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**Sector-Specific Issues and Reporting Methodologies
Supporting the General Guidelines for
the Voluntary Reporting of Greenhouse Gases
under Section 1605(b) of the Energy Policy Act of 1992**

Global Warming Potentials

Part 7 of 7 Supporting Documents

**United States Department of Energy
Washington, D.C. 20585
May 31, 1994**

Printed with soy ink on recycled paper

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**Global Warming Potentials and Other Indices
for Representing Greenhouse Gas Effects on Climate**

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7.0 Global Warming Potentials and Other Indices for the Effects of Greenhouse Gases on Climate

Your reports on emissions and emission reductions will include data on greenhouse gases in tons of each gas emitted; you will not be required to calculate the various effects of different gases on climate. However, you may wish to perform these calculations for your own purposes. For example, you may wish to evaluate the costs of competing proposed projects in terms of the beneficial effects on climate; in order to do so, you may wish to look at these effects using a common index, such as the equivalent effect in tons of carbon dioxide. You may wish to talk about such equivalencies with various stakeholders or for public relations purposes. The discussion and data in this supporting document will help you in these endeavors; however, you should recognize that the science underlying greenhouse gas indexing is still evolving.

This supporting document provides methods to account for the different effects of different gases on the atmosphere. It discusses the rationale and uses for simplified measures to represent human-related effects on climate and provides a brief introduction to a major index, the global warming potential (GWP) index. Appendix 7.A analyzes the science underlying the development of indices for concerns about climate, which is still evolving evaluates the usefulness of currently available indices, and presents the state of the art for numerical indices and their uncertainties.

For concerns about climate, the Intergovernmental Panel on Climate Change (IPCC) has been instrumental in examining relative indices for comparing the radiative influences of greenhouse gases. The IPCC developed the concept of GWPs to provide a simple representation of the relative effects on climate resulting from a unit mass emission of a greenhouse gas (IPCC 1990, 1992). Alternative measures and variations on the definition of GWPs have also been considered and reported.

7.1 Why Develop Indices for Greenhouse Gases?

An index that places greenhouse gases on an equivalent scale for their effects on climate has considerable practical value. Such an index can be used in a variety of different analyses:

- performing cost-benefit analyses of various candidate projects to reduce greenhouse gas emissions
- assessing the relative contributions of the many human activities contributing to greenhouse gas emissions
- comparing (and ranking) climate effects from competing technologies and energy uses, including consideration of different energy policies
- developing approaches to minimize the impact of human activities on the climate system

- comparing the global climate change contributions of various countries
- functioning as a signal to policymakers for encouraging some activities and discouraging others
- determining approaches most appropriate for industries and governments to meet commitments to help reduce the radiative forcing on climate from increasing concentrations and emissions of greenhouse gases.

The concept of radiative forcing on climate allows policymakers to consider the relative merits of policies without fully resolving the many uncertainties about the magnitude of climate change. Radiative forcing is defined as the change in net irradiance at the tropopause after allowing stratospheric temperatures to readjust to stratospheric equilibrium. In simplified terms, radiative forcing is the change in solar irradiation that reenters the layer of atmosphere closest to the Earth (the troposphere) instead of escaping to space (see Figure 7.1). Uncertainties exist because much is unknown about the atmospheric chemistry that affects climate change and because computational models of the global climate system are either complex and expensive or too simplified to represent all facets of the system.

Figure 7.1. Schematic Illustration of Major Components of the Coupled Atmosphere-Ocean-Ice-Land Climatic System (from Wuebbles 1993).

The direct and indirect effects of emitted gases are not completely understood. Much of the concern about the effects of greenhouse gases on climate has centered around carbon dioxide both because it is an important greenhouse gas and because its atmospheric concentration has been rapidly increasing. However, other greenhouse gases are contributing about half of the overall increase in the radiative forcing effect on climate (IPCC 1990). In addition to these direct radiative effects, research studies have shown that chemical interactions in the atmosphere can lead to indirect effects on climate.

Table 7.1 shows GWPs for five greenhouse gases. For example, it shows that every kilogram of methane emitted to the atmosphere has 56-110 times the effect on radiative forcing as a kilogram of carbon dioxide (over a 20-year period). This table is further expanded and discussed in Section 7.3.

Table 7.1. Direct Global Warming Potentials for Selected Gases^(a)

Species	Chemical Formula	Atmospheric Lifetime (years)	Global Warming Potential (Time Horizon)		
			20 years	100 years	500 years
Carbon dioxide	CO ₂	(b)	1	1	1
Methane ^(c)	CH ₄	12-18 ^(d)	56-110	19-43	9-16
Nitrous oxide	N ₂ O	121	290	320	170
Perfluoromethane	CF ₄	50000	2700	4000	6100
CFC-11	CFCl ₃	50 ± 5	5000	3900	1400
<p>(a) Referenced to the AGWP for the Bern carbon cycle model CO₂ decay response and future CO₂ atmospheric concentrations held constant at current levels (based on IPCC 1994 and WMO 1994).</p> <p>(b) Decay of CO₂ is a complex function of the carbon cycle (see text).</p> <p>(c) Includes direct and indirect components.</p> <p>(d) Includes the dependence of the residence time on CH₄ abundance (see text).</p>					

Indices like GWPs provide policymakers with a lower cost alternative to complex numerical modeling. Such models suggest that the Earth's surface temperatures could increase by as much as 3° Celsius (estimated range of 2° to 5° Celsius over the next century (IPCC 1990, 1992), owing to changes projected in the concentrations of greenhouse gases. This prediction largely depends on complex three-dimensional numerical models of the global climate system (atmosphere, oceans, and land surface). These models attempt to represent the many processes influencing climate (see Figure 7.1). They are computationally demanding, and their complexity prohibits their routine use in policy-related analyses of greenhouse gases and their effects on climate.

Other tools to analyze changes may be found in simplified models of the climate system (e.g., Jain and Wuebbles 1994; Rotmans et al. 1990) that can be coupled with models of economics/energy and climatic impacts for an integrated assessment of effects. Although such models will have many uses, significant uncertainties remain in the overall understanding of key climatic processes and feedbacks; these uncertainties will influence the detailed quantitative changes expected in future climate and have serious implications for any models attempting to predict the regional and global magnitude of future climate changes from greenhouse gases.

7.2 How to Evaluate Global Warming Potentials (GWPs)

Direct and indirect GWPs have recently been reevaluated for the new international climate and ozone assessments (IPCC 1994; WMO 1994). These assessments are not yet finished, and the GWP values are still subject to some refinements at the time this report is being prepared; nonetheless, the preliminary values for GWPs represent clear improvements in the science since the earlier assessments and will be presented here.

In prior assessments (IPCC 1990, 1992; WMO 1992), the decay response curve (see Appendix 7.1 for a definition and discussion of this term) for CO₂ used in evaluation of the GWPs was based on results from an "unbalanced" carbon cycle model that did not correctly calculate the current CO₂ concentration based on a realistic emission history. The new assessments base the CO₂ response curve on results from more sophisticated carbon cycle models with improved treatments of ocean and biospheric effects that are "balanced," giving a consistent determination of past and present concentrations of CO₂.

GWPs are very sensitive to the assumed background concentration for CO₂. The constant concentration background assumed in prior GWPs, and also used in the evaluation presented in Table 7.2, is clearly unrealistic. This assumption implies that emissions enter a system in equilibrium, whereas the carbon cycle system is currently far from the equilibrium as a result of past emissions, and CO₂ concentrations are likely to increase into the foreseeable future. However, the choice of which future scenario to assume is also uncertain. In *Radiative Forcing of Climate* (IPCC 1994), the definition for the background atmosphere is chosen to provide consistency with evaluations in earlier assessments; at the same time, as will be presented below, information is provided that allows determination of GWPs for several other assumptions of future CO₂ background concentrations.

Table 7.2 summarizes the results for GWPs included in the new assessments (as of February 1994). It presents several new gases proposed as replacements for CFCs and halons that were not considered in prior assessments (including HCFC-225a, HCFC-225cb, and CF₃I) and that have GWPs much smaller than the compounds they would replace (also see Clerbaux et al. 1993; Solomon et al. 1994). Also included are several fully fluorinated species, including SF₆, CF₄, and C₂F₆ that have very large GWPs, particularly over longer integration time scales due to their long atmospheric lifetimes (Ravishankara et al. 1993; Wuebbles and Grossman 1992; Grossman et al. 1993).

GWP values for methane in Table 7.2 include the indirect effects of methane on ozone, water vapor, hydroxyl, and carbon dioxide. The methane GWPs show a range representing uncertainties in these indirect effects.

The direct GWPs given in Table 7.2 can be readily converted to Absolute Global Warming Potentials (AGWPs) or to GWPs that depend on a changing background atmosphere (such as the scenario, labeled S650, developed for the carbon cycle chapter of IPCC 1994; the scenario stabilizes CO₂ at 650 ppmv). Table 7.3 shows the relevant factors necessary to converting to these approaches. To convert to AGWP units, multiply the numbers in Table 7.2 by the AGWP values for fixed CO₂ from the Bern carbon cycle model (line 1 in Table 7.3). By comparing the appropriate AGWPs, you can also determine the effects from using other background scenarios for CO₂.

Table 7.2. Direct Global Warming Potentials^(a)

Species	Chemical Formula	Atmospheric Lifetime (years)	Global Warming Potential (Time Horizon)		
			20 years	100 years	500 years
CO ₂	CO ₂	(b)	1	1	1
CFCs					
CFC-11	CFCl ₃	50±5	5000	3900	1400
CFC-12	CF ₂ Cl ₂	102	8000	8300	4000
CFC-13	CClF ₃	640	8700	12100	13800
CFC-113	C ₂ F ₃ Cl ₃	85	5100	4900	2200
CFC-114	C ₂ F ₄ Cl ₂	300	7000	9100	7900
CFC-115	C ₂ F ₅ Cl	1700	6300	9100	12400
HCFCs, etc.					
HCFC-22	CF ₂ HCl	13.3	4300	1600	500
HCFC-123	C ₂ F ₃ HCl ₂	1.4	310	90	30
HCFC-124	C ₂ F ₄ HCl	5.9	1500	470	140
HCFC-141b	C ₂ FH ₂ Cl ₃	9.4	1800	620	190
HCFC-142b	C ₂ F ₂ H ₃ Cl	19.5	4300	2000	600
HCFC-225CA	C ₃ F ₅ HCl ₂	2.5	590	180	50
HCFC-225CB	C ₃ F ₅ HCl ₂	6.6	1800	570	170
Carbon Tetrachloride	CCl ₄	42	2000	1400	480
Methyl Chloroform	CH ₃ CCl ₃	5.4±0.4	360	110	30

Table 7.2. (contd)

	Chemical Formula	Atmospheric Lifetime (years)	Global Warming Potential (Time Horizon)		
			20 years	100 years	500 years
Bromocarbons					
H-1301	CF ₃ Br	65	6300	5500	2100
Other					
HFC-23	CHF ₃	390	9500	12700	12400
HFC-32	CH ₂ F ₂	6	1900	570	180
HFC-43-10mee		20.8	3400	1600	490
HFC-125	C ₂ HF ₅	36.0	5000	3200	1100
HFC-134	C ₂ H ₂ F ₄	11.9	3200	1160	350
HFC-134a	CH ₂ FCF ₃	17.7	3800	1700	510
HFC-152a	C ₂ H ₄ F ₂	1.5	440	130	40
HFC-143a	C ₂ H ₃ F ₃	55	5300	4300	1600
HFC-227ea	C ₃ HF ₇	43.0	4800	3300	1100
HFC-236fa	C ₃ H ₂ F ₆	265	6200	7900	6500
HFC-245ca	C ₃ H ₃ F ₅	1.0	300	90	30
HFC-245ca	C ₃ H ₃ F ₅	9.2	2400	790	240
Chloroform	CHCl ₃	0.55	20	5	1
Methylene chloride	CH ₂ Cl ₂	0.41	30	10	3
Sulfur hexafluoride	SF ₆	3200	9300	13600	19500
Perfluoromethane	CF ₄	50000	2700	4000	6100
Perfluoroethane	C ₂ F ₆	10000	6100	9000	13500
Perfluorocyclo-butane	c-C ₄ F ₈	3200	6100	8900	12800
Perfluorohexane :	C ₆ F ₁₄	3200	5600	8900	17800
Methane ^(c)	CH ₄	12-18 ^(d)	56-110	19-43	9-16
Nitrous oxide	N ₂ O	121	290	320	170
Trifluoroiodo-methane	CF ₃ I	<0.005	<6	<<1	<<<1
(a) Referenced to the AGWP for the Bern carbon cycle model CO ₂ decay response and future CO ₂ atmospheric concentrations held constant at current levels (based on IPCC 1994 and WMO 1994).					
(b) Decay of CO ₂ is a complex function of the carbon cycle (see text).					
(c) Includes direct and indirect components.					
(d) Includes the dependence of the residence time on CH ₄ abundance (see text).					

Table 7.3 also shows the effect of using different carbon cycle models (rather than the Bern model used by IPCC); this shows that the assumptions about background CO₂ concentrations and the carbon cycle model used can affect the GWPs by up to 20 percent or so.

Table 7.3. Absolute GWPs (AGWPs)^(a)

Case	Time Horizon		
	20 years	100 years	500 years
CO ₂ , Bern Carbon Cycle Model, fixed CO ₂ (353 ppmv); used in Table 7.2	0.230	0.780	2.557
CO ₂ , Bern Carbon Cycle Model, S650 scenario (stabilized at 650 ppmv; see IPCC 1994)	0.225	0.702	2.179
CO ₂ , Wigley Carbon Cycle Model, S650 scenario (stabilized at 650 ppmv; see IPCC 1994)	0.248	0.722	1.957
CO ₂ , Enting Carbon Cycle Model, S650 scenario (stabilized at 650 ppmv; see IPCC 1994)	0.228	0.693	2.288
CO ₂ , LLNL Carbon Cycle Model, S450 scenario (stabilized at 450 ppmv; see IPCC 1994)	0.247	0.821	2.823
CO ₂ , LLNL Carbon Cycle Model, S650 scenario (stabilized at 650 ppmv; see IPCC 1994)	0.246	0.790	2.477
CO ₂ , LLNL Carbon Cycle Model, S750 scenario (stabilized at 750 ppmv; see IPCC 1994)	0.247	0.784	2.472
CO ₂ -like gas, IPCC (1990) decay function, fixed CO ₂ (353 ppmv); used in IPCC (1990, 1992)	0.267	0.964	2.848
(a) Based on IPCC (1994) in units W m ⁻² yr ppmv ⁻¹ . Multiply these numbers by 1.291 x 10 ⁻¹³ to convert from per ppmv to per kg.			

Table 7.4 summarizes some of the more important indirect effects identified from chemical interactions. The effects arising from such processes are difficult to quantify in detail, largely because evaluating them depends on uncertainties associated with treating the full interactive chemistry in current models of the atmosphere. GWPs for interactions involving emissions from short-lived gases such as NO_x and nonmethane hydrocarbons are particularly difficult to evaluate, and cannot be reliably determined at this time. Like NO_x, the inhomogeneous spatial distributions of aerosols make it extremely difficult to determine meaningful GWPs for them. Better known are the expected signs of the indirect effects relative to the direct GWPs; the signs of these effects are shown in Table 7.4.

Table 7.4. Key Indirect Effects on GWPs

Species	Indirect Effects	Sign of Effect on GWP
CH ₄	Changes in lifetimes due to changes in tropospheric OH	+
	Production of tropospheric O ₃	+
	Production of stratospheric H ₂ O	+
	Production of CO ₂	+
Cl ² Cs, HCFCs, halons and other brominated halocarbons	Depletion of stratospheric O ₃	-
CO	Production of tropospheric O ₃	+
	Production of tropospheric CO ₂	+
NO _x	Production of tropospheric O ₃	+
NMHCs	Production of tropospheric O ₃	+
	Production of tropospheric CO ₂	+

Analyses of the indirect effects resulting from emissions of methane are considered in IPCC (1994), based on modeling results from several research groups (e.g., Brühl 1993; Hauglustaine et al. 1993; Wuebbles et al. 1993). Table 7.5 summarizes the combined direct and indirect GWPs for methane, including a breakdown of the effects among various contributing factors. The direct methane effect alone is not shown because it is complicated by the indirect effect of the impact of methane on its own lifetime, as discussed earlier.

The uncertainty range in the total GWP for methane relates primarily to uncertainties in the modeling of effects on the methane response time and on the effect of ozone in the troposphere. These uncertainties largely relate to our lack of knowledge about the distribution of nitrogen oxides in the troposphere and about the simplifications of tropospheric transport and chemical processes in the models used for these evaluations. While current understanding indicates that the GWPs for methane should be within the range shown, there is no basis for selecting one value over another at this time.

Table 7.5. Total GWP for CH₄, including indirect effects^(a)

GWP	Time Horizon		
	20 years	100 years	500 years
Total CH ₄ GWP, including indirect effects	56-111	19-43	8.7-16
Fraction of total GWP due to tropospheric O ₃ change	0.15-0.37	0.13-0.35	0.10-0.31
Fraction of total GWP due to stratospheric H ₂ O change	0.04-0.12	0.03-0.12	0.03-0.10
Fraction of total GWP due to CO ₂ production	0.02-0.03	0.06-0.14	0.17-0.32
(a) Referenced to the AGWP computed for the CO ₂ decay response of the Bern carbon cycle model and future CO ₂ atmospheric concentrations held constant at current levels (from IPCC 1994).			

7.3 Conclusions

Simple measures and indices representing the potential effects of greenhouse gases on climate provide powerful tools for policy analyses. The concept of global warming potentials as developed by IPCC provides a particularly useful means for comparing the effects of greenhouse gases. GWPs have recently been reevaluated for IPCC and WMO assessments; these values are recommended for current analyses.

Users of GWPs need to be aware that advances in science will most likely result in changes to the numerical indices presented here. This implies that uses of GWPs and other indices need to be flexible to such changes.

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Appendix 7.A
Technical Basis for GWP Indices

Technical Basis for GWP Indices

Necessary criteria and definitions

Any indexing approach must be scientifically well grounded, should be subject to a minimum of uncertainties, and should be applicable to the policy concerns of interest. Scientifically, an indexing approach must consider a number of factors, including the radiative properties, radiative forcing for the gases, their effects on climate and atmospheric lifetimes, and any indirect effects on other radiatively important constituents.

Radiative properties. Chemical species in the atmosphere differ markedly in their abilities to absorb infrared radiation. Greenhouse gases absorb the Earth-emitted infrared radiation in specific energy (or wavelength) bands determined by the quantum mechanical properties of the specific molecule. Water vapor is the single most important greenhouse gas in the Earth's atmosphere. Carbon dioxide is the second most effective greenhouse gas, with its $15\ \mu\text{m}$ band dominating the infrared absorption from 12 to $18\ \mu\text{m}$. Other important greenhouse gases in the current atmosphere include ozone, methane, nitrous oxide, and the chlorofluorocarbons, particularly CFCl_3 and CF_2Cl_2 .

Radiative forcing. The radiative forcing of the surface-troposphere system (owing, e.g., to a change in greenhouse gas concentration) is defined as the change in net irradiance (in Wm^{-2}) at the tropopause after allowing stratospheric temperatures to readjust to stratospheric equilibrium. The tropopause is chosen because scientists consider the surface and troposphere to be closely coupled radiatively in a global and annual mean sense.

A key factor determining radiative forcing for a gas is the location of the wavelengths for its absorption of infrared radiation. The spectral region from about 8 to $12\ \mu\text{m}$ is referred to as the "window" region because of the relative transparency to radiation within these wavelengths. Most of the non- CO_2 greenhouse gases with the potential to affect climate all have strong absorption bands in the atmospheric window region. Relatively small changes in the concentrations of these gases can significantly increase radiative forcing.

As the concentration of a greenhouse gas becomes high, it can absorb most of the radiation in its energy bands; once any of its absorption wavelengths becomes saturated, it is unable to absorb more energy at that specific wavelength, and further increases in its concentration have a diminishing effect on climate. This is called the band saturation effect. For example, the radiative forcing from further increases in carbon dioxide concentrations in the current atmosphere will increase as the natural logarithm of its concentration because of this effect. Methane and nitrous oxide also exist at sufficient quantities that significant absorption is occurring; their forcing is found to be approximately proportional to the square root of their concentration. Also, at the wavelengths where water vapor and carbon dioxide strongly absorb infrared radiation, the greenhouse effect of other gases will be minimal. On the other hand, at wavelengths that are not saturated, absorption by other gases, such as the chlorofluorocarbons or other halocarbons, varies linearly with concentration.

Another important consideration in radiative absorption is the band overlap effect. If a gas absorbs at wavelengths that are also absorbed by other gases, then the effect on radiative forcing of increasing its concentration can be diminished. Some of the absorption bands of methane overlap with those of nitrous oxide; this needs to be carefully considered in determining their radiative forcing on climate.

Effects on climate. For a number of years, calculations made with climate models have shown, at least for well-mixed greenhouse gases, an approximately linear relationship between the global-mean radiative forcing at the tropopause and the resulting change in global mean surface temperature. Climate model calculations have shown that, for a variety of forcing mechanisms, the relationship is relatively unaffected by the nature of the forcing, whether, for example, the forcing is caused by a change in greenhouse gas concentration or a change in the solar flux.

Recent studies (Wang et al. 1991, 1992; Cox et al. 1993; Taylor and Penner 1993) suggest that the relationship between global mean radiative forcing and global mean surface temperature change is not a simple one for the gases and aerosols having strong spatial variations. The effects of these findings are likely to be most important for species with short atmospheric lifetimes (like sulfuric aerosols) or for species like ozone that have strong variations in concentrations occurring as a function of latitude and altitude.

Atmospheric lifetimes. The global lifetime of an atmospheric gas is generally defined as the ratio of total atmospheric burden to integrated global loss rate. The lifetime is the time it takes for the global amount of the gas to decay to 63.2 percent of its original concentration. The atmospheric lifetime integrates over spatial and temporal variations in the local atmospheric chemical loss frequencies for the compound. The lifetime must take into account all of the processes determining the removal of a gas from the atmosphere, including photochemical losses within the atmosphere (typically owing to photodissociation or reaction with OH), heterogeneous removal processes (e.g., loss into clouds or into raindrops), and permanent removal uptake by the land or ocean.

The atmospheric lifetimes of a number of gases have been determined based on current knowledge of these loss processes; these lifetimes have recently been updated for the IPCC (1994) and WMO (1994) assessments. the lifetimes of greenhouse gases of interest range from a few days (e.g., for CF_3I) to thousands of years (e.g., for SF_6 , CF_4 , and several perfluorocarbons). The CFCs tend to have lifetimes of 50 (for CFC-11) to 100 or more years (e.g., CFC-12), while the HCFCs and HFCs being used or considered as replacements for CFCs have much shorter lifetimes, owing to their reactivity with atmospheric OH.

The atmospheric lifetime for carbon dioxide is not a single number like most of the other greenhouse gases. Concentrations of carbon dioxide emitted into the atmosphere decay in a highly complex fashion, initially showing a very fast removal in the first few decades, a more gradual decay over roughly 100 years, and an extremely slow decline for thousands of years. This response primarily reflects processes transferring carbon dioxide among the atmosphere, the biosphere, the ocean mixed layer, and the deep ocean. The response decay curve of an impulse of carbon dioxide injected into the atmosphere also depends on the background content of carbon dioxide in the atmosphere-ocean-biosphere system, and will thus be scenario dependent (Wuebbles et al. 1994). These effects are

indicated in Figure A.1, showing response curves from the Bern carbon cycle model being used in the new IPCC assessment. Similar response curves are found with Lawrence Livermore National Laboratory's carbon cycle calculations (Wuebbles et al. 1994; Wuebbles and Jain 1993; Jain and Wuebbles 1993).

Several recent studies (Prather 1994; Wuebbles et al. 1993) and a private communication with D. Fisher indicate that the atmospheric response time for methane following a pulse emission into the current atmosphere is significantly longer (corresponding to an e-folding time as long as 17 or 18 years) than its nominal atmospheric lifetime of about 10 years. This longer response time results primarily from the nonlinear coupling among CH_4 , CO , and OH in the troposphere; increased methane leads to additional CO and reduced OH , the major sink for CH_4 .

Figure A.1. Response of Atmospheric CO_2 Following an Impulse Injection

Source: Based on results from the Bern carbon cycle model (IPCC 1994).

Indirect effects. In addition to the direct forcing effect from the emission of a gas into the atmosphere, the net radiative forcing can be modified through indirect effects relating to chemical interactions on other radiatively important constituents. For example, CFC emissions result in stratospheric chlorine that can destroy stratospheric ozone, which is also a greenhouse gas (Lacis et al. 1990; Ramaswamy et al. 1992; Schwarzkopf and Ramaswamy 1993; Wang et al. 1993). Methane emissions result in several indirect effects. Oxidation of methane is thought to result in decreased concentrations

of OH (hydroxyl largely determines the oxidation capacity of the atmosphere), increase tropospheric and lower stratospheric ozone, increased stratospheric water vapor, and increased carbon dioxide. Such indirect effects need to be considered when evaluating potential climate effect indices.

Formulations of Greenhouse Gas Indices

No single indexing approach or tool is likely to meet all of the needs of policymakers. Policy analyses often need a variety of tools, including results from the complex, as well as simpler climate modeling studies, along with careful consideration of the state of the science. No universally accepted methodology combines all of the relevant factors into a single approach.

Several different indices have been used as measures of the strength of the radiative forcing from different greenhouse gases. Some of the more important indices are described below.

Relative radiative forcing per molecule or mass. This measure compared the radiative forcing on a molecule-per-molecule basis or kilogram-per-kilogram basis of the different greenhouse gases. It is generally given relative to carbon dioxide. A radiative transfer model of the atmosphere is used to determine the radiative forcing for small perturbations of these gases relative to present-day conditions. Small perturbations are necessary to prevent the marked nonlinear absorption of carbon dioxide, methane, and nitrous oxide from affecting the radiative forcing for these gases. Table A.1 shows radiative forcing on a per-molecule basis relative to carbon dioxide for a few of the important greenhouse gases.

Hammond et al. (1990) and Handel (1991) have used such instantaneous radiative forcing in developing approaches for examining the relative importance of greenhouse gas emissions from various countries. Others (e.g., Enting and Rodhe 1991) have criticized this approach because it does not adequately consider the time horizons over which emissions of a gas can affect climate.

Past, present, and future changes in greenhouse gas concentrations. It is also useful to examine how the radiative forcing for atmospheric concentrations of greenhouse gases have changed or might change over various time periods. Published analyses of such changes, including IPCC (1990, 1992), Kiehl and Briegleb (1993), Ko et al. (1993) and Shi and Fan (1992), have shown significant changes have occurred in the radiative forcing since pre-industrial times and, depending on the scenario, significant changes are quite likely over the next century.

Table A.1. Radiative Forcing Relative to CO₂ on a per Molecule Basis.^(a)

Gas	Chemical Formula	Relative Radiative Forcing
Carbon dioxide	CO ₂	1
Methane	CH ₄	21
Nitrous oxide	N ₂ O	206
CFC-11	CFCl ₃	12400
CFC-12	CF ₂ Cl ₂	15800
HCFC-22	CF ₂ HCl	10700
Perfluoromethane	CF ₄	5460
Sulfur hexafluoride	SF ₆	38400
(a) Based on IPCC (1990, 1994). Note: Perturbation is relative to a background atmosphere for 1990 concentrations.		

Global Warming Potentials. The indexing approach for greenhouse gases that has gained the widest acceptance is the global warming potential concept originally developed for the IPCC (1990). As discussed below, this concept has continued to be modified and reevaluated in more recent assessments. Similar approaches to the IPCC definition were also developed by Rodhe (1990) and Lashof and Ahuja (1990).

GWPs are expressed as the time-integrated radiative forcing from the instantaneous release of kg (i.e., a small mass emission) of a trace gas expressed relative to that of a kg of the reference gas, carbon dioxide (IPCC 1990, 1992):

$$GWP(x) = \frac{\int_0^n a_x \cdot [x(t)] dt}{\int_0^n a_{CO_2} \cdot [CO_2(t)] dt}$$

where n = the time horizon over which the calculation is considered

a_x = the climate-related radiative-forcing response due to a unit increase in atmospheric concentration of the gas in question; and changes in the integrated radiative forcing for CO₂ will not affect the GWPs for all other gases.

Other GWP formulations

Fisher et al. (1990) and WMO (1990) presented GWP calculations for various halocarbons integrated over the entire lifetimes of the gases and using CFC-11 as the reference gas. These analyses were primarily interested in the relative radiative forcing for CFCs and potential substitutes.

Various studies (Smith and Ahuja 1989; Lashof and Ahuja 1990; Ellington et al. 1992, 1993) have suggested the application of discount rates to future radiative forcing, reflecting the increased uncertainty with time (e.g., to account for the possibility of new technologies). As discounting essentially acts to reduce the effective atmospheric lifetime, it reduces consideration of long-term effects from greenhouse gas emissions.

Other authors, such as Reilly and Richards (1993), have argued for the consideration of damage factors, which could offset future discounts, in using GWPs. Harvey (1993) proposes an alternative GWP index that accounts for the duration of capital investments in the energy sector. The possibility of coupling such factors into a revised GWP definition requires detailed study of the economics and policy implications and is beyond the scope of this supporting document.

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