Supporting Text

Response of Global Ozone to Methane Mitigation

MOZART-2 (1) model simulations for 2000 and the 2030 A2 base case were conducted for the Intergovernmental Panel on Climate Change AR-4 atmospheric chemistry experiment, as reported by Stevenson *et al.* (2). Emissions for these experiments are available at www2.nilu.no/farcry_accent/index.cfm?objectid = F978B37B-BCDC-BAD1-A6205238588A0C03&flushcache = 1&showdraft = 1.

The projected growth in ozone from 2000 to the 2030 A2 base case, 4.5 parts per billion by volume (ppbv) for the global average (Table 2), is comparable with that reported for other models (3). Relative to this 2030 base case, we consider a case where methane emissions are reduced by 65 $Mt•yr^{-1}$, which is 20% of the 2000 global anthropogenic emissions of 325 $Mt•yr^{-1}$. The spatial distribution of the steady-state change in ozone in each season is shown in Fig. 4. All population-weighted ozone averages use the projected 2030 distribution of population.

For each of the MOZART-2 simulations, we calculate the daily maximum 8-h mixing ratio at each grid cell and on each day. For years between the 2000 and 2030 A2 base case model runs, the 8-h mixing ratio is assumed to grow with a constant percent annual growth rate, estimated separately for each day and each grid cell (Fig. 5). This assumption is supported by the fact that global emissions of ozone precursors grow at roughly a constant rate in the A2 scenario (4). Relative to this interpolated base case, the reductions in 8-h ozone due to the methane emissions are assumed to approach the estimated steady-state change in ozone using an exponential function and the perturbation lifetime of methane of 12 yr (the change in ozone scales with $1 - e^{-yr/12}$).

In Table 4, the uncertainty range for the change in ozone due to changes in methane concentration (±35%) is taken as the range of six models reported by Prather *et al.* (5). There is additional uncertainty in the relationship between methane emissions and concentration (the methane feedback factor) that we do not consider in Table 4. From Prather *et al.* (5), the methane feedback factor ranges over seven models between 1.33 and 1.45, so this uncertainty is smaller than the uncertainty in the reported change in ozone due to changes in methane concentration.

Global Mortality Benefits of Reduced Ozone

Future Population. Future population is modeled based on the decadal population projections for four world regions reported by the Intergovernmental Panel on Climate Change for the A2 scenario, with total population growing to 9.17 billion in 2030 (4) (Fig. 6). The A2 scenario is a high-growth scenario, with larger projected population than many of the other Special Report on Emissions scenarios. The 2003 spatial distribution of population is from the LandScan database (Oak Ridge National Laboratory, Land Scan 2003, www.ornl.gov/sci/landscan/index.html, accessed Jan. 2005), at 30 seconds by 30 seconds resolution, which is then mapped onto the 1.9° by 1.9° MOZART-2 grid. Within each of the four world regions, the spatial distribution of population is assumed constant into the future.

Ozone–Mortality Relationship. Mortality coefficients are defined in the epidemiological studies, and applied here, as

$$\Delta Mortality = -y_0\left(e^{-\beta\Delta O_3} - 1\right)Pop$$

where $\Delta Mortality$ is in deaths per yr resulting from some change in ozone mixing ratio, y_0 is the baseline mortality rate (deaths per person per yr), β is the mortality coefficient (fraction excess mortalities per ppbv ozone), ΔO_3 is the change in ozone (ppbv), and *Pop* is the population.

We use the estimated association of daily mortality with 8-h daily maximum ozone from Bell *et al.* (6), of 0.64% (0.41–0.86%) excess mortalities per 15 ppbv increase in ozone. For cardiovascular and respiratory (CR) mortality, we use the results of Bell *et al.* (6) for

24-h ozone [0.64% (0.31–0.98%) per 10 ppbv] and convert these coefficients to daily 8-h ozone using the relationship that Bell *et al.* report between 8-h and 24-h for total mortalities.

We estimate changes in mortality by applying the above equation daily in each grid cell, dividing by 366 days per yr (for 2000 meteorology), and by using the values of y_0, ΔO_3, and *Pop* appropriate for each grid cell. In rare cases (0.0005% of grid cell-days) where the methane reduction increases the concentration of ozone, the change in ozone mortality is counted as a disbenefit (i.e., additional premature mortalities).

Fig. 7 compares the mortality coefficients from Bell *et al.* (6) with other recent studies, including both direct estimates (7, 8) and meta-analyses of the existing literature (9–15). Fig. 7 converts all reported results to common units (percentage excess mortality per ppbv 8-h ozone) by assuming ratios of 4:3:2 for 1-h maximum, 8-h maximum, and 24-h average ozone, as assumed in ref. 15.

The results of Bell *et al.* using National Morbidity, Mortality, and Air Pollution Study data with a single-day lag (6, 13) are much lower than most meta-analyses, but the results that we use from Bell *et al.* (6) use a distributed lag function, which decreases that difference. Had we used the results of Bell *et al.* (6, 13) without a distributed lag, our results would be substantially lower. Conversely, no meta-analysis has yet used the distributed lag approach, and doing so could increase our results substantially. In Table 4, the low value in the uncertainty range for β is the low end of the 95% confidence interval from Bell *et al.* (6), while the high value is the high estimate of Bell *et al.* (13).

Nonaccident baseline mortality rates for 14 regions are from the World Health Organization (16) for the year 2002, and are assumed constant into the future. The CR baseline mortality rates are taken as the sum of mortality rates for cardiovascular diseases, respiratory infections, and respiratory diseases. The 14 regions are mapped onto the MOZART-2 grid used for atmospheric modeling (Fig. 8). In mapping these 14 regions, we ensured that our estimated global average nonaccident mortality rate matched that reported by the World Health Organization (16).

Ozone Mortality Results. Table 5 reports baseline mortality rates and avoided premature mortalities in each of the 14 World Health Organization regions, which are aggregated to 9 regions in Table 3. The mortality results can be checked by using the global average population-weighted change in 8-h ozone (1.16 ppbv from Table 2), the projected 2030 population of 9.17 billion, and the global average baseline mortality rate of 0.833% per yr (16):

$$\Delta Mortality = -0.00833\left(e^{-0.000428(-1.16)(0.811)} - 1\right)9.17\times 10^{9} = -30{,}900 \text{ mortalities in 2030.}$$

where 0.811 accounts for the fraction of the steady-state ΔO_3 achieved by 2030, and 0.0428%•yr^{-1} is the β from Bell *et al.* (6). This result matches the result of the health model when no threshold is used, and matching results can be obtained as a sum of the mortalities calculated similarly for each of the 14 regions, using the population-weighted ΔO_3 and mortality rates from Table 5.

Effects of Methane Reductions on Particulate Matter. The effects of changes in methane emissions on particulate matter are complex, because methane affects the abundance of oxidants, which in turn affect the rates of formation and atmospheric lifetime of both inorganic and organic particles. Our MOZART-2 simulations indicate that reducing methane causes the concentration of the hydroxyl radical (OH) to increase and concentrations of hydrogen peroxide (H_2O_2) to decrease. The consequent effects on sulfate, nitrate, and ammonium particle concentrations are complex, with some areas increasing and others decreasing. The global annual average inorganic particulate matter (PM) at steady-state, taken as the sum of sulfate, nitrate and associated ammonium [using a global average ammonium:sulfate ratio of 1:1 from Penner *et al.* (17)] is estimated to decrease by 0.0165 $\mu g/m^3$ in populated grid cells. This change in PM is not uniform but concentrated in populated areas, with some local decreases in annual average PM greater than 0.1 $\mu g/m^3$. We do not model changes in organic aerosols due to changes in methane.

We consider the mortality benefits of these changes in PM by assuming that this inorganic PM is $PM_{2.5}$, and using a grid-based method as for ozone, but considering annual average changes in $PM_{2.5}$. We use a chronic $PM_{2.5}$-mortality relationship from Pope *et al.* (18), of 4% excess all-cause mortality per 10 $\mu g/m^3$ change in annual average $PM_{2.5}$. In estimating 2030 mortality benefits, the steady-state changes in $PM_{2.5}$ are multiplied by 81.1% to account for the long lifetime of methane. This gives ≈15,000 avoided premature mortalities in 2030, or roughly half of the ozone benefit. This estimate does not account for changes in organic aerosols, nor for changes in emissions of PM and its precursors resulting from methane abatement (such as from reduced consumption of other fuels due to the capture of methane).

Policy Analysis of Ozone Control by Means of Methane Mitigation

We use costs of methane mitigation from the International Energy Agency (IEA) (19) compilation of global opportunities for methane emissions abatement available by 2010. The IEA (19) methane abatement measures are reported for five industrial sectors (coal, oil, and natural gas operations, landfills, and wastewater treatment) and do not include methane abatement opportunities for the large agricultural sector. IEA (19) costs are in 2000 U.S. dollars, as are all monetary numbers in this study. IEA reports a negative marginal cost (net cost-saving) for reducing ≈41 $Mt{\bullet}yr^{-1}$ of methane emissions, due to the value of natural gas recovered in these projects. This is a net cost-saving only considering capital costs, operation and maintenance costs, and the value of fuel captured, ignoring other benefits such as environmental benefits. At a reduction of 65 $Mt{\bullet}yr^{-1}$, the marginal cost is positive ($104 per tonne of CH_4), but the total cost of reducing all 65 $Mt{\bullet}yr^{-1}$ is negative. We use IEA (19) costs reported at a discount rate of 10%, although we discount our benefits at 5%, because the data at 10% are disaggregated as individual measures. The IEA (19) reports sensitivity to discount rate, showing that at a 5% discount rate, ≈5% more methane can be reduced at a net cost-savings, and ≈1% more can be reduced for less than $10 per tonne of CO_2 equivalent ($230 per tonne of CH_4).

Future avoided premature mortalities are converted to a stream of constant annual benefits over the period 2010–2030 (Fig. 9), giving 15,900 mortalities•yr^{-1} as the constant annualized benefit (at a discount rate of 5%•yr^{-1}). This is divided by 65 Mt of CH_4•yr^{-1}, giving 0.0002448 avoided mortalities per tonne of CH_4 emissions reduced. Using the marginal cost of $104 per tonne of CH_4, we obtain $420,000 per avoided premature mortality. At a discount rate of 3%•yr^{-1}, the marginal cost-effectiveness is $400,000 per mortality. At 7%•yr^{-1}, it is $450,000 per mortality. In this calculation, we assume that marginal mortality benefits are constant over the range of methane emission reductions, which is reasonable as both the ozone response to methane and the relationship between ozone and mortality are fairly linear.

Because many consider it unacceptable to use different values of a statistical life (VSLs) in industrialized and developing nations, when evaluating a global policy, we present the cost-effectiveness of methane reductions in terms of a global average value, and consider a globally averaged VSL of $1 million, which the Intergovernmental Panel on Climate Change (20) suggests is reasonable. The global VSL can alternatively be derived from the $6.2 million used by the U.S. Environmental Protection Agency (EPA), and the income elasticity of VSL, which is estimated to be in the range of 0.5–0.6 (21). Using population and GDP data from the World Bank (World Bank, World Development Indicators Database 2004, www.worldbank.org/data/wdi2004/index.htm, accessed May, 2005), and an elasticity of 0.55, we estimate VSLs as follows.

- $2.2 million for the world.
- $5.5 million for high-income countries.
- $1.0 million for low- and middle-income countries.
- $1.7 million for the world, as the weighted average of high-income and low- and middle-income countries.

On this basis, a higher VSL could be justified. A VSL of ≈$1 million in developing nations is supported by the empirical studies of VSL in the review by Viscusi and Aldy (21).

Future monetized benefits are converted to a stream of constant annual benefits (as in Fig. 9), giving \$16 billion•yr^{-1} as the constant annualized benefit over 2010–2030 (at a discount rate of 5%•yr^{-1}). Dividing by 65 Mt of CH_4•yr^{-1} gives \$240 per tonne of CH_4. At a discount rate of 3%•yr^{-1}, the annual benefit is \$17 billion•yr^{-1}, or \$260 per tonne of CH_4. At 7%•yr^{-1}, it is \$15 billion•yr^{-1}, or \$230 per tonne of CH_4. The benefit of \$240 per tonne of CH_4 is converted to \$12 per tonne of CO_2 equivalent by using the 100-yr global warming potential (GWP) for methane of 21, which is the factor currently used in markets for trading carbon credits. Because our comparison of costs and benefits is done per tonne of methane, without converting to CO_2 equivalents, the inconsistency between the 5%•yr^{-1} discount rate and the much lower discount rate implied by the 100-yr GWP is not important for the cost–benefit comparison. Our conversion to CO_2 equivalents is only done to compare with CO_2 market prices and with the ancillary benefits of CO_2 mitigation. The reported range of ancillary benefits of CO_2 mitigation of \$2–500 per tonne of C (22) is converted to per ton of CO_2 by using 12/44 as the ratio of molecular weights.

As an alternative, we can also consider the global methane mitigation potential estimated by the EPA (refs. 23–25; see also ref. 26). The EPA data also consider five industrial sectors; relative to IEA, the EPA adds manure management but does not consider wastewater treatment. Global data reported by EPA are not disaggregated to the level of individual control measures but indicate that the marginal cost of reducing 65 Mt of CH_4•yr^{-1} is greater than \$210 per tonne of CH_4. Consequently, the marginal cost-effectiveness is at least \$860,000 per avoided mortality using the EPA data. However, because both the IEA and EPA omit methane abatement opportunities in some sectors, notably the large agricultural sector, the true methane abatement potential may be larger than suggested in either of these data sources.

The radiative forcing calculation for a 65 Mt•yr^{-1} decrease in methane emissions follows the approach of Naik *et al.* (27). For the 2030 change in methane concentration at steady state, the global annual average change in radiative forcing at the tropopause is estimated to be –0.103 W•m^{-2}, using the relationship provided by Ramaswamy *et al.* (28). For ozone, we calculate the radiative forcing using the radiative transfer model from the Geophysical Fluid Dynamics Laboratory global atmosphere and land surface model (29–31), which accounts for both short- and long-wave radiation. The change in ozone forcing is based on the change in the three-dimensional ozone fields between the 2030 A2 and methane control scenarios, giving –0.035 W•m^{-2}. The net radiative forcing due to changes in both methane and ozone is therefore –0.14 W•m^{-2}.

The calculation of the energy potential of methane recovery uses 92.9 trillion ft^3•yr^{-1} (1,800 Mt•yr^{-1}) as the 2002 global production of natural gas.

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