Toward a Coordinated Strategy on Ozone: Reducing Air Pollution, Long-range Transport, and Climate Forcing

J. Jason West

with contributions from:
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The UNC Climate, Health and Air Quality Lab
Questions Addressed

1) How many people die prematurely each year due to global anthropogenic air pollution?
2) What is the effect of NO$_x$ emissions from one continent on ozone air quality and human mortality in other continents?
3) Of the four ways to reduce ozone air pollution, which is best for slowing global warming?
4) Mitigation of methane emissions as a promising win-win: reducing global ozone air pollution and slowing global warming.
800,000 annual mortalities due to urban PM

The Global Burden of Anthropogenic Outdoor Air Pollution on Human Mortality: Approach

- Use global chemical transport model to provide estimates of concentration
  - Both PM and $O_3$
  - Include rural areas
  - Isolate anthropogenic pollution by subtracting modeled preindustrial concentrations

$$\Delta \text{Mortality} = [1 - \exp(-\beta \Delta X)] \times Y_0 \times \text{Pop}$$
Anthropogenic Concentrations

$\Delta$ Mortality = $[1 - \exp(-\beta \Delta X)] \times Y_0 \times \text{Pop}$

MOZART-2 surface data from Horowitz (2006)

$\Delta$ annual average daily 8-hr max. $O_3$ (2000-preindustrial)

$\Delta$ annual average $PM_{2.5}$ (2000-preindustrial)
The global burden of anthropogenic ozone and fine PM on premature human mortality

<table>
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<tr>
<th></th>
<th>O₃ Respiratory (000s)</th>
<th>PM₂.₅ Cardiopulmonary (000s)</th>
<th>PM₂.₅ Lung Cancer (000s)</th>
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• Threshold = 33.3 ppb for O₃, 5.8 µg/m³ for PM₂.₅
• Standard deviations reflect uncertainty in the CRF and simulated present-day concentration (sd=25% of simulated value)

Anenberg et al., submitted, *EHP*
Formation of Ozone and Long-Range Transport

Urban

$\text{hv}$

$\text{NO} \rightarrow \text{NO}_2$

$\text{HO}_2 \rightarrow \text{OH}$

$\text{NMVOCs, CO}$

Regional and Inter-continental

$\text{hv}$

$\text{NO} \rightarrow \text{NO}_2$

$\text{HO}_2 \rightarrow \text{OH}$

$\text{NMVOCs, CO}$

$\text{O}_3$
What is the effect of NO$_x$ reductions in one region, on ozone in all other world regions?

Reduce anthropogenic NO$_x$ emissions by 10% in each of 9 world regions, in the MOZART-2 global CTM (MACCM3 meteorology, EDGAR emissions for 1990s).
Surface $O_3$

Change from 10% regional NO$_x$ reductions

Change in surface $O_3$ (ppb), averaged over the 3-month period with highest population-weighted $O_3$ in source region.
Effect of 10% regional NO$_x$ reductions

<table>
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<tr>
<th>Source Region</th>
<th>NA</th>
<th>EU</th>
<th>FSU</th>
<th>AF</th>
<th>IN</th>
<th>EA</th>
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</table>

Change in population-weighted O$_3$ (ppt), averaged over the 3-month period with highest O$_3$ in the receptor region.
Normalized source-receptor matrix

<table>
<thead>
<tr>
<th>Source Region</th>
<th>NA</th>
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<th>FSU</th>
<th>AF</th>
<th>IN</th>
<th>EA</th>
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Change in 3-month population-weighted average O$_3$ per unit change in NO$_x$ emissions (ppb (Tg N yr$^{-1}$)$^{-1}$).
Example: Europe

EU as source

EU as receptor

EU as receptor per Tg N

Change in population-weighted O$_3$, averaged over the 3-month period with highest O$_3$ in the receptor region.
Example: North America

Change in population-weighted O₃, averaged over the 3-month period with highest O₃ in the receptor region.
Is ozone exported or NO$_y$?
### Avoided Mortalities (annual)

**Receptor Region**

<table>
<thead>
<tr>
<th>Source Region</th>
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<th>FSU</th>
<th>AF</th>
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Mortality based on Bell et al. (2004)
Intra-regional avoided mortalities: 5744; Inter-regional: 2600
## Avoided Mortalities (annual) per Tg N yr\(^{-1}\)

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<th>Receptor Region</th>
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<th>AF</th>
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Conclusions

Based on 10% regional anthropogenic NO\textsubscript{x} emission reductions:

• Inter-continental effects are $\sim$10x smaller than effects within a region.
  – Largest impact is Europe on the Former Soviet Union.
  – Control costs would need to be $\sim$10% of within-region cost for overseas reductions to be cost-effective.

• Tropical regions cause a greater $\Delta$O\textsubscript{3} per ton NO\textsubscript{x} reduced, than temperate regions.

• Avoided mortalities are greater outside of NA, EU, and FSU than within.
Ozone Precursors Affect Both Ozone Air Quality and Climate Forcing

Urban

\[ \text{hv} \rightarrow O_3 \]

\[ \text{NO} \rightarrow \text{NO}_2 \]

\[ \text{HO}_2 \rightarrow \text{OH} \]

\[ \text{NMVOCs, CO} \]

Global

\[ \text{hv} \rightarrow O_3 \]

\[ \text{NO} \rightarrow \text{NO}_2 \]

\[ \text{HO}_2 \rightarrow \text{OH} \]

\[ \text{NMVOCs, CO, CH}_4 \]
Radiative Forcing of Climate, 1750-Present

Important Contributions from Methane and Ozone

<table>
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<tr>
<th>RF Terms</th>
<th>RF values (W m⁻²)</th>
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<td>Med</td>
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<td>Med - Low</td>
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<td>Solar irradiance</td>
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<td>Total net anthropogenic</td>
<td>1.6 [0.6 to 2.4]</td>
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Ozone Precursors Affect Both Ozone Air Quality and Climate Forcing

Global

\[ \text{hv} \]

\[ \text{NO} \rightarrow \text{O}_3 \rightarrow \text{NO}_2 \]

\[ \text{HO}_2 \rightarrow \text{OH} \]

\[ \text{NMVOCs, CO, CH}_4 \]

rapid local

decadal global

\[ \text{NO}_X \]

\[ \text{OH} \]

\[ \text{CH}_4 \]

\[ \text{O}_3 \]

VOCs, CO

decadal global

\[ \text{CH}_4 \]

\[ \text{O}_3 \]

\[ \text{OH} \]

\[ \text{CH}_4 \]

\[ \text{O}_3 \]
Objectives

1) Estimate the consequences for $\Delta O_3^{srf}$ and $\Delta RF_{\text{net}}$ from 20% reductions in emissions of ozone precursors: NO$_x$, NMVOCs, CO, CH$_4$.

2) Consider the climate forcing implications of actions to improve ozone air quality, by estimating $\Delta RF_{\text{net}}/\Delta O_3^{srf}$.

Methods

- Use MOZART-2 base simulation - MACCM3 meteorology, emissions for early 1990s.
- Account for long-term changes in O$_3$ via CH$_4$ by scaling the spatial-temporal $\Delta O_3^{srf}$ distribution from the steady-state CH$_4$ mitigation simulation.
Surface ozone changes due to 20% anthropogenic reductions

Effect of global 20% anthropogenic emission reductions on 8-hr daily maximum surface $O_3$, averaged over 3 month period with highest $O_3$, at steady state.
Ozone changes
Effects of 20% reductions in anthropogenic emissions

Tropospheric $O_3$ burden

$\Delta O_3^{srf}$ global population-weighted 8hr. 3-month

$\Delta O_3^{srf}$ annual average

Short term
Steady state

NOx, NMVOC, CO, CH4

ppbv

NOx, NMVOC, CO, CH4

Tg $O_3$

NOx, NMVOC, CO, CH4
Radiative forcing
Effects of 20% reductions in anthropogenic emissions

CH₄ forcing estimated using Ramaswamy et al. (2001), O₃ forcing using GFDL AM2 radiative transfer model.
\[ \Delta \text{RF}_{\text{net}} / \Delta O_3^{\text{srf}} \]

Effects of 20% reductions in anthropogenic emissions

\[ \Delta \text{RF}_{\text{net}} \]

\[ \Delta O_3^{\text{srf}} \]

\[ \Delta \text{RF}_{\text{net}} \] per unit improvement in \( O_3 \) air quality.

Reducing methane emissions causes the greatest reduction in RF per unit improvement in \( O_3 \) air quality.
Conclusions

• Based on 20% reductions of anthropogenic emissions:
  – NO\textsubscript{x} reductions best decrease population-weighted O\textsubscript{3}\text{srfl}.
  – CH\textsubscript{4} reductions best decrease global annual O\textsubscript{3}\text{srfl}.
  – CH\textsubscript{4} reductions best decrease RF\textsubscript{net} (NO\textsubscript{x} reductions increase RF\textsubscript{net}).

• Of the means to improve ozone air quality, CH\textsubscript{4} emission reductions best decrease climate forcing (\Delta RF\textsubscript{net} / \Delta O\textsubscript{3}\text{srfl}).
  – CH\textsubscript{4} followed by CO, NMVOCs, and NO\textsubscript{x}.

• Long-term changes in O\textsubscript{3} (via CH\textsubscript{4}) are important for both radiative forcing and ozone air quality
  – NO\textsubscript{x}: +0.2 ppbv (6-14% of short-term, for 20% reduction).
  – CO: -0.1 ppbv (16-21% of short-term).

* Because of long-term climate and air quality effects, it may be desirable to emphasize CH\textsubscript{4} abatement and increase the emphasis on CO and NMVOC abatement.

West et al., GRL, 2007
Long-term changes in O$_3$ via CH$_4$

CH$_4$ and long-term O$_3$ increase per unit NO$_x$ decrease
(global annual average surface O$_3$ change)

Tropical and SH regions have much greater effect on CH$_4$
and long-term O$_3$ per ton NO$_x$ reduced
Long-term changes in $O_3$ via CH$_4$

- **Rapid**
  - Local
  - Decadal

- **Steady state**

- EU as source

- EU as receptor

- EU as receptor per Tg N

- Short term
- Steady state

Graphs show changes in $O_3$ (ppb) and $O_3$ per NO$_x$ (ppb (TgN yr$^{-1}$)) for different regions (NA, EU, FSU, AF, IN, EA, SA, SE, AU).
Background Ozone is Growing ...

Ozone trend at European mountain sites, 1870-1990 (Marenco et al., 1994).

Historic increases in background ozone from 10-15 ppb in 1860 to 20-30 ppb (Lelieveld & Dentener, 2000) are due mainly to increased methane and NO\textsubscript{X} emissions (Wang et al., 1998).

... and Will Continue to Grow!

Modeled monthly mean ozone increase in 2100 A2 scenario, relative to 2000 – average of 10 models (Prather et al., 2003).

Future increase is due about half to increased methane emissions, and half NO\textsubscript{X}. 
The “Tightening Vise” of Ozone Management

Methane emission controls offer a new opportunity for ozone air quality management on a global scale.

Ozone Abatement Strategies Evolve as our Understanding of the Ozone Problem Improves

1950s

O$_3$ smog recognized as an URBAN problem: Los Angeles, Haagen-Smit identifies chemical mechanism

1980s

Smog considered REGIONAL problem; role of biogenic VOCs discovered

Present

A GLOBAL perspective: role of intercontinental transport, background

Abatement Strategy:

NMVOCs + NO$_x$ + CH$_4$??
Global Methane Emissions

Natural: 180 Mton CH$_4$ yr$^{-1}$

Anthropogenic: 300 Mton CH$_4$ yr$^{-1}$

EDGAR3.2 & Houweling et al., 1999
How Much Methane Can Be Reduced?

Top bar: IEA (2003), for 5 industrial sectors.
Lower bar: EPA (2003), for 4 industrial and 1 agricultural sector.
* Methane – ozone response based on Fiore et al. (2002) for steady-state summer afternoon ozone in US.

Comparison: Clean Air Interstate Rule reduces 0.86 ppb over the eastern US, at $0.88 billion yr^-1, through NOX control.
Global Human Mortality Benefits of Methane & Ozone Reductions

Consider a 20% decrease in global anthropogenic methane emissions (65 Mton yr\(^{-1}\)) in 2010.
⇒ can be achieved at a net cost-savings using identified technologies (IEA, 2003).

Atmospheric Model - MOZART-2 with NCEP meteorology
• 2000 base case (CH\(_4\) = 1760 ppb)
• 2030 SRES A2 scenario (CH\(_4\) = 2163 ppb)
• 2030 A2 methane control (CH\(_4\) = 1865 ppb)

Population Distribution - Projected for 2000-2030 consistent with A2

Ozone - Mortality Relationship - Bell et al. (2004) daily time series, for 8-hr. daily max.

Baseline Mortality - Non-accident rates in 14 world regions (WHO, 2004)
⇒ Calculate avoided premature mortalities at each model grid cell on each day, assuming a low-concentration threshold of 25 ppb.
Surface Ozone Reduction

Global annual average ozone (ppb)

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>A2 2030</th>
<th>ΔO₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-hr.</td>
<td>29.1</td>
<td>33.6</td>
<td>-0.82</td>
</tr>
<tr>
<td>8-hr. daily max.</td>
<td>31.8</td>
<td>37.1</td>
<td>-0.87</td>
</tr>
<tr>
<td>8-hr. population-weighted</td>
<td>49.4</td>
<td>61.7</td>
<td>-1.16</td>
</tr>
</tbody>
</table>

A2 Anthrop. emissions 2000-2030: CH₄ +48%, NOₓ +70%

Change in 8-hr. ozone from a 65 Mton CH₄ yr⁻¹ reduction in methane emissions, at steady state (81% achieved by 2030 if implemented in 2010).
A 65 Mton yr\(^{-1}\) decrease in methane emissions will prevent \(~30,000\) premature mortalities in 2030 \((\sim 0.04\%\) of total deaths\), and \(~370,000\) from 2010-2030.
2030 Avoided Premature Mortalities

Total 2030 avoided mortalities: 30,200
2030 Avoided Mortalities per Million People

Global average: 3.29 per million people
Comparing Monetized Health Benefits with Control Costs

- ~10% of anthropogenic methane emissions can be reduced at a cost-savings.

- Marginal cost of reducing 65 Mton CH$_4$ yr$^{-1}$ (20%) is ~$100 per ton CH$_4$ (total cost is negative, IEA (2003)).

- Marginal cost-effectiveness is $420,000 per avoided mortality for the 20% reduction.

- Benefit is ~$240 per ton methane reduced (~$12 per ton CO$_2$ equivalent) when mortalities are valued at $1 million each.

- Health benefits can exceed the costs of the 20% methane reduction.

West et al. (2006) PNAS
Multiple Benefits of Reducing Methane

Reducing 65 Mton CH$_4$ yr$^{-1}$ (~20% of anthropogenic emissions) will:

- Reduce 8-hr. ozone globally by ~1 ppb.
- Reduce global radiative forcing by ~0.14 W m$^{-2}$.
- Save ~$1.9$ billion yr$^{-1}$ through implementation (IEA, 2003).
- Provide ~2% of global natural gas production.
- Prevent ~30,000 premature deaths globally in 2030, ~370,000 from 2010-2030.
- Avoid other damages to health, agriculture, and forestry, valued at ~$5$ billion yr$^{-1}$ (West & Fiore, ES&T, 2005)
# Methane in Ozone Management

<table>
<thead>
<tr>
<th></th>
<th>NO\textsubscript{X}, NMVOCs &amp; CO</th>
<th>Methane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low-cost emission reductions</strong></td>
<td>Few; least-cost options already exhausted in some regions</td>
<td>Many cost-saving and low-cost measures exist</td>
</tr>
<tr>
<td><strong>Potential for ozone reductions</strong></td>
<td>Large</td>
<td>Limited to ~2 ppb in the coming decades</td>
</tr>
<tr>
<td><strong>Time scale</strong></td>
<td>Hours to weeks</td>
<td>Realized gradually (~12 yr)</td>
</tr>
<tr>
<td><strong>Spatial scale</strong></td>
<td>Local to regional, focusing on polluted areas (also global)</td>
<td>Global, widespread benefits</td>
</tr>
<tr>
<td><strong>Impact on high-ozone episodes</strong></td>
<td>Strong</td>
<td>Ozone reduced roughly equally in all cases</td>
</tr>
<tr>
<td><strong>Radiative forcing of climate</strong></td>
<td>Small</td>
<td>Beneficial, from both methane and ozone</td>
</tr>
<tr>
<td><strong>Ancillary benefits</strong></td>
<td>Reduced fine PM, nitrogen and acidic deposition (NO\textsubscript{X}), and airborne toxics (NMVOC)</td>
<td>Many measures make methane available for energy; controls may reduce NMVOC emissions</td>
</tr>
</tbody>
</table>

If California eliminated its methane emissions, ozone would reduce by ~ 0.02 ppb  
→ suggests national / international management.

West and Fiore, *ES&T*, 2005
Methane abatement can be a cost-effective component of international long-term ozone management.

Double dividend of methane emission controls:
- Decreased greenhouse warming
- Improved air quality everywhere

Methane abatement can be a cost-effective component of international long-term ozone management.
Conclusions

• Changes in emissions of any ozone precursor (NO$_x$, VOCs, CO, or CH$_4$) affect both air quality and climate change.

• Reductions in NO$_x$ cause long-term increases in ozone (via CH$_4$) that partially counteract short-term ozone decreases (greatest long-term increase for tropical reductions).

• NO$_x$ emission reductions in NA, EU, and FSU cause more avoided mortalities outside of the source region than within.

• Of the means to reduce ozone air pollution, reducing methane best reduces climate forcing (reducing NO$_x$ increases climate forcing).

• Methane abatement can be a cost-effective component of international long-term ozone management.


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