Satellites and Health Assessments: Best Practices and Future Opportunities

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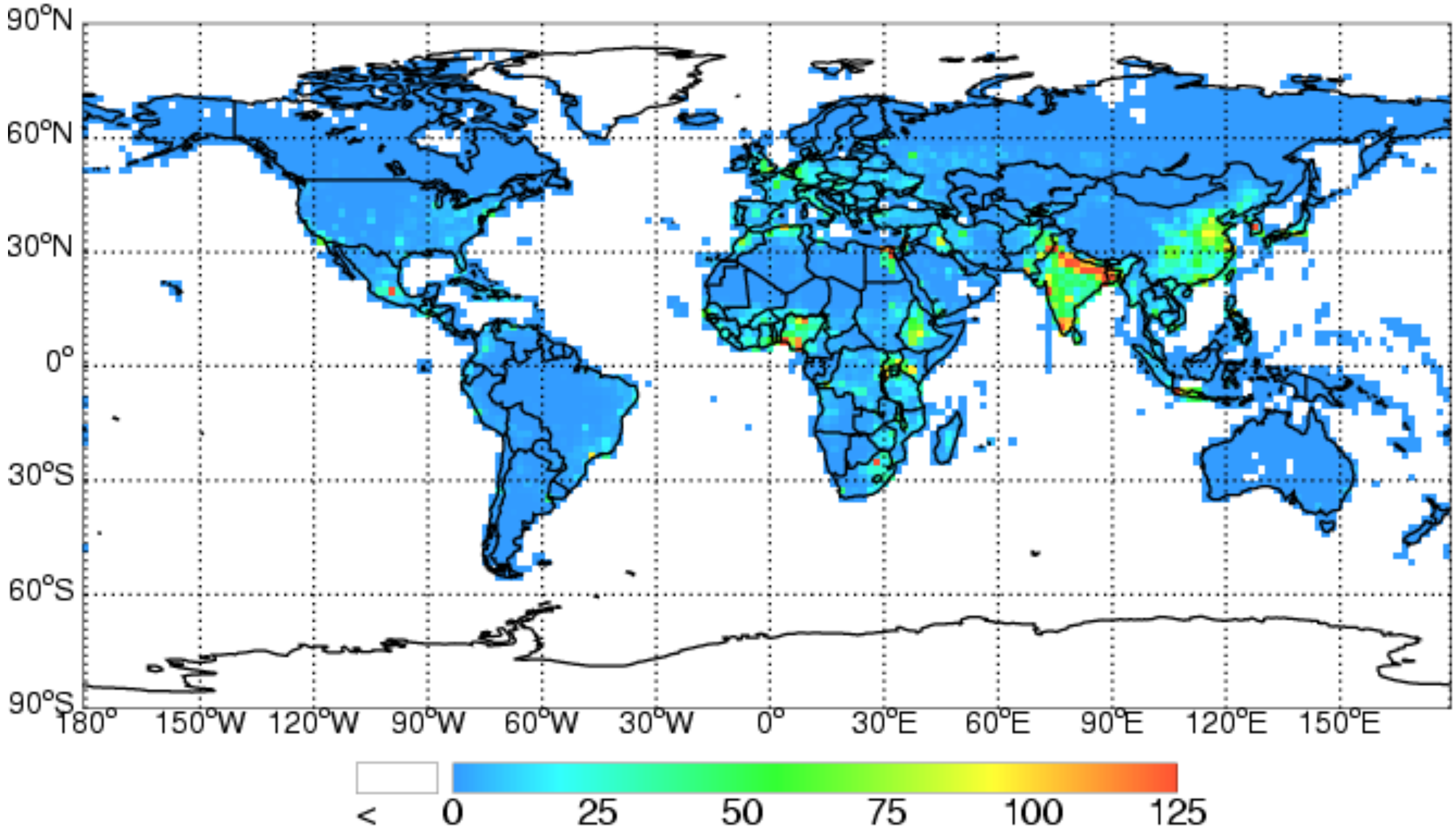
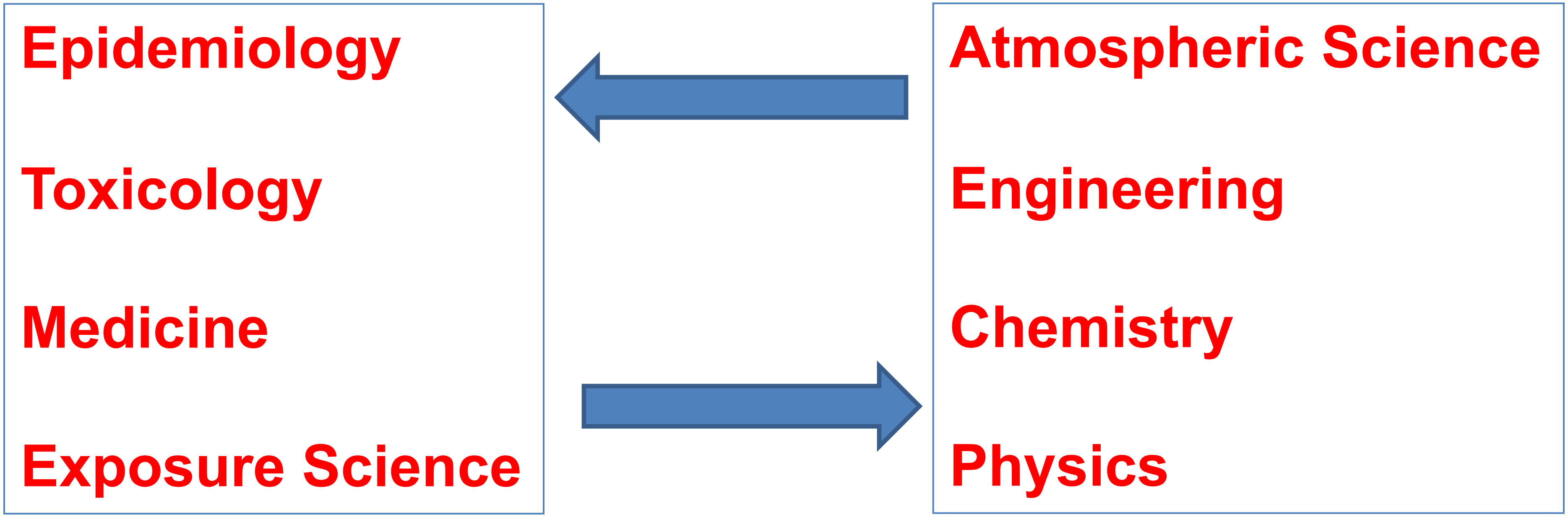
Training Goal:

Understand the basics of air pollution health impact assessment, so you can do it yourself

-20% Global Anthrop. Methane Emissions: 30,200 avoided premature deaths in 2030 due to reduced ozone



West et al., *PNAS*, 2006



Environmental Science & Technology
Feature
pubs.acs.org/est

"What We Breathe Impacts Our Health: Improving Understanding of the Link between Air Pollution and Health"

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How do we know that air pollution affects health?

Toxicology, Medicine, and Epidemiology

Epidemiology – Relationships between air pollution and health

- Find statistical relationships between air pollution and health due to variations in
  - Space
  - Time
- Need to control for variables
  - that co-vary with air pollution (e.g., temperature)
  - other socioeconomic determinants of health effect (e.g., smoking, age, income)

Air pollution epidemiology

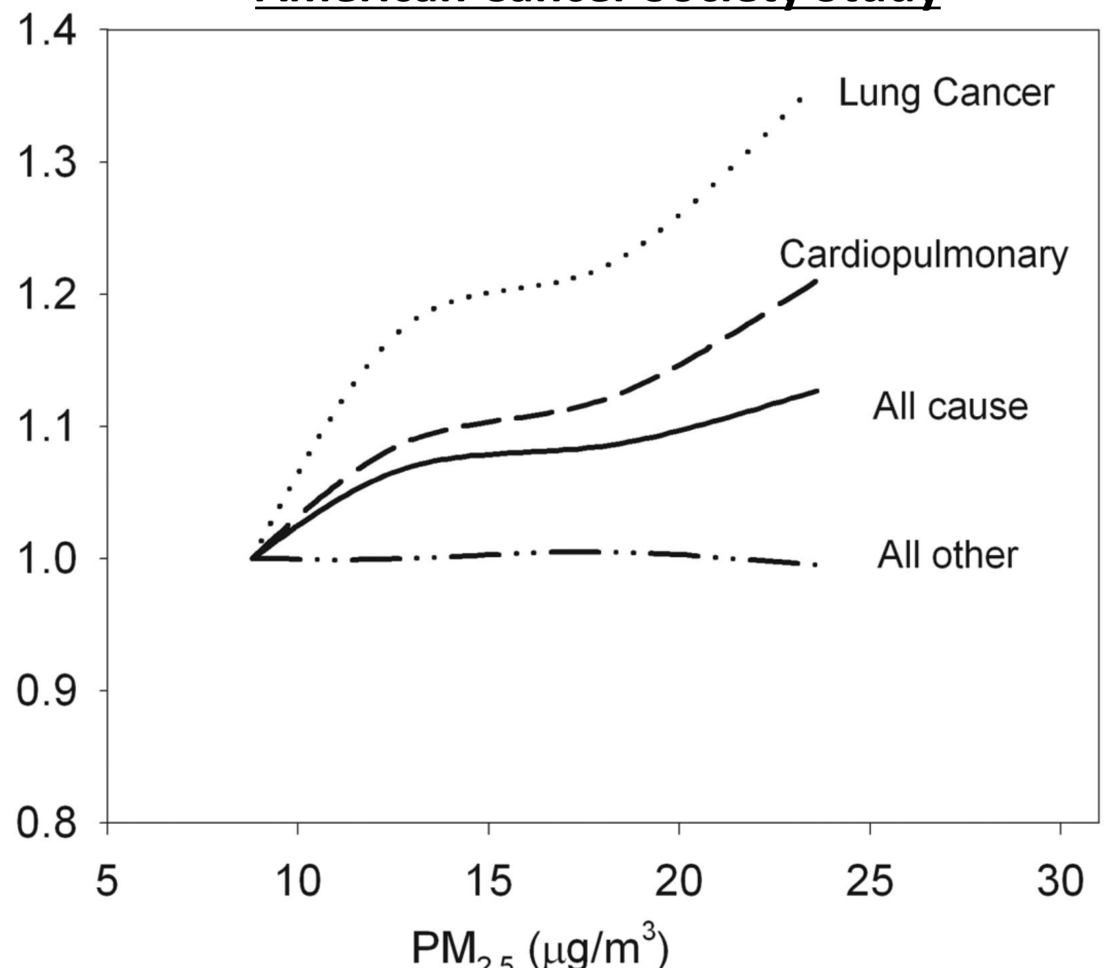
Relative Risk (RR) = ratio of probability of an event occurring in an exposed group vs. in an unexposed group

American Cancer Society Study

RR>1
Risk increase

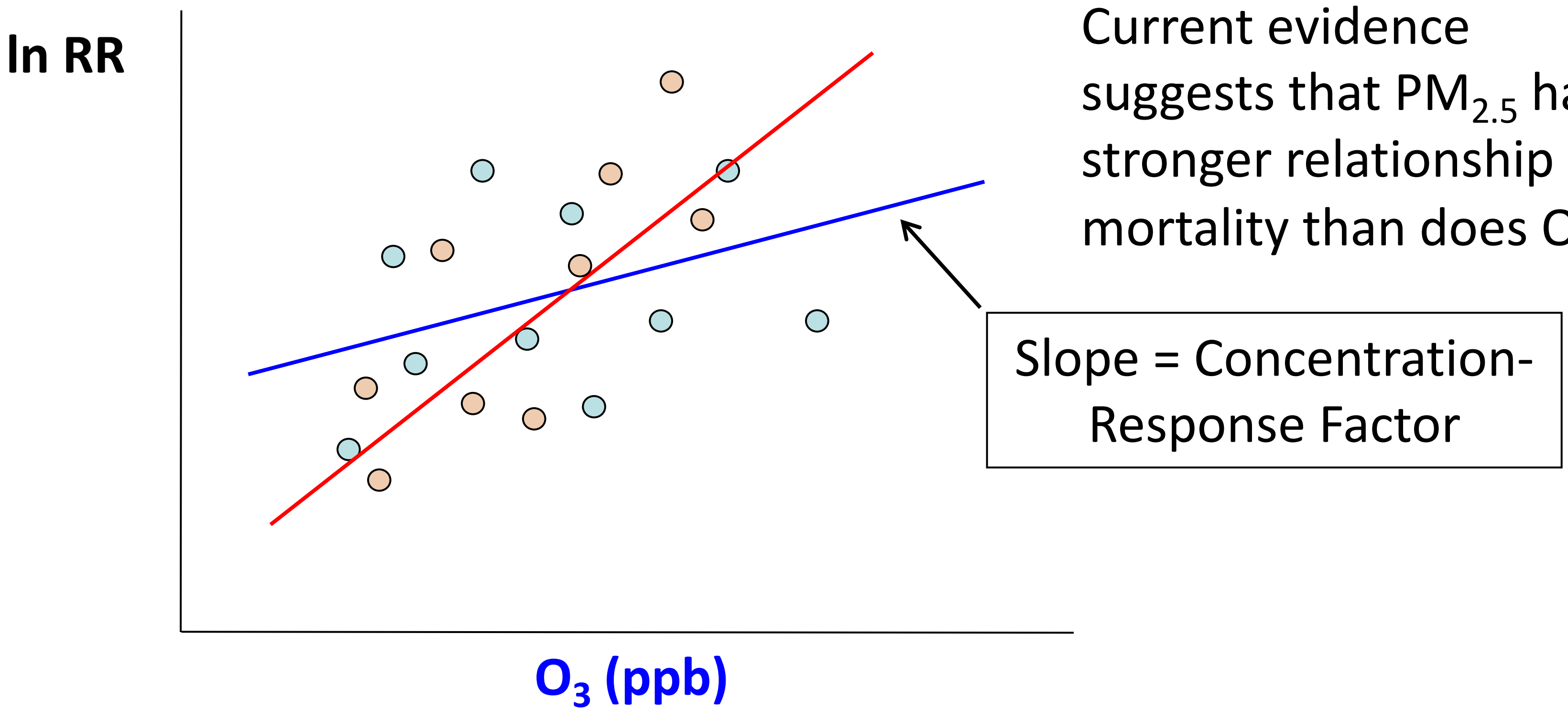
RR=1
No effect

RR<1
Risk decrease



Pope and Dockery, 2006

Air pollution mortality



Current evidence suggests that $PM_{2.5}$ has a stronger relationship with mortality than does O_3

Epidemiological Studies

Advantages

1. Works well with individual, defined, measureable pollutants (i.e. ozone)
2. Provides information for risk assessment, policy, regulations
3. Determines potential health effects caused by real-life exposures
4. Important for policy and regulations

Limitations

1. Difficult to establish cause-and-effect relationships with air pollution mixtures (i.e diesel exhaust)
2. Does not provide information on underlying mechanisms
3. Often not able to control for potential co-exposures
4. $$$$$$

Respiratory Disease Associated with Community Air Pollution and a Steel Mill, Utah Valley

C. ARDEN POPE III, PHD

Abstract: This study assessed the association between hospital admissions and fine particulate pollution (PM_{10}) in Utah Valley during the period April 1985–February 1988. This time period included the closure and reopening of the local steel mill, the primary source of PM_{10}. An association between elevated PM_{10} levels and hospital admissions for pneumonia, pleurisy, bronchitis, and asthma was observed. During months when 24-hour PM_{10} levels exceeded 150 $\mu g/m^3$, average admissions for children nearly tripled; in adults, the increase in admissions was 44 per cent. During months with mean PM_{10} levels greater than or equal to 50 $\mu g/m^3$ average admissions for children and adults increased by 89 and 47 per cent, respectively. During the winter months when the steel mill was open, PM_{10} levels were nearly double the levels experienced during the winter months when the mill was closed. This occurred even though relatively stagnant air was experienced during the winter the mill was closed. Children's admissions were two to three times higher during the winters when the mill was open compared to when it was closed. Regression analysis also revealed that PM_{10} levels were strongly correlated with hospital admissions. They were more strongly correlated with children's admissions than with adult admissions and were more strongly correlated with admissions for bronchitis and asthma than with admissions for pneumonia and pleurisy. (*Am J Public Health* 1989; 79:623–628.)

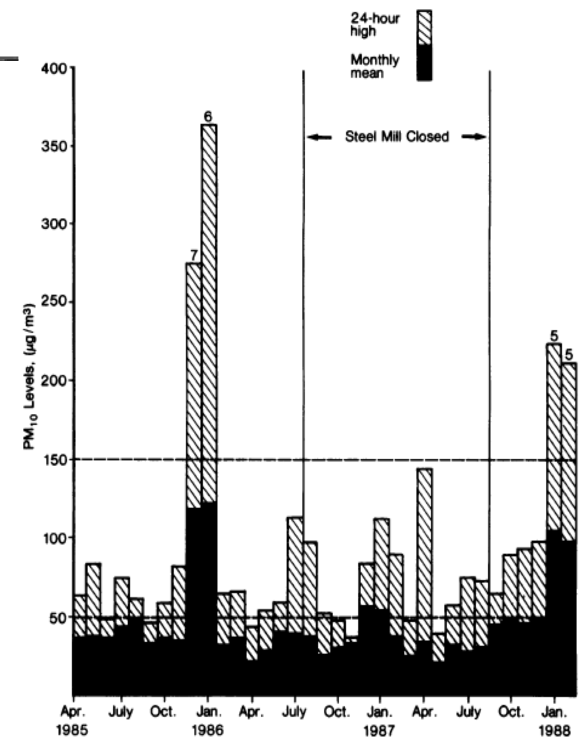


FIGURE 2—Monthly Mean and 24-Hour High PM_{10} (fine particulate pollution) Levels, Utah Valley, April 1985–January 1988

Irish coal ban: Clancy et al. (2002)

Findings Average black smoke concentrations in Dublin declined by 35·6 μg/m³ (70%) after the ban on coal sales. Adjusted non-trauma death rates decreased by 5·7% (95% CI 4–7, p<0·0001), respiratory deaths by 15·5% (12–19, p<0·0001), and cardiovascular deaths by 10·3% (8–13, p<0·0001). Respiratory and cardiovascular standardised death rates fell coincident with the ban on coal sales. About 116 fewer respiratory deaths and 243 fewer cardiovascular deaths were seen per year in Dublin after the ban.

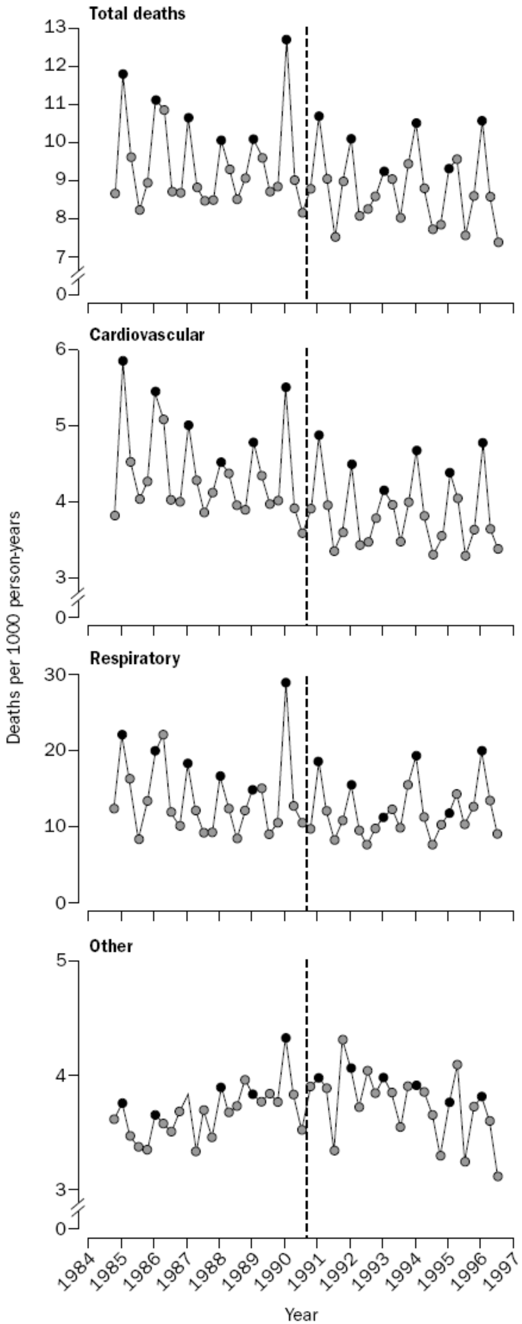


Figure 2: **Seasonal mean directly standardised death rates in Dublin, September 1984–96**
Vertical line shows date sale of coal was banned in Dublin County Borough. Black circles represent winter data.

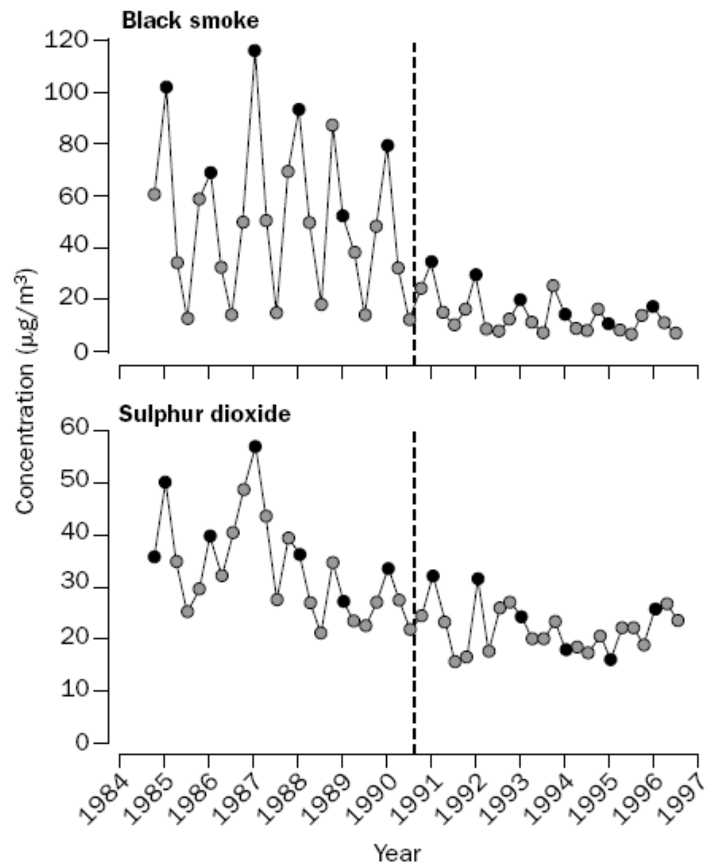
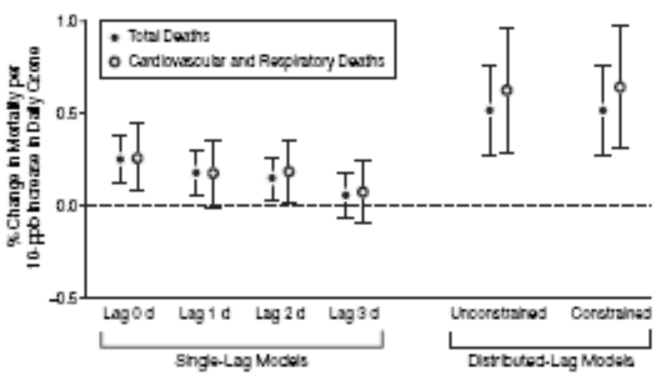


Figure 1: **Seasonal mean black smoke (upper) and sulphur dioxide (lower) concentrations, September 1984–96**
Vertical line shows date sale of coal was banned in Dublin County Borough. Black circles represent winter data.

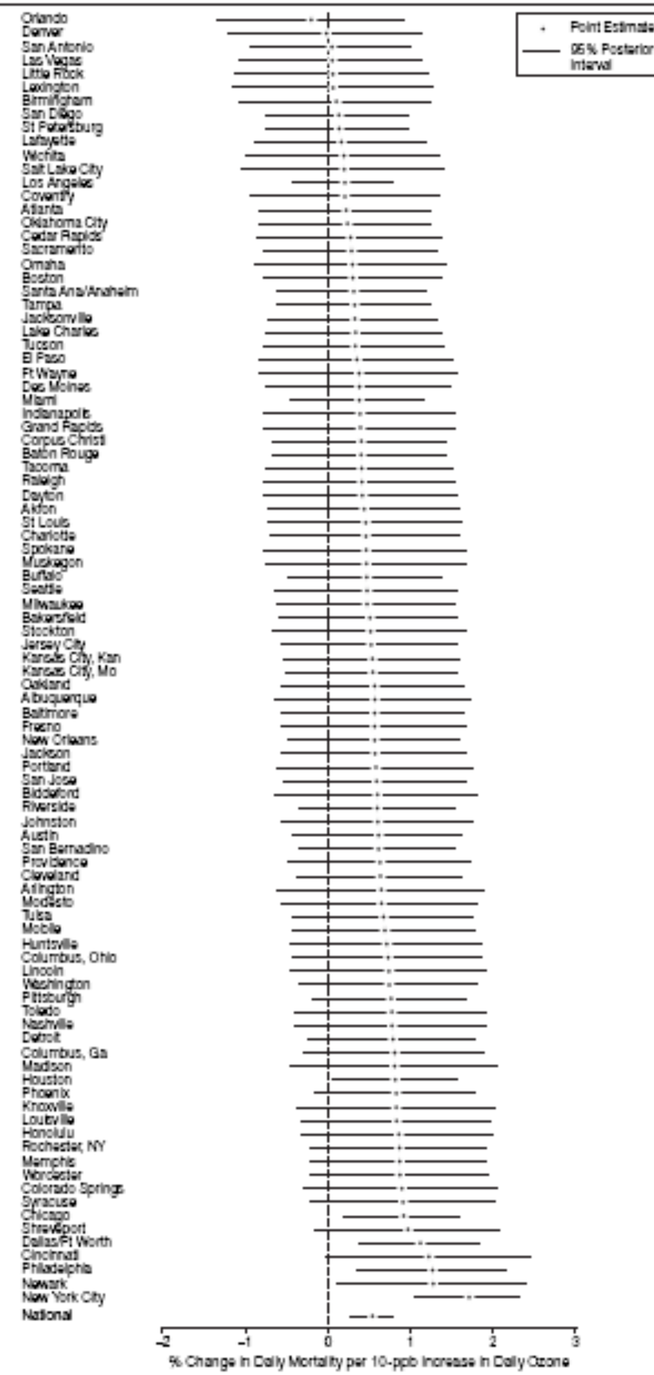
Bell et al. (2004) “Ozone and short-term mortality in 95 urban communities, 1987-2000”

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.

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



Harvard Six-Cities Study (Dockery et al., 1993):

First long-term cohort study of chronic mortality.

~8000 adults followed over many years.

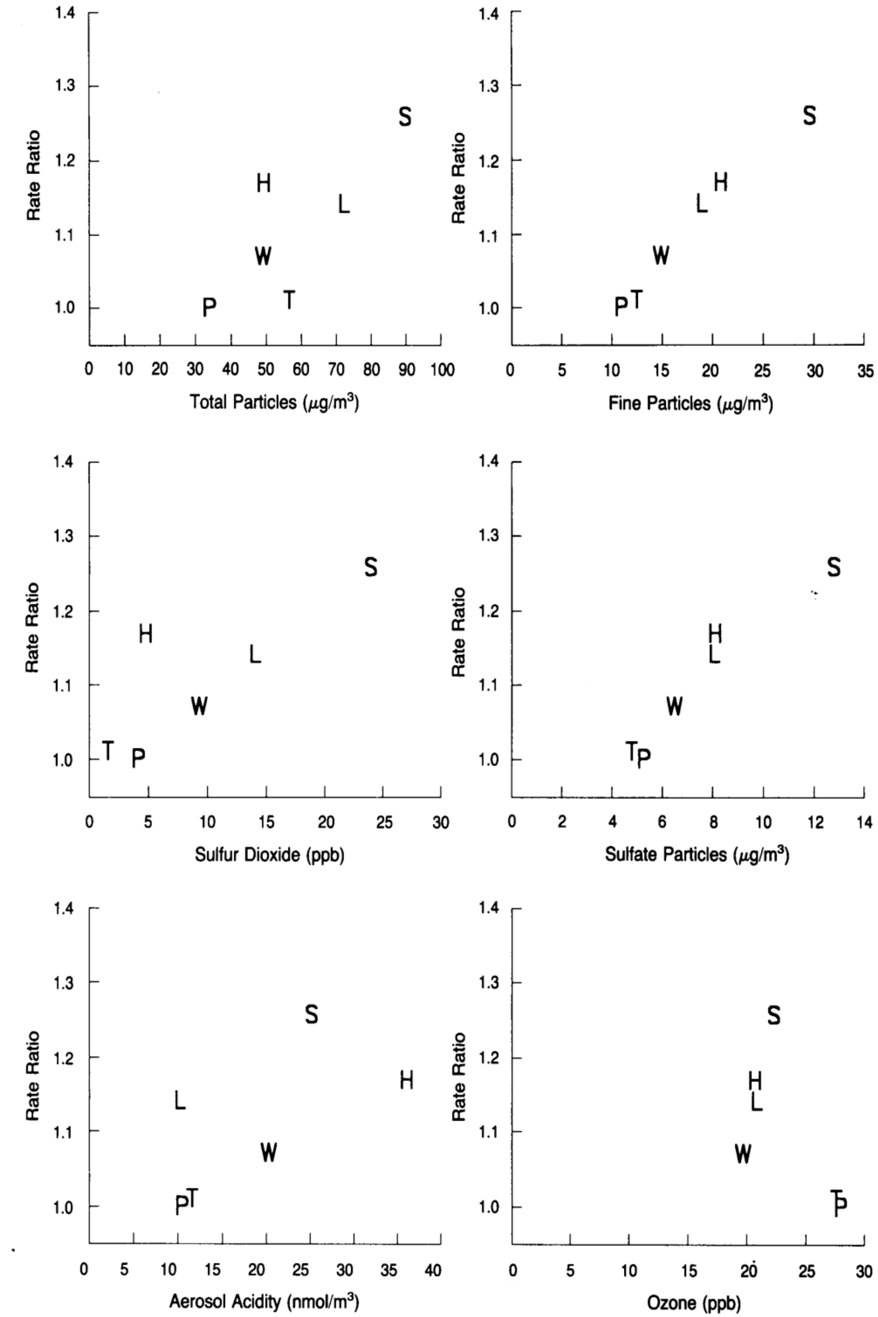


Figure 3. Estimated Adjusted Mortality-Rate Ratios and Pollution Levels in the Six Cities.
Mean values are shown for the measures of air pollution. P denotes Portage, Wisconsin; T Topeka, Kansas; W Watertown, Massachusetts; L St. Louis; H Harriman, Tennessee; and S Steubenville, Ohio.

New York Times

MONDAY, JULY 19, 1993

STUDIES SAY SOOT KILLS UP TO 60,000 IN U.S. EACH YEAR

CALL TO REDIRECT EFFORTS

Little Is Spent on Particles That Harm Mostly Young, Elderly and Those With Asthma

By PHILIP J. HILTS
Special to The New York Times

WASHINGTON, July 18 — Several studies have concluded that tens of thousands of deaths are being caused in the United States each year by a form of air pollution that for the most part falls within current legal limits: tiny particles of soot that are inhaled.

Rough calculations emerging from studies at the Environmental Protection Agency and the Harvard School of Public Health suggest that 50,000 to 60,000 deaths a year are caused by the particle pollution, a far larger number than any other form of pollution and one that rivals the death toll from some cancers.

The deaths occur mostly among children with respiratory problems, people of all ages with asthma and the elderly with illnesses like bronchitis, emphysema and pneumonia.

Harvard 6 Cities Reanalyzed (Laden et al., 2006)

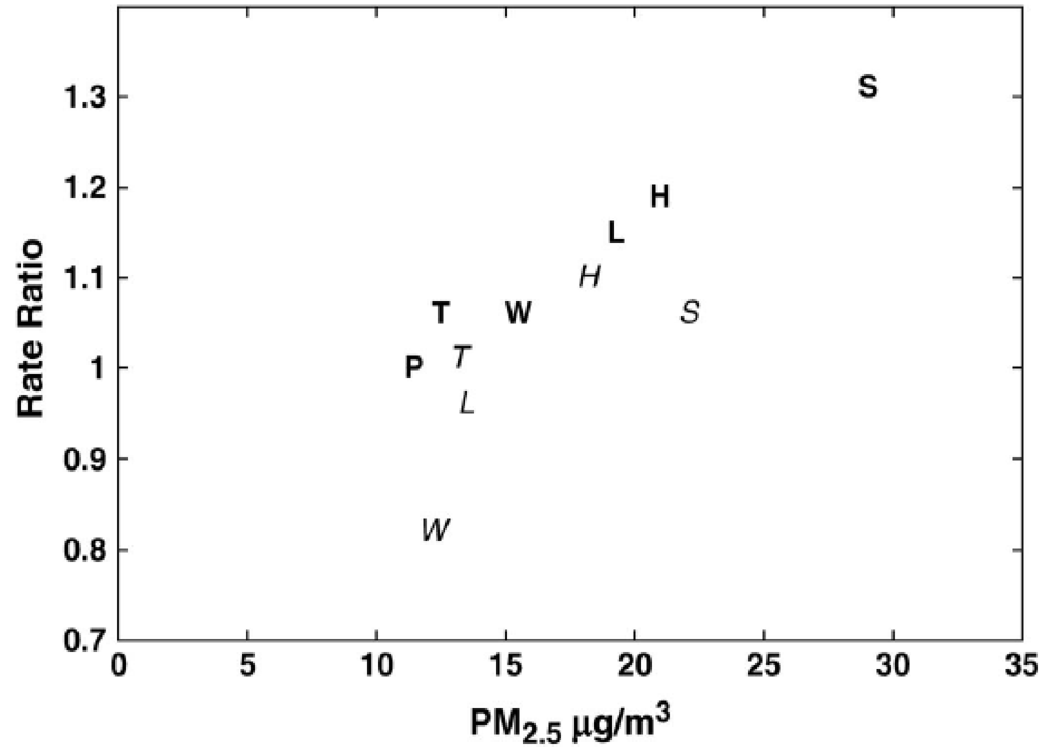


Figure 2. Estimated adjusted rate ratios for total mortality and $PM_{2.5}$ levels in the Six Cities Study by period. P denotes Portage, WI (reference for both periods); T = Topeka, KS; W = Watertown, MA; L = St. Louis, MO; H = Harriman, TN; S = Steubenville, OH. A term for Period 1 (1 if Period 2, 0 if Period 1) was included in the model. *Bold letters* represent Period 1 (1974–1989) and *italicized letters* represent Period 2 (1990–1998). In Period 1, $PM_{2.5}$ ($\mu g/m^3$) is defined as the mean concentration during 1980–1985, the years where there are monitoring data for all cities (18). In Period 2, $PM_{2.5}$ is defined as the mean concentrations of the estimated $PM_{2.5}$ in 1990–1998.

Epidemiology

vs.

Risk Assessment or Health Impact Assessment

Health impact function

$$\Delta Mort = \overbrace{(1-e^{-\beta\Delta X})}^{\text{Attributable fraction}} \times \overbrace{Pop \times y_0}^{\text{Baseline mortality}}$$

Annual deaths

Concentration-response factor

Change in concentration

Population exposed

Baseline mortality rate

y_0 is fraction of population that has health effect in a year.

Pop is not necessarily the total population.

If $\beta\Delta X$ is small, then $1-e^{-\beta\Delta X} \approx \beta\Delta X$

What would be the health benefit if all US adults had 1 μgm^{-3} less of $PM_{2.5}$?

Krewski et al. (2009) – 3% increase in risk of all-cause mortality per 10 μgm^{-3} increase in $PM_{2.5}$.

$RR = .03 / 10 = 0.003$ per μgm^{-3}

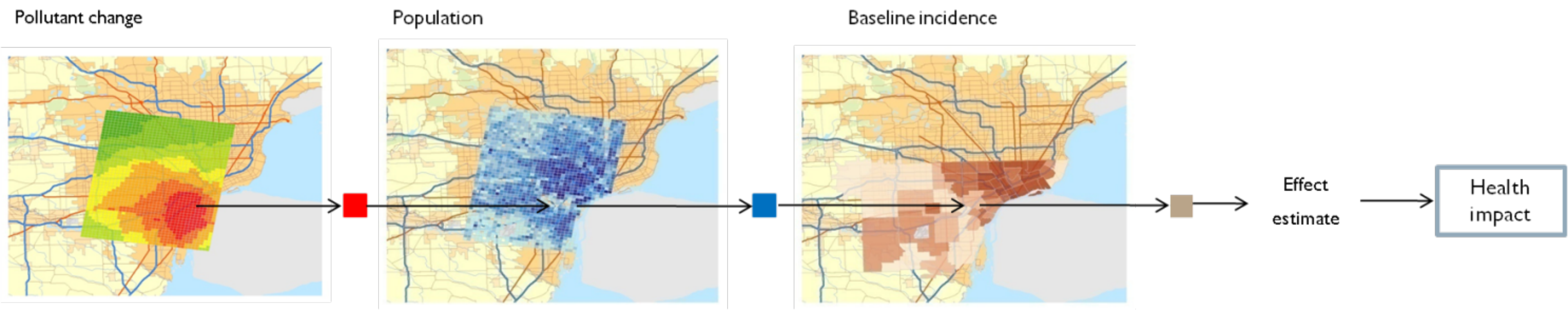
$\beta = RR / (1+RR) = .003 / (1.003) = 0.00299$ per μgm^{-3}

$\Delta X = 1\ \mu gm^{-3}$

Pop = 195 million (adult population, > 30 yrs old)

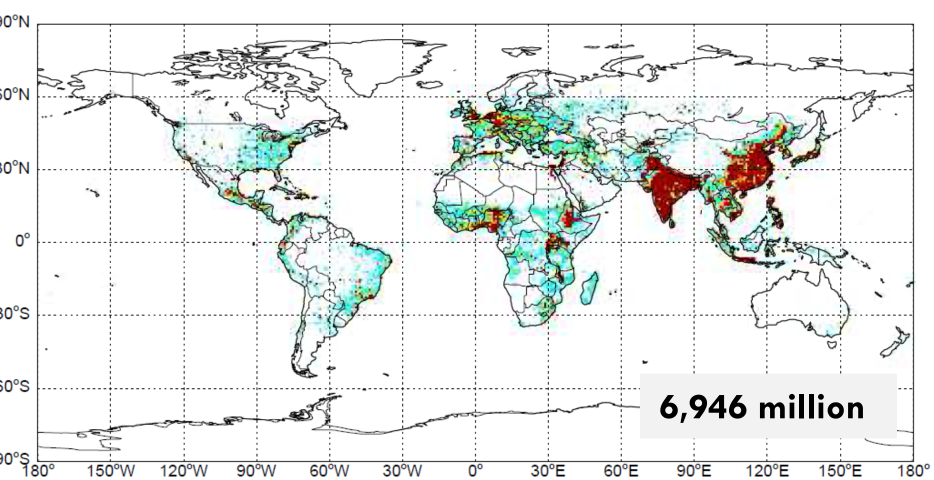
$y_0 = 0.012$ *(per year, for adults from all causes of death)*

$$\Delta Mort = (0.00299\ (\mu gm^{-3})^{-1})\ (1\ \mu gm^{-3})\ (195 \times 10^6)\ (0.012\ yr^{-1})$$
$$= 7000 \text{ deaths reduced per year}$$

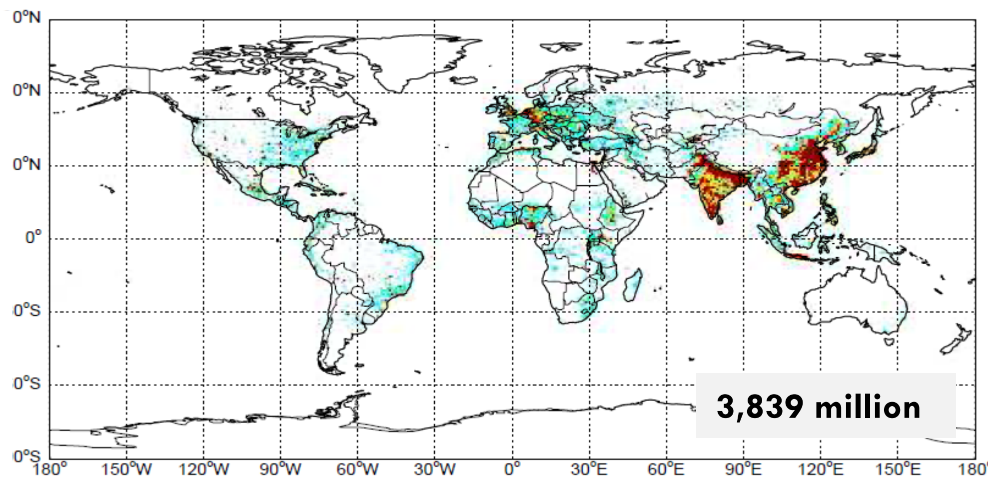

Pollutant change
Population
Baseline incidence
Effect
estimate
Health
impact

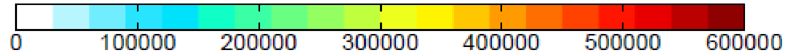
Population

Total Population, **persons**
(Landscan 2011 at 30”x30”
gridded to 0.67°x0.5°)



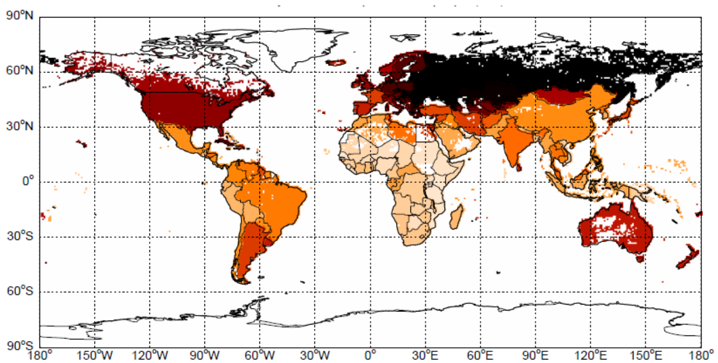
Population 25+, **persons**
(Landscan 2011 at 30”x30”
gridded to 0.67°x0.5°)



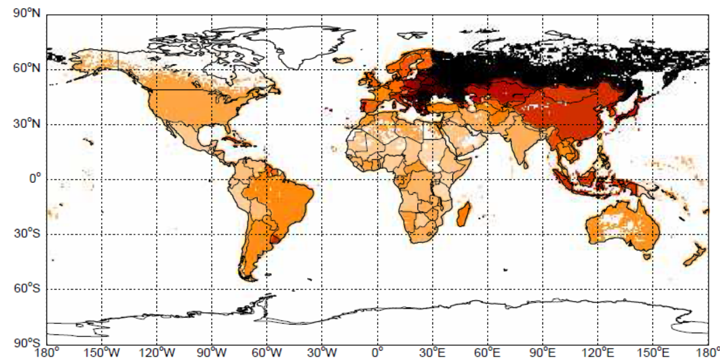


Baseline Mortality Rates

IHD



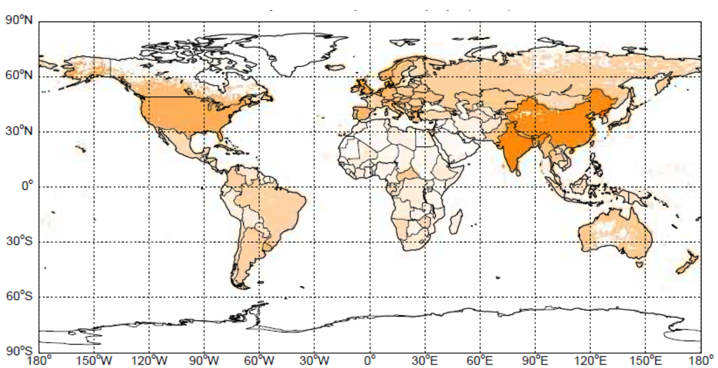
Stroke



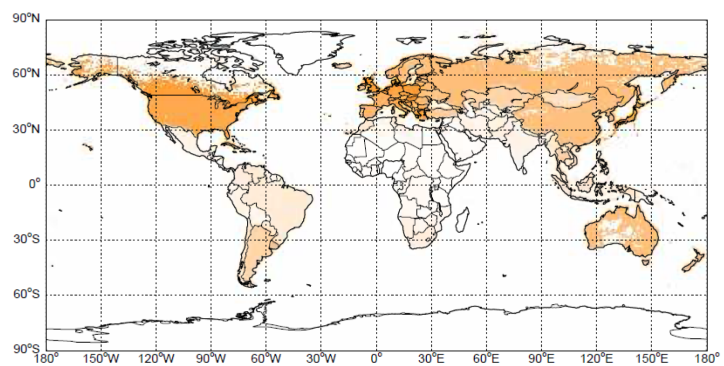
Baseline Mortality Rates, deaths per year per 100,000

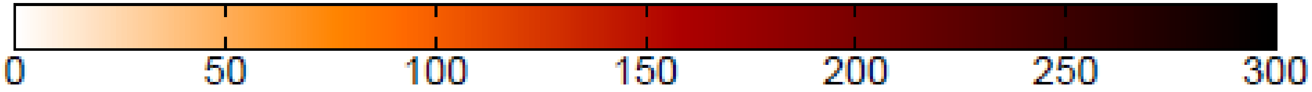
(GBD 2010, country level, AllAges > gridded to 0.67°x0.5°)

COPD



LC

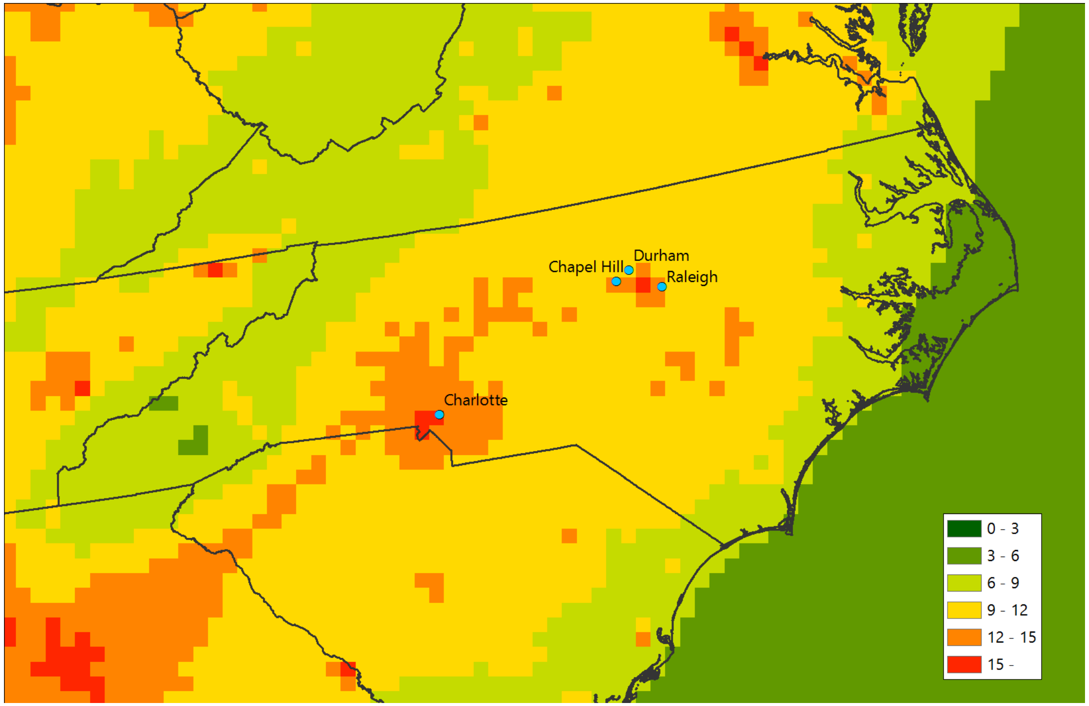


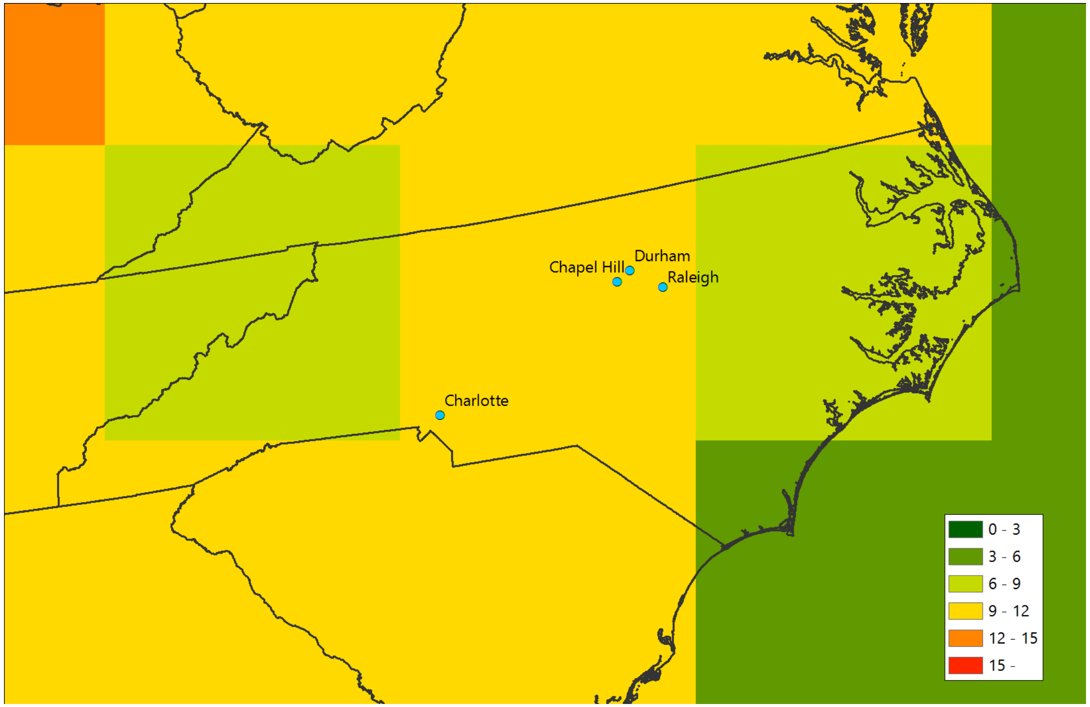


What are sources of pollutant concentrations (ΔX)?

- Observations
- Satellites
- Models
- Data Fusion

12-km CMAQ





Global model 2.8° resolution

Best Practice

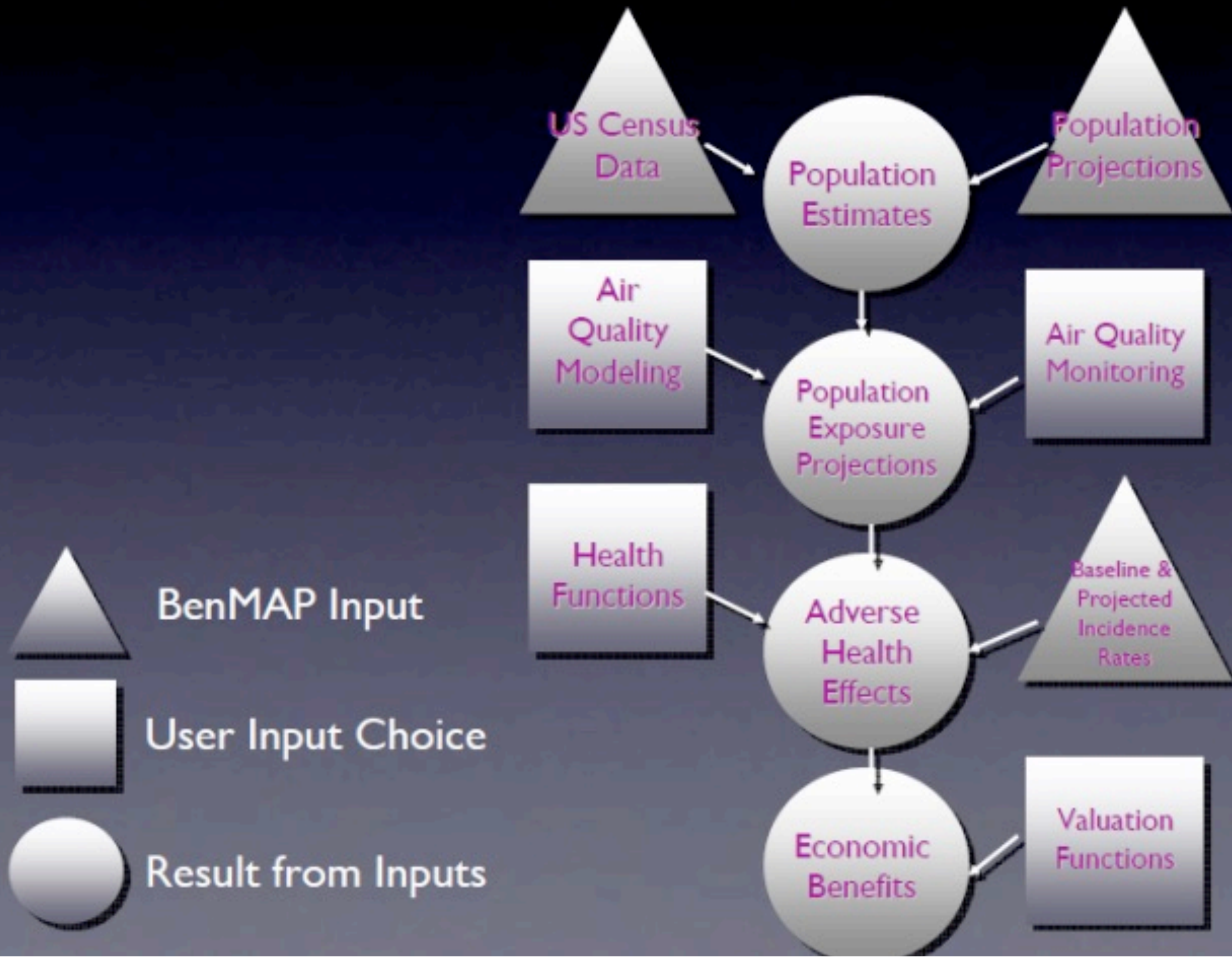
- Apply concentration-health functions in a way that agrees with the epidemiological study:
  - Air pollutant metric, averaging time.
  - Neighborhood scale concentrations
  - Same population (age, etc.)

BenMAP

Environmental Benefits Mapping and Analysis Program

- Contains population estimates and a library of baseline incidence rate data
- Built on a GIS
- User selects concentration-response functions or inputs their own

The Data BenMAP Uses to Perform a Benefits Analysis



Regulatory Impact Analysis for the Repeal of the Clean Power Plan, and the Emission Guidelines for Greenhouse Gas Emissions from Existing Electric Utility Generating Units

EPA-452/R-19-003
June 2019

Table 4-5 Estimated Avoided $PM_{2.5}$ and Ozone-Related Premature Deaths and Illnesses in 2025, 2030 & 2035 (95% Confidence Interval) [a]

		2025	2030	2035
Avoided premature death among adults				
$PM_{2.5}$	Krewski *et al.* (2009)	33 (22 to 43)	44 (30 to 58)	48 (32 to 63)
$PM_{2.5}$	Lepeule *et al.* (2012)	74 (37 to 110)	99 (49 to 150)	110 (54 to 160)
Ozone	Smith *et al.* (2009)	6 (3 to 9)	6 (3 to 9)	7 (4 to 11)
Ozone	Jerrett et al. (2009)	23 (8 to 38)	23 (8 to 38)	28 (9 to 46)
$PM_{2.5}$- related non-fatal heart attacks among adults				
	Peters et al. (2001)	37 (9 to 64)	48 (12 to 84)	50 (12 to 88)
	Pooled estimate	4 (2 to 11)	5 (2 to 14)	5 (2 to 14)
All other morbidity effects				
	Hospital admissions—cardiovascular ($PM_{2.5}$)	9 (4 to 16)	12 (5 to 22)	13 (5 to 23)
	Hospital admissions—respiratory ($PM_{2.5}$ & O_3)	19 ((6) to 40)	23 ((7) to 48)	25 ((8) to 53)
	ED visits for asthma ($PM_{2.5}$ & O_3)	54 ((3) to 150)	55 ((5) to 150)	65 ((5) to 180)
	Exacerbated asthma ($PM_{2.5}$ & O_3)	14,000 ((11,000) to 35,000)	14,000 ((11,000) to 34,000)	17,000 ((13,000) to 41,000)
	Minor restricted-activity days ($PM_{2.5}$ & O_3)	48,000 (28,000 to 67,000)	52,000 (32,000 to 71,000)	58,000 (36,000 to 80,000)
	Acute bronchitis ($PM_{2.5}$)	42 ((10) to 94)	56 ((13) to 130)	60 ((14) to 130)
	Upper resp. symptoms ($PM_{2.5}$)	770 (140 to 1,400)	1,000 (190 to 1,900)	1,100 (200 to 2,000)
	Lower resp. symptoms ($PM_{2.5}$)	540 (200 to 870)	720 (270 to 1,200)	770 (290 to 1,200)
	Lost work days ($PM_{2.5}$)	3,700 (3,100 to 4,200)	4,600 (3,900 to 5,400)	5,000 (4,300 to 5,800)
	School absence days (O_3)	8,400 (3,000 to 19,000)	8,200 (2,900 to 18,000)	9,700 (3,400 to 22,000)

[a] Values rounded to two significant figures.

Risk Analysis
AN INTERNATIONAL JOURNAL
An Official Publication of the Society for Risk Analysis

Survey of Ambient Air Pollution Health Risk Assessment Tools

Susan C. Anenberg, Anna Belova, Jørgen Brandt, Neal Fann, Sue Greco, Sarath Guttikunda, Marie-Eve Heroux, Fintan Hurley, Michal Krzyzanowski, Sylvia Medina, Brian Miller, Kiran Pandey, Joachim Roos, Rita Van Dingenen

Volume36, Issue9, Special Issue: Air Pollution Health Risks
September 2016
Pages 1718-1736

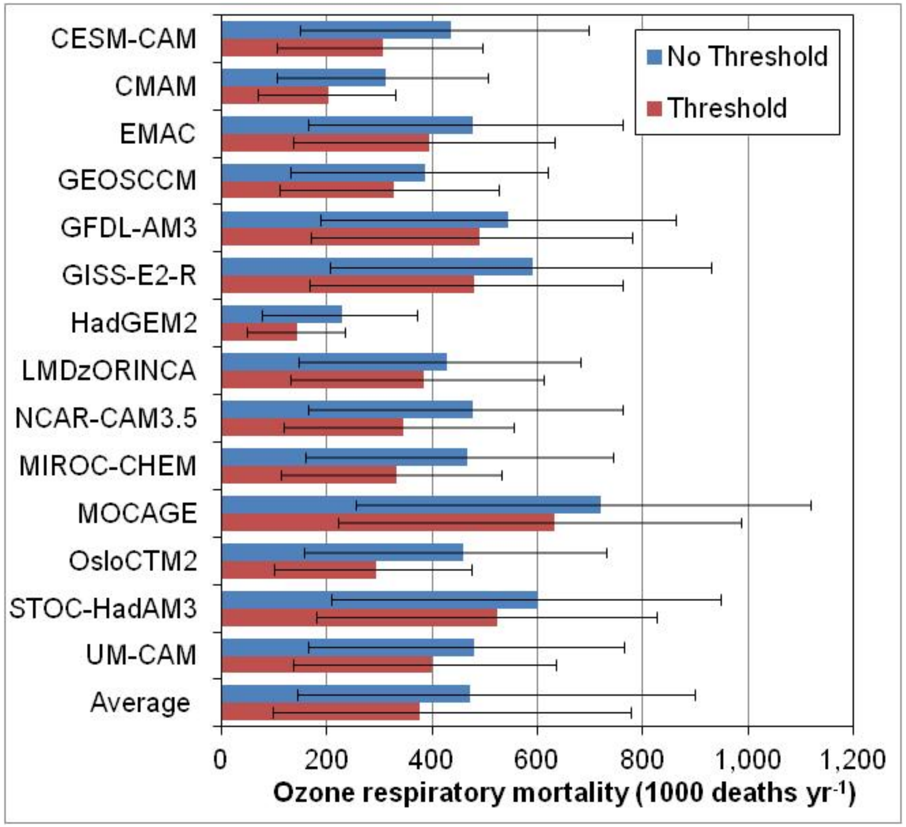
Applications of Air Pollution Risk Assessment

- Total impact of air pollution on health (GBD)
- Changes in air pollution through time
- Effects of a policy

Global mortality burden – ACCMIP ensemble

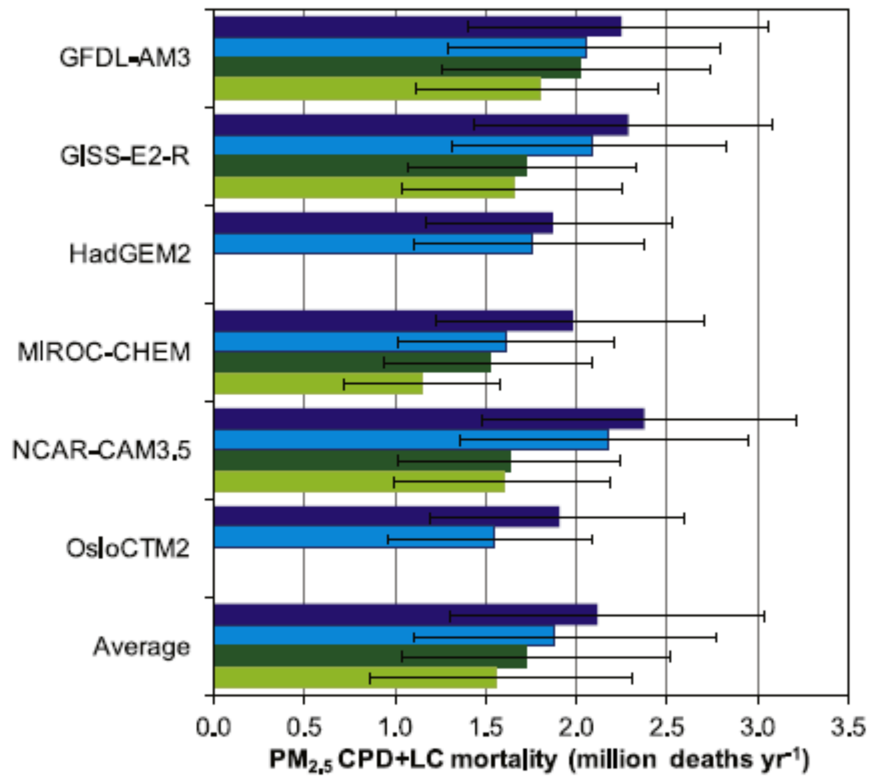
Ozone-related mortality

470,000 (95% CI: 140,000 - 900,000)



$PM_{2.5}$-related mortality(*)

2.1 million (95% CI: 1.3 - 3.0 million)



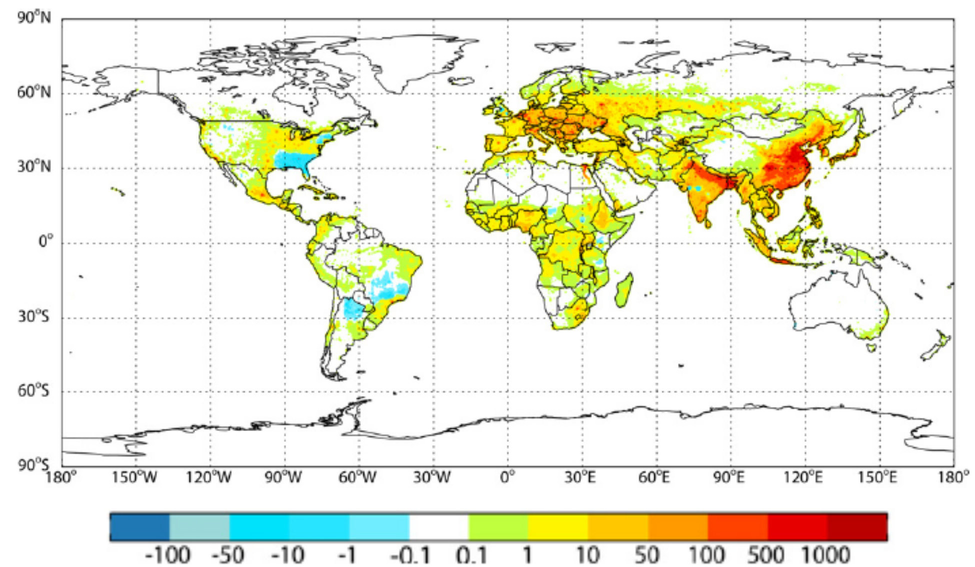
(*) $PM_{2.5}$ calculated as a sum of species (dark blue)
$PM_{2.5}$ as reported by 4 models (dark green)
Light-colored bars - low-concentration threshold (5.8 μg m^{-3})

Global Burden: $PM_{2.5}$-related mortality

Global and regional mortality per year

Regions	Total deaths	Deaths per million people (*)
North America	43,000	152
Europe	154,000	448
Former Soviet Union	128,000	793
Middle East	88,700	371
India	397,000	715
East Asia	1,049,000	1,191
Southeast Asia	158,000	564
South America	16,800	92
Africa	77,500	327
Australia	1,250	78
Global	**2,110,000**	**665**

(*) Exposed population (age 30 and older)



CPD+LC mortality , deaths yr^{-1} (1000 km^2)$^{-1}$,
multi-model mean in each grid cell , 6 models

$PM_{2.5}$ from Satellites

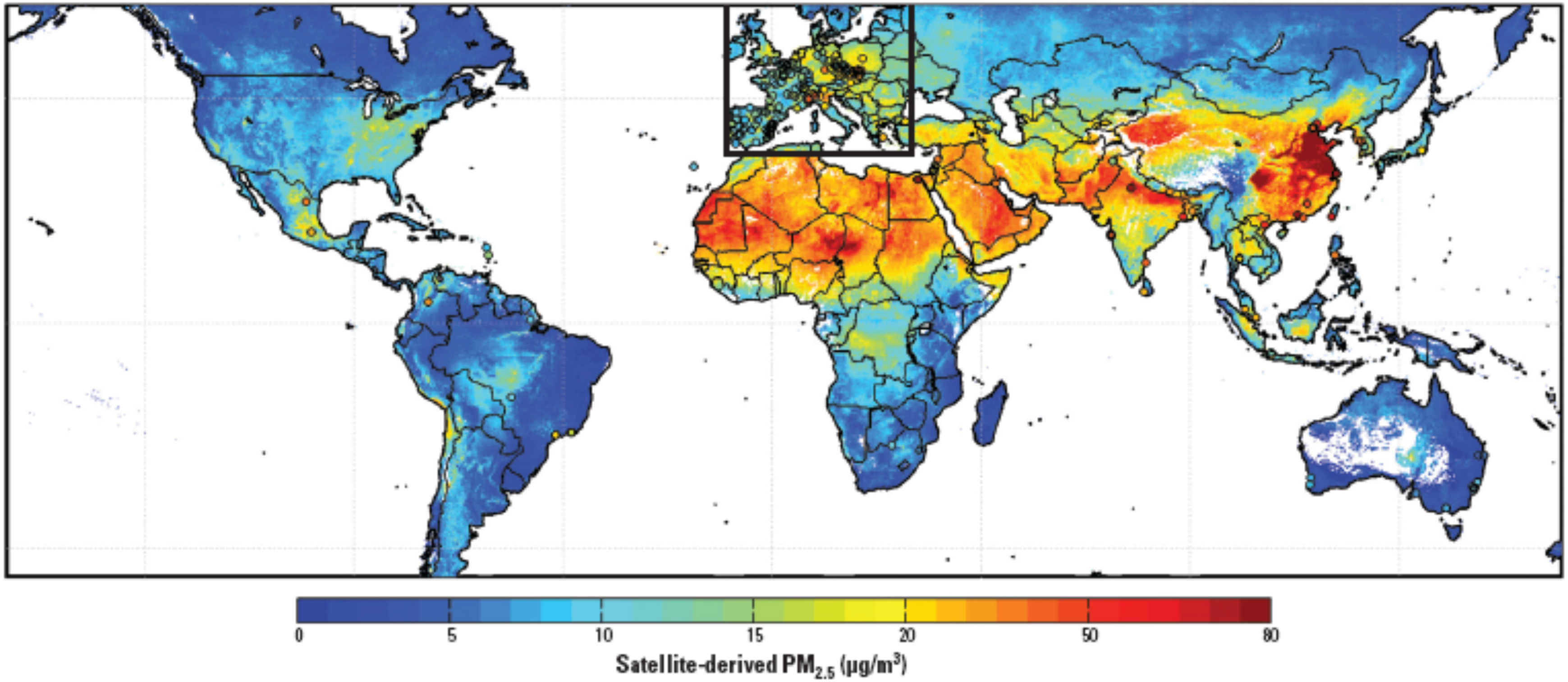


Figure 4. Global satellite-derived $PM_{2.5}$ averaged over 2001–2006. White space indicates water or locations containing < 50 measurements. Circles correspond to values and locations of comparison sites outside Canada and the United States; the black box outlines European sites.

Van Donkelaar et al., 2010

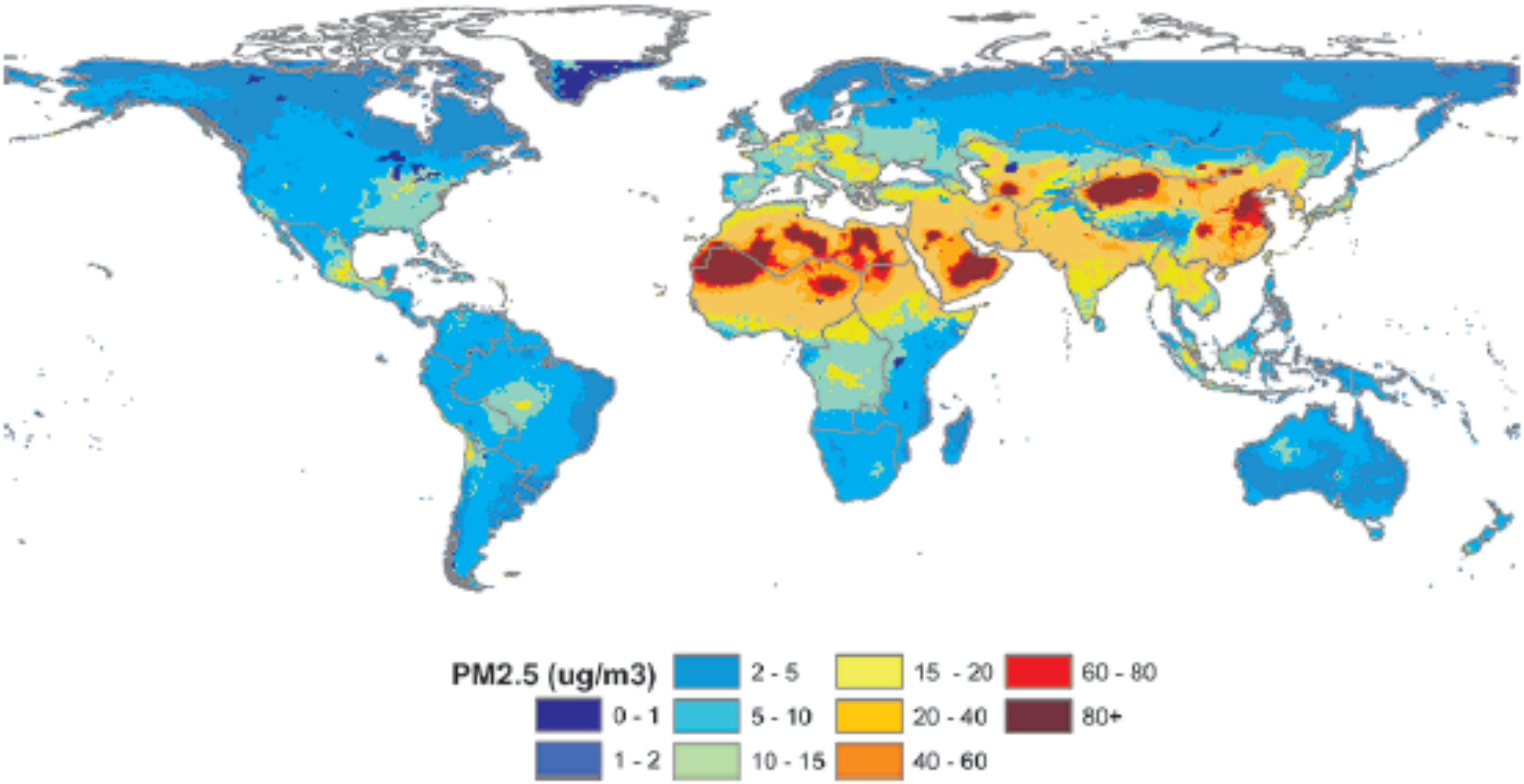


Figure 2. Estimated 2005 annual average $PM_{2.5}$ concentrations ($\mu g/m^3$). The $PM_{2.5}$ estimates are generated from the grid cell average of SAT and TM5 and calibrated with a prediction model incorporating surface measurements.

Brauer et al., 2012

Global burden of disease of air pollution (2017)

Global Deaths per Year

Ambient $PM_{2.5}$ pollution: **2.9 (2.5 – 3.4) million**

Ambient ozone pollution: **0.47 (0.18 – 0.77) million**

1 in 19 deaths globally!

Household air pollution from solid fuels: **1.6 (1.4 – 1.9) million**

1 in 45 deaths globally!

1 High systolic blood pressure
2 Smoking
3 High fasting plasma glucose
4 High body-mass index
5 Short gestation for birthweight
6 Low birthweight for gestation
7 Alcohol use
8 High LDL cholesterol
9 Child wasting
10 Ambient particulate matter
11 Low whole grains
12 High sodium
13 Low fruit
14 Unsafe water source
15 Impaired kidney function
16 Household air pollution

Ambient $PM_{2.5}$ pollution is the 8th leading risk factor for death globally.

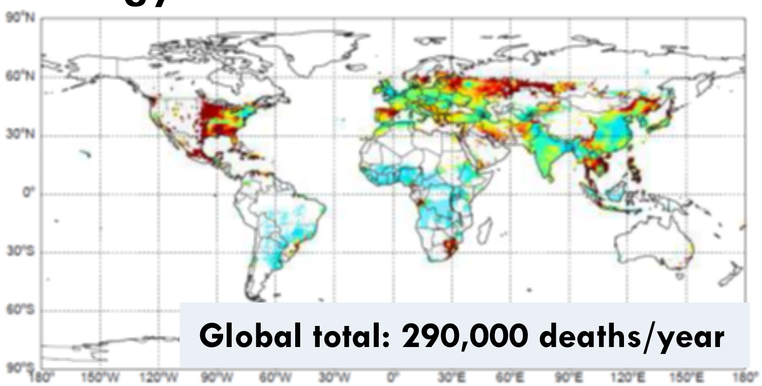
Burnett et al. (PNAS, 2018) estimate 8.9 (7.5-10.3) million deaths from $PM_{2.5}$ in 2015.

GBD 2017 Team, *Lancet*, 2018

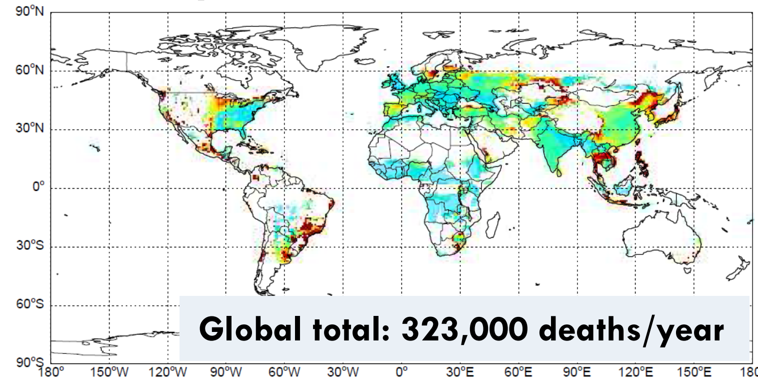
PM$_{2.5}$-related mortality (sectors zeroed-out)

Contributions of each sector to total PM$_{2.5}$ mortality (IHD+Stroke+COPD+LC),
fraction of total burden in each cell

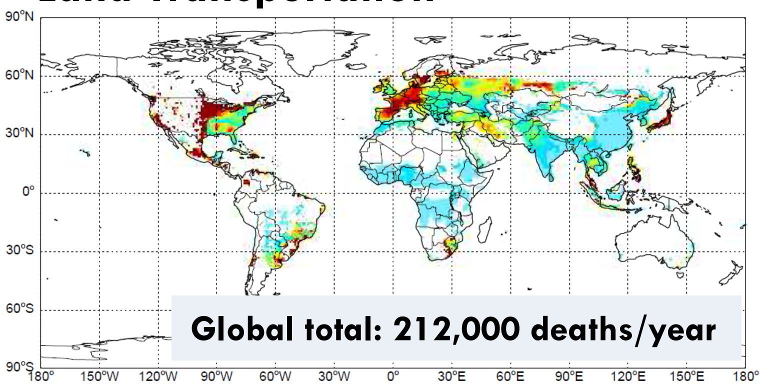
Energy



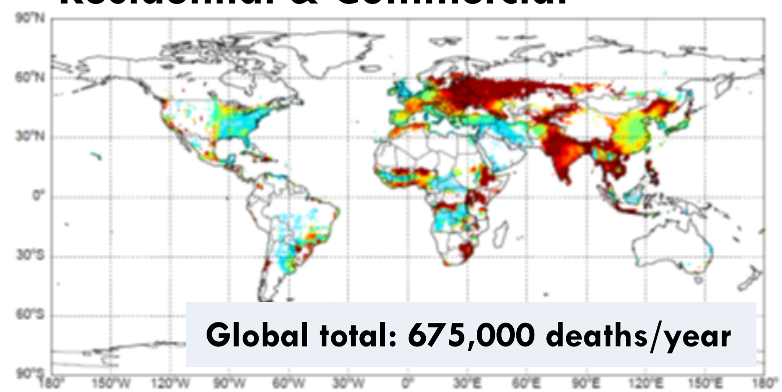
Industry

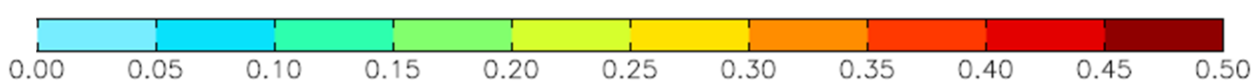


Land Transportation

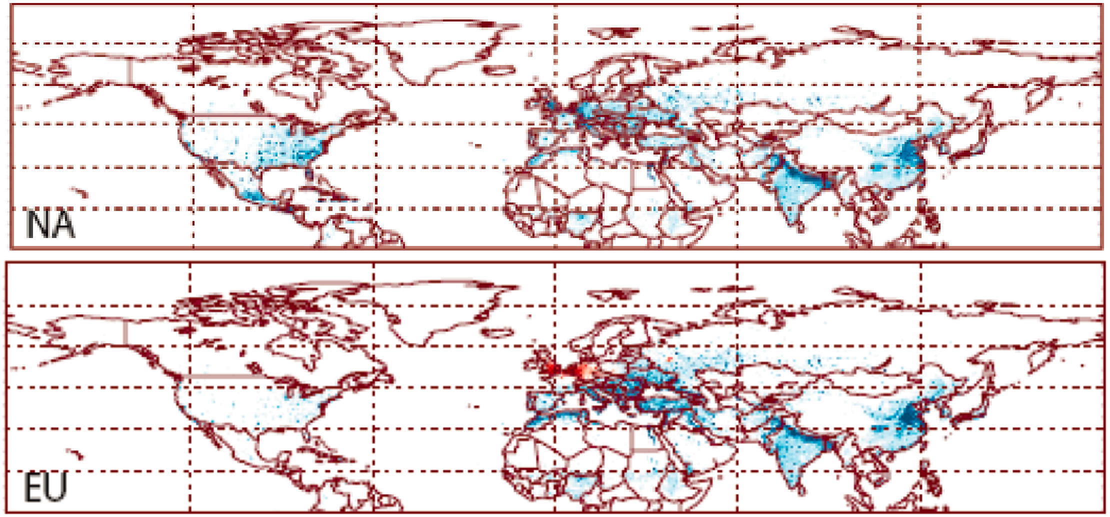


Residential & Commercial





Silva et al. (EHP, 2016)

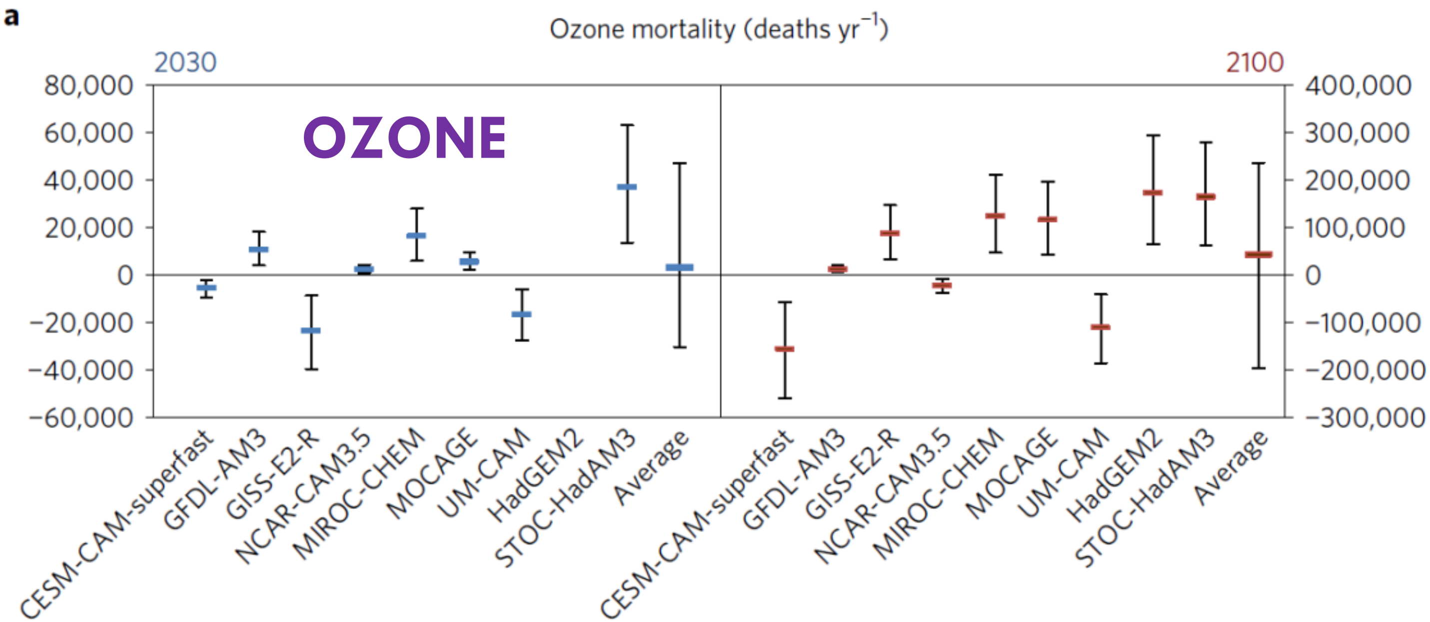


Ozone from N. American and European emissions causes more deaths outside of those regions than within

source region	receptor region				
	NA	EA	SA	EU	NH
NA	**9 (4 – 13)**	**7 (3 – 10)**	**6 (3 – 9)**	**11 (5 – 17)**	**36 (18 – 55)**
	9 (4 – 14)	4 (2 – 6)	5 (3 – 8)	6 (3 – 9)	27 (13 – 41)
EA	**2 (1 – 3)**	**43 (21 – 66)**	**6 (3 – 9)**	**5 (3 – 8)**	**59 (29 – 91)**
	1 (1 – 2)	40 (19 – 61)	5 (2 – 8)	3 (1 – 4)	49 (24 – 76)
SA	**1 (0 – 1)**	**4 (2 – 6)**	**76 (37 – 117)**	**2 (1 – 3)**	**85 (41 – 130)**
	0 (0 – 1)	3 (1 – 4)	66 (32 – 101)	1 (0 – 2)	71 (34 – 108)
EU	**2 (1 – 3)**	**8 (4 – 12)**	**6 (3 – 10)**	**17 (8 – 26)**	**38 (18 – 58)**
	1 (0 – 1)	6 (3 – 8)	6 (3 – 9)	25 (12 – 38)	40 (19 – 61)

Avoided deaths (hundreds) from 20% regional ozone precursor reductions, based on HTAP simulations, Anenberg et al. (EST, 2009)

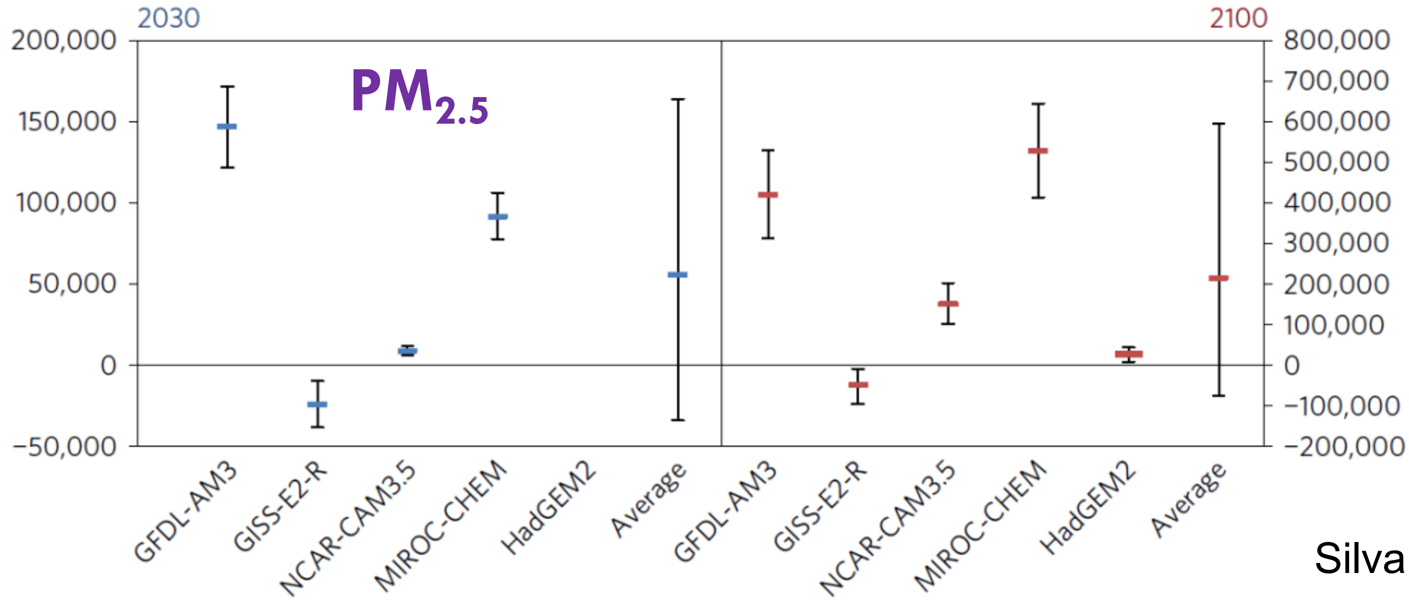
Impact of RCP8.5 Climate Change on Global Air Pollution Mortality: ACCMIP Models



Mean (95% CI)
(deaths yr^{-1})

2030
3,000
(-30,000, 47,000)

2100
44,000
(-195,000, 237,000)



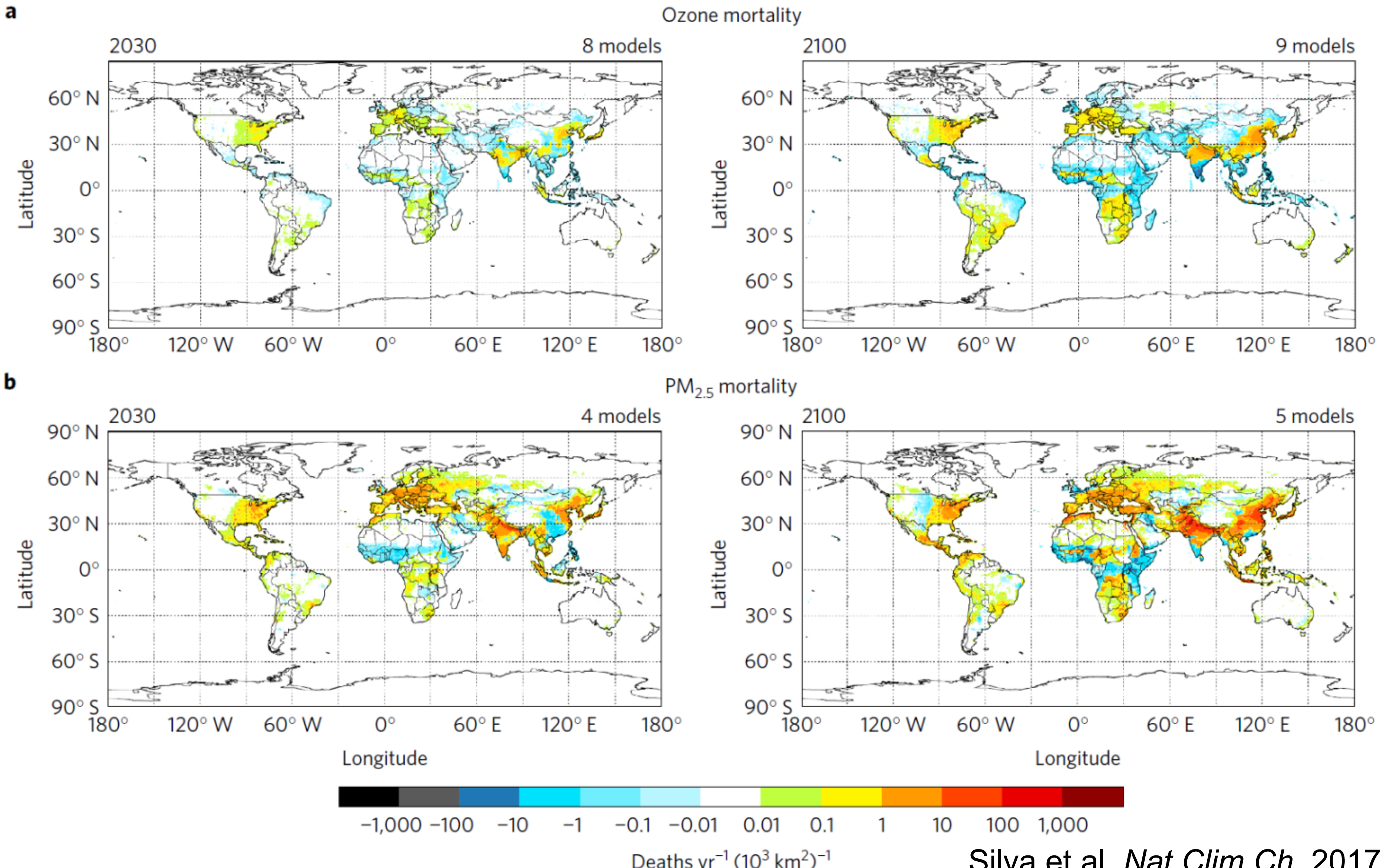
Mean (95% CI)
(deaths yr^{-1})

2030
56,000
(-34,000 , 164,000)

2100
215,000
(-76,000 , 595,000)

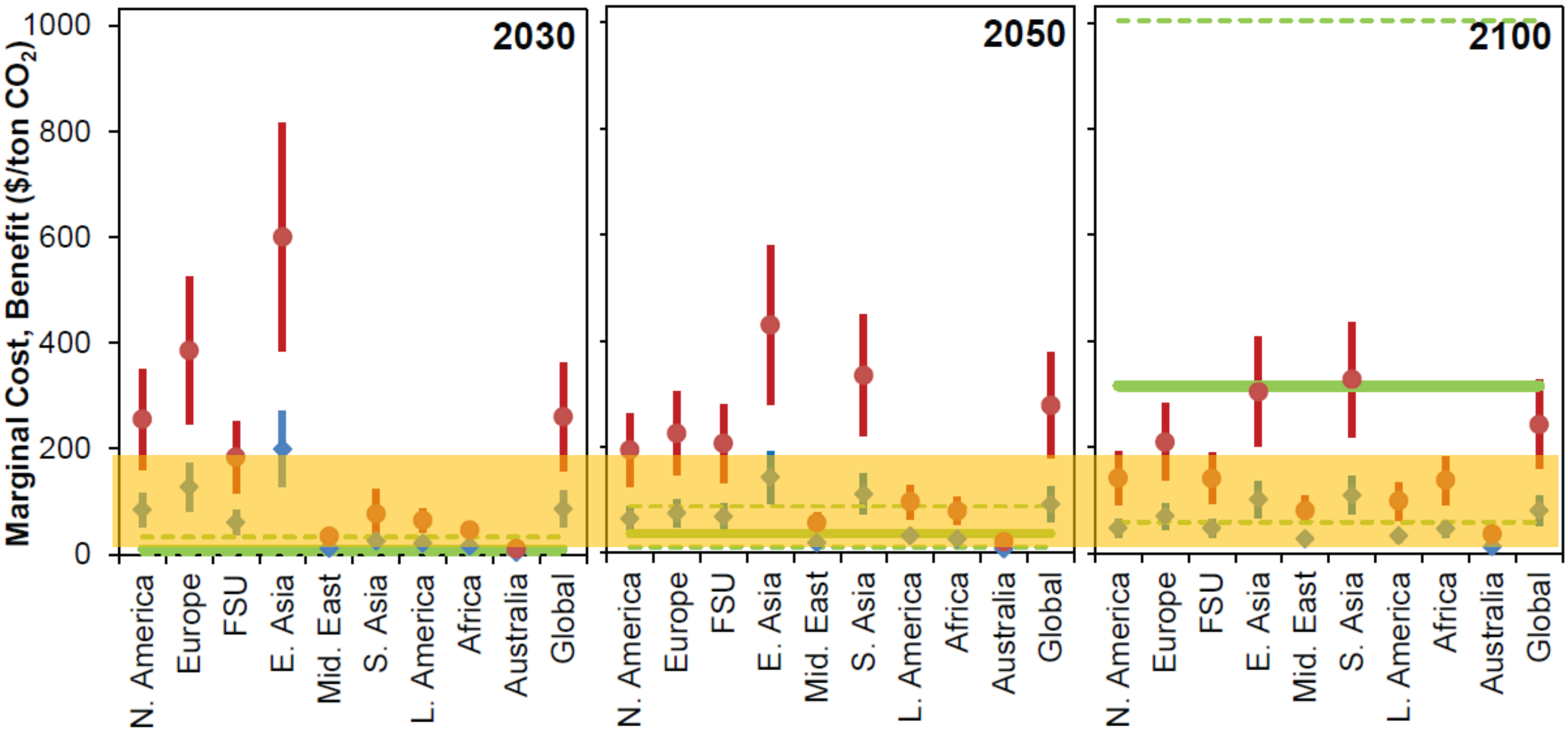
Silva et al. *Nat Clim Ch*, 2017

Impact of RCP8.5 Climate Change on Global Air Pollution Mortality: ACCMIP Models



Silva et al. *Nat Clim Ch*, 2017

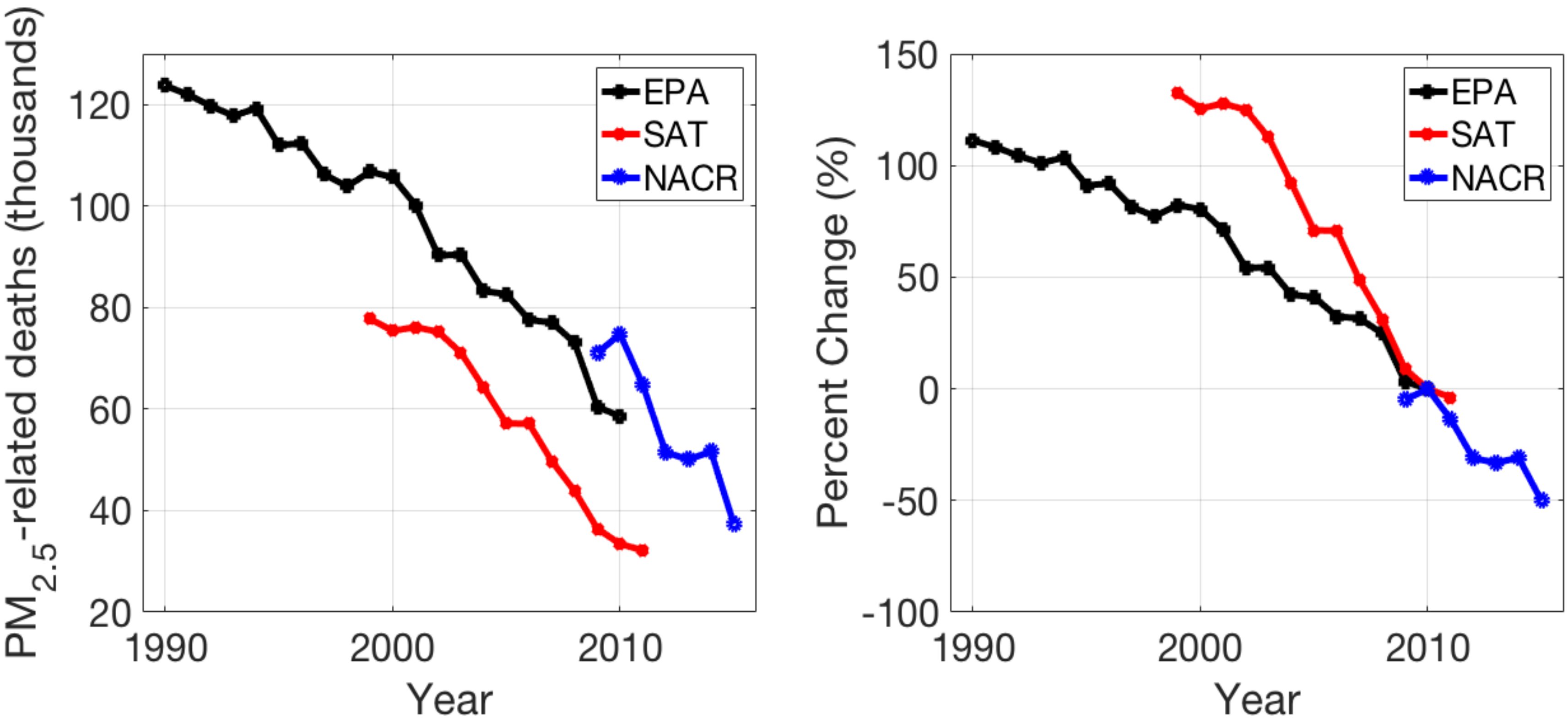
Co-benefits – Valuation of Avoided Mortality



Red: High valuation (2030 global mean $3.6 million)
Blue: Low valuation (2030 global mean $1.2 million)
Green: Median and range of global C price (13 models)

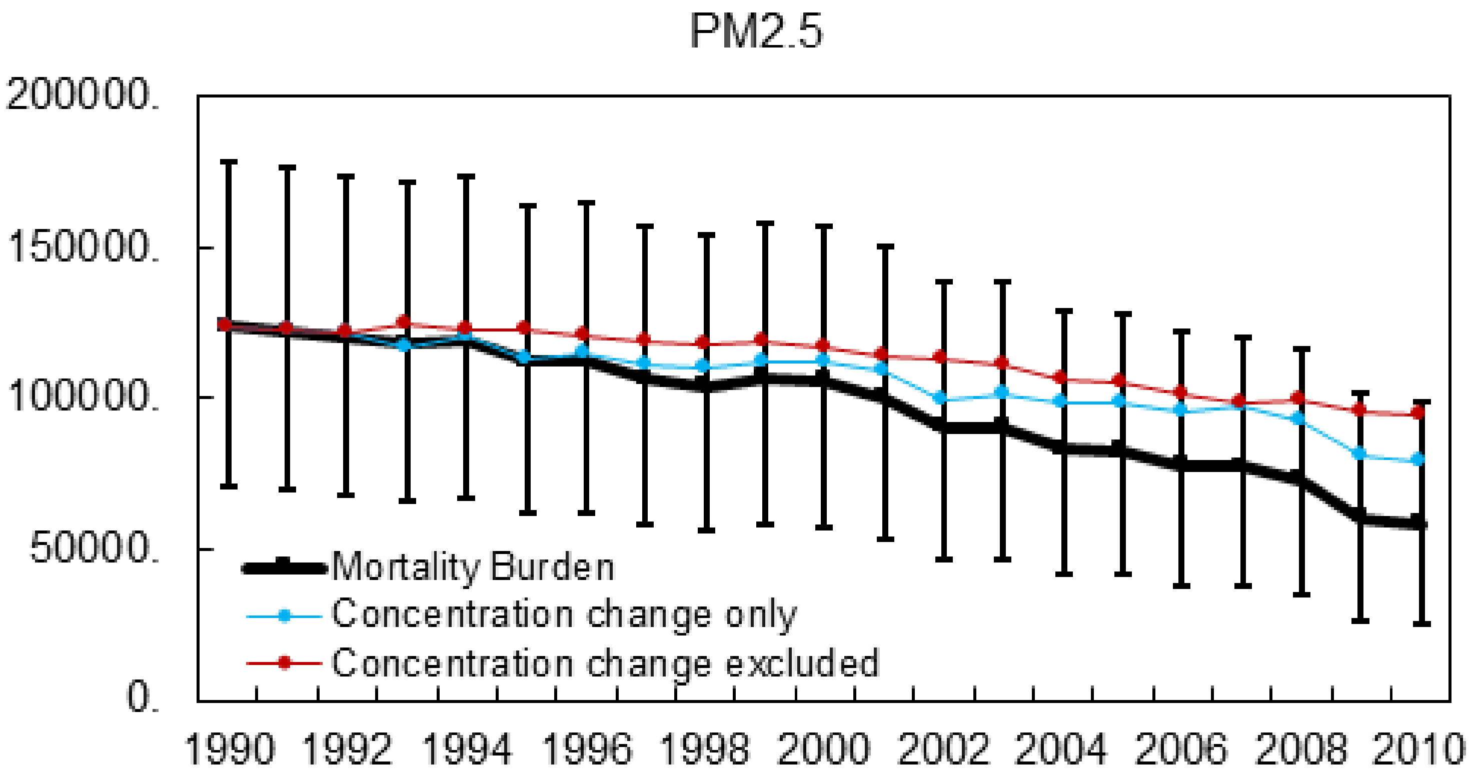
West et al. *NCC* 2013

US $PM_{2.5}$-related deaths



Zhang, ACP 2018; Nawaz, in prep.

$PM_{2.5}$ Mortality Burden (EPA)



- $PM_{2.5}$ mortality decreased by 53% from 123,700 (70,800-178,100) deaths in 1990 to 58,600 (24,900-98,500) in 2010.
- Without the decrease in $PM_{2.5}$ since 1990, the burden would have only decreased by 24%.
- $PM_{2.5}$ reductions since 1990 have decreased deaths in 2010 by about **35,800**.

Zhang, ACP 2018

Future Opportunities

- Many possible applications.

- Improved epidemiology – health and concentration data.
- Improve space/time resolution, understanding of population movement.
- Health benefits of policies using reduced-form AQ models (inMAP, EASIUR).

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INTERVENTION MODEL FOR AIR POLLUTION

Health Impacts of Air Pollution: A Tool to Understand the Consequences

Christopher Tessum | Jason Hill | Julian Marshall

Publication: Tessum, C. W.; Hill, J. D.; Marshall, J. D. InMAP: A model for air pollution interventions. *PLoS ONE* **2017**, *12* (4), e0176131 DOI: 10.1371/journal.pone.0176131.

What are the 4 pieces of information you need to do a health risk assessment?

$$\Delta Mort = \underbrace{(1 - e^{-\beta \Delta X})}_{\text{Attributable fraction}} \times \underbrace{Pop \times y_0}_{\text{Baseline mortality}}$$

Annual deaths

Concentration-response factor

Change in concentration

Population exposed

Baseline mortality rate

Health impact function

$$\Delta Mort = \overbrace{(1 - e^{-\beta \Delta X})}^{\text{Attributable fraction}} \times \overbrace{Pop \times y_0}^{\text{Baseline mortality}}$$

Annual avoided mortalities

Concentration-response factor

Change in concentration

Population exposed

Baseline mortality rate

β – from re-analysis of ACS cohort: Krewski et al. (2009) for $PM_{2.5}$, Jerrett et al. (2009) for ozone.

Pop – from LANDSCAN database at very fine resolution, adjusted for adult population.

y_0 – from WHO country- or region-level data.

Pop and y_0 fields were gridded using a GIS.

Health impact function

$$\Delta Mort = y_0 \text{ x } AF \text{ x } Pop$$

$$\Delta Mort = y_0 \text{ x } (1\text{-}exp^{-\beta \Delta X}) \text{ x } Pop$$

Baseline mortality rate

Exposed Population

ΔX = Change in concentration

β = Concentration-response factor

(≈ CPD)

- **Respiratory diseases** (RESP) (inc. COPD – chronic obstructive pulmonary disease)
- **Cardiovascular diseases** (inc. IHD – ischemic heart disease, STROKE – cerebrovascular disease)
- **Lung Cancer** (LC)

Environmental Science & Technology

Feature

pubs.acs.org/est

"What We Breathe Impacts Our Health: Improving Understanding of the Link between Air Pollution and Health"

J. Jason West,[*,†] Aaron Cohen,[*,‡] Frank Dentener,[*,§] Bert Brunekreef,[‖] Tong Zhu,[*,⊥] Ben Armstrong,[#] Michelle L. Bell,[∇] Michael Brauer,[○] Gregory Carmichael,[◆] Dan L. Costa,[¶] Douglas W. Dockery,[★] Michael Kleeman,[⊗] Michal Krzyzanowski,[⋈] Nino Künzli,[☼,◑] Catherine Liousse,[◊] Shih-Chun Candice Lung,[@] Randall V. Martin,[¢,$] Ulrich Pöschl,[♁] C. Arden Pope, III,[¥] James M. Roberts,[%] Armistead G. Russell,[€] and Christine Wiedinmyer[Я]

- Air pollution is underappreciated for global health.
- Air pollution and its health impacts are changing globally, and will change in ways interrelated with climate change.
- Air pollution science offers new possibilities: new measurement methods measuring more chemical components, cheap sensors that can be widely deployed, satellites, and models.
- There is a need for the communities of air pollution science and air pollution health effects science to work together better.

Epidemiology

Toxicology

Medicine

Exposure Science

Atmospheric Science

Engineering

Chemistry

Physics

- **Measurements of chemical components**
- **Spatially-distributed measurements (cheap sensors)**
- **Satellite observations**
- **Computer models**

Epidemiology

Toxicology

Medicine

Exposure Science

Atmospheric Science

Engineering

Chemistry

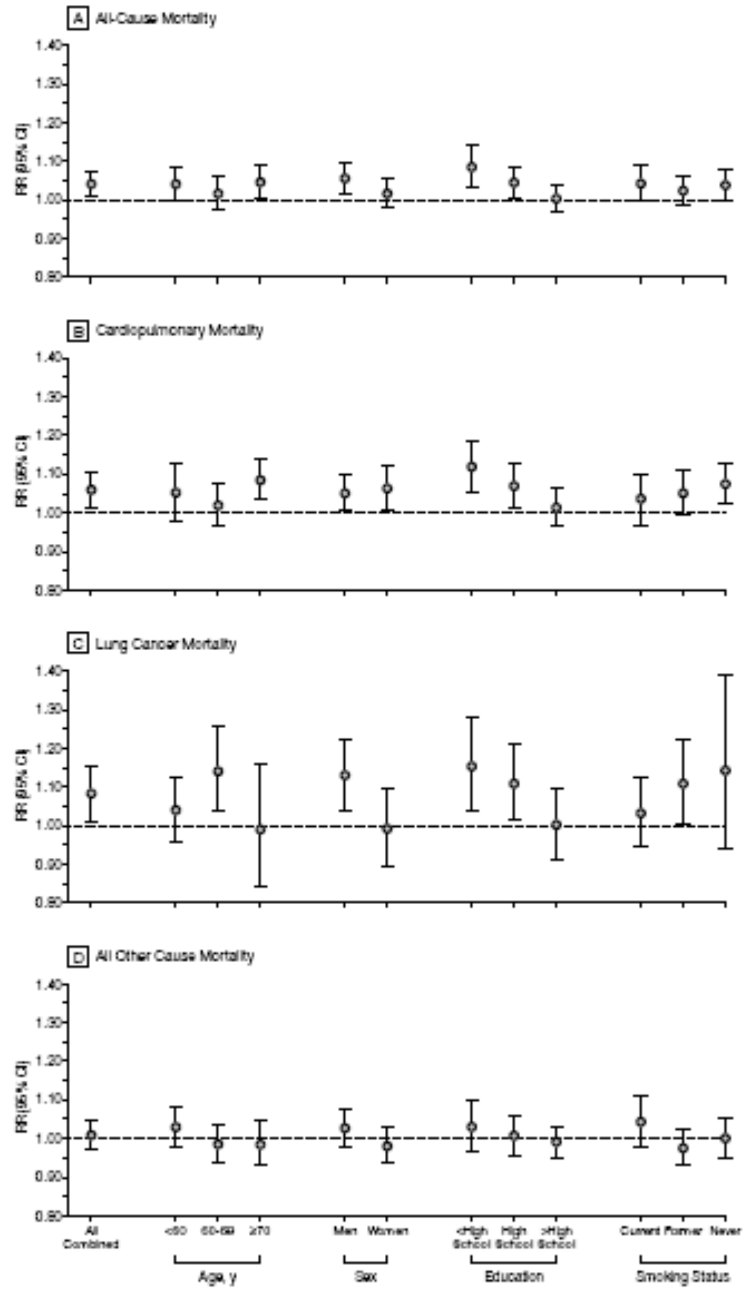
Physics

- Which pollutants to emphasize, averaging times
- Risk functions
- Biological mechanisms

American Cancer Society Study (Pope et al., 2002)

>500,000 adult volunteers followed.

Figure 4. Adjusted Mortality Relative Risk (RR) Ratio Associated With 10-μg/m² Differences of $PM_{2.5}$ Concentrations



Data presented are for 1979-1983 for the different causes of death stratified by age, sex, education, and smoking status. $PM_{2.5}$ indicates mean fine particles measuring less than 2.5 μm in diameter; CI, confidence interval.

Table 2. Adjusted Mortality Relative Risk (RR) Associated With a 10-μg/m³ Change in Fine Particles Measuring Less Than 2.5 μm in Diameter

	Adjusted RR (95% CI)*		
Cause of Mortality	1979-1983	1999-2000	Average
All-cause	1.04 (1.01-1.08)	1.06 (1.02-1.10)	1.06 (1.02-1.11)
Cardiopulmonary	1.06 (1.02-1.10)	1.08 (1.02-1.14)	1.09 (1.03-1.16)
Lung cancer	1.08 (1.01-1.16)	1.13 (1.04-1.22)	1.14 (1.04-1.23)
All other cause	1.01 (0.97-1.05)	1.01 (0.97-1.06)	1.01 (0.95-1.06)

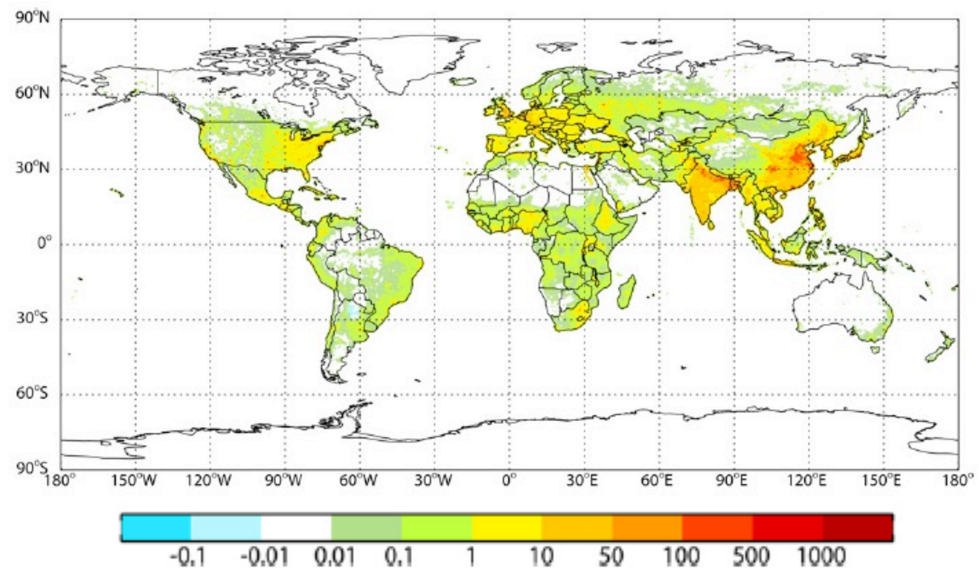
*Estimated and adjusted based on the baseline random-effects Cox proportional hazards model, controlling for age, sex, race, smoking, education, marital status, body mass, alcohol consumption, occupational exposure, and diet. CI indicates confidence interval.

Global Burden: Ozone-related mortality

Global and regional mortality per year

Regions	Total deaths	Deaths per million people (*)
North America	34,400	121
Europe	32,800	96
Former Soviet Union	10,600	66
Middle East	16,200	68
India	118,000	212
East Asia	203,000	230
Southeast Asia	33,300	119
South America	6,970	38
Africa	17,300	73
Australia	469	29
Global	**472,000**	**149**

(*) Exposed population (age 30 and older)



Respiratory mortality , deaths yr^{-1} $(1000\ km^2)^{-1}$,
multi-model mean in each grid cell , 14 models