# Estimating the global health benefits of air pollution mitigation

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# Outline

Introduction

Mitigating short-lived climate pollutants

Impacts of excess diesel NOx emissions and benefits of mitigation

Air pollution health impact assessment tools

The big picture: Where does atmospheric science fit in?

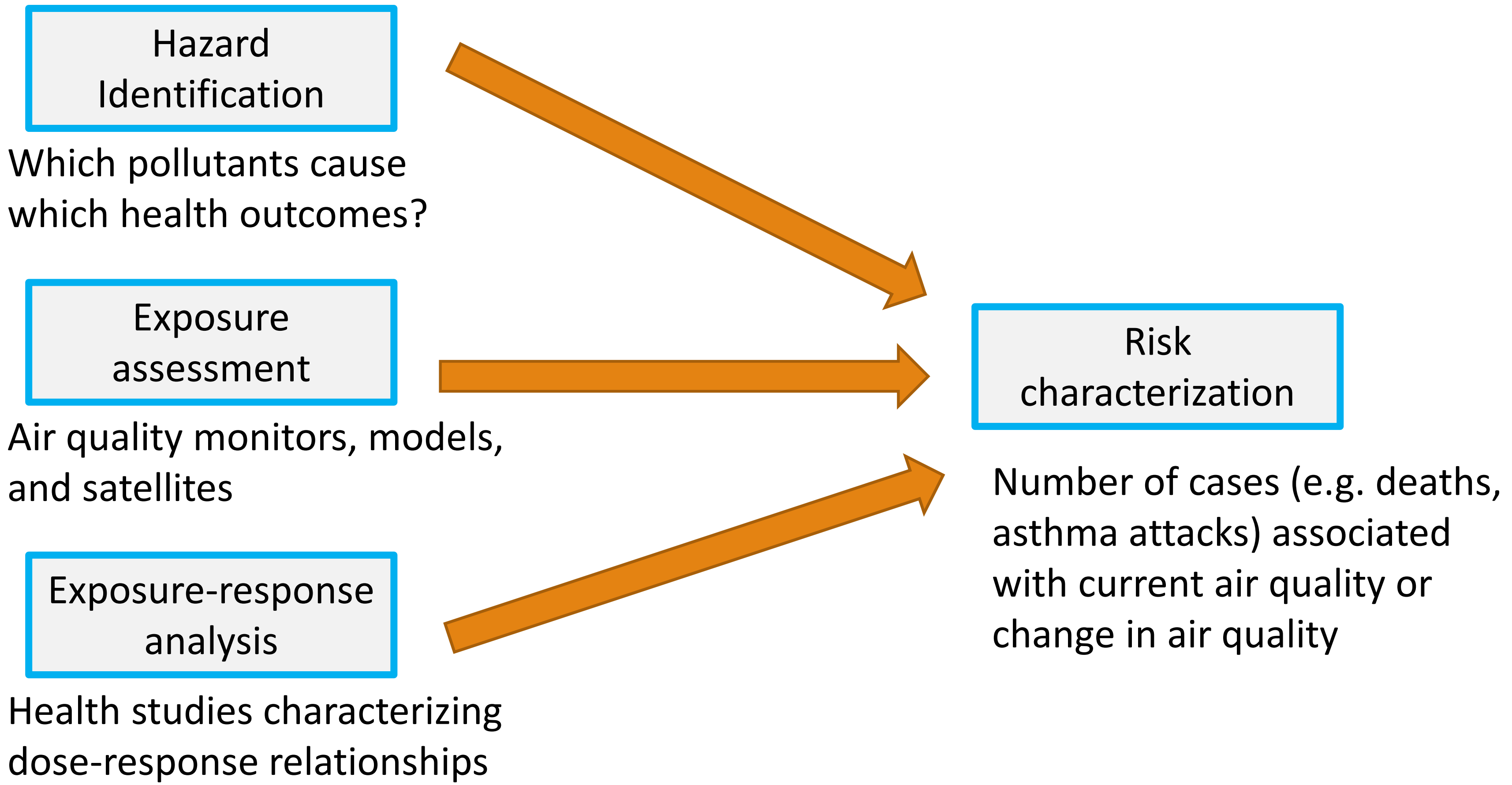
# Global Burden of Disease 2013 risk factors

| Mean rank (95% UI) | 2000 leading risks |
|---|---|
| 1·0 (1–1) | 1 Childhood undernutrition |
| 2·0 (2–2) | 2 High blood pressure |
| 3·3 (3–4) | 3 Smoking |
| 4·0 (3–6) | 4 Unsafe water |
| 5·2 (4–8) | 5 High body-mass index |
| 6·9 (5–11) | 6 Alcohol use |
| 7·6 (5–11) | 7 Household air pollution |
| 7·9 (5–11) | 8 High fasting plasma glucose |
| 9·2 (6–12) | 9 Unsafe sanitation |
| 11·5 (8–14) | 10 Unsafe sex |
| 12·0 (6–17) | 11 Suboptimal breastfeeding |
| 12·6 (7–18) | 12 Low fruit |
| 13·8 (12–15) | 13 Ambient particulate matter |
| 13·9 (6–22) | 14 High sodium |
| 15·9 (13–19) | 15 High total cholesterol |
| 17·3 (14–21) | 16 Iron deficiency |
| 17·3 (15–21) | 17 Handwashing |
| 18·8 (16–21) | 18 Low whole grains |
| 19·6 (18–22) | 19 Low glomerular filtration |
| 21·0 (19–22) | 20 Low vegetables |
| 21·1 (19–22) | 21 Low physical activity |
| 23·9 (23–27) | 22 Low nuts and seeds |
| 25·0 (23–30) | 23 Vitamin A deficiency |
| 25·3 (23–28) | 24 Drug use |
| 27·2 (24–32) | 25 Low omega-3 |

| 2013 leading risks | Mean rank (95% UI) | All age median % change | Age-standardised median % change |
|---|---|---|---|
| 1 High blood pressure | 1·0 (1–1) | 20% (15 to 26) | –13% (–16 to –9) |
| 2 Smoking | 2·6 (2–4) | 5% (–1 to 11) | –23% (–28 to –19) |
| 3 High body-mass index | 2·8 (2–5) | 26% (22 to 31) | –7% (–11 to –5) |
| 4 Childhood undernutrition | 4·2 (3–6) | –45% (–51 to –39) | –50% (–55 to –44) |
| 5 High fasting plasma glucose | 4·6 (3–6) | 31% (25 to 36) | –4% (–8 to 0) |
| 6 Alcohol use | 6·9 (5–9) | 6% (2 to 11) | –17% (–20 to –13) |
| 7 Household air pollution | 9·1 (8–12) | –10% (–21 to 2) | –28% (–38 to –18) |
| 8 Unsafe water | 10·4 (8–14) | –37% (–44 to –30) | –43% (–49 to –37) |
| 9 Unsafe sex | 10·8 (8–13) | –3% (–11 to 7) | –20% (–26 to –11) |
| 10 Low fruit | 10·8 (7–16) | 7% (1 to 14) | –22% (–26 to –16) |
| 11 High sodium | 11·4 (5–20) | 15% (7 to 24) | –16% (–22 to –10) |
| 12 Ambient particulate matter | 11·9 (10–14) | 6% (1 to 12) | –17% (–21 to –13) |
| 13 High total cholesterol | 13·4 (9–17) | 13% (6 to 22) | –18% (–23 to –12) |
| 14 Low glomerular filtration | 15·8 (14–18) | 24% (19 to 30) | –7% (–11 to –3) |
| 15 Low whole grains | 16·3 (13–20) | 17% (12 to 23) | –14% (–18 to –10) |
| 16 Unsafe sanitation | 17·0 (14–20) | –42% (–48 to –36) | –47% (–53 to –42) |
| 17 Low physical activity | 18·5 (16–21) | 20% (15 to 27) | –13% (–17 to –9) |
| 18 Iron deficiency | 18·6 (14–22) | –10% (–14 to –7) | –19% (–22 to –16) |
| 19 Suboptimal breastfeeding | 18·6 (14–23) | –40% (–47 to –32) | –44% (–51 to –37) |
| 20 Low vegetables | 20·2 (18–22) | 4% (–2 to 10) | –24% (–28 to –20) |
| 21 Handwashing | 22·5 (21–25) | –37% (–44 to –31) | –43% (–49 to –37) |
| 22 Drug use | 23·1 (22–25) | 33% (27 to 40) | 10% (5 to 15) |
| 23 Low nuts and seeds | 24·0 (21–28) | 2% (–3 to 8) | –25% (–29 to –21) |
| 24 Low omega-3 | 25·9 (23–29) | 16% (7 to 27) | –15% (–21 to –7) |
| 25 Low fibre | 26·1 (24–28) | 15% (3 to 29) | –16% (–24 to –5) |

(Institute for Health Metrics and Evaluation, 2015)

# Risk assessment framework

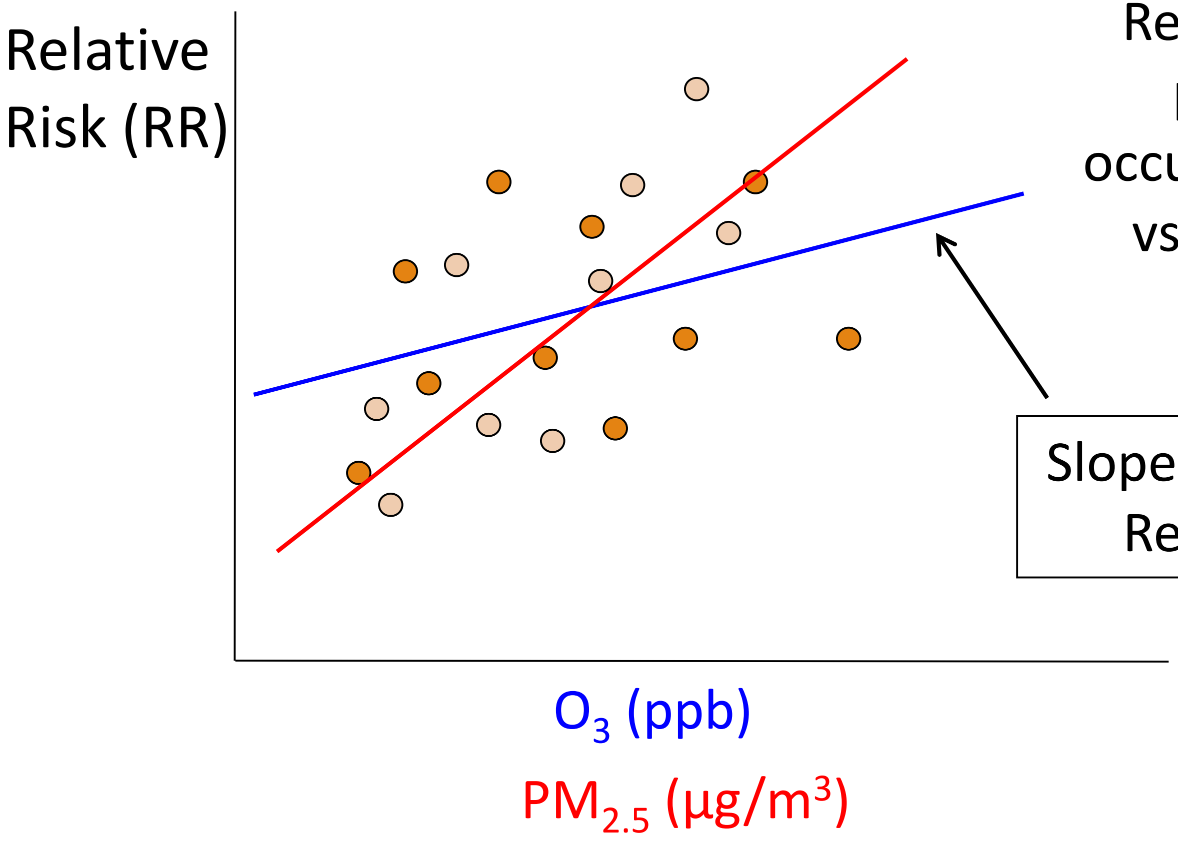


# Air pollution epidemiology

RR>1
Risk increase

RR=1
No effect

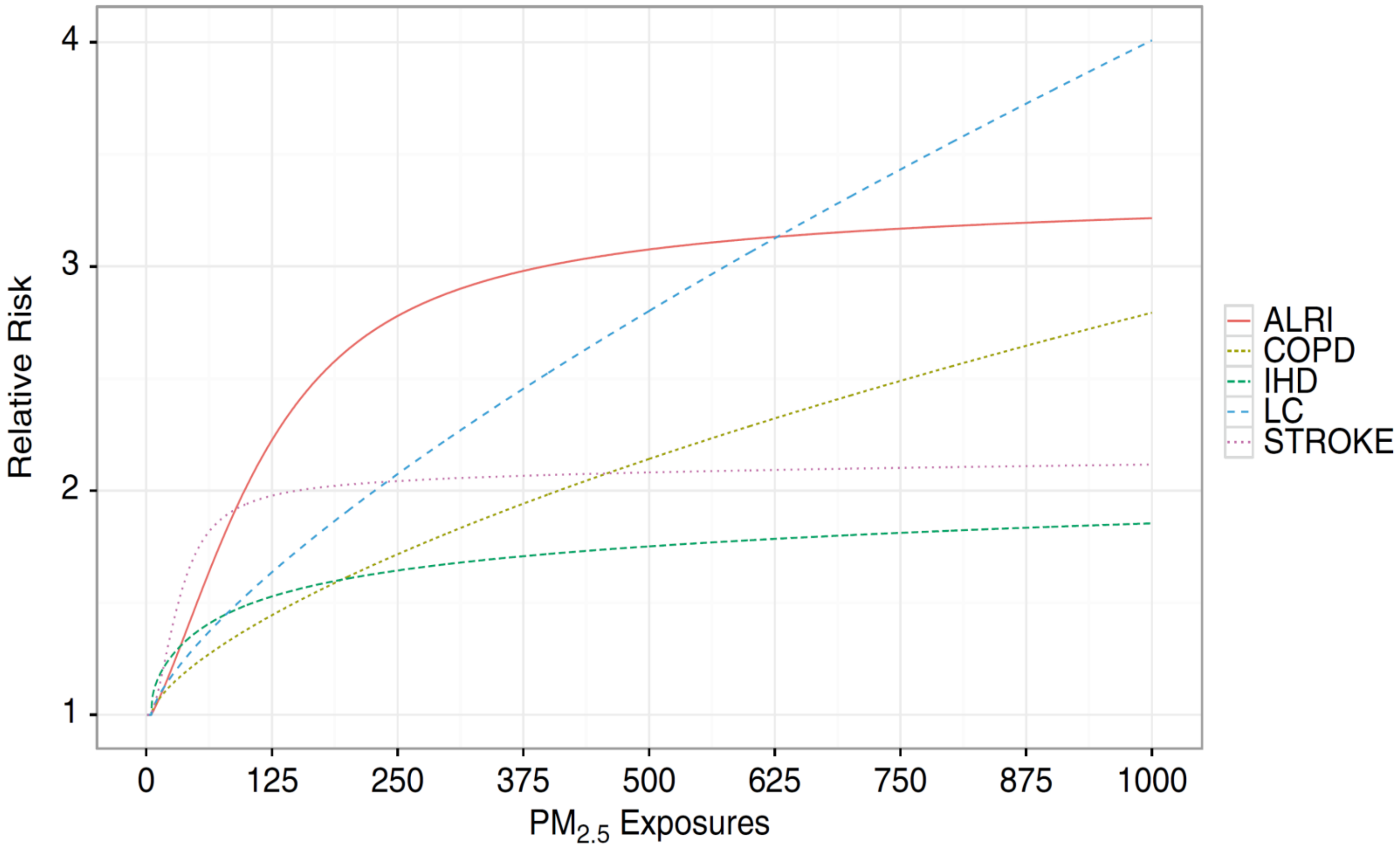
RR<1
Risk decrease




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

Slope = Concentration-Response Factor

# $PM_{2.5}$ concentration-response relationships




Burnett et al. 2014, Pillarisetti et al. 2016

# Ozone concentration-response relationship

| Study | Concentration metric | Risk estimates |
|---|---|---|
| Bell et al. (2004) | 10 ppb increase in 8-hr daily max | Cardiopulmonary: 1.0052 (1.0027-1.0077) |
| Jerrett et al. (2009) | 10 ppb increase in summer mean of 1hr daily max | Respiratory: 1.04 (1.01-1.067) |
| Turner et al. (2016) | 10 ppb increase in annual mean of 8hr daily max | Respiratory: 1.12 (1.08-1.16)<br>Circulatory: 1.03 (1.01-1.05) |

# 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 deaths

Concentration-response factor

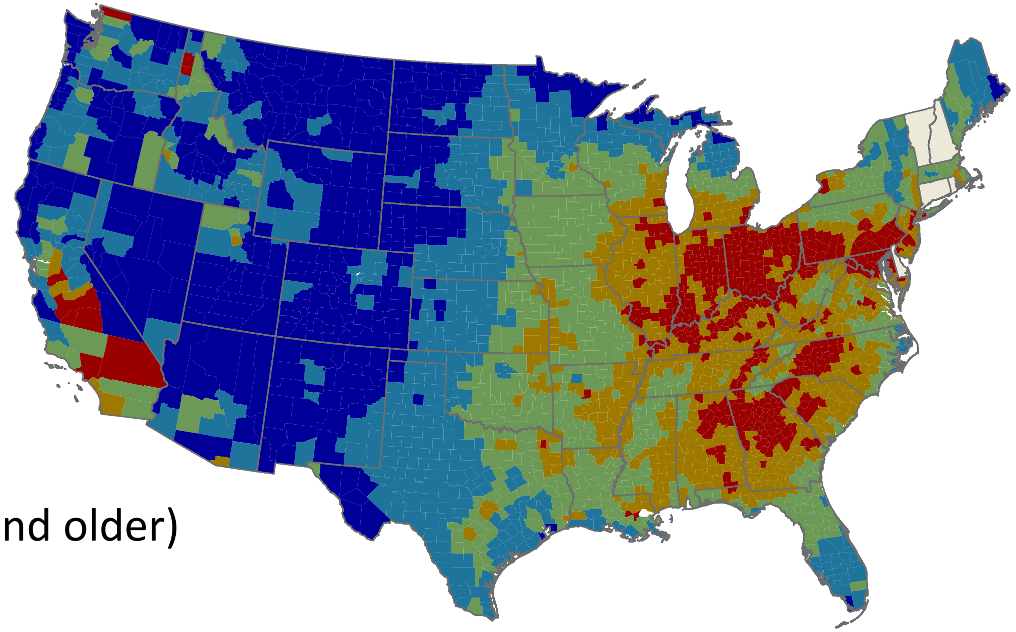
Change in concentration

Population exposed

Baseline mortality rate

# Estimated impacts of $PM_{2.5}$ in the U.S.

**$PM_{2.5}$ associated with 130,000 - 320,000 premature deaths in the U.S. in 2005 (5.4% of all deaths nationwide)**




**Other Effects:**

**Adults**:

- 18,000,000 lost work days (age 18-65)
- 180,000 heart attacks (age 17 and older)
- 83,000 cases of chronic bronchitis (age 26 and older)
- 62,000 hospitalizations for cardiovascular effects (age 17 and older)
- 30,000 hospitalizations for respiratory effects (all ages)

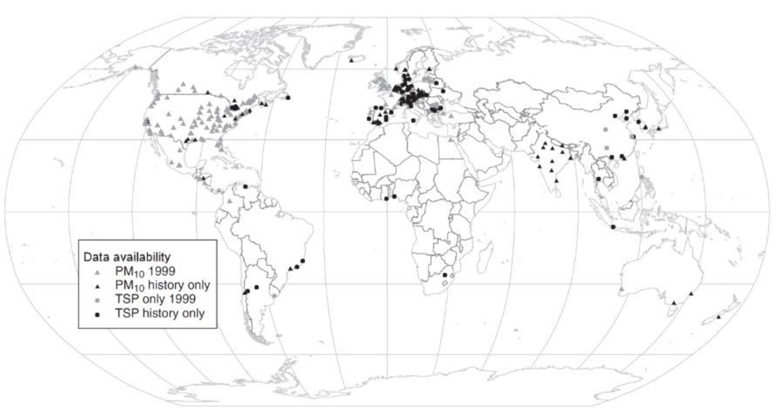
**Children**:

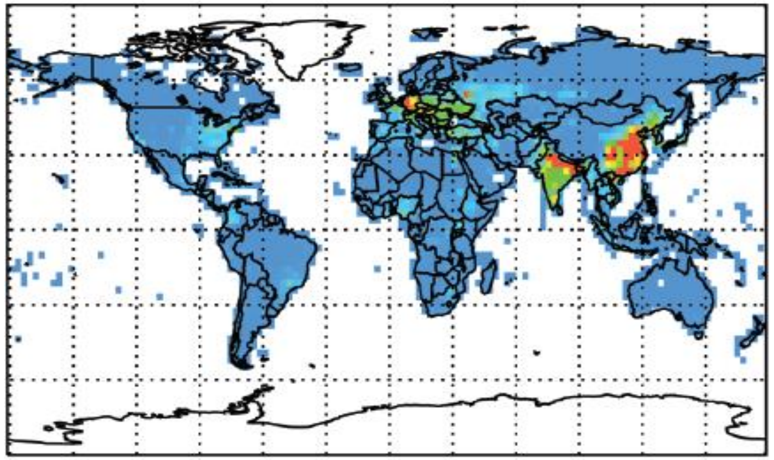
- 110,000 emergency department visits related to asthma (<18 years of age)
- 200,000 cases of acute bronchitis (age 8-12)
- 2,500,000 cases of exacerbation of asthma (age 6-18)

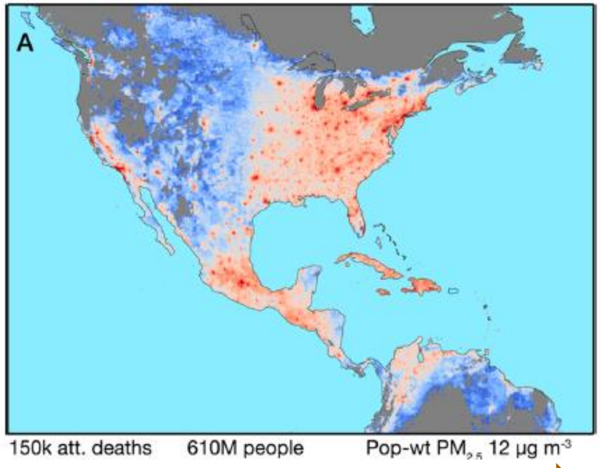
Fann et al. (2011)

# $PM_{2.5}$ and ozone global burden of disease estimates

**Figure 17.1** Cities from which data on exposure to $PM_{10}$ or TSP during 1985–1999 are available from monitoring cites






2004: **Surface air quality monitors** used to estimate 800,000 premature deaths associated with urban $PM_{2.5}$ (Cohen et al. 2004)

2010: **Global chemical transport model** used to estimate 3.7 million $PM_{2.5}$ deaths and 700,000 ozone deaths globally (Anenberg et al. 2010)

2012: **Satellite observations, global chemical transport model, and ground observations combined** to estimate 3.2 million $PM_{2.5}$ deaths and 152,000 ozone deaths (Lim et al. 2012)

2015: **2012 methods refined** to estimate 2.9 million $PM_{2.5}$ deaths and 237,000 ozone deaths (Forouzanfar et al. 2015, Apte et al. 2015)

# Using atmospheric models to estimate global air pollution health impacts

$$\Delta Mort = (1 - e^{-\beta \Delta X}) \times Pop \times y_0$$

Concentration-response factor

**Change in concentration**

Exposed population

Baseline mortality rate

**Ground-level Monitoring**

Advantages:
- Actual concentrations
- Real-world exposure for people living nearby

Disadvantages:
- Incomplete coverage (esp. in developing world)
- May not represent exposure accurately for people living far from monitor
- Cannot conduct experiments

**Modeling**

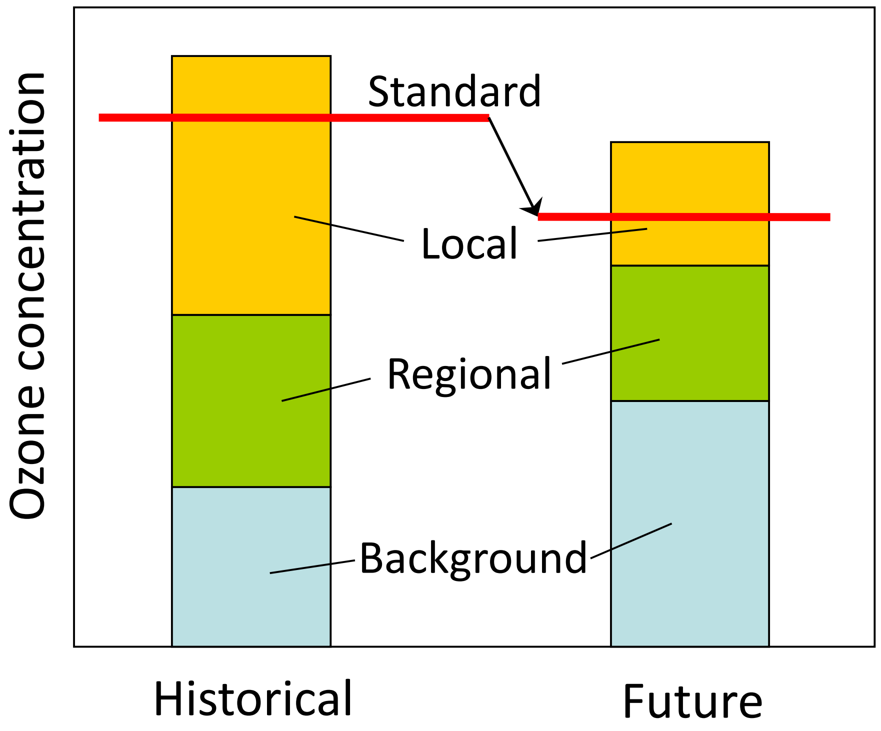
Advantages:
- Complete spatial coverage
- Ability to conduct experiments

Disadvantages:
- Simulated concentrations may not be accurate
- Coarse resolution obscures fine spatial gradients of concentration (may miss urban peaks)

Can leverage satellite observations for present-day

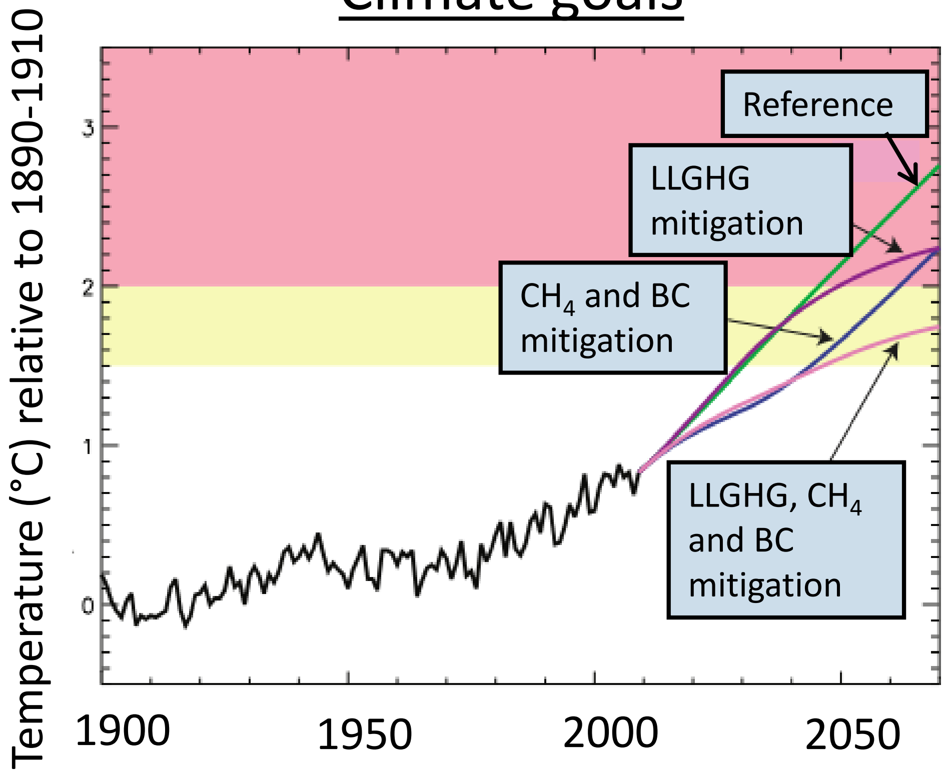
# Global impacts of air pollution

Air quality goals



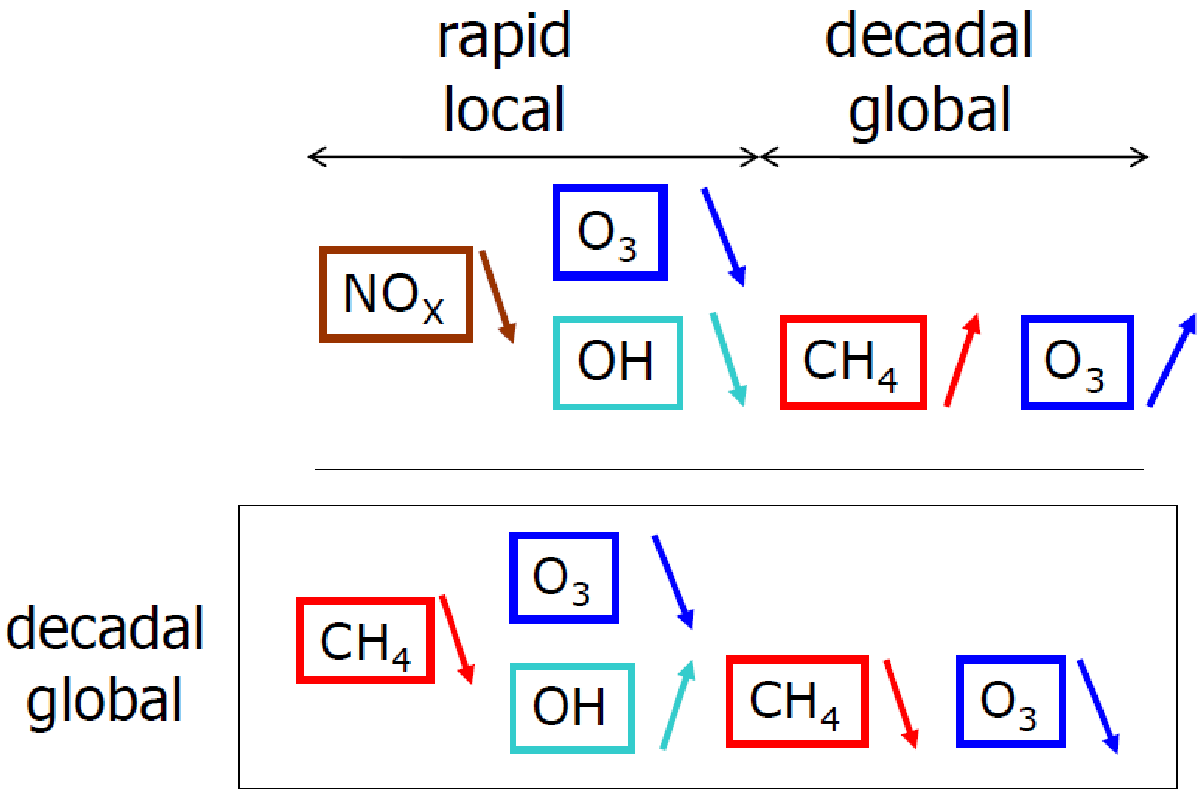

Keating et al. 2004

Climate goals




UNEP/WMO Integrated Assessment of Black Carbon and Tropospheric Ozone 2011; Shindell et al. 2012

# Policy scenarios for mitigating short-lived climate pollutants: BC and methane



# UNEP/WMO Integrated Assessment of Black Carbon and Tropospheric Ozone

Screened ~2000 emission control measures in GAINS database

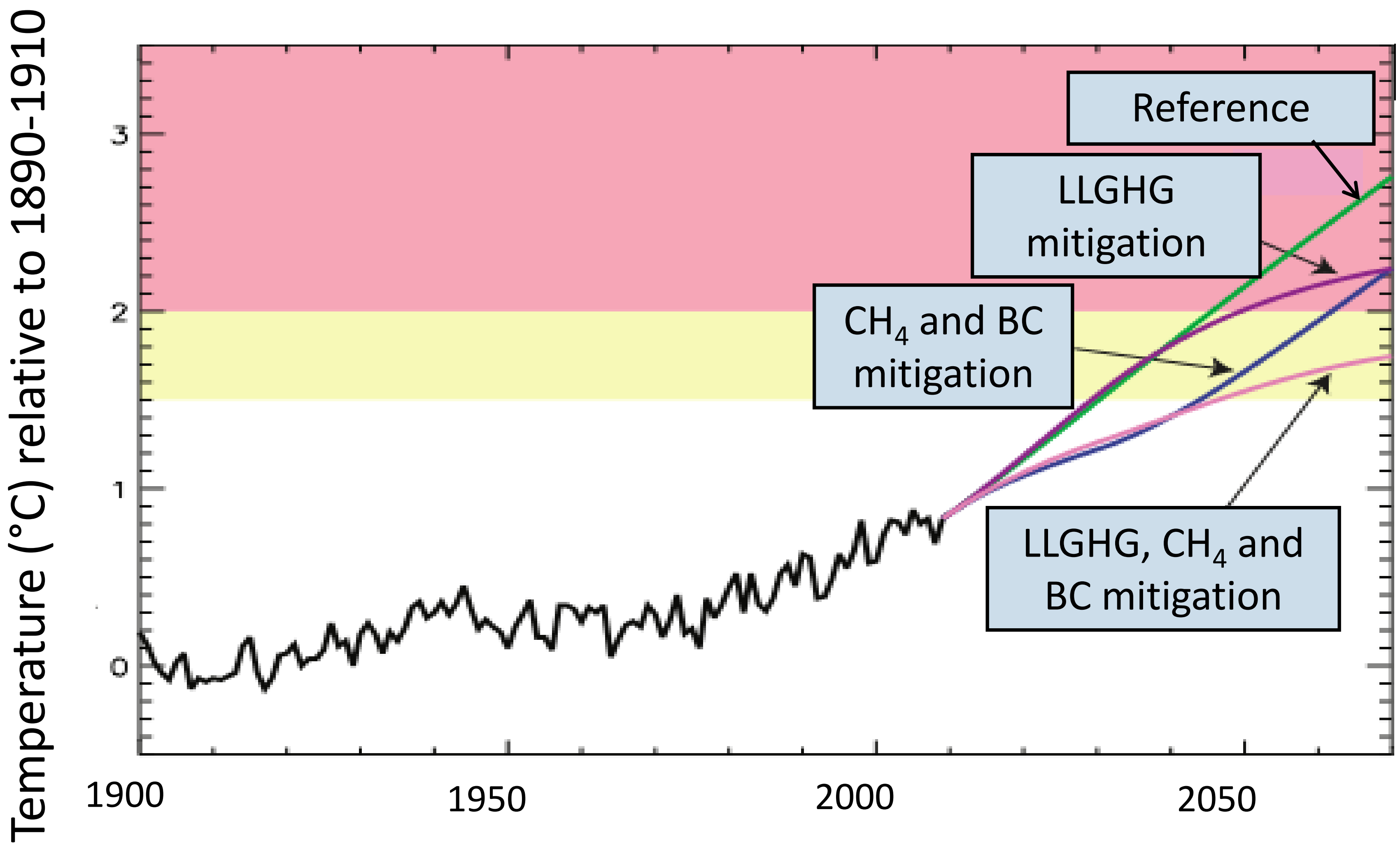
Identified 14 specific BC and methane emission control measures based on potential benefits for near-term climate

Examined 5 emission scenarios:

- Present-day (2005)
- 2030 reference (World Energy Outlook, IEA 2009)
- **Methane** measures
- Methane + **BC Group 1** measures (technological – i.e. diesel particulate filters, improving biomass cook stoves)
- Methane + BC Group 1 + **BC Group 2** measures (policy – i.e. elimination of high-emitting vehicles and biomass cook stoves)

Calculated climate, health, agricultural, and economic benefits

# Near-term climate benefits




UNEP/WMO Integrated Assessment of BC and Ozone, 2011; Shindell et al. *Science*, 2012

# Δ global pop.-weighted avg. $PM_{2.5}$ conc. relative to 2030 reference

(annual avg.)

Methane measures

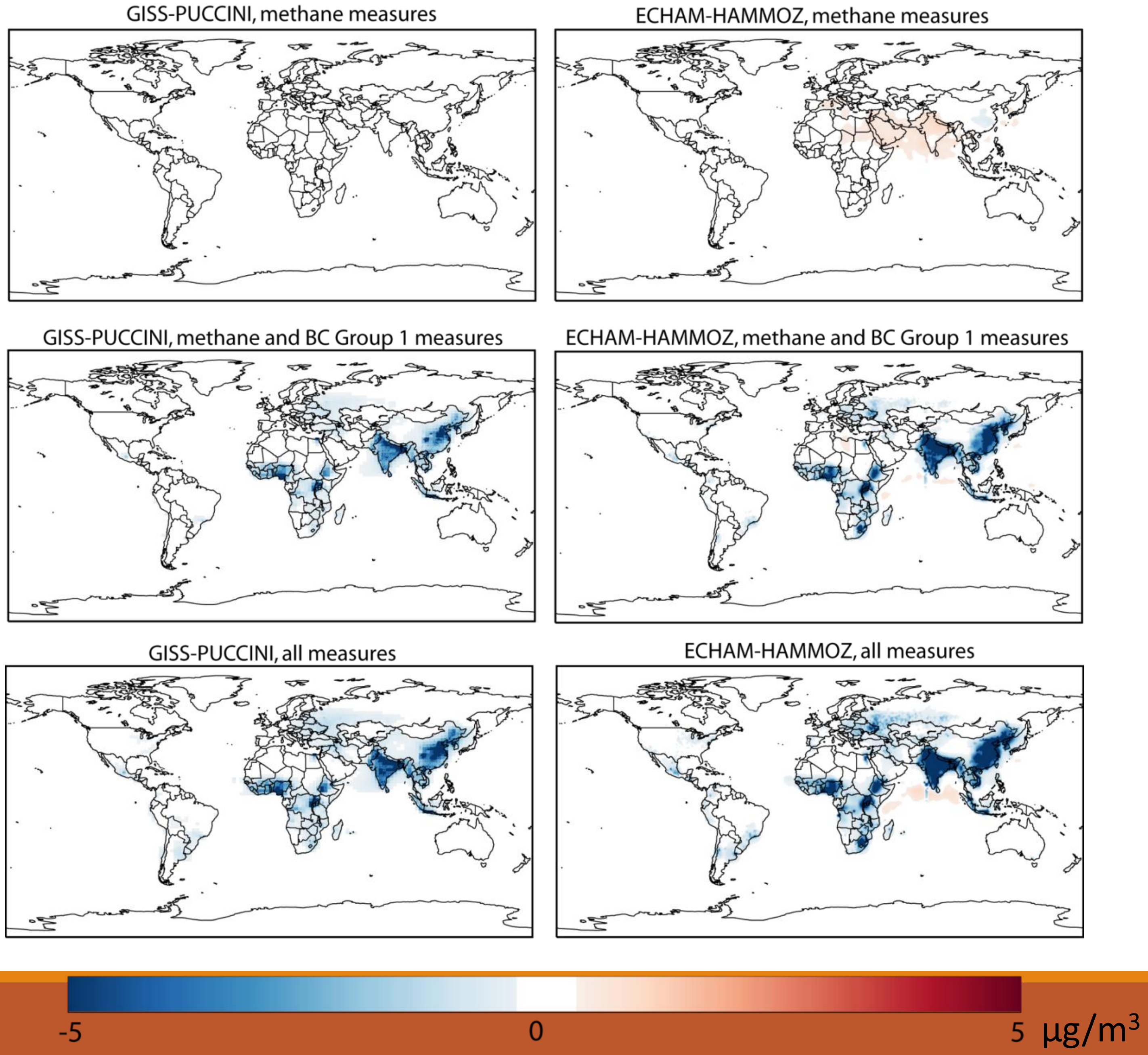
↓0 μg/m$^3$

+ BC Group 1 measures

↓ 2.9 – 3.6 μg/m$^3$

+ BC Group 2 measures

↓ 4.0 – 4.9 μg/m$^3$




Anenberg et al. *EHP*, 2012

# Δ global pop.-weighted avg. ozone conc. relative to 2030 reference

(6-mo. avg. of 1-hr. daily max.)

Methane measures

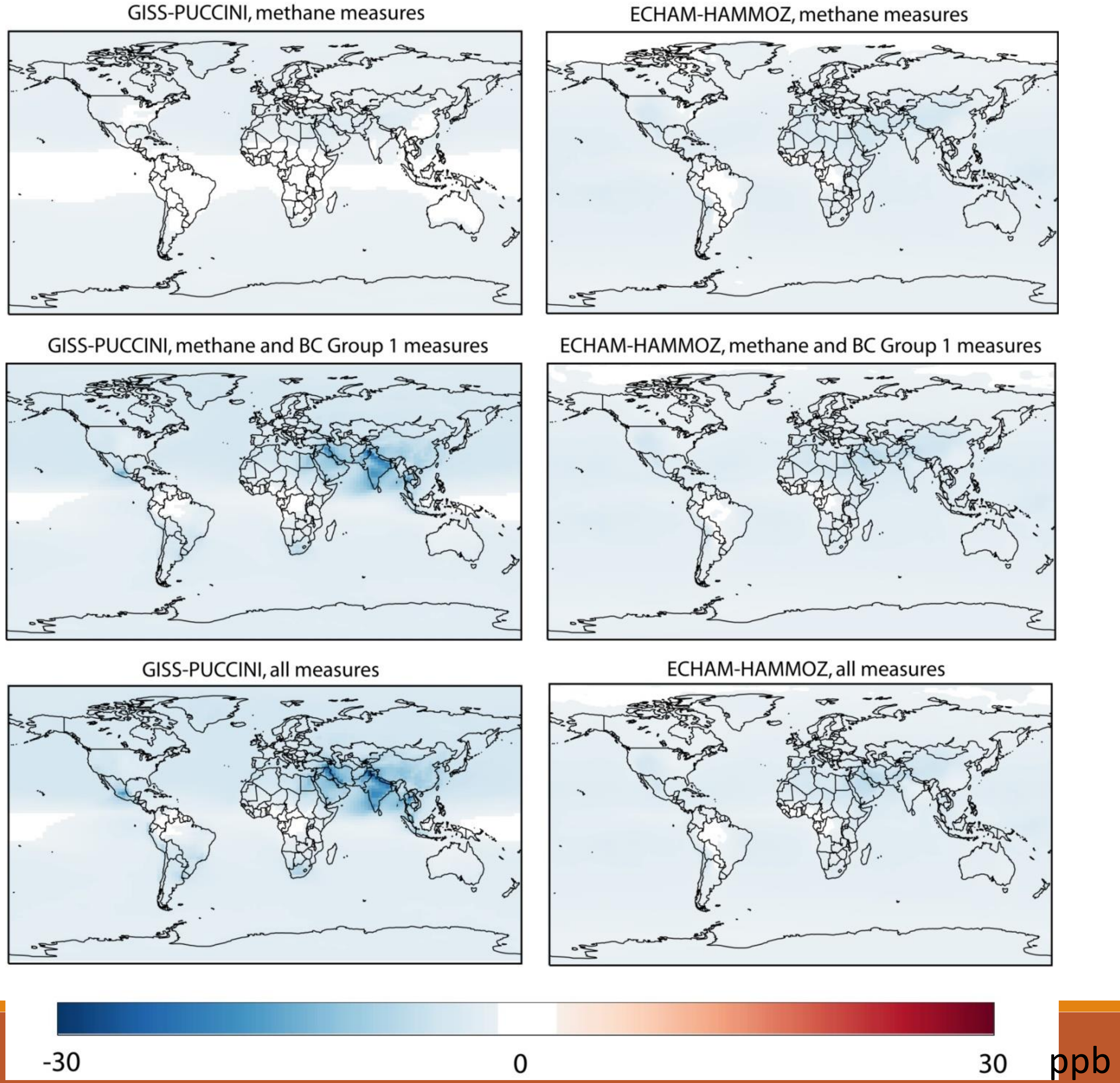
↓2.8 - 4.1 ppb

+ BC Group 1 measures

↓5.0 – 10.0 ppb

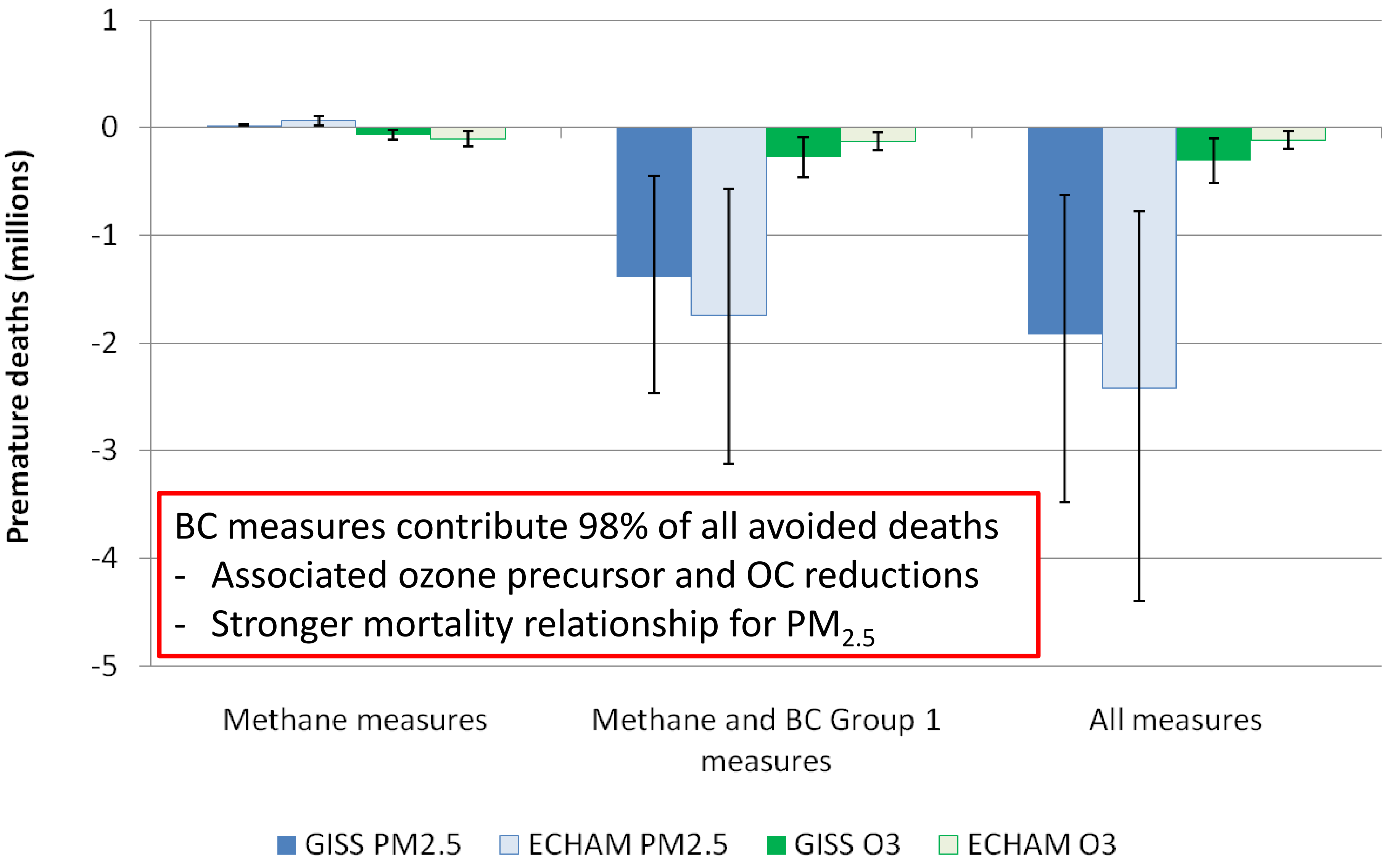
+ BC Group 2 measures

↓4.7 – 11.0 ppb



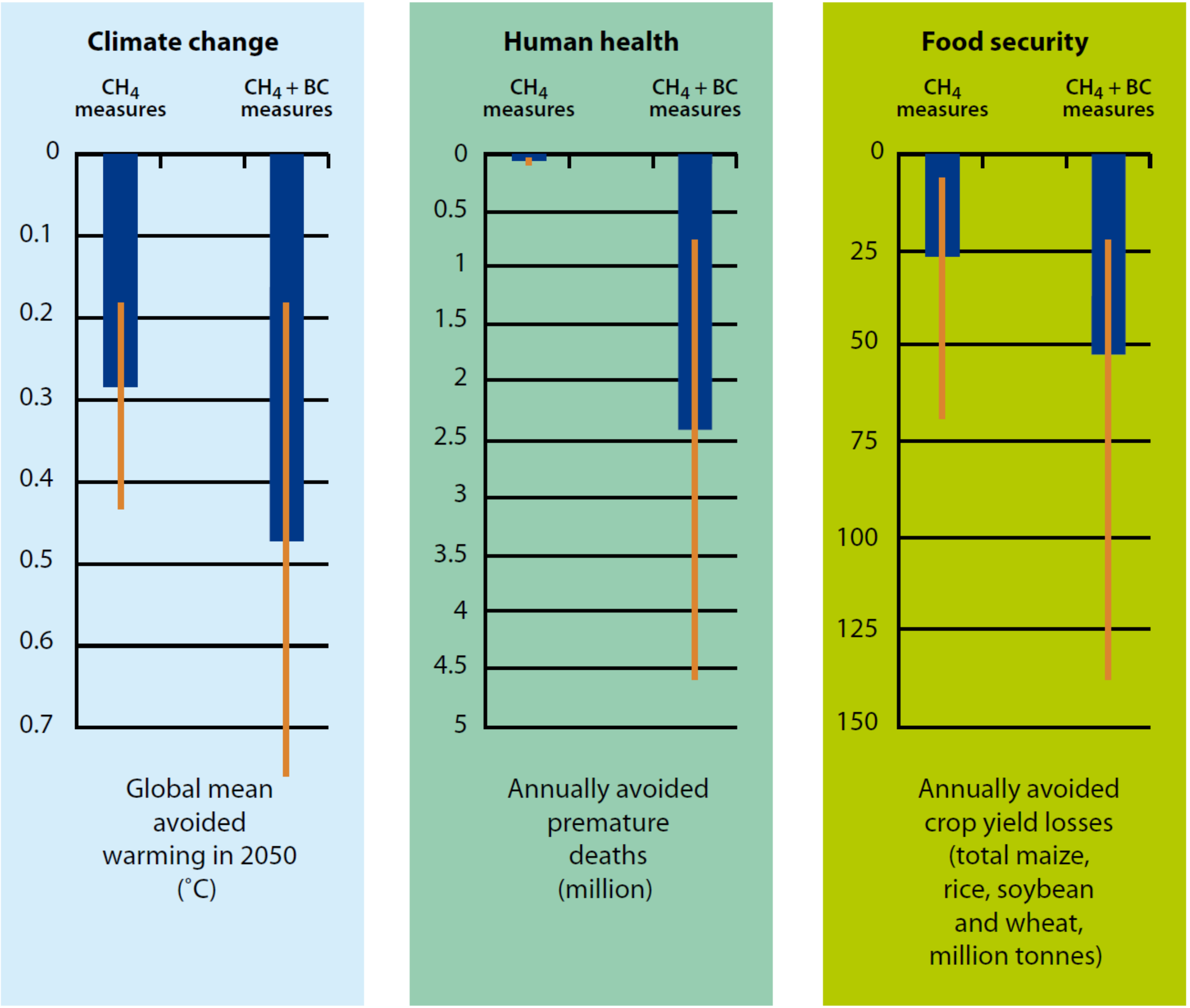

Anenberg et al. *EHP*, 2012

# Change in $PM_{2.5}$ and ozone-related premature deaths relative to 2030 reference

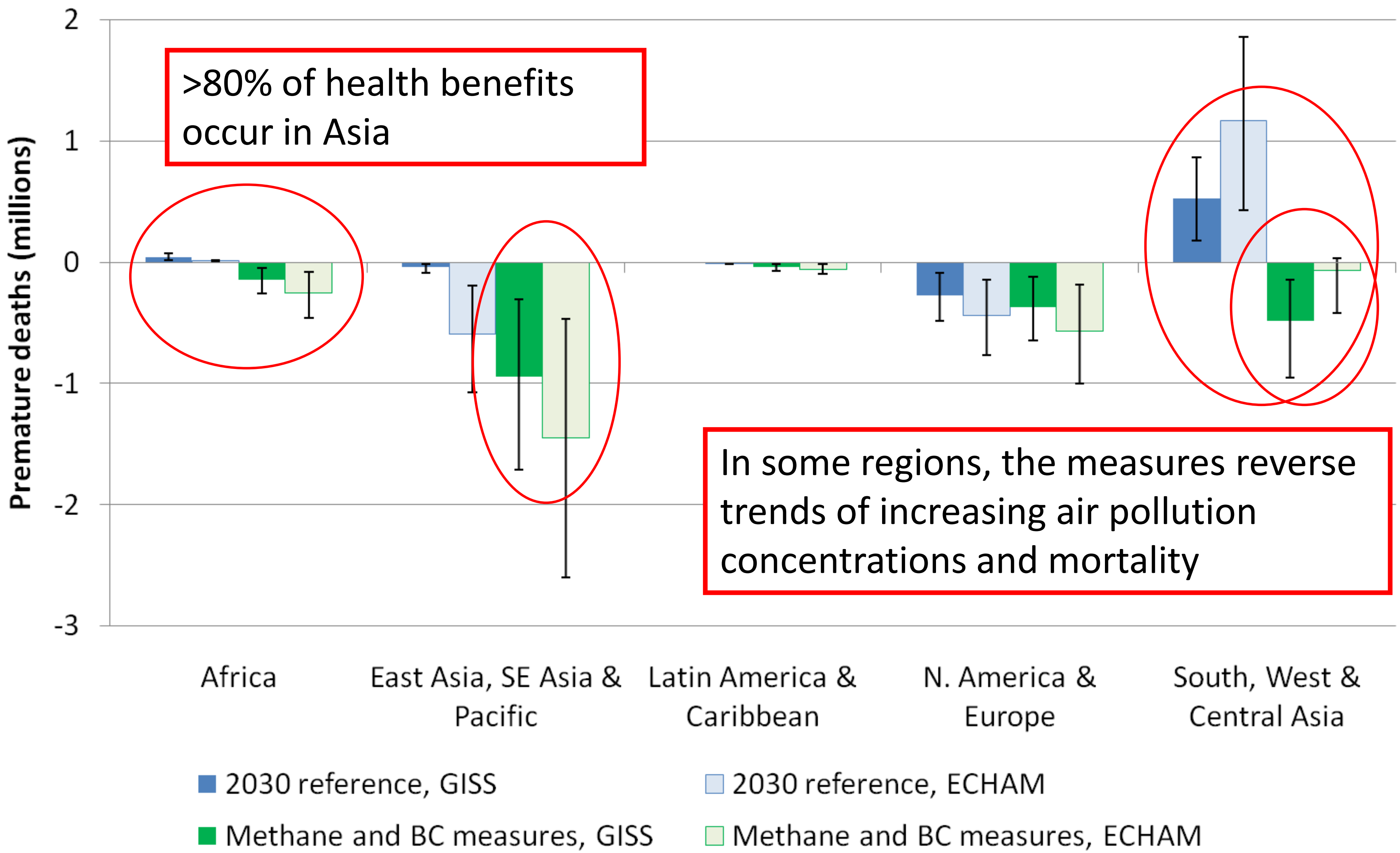



Anenberg et al. *EHP*, 2012

# Benefits of mitigating short-lived climate forcers



# Change in $PM_{2.5}$ and ozone-related premature deaths relative to 2005




Anenberg et al. *EHP*, 2012

# Short-lived Climate Pollutants: Key messages

In addition to the climate benefits, fully implementing these 14 measures could:

- Reduce global population-weighted average surface $PM_{2.5}$ and ozone concentrations by 23-34% and 7-17%
- Avoid 0.6-4.4 and 0.04-0.52 million $PM_{2.5}$ and ozone-related deaths in 2030

>80% of health benefits occur in Asia

BC measures achieve 98% of health benefits from all measures

- Associated ozone precursor and OC reductions
- Stronger mortality relationship for $PM_{2.5}$ relative to ozone

Health benefits from replacing biomass and coal stoves with cleaner fuels and stoves are greatest and are underestimated

# Climate and Clean Air Coalition to Reduce SLCPs


Partners:
50 countries
16 Intergovernmental Organizations
45 Non-governmental organizations

CCAC Initiatives:

DIESEL | OIL & GAS | WASTE | BRICKS | HFC | COOKSTOVES | AGRICULTURE

SNAP | FINANCE | ASSESSMENTS | HEALTH

# Excess diesel vehicle NOx emissions

Diesels emit ~70% of global transportation emissions of nitrogen oxides (NOx), a key $PM_{2.5}$ and ozone precursor.

All major vehicle markets have implemented motor vehicle emission control programs

- Most stringent: Euro VI and U.S. EPA 2010 for heavy-duty vehicles and Euro 6 and Tier 2 for light-duty vehicles
- ~70% of vehicles globally are certified to European-based standards, with the remainder certified primarily to U.S. standards
- U.S. phasing in LEV III/Tier 3 standards for light-duty vehicles for model years 2017-2025
- California also established a voluntary low NOx standard for heavy-duty vehicles beginning with model year 2010

However, diesel vehicles have historically emitted far more NOx under real-world operating conditions than during laboratory certification testing

- U.S.: up to 40x higher for Volkswagen cars with defeat devices (U.S. EPA 2015)
- Europe: average 7x higher (Franco et al. 2014)
- Japan: average 5x higher (MLIT 2016)

A minority of cars tested below Euro 6 emission limits, demonstrating that manufacturers are technically capable of meeting low NOx emissions under a range of real-world operating conditions

# Impacts and mitigation of excess diesel NOx emissions in 11 major vehicle markets

Developed inventory of real-world diesel NOx emissions in 2015 from light- and heavy-duty on-road vehicles in 11 major markets representing 80% of 2014 global diesel vehicle sales

- Australia, Brazil, Canada, China, EU-28, India, Japan, Mexico, Russia, South Korea, U.S.

Developed realistic diesel NOx emission policy scenarios for year 2040 considering specific circumstances of each country

Used global chemical transport modeling (GEOS-Chem) to simulate impacts of NOx emission changes on $PM_{2.5}$ and ozone concentrations

Quantified impacts on global $PM_{2.5}$ and ozone-related mortality, crop yields, and climate change for:

- Damages of real-world non-compliance of diesel vehicles in 2015 (“excess diesel NOx”)
- Potential benefits of tighter diesel NOx emission standards by 2040

# Survey of ambient air pollution health impact assessment tools

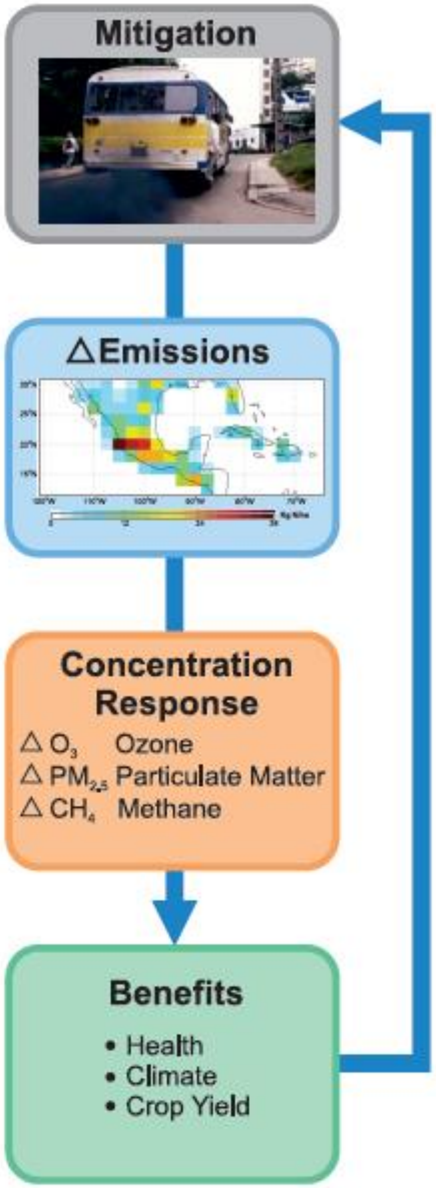
Many assessment contexts, including:

- National ambient air quality standards regulatory support in data-rich countries
- National ambient air quality standards regulatory support in data-poor countries
- Concentrations reduced to specific levels, like WHO air quality guidelines
- Emissions reduced by multi-governmental agreements (e.g. long-range transport)
- Emissions reduced by international development projects (e.g. World Bank)

Advantages of computer-based tools in estimating air pollution health impacts:

- Simplicity (lowers barrier of entry for new analysts)
- Consistency
- Comparability among assessments

Little information exists about various air pollution health impact assessment tools.



# Sample results for technical characteristics

| Characteristic | AirCounts™ | AIRQ2.2 | BenMAP-CE | EBD | GMAPS | IOMLIFET | LEAP-IBC | SIM-Air | TM5-FASST |
|---|---|---|---|---|---|---|---|---|---|
| $PM_{2.5}$ concentration-response relationship: | | | | | | | | | |
| User-defined | | x | x | | | x | x | | |
| American Cancer Society[3,56] | x | x | x | | x | x | x | x | x |
| GBD Integrated Exposure Response[15] | | | x | x | | | In prep | | x |
| Other | | x | x | | | | | | |
| Population data source: | | | | | | | | | |
| User-defined | | x | x | x | | x | | | |
| United Nations | x | | | | | | | | x |
| CIESIN[a] | | x | | | x | | x | x | x |
| Other | | | x | | | | | | |
| Baseline incidence data source: | | | | | | | | | |
| User-defined | | x | | x | | x | | | |
| World Health Organization | x | | x | | x | | | x | x |
| Other | | | | | | | x | x | |

# Exposure information source

| Exposure Information Source | User Input | Global Scope | Regional Scope |
|---|---|---|---|
| Any concentration input by user | Concentration | BenMAP-CE[a]<br>AirQ2.2<br>IOMLIFET | EBD |
| *In situ* monitor | Concentration | | Aphekom[b] |
| Global chemical transport model (input by user) | Concentration | | EVA |
| Regional or urban atmospheric chemistry model (input by user) | Emissions | SIM-Air | EVA |
| Reduced-form chemical transport model | Emissions | LEAP-IBC[c]<br>TM5-FASST[d] | EcoSense[d] |
| Reduced-form econometric model | Economic and climate indicators | GMAPS[e] | |
| Intake fraction (primary $PM_{2.5}$ only) | Emissions | AirCounts™ [f] | |

Anenberg et al, Risk Analysis, 2015

# Survey of ambient air pollution health risk assessment tools: key findings

- Key commonalities: PM2.5, mortality, concentration-response functions
- Key differences: exposure information source, format
- Trade-off between technical refinement and accessibility
- Select for the appropriate geographical scope, resolution, and maximum degree of technical rigor within resource constraints
- Need a systematic intercomparison among tool inputs, assumptions, calculations
- Opportunities to better account for multiple sources of uncertainty and integrate multiple stressors

Anenberg et al, Risk Analysis, 2015

# The big picture: Where does atmospheric science fit in?

In short, at all steps of air pollution risk assessment: Hazard identification, exposure assessment, exposure response relationship, risk characterization

Advances in atmospheric science have improved awareness of air pollution health risks and contributed to policy development around the world. Some evidence:

- Global Burden of Disease study and other air pollution health impact assessments
- Studies quantifying the public health benefits of policies related to air quality and climate change
- Policy analysis tools enabling health impact estimates across a range of assumptions, scenarios, locations

And they will continue having an impact! For example, by:

- Narrowing uncertainties in exposure estimates
- Elucidating impacts of climate change and its mitigation on emissions, concentrations, atmospheric chemistry
- Improving understanding of impacts across concentrations, populations, pollution mixtures
- Enabling development of tools to quantify multiple impacts of air pollution and climate change (health, climate, agriculture, ecosystems, etc.)

# Questions?

Interdisciplinary analyses are team efforts. This work would not have been possible without:

Drew Shindell, Daven Henze, Forrest Lacey, Ray Minjares, Josh Miller, Zig Klimont, Chris Malley, Lisa Emberson, Rita van Dingenen, Jason West, Bryan Hubbell, Neal Fann, and many other collaborators

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