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Greenhouse Gas Indices

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1. OBJECTIVES OF THE RESEARCH

Systems for computing the relative importance of different greenhouse gases are needed to support economic and policy analysis of issues of global change. Potentially, these relationships among gases will be used for several purposes: (1) to rank the relative worth of mitigation measures, (2) for summing the overall level of achievement under national targets for emissions reductions, and (3) as exchange rates in systems of emission permits trading. The weighting schemes used to date are based on the concept of Global Warming Potential (GWP), which is an integrated measure of radiative forcing which has several shortcomings for these purposes. It treats radiative gases as independent and additive in their effects, it assumes each has a fixed lifetime regardless of the chemical and physical state of the atmosphere, and it treats integrated radiative forcing over some arbitrary time period as a proxy for the social and environmental effects of global environmental change. Each of these assumptions, made in the interest of simplicity, is incorrect to some degree.

The objective of this DOE-sponsored research, carried out with the support of DOE Grant No. DE GF02-93ER61713, has been to analyze the various components of a relative gas index, and to seek a procedure that is simple and transparent but still representative of the relationship among gases. To compare the relative effects on climate change of emissions of various kinds, including aerosol precursors, the approach pursued in this research has been to develop a

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[computer algorithm encompassing the critically-linked elements which determine gas lifetimes and radiative influence, and the resulting climate effects. Elements to be considered in the course of the work have included the following:

- Regional economic growth and emissions, and the influence of mitigation measures,
- The latitudinal distribution of emissions,
- Chemical auto-feedbacks (, the influence of methane concentration on its own lifetime)
- Chemical-chemical feedbacks (, the influence of CO on the lifetime of methane)
- Multiple gases and aerosols, and their interactions,
- The linking of gas effects to damage measures, to seek an economic definition of relative weights.

As an outcome of this research, new capacity has been developed for analysis of these multi-gas issues as they relate to climate change. This report covers the accomplishments on this task. Publications and reports that have resulted in whole or in part from this research grant are listed in Section 3, and are included as attachments to this report.]

2. DEVELOPMENT OF ANALYSIS COMPONENTS

In this section we describe the modeling capability that has been put in place. In Section 3 we list research topics to which it has been applied.

2.1 Emissions Forecasts with Latitudinal Distribution

For analysis of the relative contributions to climate change and its effects of different greenhouse gases, a model of emissions is needed which includes each of the long-lived gases, carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and chlorofluorocarbons (CFCs) and their substitutes. Also important are emissions of several short-lived trace gases: nitrogen oxides (NO_x), sulfur dioxide (SO₂), carbon monoxide (CO). These gases drive atmospheric chemistry and so influence radiative forcing, through sulfate aerosol production, ozone (O₃) production and

CH₄ destruction. To accurately model atmospheric chemistry and to take account of expected shifts of emissions (e.g., from Europe and North America to China and Southern Asia) the geographic location and timing of these emissions are also significant, particularly for the short-lived trace gases.

To serve these functions within the integrated framework we have developed the Emissions Prediction and Policy Analysis (EPPA) Model (Yang *et al.*, 1996). EPPA is a multi-region, multi-sector, computable general equilibrium (CGE) model. The model is recursive-dynamic in that savings (and thus investment) in any period influence the capital stock in subsequent periods. The model covers the period 1985 to 2100 in five-year steps. The world is divided into 12 economic regions (consisting of individual or aggregated countries) which are linked by multi-lateral trade. The economic structure of each region consists of a number of production and consumption sectors, plus one government sector and one investment sector. The production breakdown is designed to highlight the seven sub-components of the energy sector, because of their importance in the production of climate-relevant gases. Two of the seven are potential future energy supply or "backstop" sectors. One of the backstops represents heavy oils, tar sands and shale, and produces a perfect substitute for refined oil. The other is a non-carbon electricity source, which represents the possible expansion of technologies like advanced nuclear and solar power.

Each of the eight non-backstop producer sectors (five energy and three non-energy) is modeled by a nested set of production functions in which the degree of substitutability among input factors is assumed constant at each level of the nesting. These so-called "constant-elasticity-of-substitution" (CES) functions allow a flexible representation of the degree of substitution between inputs to the production process. The output of each sector results from the combination of intermediate goods and energy provided by one or more of the energy sectors,

and three primary factors: labor, capital, and for some sectors a fixed factor. The fixed factor represents land in agriculture, geological reserves in the production of oil, gas and coal, and nuclear and hydropower capacity in the electricity sector.

All goods are traded among regions, and all but two are treated with an Armington specification (i.e., goods from abroad are assumed to be imperfect substitutes for domestic ones, and imports for the same general purpose from different regions are assumed not to be identical to one another). The two exceptions are crude oil and natural gas; imported and domestic supplies of each are treated as perfect substitutes.

Emissions for each region are then a function of the levels of activity in key production sectors, and in some consumer sectors. Energy use in production and consumption generates varying amounts of CO₂, CH₄, N₂O, SO₂, CO and NO_x, depending on the fossil fuel source, and the emissions control policies assumed to be in place. Similarly, trace gas emissions result from other human activities included in the model. For example, a component of anthropogenic CH₄ emissions is driven by the level of activity in the agriculture sector.

Emissions by each EPPA region are then resolved to emissions by 7.8° latitude band, to provide the needed input to the coupled climate-chemistry model (Yang *et al.*, 1996). Emissions of the long-lived gases (CO₂, N₂O, CH₄ and the CFCs) are distributed by a mapping function that remains constant over time since exact emission location is not critical for these. Emissions of the short-lived gases (CO, NO_x and SO_x), whose locations are important, are distributed within each region according to the time varying internal distribution of population, and sums across the 12 regions by latitude band yields the latitude totals. This model of emissions by gas and by latitude band provide a time series of input data to the chemistry-climate model, and to the studies of relative gas influence, both described below.

2.1 Coupled Model of Atmospheric Chemistry

To support the multi-gas analysis of atmospheric composition we have developed a coupled two-dimensional atmospheric model of chemistry and climate. This is a finite difference

model on latitude-pressure coordinates, and the continuity equations for trace constituents are solved in mass conservative or flux form (Sokolov and Stone, 1998; Wang, Prinn, and Sokolov, 1998). The local trace species tendency is thus a function of convergence due to two-dimensional advection, parameterized north-south eddy transport, and convective transports, and local true production or loss due to surface emission or deposition and atmospheric chemical reactions.

The atmospheric chemistry model includes 25 chemical species including CO_2 , CH_4 , N_2O , O_3 , CO , H_2O , NO_x , HO_x , SO_2 , sulfate aerosol and chlorofluorocarbons. There are 41 gas-phase and 12 heterogeneous reactions. The continuity equations for CFCl_3 , CF_2Cl_2 , N_2O , O_3 , CO , CO_2 , NO , NO_2 , N_2O_5 , HNO_3 , CH_4 , CH_2O , SO_2 , and H_2SO_4 include convergences due to transport whereas the remaining very reactive atoms, free radicals, or molecules are assumed to be unaffected by transport because of their very short lifetimes. Water vapor and air (N_2 and O_2) mass densities are computed using full continuity equations as a part of the climate model to which the chemical model is coupled. The latter model also provides wind speeds, temperature, solar radiation flux and precipitation which are used in the chemistry formulation.

In its present form the chemical model uses specified stratospheric photochemical destruction rates computed off-line in a global 3D stratospheric model. The model at present does not consider non-methane hydrocarbons but a simplified treatment of these is planned for future versions. The advection scheme is fourth-order positive-definite and is used in a time-splitting procedure to calculate advection in each spatial dimension in order. Then a non-oscillatory scheme is used to limit numerical errors induced by possible spurious estimates of fluxes. Finally, a mass adjustment for correcting the error induced by time-splitting and possible non-convergence-free wind fields is used.

The chemical model is run almost fully interactively with the 2D-LO climate model (Wang, Prinn, and Sokolov, 1998). The model computes the zonal-means of predicted species

concentrations over land and ocean (or both) on the 24 latitudinal by nine vertical layers (seven tropospheric and two stratospheric) grid of the 2D-LO model. The time stepping for the chemistry is 20 minutes for advection, one hour for physics (other than radiation), and three hours for photochemistry. The chemistry and climate dynamics (with the exception of O_3) are fully interactive: specifically every five hours the calculated radiative forcing is updated by the predicted concentrations of CO_2 , CH_4 , N_2O , chlorofluorocarbons, and sulfate aerosol. Aerosols can also affect radiative forcing indirectly through increasing the reflectivity of water clouds. This indirect aerosol effect is poorly understood and highly uncertain. In most applications we follow the Intergovernmental Panel on Climate Change (IPCC) and assume somewhat arbitrarily that indirect aerosol radiative forcing is twice the calculated direct radiative forcing. North-south transport in the coupled model, which is based on predicted winds and a parameterized eddy transport scheme, has been tested using the chlorofluorocarbon $CFCI_3$. While further improvements are planned, the current version provides a reasonably good simulation of observed distributions of CH_4 , CO , and O_3 (Wang, Prinn, and Sokolov, 1998), and predicts OH concentrations and distributions in reasonable agreement with those derived from CH_3CCl_3 . OH is the major gas-phase species removing CH_4 , CO , SO_2 , and NO_x from the atmosphere.

3. APPLICATION OF NEW MODEL CAPABILITY TO MULTI-GAS ISSUES

3.1 Studies of Multi-Gas Interactions

The model components described above have been integrated into the MIT Integrated Global System Model (IGSM), which is the needed tool for analysis of multi-gas effects in climate change, and for assessment of the relative influence of different gases. The IGSM model is described by Prinn *et al.* (1998). Included in the model description are the multi-gas emissions forecasts and the effect of the trace gases (particularly SO_2 as an aerosol precursor) on the latitudinal distribution of the radiative forcing of temperature change.

This new coupled model of atmospheric chemistry and climate has been applied to several studies of the details of multi-gas interactions in the atmosphere. To gauge the overall effect of the complex interactions among emissions, atmospheric chemistry and climate, Wang and Prinn (1997) conducted a series of 120-year simulations using alternative emissions predictions and different assumptions for climate and chemistry model parameters. To study the influence of individual chemical species, sensitivity runs were made which included or excluded the particular gases. The hydroxyl radical (OH) is the key atmospheric component determining the lifetime of particular gases (importantly including methane) and Wang and Prinn (1998a) conducted a study of the evolution of tropospheric concentrations of OH along with other atmospheric components. The results indicate possible significant changes in the lifetime of CH₄ over the next century. Similarly, there is a strong interaction between CO and CH₄ in the atmosphere (both being destroyed in a reaction with OH) and possible trends in CO over the next century also were analyzed by Wang and Prinn (1998b) using the global chemistry-climate model.

3.2 Application of the Multi-Gas Capability to Policy Studies

The IGSM, with the multi-gas analysis capability developed as part of this research, has been applied to several studies of global climate policy. Two of these have been published. Jacoby *et al.* (1997) who used the model to analysis the effects of control policies that are applied to only a subset of nations. The analysis specifically shows what effect a restrictive policy will have on changes in atmospheric CO₂ concentrations over the next century. Also studied is the effect of the policy on global temperature change, taking account of the effects of CO₂ control policies on the emissions of other greenhouse gases and of CO and NO_x. In this study, the emissions of non-CO₂ greenhouse-relevant gases were assumed to be free of direct controls, although they are influenced by the controls applied to CO₂.

3.3 Studies of Multi-Gas Weighting Functions

We have conducted two studies which illustrate the application of the new multi-gas analysis capability to issues in the construction of gas weighting systems. One demonstrates the influence of emissions control policy on the lifetime of methane, estimating the error introduced by assuming this lifetime is independent of the overall chemical composition of the atmosphere. The other explores the consistence of IPCC-derived GWP measures with a weighting procedure that takes climate damage into account.

Policy Effects on Gas Lifetimes. The GWP approach implicitly assumes that the chemical composition of the atmosphere does not change sufficiently from the current condition (under which gas lifetimes were estimated by the IPCC). In fact, policy changes, such as controls on CO₂ can have just such an effect. This phenomenon was investigated using the following experiment. A comparison was made between the path of methane concentrations under the following three cases, shown in Table 1. Account was taken of the emissions of five gases: CH₄, CO₂, SO₂, NO_x and CO. The analysis is based on three cases involving control of different combinations of gases. When a gas assumes its reference case emissions, as defined by the MIT EPPA model (Yang *et al.*, 1996) the case is denoted R; when a gas is under control, the case is denoted C.

Table 1. Cases for Analysis of Methane Contribution

GAS/CASE	1	2	3
CH ₄	R	C	C
CO ₂	R	R	C
SO ₂	R	R	C
NO _x	R	R	C
CO	R	R	R

Case 1. A reference case using the Integrated Global System Model. No policy restrictions are imposed on emissions. This case is noted RRRRR.

Case 2. Methane only is controlled at the 1990 level. This case is noted CRRRR.

Case 3. Methane is controlled at the 1990 level as in Case 2. In addition, CO₂ also is controlled at the 1990 level. Because CO₂ control comes largely through a reduction in coal burning, there is an associated reduction of the emissions of SO_x and NO_x. This association is approximated by also holding these two gases at their 1990 levels, which yields the notation CCCCCR.

For this experiment, CO (which also has a strong interaction with methane chemistry) is held at its reference value throughout. The resulting forecasts of these gases are shown in Figures 1 and 2. Also shown in the figures is are the IS92a forecasts of the IPCC.

The question at issue is whether there is a difference in predicted methane concentrations between Case 2 and Case 3. That is, is the lifetime of methane affected by the imposition of a policy on CO₂, which changes the emissions of other greenhouse-relevant gases, and which in turn changes the physical state of the atmosphere (through influences on temperature, humidity, etc.)? The result is shown in Figure 3. The top part of the figure shows the mixing ratio of

methane under the three cases. It can be seen that the addition of controls on CO₂ (and associated NO_x and SO_x) raises the concentration of methane in the atmosphere (given the same 1990 control levels for methane in both Cases 2 and 3). The percent change (Case 3 relative to Case 2) is shown in the lower part of the figure. By 2100 the resulting estimate of methane concentration (and thus its instantaneous radiative forcing) differs by some 16% as a result of policy influences on gases other than methane.

Consistency of GWP with Economic Concepts. Another shortcoming of the GWP concept is that, although it is supposed to be used as an exchange rate among gases in economic calculations, it has no economic content. To explore the degree of potential inconsistency between the GWP values as proposed by the IPCC and an economics-based measure, an alternative index was developed for comparison. Referred to as the Relative Damage Index (RDI), for methane this measure is defined as

$$RDI = \frac{\text{Discounted Sum of Damage (CH}_4\text{)}}{\text{Discounted Sum of Damage (CO}_2\text{)}}$$

where damage is expressed as a function of temperature change. The temperature change associated with each of the gases was calculated by introducing a pulse in 1990 and using the IGSM to compute the ΔT over the period 1990 to 2100. Following the economics literature on climate change, the level of damage associated with a given temperature change was expressed as a percentage of GDP. The function was assumed to be exponential in temperature, with zero loss at $\Delta T = 0$. A set of GDP loss values was tested for $\Delta T = 3^\circ\text{C}$ which ranges from 1% to 5%.

The question then is the following. For what loss functions (assuming the temperature response to greenhouse gases of the reference version of the IGSM) and what discount rates is the standard IPCC value of the GWP for methane consistent with the RDI (with its analysis of climate response to radiative forcing and its economic basis)? The results are shown in Table 2.

Table 2. Relative Damage Index for Methane

Discount Rate	% GDP Loss at $\Delta T = 3^{\circ}\text{C}$				
	1%	2%	3%	4%	5%
1%	28.4	25.7	23.7	22.2	21.0
2%	35.2	32.7	30.9	29.5	28.3
3%	41.0	38.9	37.2	36.0	34.9
4%	46.0	44.1	42.7	41.6	40.6
5%	50.2	48.6	47.4	26.4	45.6

The IPCC value for the GWP for methane (in relation to CO_2) for a 100 year integration period is 24.5. As Table 2 shows, this value is most closely consistent with a GDP loss at 3°C of between 2% and 3% and a discount rate of 1%. More important, and index based on radiative forcing alone, like the GWP, when calculated on a 100 year horizon, is consistent with the RDI only for interest rates near 1%. As the table shows, this result holds for a wide range of assumptions of the economic impact of climate change. This discount rate is far below even the lowest rates commonly discussed in relation to the climate issue.

This result suggests that, if a GWP concept is to be used in setting multigas climate policies, an integration period of less than 100 years will be needed to provide consistency with simple economic concepts of the relative impact of different gases.

3. PUBLICATIONS AND REPORTS RESULTING FROM THIS RESEARCH

Jacoby, H., R. Eckaus, A. Ellerman, R. Prinn, D. Reiner and Z. Yang (1997). CO₂ Emissions Limits: Economic Adjustments and the Distribution of Burdens, *The Energy Journal* **18:3**, July. (Originally released as MIT Joint Program on the Science and Policy of Global Change, Report No. 9, May 1996.)

MIT Joint Program (1996), A Caution About Global Warming Potentials, MIT Joint Program on the Science and Policy of Global Change, Climate Science and Policy Note #1.

Prinn, R., H. Jacoby, A. Sokolov, C. Wang, X. Xiao, Z. Yang, R. Eckaus, P. Stone, E. Ellerman, J. Melillo, J. Fitzmaurice, D. Kicklighter, G. Holian, and Y. Liu (1998). Integrated Global System Model for Climate Policy Assessment: Feedbacks and Sensitivity Studies, *Climatic Change*, in press. (Originally released as MIT Joint Program on the Science and Policy of Global Change, Report No. 7, June 1996.)

Wang, C. and Prinn (1997). Interactions Among Emissions, Atmospheric Chemistry, and Climate Change: Implications for Future Trends, MIT Joint Program on the Science and Policy of Global Change, Report No. 25, September.

Wang, C., and R. Prinn (1998a). Combined Effects of Anthropogenic Emissions and Resultant Climatic Changes on Atmospheric OH, MIT Joint Program on the Science and Policy of Global Change, Report No. 34, April.

Wang, C., and R. Prinn (1998b). Impact of Emissions, Chemistry, and Climate on Atmospheric Carbon Monoxide: 100-Year Predictions from a Global Chemistry-Climate Model, MIT Joint Program on the Science and Policy of Global Change, Report No. 35, April.

Wang, C., R. Prinn and A. Sokolov (1998). A Global Interactive Chemistry and Climate Model: Formulation and Testing, *Journal of Geophysical Research* **103:3399-3417**. (Originally released as MIT Joint Program on the Science and Policy of Global Change, Report No. 24, September 1997).

Yang, Z., R. Eckaus, A. Ellerman and H. Jacoby (1996). The MIT Emission Prediction and Policy Analysis Model, MIT Joint Program on the Science and Policy of Global Change, Report No. 6, May.

Sokolov, A. and P. Stone (1998). A flexible climate model for use in integrated assessments. *Climate Dynamics* **14: 291-303**. (Originally released as MIT Joint Program on The Science and Policy of Global Change, Report No. 17, March 1997).

Figure 1. Emission Paths for CH_4 , NO_x and SO_x

Figure 2. Emission Paths for CO₂ and CO

Figure 3. Effect of Alternative Control Regimes on the Methane Mixing Ratio.