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Global health benefits of mitigating ozone pollution with methane emission controls

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Methane (CH₄) contributes to the growing global background concentration of tropospheric ozone (O₃), an air pollutant associated with premature mortality. Methane and ozone are also important greenhouse gases. Reducing methane emissions therefore decreases surface ozone everywhere while slowing climate warming, but although methane mitigation has been considered to address climate change, it has not for air quality. Here we show that global decreases in surface ozone concentrations, due to methane mitigation, result in substantial and widespread decreases in premature human mortality. Reducing global anthropogenic methane emissions by 20% beginning in 2010 would decrease the average daily maximum 8-h surface ozone by ≈1 part per billion by volume globally. By using epidemiologic ozone-mortality relationships, this ozone reduction is estimated to prevent ≈30,000 premature all-cause mortalities globally in 2030, and ≈370,000 between 2010 and 2030. If only cardiovascular and respiratory mortalities are considered, ≈17,000 global mortalities can be avoided in 2030. The marginal cost-effectiveness of this 20% methane reduction is estimated to be ≈\$420,000 per avoided mortality. If avoided mortalities are valued at \$1 million each, the benefit is ≈\$240 per tonne of CH₄ (≈\$12 per tonne of CO₂ equivalent), which exceeds the marginal cost of the methane reduction. These estimated air pollution ancillary benefits of climate-motivated methane emission reductions are comparable with those estimated previously for CO₂. Methane mitigation offers a unique opportunity to improve air quality globally and can be a cost-effective component of international ozone management, bringing multiple benefits for air quality, public health, agriculture, climate, and energy.

human health | mortality | tropospheric ozone | air quality

Tropospheric ozone (O₃) is an oxidant that damages agriculture, ecosystems, and materials. Ozone also adversely affects human health and has been associated in epidemiologic studies with daily premature mortality (1–10). Surface O₃ concentrations have historically increased in both polluted and remote regions and now frequently exceed regulatory standards (11–14). Global background surface O₃ concentrations have roughly doubled since preindustrial times (15), primarily because of increases in anthropogenic emissions of nitrogen oxides (NO_x) and methane (CH₄) (16), and are projected to continue to increase (17, 18).

Tropospheric O₃ is formed from photochemical reactions involving NO_x and volatile organic compounds (VOCs). Although nonmethane VOCs are the dominant anthropogenic VOCs contributing to O₃ formation in polluted regions, CH₄ is the primary anthropogenic VOC in the global troposphere (19). Because CH₄ reacts slowly (lifetime of 8–9 yr), it affects global background concentrations of O₃. Because this background underlies the O₃ produced on urban and regional scales, CH₄ mitigation reduces O₃ concentrations by roughly the same amount in polluted regions as in rural regions (19, 20).

Methane and O₃ are also greenhouse gases, which rank behind only carbon dioxide (CO₂) in anthropogenic radiative forcing of

climate (21). Consequently, abatement of CH₄ emissions both reduces surface O₃ concentrations everywhere and slows greenhouse warming (19, 20). Methane abatement has been considered a low-cost means of addressing climate change (22, 23), particularly to influence the short-term rate of climate change. However, CH₄ abatement has not been considered for air quality management, mainly because O₃ pollution has traditionally been considered a local and regional problem, and the local benefits of local CH₄ reductions are small.

Here we examine the global reduction in O₃ and consequent decrease in premature human mortalities resulting from CH₄ emission controls. We first estimate the global decrease in surface O₃ concentration due to CH₄ mitigation, using the MOZART-2 global three-dimensional tropospheric chemistry-transport model (24, 25). This spatial distribution of O₃ is then overlaid on projections of population, and avoided premature mortalities are estimated by using daily O₃-mortality relationships from epidemiologic studies (6–9). Results are presented as the number of avoided premature mortalities due to the CH₄ reduction, the marginal cost-effectiveness per avoided mortality (using the marginal cost of CH₄ mitigation), and the monetized benefit per tonne of CH₄ reduced [using a value of a statistical life (VSL)].

Response of Global Surface Ozone to Methane Mitigation

Methods. We consider a CH₄ emission reduction of 65 Mt-yr⁻¹ (1 Mt = 10⁹ kg) (≈20% of current global anthropogenic emissions), which is assumed to be immediate in 2010 and sustained relative to the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES) A2 scenario (26) until 2030. A compilation of global CH₄ abatement options in five industrial sectors (27) suggests that 65 Mt-yr⁻¹ can be reduced by 2010 at a net cost savings, using identified abatement options.

The MOZART-2 simulations use uniform global mixing ratios of CH₄, and spatially and temporally distributed emissions of other O₃ precursors, as other studies have done (19, 28). We conduct four simulations with MOZART-2, as shown in Table 1. Simulations I and III use CH₄ mixing ratios and emissions of other O₃ precursors as specified for the Intergovernmental Panel on Climate Change AR-4 2000 and 2030 A2 atmospheric chemistry experiments (29). In the CH₄ reduction cases (simulations II and IV), the decreased CH₄ mixing ratios are the steady-state mixing ratios resulting from a 65 Mt-yr⁻¹ emission

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Abbreviations: CR, cardiovascular and respiratory; PM, particulate matter; ppbv, part(s) per billion by volume; VOC, volatile organic compound; VSL, value of a statistical life.

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Table 1. Four MOZART-2 simulations conducted in this study

Simulation	Fixed CH ₄ mixing ratio, ppbv	Global anthropogenic NO _x emissions, Mt-yr ⁻¹ as NO ₂
I: 2000 base case	1,760	124.8
II: 2000 CH ₄ reduction	1,460*	124.8
III: 2030 A2	2,163	212.7
IV: 2030 A2, CH ₄ reduction	1,865*	212.7

*Fixed global CH₄ mixing ratios at steady state, corresponding to an emission reduction of 65 Mt-yr⁻¹ of CH₄.

reduction versus the corresponding base cases (simulations I and III), assuming a CH₄ feedback factor of 1.4 (28). We do not consider any effects of changes in future climate on O₃ distributions in projecting to 2030 (30, 31), nor do we consider the decrease in global mean temperature due to CH₄ reductions, which could amplify the O₃ decrease that we estimate. MOZART-2 has a horizontal resolution of ≈1.9° by 1.9° and 28 vertical levels. In all cases, we use meteorological fields from the National Centers for Environmental Prediction reanalysis (32), beginning in July 1998, with an 18-month initialization, before focusing on results for the meteorological year 2000.

Results. Between 2000 and 2030 (simulations I and III), we project the population-weighted global average 8-h daily maximum surface O₃ mixing ratio to increase by 12.3 parts per billion by volume (ppbv) (25%) (Table 2), primarily because of projected increases in anthropogenic emissions of NO_x (70%) and CH₄ (48%). The 65 Mt-yr⁻¹ CH₄ emission reduction decreases the steady-state population-weighted mean 8-h O₃ by 1.16 ppbv (1.9%, Table 2). This sensitivity is in agreement with other models (18, 19, 28, 33), and these results together suggest that global surface O₃ responds fairly linearly to changes in CH₄ (33). Decreases in O₃ due to CH₄ reductions are widespread globally (Fig. 1), with the largest O₃ decreases occurring over the Middle East, North Africa, and Europe, because of greater down-welling from the free troposphere and greater availability of NO_x. This spatial pattern is similar to previous results (19, 20), suggesting that the pattern is independent of the extent of methane abatement. Methane controls initiated in 2010 will yield ≈81% of this steady-state O₃ change by 2030, assuming exponential decay with a CH₄ perturbation lifetime of ≈12 yr (28).

Table 2. Global average O₃ mixing ratios (ppbv) in the 2000 and 2030 A2 base model runs (simulations I and III), and the steady-state change in O₃ due to a 65 Mt-yr⁻¹ reduction in CH₄ emissions, relative to the 2030 base (simulation IV minus simulation III)

Parameter	2000	2030 A2	ΔO ₃ 2030
24-h average	29.1	33.6	-0.82
8-h daily maximum	31.8	37.1	-0.87
8-h maximum population-weighted	49.4	61.7	-1.16

The steady-state change in O₃ when 65 Mt-yr⁻¹ are reduced relative to the 2000 base case (simulation II vs. simulation I) is virtually identical to the change in Table 2 (-1.11 ppbv for population-weighted 8-h O₃), indicating that the projected changes in nonmethane O₃ precursors between 2000 and 2030 have little effect on the O₃ sensitivity to CH₄. This insensitivity presumably reflects the fact that there is little change in hydroxyl radical (OH) concentrations, because of similar emission ratios of NO_x to (CO + VOCs) in 2000 and 2030 (16). Therefore, although the A2 scenario includes larger growth in emissions of O₃ precursors than other SRES scenarios, and larger than the “Current Legislation” scenario of Dentener *et al.* (18), this high growth does not strongly affect the O₃-CH₄ sensitivity.

Indirect Effects of Methane Reductions on Particulate Matter (PM).

Methane reductions also indirectly affect PM concentrations through complex oxidant chemistry. MOZART-2 (25) results suggest that CH₄ reductions cause a global net decrease in inorganic PM, because of decreases in hydrogen peroxide that in turn reduce sulfate production. Inorganic PM concentrations also increase at some locations, where the increased gas-phase oxidation (due to increased OH concentrations) dominates the change in sulfate production. Although the global average decrease is only ≈0.5% of the inorganic PM (sulfate, nitrate, and associated ammonium), the decrease is concentrated in populated regions. Confidence in the change in PM is lower than for O₃ because of competing influences on inorganic PM, and because we have neglected changes in organic PM.

Global Mortality Benefits of Reduced Ozone

Methods. Ozone has been associated in epidemiologic studies with adverse health effects including hospital admissions and

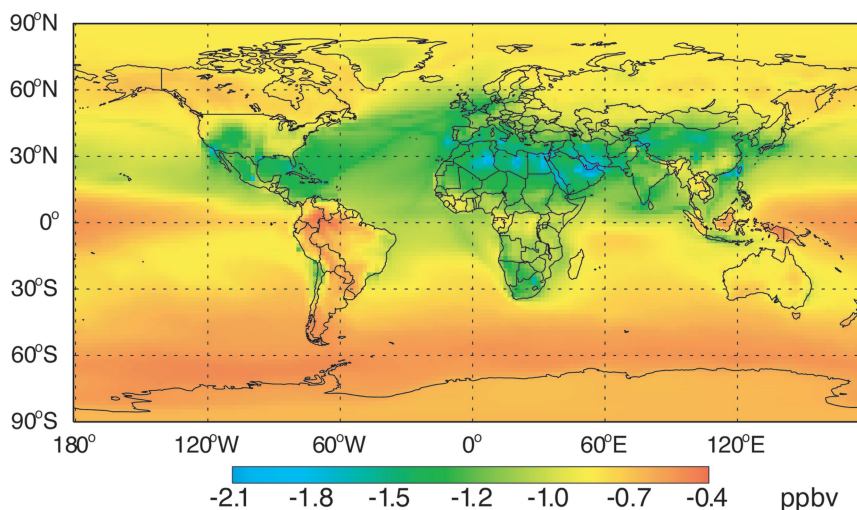


Fig. 1. Change in annual average daily maximum 8-h surface O₃ mixing ratios, at steady state, due to a 65 Mt-yr⁻¹ reduction in CH₄ emissions relative to the 2030 A2 base case (simulation IV minus III).

benefits of CH₄ mitigation have not. Our estimate for CH₄ of \$12 per tonne of CO₂ equivalent is comparable with the range estimated previously for CO₂ of \$0.5–\$140 per tonne of CO₂ (41). Unlike the ancillary benefits of CO₂ mitigation, however, the ancillary benefits of CH₄ mitigation do not depend on the location or means of CH₄ abatement, because the health benefits of CH₄ mitigation result from reactions involving the CH₄ itself, and CH₄ emissions affect O₃ globally regardless of emission location.

The compilation of CH₄ abatement measures used in this study (27) considers five industrial sectors (coal, oil, and natural gas operations, landfills, and wastewater treatment) for which methane abatement opportunities are well understood. Because this compilation neglects abatement opportunities in the large agricultural sector, it may underestimate the availability of low-cost CH₄ options, which would suggest that CH₄ mitigation is more cost-effective than estimated here. On the other hand, a separate compilation by the U.S. Environmental Protection Agency (42–44) suggests that less CH₄ can be reduced at low cost (see the supporting information and ref. 20).

Methane mitigation also benefits climate, because it reduces the radiative forcing of both CH₄ and O₃. The 65 Mt-yr⁻¹ CH₄ reduction would decrease global radiative forcing by 0.14 W·m⁻², from CH₄ and O₃ together (at steady state). In contrast, reductions in NO_x emissions decrease O₃ forcing but increase CH₄ forcing (45), with a net effect that could be positive or negative depending on location (46).

Methane is also an important source of global energy, and capturing half of the 65 Mt-yr⁻¹ for energy use would provide ≈2% of current global natural gas production. The reductions in O₃ concentrations would also result in benefits to human health (morbidity) and agriculture (47), which we previously estimated to be smaller than the monetized benefits of avoided mortalities estimated here (20). Methane mitigation may further benefit air quality and climate by removing other pollutants (e.g., VOCs) through the same actions that reduce CH₄ emissions, and by increasing the availability of natural gas, which may reduce emissions of CO₂ and air pollutants from the combustion of other fossil fuels. In addition, because the reductions in O₃ are widespread globally, CH₄ mitigation may increase the net primary productivity of plants, causing increased uptake of CO₂ (48). Finally, methane mitigation may affect stratospheric O₃, but the direction of that influence is not certain (49).

The effects of CH₄ mitigation on surface O₃ concentrations are widespread globally, and are delayed. These characteristics differ from other means of controlling O₃, as well as most actions to manage air quality, which abate local and regional pollution over hours to weeks. Because of its global impacts, with small

local benefits, CH₄ mitigation for air quality purposes (as for climate) will best be implemented at national and international levels. Furthermore, the potential for reducing O₃ through CH₄ mitigation is limited to a few parts per billion by volume. Methane mitigation is therefore most appropriate for international and long-term (decadal) O₃ management, where CH₄ mitigation for background O₃ is complementary to local and regional O₃ management through reductions in emissions of NO_x and nonmethane VOCs (20).

Important uncertainties in this study lie in the relationship between O₃ and mortality, and between CH₄ emissions and global surface O₃ concentrations. Because CH₄ affects O₃ globally, this research highlights the need to improve understanding of O₃ mortality in developing nations, and of the relationship between O₃ and mortality at low concentration, including consideration of possible thresholds. Future research should also investigate the effects of CH₄ mitigation on PM concentrations, and its implications for air quality, public health, and climate. Finally, future research should further examine opportunities to abate CH₄ emissions, emphasizing the large agricultural sector.

Conclusions

As background O₃ concentrations increase, meeting national O₃ standards increasingly becomes an international problem (50–52). Methane mitigation reduces surface O₃ everywhere, offering a unique opportunity to improve air quality globally. We estimate that reducing ≈20% of current global anthropogenic CH₄ emissions, which can be achieved at a net cost-savings by using identified technologies, will reduce O₃ mixing ratios globally by ≈1 ppbv and prevent ≈30,000 premature mortalities globally in 2030 and ≈370,000 mortalities between 2010 and 2030. If these mortalities are valued at \$1 million each, the monetized benefit is ≈\$240 per tonne of CH₄, or ≈\$12 per tonne of CO₂ equivalent. These benefits exceed the marginal costs of the 20% anthropogenic CH₄ reduction (≈\$100 per tonne of CH₄) and demonstrate that CH₄ mitigation has ancillary benefits to air quality and human health that are comparable with those previously estimated for CO₂. Methane mitigation benefits air quality, public health, agriculture, climate, and energy, and should increasingly be considered a cost-effective component of international long-term O₃ management.

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1. U.S. Environmental Protection Agency (1996) *Air Quality Criteria for Ozone and Related Photochemical Oxidants* (Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC), EPA Publication EPA/600/P-93/004cF.
2. Levy, J. I., Carrothers, T. J., Tuomisto, J. T., Hammitt, J. K. & Evans, J. S. (2001) *Environ. Health Perspect.* **109**, 1215–1226.
3. Thurston, G. D. & Ito, K. (2001) *J. Exposure Anal. Environ. Epidemiol.* **11**, 286–294.
4. Anderson, H. R., Atkinson, R. W., Peacock, J. L., Marston, L. & Konstantinou, K. (2004) *Meta-Analysis of Time-Series Studies and Panel Studies of Particulate Matter (PM) and Ozone (O₃)* (WHO, Geneva).
5. Gryparis, A., Forsberg, B., Katsouyanni, K., Analitis, A., Touloumi, G., Schwartz, J., Samoli, E., Medina, S., Anderson, H. R., Niciu, E. M., et al. (2004) *Am. J. Respir. Crit. Care Med.* **170**, 1080–1087.
6. Bell, M. L., McDermott, A., Zeger, S. L., Samet, J. M. & Dominici, F. (2004) *J. Am. Med. Assoc.* **292**, 2372–2378.
7. Bell, M. L., Dominici, F. & Samet, J. M. (2005) *Epidemiology* **16**, 436–445.
8. Ito, K., De Leon, S. F. & Lippman, M. (2005) *Epidemiology* **16**, 446–457.
9. Levy, J. I., Chemerynski, S. M. & Sarnat, J. A. (2005) *Epidemiology* **16**, 458–468.
10. Schwartz, J. (2005) *Am. J. Respir. Crit. Care Med.* **171**, 627–631.
11. Volz, A. & Kley, D. (1988) *Nature* **332**, 240–242.
12. Marengo, A., Gouget, H., Nedelec, P., Pages, J. P. & Karcher, F. (1994) *J. Geophys. Res.* **99**, 16617–16632.
13. Vingarzan, R. (2004) *Atmos. Environ.* **38**, 3431–3442.
14. Lelieveld, J., van Aardenne, J., Fischer, H., de Reus, M., Williams, J. & Winkler, P. (2004) *Science* **304**, 1483–1487.
15. Lelieveld, J. & Dentener, F. J. (2000) *J. Geophys. Res.* **105**, 3531–3551.
16. Wang, Y. H. & Jacob, D. J. (1998) *J. Geophys. Res.* **103**, 31123–31135.
17. Prather, M., Gauss, M., Bernsten, T., Isaksen, I., Sundet, J., Bey, I., Brasseur, G., Dentener, F., Derwent, R., Stevenson, D., et al. (2003) *Geophys. Res. Lett.* **30**, 1100.
18. Dentener, F., Stevenson, D., Cofala, J., Mechler, R., Amann, M., Bergamaschi, P., Raes, F. & Derwent, R. (2005) *Atmos. Chem. Phys.* **5**, 1731–1755.
19. Fiore, A. M., Jacob, D. J., Field, B. D., Streets, D. G., Fernandes, S. D. & Jang, C. (2002) *Geophys. Res. Lett.* **29**, 1919.
20. West, J. J. & Fiore, A. M. (2005) *Environ. Sci. Technol.* **39**, 4685–4691.
21. Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G. Y. & Solomon, S. (2001) in *Climate Change 2001: The Scientific Basis*, eds. Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K. & Johnson, C. A. (Cambridge Univ. Press, Cambridge, U.K.), pp. 349–416.
22. Reilly, J., Prinn, R., Harnisch, J., Fitzmaurice, J., Jacoby, H., Kicklighter, D., Melillo, J., Stone, P., Sokolov, A. & Wang, C. (1999) *Nature* **401**, 549–555.

23. Hayhoe, K., Jain, A., Pitcher, H., MacCracken, C., Gibbs, M., Wuebbles, D., Harvey, R. & Kruger, D. (1999) *Science* **286**, 905–906.
24. Horowitz, L. W., Walters, S., Mauzerall, D. L., Emmons, L. K., Rasch, P. J., Granier, C., Tie, X. X., Lamarque, J. F., Schultz, M. G., Tyndall, G. S., *et al.* (2003) *J. Geophys. Res.* **108**, 4784.
25. Tie, X., Madronich, S., Walters, S., Edwards, D. P., Ginoux, P., Mahowald, N., Zhang, R., Luo, C. & Brasseur, G. (2005) *J. Geophys. Res.* **110**, D03204.
26. Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T. Y., Kram, T., *et al.* (2000) *Special Report on Emissions Scenarios* (Cambridge Univ. Press, Cambridge, U.K.).
27. International Energy Agency Greenhouse Gas R&D Programme (2003) *Building the Cost Curves for the Industrial Sources of Non-CO₂ Greenhouse Gases* (International Energy Agency, Cheltenham, U.K.), PH4/25.
28. Prather, M., Ehhalt, D., Dentener, F., Derwent, R., Dlugokencky, E., Holland, E., Isaksen, I., Katima, J., Kirchhoff, V., Matson, P., *et al.* (2001) in *Climate Change 2001: The Scientific Basis*, eds. Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K. & Johnson, C. A. (Cambridge Univ. Press, Cambridge, U.K.), pp. 239–287.
29. Stevenson, D., Dentener, F. J., Schultz, M. G., Ellingsen, K., van Noije, T. P. C., Wild, O., Zeng, G., Amann, M., Atherton, C. S., Bell, N., *et al.*, *J. Geophys. Res.*, in press.
30. Hogrefe, C., Lynn, B., Civerolo, K., Ku, J. Y., Rosenthal, J., Rosenzweig, C., Goldberg, R., Gaffin, S., Knowlton, K. & Kinney, P. L. (2004) *J. Geophys. Res.* **109**, D22301.
31. Knowlton, K., Rosenthal, J. E., Hogrefe, C., Lynn, B., Gaffin, S., Goldberg, R., Rosenzweig, C., Civerolo, K., Ku, J. Y. & Kinney, P. L. (2004) *Environ. Health Perspect.* **112**, 1557–1563.
32. Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., *et al.* (1996) *Bull. Am. Meteorol. Soc.* **77**, 437–471.
33. Shindell, D. T., Faluvegi, G., Bell, N. & Schmidt, G. A. (2005) *Geophys. Res. Lett.* **32**, L040803.
34. Pope, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K. & Thurston, G. D. (2002) *J. Am. Med. Assoc.* **287**, 1132–1141.
35. Borja-Aburto, V. H., Castillejos, M., Gold, D. R., Bierzwinski, S. & Loomis, D. (1998) *Environ. Health Perspect.* **106**, 849–855.
36. O'Neill, M. S., Loomis, D. & Borja-Aburto, V. H. (2004) *Environ. Res.* **94**, 234–242.
37. Kim, S. Y., Lee, J. T., Hong, Y. C., Ahn, K. J. & Kim, H. (2004) *Environ. Res.* **94**, 113–119.
38. World Health Organization (2004) *The World Health Report 2004: Changing History* (WHO, Geneva).
39. Markandaya, A., Halsnaes, K., Lanza, A., Matsuoka, Y., Maya, S., Pan, J., Shogren, J., Seroa de Motta, R. & Zhang, T. (2001) in *Climate Change 2001: Mitigation*, eds. Metz, B., Davidson, O., Swart, R. & Pan, J. (Cambridge Univ. Press, Cambridge, U.K.), pp. 451–498.
40. Cifuentes, L., Borja-Aburto, V. H., Gouveia, N., Thurston, G. & Davis, D. L. (2001) *Science* **293**, 1257–1259.
41. Hourcade, J.-C., Shukla, P., Cifuentes, L., Davis, D., Edmonds, J., Fisher, B., Fortin, E., Golub, A., Hohmeyer, O., Krupnick, A., *et al.* (2001) in *Climate Change 2001: Mitigation*, eds. Metz, B., Davidson, O., Swart, R. & Pan, J. (Cambridge Univ. Press, Cambridge, U.K.), pp. 499–559.
42. U.S. Environmental Protection Agency (1999) *U.S. Methane Emissions 1990–2010: Inventories, Projections, and Opportunities for Reductions* (U.S. Environmental Protection Agency, Washington, DC), EPA Publication 430-R-99-013.
43. U.S. Environmental Protection Agency (2003) *International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to the Energy Modeling Forum, Working Group 21* (U.S. Environmental Protection Agency, Washington, DC), www.epa.gov/methane/pdfs/methodologych4.pdf.
44. Delhotal, K. C., de la Chesnaye, F. C., Gardiner, A., Bates, J. & Sankovski, A., *Energy J.*, in press.
45. Fuglestedt, J. S., Berntsen, T. K., Isaksen, I. S. A., Mao, H. T., Liang, X. Z. & Wang, W. C. (1999) *Atmos. Environ.* **33**, 961–977.
46. Naik, V., Mauzerall, D., Horowitz, L., Schwarzkopf, M. D., Ramaswamy, V. & Oppenheimer, M. (2005) *J. Geophys. Res.* **110**, D24306.
47. Mauzerall, D. L. & Wang, X. P. (2001) *Annu. Rev. Energy Environ.* **26**, 237–268.
48. Felzer, B., Kicklighter, D., Melillo, J., Wang, C., Zhuang, Q. & Prinn, R. (2004) *Tellus* **56**, 230–248.
49. World Meteorological Organization (2003) *Scientific Assessment of Ozone Depletion: 2002* (Global Ozone Research and Monitoring Project, World Meteorological Organization, Geneva), Report No. 47.
50. Akimoto, H. (2003) *Science* **302**, 1716–1719.
51. Holloway, T., Fiore, A. & Hastings, M. G. (2003) *Environ. Sci. Technol.* **37**, 4535–4542.
52. Keating, T. J., West, J. J. & Farrell, A. E. (2004) in *Intercontinental Transport of Air Pollution*, ed. Stohl, A. (Springer, Berlin), pp. 295–320.