

Radiative Forcing Due to Reactive Gas Emissions

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ABSTRACT

Reactive gas emissions (CO, NO_x, VOC) have indirect radiative forcing effects through their influences on tropospheric ozone and on the lifetimes of methane and hydrogenated halocarbons. These effects are quantified here for the full set of emissions scenarios developed in the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios. In most of these no-climate-policy scenarios, anthropogenic reactive gas emissions increase substantially over the twenty-first century. For the implied increases in tropospheric ozone, the maximum forcing exceeds 1 W m⁻² by 2100 (range -0.14 to +1.03 W m⁻²). The changes are moderated somewhat through compensating influences from NO_x versus CO and VOC. Reactive gas forcing influences through methane and halocarbons are much smaller; 2100 ranges are -0.20 to +0.23 W m⁻² for methane and -0.04 to +0.07 W m⁻² for the halocarbons. Future climate change might be reduced through policies limiting reactive gas emissions, but the potential for explicitly climate-motivated reductions depends critically on the extent of reductions that are likely to arise through air quality considerations and on the assumed baseline scenario.

1. Introduction

Anthropogenic emissions of the reactive gases, carbon monoxide (CO), nitrogen oxides (NO_x = NO + NO₂, emitted mainly as NO) and nonmethane volatile organic compounds (VOC; a group including ethane, acetylene, propane, propene, toluene, etc.) affect the reactive chemistry of the earth's atmosphere, and so influence the rates of production and decay of many other species. Thus, although these gases are not, themselves, notable greenhouse gases, they have an indirect greenhouse effect by influencing the abundances of various greenhouse gases. We consider here their effects on methane (CH₄), tropospheric ozone (O₃) and a range of hydrogenated halocarbons such as hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) (Shine et al. 1990; Johnson and Derwent 1996; Fuglestedt et al. 1996), gases that do have direct radiative forcing effects. We do not consider their possible effects on aerosols, whose abundances could be affected by

reactive gas-induced changes in tropospheric hydroxyl radicals (OH) and O₃.

The purpose of this paper is to describe and quantify the radiative forcing effects of these reactive gases for the full range of scenarios from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES; Nakićenović and Swart 2000). The quantification presented here is performed using new relationships developed for the IPCC's Third Assessment Report (TAR) that represent the weighted average of results from 12 global 3D chemistry models (Prather and Ehhalt 2001). Given the substantial uncertainty in the more complex model results and the limits on the number of assessment scenarios that could be computed with 3D models, the results may be justifiably represented by simple linear relationships relating greenhouse gas lifetimes and tropospheric ozone increment to reactive gas emissions. As derived by the IPCC, these relationships were calibrated over a range of changes from the current atmosphere to the largest SRES emissions. They enable evaluation of the implications of a variety of emissions scenarios in a consistent framework, as is done in this paper.

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We begin with a brief description of the SRES scenarios. We then give individual assessments of the effects of changing emissions of reactive gases on the greenhouse gases methane, tropospheric ozone, and halocarbons. We conclude with a summary of the total radiative forcing and a discussion of the potential for reducing future climate change through reductions in reactive gas emissions.

2. Emissions scenarios

The SRES emissions scenarios are based on four different narrative “story lines” (labeled A1, A2, B1, and B2) that determine the driving forces for emissions (population growth and demographic change, socioeconomic development, technological advances, etc.) Briefly, the A/B distinction corresponds to an emphasis on market forces (A); or sustainable development (B). The 1/2 distinction corresponds to higher rates of economic growth, and economic and technological convergence between developing and more developed nations (1); or lower economic growth rates and a much more heterogeneous world (2).

Of the 35 complete scenarios, 6 have been selected by IPCC as illustrative cases: 1 “marker” scenario from each story line; and 2 others from the A1 story line that are characterized by different energy technology developments. The marker scenarios are labeled A1B-AIM, A2-ASF, B1-IMAGE, and B2-MESSAGE, and the two other illustrative scenarios are A1FI-MiniCAM and A1T-MESSAGE. Here, the appended acronyms refer to the assessment models used to calculate the emissions scenarios (details in Nakićenović and Swart 2000). (For simplicity, these model designations will be omitted henceforth.) The technology options in the A1 scenarios are designated by FI for fossil-fuel intensive, T for technological developments focused on nonfossil-fuel sources, and B for a balanced development across a range of technologies.

The SRES scenarios do not incorporate any direct, climate-related emissions control policies. They do, however, incorporate, both directly and indirectly, emissions control policies arising as assumed responses to other environmental concerns. In line with recent research (Grübler 1998), emissions controls for sulfur dioxide (SO_2) are accounted for as responses to acidic precipitation and urban air pollution problems.

For the reactive gases, emissions controls were not incorporated into the scenarios in any systematic way. Since these gases are responsible for pollution through photochemical production of ozone as well as contributing to acidic precipitation (HNO_3 from NO_x), there are currently controls on their emissions in many regions around the globe. While such controls are largely in response to local air quality issues, they have wider implications since reactive gas emissions may also cause hemisphere-wide deterioration of air quality (although the recognition of this aspect is relatively new; see, e.g.,

TABLE 1. Fractional changes in anthropogenic emissions of CO , NO_x , VOC, and CH_4 under the SRES illustrative scenarios. Changes are expressed relative to 1990 emissions [i.e., $E(\text{Year})/E(1990)$]. Values less than 1.0 are in bold. The adopted 1990 anthropogenic emissions levels are $E(\text{CO}) = 879 \text{ Tg yr}^{-1}$, $E(\text{NO}_x) = 30.9 \text{ Tg(N) yr}^{-1}$, $E(\text{VOC}) = 139.1 \text{ Tg yr}^{-1}$, and $E(\text{CH}_4) = 309 \text{ Tg yr}^{-1}$.

Gas	Yr	A1B	A1FI	A1T	A2	B1	B2
CO	2050	1.38	2.46	2.01	1.62	0.54	1.50
	2100	1.89	2.92	2.36	2.65	0.41	2.28
NO_x	2050	1.55	3.07	1.97	2.30	1.26	1.76
	2100	1.30	3.55	0.91	3.53	0.61	1.98
VOC	2050	2.01	2.32	1.74	1.62	0.84	1.56
	2100	1.39	3.02	0.92	2.46	0.63	1.22
CH_4	2050	1.46	2.03	1.61	1.93	1.16	1.63
	2100	0.93	2.37	0.88	2.87	0.76	1.93

Mayer et al. 2000; Wild et al. 2001). Direct responses to these air quality issues appear to be lacking in most of the SRES scenarios; although reactive gas emissions do change in response to fuel and technology choices.

In the future, increasing national and international pressures to control air quality might reduce reactive gas emissions relative to the SRES scenarios, particularly given the level of ozone increases implied by some of the scenarios, so the present study should be considered as providing upper limits to the effects of reactive gas emissions. The availability of simple relationships between reactive gas emissions and ozone abundances, as developed in the TAR, will aid in the construction of improved future emissions scenarios.

In the present analysis, it is the emissions of CO , NO_x , VOC, and CH_4 that control tropospheric chemistry and hence the abundance of O_3 , CH_4 , HFCs, and HCFCs. To summarize these, Table 1 gives anthropogenic emissions for the six illustrative scenarios in 2050 and 2100 relative to their 1990 levels. For A1FI and A2, anthropogenic emissions of these gases show steady increases over the twenty-first century, with reactive gas emissions approximately 2.5 to 3.5 times their 1990 values by 2100. For A1B and A1T, CO emissions increase steadily over the twenty-first century, while other gases show emissions increases initially, and then decrease during the second half of the twenty-first century. In A1T, NO_x , VOC, and CH_4 , emissions in 2100 are lower than in 1990. In A1B, only CH_4 has 2100 emissions below the 1990 level. The B2 scenario has steady emissions increases over the twenty-first century, except for VOC emissions—which increase initially, and then decrease. For all four gases in the B1 scenario, emissions in 2100 are below their 1990 levels (substantially for CO). Both NO_x and CH_4 show relatively small initial increases before declining, whereas CO and VOC emissions decline steadily over the twenty-first century.

3. Effect on methane

In the IPCC TAR (Prather and Ehhalt 2001) CH_4 abundances are determined using a standard global-mean, mass-balance equation:

TABLE 2. Effect of reactive gases on global-mean tropospheric CH₄ abundance (ppb). Absolute values are given for the base case (none) where anthropogenic emissions of reactive gases are held constant at 1990 levels. All other results, labeled with a plus or minus, show the relative effects (ppb). For example if CO emissions are included in the A1B scenario, the 2050 abundance of CH₄ rises from 2399 ppb (base case) to 2399 + 79 = 2478 ppb. The precision here is for numerical convenience and does not reflect accuracy. Abundances for the combined scenario (all) were calculated with the model described here and differ slightly, but not significantly from those in the TAR.

Yr	Case	A1B	A1FI	A1T	A2	B1	B2
2050	none	2399	2849	2539	2762	2059	2438
	+CO	+79	+272	+195	+137	-83	+93
	+NO _x	-180	-549	-295	-388	-89	-215
	+VOC	+108	+113	+73	+64	-13	+56
	all	+1	-174	-34	-195	-182	-70
2100	none	1845	3645	1863	4156	1624	2988
	+CO	+156	+778	+143	+539	-103	+349
	+NO _x	-97	-1174	-53	-1106	+79	-381
	+VOC	+71	+369	+25	+223	-30	+44
	all	+125	-229	+297	-414	-56	-13

$$dC/dt = E/2.78 - C/\tau_{\text{OH}} - C/\tau_{\text{STRAT}} - C/\tau_{\text{SOIL}} \quad (1)$$

where C is global-mean tropospheric abundance of CH₄ in ppb (where 1 ppb = 10⁻⁹ mole fraction relative to dry air), E is total CH₄ emissions (Tg yr⁻¹) from both natural and anthropogenic sources, the divisor 2.78 [Tg (ppb)⁻¹] is a conversion factor, and the τ are lifetimes (inverse loss frequencies) that define the tropospheric sink (τ_{OH}), the stratospheric sink ($\tau_{\text{STRAT}} = 120$ yr) and the soil sink ($\tau_{\text{SOIL}} = 160$ yr). The tropospheric lifetime, τ_{OH} , varies with changes in CH₄ abundance and reactive gas emissions according to:

$$\begin{aligned} d(\ln\tau_{\text{OH}})/dt = & -0.32d(\ln C)/dt + 0.0042dE(\text{NO}_x)/dt \\ & - 0.000105 dE(\text{CO})/dt \\ & - 0.000315 dE(\text{VOC})/dt. \end{aligned} \quad (2)$$

In Eqs. (1) and (2), emissions are in Tg yr⁻¹ except for NO_x which is in Tg(N) yr⁻¹. It is assumed that natural emissions of CH₄, CO, VOC, and NO_x remain constant and that the SRES scenarios therefore describe all changes in emissions.

As in the IPCC Second Assessment Report (Prather et al. 1996) and the TAR (Prather and Ehhalt 2001), total CH₄ emissions defined by the scenarios are adjusted by a constant offset in all years in order to ensure a balanced initial budget (here, in the year 2000). The assumed mid-2000 values are $\tau_{\text{OH}} = 9.6$ yr, $C = 1764$ ppb, and $dC/dt = 8$ ppb yr⁻¹. The initial abundances for year 2000 are based on recent observations (see TAR) and Eqs. (1) and (2) are used to integrate to year 2100.

Table 2 shows CH₄ abundance projections for the six SRES illustrative scenarios in the years 2050 and 2100. The baseline case, labeled none in Table 2, is where reactive gas emissions changes are ignored [i.e., lifetime changes arise only through the direct CH₄ feedback term in Eq. (2)]. The +CO, +NO_x, and +VOC rows in Table 2 show deviations from the base case when only those particular reactive gas terms are included in Eq. (2). The “all” row shows results when all reactive gas effects are included.

In the scenarios where all reactive gas emissions increase, CO and VOC effects (which increase lifetime and, hence, lead to greater abundances) are more than offset by the effect of NO_x (which acts oppositely—cf. Isaksen and Jackman 1999; Kheshgi et al. 1999; Wild et al. 2001). In B2, where all emissions decrease, the opposite counterbalancing influences occur. Thus, while individual reactive gas emissions may have very large effects on CH₄ abundances, their correlated emissions lead to much smaller net impacts.

Figure 1 (top) expresses these results in terms of changes in total methane radiative forcing from 1990 and extends them to the full set of SRES scenarios. The abundance–forcing relationship is as used in the IPCC TAR (Ramaswamy 2001), with spectral overlap with N₂O accounted for (cf. Shine et al. 1990). The effect of CH₄-related changes in stratospheric water vapor is included in the forcing value, while the effect of CH₄-related changes in tropospheric ozone is counted separately (see next section). The forcing shown is that for the all case of Table 2 (i.e., accounting for CO, NO_x, and VOC emissions). The B1 scenario leads to the lowest forcing for most of the 2000–2100 interval. Maximum forcings come from scenarios not included in the illustrative scenarios set.

Figure 1 (bottom) isolates the reactive gas component of the methane forcings in the top panel. The maximum effect of the reactive gases on methane forcing is a relatively small ± 0.2 W m⁻². The range spanned by the illustrative scenarios is considerably smaller than the full 35-scenario range.

4. Effect on tropospheric ozone

The IPCC TAR gives the following corrected relationship for tropospheric ozone burden changes (Prather and Ehhalt 2001; see notes to Table 4.11):

$$\begin{aligned} d(\text{O}_3)/dt = & 5.0d(\ln C)/dt + 0.125dE(\text{NO}_x)/dt \\ & + 0.0011dE(\text{CO})/dt \\ & + 0.0033dE(\text{VOC})/dt, \end{aligned} \quad (3)$$

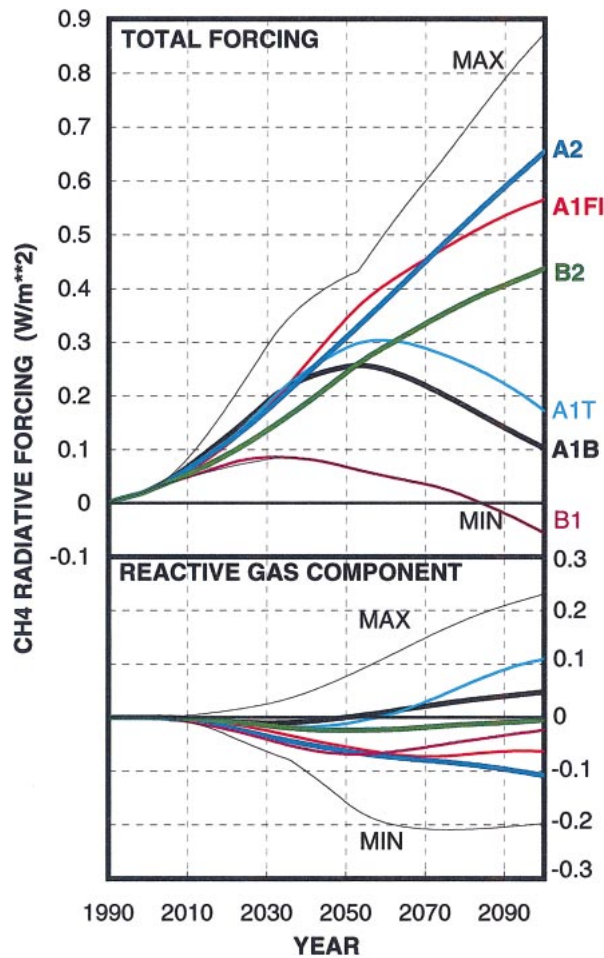


FIG. 1. (top) Total methane radiative forcing for the 6 SRES illustrative scenarios together with the envelope over all 35 complete scenarios. At different times, different scenarios may be the extremes. All reactive gas effects are included in calculating the concentration changes. The effects of stratospheric water vapor changes arising from methane oxidation are included in the forcing. (bottom) Contribution to methane radiative forcing (top) arising solely from changes in reactive gas emissions.

where O_3 is tropospheric-mean ozone burden in Dobson units (DU) and other symbols are as in Eq. (2). This is not the equation used in TAR projections of radiative forcing, global-mean temperature, or global-mean sea level changes, which employed an earlier version of Eq. (3) with coefficients approximately one-third larger. It is, however, a more accurate representation of strictly tropospheric changes in ozone. It does not include attendant changes in stratospheric ozone. Results from the models used in the TAR assessment suggest that accounting for stratospheric ozone changes would lead to an increase in radiative forcing, but this is highly uncertain.

Having solved Eq. (3), ozone burden changes are converted to radiative forcing using the calibration relationship given in the TAR, $+1DU = +0.042 \text{ W m}^{-2}$;

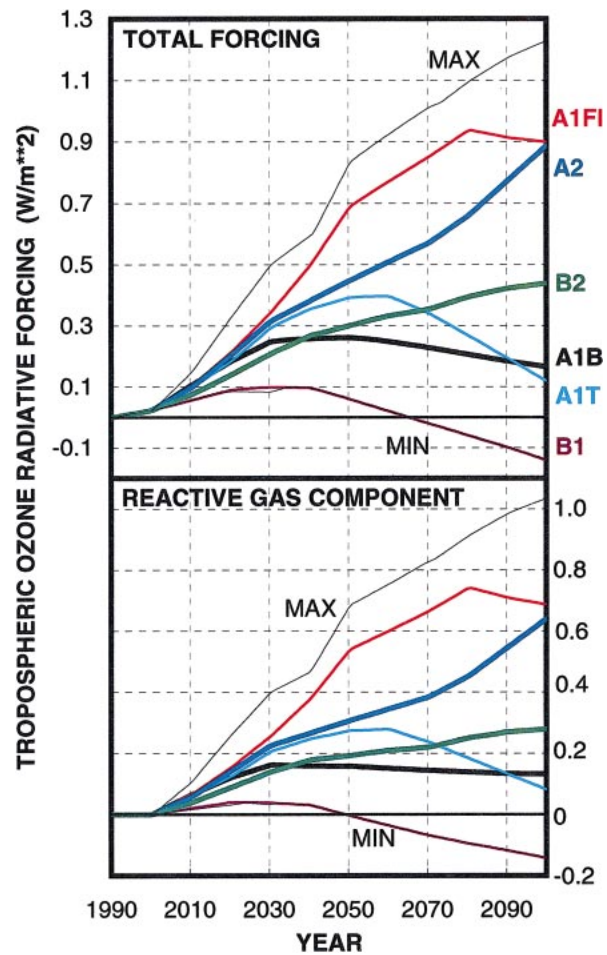


FIG. 2. (top) Tropospheric ozone radiative forcing for the 6 SRES illustrative scenarios together with the envelope over all 35 complete scenarios. At different times, different scenarios may be the extremes. Forcing includes the effects of both methane concentration and reactive gas emissions changes. (bottom) Contribution to tropospheric ozone radiative forcing (top) arising solely from changes in reactive gas emissions. The difference, (top) minus (bottom), gives the effect of methane emissions changes.

and a year-2000 reference level of $+0.35 \text{ W m}^{-2}$ is assumed.

It should be noted that reactive gas effects on tropospheric ozone forcing arise in two ways, directly through the $E(\text{CO})$, $E(\text{NO}_x)$, and $E(\text{VOC})$ terms in Eq. (3), and indirectly through their influence on CH_4 abundances [see Eqs. (1) and (2)]. Both effects are included in the results given here.

Figure 2 (top) shows future tropospheric ozone forcing changes from 1990 based on Eq. (3). Results from the 6 illustrative scenarios are shown specifically, together with the envelope for all 35 SRES scenarios. The individual influences of CO and VOC emissions are clear cut; for both, greater emissions increase ozone forcing both directly [Eq. (3)] and indirectly (through the effects on CH_4 abundance). For NO_x , there are compensating direct and indirect influences, but the direct

influence dominates in all SRES scenario cases. Reactive gases account for 60%–80% of the tropospheric ozone forcing (Fig. 2, bottom) with the remainder coming from changes in methane emissions.

The emissions in many of these scenarios imply very large increases in global-mean tropospheric ozone burdens, reaching levels substantially higher than present [cf. the maximum forcing over 2000–2100 in Fig. 2 (top) of around 0.9 W m^{-2} with the year-2000 value of 0.35 W m^{-2}]. The implied high urban ozone levels are unlikely to be tolerated based on air quality considerations. In particular, they would be inconsistent with some of the assumptions underlying the SRES scenarios, most obviously for those scenarios that assume high incomes and/or a high degree of focus on environmental issues (i.e., all except the A2 scenario family). Thus, for most of the SRES scenarios, as noted earlier, it is likely that the projected emissions of reactive gases are too high and that lower projections would be estimated if local or regional air quality issues were explicitly accounted for. Note, however, that the ozone values calculated here refer to average tropospheric ozone levels, and that the global modeling studies of the TAR give only the increase in background levels and these are not adequate to predict urban ozone levels.

5. Effect on halocarbons

The hydrogenated halocarbons (methyl chloroform, HCFCs, and HFCs) are removed from the atmosphere by reaction with OH in the troposphere. In response to changes in CH_4 and reactive gas emissions, the abundance of OH will change and this will alter the lifetimes of these halocarbons. These changes will run parallel to those of the tropospheric lifetime of methane [τ_{OH} ; see Eq. (2)]:

$$\tau_X(t)/\tau_X(2000) = \tau_{\text{OH}}(t)/\tau_{\text{OH}}(2000), \quad (4)$$

where X refers to a particular HCFC or HFC. For the SRES scenarios, reactive gas emissions cause both increases and decreases in τ_{OH} relative to the year-2000 value. In the SRES and the TAR, emissions are specified and abundances calculated for the following hydrogenated gases: methyl chloroform, HCFC-22, HCFC-123, HCFC-141b, HCFC-142b, HFC-23, HFC-32, *HFC-125*, *HFC-134a*, *HFC-143a*, *HFC-227ea*, *HFC-245ca* and HFC-43-10mee. (Total HCFC-plus-HFC radiative forcing is dominated by the gases italicized in this list.) It is a simple matter to calculate, scenario by scenario, the total forcings using halocarbon lifetime variations determined only by those CH_4 -induced changes in OH that are not the result of changes in reactive gas emissions (i.e., those due only to CH_4 emissions changes). Comparing these with forcing changes that account additionally for reactive gas-induced lifetime variations allows us to identify the components of change due solely to reactive gases: i.e., the difference quantifies the effect of reactive gas emissions, which is shown in Fig. 3.

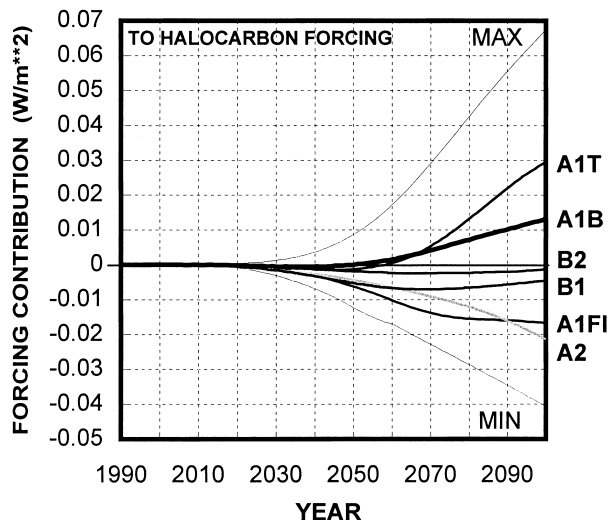


FIG. 3. Contribution to the radiative forcing from hydrogenated halocarbons that arises due to changes in reactive gas emissions: results for the 6 SRES illustrative scenarios together with the envelope over all 35 complete scenarios. This contribution reflects the effects of reactive gas-induced lifetime changes.

(Note that, although there are only four distinct halocarbon scenarios in the SRES set, since each scenario has different methane and reactive gas emissions, halocarbon forcing values are different for each scenario.)

As might be expected from Eq. (4), the reactive gas influence on halocarbon forcing looks qualitatively similar to that on CH_4 forcing (cf. Fig. 3 and bottom of Fig. 1). The halocarbon effect, however, is smaller; approximately 10% of the CH_4 effect in 2050 rising to around 25% by 2100. Thus, the effect on tropospheric ozone remains the dominant influence of reactive gas emissions.

6. Discussion and conclusions

The individual effects of reactive gas emissions on radiative forcing through methane, tropospheric ozone, and the hydrogenated halocarbons are shown at the bottom of Figs. 1 and 2, and in Fig. 3. Tropospheric ozone influences are the most important. Forcing changes due to modification of greenhouse gas lifetimes, primarily through changes in OH abundances, are several times smaller than forcing due to ozone changes, except for scenarios with small overall forcing. This is due in large part to the balance between the effect of increasing NO_x emissions (which increase OH) and increasing CO plus VOC emissions (which decrease OH).

All three reactive gas categories (i.e., CO, NO_x , and VOC) contribute to net radiative forcing in qualitatively the same way, with reduced emissions leading to less forcing. For CH_4 and the hydrogenated halocarbons, reduced NO_x emissions lead to greater forcing, but this is more than offset by the effect of NO_x emissions on tropospheric ozone (a possibility noted, e.g., by Kheshgi

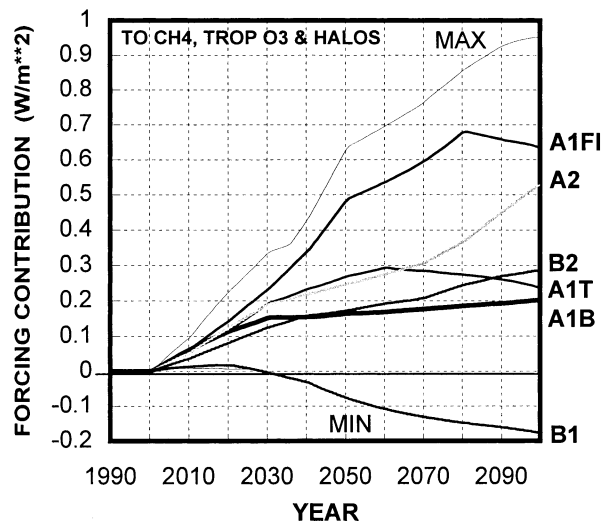


FIG. 4. The effect of reactive gas emissions on total radiative forcing for the 6 SRES illustrative scenarios together with the envelope over all 35 complete scenarios. At different times, different scenarios may be the extremes. The figure shows the sum of effects arising through methane (Fig. 1, bottom), tropospheric ozone (Fig. 2, bottom), and hydrogenated halocarbons (Fig. 3), amplified slightly (approx 5%) by attendant changes in temperature-related feedbacks on the carbon cycle.

et al. 1999, p. 19 188; a similar offsetting effect occurs in the work of Mayer et al. 2000 and Wild et al. 2001).

There is considerable uncertainty in these results. The model studies from which the relationships used here were derived, for example, gave future ozone changes varying from the central value by $\pm 30\%$ (Prather and Ehhalt 2001). Improvements in ozone modeling are of obvious importance in quantifying the radiative forcing effects of reactive gas emissions.

The combined effects of all forcings are shown in Fig. 4. Note that the forcings in Fig. 4 differ slightly from the sum of the forcings in Fig. 1 (bottom), Fig. 2 (bottom), and Fig. 3 (roughly 5% greater). This is because of a feedback from reactive gas emissions through climate to the carbon cycle. The results in Fig. 4 were determined by comparing total radiative forcing for each scenario including all forcing agents, first in the absence of changes in reactive gas emissions and, second, with these emissions changes included. In the full calculation involving all greenhouse gases and the reactive gases the warming is inflated slightly by the reactive gases. This additional warming then, through positive temperature feedbacks on the carbon cycle, leads to slightly higher CO_2 abundances and, hence, to a slightly amplified forcing increase. The additional CO_2 amount and the consequent forcing amplification depend on the assumed climate sensitivity; an equilibrium $2 \times \text{CO}_2$ warming of 2.6°C is used here.

Figure 4 provides insight into the value of reactive gas emissions reductions as a specific climate mitigation strategy; but the issue is a complex one because future levels of such emissions will also be determined by air

quality issues. In practice, the extent of climate mitigation that might be achieved in this way depends on the difference between the emissions targets of the policy scenario and the emissions for a baseline no-climate-policy scenario. To isolate the climate policy implications, however, it is necessary that the baseline scenario adequately accounts for nonclimate policies, such as those arising from air quality considerations.

If the SRES scenarios are assumed to be valid as no-climate-policy baselines, then the forcings in Fig. 4 give the potential for climate mitigation corresponding to the case where the (climate-motivated) policy target is to keep emissions at 1990 levels. The relevance of these results depends, not only on the realism of the SRES scenarios as no-climate-policy scenarios that account fully for all other policies, but also on the realism of the 1990 emissions levels as targets. In some of the SRES scenarios, reactive gas emissions decrease relative to their 1990 levels so, in these cases, the target is clearly unrealistic (these are the cases where the reactive gas contribution to forcing is negative). The realism of the SRES scenarios as no-policy baselines is also debatable because the SRES scenarios do not take the likely responses to air quality issues into account adequately. For this reason, therefore, Fig. 4 almost certainly overestimates the potential for climate mitigation that might be achieved as a response to direct climate policies. We note, however, that the present analysis does not account for possible reactive gas influences on stratospheric ozone, which would add to the mitigation potential. Nor, as noted earlier, do we account for possible influences on aerosols.

In spite of these shortcomings, Fig. 4 still provides useful insights into the potential for climate mitigation via reactive gas emissions reductions. In absolute terms, the potential forcing reduction for the assumed target ranges up to 0.63 W m^{-2} in 2050 and 0.95 W m^{-2} in 2100. The potential, as is clear from Fig. 4, is strongly dependent on the assumed baseline no-policy scenario (cf. Smith et al. 2000). Greatest potential reductions occur in scenarios that have the highest total radiative forcing, since, when correlated across scenarios, reactive gas forcing is related to total forcing ($r = 0.67$ in 2050, $r = 0.75$ in 2100). On average, reactive gas forcing accounts for about 5% of total forcing (range, -4% to $+12\%$).

Hansen et al. (2000), in investigating a range of mechanisms for reducing future climate change, have noted that reducing reactive gas emissions might have valuable climate mitigation effects. Our work quantifies Hansen et al.'s claim, and confirms their conclusion. Just how much climate mitigation might be possible as a direct response to climate policies, however, cannot be quantified at present because of the uncertainties noted above. If air quality considerations kept future emissions of reactive gases close to present levels, the direct climate-policy mitigation potential would be small. Better quantification of this potential requires, at least as a

first step, modification of the SRES scenarios to account more fully for the effects of nonclimate environmental policies. It is clear from our results that reactive gas emissions reductions cannot be considered as a replacement for strategies to reduce greenhouse gas emissions; however, the climate implications of reducing reactive gas emissions provide an important additional incentive for their reduction.

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