

Future atmospheric methane concentrations in the context of the stabilization of greenhouse gas concentrations

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Abstract. Tropospheric CH₄ concentration depends, according to modeled tropospheric processes, on many factors, including emissions of CH₄ as well as NO_x and CO. Illustrative analyses of the relation between emissions and CH₄ concentration give some guidance on the role of CH₄ in the stabilization of greenhouse gas concentrations. The contribution of CH₄ to radiative forcing at the time of stabilization is expected to be modest, provided CH₄ and CO emissions do not go far beyond current rates. However, in cases leading to stabilization the potential mitigation of increases in radiative forcing by methane control could be comparable to that of CO₂ control over the next century. Whether or not this potential is realized will depend partially on the cost of deep reductions of CH₄, NO_x, CO, or CO₂ emissions over the next century, which is not known.

1. Introduction

The objective of the Framework Convention on Climate Change (FCCC article 2 [United Nations, 1992]) is, in part, the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” While a specific concentration level and time path to reach stabilization for greenhouse gases has not been stated, analyses of illustrative scenarios for future CO₂ emissions which lead to stable CO₂ concentrations have given some guidance to what is required in order to reach CO₂ stabilization at various levels [Enting *et al.*, 1994; Wigley *et al.*, 1996]. The rise in CH₄ concentration from preindustrial times to 1992 accounted for an estimated increase in radiative forcing of 0.47 W m⁻², compared to 1.56 W m⁻² for CO₂ [Intergovernmental Panel on Climate Change (IPCC), 1996]. While stabilization of methane at current concentration is expected to require a modest reduction (of order 10% [cf. Dlugokencky *et al.*, 1998]) in methane emissions, it may be beneficial to stabilize methane at some other concentration.

In this study, the effect of CH₄, CO, and NO_x emissions on CH₄ concentration is modeled using the method described in section 2. The contribution of each greenhouse gas to the CO₂ equivalent stabilization level can be represented by its contribution to the change in the radiative forcing of climate since preanthropogenic times. The contribution of CH₄ to the stabilization level will depend on the steady state relation between CH₄ concentration and emissions after the hypothetical time at which greenhouse gas concentrations have been stabilized. The modeled steady state relation between CH₄ concentration and CH₄, CO, and NO_x emissions is given in section 3. The contribution of CH₄ to radiative forcing change leading to stabilization depends on the emissions scenario. Analyses of illustrative emission scenarios for the next century are shown in section 4. Scenarios are chosen in which emissions either fol-

low a scenario of how emissions might change without interventions intended to limit climate change or are reduced in order to eventually lead to stable greenhouse gas concentrations. The potential effects of CH₄ on radiative forcing on approach to stabilization are discussed further in section 5.

2. Method

Concentrations of CO₂ and CH₄ are calculated using the Integrated Science Assessment Model (ISAM [Jain *et al.*, 1994]) given future scenarios, or past reconstructions, of emissions. ISAM has been used extensively in past assessments of climate effects of emissions [Schimel *et al.*, 1996, 1995; Wigley *et al.*, 1997] and climate policy analyses related to greenhouse gas emissions [e.g., Hammitt *et al.*, 1996; Hayhoe *et al.*, 1998; Ksheshgi *et al.*, 1997]. The carbon cycle component [Jain *et al.*, 1995, 1996; Ksheshgi *et al.*, 1996] is representative of current global carbon cycle models [Enting *et al.*, 1994]. Tropospheric CH₄ concentration is calculated by simulating the main chemical processes influencing global levels of CH₄, CO, and hydroxyl (OH). Removal rates of CH₄ and CO take account of oxidation by OH, soil uptake, and stratospheric transport [Jain *et al.*, 1994].

Reaction with the OH radical is responsible for up to 90% of the tropospheric CH₄ sink, making the tropospheric concentrations of OH and CH₄ the most important factors influencing the rate at which CH₄ is destroyed. OH concentration is primarily determined by the concentrations of CH₄, CO, NO_x, nonmethane hydrocarbons (NMHCs), tropospheric ozone, and water vapor [Prather *et al.*, 1996; Wuebbles *et al.*, 1999]. With sharp spatial and temporal gradients, an observation-based estimate of the global concentration of OH is difficult to make, as are the rates of OH production and destruction, which depend on other atmospheric constituents. In attempts to adequately represent all significant chemical and dynamic processes determining local OH concentrations, detailed two-dimensional (2-D) or three-dimensional chemical transport models of the atmosphere are required. However, to incorporate OH chemistry into methane modeling for scenario anal-

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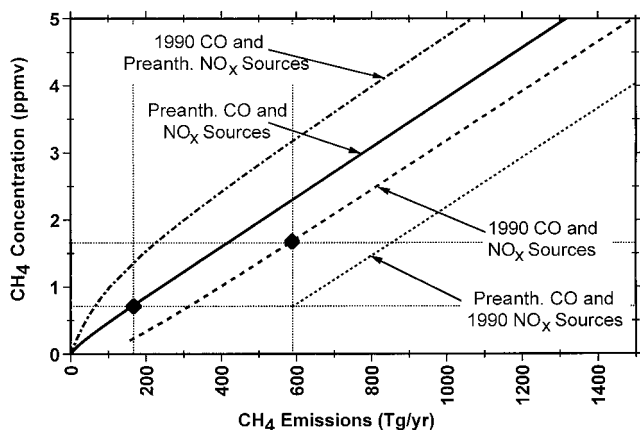


Figure 1. Modeled equilibrium relation between global CH_4 emissions and steady atmospheric CH_4 concentration for fixed source rates of CO (excluding sources from methane) and NO_x . Specified NO_x source rates of $10 \text{ Tg (N) yr}^{-1}$ in preanthropogenic times and $55 \text{ Tg (N) yr}^{-1}$ in 1990 are consistent with the NO_x source budget of Prather *et al.* [1995]. Specified non- CH_4 sources of CO of $1754 \text{ Tg (CO) yr}^{-1}$ in 1990 is consistent with the IS92 emissions scenarios [Leggett *et al.*, 1992] plus modeled sources generated by nonmethane hydrocarbons; sources of CO from CH_4 oxidation are modeled and depend on modeled CH_4 and OH concentrations. Estimates of CH_4 concentration and emissions, shown by diamonds, of 1.7 ppmv and $593 \text{ Tg (CH}_4\text{) yr}^{-1}$ in 1990 and 0.7 ppmv and $160 \text{ Tg (CH}_4\text{) yr}^{-1}$ in preanthropogenic times are from concentration measurements and source and sink budgets [Prather *et al.*, 1995, 1996]. A non- CH_4 source of CO of $620 \text{ Tg (CO) yr}^{-1}$ in preanthropogenic times was chosen so that the model gave the preanthropogenic CH_4 concentration for a CH_4 emission rate of $160 \text{ Tg (CH}_4\text{) yr}^{-1}$.

ysis, simplified schemes are used which reproduce the important influences on OH while remaining straightforward and computationally feasible [see, e.g., Osborn and Wigley, 1994; Prather, 1996; Rotmans *et al.*, 1990; Thompson *et al.*, 1992].

In ISAM the concentration of OH is determined by the photochemical balance between the total tropospheric production of OH and the loss rate due to reaction with CH_4 , CO, and NMHCs [Jain *et al.*, 1994]. The loss rate of OH is determined by reactions between OH and CH_4 , CO, and NMHCs, with reaction rate constants taken from DeMore *et al.* [1997]. The production rate of OH is based on a correlation giving the global OH production rate as a function of NO_x emissions and CH_4 concentration on the basis of results of a well established 2-D (latitude and altitude) chemical-radiative transport model of the global atmosphere [Kinnison *et al.*, 1994; Kotamarthi *et al.*, 1999; Wuebbles *et al.*, 1999, 1991].

The 2-D model used has a full representation of NO_x , HO_x , CH_4 , O_3 , and CO chemistry relevant to tropospheric and stratospheric chemistry. The current version of the 2-D model has an improved representation of the troposphere and includes a representation of the nonlocal convective mixing following the approach of Strand and Hov [1993] and Prather *et al.* [1987]. The convective mixing rates for deep and shallow convection on the 2-D zonal average model grid are based on the work of Langner *et al.* [1990]. We made several tests of the performance of the convective scheme by using radon 222 as a short-lived tracer and emission rates corresponding to the Jacob *et al.* [1997] evaluation of vertical tropospheric mixing rates

in 2-D and 3-D models for the World Climate Research Programme. As a check of our model estimated tropospheric OH distribution, the 2-D model estimated tropospheric lifetime for CH_3CCl_3 due to reaction with OH is compared with observations for 1990. The OH-driven tropospheric lifetime of CH_3CCl_3 calculated with the 2-D model is 4.5 years as opposed to the value of 5.9 years recommended by Prather *et al.* [1996]. The CH_4 lifetime for 1990 is 7.5 years. Previous estimates of CH_4 lifetime range from 8 to 11 years [Fung *et al.*, 1991; Prather *et al.*, 1996]. Results could be scaled up by 20% to bring the CH_3CCl_3 and CH_4 lifetimes in accord with the recommended values for 1990, as was done by Fung *et al.* [1991]. The cause of this apparent difference in lifetime remains an open question for consideration in detailed studies. Furthermore, such an exercise [Fung *et al.*, 1991] would not qualitatively impact our conclusions and is not included in the results presented in this paper. Tropospheric water vapor, cloud cover, and cloud height are thought to be additional factors determining the concentration of OH. It remains, however, unclear how these factors might change in the future with climate change and what their effect on OH will be [IPCC, 1996]. In this study, these factors are assumed to remain the same as for the present atmosphere.

In ISAM, OH production rate S_{OH} is specified as a function of NO_x emissions S_{NO_x} and CH_4 concentration X_{CH_4} , which is based on a correlation to 2-D model results. In a 2-D model simulation of the 110-year IPCC scenario IS92a [Leggett *et al.*, 1992], results give global average S_{OH} , S_{NO_x} , and X_{CH_4} which are virtually collinear, and so a linear relation is sufficient over this range of conditions. However, since there is collinearity of the three time series, the IS92a scenario results are not sufficient for accurate calibration of the linear relation. We calculated an additional, steady state, 2-D model result under 1990 conditions, except with methane emissions that were 20% higher. This perturbation of the 1990 conditions was sufficient to separate the effects of methane concentration and NO_x emissions on OH production. This linear correlation is given by

$$S_{\text{OH}} = \left[\frac{S_{\text{NO}_x}}{2.53 \text{ Tg (N) yr}^{-1}} + \frac{X_{\text{CH}_4}}{0.070 \text{ ppmv (CH}_4\text{)}} + 18.3 \right] \cdot 10^4 \frac{\text{molecules (OH)}}{\text{cm}^3 \text{ sec}} \quad (1)$$

While we use a linear relation for OH production, the OH concentration calculated by either the 2-D model or ISAM exhibits nonlinear dependence on CH_4 , CO, and NO_x emissions in results presented in the following sections.

3. Tropospheric Steady State Results

Since CH_4 has a relatively short lifetime (a decade) in comparison to the times considered [Enting *et al.*, 1994; Wigley *et al.*, 1996] for approach to a stable CO_2 concentration (centuries), a smooth change in emissions like that in CO_2 stabilization examples will lead to CH_4 concentrations which do not stray far from steady state equilibrium with emissions. Constant levels of CH_4 concentration in the troposphere shown in Figure 1 are modeled to result from steady emission rates of CH_4 for given source rates of CO and NO_x . There are three modeled sources of CO: combustion and atmospheric production from either CH_4 or NMHCs [Prather *et al.*, 1995]. For the steady states shown in Figure 1, CO produced by atmospheric

CH₄ oxidation is calculated by the model (endogenous) while the other two sources of CO are specified at rates consistent with a modeled reconstruction of tropospheric chemistry either in 1990 or in a preanthropogenic state.

Four curves are shown in Figure 1, corresponding to the four combinations of NO_x and nonmethane CO sources at either preanthropogenic or 1990 rates. In every case, CH₄ concentration increases (and OH concentration decreases, except in the case with preanthropogenic NO_x and 1990 CO sources) with increasing CH₄ emissions. Furthermore, higher NO_x source rates lead to higher OH production and concentration, which leads to lower CH₄ concentration, while higher CO source rates lead to lower OH concentration and higher CH₄ concentration. For cases in which the source rates of CH₄ and CO are low, OH concentration is high, and we expect other sinks of OH which are not well modeled will become significant; therefore for tropospheric average OH concentration >10⁻⁷ ppmv, curves in Figure 1 have been truncated.

Note that in Figure 1 the change in CH₄ concentration from preanthropogenic times to 1990 (marked by diamonds in Figure 1) was apparently less sensitive to CH₄ emissions than if NO_x and nonmethane CO sources are held fixed at either 1990 rates or preanthropogenic rates. This is because NO_x and nonmethane CO source rates do differ between the model reconstructions of atmospheric conditions for preanthropogenic and 1990 (see the Figure 1 caption) in such a way as to reduce CH₄ concentration change. If CH₄ emissions were reduced to their preanthropogenic rate while maintaining 1990 NO_x source rates, projected CH₄ concentration would fall well below its preanthropogenic concentration. Figure 1 illustrates that CH₄, CO, and NO_x emissions might all play an important role in the stabilization level of CH₄ concentration, regardless of whether the level is near its preanthropogenic or 1990 value.

Assessing the contribution of CH₄ to radiative forcing of climate at the hypothetical time of stabilization of CO₂ concentration requires some inference of CH₄, CO, and NO_x emissions at that time. By the time CO₂ concentration stabilizes, in analyses of illustrative CO₂ stabilization pathways considered by the IPCC [1996], fossil CO₂ emissions are reduced by at least 50% from the current rate. Afterward, to maintain a constant CO₂ concentration, anthropogenic CO₂ emissions have to essentially cease, regardless of the stabilization concentration level [Archer *et al.*, 1998]. We do not, however, know how human activities would be changed to eliminate CO₂ emissions, nor do we know how CH₄, CO, and NO_x emissions would be changed to reduce CH₄ concentration. Nevertheless, some simple estimates can be made to compare the potential effect on radiative forcing of CH₄ relative to that of CO₂ at example stabilization levels. If CH₄, CO, and NO_x emissions were all to return to their preanthropogenic rates, then CH₄ concentration would return to its preanthropogenic concentration (assuming that CH₄ concentration was insensitive to, e.g., the climate effects of CO₂), and CH₄ would not contribute to the net radiative forcing change since preanthropogenic time. However, methane could potentially be stabilized at levels greater, or less than, its preanthropogenic level.

Radiative forcing is calculated using the formulae given by Harvey *et al.* [1997], which provide a close fit to the results of detailed radiative transfer calculations. These calculations simulate the complex variations of absorption and emission with wavelength for the gases included and account for the overlap between absorption bands of the gases and the effects of clouds [IPCC, 1996]. The radiative forcing formulae depend primarily

on concentrations. For CO₂ the formulae is well approximated by a logarithmic dependence of radiative forcing on CO₂ concentration, whereas for CH₄ the formulae is well approximated by a square root dependence of radiative forcing on CH₄ concentration.

Changes in the atmospheric concentrations of CH₄, CO, and NO_x are thought to be affecting the distribution of ozone in the troposphere and stratosphere, which can indirectly effect the radiation budget of the Earth-atmosphere system [IPCC, 1996]. Calculations indicate that an increase in tropospheric ozone over the past decades (suggested by some measurements) should add to global warming [Haughustaine *et al.*, 1994; Lalic *et al.*, 1990; World Meteorological Organization (WMO), 1999]. On the other hand, analyses of the climate effects from the observed decrease in stratospheric ozone have generally found a cooling influence on climate [Ramaswamy *et al.*, 1992; WMO, 1999]. These analyses also show that radiative forcing depends on the latitudinal pattern of stratospheric ozone loss. In this study, we do not include the indirect radiative forcing effects of emissions on ozone discussed, e.g., by Prather *et al.* [1995] because of the large uncertainties in the vertical distribution in ozone and temperature changes estimated by existing models.

Table 1 summarizes several illustrative comparisons. For example, if CH₄ concentration were stabilized at 0.35 ppmv (half its preanthropogenic level), this would result in a decrease in radiative forcing of 0.28 W m⁻² from its preanthropogenic level. The amount that CO₂ concentration would have to be reduced to yield the same reduction in radiative forcing depends on the base CO₂ concentration from which it is reduced, since CO₂ radiative forcing is approximately proportional to the log of CO₂ concentration [Harvey *et al.*, 1997]. Suppose CO₂ concentration were stabilized at 550 ppmv (the base concentration), which is 185 ppmv greater than present; the decrease in CH₄ concentration to 0.35 ppmv would be equivalent (in radiative forcing) to a decrease of 25 ppmv CO₂. A contribution of 25 ppmv equivalent CO₂, at the hypothetical time of stabilization, is small relative to the range of CO₂ stabilization levels that are being discussed (e.g., 450–1000 ppmv CO₂ as given by IPCC [1996]). If the results shown in Figure 1 are roughly accurate, then CH₄ would be a small, but not negligible, contributor to radiative forcing at the time of CO₂ stabilization, as long as CH₄ and CO emissions were not significantly greater than present.

4. Analysis of Illustrative Scenarios Leading to Stabilization of CO₂ and CH₄ Concentrations

Considerable attention has been paid to the stabilization of CO₂ concentration in the atmosphere in response to concerns about the impacts of global climate change and the objective of the Framework Convention on Climate Change. The future emissions of CO₂ estimated to arrive at constant levels of CO₂ concentration ranging from 350 to 1000 ppmv have been analyzed [Enting *et al.*, 1994; Schimel *et al.*, 1995; Wigley *et al.*, 1996], and the timing over which emissions would need to be reduced from future scenarios of emissions has been discussed [Khesghi *et al.*, 1997; Wigley *et al.*, 1997]. The stabilization of CO₂ concentration below current levels is expected to require extreme reductions (or the creation of net CO₂ sinks) in CO₂ emissions [Enting *et al.*, 1994], and the stabilization of CO₂ concentration at any level will require eventual reduction of

Table 1. Comparison of Illustrative Stabilization Levels for CH₄ and CO₂

CH ₄ Stabilization Level, ppmv CH ₄	CH ₄ Radiative Forcing,* W m ⁻²	CO ₂ Stabilization Level, ppmv CO ₂	CH ₄ Contribution to Stabilization Level, ppmv CO ₂ Equivalent
0.7	0	...	0
0	-0.95	550	-77
		750	-105
0.35	-0.28	550	-25
		750	-34
1.7 (1990 concentration)	+0.53	550	+48
		750	+66
2.8 (2100 concentration for IS92a)	+0.95	550	+89
		750	+122

CH₄ radiative forcing is defined as the change of radiative forcing from preanthropogenic times for which the concentration is taken to be 0.7 ppmv. CO₂ equivalence is defined as the change in CO₂ concentration from its stabilization level to give a radiative forcing change (calculated using the formulae given by *Harvey et al.* [1997]) equal to the CH₄ radiative forcing given in the second column.

*CH₄ – N₂O absorption overlap not included, which leads to an estimate of CH₄ radiative forcing that is high by 0.06 W m⁻² for current N₂O and CH₄ concentrations [cf. *Shine et al.*, 1990].

net fossil CO₂ emissions to a fraction of a Gt C yr⁻¹ [*Archer et al.*, 1998].

There have not been comparable analyses of stabilization of CH₄ concentration. Concurrent reductions of both CO₂ and CH₄ emissions are being considered in international negotiations [*United Nations*, 1997]. While the extent of CO₂ and CH₄ emission reductions may well differ, we have chosen to analyze a set of emissions scenarios where anthropogenic CH₄, CO, and NO_x emissions are reduced by the same extent as are fossil CO₂ emissions for cases where CO₂ concentration is stabilized at from 450 to 750 ppmv following the trajectories given by *Wigley et al.* [1996]. To construct these scenarios, we first choose the IPCC IS92a [*Leggett et al.*, 1992] scenario as a baseline for emissions of CO₂, CO, CH₄, and NO_x, in which emissions grow without controls intended to mitigate climate change, a so-called nonintervention scenario. Let $S_{i,IS92a}$ be the source or emission rate of $i = \text{CH}_4, \text{NO}_x, \text{CO}$, or fossil CO₂. Let the preanthropogenic component of emissions for CH₄, NO_x, and CO be $S_{i,natural}$; we use values given in the Figure 1 caption. The baseline anthropogenic sources of each gas i , $S_{i,IS92a} - S_{i,natural}$, is reduced by the same relative fraction as fossil CO₂ emissions, which are estimated to lead to stabilization at $x50$ ppmv (where x is 4, 5, 6, or 7). Let $S_{\text{fossil CO}_2, \text{WRE}x50}$ be the emission rate of fossil CO₂ calculated by the ISAM model to lead to the emission pathways specified by *Wigley et al.* [1996] which lead to stable CO₂ concentrations of 450–750 ppmv, referred to here as the WRE x 50 trajectories after the authors Wigley, Richels, and Edmonds. Note that the emissions pathways leading to CO₂ concentration stabilization, specified by *Wigley et al.* [1996], were made by first constructing a scenario very close to the IS92a scenario as a reference and then choosing reductions in emissions from that scenario sufficient to lead to CO₂ stabilization while satisfying a least cost principle. Let $S_{i, \text{MSA}x50}$ represent the resulting total emissions of CH₄, NO_x, and CO corresponding to the reductions implied in the WRE x 50 fossil CO₂ emissions, which is given by

$$S_{i, \text{MSA}x50} = S_{i, \text{IS92a}} - (S_{i, \text{IS92a}} - S_{i, \text{natural}}) \cdot \frac{(S_{\text{fossil CO}_2, \text{IS92a}} - S_{\text{fossil CO}_2, \text{WRE}x50})}{S_{\text{fossil CO}_2, \text{IS92a}}} \quad (2)$$

and are defined from 1990 until 2100, the extent of time over which the IS92a scenario is defined. We will refer to these

cases as the methane stabilization analogs (MSA). These illustrative scenarios are analyzed to show the modeled dependence of methane radiative forcing on a range of future emissions of CH₄, NO_x, and CO. In detailed scenarios of future human activities we expect that reductions of, for example, CO₂ emissions will lead to associated reductions in CO and NO_x as was examined by *Jacoby et al.* [1998].

Figure 2 shows projections of CH₄ concentration for the IS92a scenario and for four stabilization cases labeled MSA corresponding to fossil CO₂ emissions reductions leading to stabilization at from 450 to 750 ppmv CO₂. In the scenarios MSA450 to MSA750 shown in Figure 2a, sources of CH₄, CO, and NO_x are all reduced from their IS92a baseline according to (2). In Figure 2b, sources of CH₄ are reduced, while sources of CO and NO_x follow their IS92a baseline. In Figure 2c, sources of CH₄ and CO are reduced, while sources of NO_x follow their IS92a baseline. In all cases, NMHCs follow IS92a. In all MSA cases, CH₄ concentration begins to decline by 2100. Furthermore, CH₄ concentration falls to below the 1990 value in the MSA450 and MSA550 cases in Figure 2a and also in the MSA650 case in Figure 2b. Even greater reductions in CH₄ concentration are modeled to occur (Figure 2c) if NO_x sources follow their IS92a baseline and CO sources are reduced.

In Figure 2 the ISAM CH₄ concentration results for the IS92a scenario are also compared with those of the 2-D model. Input to the 2-D model are zonal patterns of 1990 CH₄, NO_x, CO, and NMHC emissions, which are scaled by global emission rates which grow according to the IS92a scenario [*Leggett et al.*, 1992]. The ISAM model reproduces the globally averaged 2-D model result up until 2060, after which the ISAM CH₄ concentration is slightly higher; the close reproduction is not surprising since OH production from the 2-D model result was used to calibrate OH production in ISAM. This analysis of the IS92a scenario, as well as the 2-D model results of *Derwent* [1996], gives a CH₄ concentration which is ~20% lower than the IPCC projection [*Prather et al.*, 1996] of 3.6 ppmv in 2100, which prescribed constant NO_x, CO, and NMHC emissions at 1990 rates.

Figure 3 shows the calculated change in radiative forcing of climate from its preanthropogenic estimate due to changes in CO₂ and CH₄ concentrations. The CO₂ concentration changes correspond to the IS92a emission scenario [*Leggett et al.*, 1992] and to the four concentration pathways WRE450 through

WRE750 [Wigley *et al.*, 1996]. The CH₄ concentration changes correspond to the IS92a and the MSA450 through MSA750 emissions, with corresponding concentrations shown in Figure 2a. As with concentrations the radiative forcing due to CO₂ continues to rise (by design of the CO₂ pathways, see Wigley *et al.* [1996]) in all cases, while that due to CH₄ begins to fall in all MSA cases by 2100. The radiative forcing due to CO₂ is certainly larger than that due to CH₄. The radiative forcing reduction, defined as the radiative forcing of the IS92a scenario minus that of a WRE or MSA cases, increases for all WRE and MSA cases on approach to 2100.

Table 2 gives the radiative forcing reduction caused by reductions (from IS92a) in CO₂ concentrations in the WRE cases and reductions in CH₄ concentrations in the 12 MSA cases (reductions in CH₄, CO, and NO_x emissions) shown in Figure 2. For the cases shown in Figure 3 the CH₄ radiative

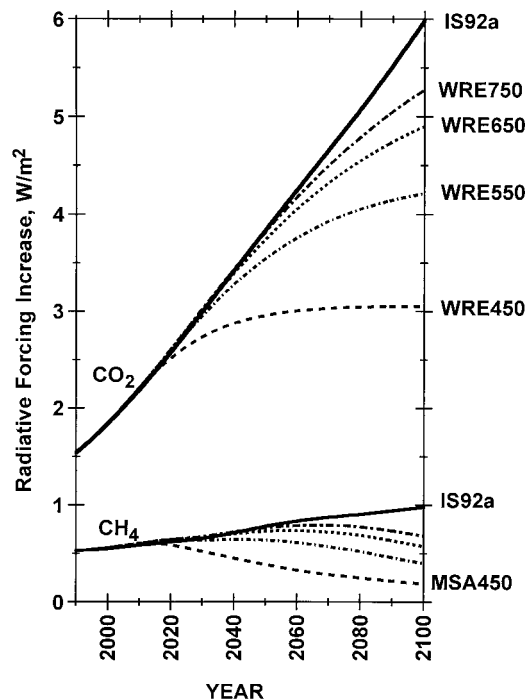
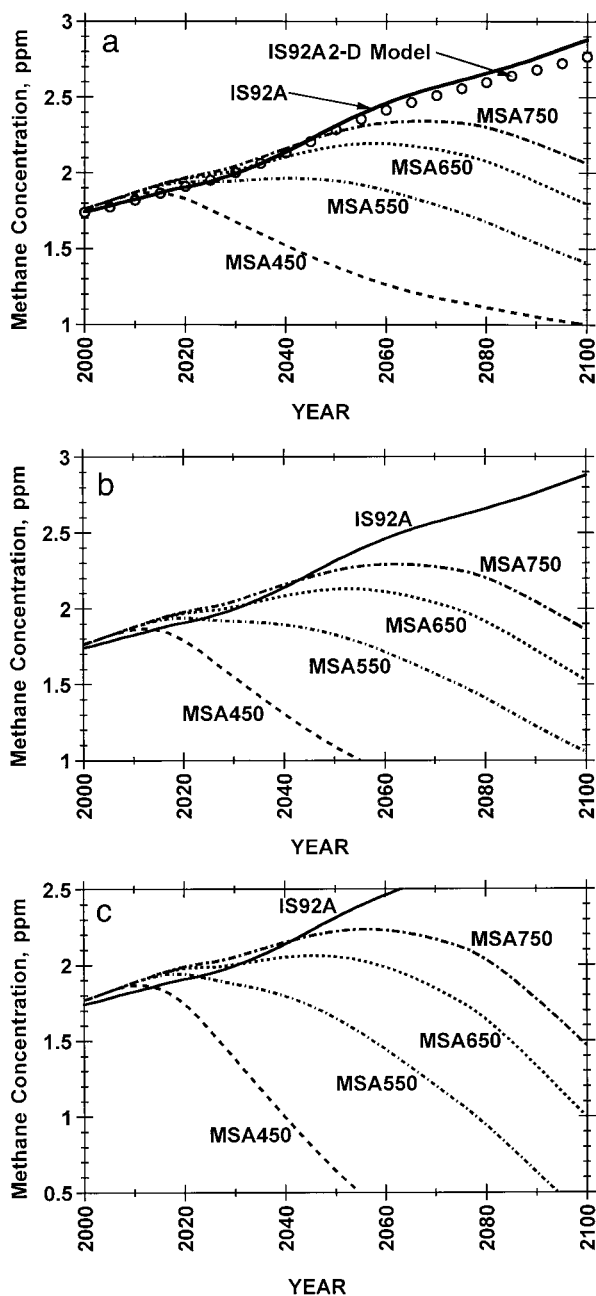


Figure 3. Modeled radiative forcing increase due to CO₂ and CH₄ concentration changes from preanthropogenic concentrations of 278 ppmv CO₂ and 0.7 ppmv CH₄. Results are shown for the IS92a emissions scenario, the four CO₂ stabilization cases WRE450 through WRE750 [Wigley *et al.*, 1996], and the four associated CH₄ cases MSA450 through MSA750 where CH₄, CO, and NO_x sources are reduced (see Figure 2a).

forcing reduction ranges from 27 to 52% of that for the corresponding (e.g., MSA550 relative to WRE550) CO₂ radiative forcing reduction (see combinations 5–9 in Table 2). If NO_x emissions followed IS92a as in the MSA cases in Figure 2c, then the CH₄ radiative forcing reductions are comparable, 73

Figure 2. (Opposite) Model projection of CH₄ concentration for various future CH₄, CO, and NO_x sources. As an illustrative baseline case, CH₄, CO, NMHCs, and NO_x sources change according to the IPCC scenario IS92a [Leggett *et al.*, 1992]; the resulting CH₄ concentration calculated from the globally aggregated model and the two-dimensional model are intercompared in Figure 2a. In the four cases labeled MSA450 through MSA750 in Figure 2a the anthropogenic components of CH₄, CO, and NO_x sources are reduced from their baseline according to (2). These emissions are reduced by the same relative extent as fossil CO₂ emissions are reduced from the IS92a CO₂ emission baseline in order to lead to stabilization of CO₂ concentration at 450, 550, 650, and 750 ppmv CO₂ according to the CO₂ concentration time pathways defined by Wigley *et al.* [1996]. The anthropogenic component is taken to be the difference between the source scenario and “natural” sources, which are assumed to be constant at their preanthropogenic rates given in Figure 1. In the methane stabilization analog (MSA) cases in Figure 2b, the anthropogenic components of CH₄ sources are reduced from their baseline by the same relative extent as CO₂ emissions, while CO and NO_x sources follow the IS92a baseline. In the MSA cases in Figure 2c the anthropogenic components of CH₄ and CO sources are reduced from their baseline by the same relative extent as CO₂ emissions, while NO_x sources follow the IS92a baseline.

Table 2. Radiative Forcing Reduction From the IS92a Scenario of 16 Different Combinations of Emissions of CO₂, CH₄, CO, and NO_x

Combination	Future Emissions				Radiative Forcing Reduction, W m ⁻² (%)				
	CO ₂	CH ₄	CO	NO _x	2020 A.D.	2040 A.D.	2060 A.D.	2080 A.D.	2100 A.D.
1	WRE450	IS92a	IS92a	IS92a	0.06	0.54	1.25	2.03	2.93
2	WRE550	IS92a	IS92a	IS92a	*	0.14	0.49	1.02	1.76
3	WRE650	IS92a	IS92a	IS92a	*	*	0.20	0.53	1.08
4	WRE750	IS92a	IS92a	IS92a	*	*	*	0.29	0.71
5	IS92a	MSA450	MSA450	MSA450	0.03 (52%)	0.26 (48%)	0.51 (41%)	0.65 (32%)	0.79 (27%)
6	IS92a	MSA550	MSA550	MSA550	*	0.07 (48%)	0.22 (45%)	0.38 (37%)	0.58 (33%)
7	IS92a	MSA650	MSA650	MSA650	*	*	0.10 (50%)	0.22 (41%)	0.41 (38%)
8	IS92a	MSA750	MSA750	MSA750	*	*	*	0.13 (45%)	0.30 (42%)
9	IS92a	MSA450	IS92a	IS92a	0.05 (77%)	0.36 (67%)	0.69 (55%)	0.89 (44%)	1.06 (36%)
10	IS92a	MSA550	IS92a	IS92a	*	0.10 (68%)	0.29 (60%)	0.50 (49%)	0.76 (43%)
11	IS92a	MSA650	IS92a	IS92a	*	*	0.13 (65%)	0.28 (53%)	0.52 (48%)
12	IS92a	MSA750	IS92a	IS92a	*	*	*	0.17 (58%)	0.38 (53%)
13	IS92a	MSA450	MSA450	IS92a	0.07 (109%)	0.53 (109%)	†	†	†
14	IS92a	MSA550	MSA550	IS92a	*	0.14 (96%)	0.42 (85%)	0.75 (73%)	†
15	IS92a	MSA650	MSA650	IS92a	*	*	0.18 (91%)	0.40 (76%)	0.80 (74%)
16	IS92a	MSA750	MSA750	IS92a	*	*	*	0.23 (81%)	0.55 (78%)

The radiative forcing reductions of the first four combinations are due to CO₂ concentrations that are lower for the Wigley, Richels, and Edmonds (WRE) [Wigley *et al.*, 1996] CO₂ emissions than for the IS92a scenario (radiative forcing shown in Figure 3). The following 12 combinations are due to CH₄ concentrations (concentrations shown in Figure 2) that are lower for the methane stabilization analog (MSA) emissions than for the IS92a scenario. The reduction in CH₄ radiative forcing for the last 12 combinations is given relative to (in percent) the CO₂ radiative forcing reduction for the corresponding WRE emissions in parentheses; for example, for combination 10 (MSA550 CH₄ emissions, IS92a for the other three gases) the radiative forcing reduction in 2060 of 0.29 W m⁻² is 60% of the WRE550 radiative forcing of 0.49 W m⁻².

*Difference between the IS92a baseline CO₂ emissions and the emissions calculated from WRE CO₂ concentration pathways using ISAM is small enough that the difference is highly dependent on the carbon cycle model used.

†High OH concentrations.

to 109%, to the corresponding CO₂ radiative forcing reductions (see combinations 13–16 in Table 2).

Emissions scenarios spanning 100 years or more into the future represent features of systems which are inherently unpredictable. One foundation of emission scenarios is the reconstruction of current emissions and emission trends. The uncertainty of estimates of recent emissions of CH₄ [e.g., Prather *et al.*, 1996] is sufficient to account for the recent slowdown in the rise of CH₄ concentration discussed by Dlugokencky *et al.* [1998], although it might not necessarily be the cause. Scenarios for future emissions of CH₄, CO, and NO_x will, of course, be more uncertain than current estimates of emissions. Scenario analyses should be viewed in the context of the inherent uncertainties.

The case studies shown above considered a range of CO₂ stabilization levels and reductions of different combinations of CH₄, NO_x, and CO emissions all based on one common reference scenario (IS92a). Leggett *et al.* [1992] did consider a range of nonintervention scenarios with different extents of emissions growth. In IS92a, CO₂ fossil emissions grew by a factor of 3.3, while CH₄ emissions grew by a factor of 2.2 from 1990 to 2100. In higher emission scenarios, CO₂ emissions growth further outpaced CH₄ emissions growth, while in lower emission scenarios the opposite was the case. Given CO₂ stabilization trajectories associated with these alternative nonintervention scenarios, the case studies presented here could be repeated with alternative reference scenarios.

In these case studies the potential reduction of radiative forcing by methane control could be comparable to that of CO₂ over the next century; whether or not this potential is realized will depend, partially, on the cost of deep reductions of CH₄, NO_x, CO, or CO₂ emissions over the next century, which is not known. However, the contribution of CH₄ to radiative forcing at the time of stabilization is expected to be

modest, as discussed in section 3, as long as CH₄ and CO emissions do not exceed current rates. These statements can both be consistent because for these cases (over the next hundred years) the CO₂ radiative forcing reduction is smaller than the CO₂ radiative forcing, while the CH₄ radiative forcing reduction is comparable to the CH₄ radiative forcing (see Figure 3).

5. Concluding Discussion

While there is scope in reducing total radiative forcing via reduction in CH₄ concentration, there remain large uncertainties in quantification of methane emissions and in the mechanisms which control OH concentration, which is the limiting component in the destruction of CH₄ in the atmosphere. A least cost approach to reducing radiative forcing of climate over the next century would include some reduction of emissions of both gases since modest reductions of both would likely cost less than larger reductions of just one [Hayhoe, 1997]; furthermore, the most effective means of reducing CH₄ concentration may be to take some measures to raise tropospheric OH concentration, such as the reduction of CO and NMHC emissions or maintenance of NO_x emissions. The effectiveness of reducing total radiative forcing by altering, e.g., NO_x emissions may be sensitive to the location of emissions and offset by resulting changes in tropospheric ozone, which is a greenhouse gas. In addition, changes in CH₄, CO₂, NO_x, and CO also have other benefits/impacts, such as CO₂ fertilization and air pollution which might influence which emissions are controlled. These considerations could be taken into account in deciding the timing and extent of emission reductions intended to control CH₄ concentration. An informed decision will require improved knowledge of CH₄ sources and sinks as well as an assessment of the uncertainties.

At this time, a negotiated agreement has been forged in

Kyoto to reduce emissions of gases, including CH₄ and CO₂, in response to climate change concerns [United Nations, 1997]. Targets have not encompassed emissions of NMHCs, NO_x, or CO, which affect sinks of CH₄. Nevertheless, emissions of these gases would likely be affected by measures to control, e.g., CO₂ emissions. It is understood that the emissions targets laid out in the Kyoto agreement, if met, extend over too short a time span to mitigate climate change [Bolin, 1998; Kheshgi et al., 1997; Wigley et al., 1997] and would have to be viewed as a first step toward deeper long-lasting reductions in emissions if radiative forcing of climate by greenhouse gases were to be halted. It is also understood that if the increase in radiative forcing is to be halted, CO₂ emissions would need to be virtually eliminated [Archer et al., 1998], although, for the stabilization levels being considered, this would not need to occur within the next century [IPCC, 1996]. For the intervening century or more, results of this study show there is reason to consider emissions of NMHCs, NO_x, and CO in future strategies to control radiative forcing from greenhouse gases.

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