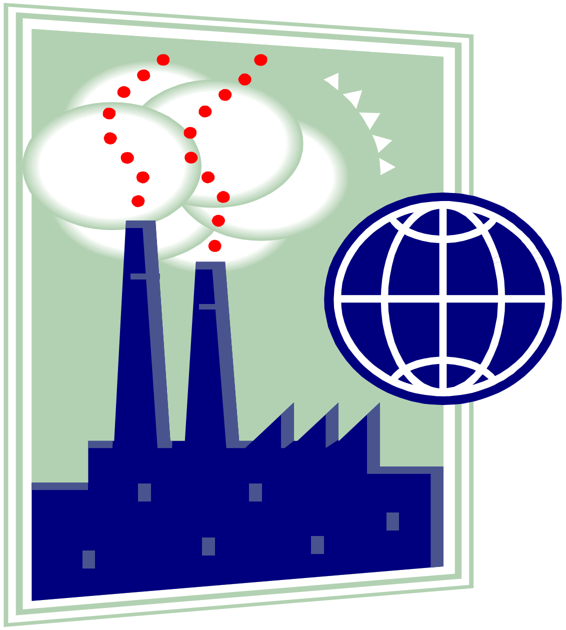


Ozone Air Quality Management through Methane Emission Reductions: Global Health Benefits

J. Jason West, Arlene M. Fiore,
Larry W. Horowitz, and Denise L. Mauzerall

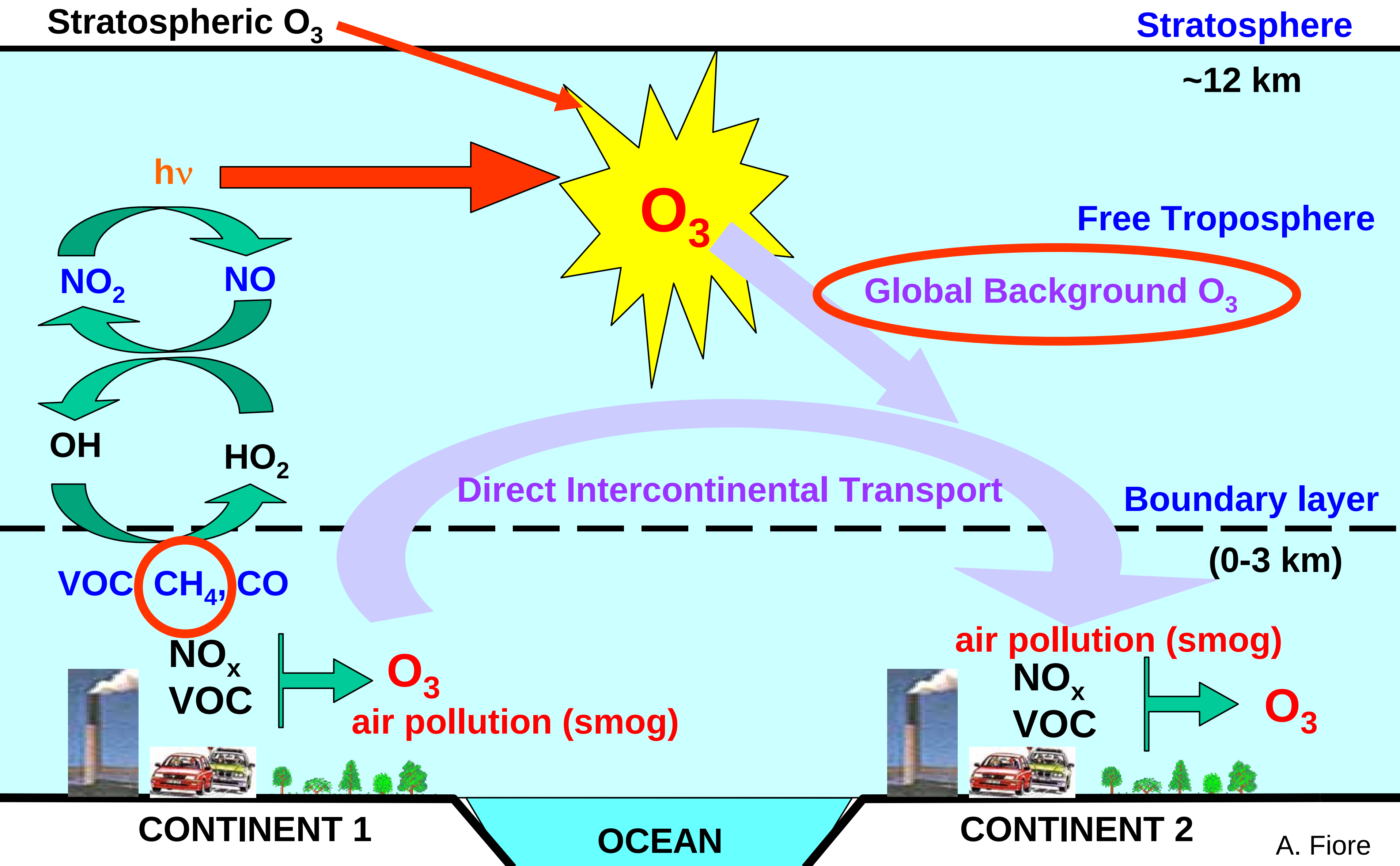
November 15, 2005

Geophysical Fluid Dynamics Laboratory
GFDL
NOAA

Princeton University

Air quality-Climate Linkage:

CH_4 contributes to background O_3 in surface air
CH_4, O_3 are important greenhouse gases



Stratospheric O_3

Stratosphere

~12 km

$h\nu$

O_3

Free Troposphere

Global Background O_3

NO_2

NO

OH

HO_2

Direct Intercontinental Transport

Boundary layer

(0-3 km)

VOC, CH_4, CO

NO_x
VOC

O_3
air pollution (smog)

air pollution (smog)

NO_x
VOC

O_3

CONTINENT 1

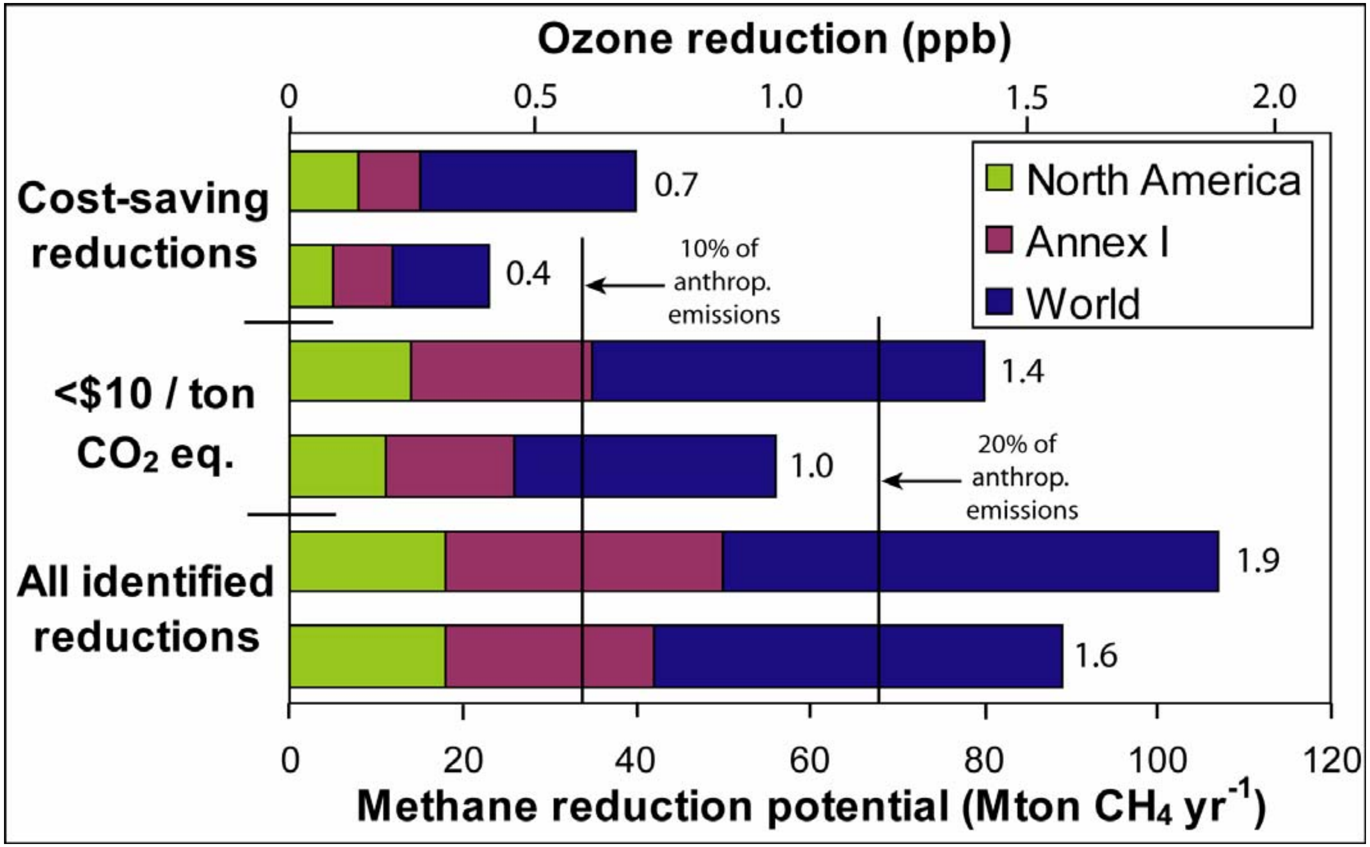
OCEAN

CONTINENT 2

A. Fiore

How Much Ozone Can Be Reduced Via Methane?

50% reduction in anthropogenic CH_4 emissions (Fiore *et al.*, GRL, 2002)
⇒ **~3 ppb** ozone decrease in US summer (steady-state)
⇒ ~57% realized in 10 yr, ~81% in 20 yr



West & Fiore, ES&T (2005)

Top bar: IEA (2003), for 5 industrial sectors.
Lower bar: EPA (2003), for 4 industrial and 1 agricultural sector.

Comparison: Clean Air Interstate Rule reduces 0.86 ppb over the eastern US, at $0.88 billion yr^{-1}, through NO_X 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

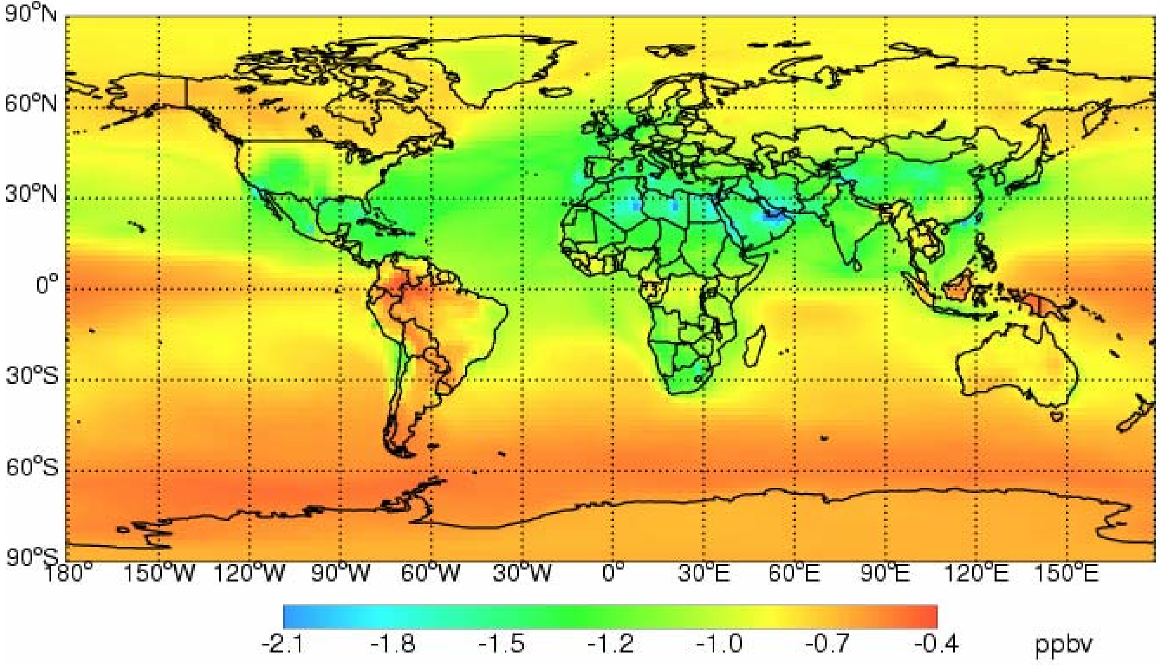
Ozone - Mortality Relationship - Bell *et al.* (2004) daily time series, for 8-hr. daily max.

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

Annual Average



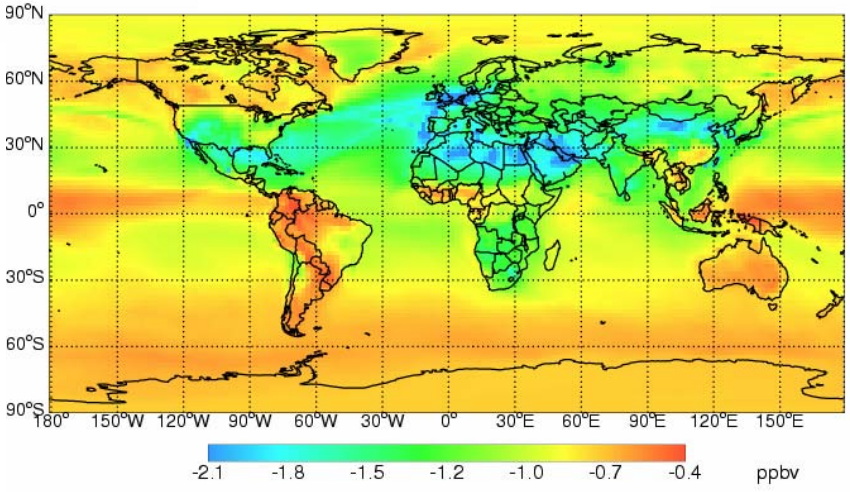
Change in 8-hr. ozone from a 65 Mton CH_4 yr^{-1} reduction in methane emissions, at steady state (81% achieved by 2030 if implemented in 2010).

Global annual average ozone (ppb)

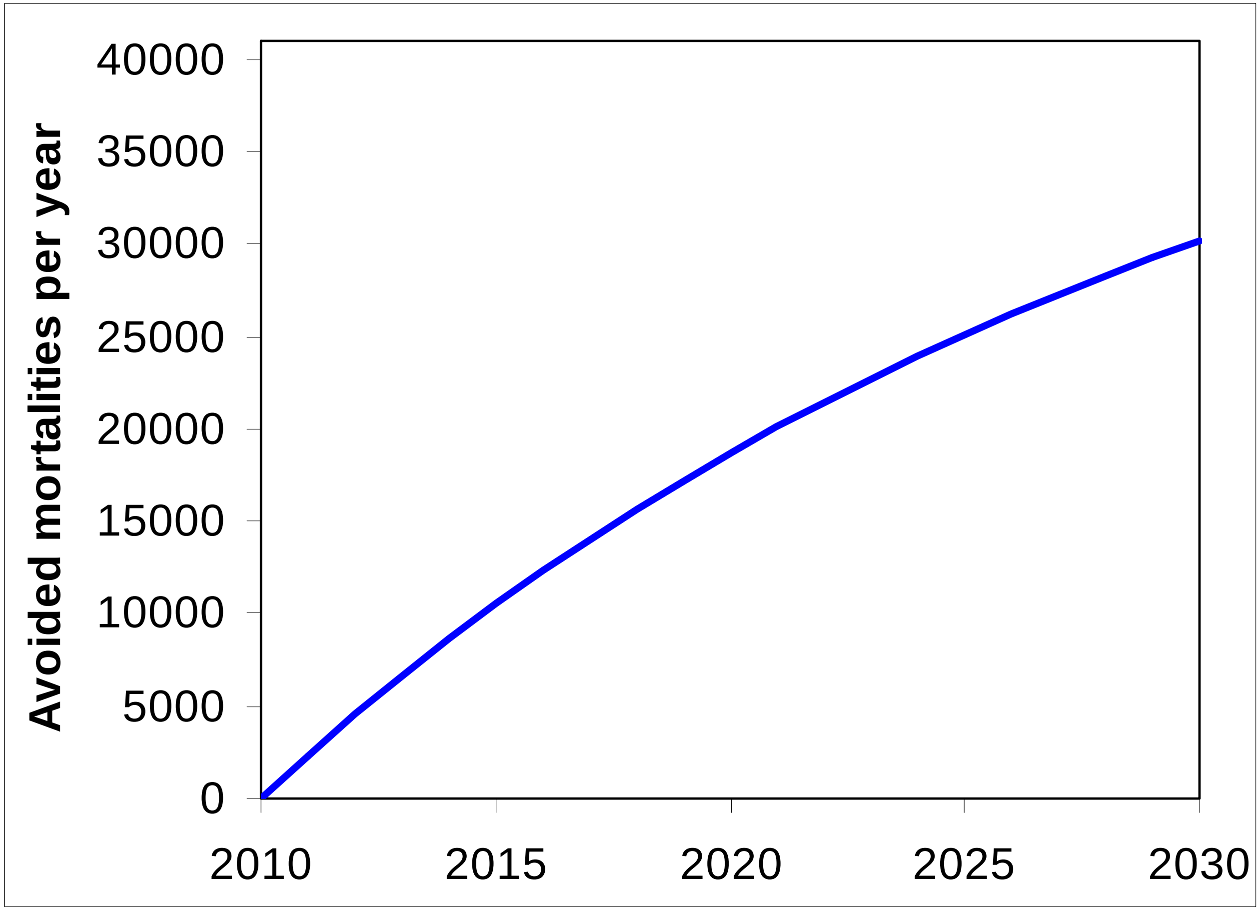
	2000	A2 2030	ΔO_3
24-hr.	29.1	33.6	**-0.82**
8-hr. daily max.	31.8	37.1	**-0.87**
8-hr. population-weighted	49.4	61.7	**-1.16**

A2 Anthrop. emissions 2000-2030:
CH_4 +48%, NO_X +70%

Jun-Jul-Aug

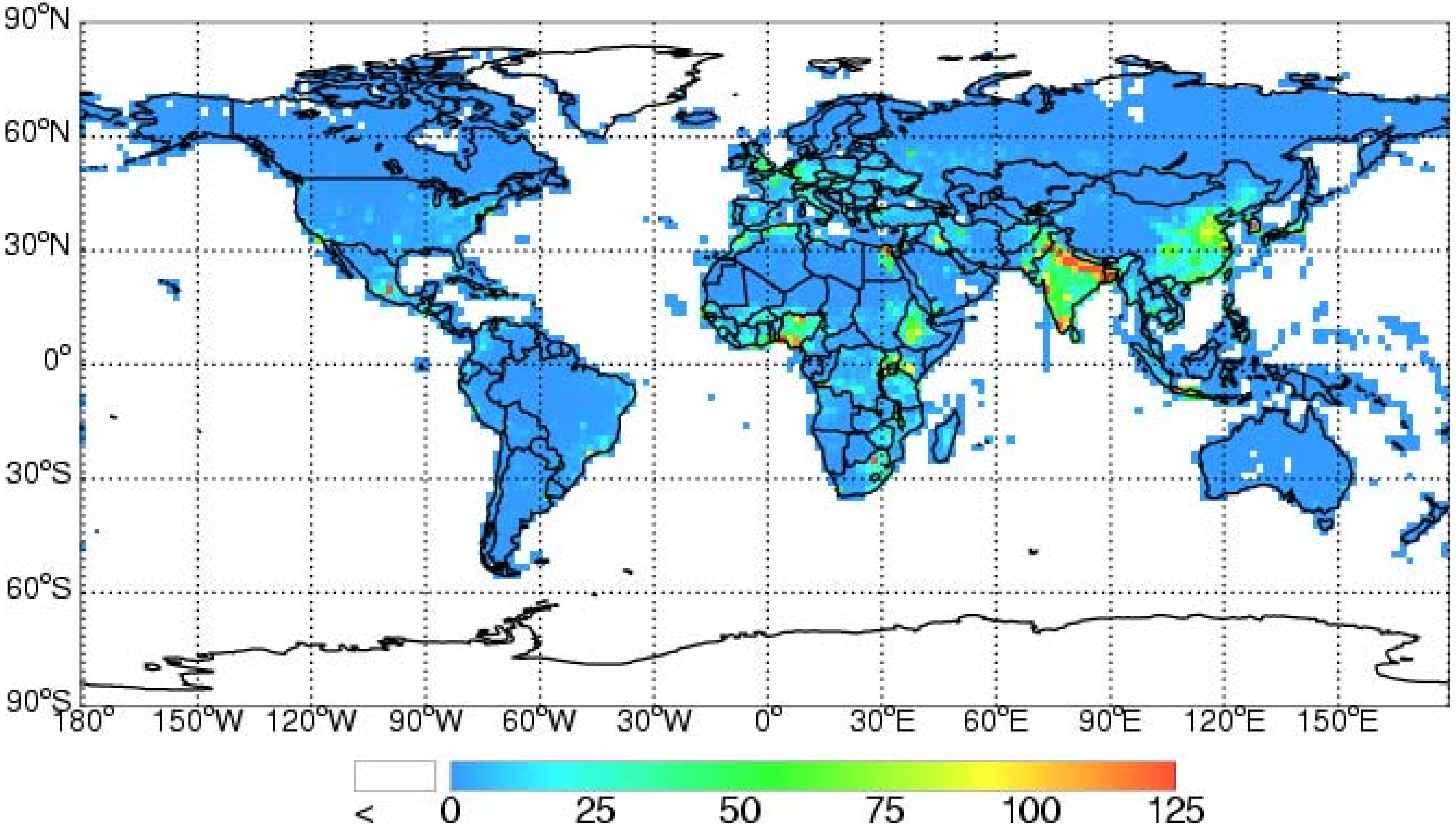


Mortality Benefits of Reduced Ozone



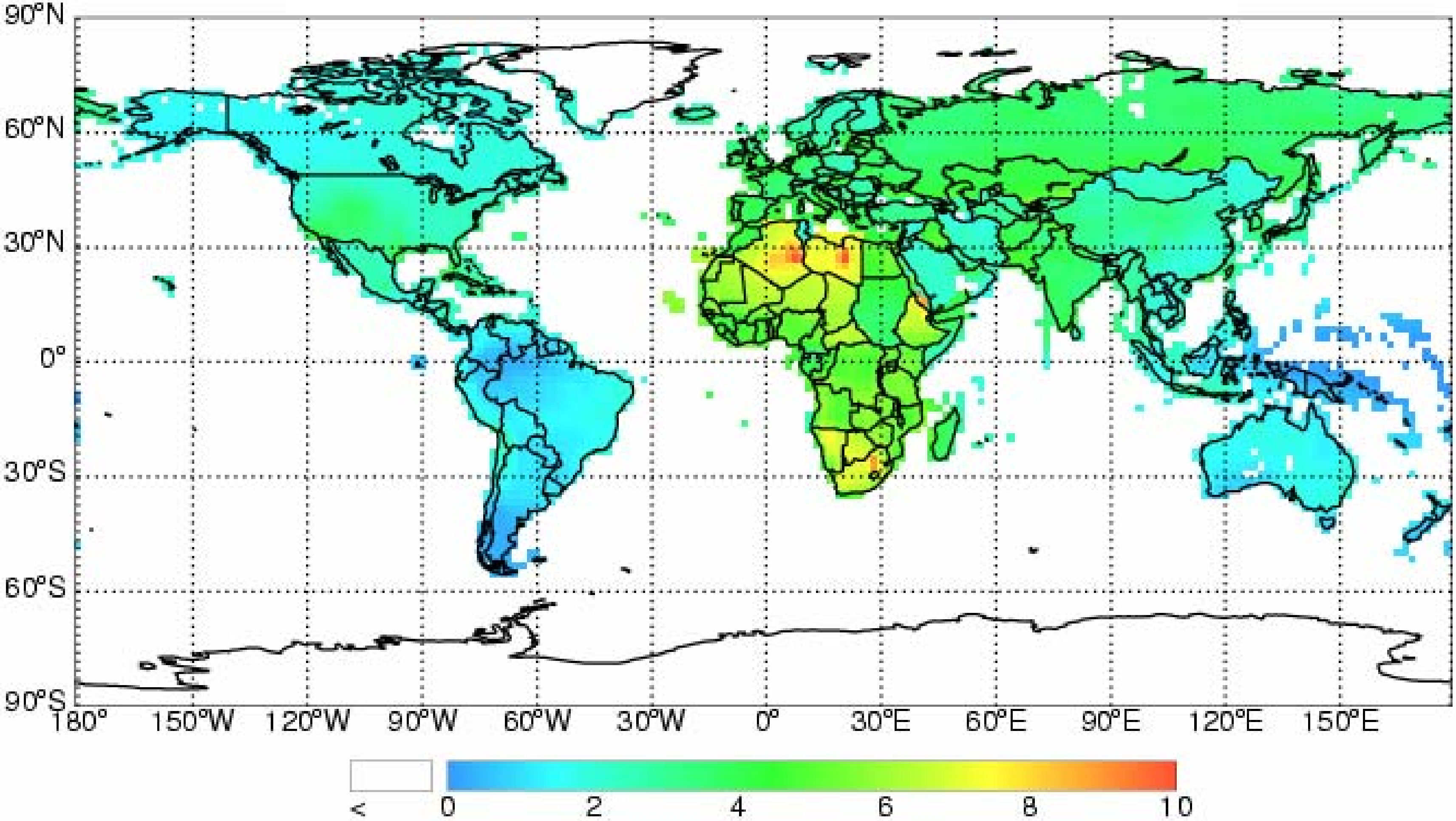
- A 65 Mton yr^{-1} decrease in methane emissions will prevent ~30,000 premature mortalities in 2030 (~0.04% of total deaths), and ~370,000 from 2010-2030.

2030 Avoided Premature Mortalities



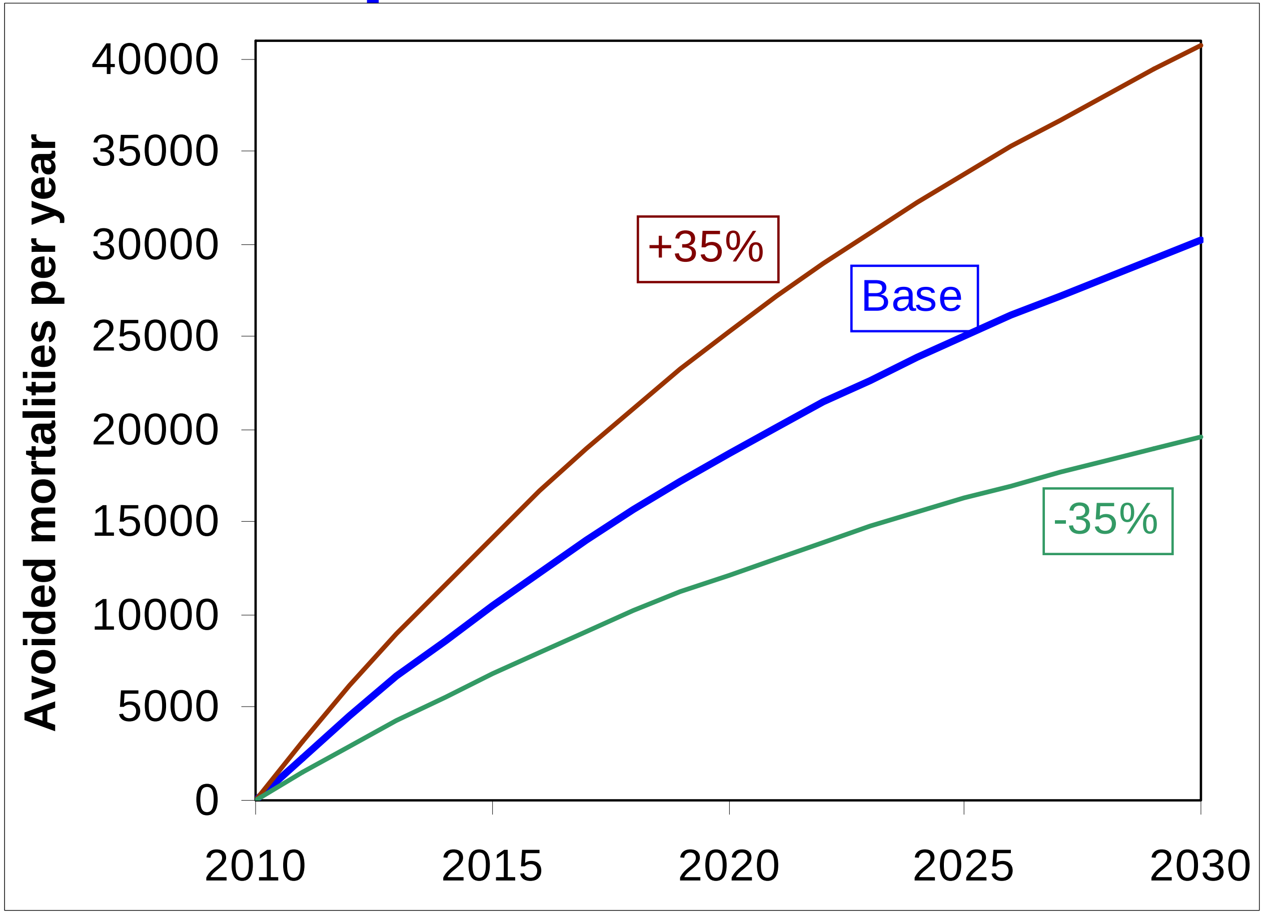
Total 2030 avoided mortalities: 30,200

2030 Avoided Mortalities per Million People



Global average: 3.29 per million people

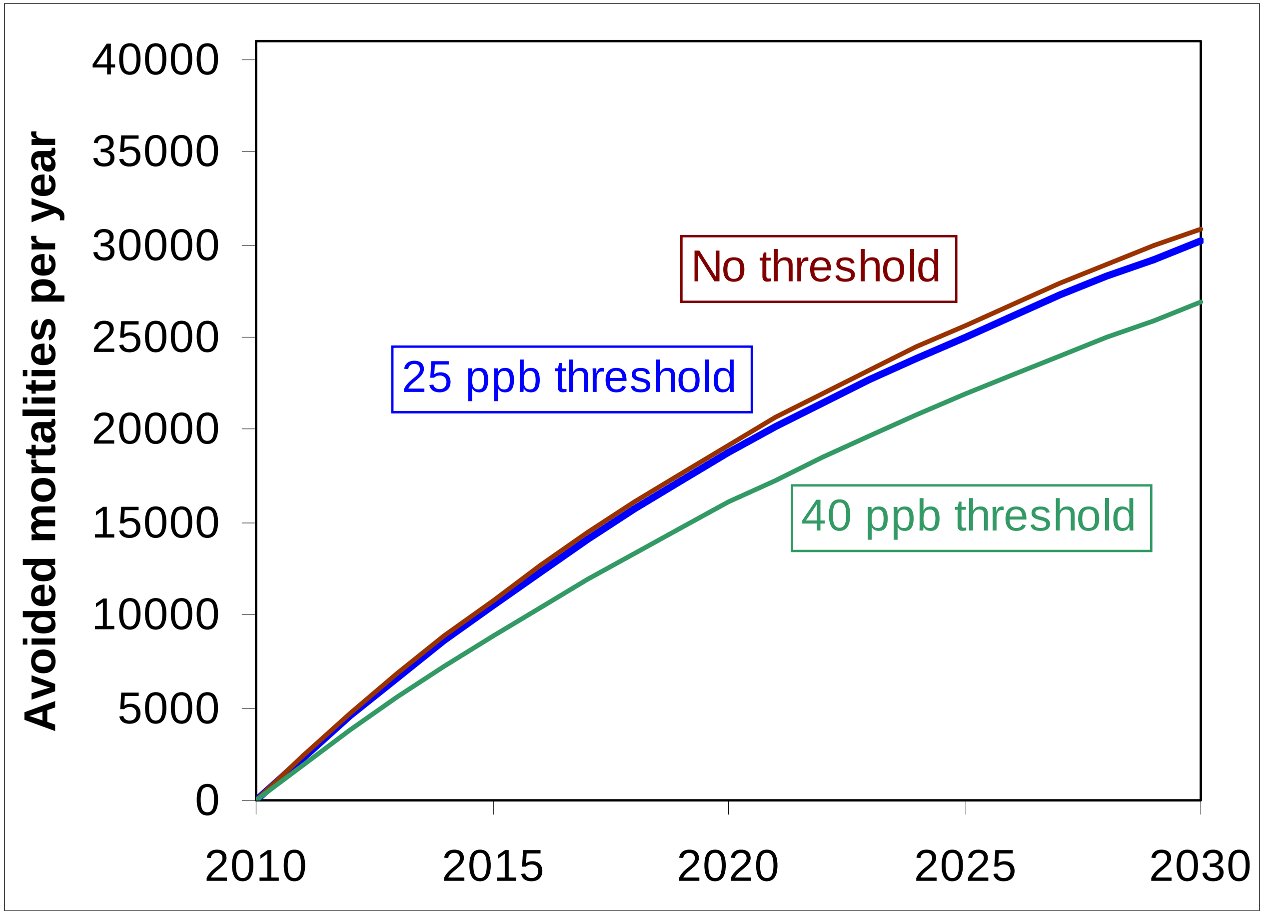
Mortality Benefits – Sensitivity to ozone response to methane



Base 2030 avoided mortalities = 30,200

1) Ozone response to methane 19,600 – 40,700
2) Low-concentration health threshold
3) Ozone-mortality relationship (*β*)

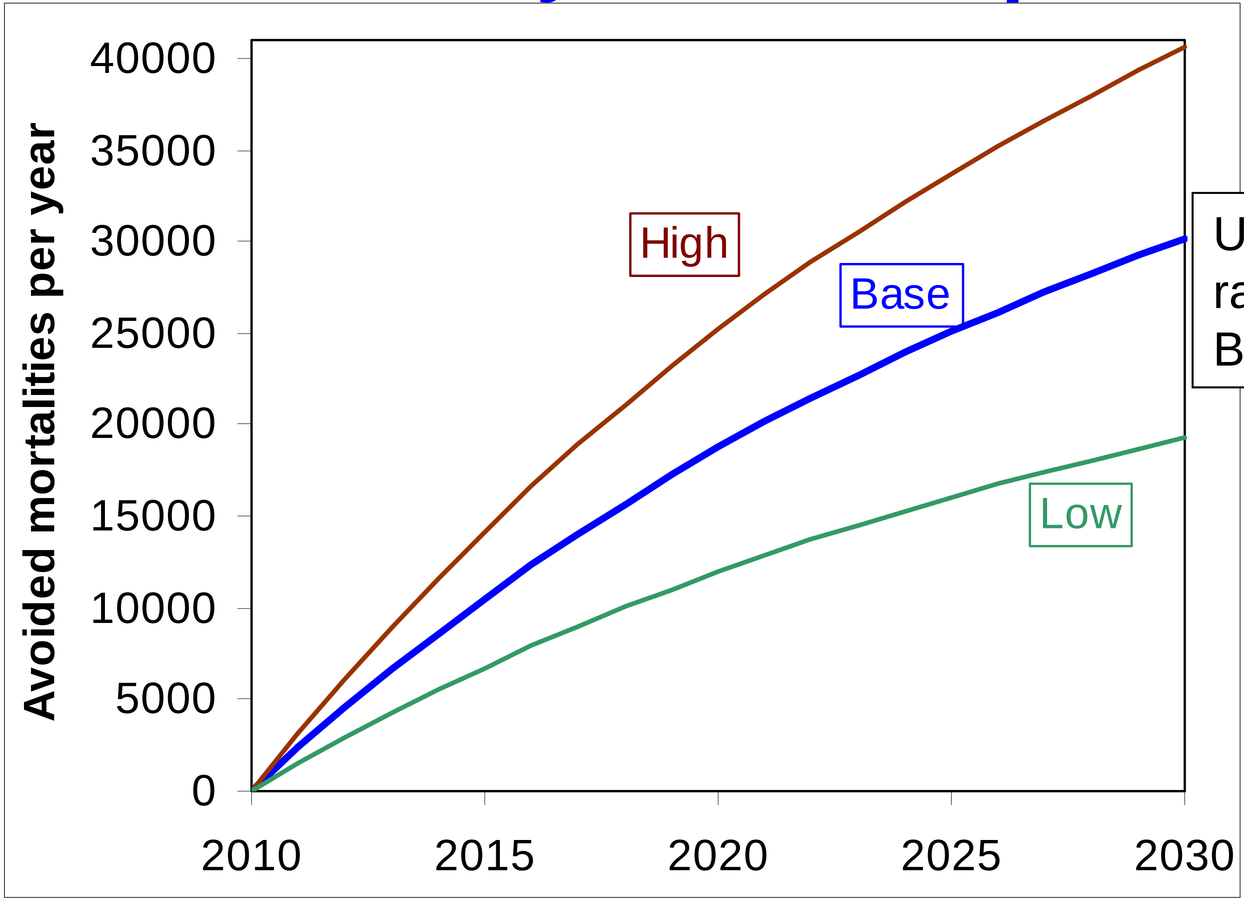
Mortality Benefits – Sensitivity to low-concentration ozone threshold



Base 2030 avoided mortalities = 30,200

1)	Ozone response to methane	19,600 – 40,700
2)	Low-concentration health threshold	26,900 – 30,900
3)	Ozone-mortality relationship (β)	

Mortality Benefits – Sensitivity to ozone-mortality relationship



Uncertainty range from Bell et al (2004)

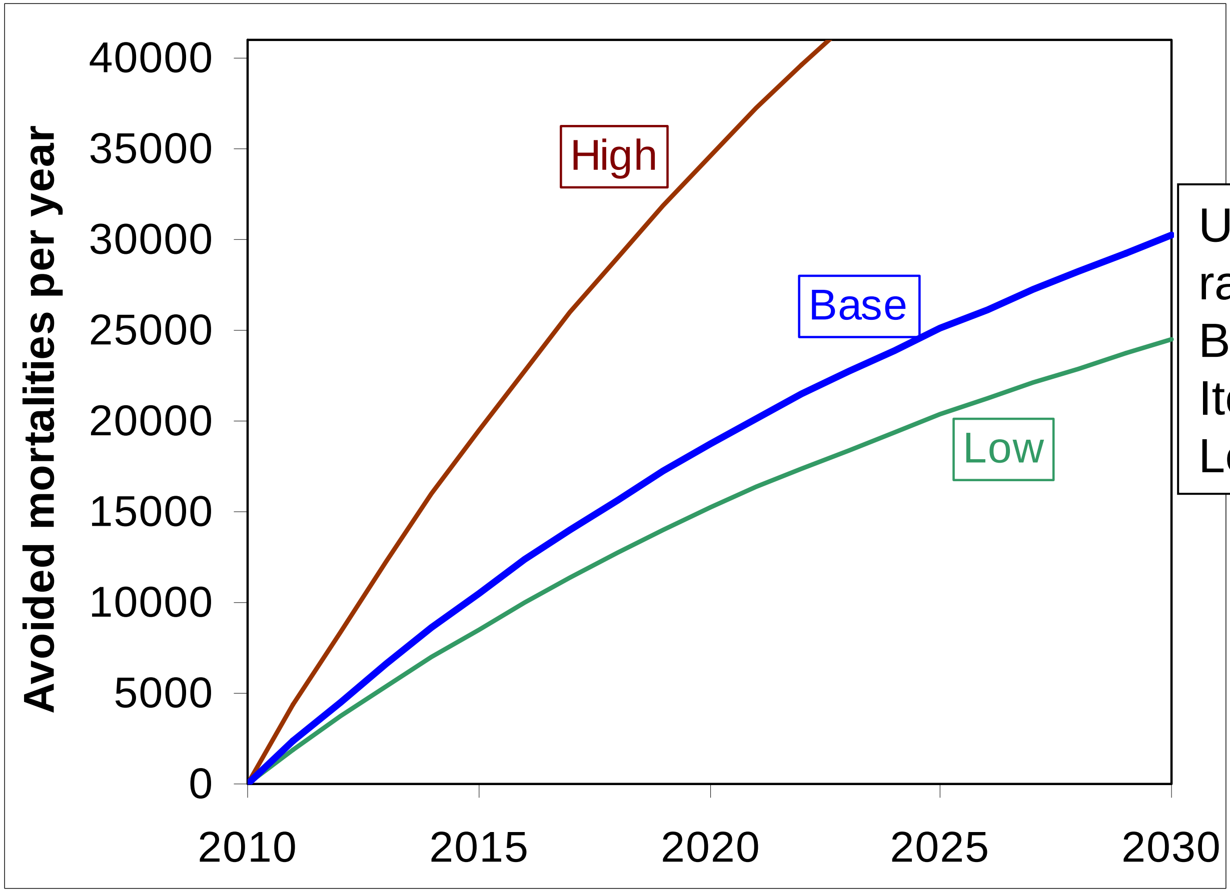
Base 2030 avoided mortalities = 30,200

1) Ozone response to methane 19,600 – 40,700

2) Low-concentration health threshold 26,900 – 30,900

3) Ozone-mortality relationship (β) 19,300

Mortality Benefits – Sensitivity to ozone-mortality relationship



Uncertainty range spanning Bell et al (2005), Ito et al (2005), Levy et al (2005).

Base 2030 avoided mortalities = 30,200

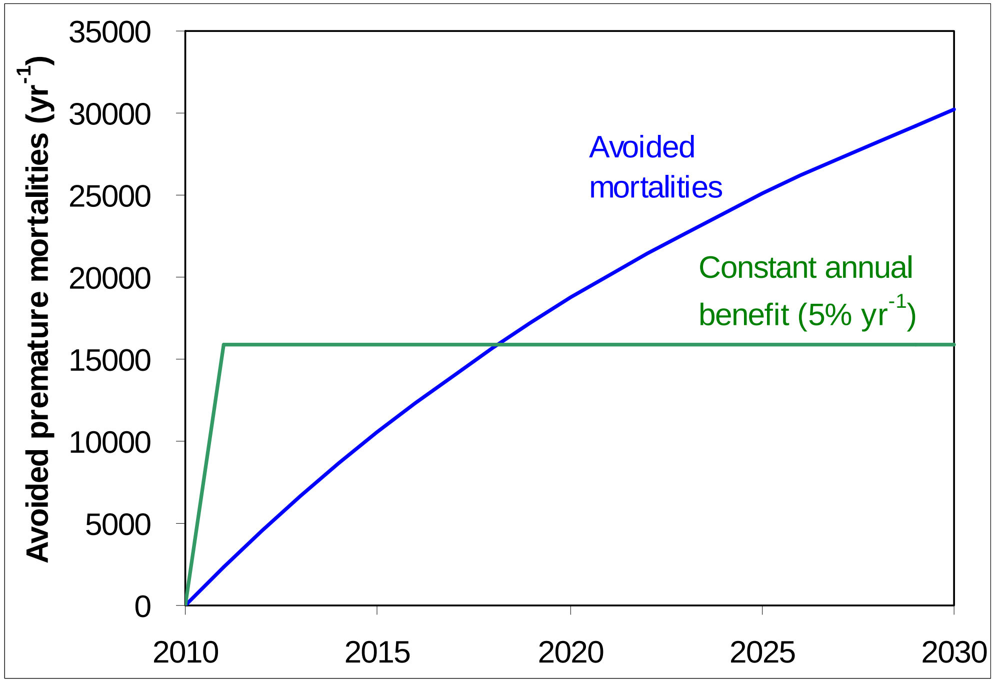
1)	Ozone response to methane	19,600 – 40,700
2)	Low-concentration health threshold	26,900 – 30,900
3)	Ozone-mortality relationship (β)	19,300 – 55,800

Global Mortality – Monetized Benefits

Marginal cost of reducing 65 Mton CH_4 yr^{-1} is ~\$100 per ton CH_4
(total cost is negative, IEA (2003)).

⇒ Discount avoided mortalities to a constant stream (5% yr^{-1}):
~16,000 yr^{-1}.

⇒ Marginal cost-effectiveness:
\$420,000 per avoided mortality



Assume global-average Value of a Statistical Life (IPCC, 2001): **\$1 million**.

⇒ Benefit of methane reductions is **\$240 per ton CH_4**
= \$12 per ton CO_2 eq.

“Air quality ancillary benefits of CO_2 mitigation”
= \$0.5 - \$140 per ton CO_2 (IPCC, 2001)

Methane in Ozone Management

	NO_X, NMVOCs & CO	**Methane**
Low-cost emission reductions	Few; least-cost options already exhausted in some 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 (~12 yr)
Spatial scale	**Local to regional, focusing on polluted areas** (also global)	Global, widespread benefits
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 (NMVOC)	**Many measures make methane available for energy**; controls may reduce NMVOC emissions

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

West, J. J., and A. M. Fiore (2005) *Environmental Science & Technology*.

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)

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

O_3 smog recognized as an URBAN problem: Los Angeles, Haagen-Smit identifies chemical mechanism

Smog considered REGIONAL problem; role of biogenic VOCs discovered

A GLOBAL perspective: role of intercontinental transport, background

1950s

1980s

Present

Abatement Strategy:

NMVOCs

+ NO_x

+ CH_4

A. Fiore

Conclusions

- **Methane emission reductions decrease ozone and improve air quality everywhere, while also reducing greenhouse warming.**
- A 20% reduction of current global anthropogenic methane emissions will:
  - Come at a net cost-savings using identified technologies.
  - Avoid roughly 30,000 premature mortalities in 2030 (17,000-56,000), ~370,000 from 2010-2030.
- Monetized health benefits are estimated to be \$240 per ton CH_4 (\$12 per ton CO_2 eq.) - which can justify the 20% methane reduction.
- Methane abatement can be a cost-effective component of international long-term (decadal) ozone management.

Double dividend of methane controls:
Decreased greenhouse warming and improved air quality

Ozone Management by Reducing Methane Emissions

- West, J. J., and A. M. Fiore (2005) Management of tropospheric ozone by reducing methane emissions, *Environmental Science & Technology*, 39(13): 4685-4691, doi: 10.1021/es048629f.

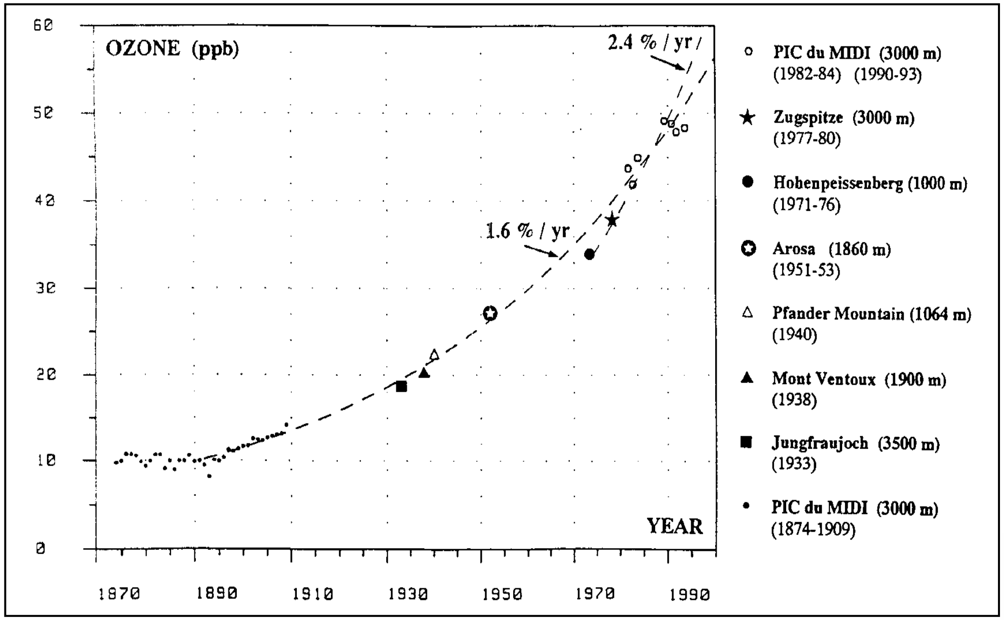
- West, J. J., A. M. Fiore, L. W. Horowitz, D. L. Mauzerall (submitted) Mitigating ozone pollution with methane emission controls: global health benefits, *Proceedings of the National Academy of Sciences*.

- West, J. J., A. M. Fiore, V. Naik, L. W. Horowitz, D. L. Mauzerall (in preparation) Ozone air quality and radiative climate forcing consequences of changes in ozone precursor emissions.

- Fiore, A. M., D. J. Jacob, B. D. Field, D. G. Streets, S. D. Fernandes, C. Jang (2002) Linking ozone pollution and climate change: the case for controlling methane, *Geophys. Res. Lett.*, 29(19): 1919.

www.princeton.edu/~jwest

Background Ozone is Growing …



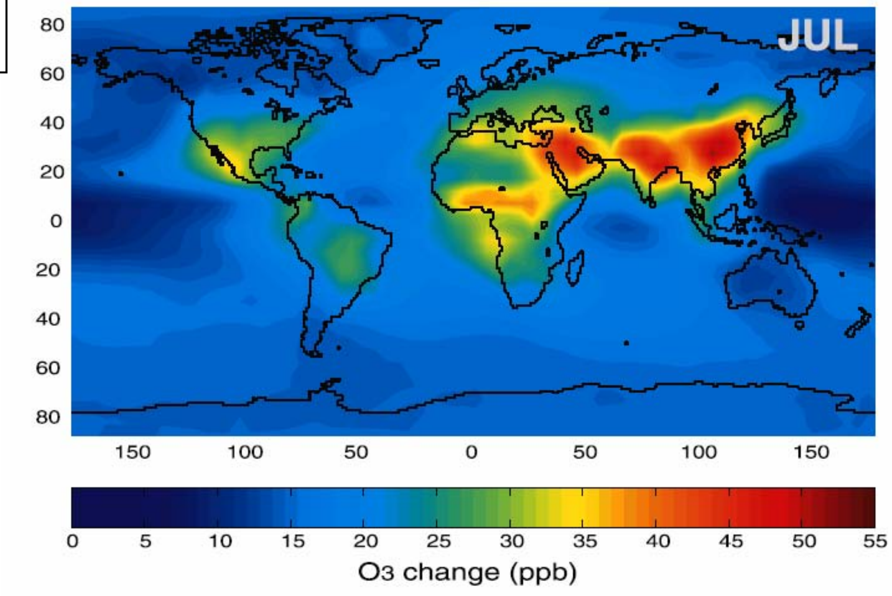
Ozone trend at European mountain sites, 1870-1990 (Marenco et al., 1994).

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_X emissions (Wang *et al*., 1998).

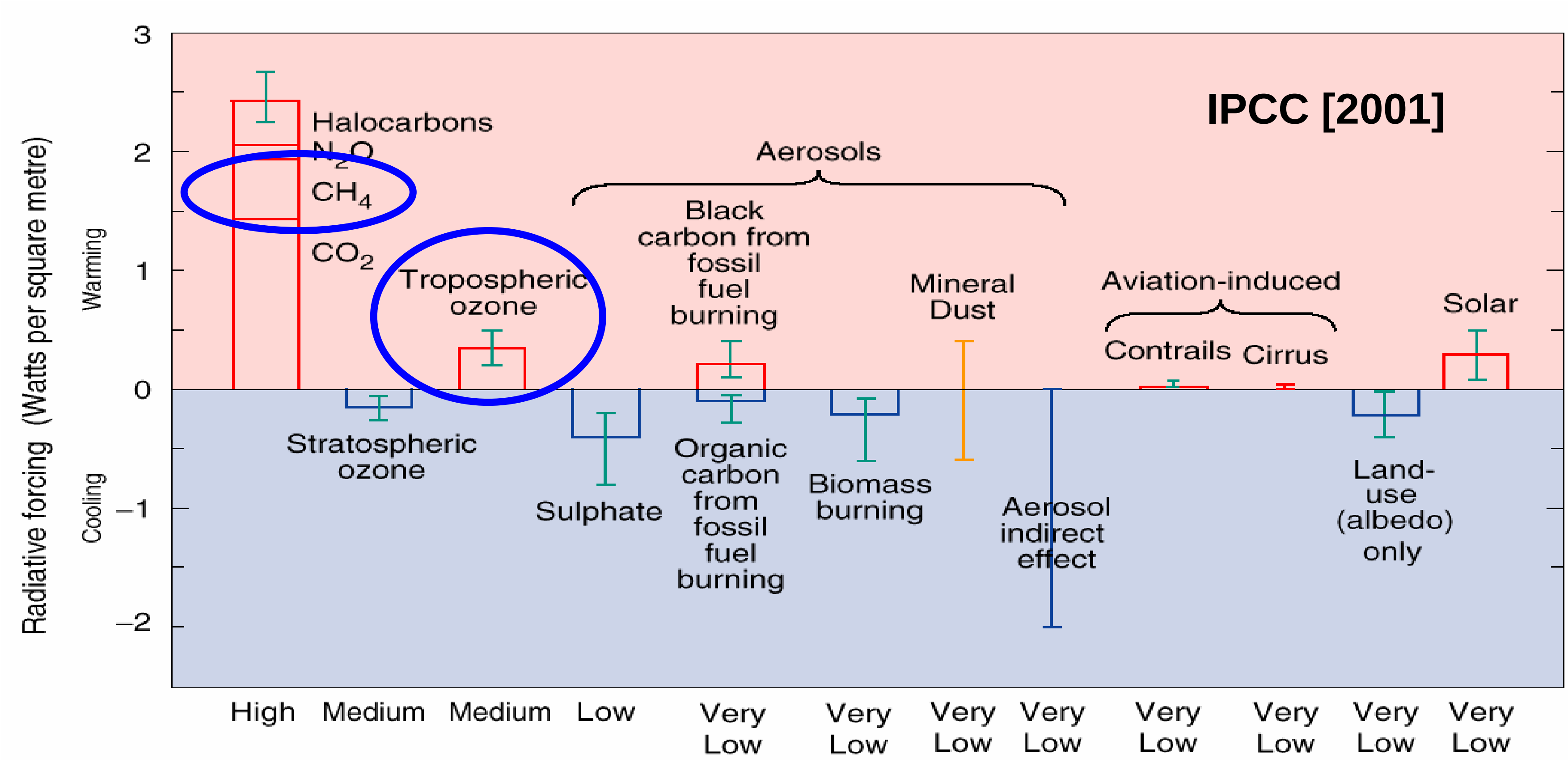
… and Will Continue to Grow!

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_X.

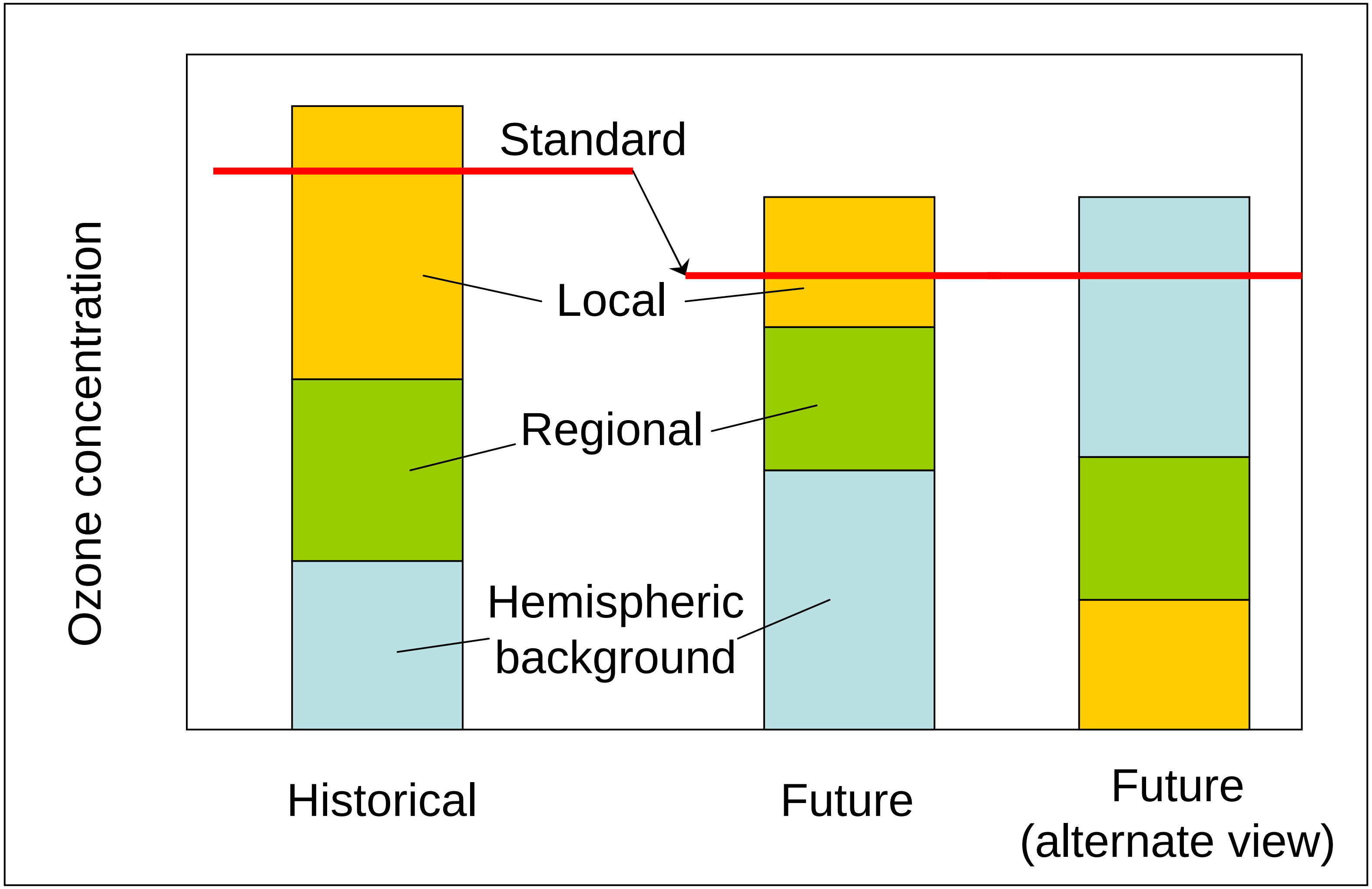


Radiative Forcing of Climate, 1750-Present:
Important Contributions from Methane and Ozone



Level of scientific understanding

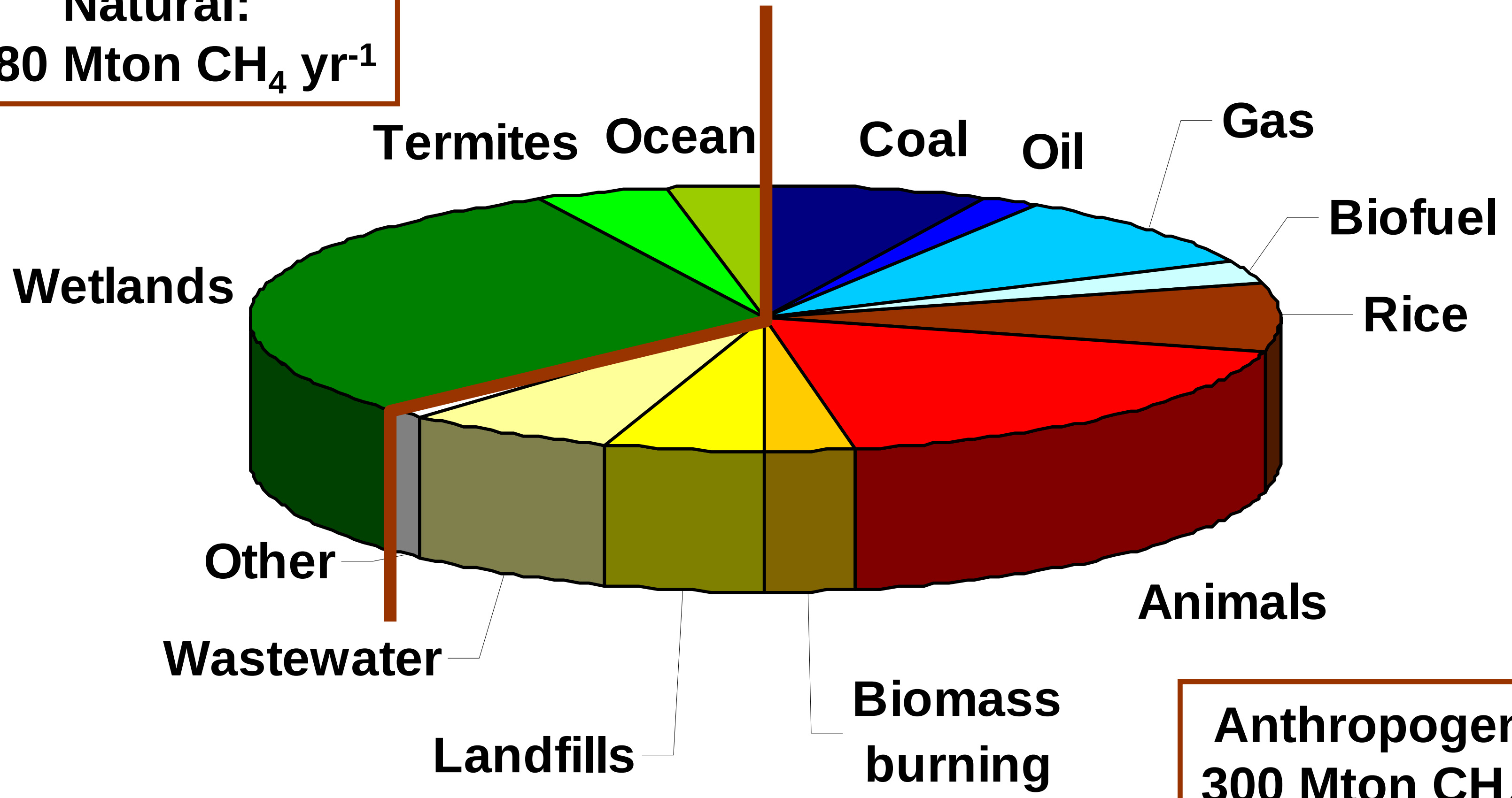
The “Tightening Vise” of Ozone Management



Keating, T. J., J. J. West, and A. Farrell (2004) Prospects for international management of intercontinental air pollutant transport, in A. Stohl, Ed., *Intercontinental Transport of Air Pollution*, Springer, p. 295-320.

Global Methane Emissions

Natural:
180 Mton CH_4 yr^{-1}



Anthropogenic:
300 Mton CH_4 yr^{-1}

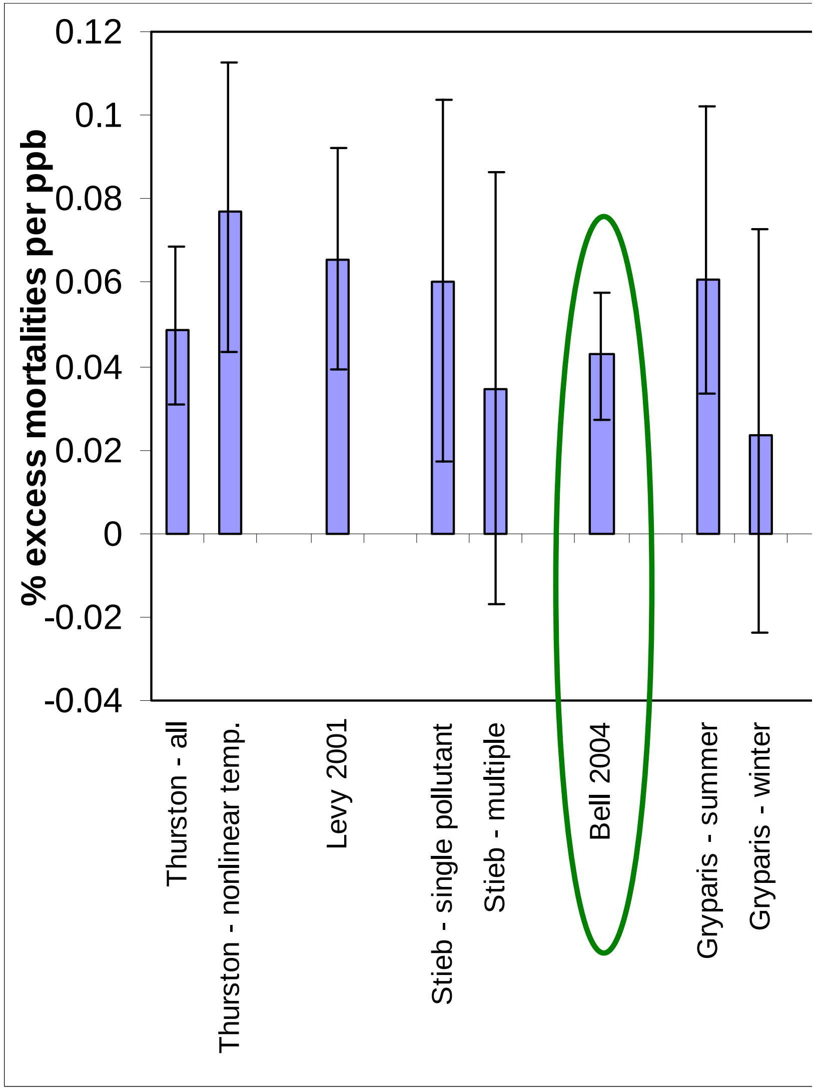
EDGAR3.2 &
Houweling *et al.*, 1999

2030 Avoided Premature Mortalities

Due to a 65 Mton yr^{-1} decrease in methane emissions, beginning in 2010.

	Total mortalities		**Cardio & Respiratory**	
Region	number	per 10^6 people	number	per 10^6 people
Africa	6920	5.59	2070	1.68
North America	1110	2.81	700	1.77
Latin America	1790	1.88	960	1.01
South-East Asia	7790	3.33	4550	1.95
Western Europe	1900	3.86	1260	2.56
E. Europe & Former Soviet Union	1790	3.50	1560	3.06
Eastern Mediterranean	3150	3.69	1660	1.94
Western Pacific	500	2.86	310	1.77
East Asia	5250	2.36	3610	1.63
Global	30200	3.29	16700	1.82

Ozone Health
Meta-analyses and direct e



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

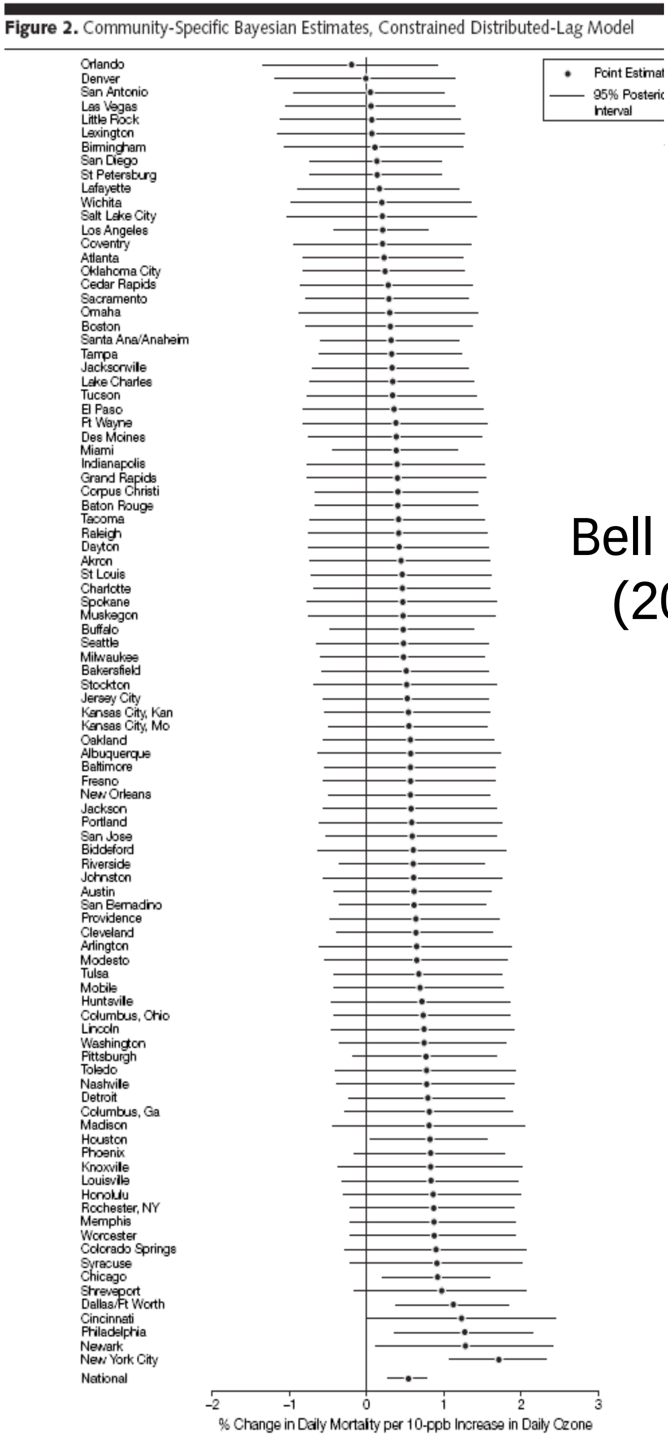
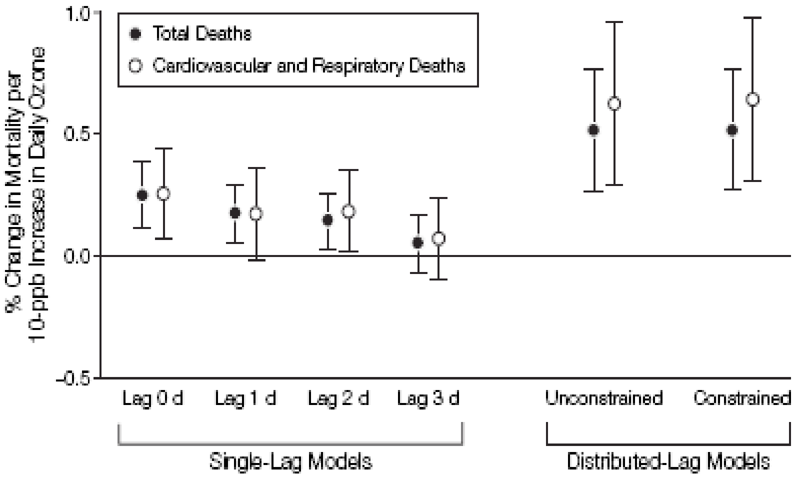


Figure 2. Community-Specific Bayesian Estimates, Constrained Distributed-Lag Model

Bell *et al.*
(2004)

Ozone Mortality

Figure 1. Percentage Change in Daily Mortality for a 10-ppb Increase in Ozone for Total and Cardiovascular Mortality, for Single-Lag and Distributed-Lag Models

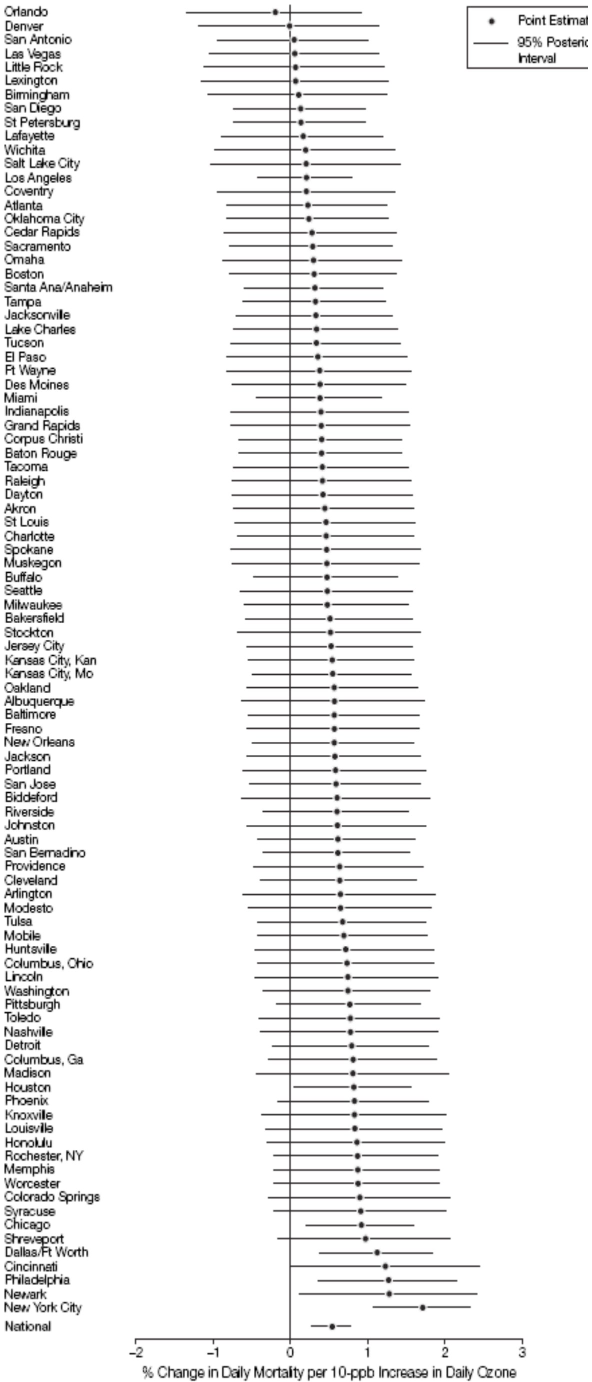


The single-lag model reflects the percentage increase in mortality for a 10-ppb increase in ozone on a single day. The distributed-lag model reflects the percentage change in mortality for a 10-ppb increase in ozone during the previous week. Error bars indicate 95% posterior intervals.

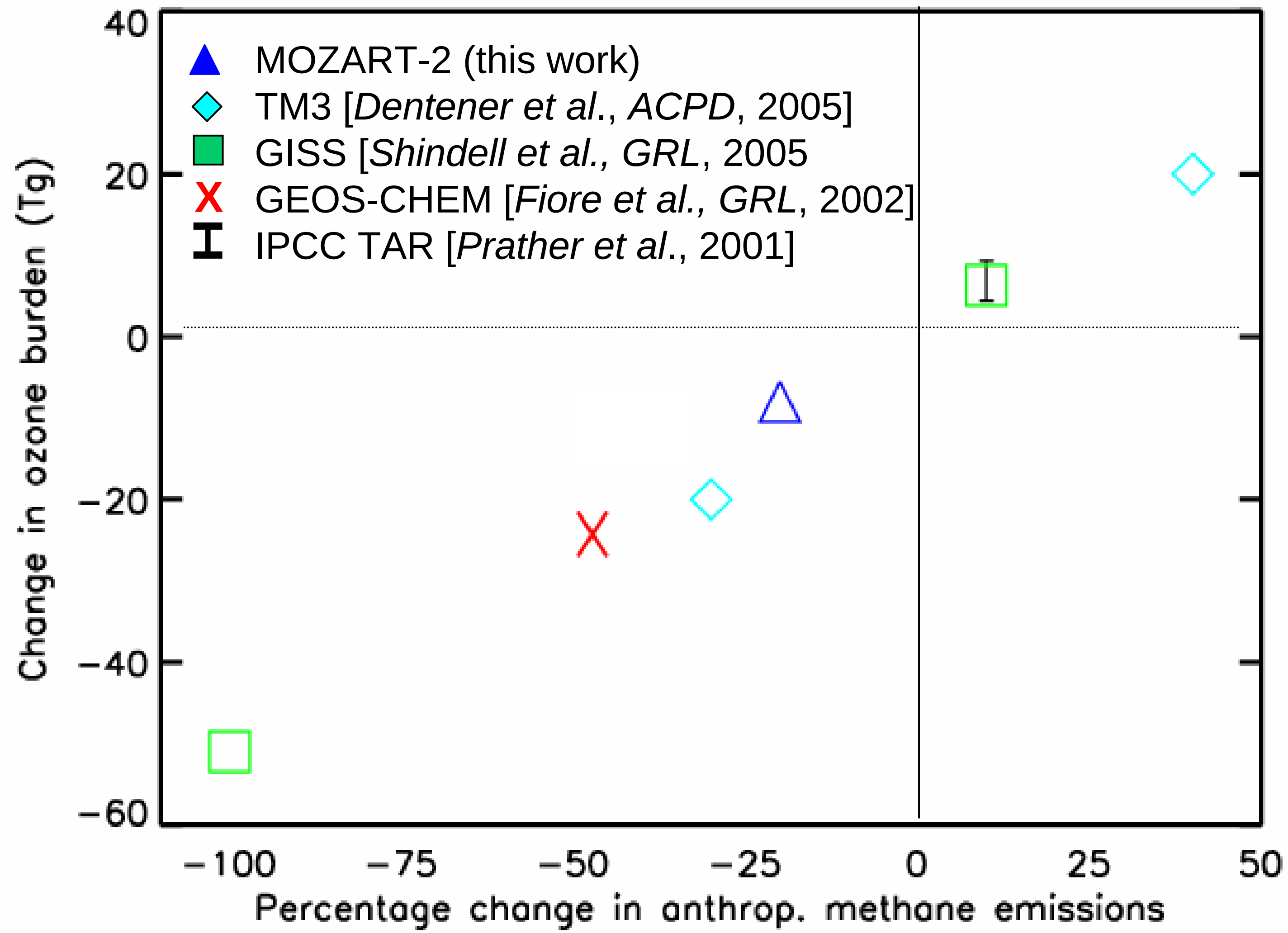
$$\Delta Mortality = -\left[y_0\left(e^{-\beta\Delta O_3}-1\right)\right]Pop$$

Bell *et al.* (2004)

Figure 2. Community-Specific Bayesian Estimates, Constrained Distributed-Lag Model

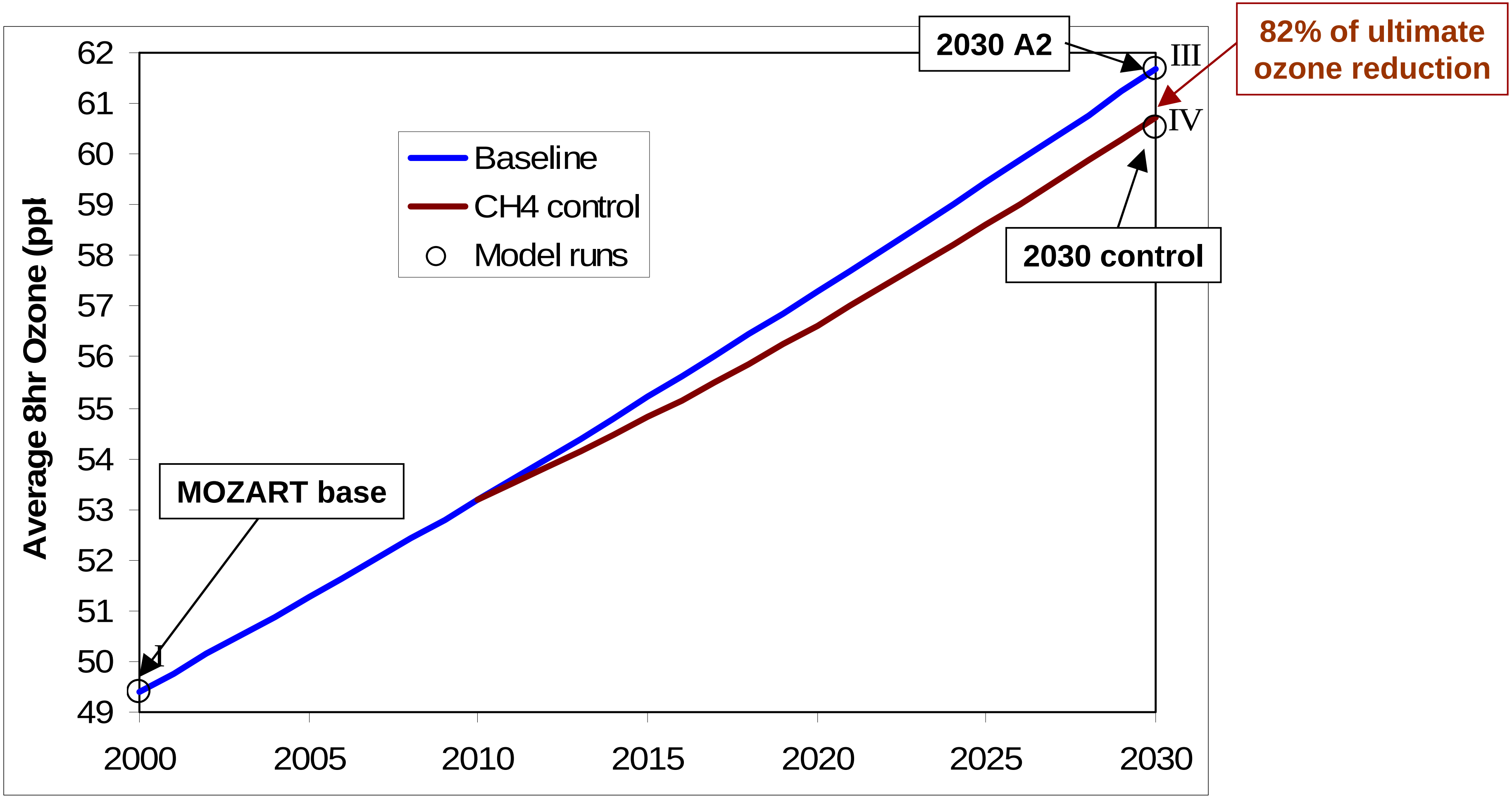


Tropospheric ozone response to anthropogenic methane emission changes is fairly linear



Shindell et al., 2005 report that tropospheric ozone responds linearly to 10, 25, 50, 75, 100% decreases in anthropogenic CH_4

Projecting ozone 2000-2030



Population-weighted global annual average 8-hr. concentration

Monetized Non-mortality Benefits of Global Ozone Reductions

Assume: $\Delta O_3 \propto \Delta(CH_4 \text{ emissions})$, $\Delta(\text{monetized benefits}) \propto \Delta O_3$

Benefits per 1 ppb ozone reduction ($billion yr^{-1} ppb^{-1})

	US	EU-15	China, S. Korea, Japan	Extrapolate Globally
Agriculture	0.40	0.51	0.42	2.8 (0.04 - 5.6)
Forestry	0.44			1.7 (0.5 - 2.9)
Human health (non-mortality)	0.59	0.60		3.0 (2.0 - 4.1)
TOTAL				7.5 (4.4 - 10.7)

Apply methane-ozone sensitivity: \$7.5 billion yr^{-1} ppb^{-1} (\$4.4-10.7)

→ \$132 per ton CH_4 (\$78-\$189)

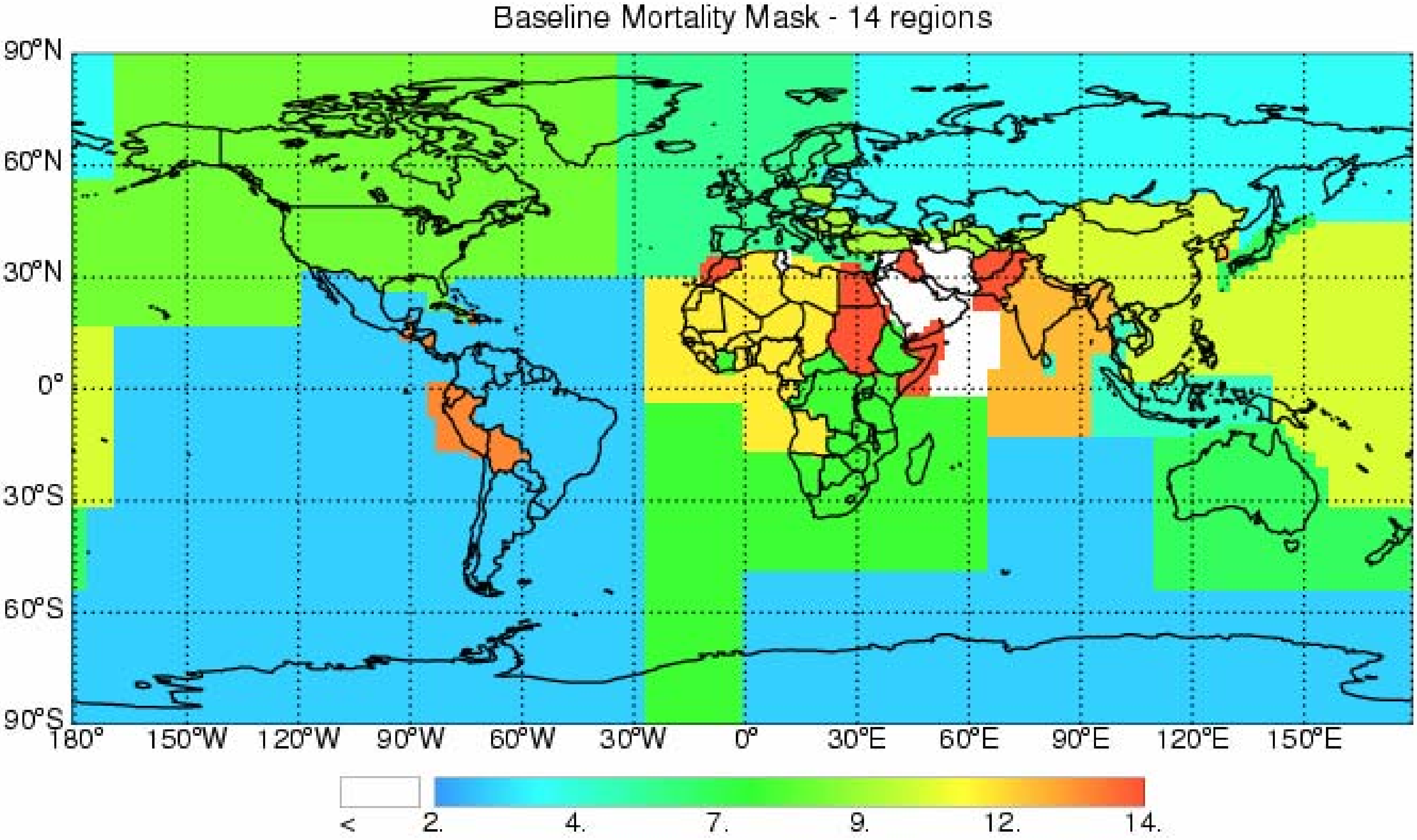
Discount future benefits (5% yr^{-1}): **\$81 per ton CH_4 (\$48-\$116)**

= \$3.9 per ton CO_2 eq. (\$2.3-5.5)

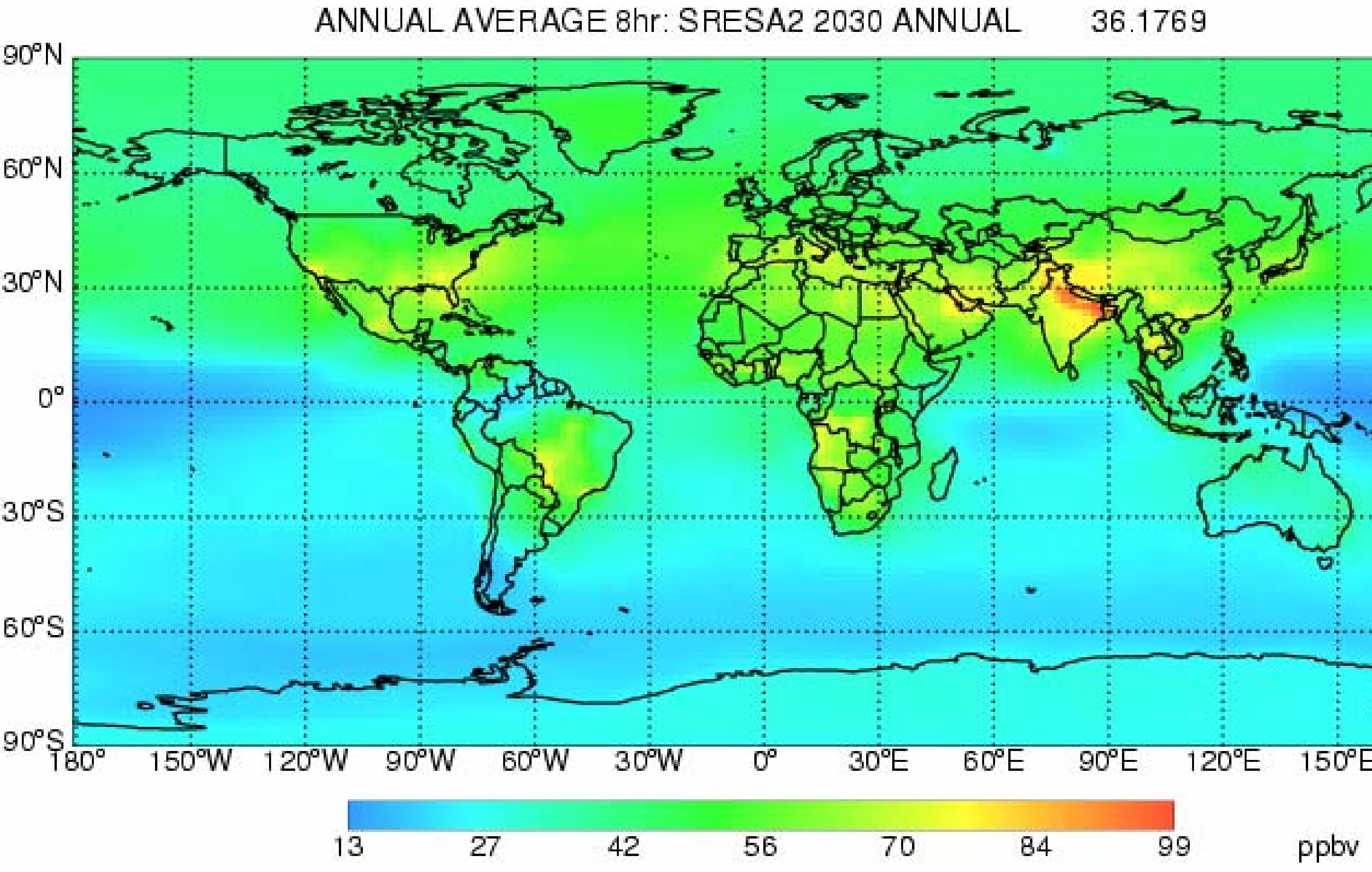
West, J. J., and A. M. Fiore (2005)

Sources: EPA (1999a); EPA (1999b); Cofala *et al.* (2001); Wang & Mauzerall (2004)

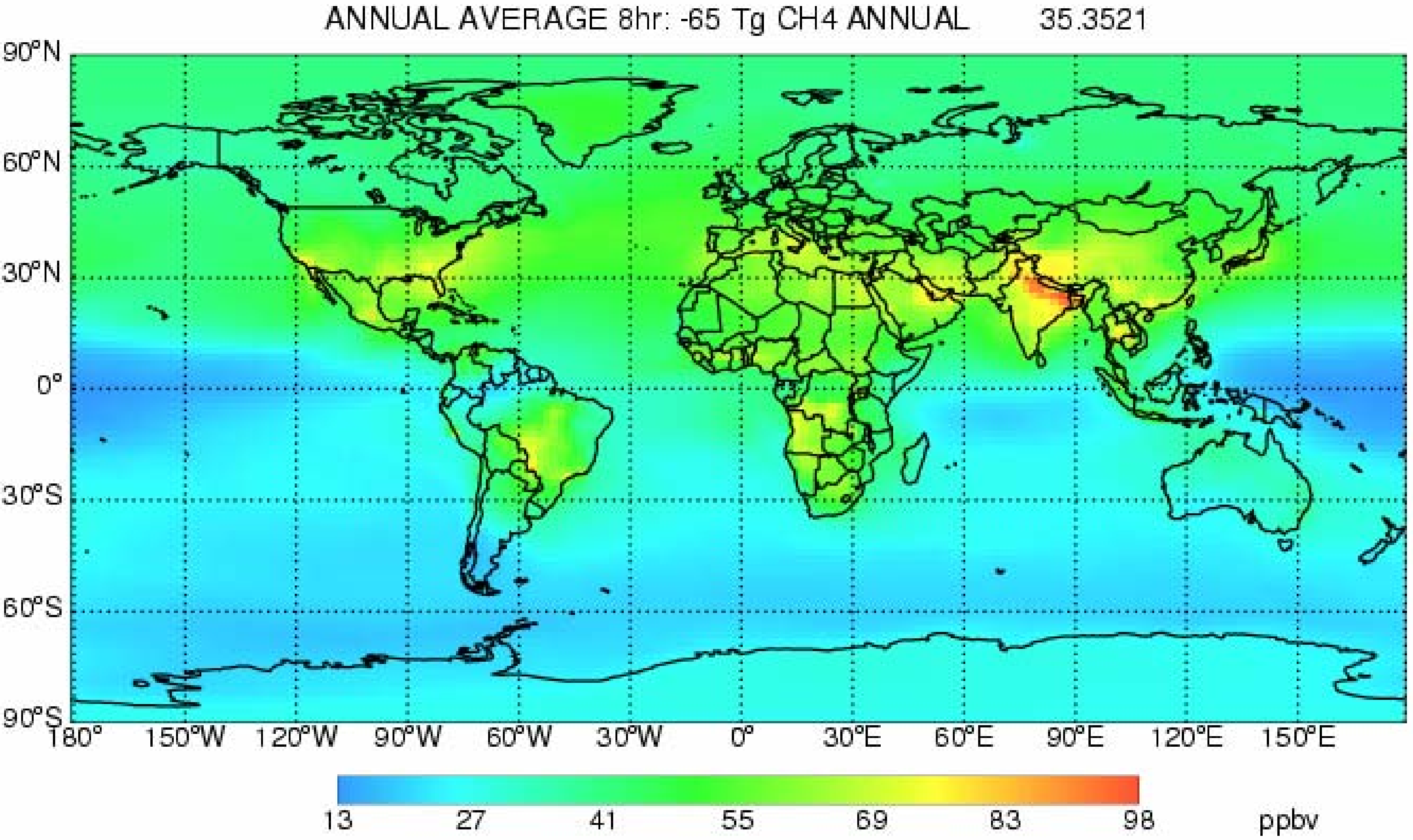
Baseline Mortality

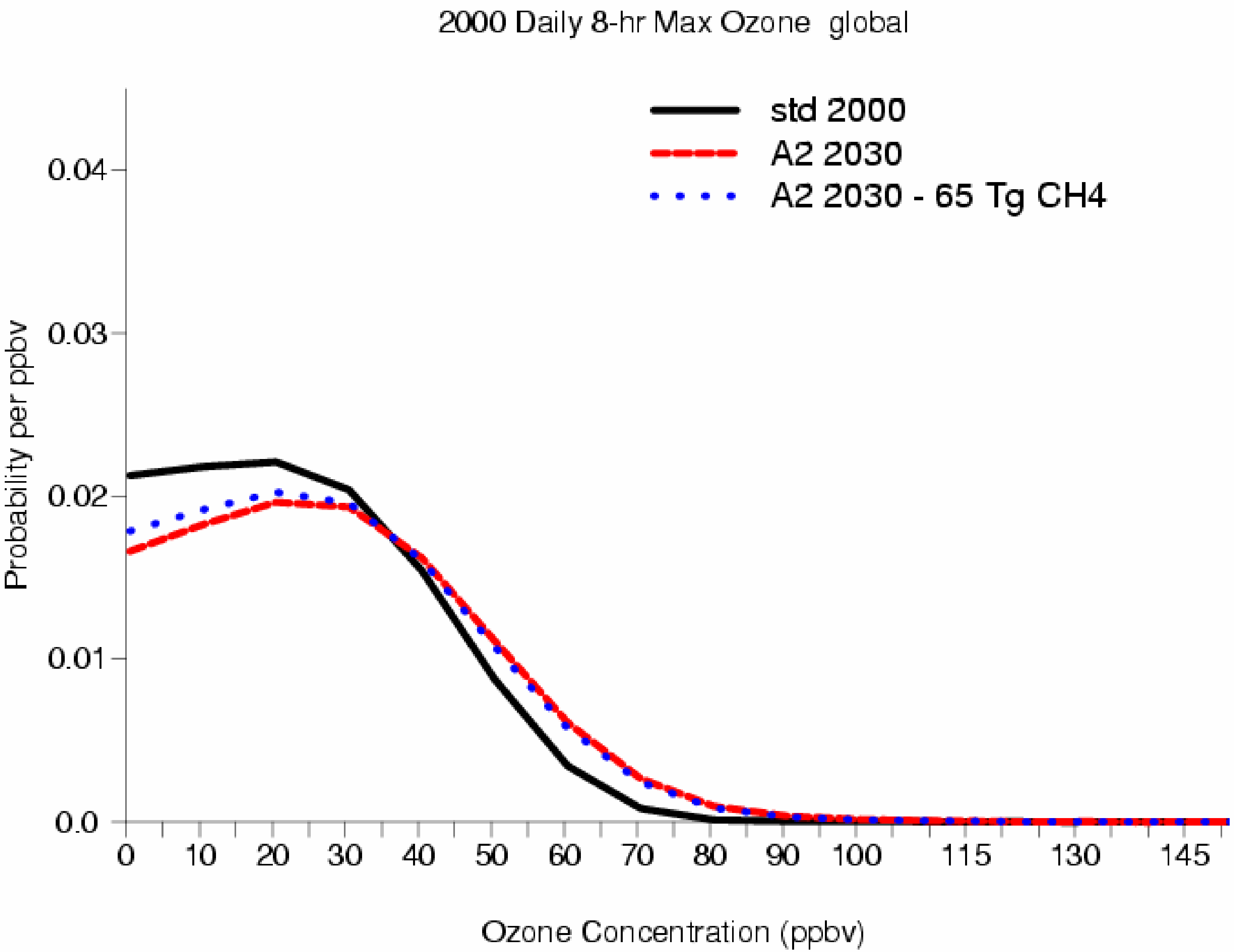


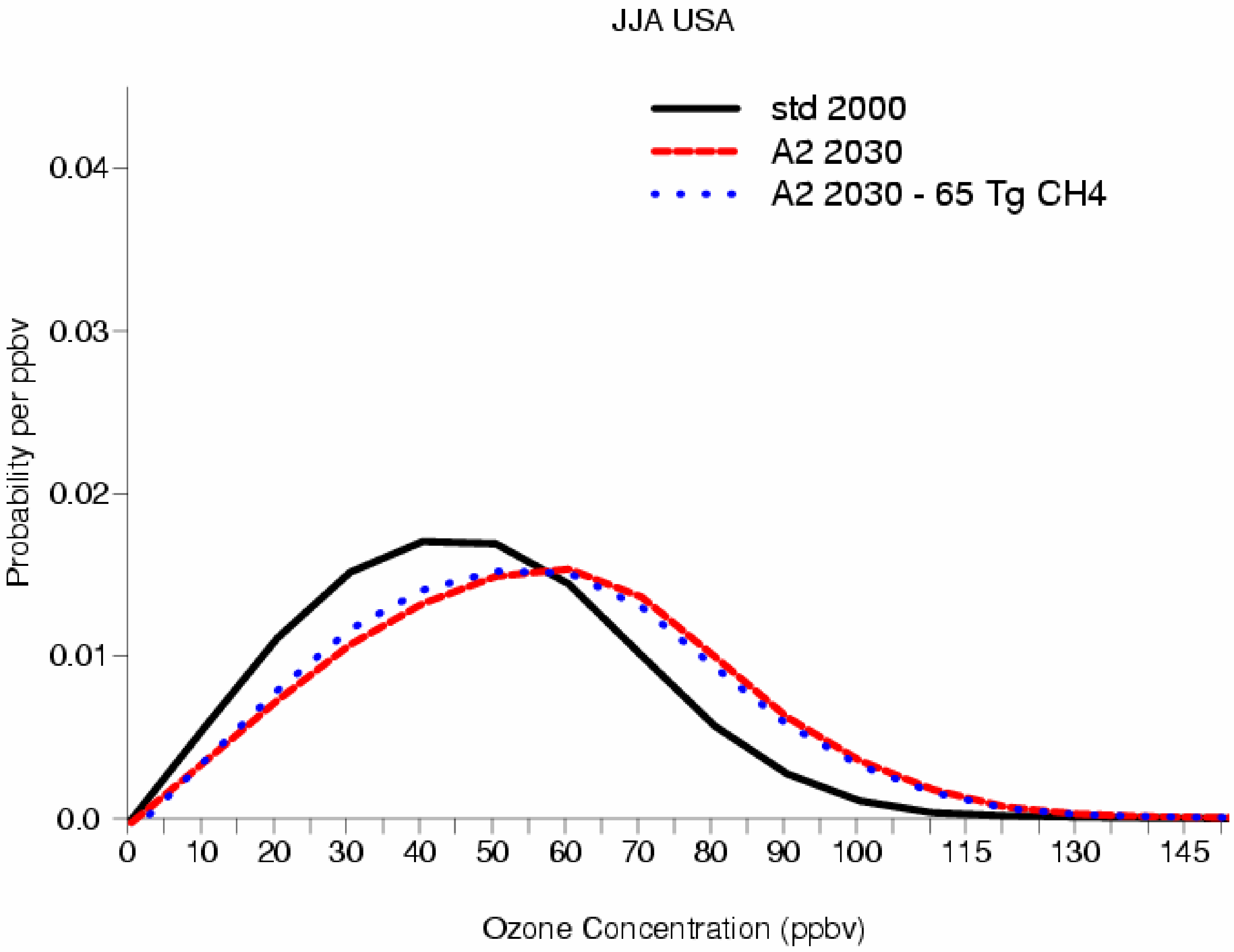
Projected A2 2030 ozone – annual average 8hr



Projected 2030 8hr ozone, with methane control

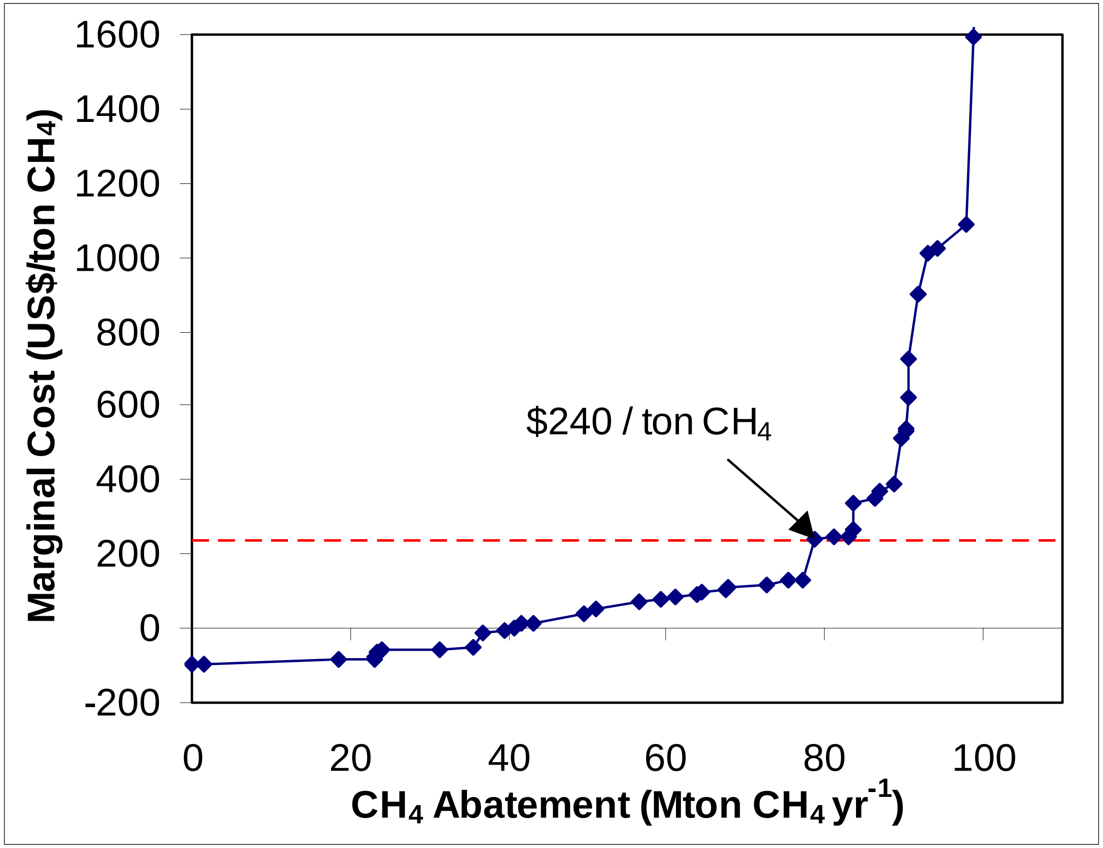



2000 Daily 8-hr Max Ozone global
std 2000
A2 2030
A2 2030 - 65 Tg CH4
Probability per ppbv
0.04
0.03
0.02
0.01
0.0
0
10
20
30
40
50
60
70
80
90
100
115
130
145
Ozone Concentration (ppbv)


JJA USA
std 2000
A2 2030
A2 2030 - 65 Tg CH4
Probability per ppbv
0.04
0.03
0.02
0.01
0.0
0
10
20
30
40
50
60
70
80
90
100
115
130
145
Ozone Concentration (ppbv)

Marginal Costs & Benefits of Methane Reductions

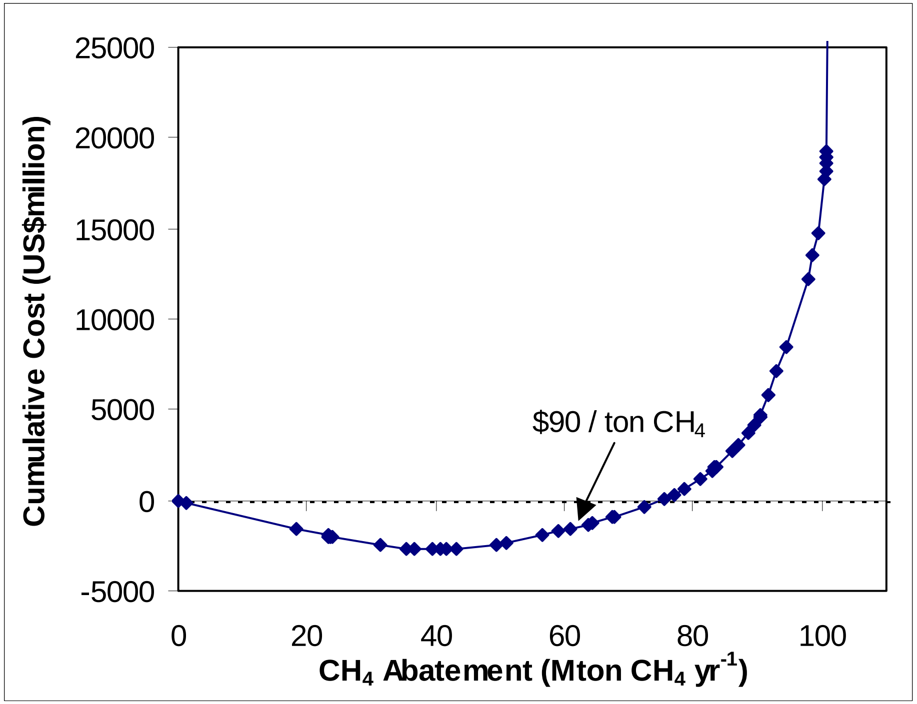
Accounting for all global measures less than \$240 per ton CH_4 …



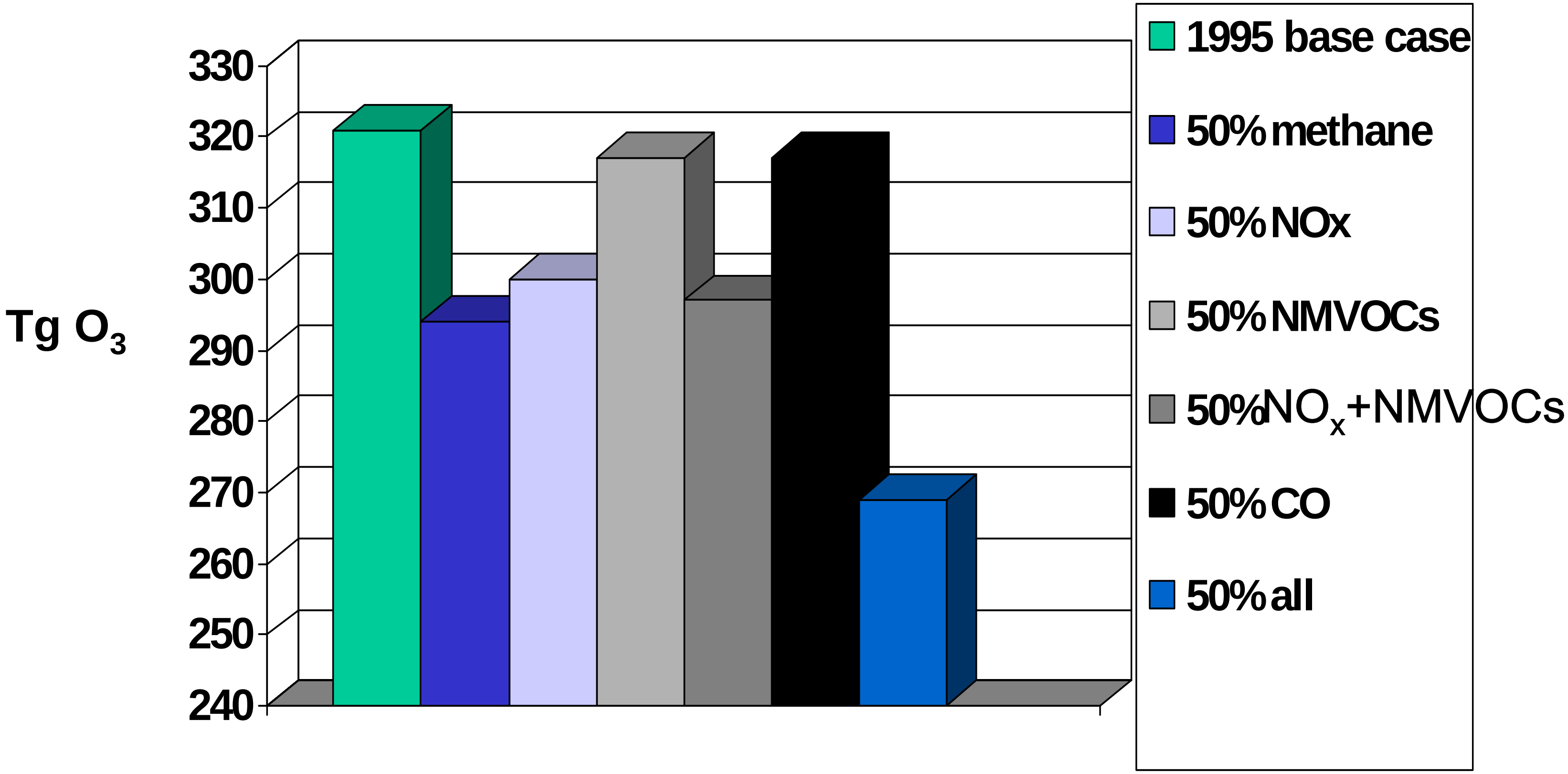
Marginal costs from IEA (2003) for 5 industrial sectors.

… a global reduction of 79 Mton CH_4 yr^{-1} can be justified, ~24% of current global anthropogenic emissions.

Cumulative Costs – IEA data



Anthropogenic Methane Emissions Enhance the Tropospheric Ozone Background

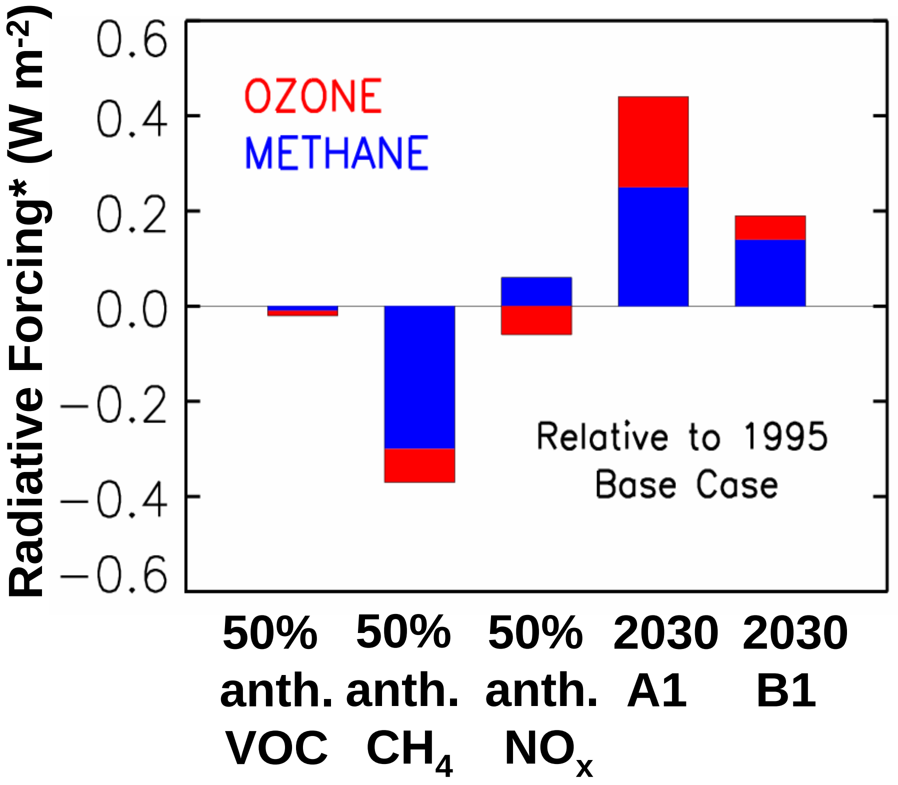


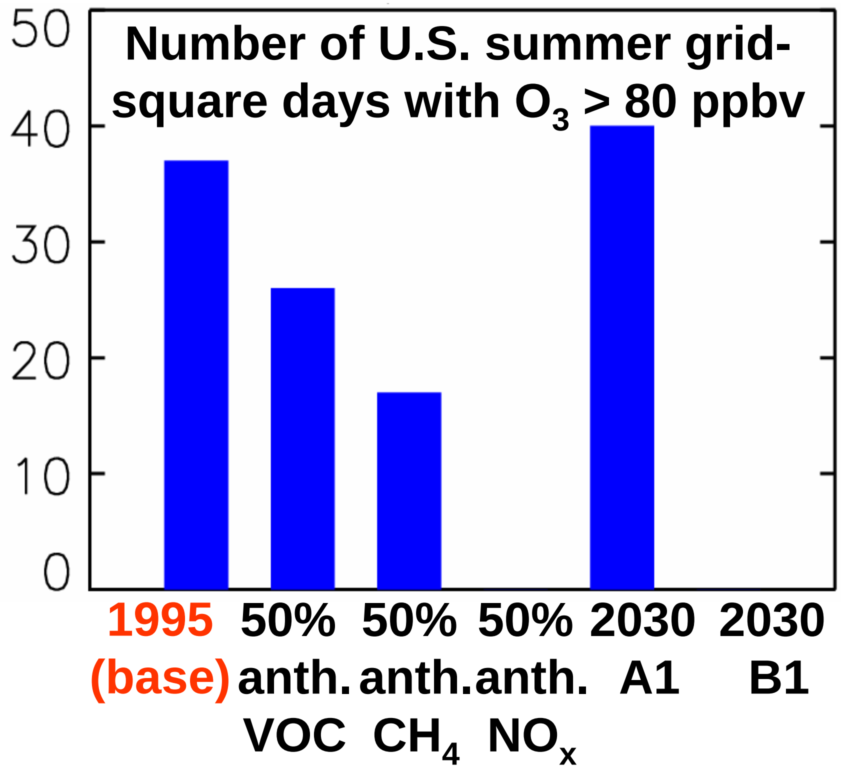
Sensitivity of global tropospheric ozone inventory in GEOS-CHEM to 50% global reductions in anthropogenic emissions

→ Anthropogenic emissions of NO_x and methane have largest influence on tropospheric ozone…. climate? air pollution?

Fiore et al., GRL, 2002

Double dividend of Methane Controls: Decreased greenhouse warming and improved air quality





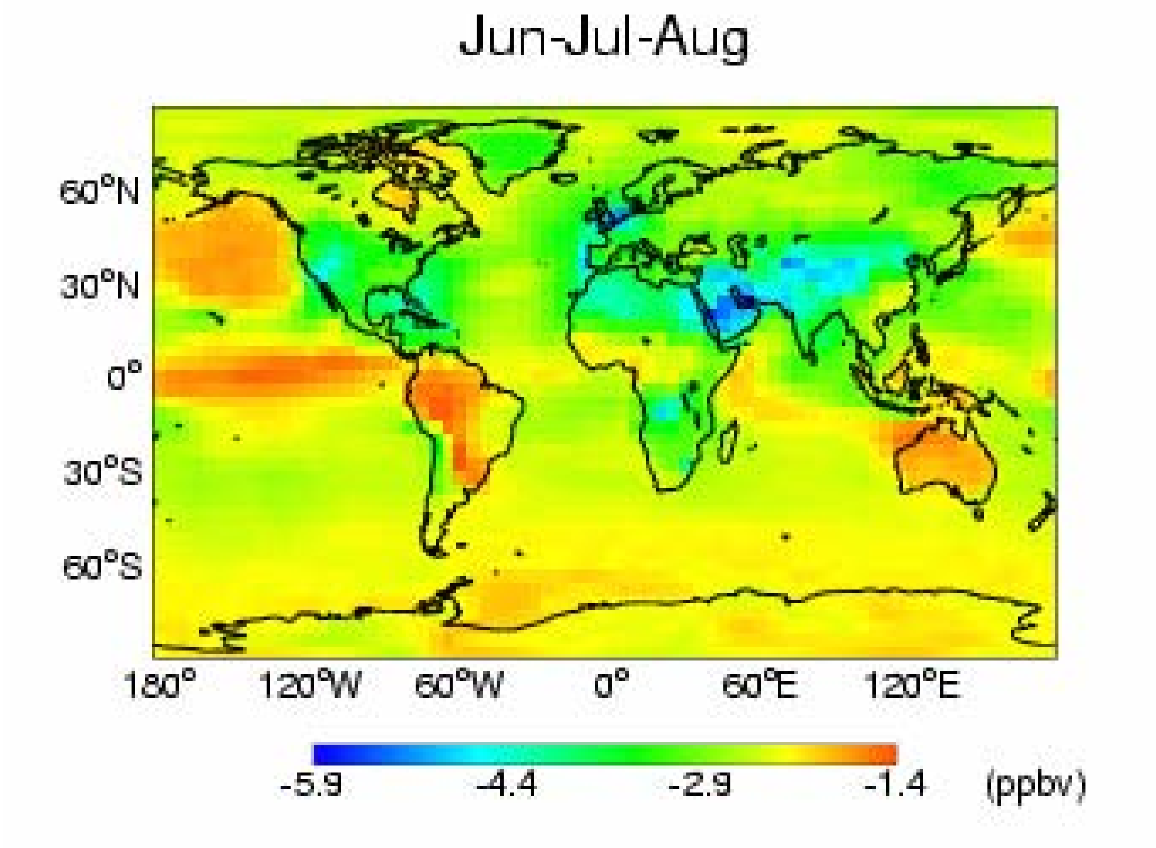
IPCC scenario	Anthrop. NO_x emissions (2030 vs. present)		Methane emissions (2030 vs. present)
	Global	U.S.	
A1	+80%	-20%	+30%
B1	-5%	-50%	+12%

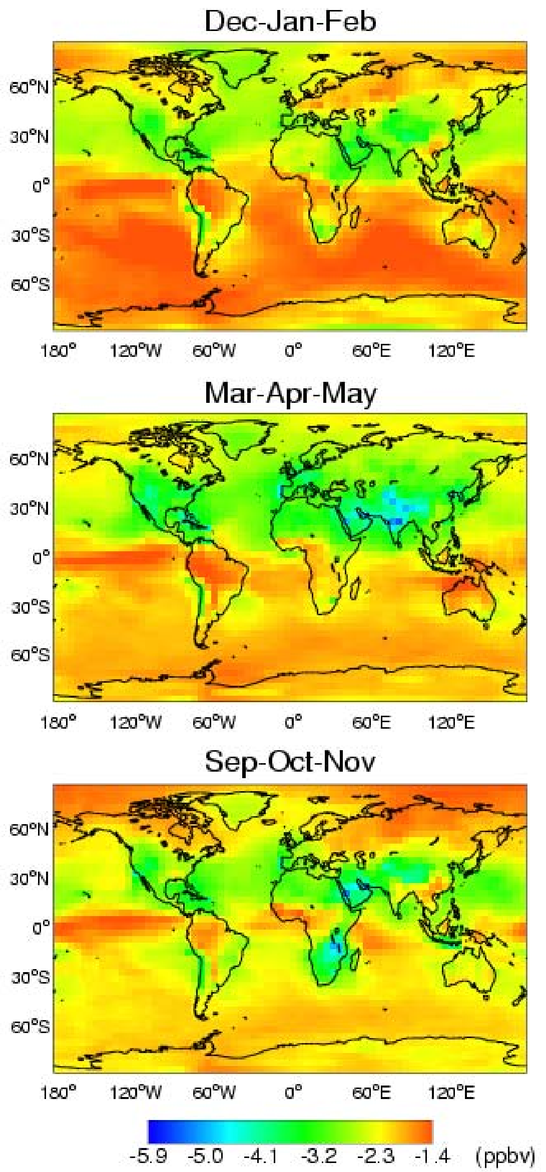
CH_4 links air quality & climate via background O_3

Fiore et al., GRL, 2002

Response of Global Ozone to Methane Emissions

50% reduction in global anthrop. CH_4 emissions





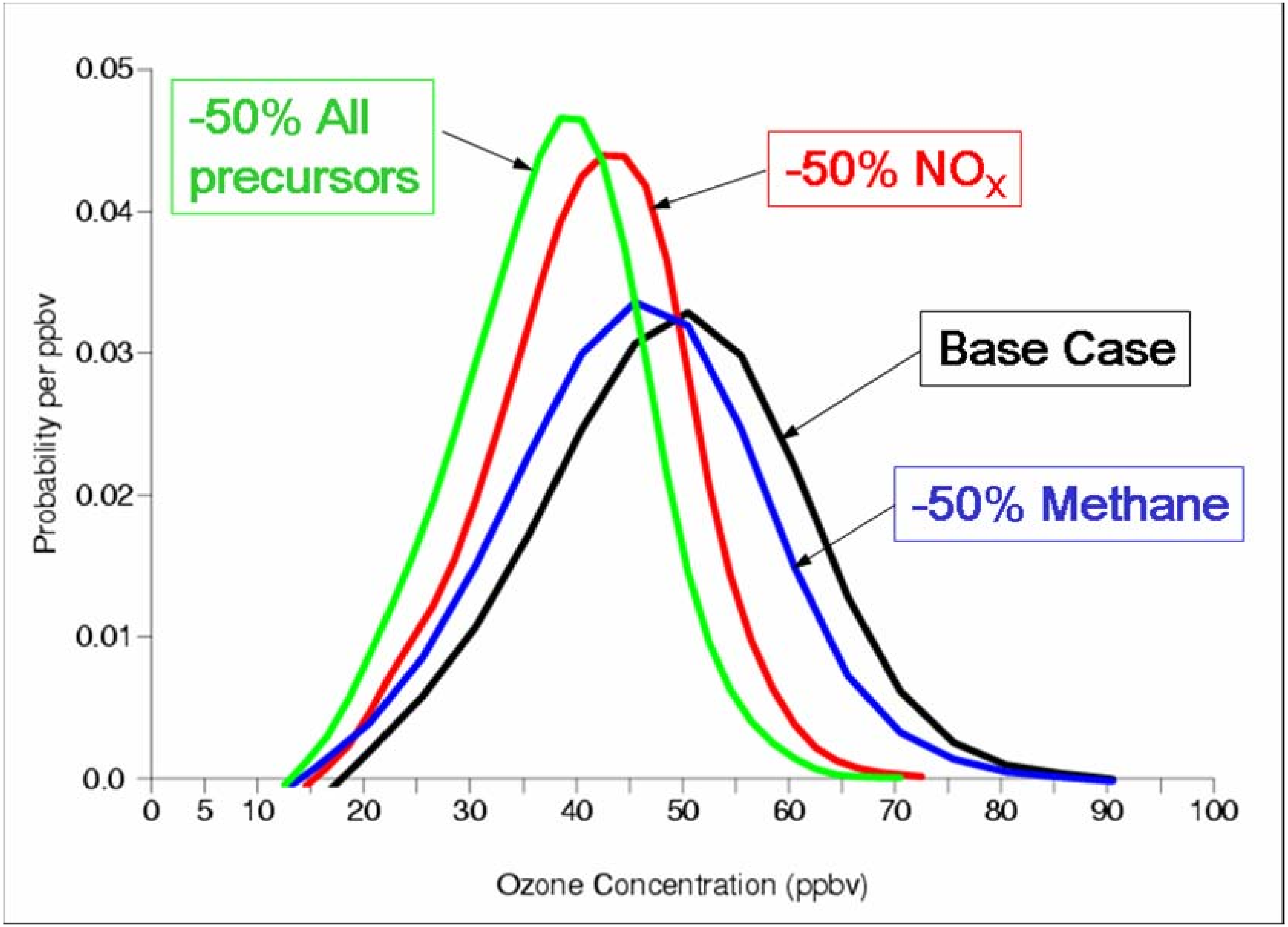
- Ozone decreases by 1-6 ppb
- 3 ppb over land in US summer

** ~60% of reduction in 10 yr,
~80% in 20 yr.

Using the GEOS-CHEM model,
as described by Fiore *et al.*, GRL (2002)

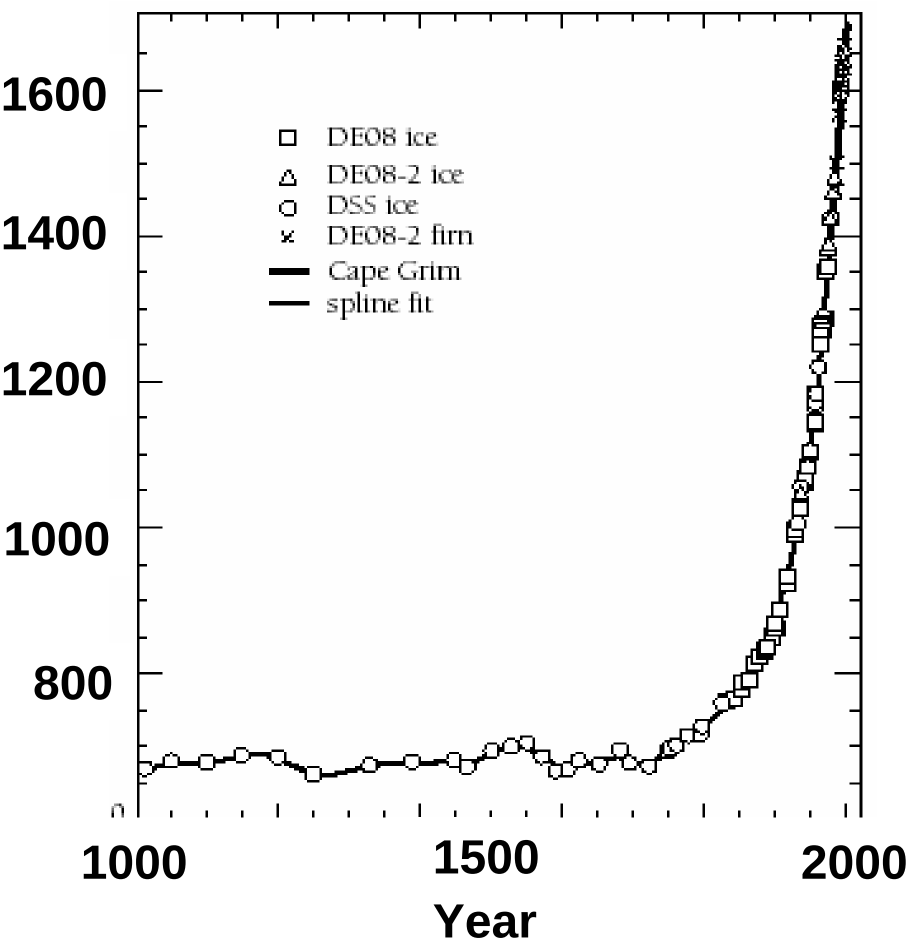
Effect of ozone precursor reductions –

Surface Ozone Frequency Distribution
(U.S. summer afternoons)

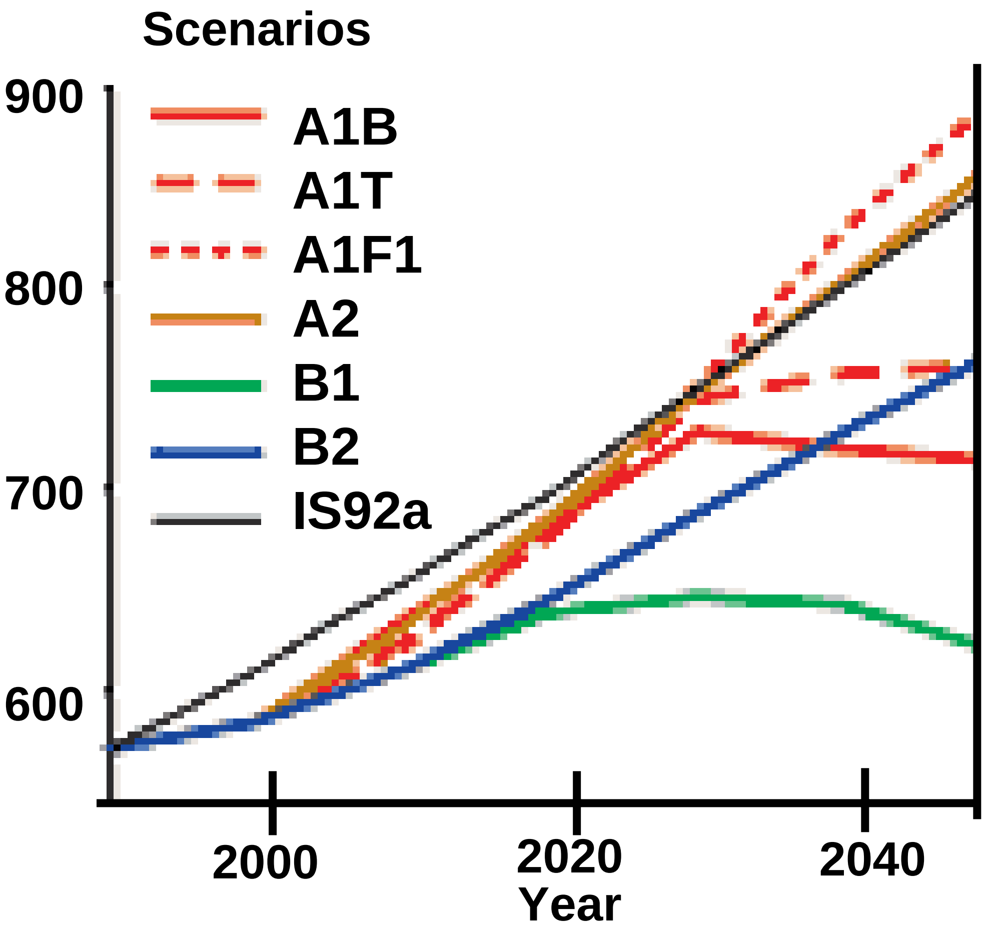


Atmospheric CH_4: Past Trends, Future Predictions

Variations of CH_4 Concentration (ppbv)
Over the Past 1000 years
[*Etheridge et al*., 1998]

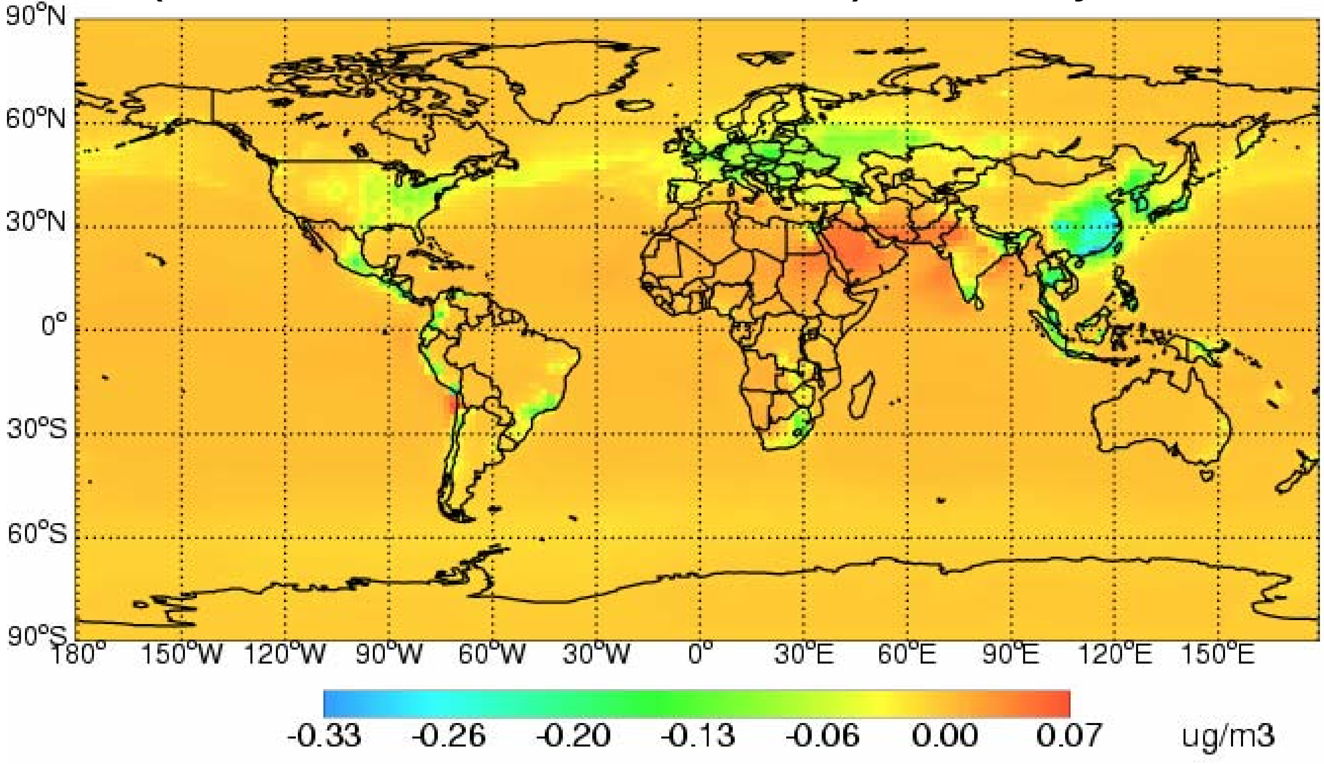


IPCC [2001] Projections of Future
CH_4 Emissions (Tg CH_4) to 2050

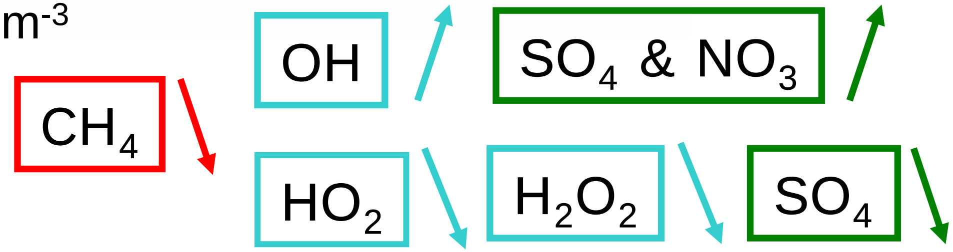


Effect of Methane Reductions on PM

Annual average change in inorganic PM
(sulfate + nitrate + ammonium) at steady state.



Global average ΔPM: -0.007 μg m^{-3}
Population-weighted ΔPM: -0.070 μg m^{-3}



CH_4

OH

HO_2

SO_4 & NO_3

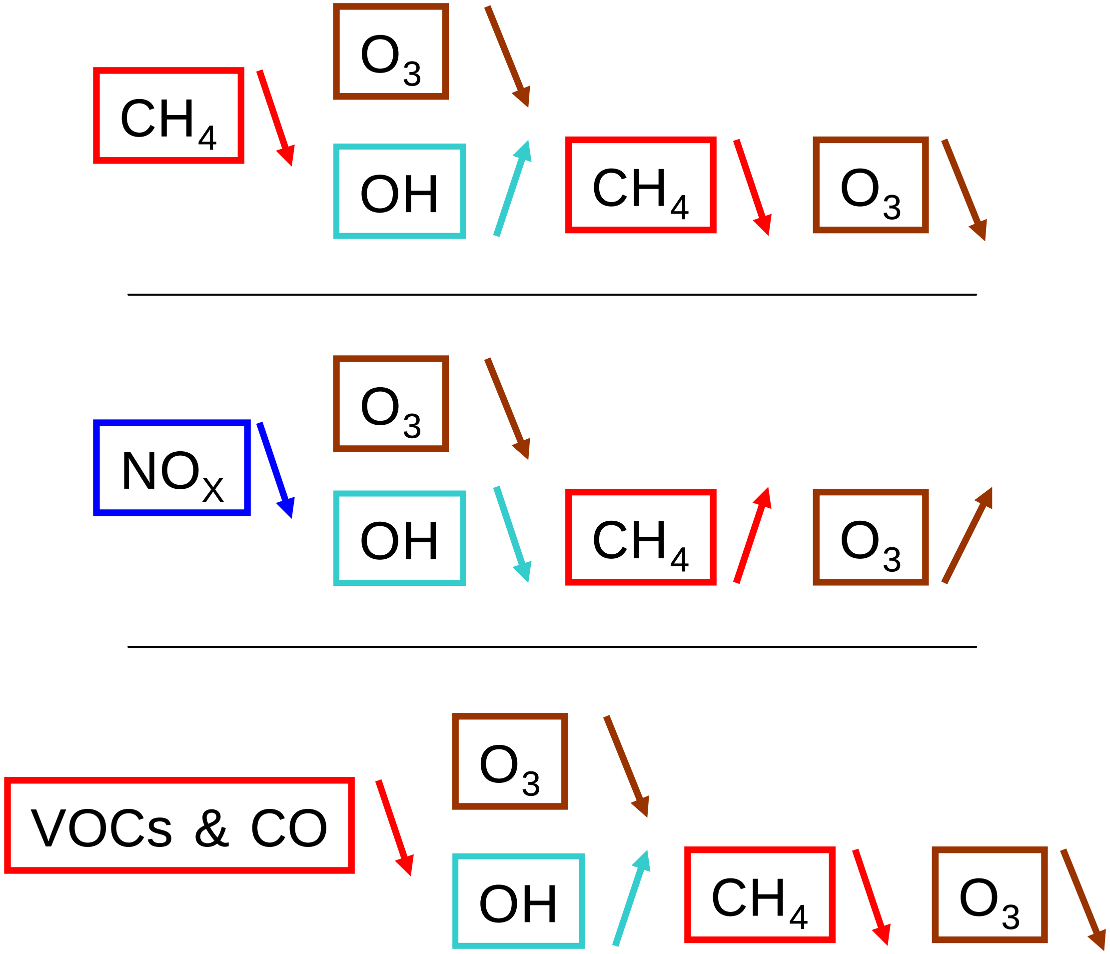
H_2O_2

SO_4

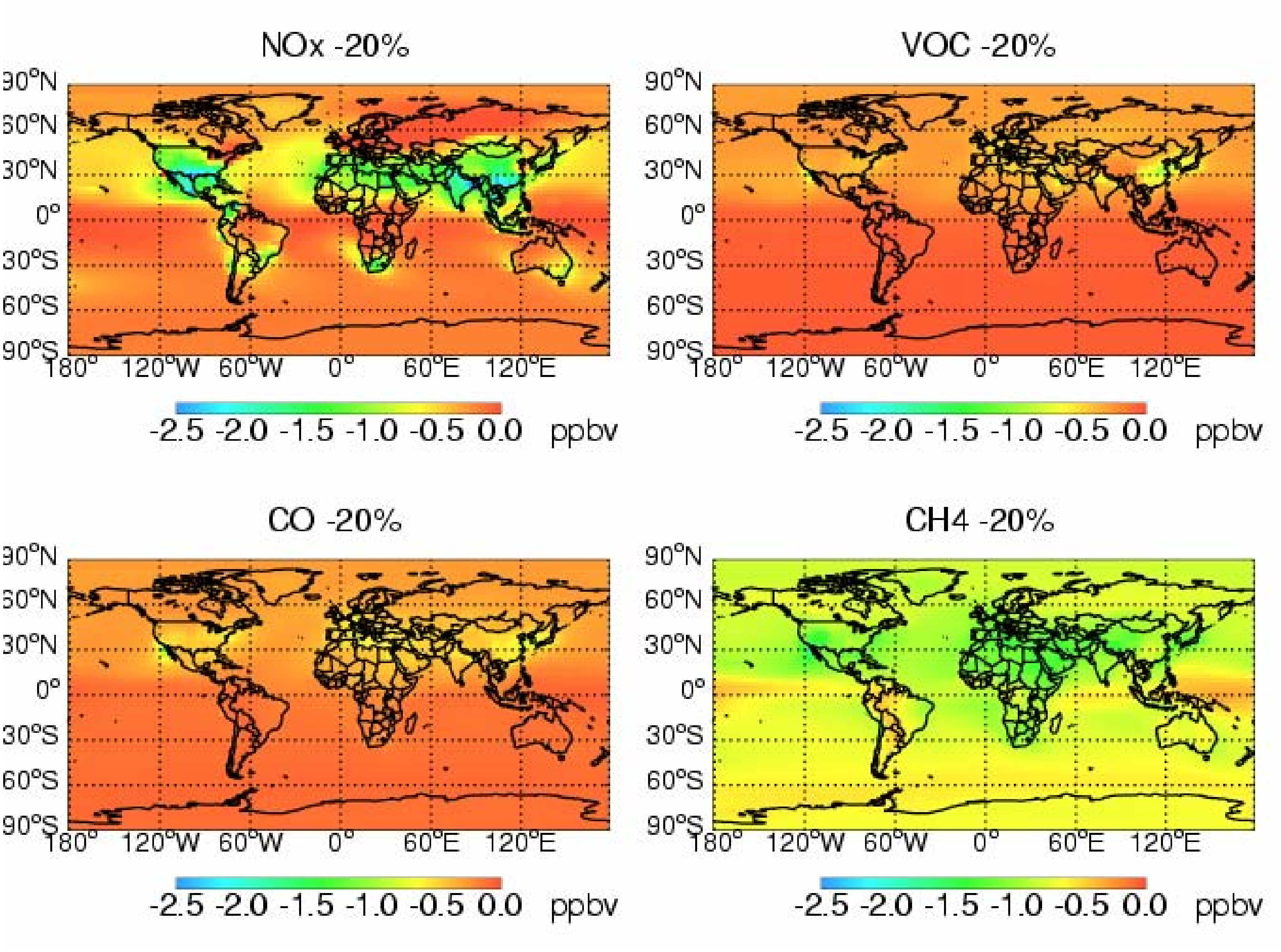
Ozone air quality and climate effects of ozone precursors

Experimental design

- Use MOZART-2 1990 base run.
- Reduce anthropogenic emissions of ozone precursors by 20%.
- Report changes in surface ozone and net radiative forcing, using the AM2 standalone radiation model.



Surface ozone changes



Annual average 8hr daily maximum ozone, at steady state.

Ozone air quality and climate effects of ozone precursors

Tropospheric O_3 burden (Tg O_3)

Global population-weighted ann.
8hr. O_3 conc. (ppbv)

Δ Radiative Forcing (W m^{-2}) - CH_4
- O_3
- Net

ΔRF / ΔO_3 (W m^{-2} ppb^{-1})