table A.2: Methane emissions from rice paddies (Tg)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	1.3	1.4	1.5	1.5	1.6	1.7	2.0	2.3
JPN	3.1	3.2	3.5	3.7	3.9	4.0	4.8	5.7
EEC	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.6
OOE	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
EET	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
FSU	0.5	0.5	0.6	0.6	0.6	0.7	0.8	0.9
EEX	10.9	11.4	12.3	13.1	13.7	14.3	19.1	25.1
CHN	36.4	38.1	42.2	46.6	50.8	55.3	81.8	113.1
IND	20.3	22.1	24.3	26.7	29.0	31.4	45.4	61.9
DAE	7.8	7.8	8.4	9.1	9.8	10.6	14.5	19.0
BRA	1.9	2.0	2.2	2.4	2.6	2.9	4.1	5.3
ROW	17.1	17.7	18.9	20.5	22.0	23.7	31.6	37.7
Total	100	105	115	125	135	145	205	272

Table A.3: Breakdown of methane emissions from animal populations (Tg)

	Cattle emissions	Buffalo emissions	Sheep emissions	Goat emissions	Total emissions	Increase by 5%
USA	6.0	0.00	0.09	0.01	6.1	6.4
JPN	0.3	0.00	0.00	0.00	0.3	0.3
EEC	5.5	0.01	0.70	0.05	6.3	6.6
OOE	3.0	0.03	2.09	0.07	5.2	5.4
EET	1.8	0.01	0.23	0.01	2.0	2.1
FSU	6.7	0.02	1.14	0.03	7.9	8.3
EEX	0.0	0.32	0.80	0.44	1.6	1.6
CHN	2.2	0.98	0.48	0.32	4.0	4.2
IND	6.9	3.76	0.21	0.50	11.3	11.9
DAE	0.3	0.46	0.00	0.01	0.8	0.9
BRA	7.1	0.04	0.09	0.05	7.3	7.6
ROW	15.4	1.19	1.12	0.92	18.6	19.5
Total	55.1	6.8	7.0	2.4	71.3	74.8

Table A.4: Methane emissions from enteric fermentation (Tg)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	6.4	7.0	7.7	8.3	8.9	9.5	12.2	14.4
JPN	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.7
EEC	6.6	6.9	7.3	7.8	8.1	8.4	9.6	10.5
OOE	5.4	5.6	5.9	6.3	6.5	6.8	7.9	8.6
EET	2.1	2.2	2.3	2.5	2.7	2.9	3.7	4.5
FSU	8.3	8.8	9.8	10.7	11.5	12.3	16.2	19.7
EEX	1.6	1.8	2.0	2.2	2.3	2.5	3.7	5.5
CHN	4.2	4.5	5.2	6.0	6.8	7.7	13.2	20.8
IND	11.9	13.5	15.5	17.8	20.1	22.6	37.6	58.1
DAE	0.9	0.8	0.9	1.1	1.2	1.3	2.1	3.0
BRA	7.6	8.2	9.4	10.7	12.1	13.7	22.4	32.8
ROW	19.5	20.5	22.7	25.6	28.5	31.6	47.5	61.3
Total	74.8	80.2	89.1	99.3	109.2	119.7	176.6	239.8

Table A.5: Methane emissions from animal wastes (Tg)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	3.9	4.2	4.6	5.0	5.4	5.7	7.3	8.7
JPN	0.9	0.9	1.0	1.2	1.2	1.3	1.7	2.1
EEC	5.0	5.3	5.6	5.9	6.2	6.4	7.3	7.9
OOE	2.1	2.2	2.3	2.5	2.6	2.7	3.1	3.4
EET	1.8	1.9	2.0	2.2	2.4	2.5	3.2	3.9
FSU	4.2	4.5	5.0	5.4	5.9	6.2	8.2	10.1
EEX	2.1	2.3	2.5	2.7	3.0	3.2	4.7	7.0
CHN	2.9	3.1	3.6	4.2	4.8	5.4	9.3	14.6
IND	1.6	1.8	2.0	2.3	2.6	2.9	4.9	7.6
DAE	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.6
BRA	1.1	1.1	1.3	1.5	1.7	1.9	3.1	4.5
ROW	2.6	2.8	3.1	3.4	3.8	4.2	6.4	8.2
Total	28.3	30.2	33.3	36.6	39.6	42.8	59.7	78.6

Table A.6: GNP per capita from GREEN ($ per person)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	15432	16720	18179	19873	21306	22902	32123	43959
JPN	10477	12269	14384	16907	19021	21563	37355	60105
EEC	6920	7647	8445	9326	10080	10930	15379	20613
OOE	6648	6912	7203	7558	7805	8124	9894	11919
EET	2007	2223	2467	2734	2965	3225	4603	6090
FSU	2298	2506	2762	3060	3316	3597	5012	6537
EEX	1599	1679	1776	1893	1995	2121	2922	4153
CHN	424	491	572	673	780	912	1769	3388
IND	242	273	311	358	404	461	835	1466
DAE	1501	1700	1950	2256	2564	2935	5318	9421
BRA	1374	1528	1720	1963	2215	2514	4386	7587
ROW	707	733	763	795	816	843	1029	1262

Table A.7: Methane emissions from landfills (Tg)

Region	1985	1990	1995	2000	2005	2010	2030	2050
USA	9.57	10.03	10.48	10.90	11.27	11.61	12.55	12.58
JPN	3.28	3.38	3.48	3.56	3.62	3.64	3.62	3.54
EEC	5.77	5.84	5.91	5.96	5.99	6.00	5.93	5.64
OOE	2.04	2.19	2.34	2.48	2.60	2.71	3.07	3.24
EET	0.61	0.66	0.71	0.77	0.81	0.86	1.09	1.29
FSU	1.65	1.80	1.95	2.10	2.24	2.39	3.08	3.68
EEX	2.71	3.16	3.66	4.23	4.81	5.46	8.77	12.75
CHN	1.14	1.32	1.54	1.77	2.01	2.26	3.76	5.69
IND	0.47	0.56	0.65	0.76	0.87	1.00	1.71	2.66
DAE	0.68	0.79	0.91	1.04	1.18	1.33	2.16	3.21
BRA	0.48	0.56	0.66	0.76	0.86	0.98	1.61	2.41
ROW	1.59	1.85	2.15	2.49	2.85	3.24	5.20	7.37
Total	30	32.1	34.4	36.8	39.1	41.5	52.6	64.1

Table A.8: Population from GREEN (millions)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	239.3	249.9	260.0	269.1	277.2	284.6	301.5	296.8
JPN	120.8	123.5	125.9	127.8	129.0	129.2	123.6	117.4
EEC	321.9	324.0	326.1	327.6	327.7	326.8	316.5	296.2
OOE	118.4	126.8	135.3	143.1	150.0	155.8	174.6	182.1
EET	118.2	120.7	123.1	125.6	127.9	129.8	135.1	137.6
FSU	277.5	288.8	297.4	305.1	312.5	319.6	343.4	356.7
EEX	655.1	743.7	838.1	936.8	1,038.3	1,141.3	1,543.3	1,853.5
CHN	1,040.3	1,117.4	1,196.6	1,269.5	1,331.6	1,385.8	1,565.0	1,625.5
IND	750.9	831.9	913.0	991.9	1,070.6	1,144.9	1,394.2	1,571.4
DAE	174.4	189.7	203.9	217.2	229.9	241.6	280.0	299.7
BRA	135.6	150.2	164.5	177.7	189.4	200.9	241.7	265.0
ROW	869.0	993.8	1,132.1	1,283.4	1,446.4	1,617.3	2,342.8	2,979.9
Total	4,821.3	5,260.1	5,716.2	6,174.8	6,630.5	7,077.6	8,761.8	9,981.7

Table A.9: Methane emissions from domestic sewage treatment

	1985	1990	1995	2000	2005	2010	2030	2050
USA	1.24	1.30	1.35	1.40	1.44	1.48	1.56	1.54
JPN	0.63	0.64	0.65	0.66	0.67	0.67	0.64	0.61
EEC	1.67	1.68	1.69	1.70	1.70	1.69	1.64	1.54
OOE	0.61	0.66	0.70	0.74	0.78	0.81	0.91	0.94
EET	0.61	0.63	0.64	0.65	0.66	0.67	0.70	0.71
FSU	1.44	1.50	1.54	1.58	1.62	1.66	1.78	1.85
EEX	3.40	3.86	4.35	4.86	5.38	5.92	8.00	9.61
CHN	5.39	5.79	6.20	6.58	6.90	7.19	8.11	8.43
IND	3.89	4.31	4.73	5.14	5.55	5.94	7.23	8.15
DAE	0.90	0.98	1.06	1.13	1.19	1.25	1.45	1.55
BRA	0.70	0.78	0.85	0.92	0.98	1.04	1.25	1.37
ROW	4.51	5.15	5.87	6.65	7.50	8.39	12.15	15.45
Total	25	27.3	29.6	32.0	34.4	36.7	45.4	51.8

Table A.10: Coal output from GREEN (millions of $)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	26,744	27,825	22,530	16,186	12,619	11,399	8,547	7,678
JPN	8,823	9,101	9,883	8,448	7,853	7,401	9,171	10,499
EEC	14,063	13,046	11,176	8,272	6,745	6,251	5,045	4,427
OOE	6,999	7,600	7,776	7,553	7,535	7,616	8,643	9,492
EET	15,561	18,140	18,023	17,897	17,393	18,528	16,963	11,930
FSU	20,617	25,526	33,040	39,650	42,433	47,460	47,248	31,225
EEX	5,914	5,981	6,503	6,774	6,699	6,568	6,595	7,125
CHN	24,333	29,894	30,719	31,227	31,350	34,678	38,520	33,434
IND	5,347	6,243	7,127	8,216	9,125	11,012	13,654	10,765
DAE	1,193	1,199	1,469	1,905	2,323	2,861	4,051	4,194
BRA	402	213	217	275	359	517	1,089	1,420
ROW	2,081	1,996	2,222	2,548	2,950	3,504	2,904	1,533
Total	132,076	146,764	150,686	148,951	147,382	157,794	162,430	133,722

Table A.11: Methane emissions from coal mining (Tg)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	4.6	4.8	5.1	5.5	5.8	6.6	7.9	9.3
JPN	0.4	0.4	0.4	0.5	0.6	0.6	0.7	0.8
EEC	1.4	1.3	1.3	1.4	1.4	1.5	1.6	1.6
OOE	1.4	1.5	1.8	2.1	2.4	2.8	3.8	4.8
EET	1.4	1.4	1.3	1.1	1.0	0.9	1.3	2.8
FSU	8.4	10.1	8.1	6.9	5.9	5.6	9.0	15.2
EEX	7.3	8.9	8.1	7.4	6.3	5.9	7.9	9.7
CHN	1.4	1.7	1.7	1.7	1.8	1.9	3.7	7.1
IND	4.0	4.6	3.6	2.9	2.4	2.1	2.5	2.9
DAE	0.1	0.1	0.1	0.2	0.2	0.2	0.4	0.7
BRA	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2
ROW	0.6	0.6	0.6	0.7	0.9	1.0	1.6	2.3
Total	31.1	35.5	32.2	30.4	28.7	29.2	40.6	57.5

Table A.12: Natural gas output from GREEN (millions of $)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	47693.57	47105.90	47325.87	49006.46	51358.38	56680.30	46008.91	31070.27
JPN	468.73	360.35	372.85	442.37	523.69	402.29	171.37	139.60
EEC	29128.903	25397.35	25329.87	26150.85	27261.91	29798.3	30125.74	27511.48
OOE	15092.986	14233.11	15414.18	16758.11	18041.84	20350.19	16509.75	10021.77
EET	8347.909	7980.346	7836.738	7707.581	7577.358	8092.598	8654.042	4964.14
FSU	72667.791	88507.66	72257.8	61635.46	53522.69	53561.78	72691.31	98229.92
EEX	31106.421	31975.7	38596.64	44838.1	49539.35	48044.96	76244	192481.8
CHN	1806.117	2143.783	2504.007	2965.399	3472.943	4296.887	7941.17	13217.56
IND	529.572	688.3682	711.0298	706.6651	771.0427	865.1317	1235.021	1884.185
DAE	462.509	463.9345	535.9715	671.0786	840.1702	1060.646	1715.935	2471.247
BRA	196.953	726.9158	779.2684	844.2494	931.2176	1131.787	1054.06	767.9396
ROW	13216.068	11319.44	13593.07	16491.62	19576.75	23203.8	41409.99	63033.6

Table A.13: Methane emissions from venting and flaring operations (Tg)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	2.6	2.6	2.6	2.7	2.8	3.1	2.1	1.3
JPN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EEC	1.0	0.9	0.9	1.0	1.0	1.1	1.2	1.2
OOE	0.9	0.8	0.9	1.0	1.1	1.2	1.0	0.6
EET	0.5	0.4	0.4	0.4	0.3	0.4	0.4	0.2
FSU	3.5	4.2	3.2	2.6	2.1	2.0	2.4	2.9
EEX	11.4	11.7	5.2	3.8	3.1	2.3	3.5	8.5
CHN	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.8
IND	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.1
DAE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
BRA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ROW	0.3	0.3	0.3	0.4	0.5	0.6	1.0	1.4
Total	20.3	21.3	13.9	12.1	11.3	11.0	12.1	17.1

Table A.14: Methane emissions from transmission and distribution loss (Tg)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	3.9	3.8	3.8	4.0	4.2	4.6	3.1	1.9
JPN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EEC	1.5	1.4	1.4	1.4	1.5	1.6	1.7	1.8
OOE	1.3	1.3	1.4	1.5	1.6	1.8	1.4	1.0
EET	0.7	0.6	0.6	0.5	0.5	0.5	0.6	0.3
FSU	5.3	6.2	4.8	3.9	3.2	2.9	3.5	4.3
EEX	17.1	17.4	7.7	5.6	4.6	3.5	5.3	12.6
CHN	0.2	0.3	0.3	0.3	0.3	0.3	0.7	1.1
IND	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
DAE	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
BRA	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.0
ROW	0.5	0.4	0.5	0.6	0.7	0.8	1.4	2.2
Total	30.5	31.6	20.6	18.0	16.8	16.3	17.9	25.4

Table A.15: Emissions of greenhouse-relevant gases from biomass burning

Annual deforestation rate	0.3%							
	1985	1990	1995	2000	2005	2010	2030	2050
World agricultural output	1460611	1624117	1914817	2251404	2586485	2954568	5161255	8423257
Period growth rates		8%	13%	13%	11%	11%	56%	47%
Growth parameter for agric.	0.75							

Nitrous Oxide Emissions Tg N	1985	1990	1995	2000	2005	2010	2030	2050
Gain of cultivated land	0.40	0.41	0.41	0.42	0.42	0.43	0.46	0.49
Biomass burning total	0.60	0.61	0.63	0.66	0.68	0.70	0.83	0.99
SA+SV+PW	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
PA+FW	0.171	0.173	0.176	0.178	0.181	0.184	0.195	0.207
AW	0.12	0.13	0.15	0.17	0.19	0.21	0.32	0.48

Methane Emissions Tg CH4	1985	1990	1995	2000	2005	2010	2030	2050
Biomass burning total	48	49	51	52	54	56	66	79
SA+SV+PW	24.7	24.7	24.7	24.7	24.7	24.7	24.7	24.7
PA+FW	13.6	13.9	14.1	14.3	14.5	14.7	15.6	16.6
AW	9.7	10.5	11.9	13.4	14.9	16.5	25.8	38.0

NOx Emissions Tg N	1985	1990	1995	2000	2005	2010	2030	2050
Biomass burning total	12	12	13	13	14	14	17	20
SA+SV+PW	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
PA+FW	3.4	3.5	3.5	3.6	3.6	3.7	3.9	4.1
AW	2.4	2.6	3.0	3.4	3.7	4.1	6.5	9.5

SOx Emissions Tg S	1985	1990	1995	2000	2005	2010	2030	2050
Biomass burning total	2.5	3	3	3	3	3	3	4
SA+SV+PW	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
PA+FW	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.9
AW	0.5	0.5	0.6	0.7	0.8	0.9	1.3	2.0

CO Emissions Tg CO	1985	1990	1995	2000	2005	2010	2030	2050
Biomass burning total	800	817	844	874	902	932	1102	1322
SA+SV+PW	411.5	411.5	411.5	411.5	411.5	411.5	411.5	411.5
PA+FW	227.4	230.9	234.4	237.9	241.5	245.1	260.3	276.3
AW	161.1	174.6	198.0	224.1	249.2	275.8	430.2	634.2

Table A.16: Nitrous oxide emissions from fertilizer use (Tg)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	0.24	0.26	0.30	0.33	0.36	0.40	0.55	0.68
JPN	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.05
EEC	0.26	0.28	0.30	0.32	0.34	0.36	0.43	0.48
OOE	0.08	0.08	0.09	0.10	0.10	0.11	0.13	0.15
EET	0.11	0.11	0.12	0.14	0.15	0.16	0.22	0.29
FSU	0.27	0.30	0.34	0.38	0.42	0.46	0.65	0.85
EEX	0.14	0.15	0.17	0.19	0.21	0.23	0.39	0.63
CHN	0.34	0.37	0.45	0.55	0.65	0.76	1.49	2.64
IND	0.14	0.17	0.20	0.24	0.28	0.33	0.62	1.06
DAE	0.02	0.02	0.02	0.03	0.03	0.04	0.07	0.11
BRA	0.02	0.02	0.03	0.03	0.04	0.04	0.08	0.13
ROW	0.11	0.12	0.14	0.16	0.18	0.21	0.35	0.48
Total	1.75	1.91	2.18	2.50	2.80	3.13	5.01	7.54

Table A.17: Industrial output from GREEN (millions of $)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	6,008,517	6,841,805	7,795,180	8,871,540	9,842,121	10,872,965	16,259,380	21,929,621
JPN	2,305,872	2,801,664	3,372,142	4,040,492	4,600,763	5,114,796	8,155,477	12,440,719
EEC	4,367,130	4,939,828	5,536,173	6,186,032	6,729,601	7,278,335	9,969,225	12,547,217
OOE	1,416,314	1,607,658	1,804,587	2,018,186	2,195,838	2,377,854	3,309,362	4,211,371
EET	376,604	438,124	508,301	584,377	652,452	718,699	1,090,897	1,490,959
FSU	557,751	631,709	767,550	906,208	1,037,954	1,159,594	1,817,406	2,522,048
EEX	1,026,142	1,233,653	1,503,568	1,799,352	2,110,069	2,459,834	4,970,393	9,126,743
CHN	525,968	698,011	883,262	1,113,722	1,365,320	1,658,611	3,653,341	7,249,197
IND	202,359	257,495	324,295	407,690	499,109	608,276	1,360,989	2,709,144
DAE	466,426	599,075	745,646	923,958	1,114,235	1,335,011	2,783,247	5,249,704
BRA	345,204	421,195	523,386	648,682	782,888	938,950	1,972,180	3,721,312
ROW	930,770	1,088,265	1,305,669	1,581,732	1,871,577	2,193,705	4,012,517	6,333,827
Total	18,529,056	21,558,482	25,069,760	29,081,969	32,801,928	36,716,631	59,354,414	89,531,862

Table A.18: Nitrous oxide emissions from adipic acid (Tg)

Region	1985	1990	1995	2000	2005	2010	2030	2050
USA	0.15	0.17	0.19	0.21	0.23	0.25	0.32	0.37
JPN	0.06	0.07	0.08	0.09	0.10	0.11	0.15	0.19
EEC	0.11	0.12	0.14	0.15	0.16	0.17	0.20	0.23
OOE	0.04	0.04	0.04	0.05	0.05	0.06	0.07	0.08
EET	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02
FSU	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.04
EEX	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CHN	0.01	0.02	0.02	0.03	0.03	0.03	0.06	0.09
IND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BRA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.4	0.4	0.5	0.6	0.6	0.7	0.8	1.0

Table A.19: Energy-intensive industry (transportation) output from GREEN (millions of $)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	394,546	480,308	549,667	626,276	694,094	767,588	1,128,488	1,495,909
JPN	272,185	318,589	385,906	464,670	530,700	588,268	927,691	1,411,406
EEC	353,683	373,264	421,236	471,087	511,360	552,056	737,791	916,243
OOE	96,485	107,628	122,405	137,487	149,376	161,574	223,673	287,170
EET	76,123	88,651	99,816	112,525	124,210	136,272	202,997	272,265
FSU	104,836	130,959	141,325	161,027	182,659	202,659	336,327	489,694
EEX	84,270	101,672	123,775	142,413	162,169	179,999	388,294	832,247
CHN	135,690	180,731	230,374	292,751	361,337	443,018	987,438	1,962,344
IND	25,359	32,590	41,791	53,304	66,182	81,442	187,069	379,014
DAE	54,186	66,114	82,618	102,491	123,977	149,694	315,053	601,328
BRA	35,990	55,406	68,696	85,177	103,500	126,015	262,652	477,781
ROW	394,546	480,308	549,667	626,276	694,094	767,588	1,128,488	1,495,909
Total	2,027,901	2,416,220	2,817,276	3,275,485	3,703,659	4,156,174	6,825,962	10,621,309

Table A.20: Nitrous oxide emissions from fossil fuel combustion (Tg)

Region	1985	1990	1995	2000	2005	2010	2030	2050
USA	0.12	0.14	0.16	0.19	0.21	0.23	0.34	0.45
JPN	0.08	0.09	0.11	0.14	0.16	0.17	0.27	0.42
EEC	0.10	0.11	0.12	0.13	0.14	0.16	0.21	0.27
OOE	0.02	0.03	0.03	0.03	0.04	0.04	0.05	0.07
EET	0.02	0.03	0.03	0.03	0.04	0.04	0.06	0.08
FSU	0.03	0.04	0.04	0.05	0.05	0.06	0.10	0.14
EEX	0.03	0.04	0.04	0.05	0.06	0.07	0.14	0.26
CHN	0.04	0.05	0.07	0.09	0.11	0.13	0.29	0.58
IND	0.01	0.01	0.01	0.02	0.02	0.02	0.06	0.11
DAE	0.02	0.02	0.03	0.04	0.04	0.05	0.11	0.20
BRA	0.01	0.02	0.02	0.02	0.03	0.04	0.07	0.14
ROW	0.01	0.02	0.02	0.02	0.03	0.03	0.06	0.10
Total	0.5	0.6	0.7	0.8	0.9	1.0	1.8	2.8

Table A.21: Primary energy consumption from GREEN (millions of $)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	64,325	67,594	72,125	77,238	81,414	86,934	102,507	129,801
JPN	12,493	16,256	20,092	23,894	26,562	27,087	47,163	74,494
EEC	37,651	40,804	44,230	47,608	49,739	51,574	61,257	79,835
OOE	13,405	14,695	16,142	17,640	18,763	20,184	24,169	28,864
EET	14,867	16,461	16,737	16,979	16,873	17,734	21,419	27,249
FSU	49,145	54,930	53,989	53,572	51,749	53,957	67,543	84,802
EEX	19,689	21,763	24,388	27,138	29,940	32,859	51,651	90,343
CHN	20,994	25,469	27,340	29,301	30,749	34,355	56,170	101,692
IND	5,425	6,463	7,417	8,481	9,438	10,995	20,330	38,625
DAE	4,489	5,010	6,056	7,194	8,349	9,448	16,182	29,811
BRA	2,163	4,923	5,797	6,593	7,372	7,978	12,974	25,624
ROW	13,351	14,630	16,839	19,495	22,159	25,202	40,068	63,101
Total	257,997	288,997	311,153	335,131	353,105	378,308	521,435	774,243

Table A.22: NO_X emissions from fossil fuels (Tg)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	5.9	6.0	6.2	6.3	6.4	6.5	6.9	7.4
JPN	0.4	0.5	0.5	0.6	0.6	0.6	0.8	1.1
EEC	3.4	3.5	3.7	3.8	3.9	4.0	4.4	5.0
OOE	1.3	1.4	1.4	1.5	1.6	1.6	1.8	1.9
EET	1.1	1.2	1.2	1.3	1.2	1.3	1.6	2.0
FSU	5.0	5.6	5.5	5.4	5.2	5.5	6.8	8.6
EEX	2.0	2.2	2.5	2.8	3.1	3.3	5.3	9.2
CHN	2.1	2.6	2.7	2.9	3.1	3.4	5.6	10.2
IND	0.6	0.7	0.8	0.9	1.0	1.1	2.1	4.0
DAE	0.3	0.4	0.5	0.6	0.6	0.7	1.3	2.3
BRA	0.3	0.6	0.7	0.8	0.9	1.0	1.7	3.3
ROW	0.8	0.9	1.0	1.2	1.4	1.6	2.5	3.9
Total	23.2	25.5	26.7	28.0	29.0	30.7	40.6	58.9

Table A.23: CO emissions from fossil fuels (Tg)

	1985	Scaled down	1990	1995	2000	2005	2010	2030	2050
USA	82.6	82.6	83.4	84.0	84.7	85.3	86.1	88.6	90.5
JPN	20.7	20.7	21.3	22.5	23.6	24.5	25.0	25.7	26.5
EEC	34.2	34.2	34.2	34.8	35.5	36.0	36.8	37.4	37.8
OOE	21.6	21.6	22.2	23.0	23.9	24.6	25.4	26.1	26.7
EET	12.6	8.8	9.9	10.5	11.2	11.6	12.4	16.1	19.8
FSU	77.8	54.5	62.9	74.4	84.7	91.4	99.9	141.8	183.1
EEX	83.9	58.7	63.3	71.2	77.7	82.8	87.6	144.8	270.8
CHN	60.2	42.1	50.6	57.0	63.9	70.3	79.8	138.6	234.6
IND	40.2	28.1	32.7	38.2	44.9	51.2	60.0	113.6	201.0
DAE	18.2	12.7	13.9	16.4	19.4	22.7	26.9	47.9	79.6
BRA	41.7	29.2	30.8	34.3	41.9	50.6	63.9	129.7	217.2
ROW	76.9	53.8	55.9	63.7	73.9	84.5	96.8	155.2	218.8
Total	570.6	447.2	481.2	530.0	585.3	635.5	700.7	1065.4	1606.5

Table A.24: SO_X emissions from fossil fuels (Tg)

	1985	1990	1995	2000	2005	2010	2030	2050
USA	9.7	10.0	10.2	10.5	10.7	11.1	12.0	12.8
JPN	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.2
EEC	7.5	7.4	7.7	7.9	8.1	8.5	9.0	9.3
OOE	3.4	3.6	3.9	4.3	4.6	4.9	5.7	6.4
EET	9.4	10.9	11.3	11.8	12.1	13.1	16.9	21.2
FSU	11.2	13.9	17.0	19.9	21.7	24.2	36.8	50.2
EEX	4.5	4.8	5.4	5.7	5.9	6.0	10.1	21.8
CHN	9.6	12.1	13.5	15.1	16.4	18.8	33.8	61.4
IND	1.2	1.5	1.8	2.1	2.4	2.9	6.0	11.5
DAE	0.8	0.8	1.0	1.3	1.5	1.9	3.5	6.2
BRA	0.6	0.6	0.6	0.8	1.0	1.4	3.2	5.8
ROW	1.8	1.8	2.1	2.5	3.0	3.5	5.8	8.5
Total	60.4	68.1	75.3	82.7	88.3	97.1	143.9	216.3

Table A.25: SO_X emissions from industrial sources (Tg)

Region	1985	1990	1995	2000	2005	2010	2030	2050
USA	1.12	1.20	1.28	1.37	1.44	1.52	1.77	1.98
JPN	1.36	1.51	1.66	1.82	1.95	2.06	2.47	2.90
EEC	0.93	0.99	1.05	1.11	1.16	1.20	1.35	1.47
OOE	1.10	1.18	1.25	1.32	1.38	1.44	1.63	1.78
EET	0.68	0.74	0.80	0.86	0.91	0.96	1.12	1.26
FSU	1.47	1.56	1.73	1.89	2.03	2.15	2.55	2.88
EEX	0.64	0.70	0.78	0.85	0.93	1.00	1.35	1.72
CHN	0.42	0.49	0.55	0.63	0.70	0.77	1.08	1.44
IND	0.04	0.04	0.05	0.05	0.06	0.06	0.09	0.12
DAE	0.26	0.30	0.34	0.38	0.41	0.46	0.62	0.80
BRA	0.18	0.20	0.22	0.25	0.27	0.30	0.41	0.53
ROW	1.79	1.94	2.13	2.36	2.58	2.80	3.57	4.26
Total	10.0	10.8	11.8	12.9	13.8	14.7	18.0	21.1

Table A.26: Carbon emissions from GREEN

in 10^{15} g C	1985	1990	1995	2000	2005	2010	2030	2050
USA	1.276	1.348	1.442	1.547	1.632	1.738	1.995	2.700
JPN	0.260	0.340	0.420	0.501	0.558	0.522	0.589	1.004
EEC	0.758	0.825	0.894	0.961	1.003	1.033	1.159	1.624
OOE	0.269	0.297	0.327	0.358	0.381	0.408	0.486	0.602
EET	0.320	0.362	0.368	0.373	0.370	0.389	0.476	0.649
FSU	0.932	1.039	1.076	1.110	1.102	1.170	1.520	1.991
EEX	0.383	0.426	0.475	0.525	0.576	0.628	0.984	2.014
CHN	0.501	0.608	0.648	0.690	0.719	0.804	1.335	2.596
IND	0.126	0.150	0.173	0.198	0.221	0.258	0.488	0.977
DAE	0.098	0.109	0.132	0.156	0.182	0.205	0.334	0.705
BRA	0.046	0.099	0.117	0.133	0.149	0.163	0.283	0.695
ROW	0.285	0.312	0.359	0.415	0.472	0.546	0.906	1.638
Total	5.254	5.915	6.430	6.968	7.364	7.864	10.556	17.193

Equations describing the Green Emissions Submodel may

be found in the library of

the Joint Program on the Science and Policy of Global Change