Management of Tropospheric Ozone by Reducing Methane Emissions

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Background concentrations of tropospheric ozone are increasing and are sensitive to methane emissions, yet methane mitigation is currently considered only for climate change. Methane control is shown here to be viable for ozone management. Identified global abatement measures can reduce ~10% of anthropogenic methane emissions at a cost-savings, decreasing surface ozone by 0.4−0.7 ppb. Methane controls produce ozone reductions that are widespread globally and are realized gradually (~12 yr). In contrast, controls on nitrogen oxides (NO_X) and nonmethane volatile organic compounds (NMVOCs) target high-ozone episodes in polluted regions and affect ozone rapidly but have a smaller climate benefit. A coarse estimate of the monetized global benefits of ozone reductions for agriculture, forestry, and human health (neglecting ozone mortality) justifies reducing ~17% of global anthropogenic methane emissions. If implemented, these controls would decrease ozone by ~1 ppb and radiative forcing by ~0.12 W m^{-2}. We also find that climate-motivated methane reductions have air quality-related ancillary benefits comparable to those for CO_2. Air quality planning should consider reducing methane emissions alongside NO_X and NMVOCs, and because the benefits of methane controls are shared internationally, industrialized nations should consider emphasizing methane in the further development of climate change or ozone policies.

Introduction

Air quality managers face significant challenges to meet new standards for tropospheric ozone in the United States (80 ppb), Europe (60 ppb), and elsewhere. These domestic challenges are exacerbated by the long-range transport of emissions from other nations (*1*) and by the growth in global background ozone concentrations (*2*). This increase in background ozone is evident in observations (*3*−*6*), and models have estimated that surface ozone in remote regions has doubled, for example, from 10 to 15 ppb in 1860 to 20−30 ppb in 1993 (*7*). This historic increase in tropospheric ozone concentrations has been attributed in part to increases in global anthropogenic emissions of methane (*8*). Future background ozone concentrations are projected to continue to grow, with that increase due about half to increases in emissions of nitrogen oxides (NO_X) and half to methane under one scenario (*9*).

Increases in background ozone raise the baseline upon which local-to-regional ozone builds. In polluted regions, ozone formation is driven by the rapid photochemical oxidation of nonmethane volatile organic compounds (NMVOCs) in the presence of NO_X. Methane has little effect on the ozone formed daily in an urban plume, because it reacts very slowly (with a lifetime of 8−9 yr). Methane, however, is well-mixed throughout the troposphere and is more abundant than all NMVOCs combined; anthropogenic methane is estimated to contribute roughly 7 times that of anthropogenic NMVOCs to the total tropospheric ozone burden (*10*).

Methane and ozone are also greenhouse gases (GHGs), which rank only behind CO_2 in their contributions to anthropogenic climate forcing (*11*). Several studies suggest that methane emissions can be controlled inexpensively and can play a major role in a near-term climate strategy (*12*−*14*); methane abatement has thus been mainly discussed for climate purposes. Although the importance of methane for ozone formation has long been appreciated (*15*), methane has not been considered in ozone management, because the local ozone benefits of local methane reductions are small.

In this study, we use recent estimates of the sensitivity of surface ozone to changes in methane emissions, along with estimates of the costs of methane abatement and the monetized benefits of ozone reductions, to explore the viability of managing ozone through methane emission reductions. Our coarse estimate of monetized benefits is also an estimate of the global ancillary benefits of methane controls that are currently being pursued to decrease greenhouse warming. We conclude by discussing the possible role of methane alongside NO_X and NMVOCs in ozone management, in light of its unique dual benefits for background ozone and for climate.

Response of Ozone to Methane Emission Reductions

Fiore et al. (*10*) previously used the GEOS−CHEM global three-dimensional model of tropospheric chemistry to estimate that reducing 50% of global anthropogenic methane emissions would decrease average summer afternoon surface ozone concentrations by 3 ppb over the United States. Additional results from these simulations are presented here.

Figure 1 shows that a 50% reduction in anthropogenic methane emissions decreases surface ozone by 1−6 ppb globally. Over land, typical ozone reductions are 3−4 ppb, with the largest reductions often in populated regions of the northern mid-latitudes. Because methane mainly affects ozone in the free troposphere, the largest changes in surface ozone occur where air from the free troposphere is transported frequently to the surface. These include regions at high elevation and regions where strong downwelling occurs, such as the Middle East in summer (*16*). Because of the long lifetime of methane, the spatial ozone response does not reflect the location of methane emissions. In general, changes

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10.1021/es048629f CCC: $30.25
Published on Web 05/28/2005

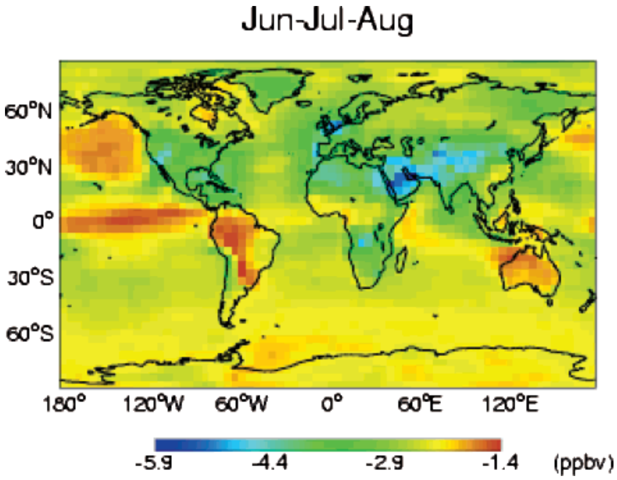

FIGURE 1. Global change in mean summer (June−July−August) afternoon (1300 to 1700 local time) surface ozone (ppb) ultimately achieved when anthropogenic methane emissions are decreased by 50% in the GEOS−CHEM tropospheric chemistry model (driven by assimilated meteorology from NASA GEOS-1 at 4° × 5° horizontal resolution), as described by Fiore et al. (*10*).

in ozone in the northern hemisphere (NH) summer are consistent with the 3 ppb estimate for the United States. We use this 3 ppb sensitivity in our estimates below; it is within the range of six models reported elsewhere (*17*) and is appropriate for NH summer, with slightly smaller values relevant for the southern hemisphere (SH) and in winter (see Supporting Information).

Methane controls will achieve the ozone reductions in Figure 1 gradually. Using the perturbation lifetime of methane of 12 years (*17*), ~60% of the estimated reductions will be realized in 10 years and ~80% in 20 years. In contrast, NO_X and NMVOC controls reduce ozone rapidly (hours to weeks), with benefits that are largely concentrated near the controlled sources.

NO_X controls also effectively reduce ozone during high-ozone episodes (Figure 2, as do NMVOC controls at the urban scale not reflected in Figure 2). Because methane affects background ozone, methane controls decrease ozone concentrations by a similar increment over the whole ozone distribution, although its effect on the highest ozone episodes (>80 ppb) is smaller. The latter result reflects the smaller contribution of background ozone to high-ozone events, as the stagnant meteorological conditions common in such events suppress mixing between the surface and the free troposphere (*18*). Finally, Figure 2 shows that reductions in ozone are roughly additive when both methane and NO_X are reduced, indicating that the benefits of methane reductions on background ozone are complementary to the large local and regional benefits of NO_X controls.

Ozone Control via Methane Reductions: Potential and Cost

Global anthropogenic emissions of methane derive 39−51% from agricultural sources and 21−30% from energy, with landfills and biomass burning contributing much of the rest (*19*, *20*). Global cost curves for methane abatement compiled by IEA (*21*) and EPA (*22*−*24*) are based on the costs of many individual control technologies applied in several regions of the world (Figure 3). These data sets emphasize abatement opportunities for industrial sources and neglect many opportunities in the large agricultural sector (e.g., cattle and rice cultivation), for which costs are not as well quantified. These data sets (or previous versions) have been used in previous studies (*12*, *13*, *25*, *26*). IEA (*21*) considers the five industrial sectors: solid waste, coal, oil, and gas operations and wastewater. EPA (*23*) considers four of the same sectors (not wastewater) and also considers manure management. Figure 4 shows that by 2010, ~10% of anthropogenic methane emissions can be reduced at a net cost savings. These negative marginal costs reflect the value of recovered natural gas and represent a net savings for social welfare (neglecting transaction and management costs), although individual firms may bear positive costs. The EPA (*23*) estimates are smaller than those of IEA (*21*), mainly because the EPA (*23*) does not include methane reductions from wastewater, which are about 40% of the cost-saving reductions identified by IEA (*21*). Because these studies omit other abatement op-

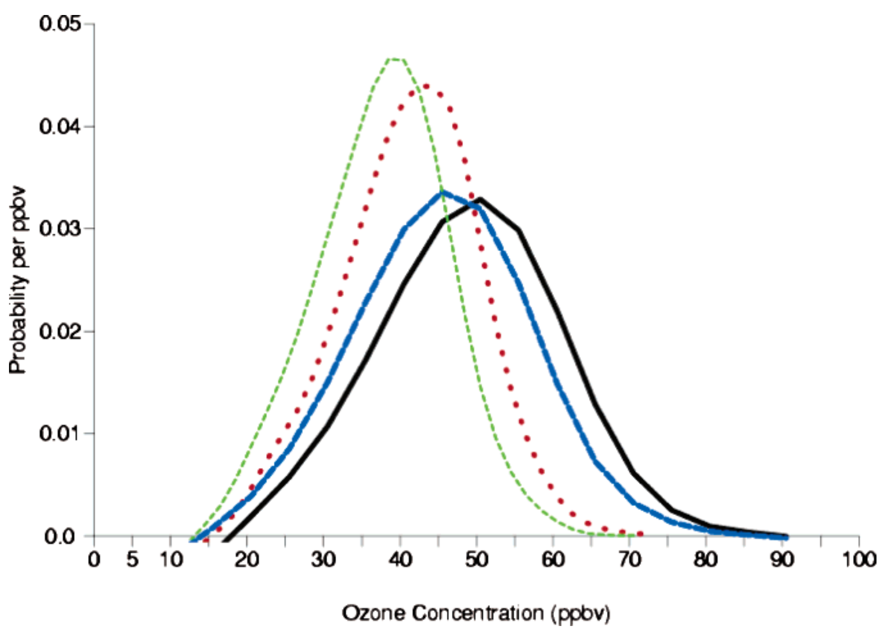

FIGURE 2. Frequency distribution of daily mean afternoon (1300−1700 local time) ozone concentrations in surface air for summer 1995 in the United States as simulated with the GEOS−CHEM model (solid black). Also shown are results when global anthropogenic ozone precursor emissions are reduced by 50% as described by Fiore et al. (*10*): methane only (thick-dashed blue), NO_X only (dotted red), and methane, NO_X, NMVOC, and CO (thin-dashed green). NMVOC and CO reductions have a negligible impact on surface O_3 in the 4° × 5° resolution used here, so the thin-dashed green line reflects the combined impact from 50% decreases in anthropogenic methane and NO_X.

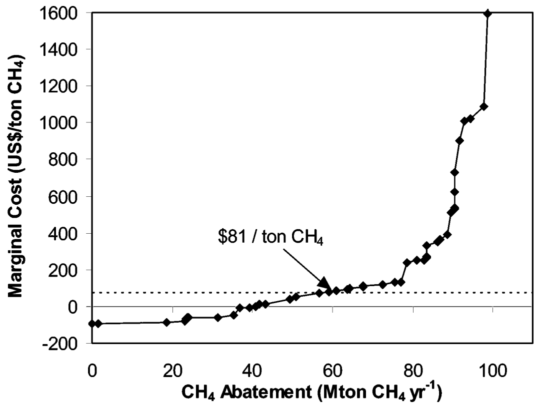

FIGURE 3. Marginal global costs of methane abatement from five industrial sectors, using data from IEA (*21*; solid line). Our estimated marginal benefit of methane reductions ($81/ton CH_4) is shown as a horizontal line (dashed), since we assume that benefits are proportional to the methane reductions.

portunities, particularly in agriculture, the true methane abatement potential may be greater than either estimate.

These estimates of the available global methane reductions are combined with the 3 ppb sensitivity (previous section) to estimate the potential for decreasing ozone through methane control, assuming that ozone responds proportionally to changes in methane emissions (Figure 4). Global methane reductions identified as having a net cost savings can reduce ozone by 0.4−0.7 ppb, with double that potential for less than $10 per ton CO_2 equiv, the cost of a modest climate abatement strategy. All identified methane controls globally would reduce ozone by 1.6−1.9 ppb. Roughly half of these methane reductions are in industrialized nations.

While cost-saving methane reductions are available, decreasing ozone by 1 ppb through local or regional controls on NO_X and NMVOCs in industrialized nations often requires major regulatory action at high cost. For example, recently proposed controls on NO_X emissions from electricity generating plants in the eastern United States are expected to cost $884 million yr^{-1}, reducing ozone (average 8-h summer population-weighted) by 0.86 ppb (*27, 28*). Decreasing ozone by 1 ppb through NO_X and NMVOC controls in all polluted

TABLE 1. Annual Nonmortality Benefits of a Uniform 1 ppb Ozone Reduction (in $Billion yr^{-1} ppb^{-1})[a]

	United States	EU-15	East Asia	global[b]
agriculture	0.40	0.51	0.42	2.8 (0.04−5.6)
forestry	0.44			1.7 (0.5−2.9)
human health (nonmortality)	0.59	0.60		3.0 (2.0−4.1)
total	1.4	>1.1	>0.4	7.5 (4.4−10.7)

[a] Derived from regional studies (*29*−*33*). [b] Global benefits extrapolated from regional studies with estimated uncertainty (in parentheses, 90% confidence interval from EPA (30) applied proportionally to the central estimates).

regions of the globe is therefore expected to cost many billions of dollars annually.

Monetized Benefits of Global Ozone Reductions

The monetized benefits of ozone reductions for human health, agriculture, and forestry have been estimated previously in regional studies. Here, we make a coarse estimate of the global monetized benefits of methane emission controls by combining several regional estimates (*29*−*33*) and extrapolating to the global scale. Our estimate excludes ozone-induced premature human mortality, and we may therefore substantially underestimate the true total benefit. We assume throughout that changes in ozone are proportional to methane reductions and that the monetized benefits are proportional to the ozone reduction. We follow several steps:

(a) Compile Regional Benefit Estimates per ppb of Ozone Reduced. Regional estimates of monetized benefits from individual studies (*29*−*33*) are divided by the ozone reductions considered in those studies to give the annual benefit per ppb of ozone reduced. In Table 1, these benefits are also adjusted to 2000 U.S. dollars (see Supporting Information) for consistency with the costs in Figure 4. The human health benefits in Table 1 are limited to nonmortality benefits, morbidity (mainly avoided minor restricted activity days) and worker productivity in the United States (*29*) and morbidity in the EU (*32*), and neglect the possible effects of ozone reductions on premature mortality. Recent epide-

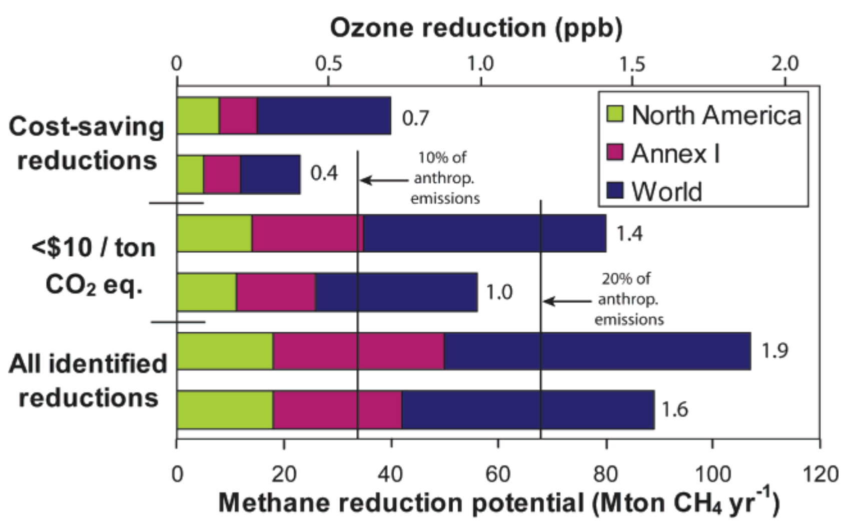

FIGURE 4. Methane emission reduction potential in 2010 in North America, Annex I, and the world estimated by IEA (top bar of each pair, *21*) and EPA (lower bar, *23*). The top axis and the numbers to the right of the bars show the resulting reductions in northern hemisphere summer surface ozone ultimately achieved if the available methane reductions are implemented. These reductions would be fully achieved after more than 20 years. Annex I refers to all nations in Annex I of the United Nations Framework Convention on Climate Change. For EPA (*23*) at <$10/ton CO_2 equiv, we used their estimates for $200/ton CH_4, which is $9.5/ton CO_2 equiv using their global warming potential of 21. Percentages are relative to current global anthropogenic emissions, taken as 340 Mton CH_4 yr^{-1}.

miological time-series analyses suggest strongly that ozone affects daily mortality (e.g., *34*, *35*), and where the benefits of avoided ozone mortality have been estimated, the total health benefits increase dramatically. For example, including ozone mortality increases the estimate of U.S. health benefits in Table 1 by roughly a factor of 5 (*34*). Mortality benefits in the EU are estimated to be \$0.34−9.5 billion yr^{-1} ppb^{-1}, depending on how premature mortality is valued (*32*, *33*).

(b) Extrapolate to Global Benefits. Regional estimates are combined in Table 1 to give the monetized benefits of a spatially and temporally uniform 1 ppb ozone decrease. The sum of the regional estimates alone gives \$3.0 billion yr^{-1} ppb^{-1}, which can be thought of as a lower limit for global benefits. We extrapolate globally using data on global population, grain production, and commercial forestry, yielding a total global benefit of \$7.5 billion yr^{-1} ppb^{-1} (see Supporting Information).

Because most of the individual studies above do not present estimates of uncertainty, the 90% confidence intervals from the U.S. EPA (*30*) are applied proportionally to our global estimates of the agriculture, forestry, and human health benefits. This approach likely underestimates the true uncertainty in our extrapolation to the global scale. This uncertainty range of \$4.4−10.7 billion yr^{-1} ppb^{-1} is carried forward in further calculations.

(c) Estimate Benefit per Ton of Methane. This estimate of the nonmortality global benefit of a uniform ozone reduction is then multiplied by the 3 ppb sensitivity (Response of Ozone to Methane Emission Reductions section) to give a marginal benefit of \$132 per ton of methane emissions reduced (\$78−189).

(d) Discount the Future Benefits. Because methane reductions would decrease ozone gradually, the future benefits of methane reductions should be discounted. Ozone concentrations and future benefits are represented as exponentially approaching the ultimate marginal benefit (\$132 per ton CH_4), using the 12-yr perturbation lifetime of methane (*17*). These increasing benefits are then converted into a stream of constant annual benefits, which has the same net present value at the selected discount rate. This approach neglects future changes in population and commodity prices. Using a 5% yr^{-1} real discount rate, the marginal benefit of methane reductions is \$81 per ton CH_4 (\$48−116), shown as the dashed line in Figure 3. At 3% yr^{-1}, it is \$89 per ton CH_4 (\$52−128), and at 7% yr^{-1}, \$73 per ton CH_4 (\$43−105). This estimate is consistent with a previous study in which the monetized benefits from reducing ozone through methane mitigation were estimated, using different methods, to be \$112 per ton CH_4 (*33*).

From a cost−benefit perspective, methane controls are justifiable for marginal costs less than this marginal benefit (\$81 per ton CH_4). Measures with a negative marginal cost can reduce ~10% of current anthropogenic emissions (Figure 4). These reductions can be justified on their cost savings alone, regardless of benefits for ozone or climate.

Accounting for all control measures globally with marginal cost less than \$81 per ton CH_4 (\$48−116), where the curves in Figure 3 cross, suggests that a global reduction of 59 Mton CH_4 yr^{-1} (49−72 Mton CH_4 yr^{-1}, using IEA (*21*) data), about 17% (15−21%) of anthropogenic emissions, can be justified on the basis only of nonmortality ozone benefits and neglecting benefits to climate.

Ancillary Benefits of Climate-Motivated Methane and CO_2 Reductions

Because the major sources of CO_2 emissions are also sources of air pollutants, CO_2 mitigation is widely recognized to have ancillary benefits for air pollution and public health (*36*). For methane mitigation, however, air pollution ancillary benefits have received little attention to date. Our estimated marginal benefit above is also a measure of the ancillary benefits of methane reductions that are motivated for climate purposes. The ancillary benefit of methane controls (converting units) is \$3.9 per ton CO_2 equiv (\$2.3−5.5) or \$14 per ton C equiv (\$8.3−20), which is comparable to the range previously estimated for CO_2 in populated regions of \$2−500 per ton C equiv (*37*).

The ancillary benefits of methane reduction result from reactions involving methane itself, unlike those for CO_2 mitigation, which result from reductions in co-emitted air pollutants. The ancillary benefits of CO_2 mitigation are location- and time-specific and depend strongly on the means by which CO_2 emissions are reduced. In contrast, because methane affects ozone slowly, the ancillary benefits of methane mitigation are equal irrespective of the location and time of the reductions. The ancillary benefits of methane reductions likely depend little on the abatement measure, although some actions may additionally reduce co-emitted NMVOCs or may affect other pollutant emissions through the combustion of captured methane (not quantified here).

Discussion of Uncertainties

Our estimate of the global monetized benefits of methane reductions is coarse and, because we extrapolate globally from existing regional studies, caution should be taken in interpreting these results. Our estimate neglects many types of benefits and therefore is likely biased low. The most important of these is likely the reduced mortality from decreased ozone, but we have also neglected impacts for several agricultural products as well as for natural ecosystems.

Further, our benefit estimate assumes proportionality with ozone. Health effects are often assumed to be linear or nearly linear functions of changes in concentration, and some studies find little indication of threshold effects at low ozone concentrations (*35*). Agricultural impacts are estimated using either indicators of average ozone concentration that have nearly linear relationships (*31*) or threshold indicators that suggest nonlinear functions. Our assumption that monetized benefits are proportional to the ozone reduction may overestimate the benefits for the effects considered in regions where ozone concentrations are low. Future research should estimate the global benefits of methane reductions directly using damage functions and atmospheric concentrations, rather than extrapolating from regional studies, and should consider the effects of possible thresholds on impacts.

The costs of methane abatement are also uncertain. Because the sources used here neglect abatement opportunities in many sectors—particularly in agriculture, the largest anthropogenic sector—this study likely underestimates the true low-cost methane abatement potential. Research to identify and better quantify methane emission controls will likely lower costs and increase the estimated methane reductions available. Policy analyses should also consider the distributional and social effects of methane reductions.

Finally, although current models give similar sensitivities of background ozone to changes in methane emissions, modeling this dependency is still relatively new. Future research should consider whether background ozone responds proportionally to changing methane emissions, how the sensitivity varies under future scenarios of other ozone precursor emissions, and possible indirect effects of methane reductions on particulate matter concentrations. Future research should also strive to reduce uncertainty in the sources of methane emissions and in the atmospheric methane budget.

Using Methane Controls to Manage Ozone

The comparative advantages of managing ozone through methane emissions reductions and NO_X and NMVOC controls

TABLE 2. Advantages of Ozone Management via Local and Regional NO_X and NMVOC Emission Reductions and via Methane Emission Reductions

	NO_X and NMVOCs	methane
low-cost emission reductions	few; least-cost options already exhausted in some polluted regions	many cost-saving and low-cost measures exist
potential for ozone reductions	large	limited to ~2 ppb in the coming decades
time scale	hours to weeks	realized gradually over ~12 yr
spatial scale	local to regional, focusing on polluted areas (NO_X also global)	global, with benefits for all nations, ecosystems, and agriculture
impact on high-ozone episodes	strong	ozone reduced roughly equally in all cases
radiative forcing of climate	small	beneficial, from both methane and ozone
ancillary benefits	reduced fine PM, nitrogen and acidic deposition (NO_X), and airborne toxics (NMVOCs)	many measures make methane available for energy, addressing energy security; controls may also reduce NMVOC emissions

are summarized in Table 2. Although each approach has advantages, the potential to reduce ozone through methane emission reductions is limited to ~2 ppb in the near future, which is comparable to major air quality initiatives but is not sufficient to achieve ozone standards in many places. Methane reductions can therefore best be used to complement local and regional NO_X and NMVOC controls.

Methane reductions produce ozone reduction benefits that are spatially widespread and delayed, while the effects of NO_X and NMVOC controls are immediate and local-to-regional (although NO_X also affects global background ozone). Because the local benefits of methane control are small, local air quality authorities lack incentive to reduce methane. For example, even if California eliminated its methane emissions, the benefit would be only ~0.02 ppb. Given that benefits are shared globally, national or international actions to control methane may be necessary or desirable.

Methane reductions would also benefit ecosystems globally. Because ozone inhibits the primary productivity of plants (*38*), reducing methane can have a greater benefit for climate by decreasing ozone and increasing plant uptake of CO_2. Methane may also affect stratospheric ozone and the transmission of ultraviolet radiation. Stratospheric methane reductions could mitigate ozone depletion by reducing water vapor (*39*), but this benefit may be offset if the reduced stratospheric methane increases concentrations of the chlorine radical (reducing formation of hydrochloric acid), thereby increasing chlorine-catalyzed ozone destruction. Finally, many abatement options make methane available for energy purposes, providing energy resources that may address energy security locally.

NO_X and NMVOC reductions have little net effect on radiative forcing, as the NO_X reductions increase the lifetime of methane, which roughly cancels the decreased ozone forcing (*40*). However, NO_X and NMVOC reductions have additional air quality benefits, including lower concentrations of fine particles ($PM_{2.5}$), such as nitrate and secondary organic aerosols, and may be necessary to attain $PM_{2.5}$ standards in some regions. NO_X reductions also reduce nitrogen and acidic deposition, and NMVOC reductions can reduce emissions of some airborne toxics.

Methane Reduction Scenario

Our analysis suggests that a reduction in global methane emissions of 59 Mton CH_4 yr^{-1} (49−72 Mton CH_4 yr^{-1}), which is ~17% of anthropogenic methane, can be justified by the benefits to agriculture, forestry, and human health from reduced background ozone. A global reduction of 59 Mton CH_4 yr^{-1} would

(i) reduce the NH summer ozone background by about 1.0 ppb, with slightly smaller reductions in winter and in the SH.

(ii) reduce global radiative forcing of climate by about 0.12 W m^{-2} (0.10 W m^{-2} from methane and the remainder from ozone).

(iii) come at a global net cost savings of about \$1.7 billion yr^{-1} (the sum of costs for all measures globally less than \$81 per ton CH_4^{-1} marginal cost, using IEA (*21*)).

(iv) avoid damages to agriculture, forestry, and human health valued at \$7.8 billion yr^{-1} (\$4.6−11 billion yr^{-1}).

(v) provide roughly 2% of the current global natural gas production, assuming that half of the 59 Mton yr^{-1} were captured for energy.

Methane Controls for Ozone and Climate Management

Methane is both the shortest-lived of the well-mixed GHGs, and as presented here, is a viable means of long-term (decadal) air quality planning to attain ozone standards. It is also the only known means by which anthropogenic emissions affect concentrations of a criteria air pollutant primarily on a global scale.

This coarse analysis suggests that methane emission reductions are viable as a component of long-term ozone management. Implementing global methane abatement measures identified as cost-saving can reduce background ozone by 0.4−0.7 ppb. At least this quantity of ozone can be reduced more cost effectively through methane than by implementing NO_X and NMVOC controls in all polluted regions of the world. Methane abatement brings reductions in ozone that are shared globally, with benefits for health, agriculture, and natural ecosystems, as well as reduced radiative forcing of climate, although these benefits are realized gradually (~12 yr).

Accounting for the monetized global benefits of ozone reductions for agriculture, forestry, and human health (nonmortality), and discounting the delayed ozone benefits, we estimate that the marginal benefits of methane emission reductions are \$81 per ton CH_4 (\$48−116), or \$3.8 per ton CO_2 equiv (\$2.3−5.5). Setting marginal benefits equal to marginal costs, we find that roughly 17% (15−21%) of global anthropogenic methane emissions can be reduced justifiably for air quality purposes, irrespective of additional benefits to climate. Reducing this quantity of methane emissions would decrease NH summer ozone by ~1 ppb and reduce global radiative forcing of climate by 0.12 W m^{-2}. From a climate perspective, actions currently underway or proposed to reduce methane (e.g., *41*) are estimated here to generate ancillary air quality benefits that are comparable to those previously estimated for CO_2 mitigation in populated regions. This study likely underestimates both the cost-effective methane reductions available (by neglecting agricultural sources) and the total monetized benefits of reducing methane (by neglecting ozone mortality), and future research should address these and other uncertainties in this study.

With substantial challenges to meet ozone standards in some urban areas, particularly with tightening standards and increasing background concentrations, long-term ozone planning should consider adopting cost-effective methane reductions alongside NO_X and NMVOC controls. Climate policies should likewise consider increasing emphasis on methane because of its air quality benefits. Because the benefits of methane control are shared internationally, industrialized nations should consider building support for increased near-term methane reductions, unilaterally or cooperatively, through the further development of policies addressing climate change or ozone, including the Convention on Long-Range Transboundary Air Pollution (*2, 42*). Since the location of methane reductions matters little, such actions can encourage emissions trading and controls in developing nations. Finally, international development and aid organizations should consider emphasizing methane recovery projects with benefits for local energy supply.

Acknowledgments

We thank T. Keating, A. Grambsch, D. Jacob, D. Kruger, C. Delhotal, B. DeAngelo, J. Levy, J. DeMocker, D. Mauzerall, L. Horowitz, M. Prather, and three anonymous referees. The opinions expressed are those of the authors and are not necessarily those of AAAS, the U.S. EPA, NOAA, or the U.S. Department of Commerce. The GEOS-CHEM model is managed by the Atmospheric Chemistry Modeling Group at Harvard University with support from the NASA Atmospheric Chemistry Modeling and Analysis Program.

Supporting Information Available

Calculation methods and notes as well as global maps of ozone reductions from methane control. This material is available free of charge via the Internet at http://pubs.acs.org

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Received for review September 2, 2004. Revised manuscript received April 18, 2005. Accepted April 20, 2005.

ES048629F