Climate and Health Program
at the Mailman School of Public Health

COLUMBIA UNIVERSITY | MAILMAN SCHOOL of PUBLIC HEALTH
ENVIRONMENTAL HEALTH SCIENCES

Air Pollution and Climate Change: A Public Health Perspective

Mike He

Introduction to Atmospheric Chemistry

April 18, 2019

Overview

- Which air pollutants are of greatest health concern and why?
- Ozone and Particulate matter
  - Background and history
  - Case studies
  - Current research
- How might climate change affect air quality?

Air Pollution: the Big Picture

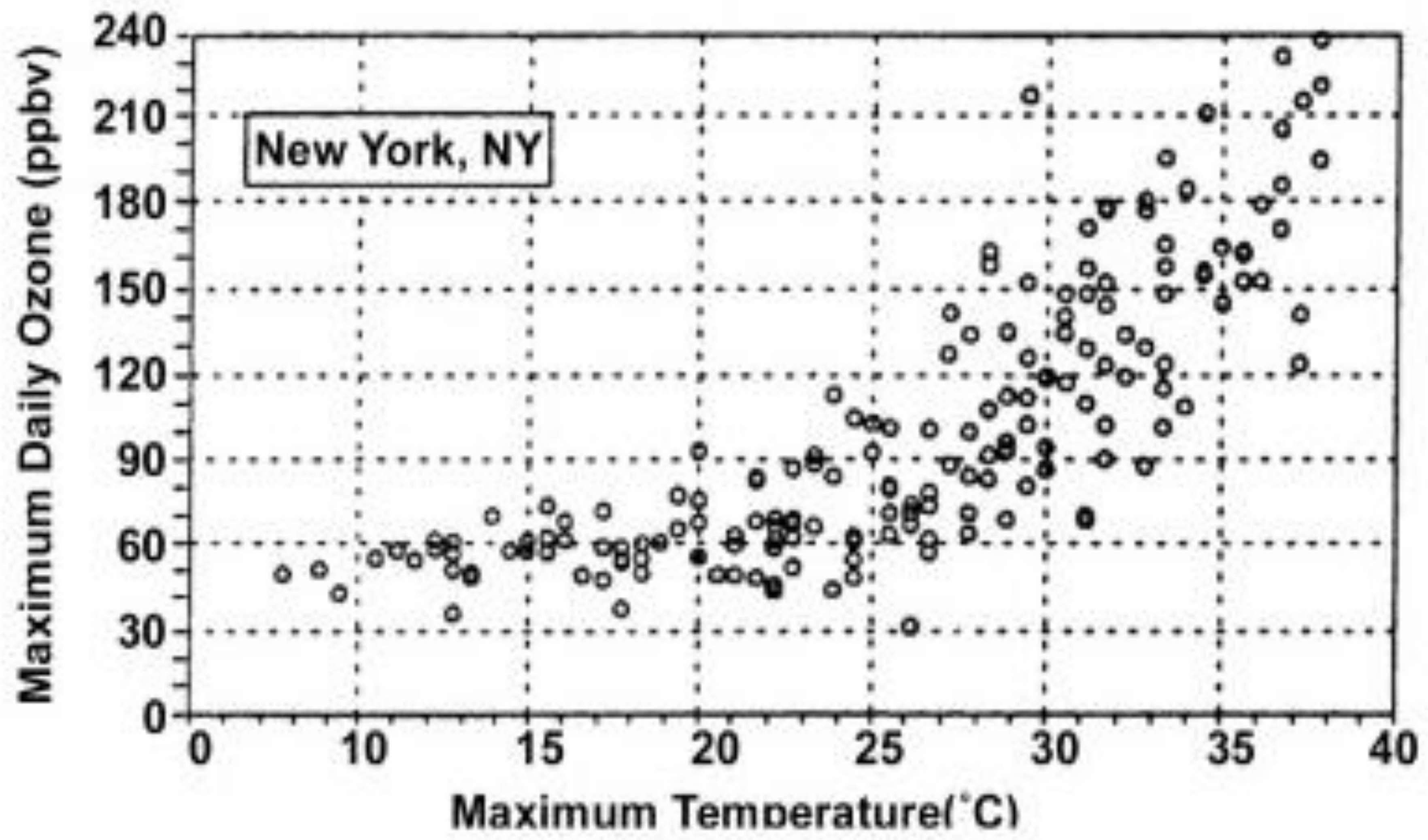
- Most but not all health-relevant outdoor air pollutants are produced by burning of fossil fuels
- The mixtures of air pollutants produced by burning of fuels can both
  - Adversely affect human health
  - Promote climate change
- In addition:
  - Climate influences air pollution concentrations via several mechanisms
  - Climate can affect other aspects of air quality, including smoke from agricultural or wild fires, and aero-allergens like pollen and mold spores

Criteria Air Pollutants

- Carbon monoxide (CO)
- Nitrogen dioxide (NO_2)
- Lead (Pb)
- Sulfur dioxide (SO_2)
- Ozone (O_3)
- Particulate matter ($PM_{2.5}$, PM_{10})

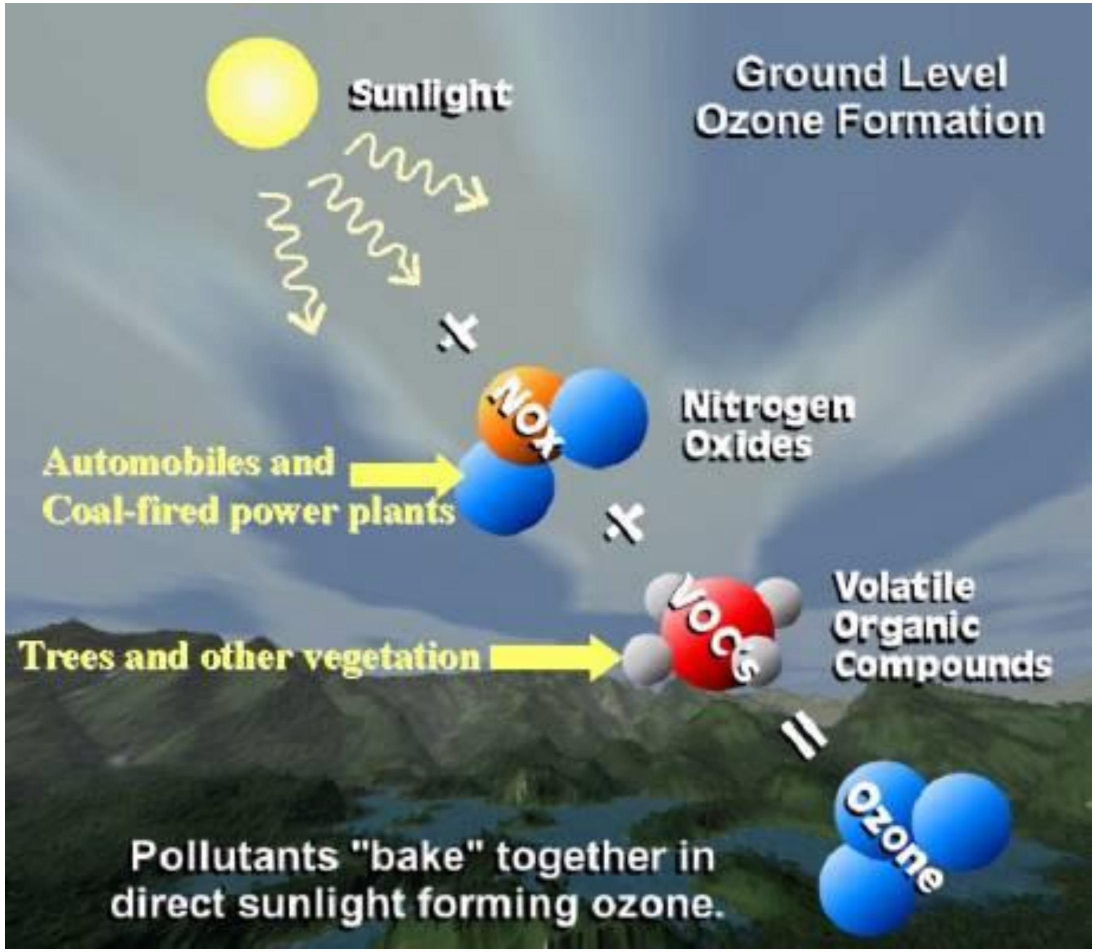
Ground-level Ozone

- A “secondary pollutant” i.e., formed via reactions in the atmosphere from primary pollutants (NO_x and VOCs) in the presence of sunlight
  - Where do NOx and VOCs come from?
- Higher temperatures favor ozone formation
- Strong oxidant that damages cells lining the respiratory system, resulting in a variety of adverse health outcomes, including lung function decrease, asthma attacks, and premature death
- Ozone is also a greenhouse gas



Source: US EPA (1991); in Kleinman and Lipfert, 1996.

Ozone Formation



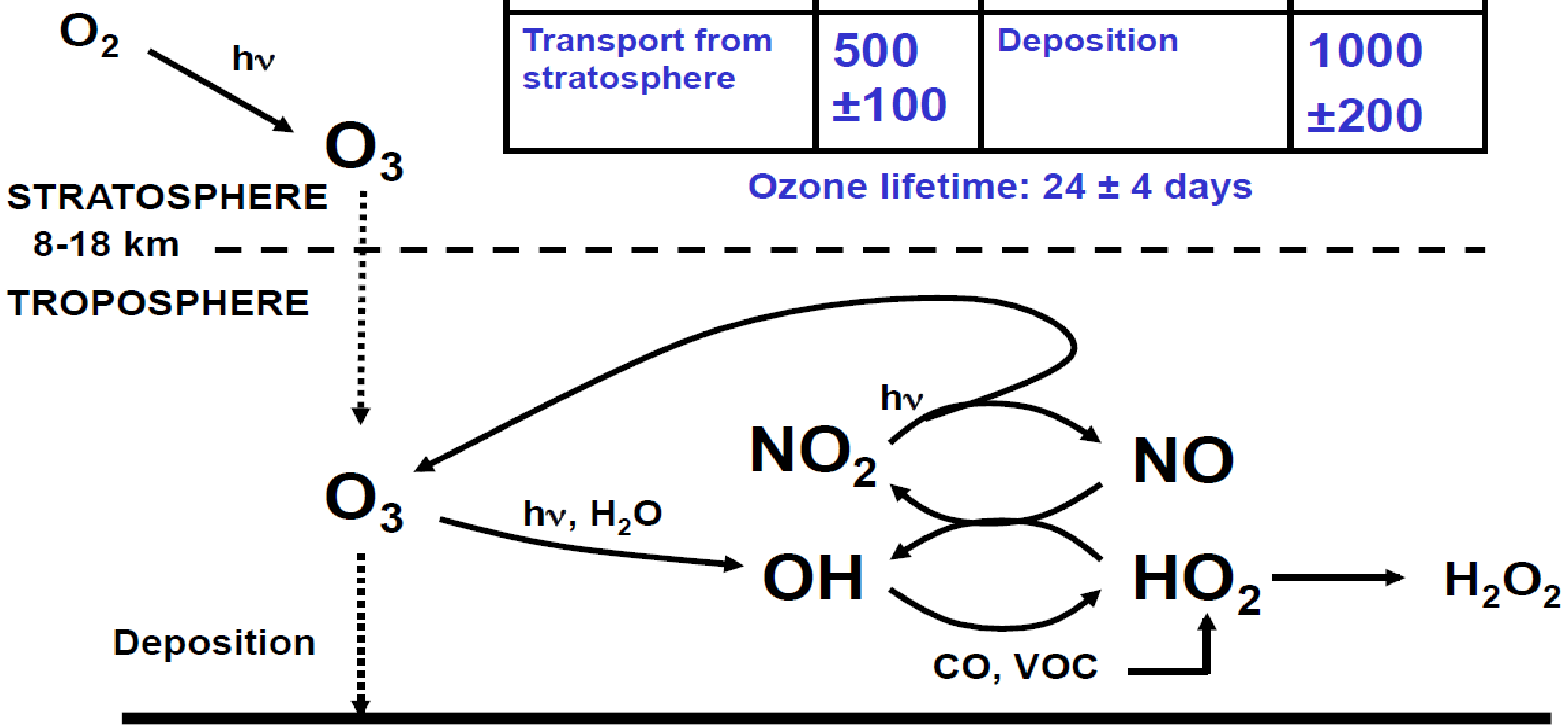
USDA Forest Service, 2013

GLOBAL BUDGET OF TROPOSPHERIC OZONE (Tg O_3 yr^{-1})

IPCC (2007) average of 12 models

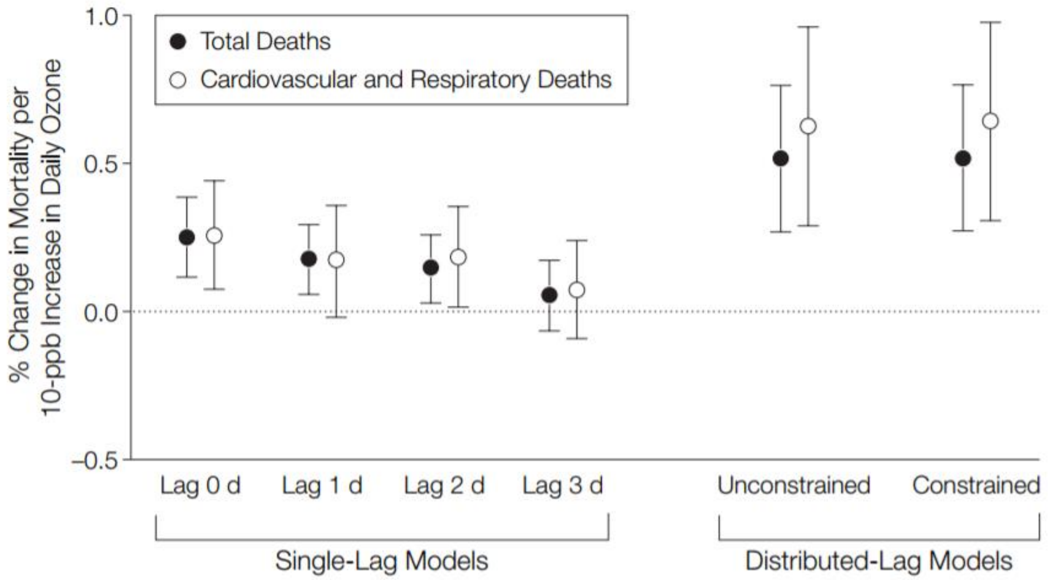
Chem prod in troposphere	4700 ±700	Chem loss in troposphere	4200 ±500
Transport from stratosphere	500 ±100	Deposition	1000 ±200

Ozone lifetime: 24 ± 4 days



Ozone and Acute Deaths

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

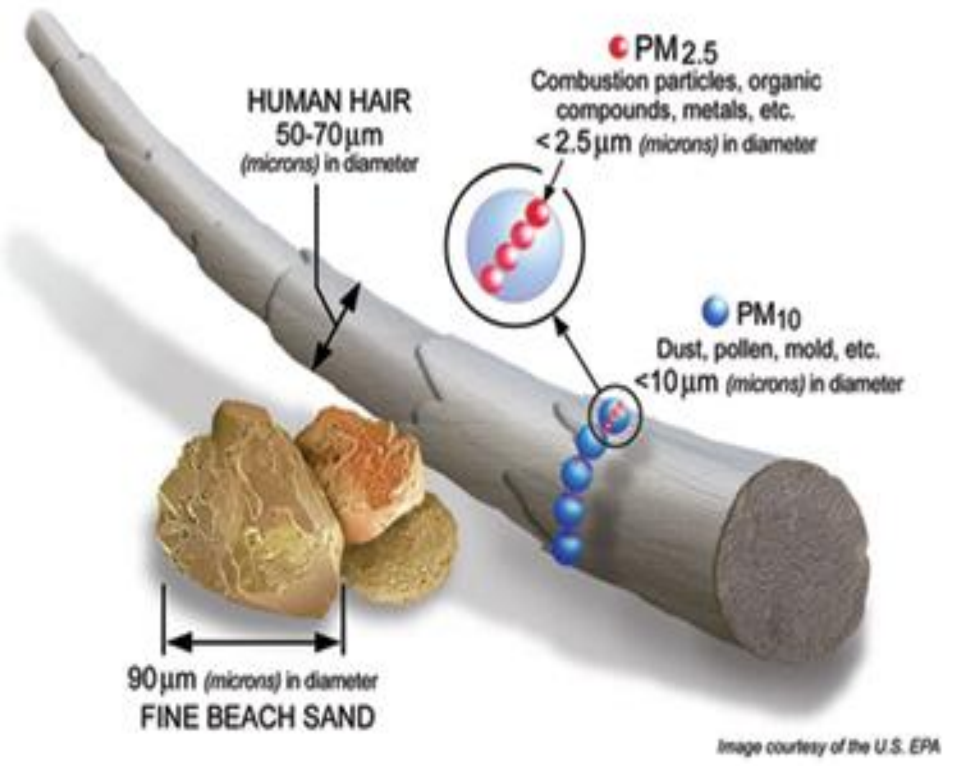


The single-lag model reflects the percentage increase in mortality for a 10-ppb increase in ozone on a single day. The distributed-lag model reflects the percentage change in mortality for a 10-ppb increase in ozone during the previous week. Error bars indicate 95% posterior intervals.

Bell et al., 2004

Particulate Matter ($PM_{2.5}$, PM_{10})

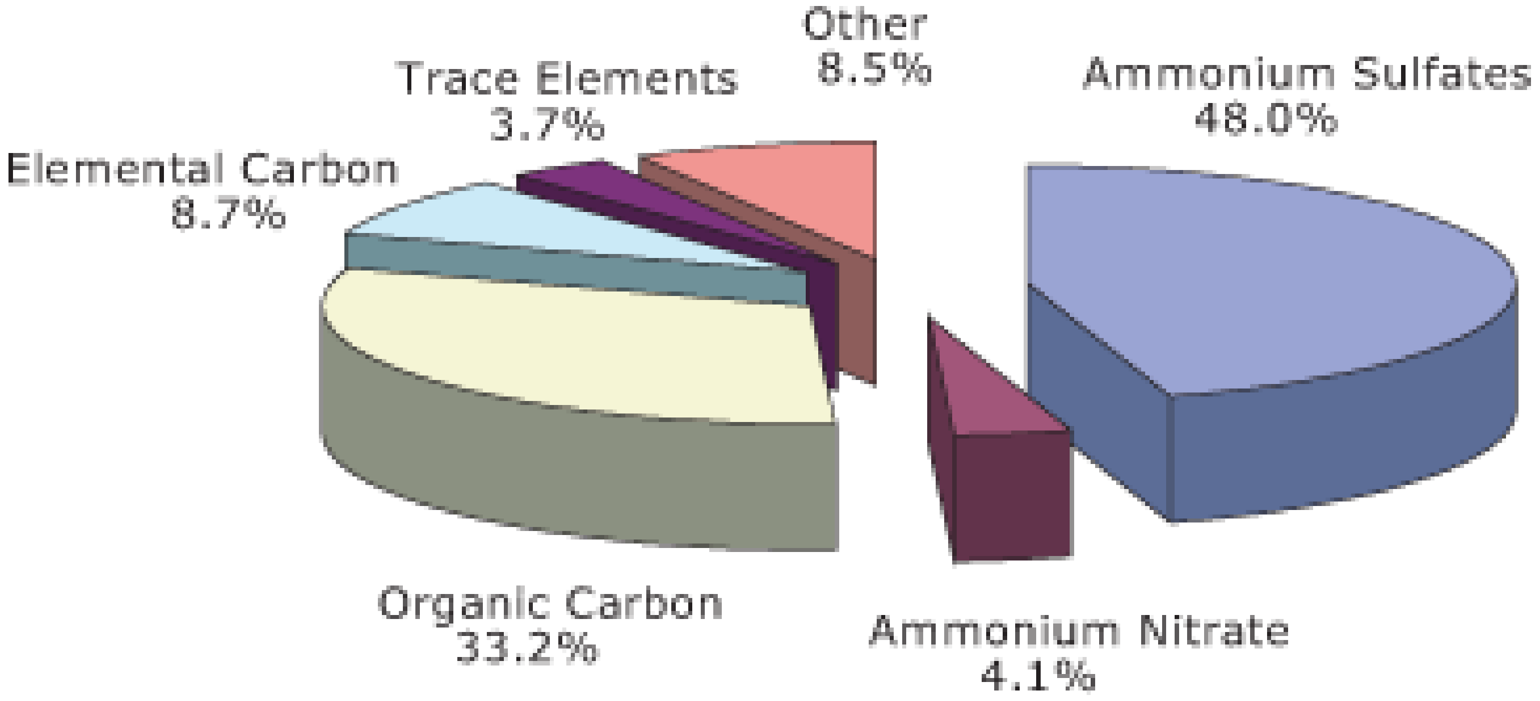
- A complex mixture of extremely small particles and liquid droplets, made up of acids, organic chemicals, metals, and soil or dust particles (EPA 2010)
- Divided into two subcategories: inhalable coarse particles (PM_{10}) and fine particles ($PM_{2.5}$)
- $PM_{2.5}$ is a big concern: bypass body's defense mechanism, and no natural clearance process



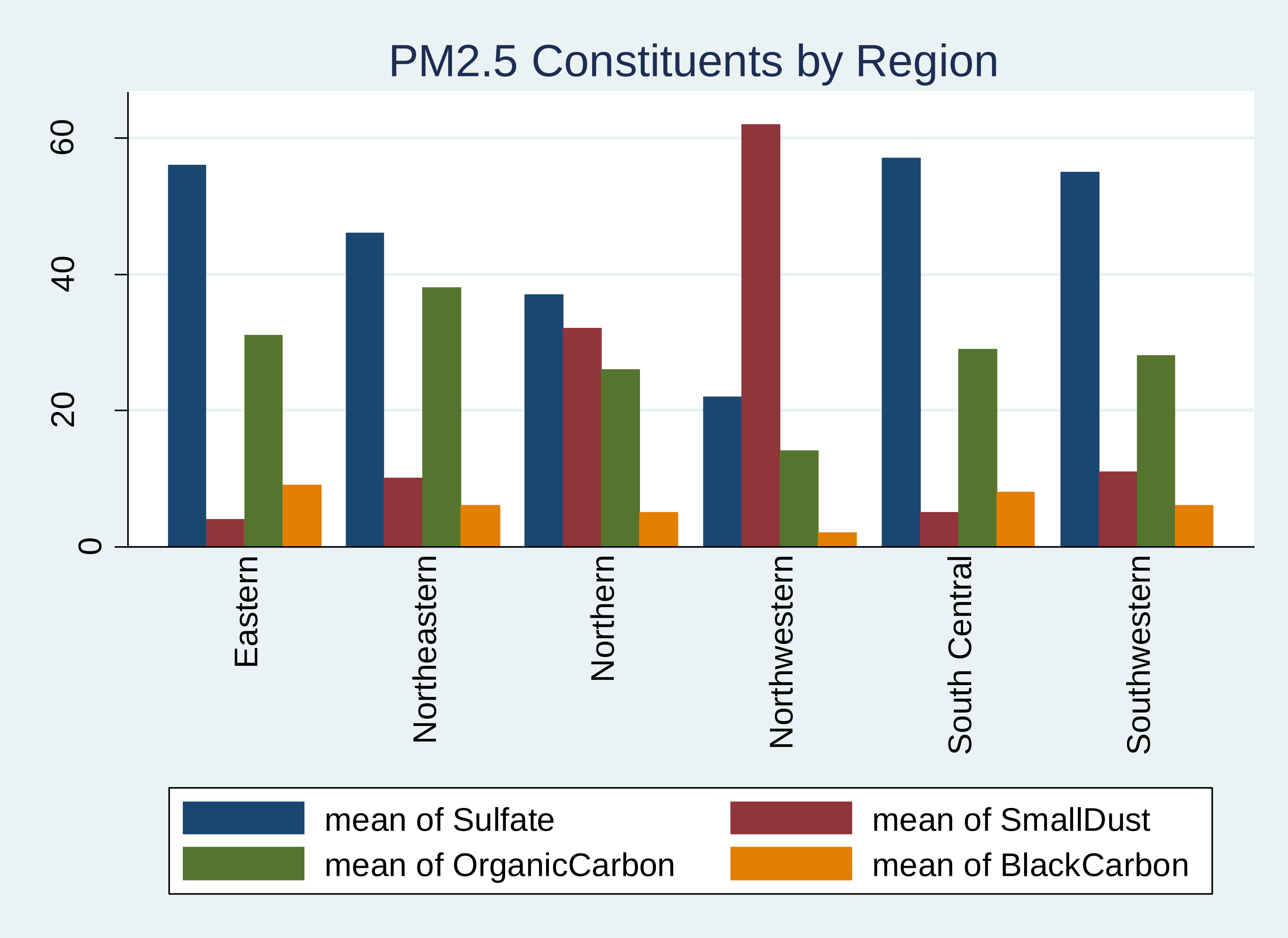
Particulate Matter ($PM_{2.5}$, PM_{10})

- Can be either primary or secondary; produced by combustion, atmospheric reactions, and mechanical processes
- Wide range of physical/chemical properties
- Wide range of human health impacts, including premature death
- Higher temperatures may favor secondary formation processes in the atmosphere
- Some particle types contribute to climate warming; others to climate cooling
  - Which?

$PM_{2.5}$ Composition



Annual average fine particle data for 2001 from the Look Rock station of the Tennessee Valley Authority. Source: http://www.tva.gov/environment/air/ontheair/fine_particles_smokies.htm


PM2.5 Constituents by Region
0
20
40
60
Eastern
Northeastern
Northern
Northwestern
South Central
Southwestern
mean of Sulfate
mean of SmallDust
mean of OrganicCarbon
mean of BlackCarbon

WHAT IS EPIDEMIOLOGY?

EPI **DEMOS** **LOGOS**

upon people study

EPIDEMIOLOGY?

The study of "what befalls a population"

The study of the distribution and determinants of health and disease in specified populations

LINKING EXPOSURE TO DISEASE OUTCOME (IN HUMAN POPULATIONS)

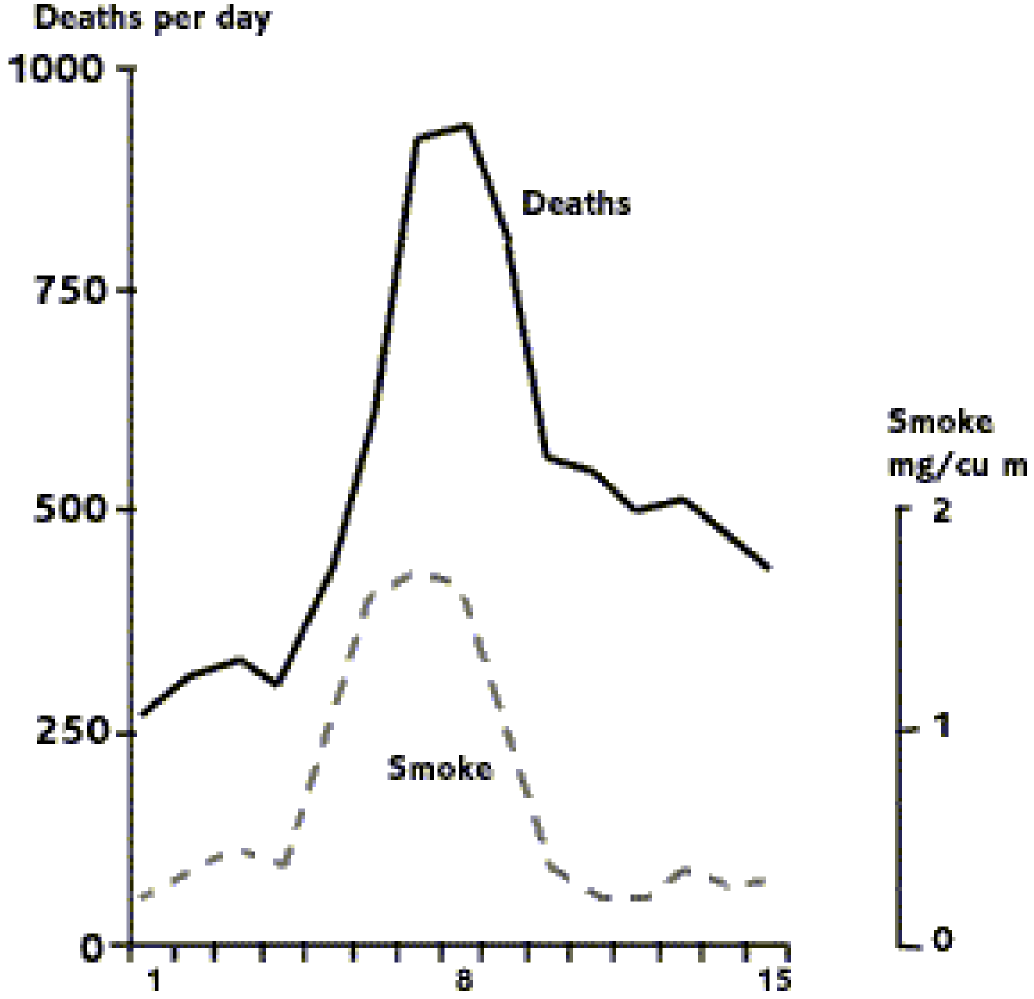
Epidemiology is a not a body of knowledge:
It's a methodology, a way of studying a health problem.

Health Effects of PM

- Historical experience provides strong evidence for causal relationship between PM exposure and premature death
- Modern epidemiologic studies have consistently found significant associations with a range of adverse health outcomes
- Two primary epidemiologic study designs:
  - **Time series studies of acute effects**
  - **Cohort studies of chronic effects**

London, December, 1952

London Killer Fog, December, 1952



UK Met Office, 2009

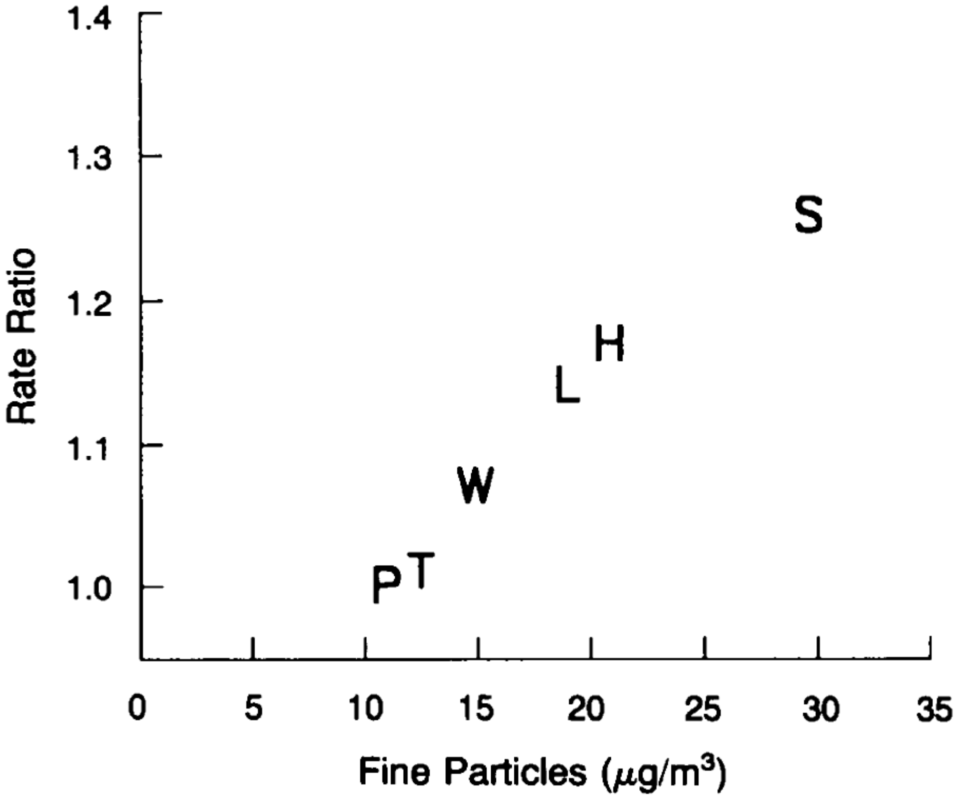
Time Series Epidemiology

- Addresses short-term, acute effects of air pollution
- Involves analysis of a series of daily observations of air pollution and health data
- Widely used and economical approach, often utilizing readily-available data
- Most air pollution epidemiology studies have followed this design

Prospective Cohort Studies

- They address longer-term, more chronic effects
- Approach:
  - Large populations in multiple cities enrolled and then followed for many years to determine disease or mortality experience
  - Must control for potential “spatial” confounders, e.g., smoking, income, race, diet, occupation
  - Assessment of confounders at individual level is an advantage over cross-sectional, “ecologic” studies

Harvard Six Cities Study



- Long-term average concentrations of fine particle air pollution were associated with mortality rates, controlling for individual-level risk factors across six US cities

Dockery et al., 1993


WILDLIFE PARK

A replication in a larger cohort:

Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution

Pope, C.A. et al., Journal of the American Medical Association: 287, 1132-1141, 2002

American Cancer Society Cohort Study

- Original study had nothing to do with air pollution, so this was "opportunistic epidemiology"
- Objective: To assess the relationship between long-term exposure to fine particulate air pollution and all-cause, lung cancer, and cardiopulmonary mortality
- Approach: Vital status and cause of death data were collected by the American Cancer Society through 1998 in 500,000 U.S. adults from 50 urban areas for which air pollution exposure data were available in 1980.

ACS Cohort Results

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.

Pope et al. 2002

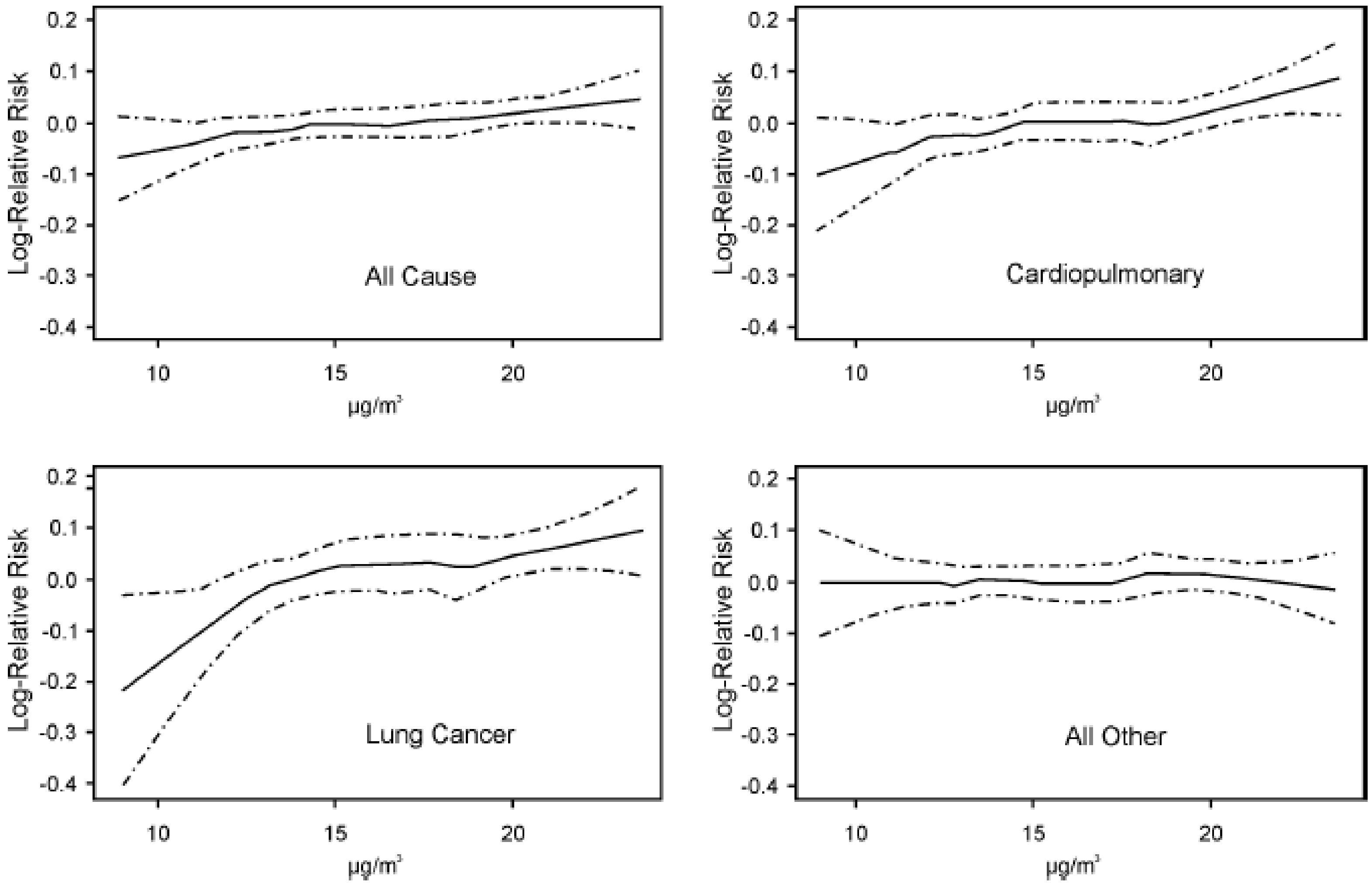


Figure 8-9. Natural logarithm of relative risk for total and cause-specific mortality per 10 μg/m³ $PM_{2.5}$ (approximately the excess relative risk as a fraction), with smoothed concentration-response functions. Based on Pope et al. (2002) mean curve (solid line) with pointwise 95% confidence intervals (dashed lines).

Conclusion

"Long-term exposure to combustion-related fine particle air pollution is an important environmental risk factor for cardiopulmonary and lung cancer mortality."

Beijing: Before and After Olympics

http://news.bbc.co.uk/2/hi/in_pictures/7506925.stm

The Air Pollution Brick

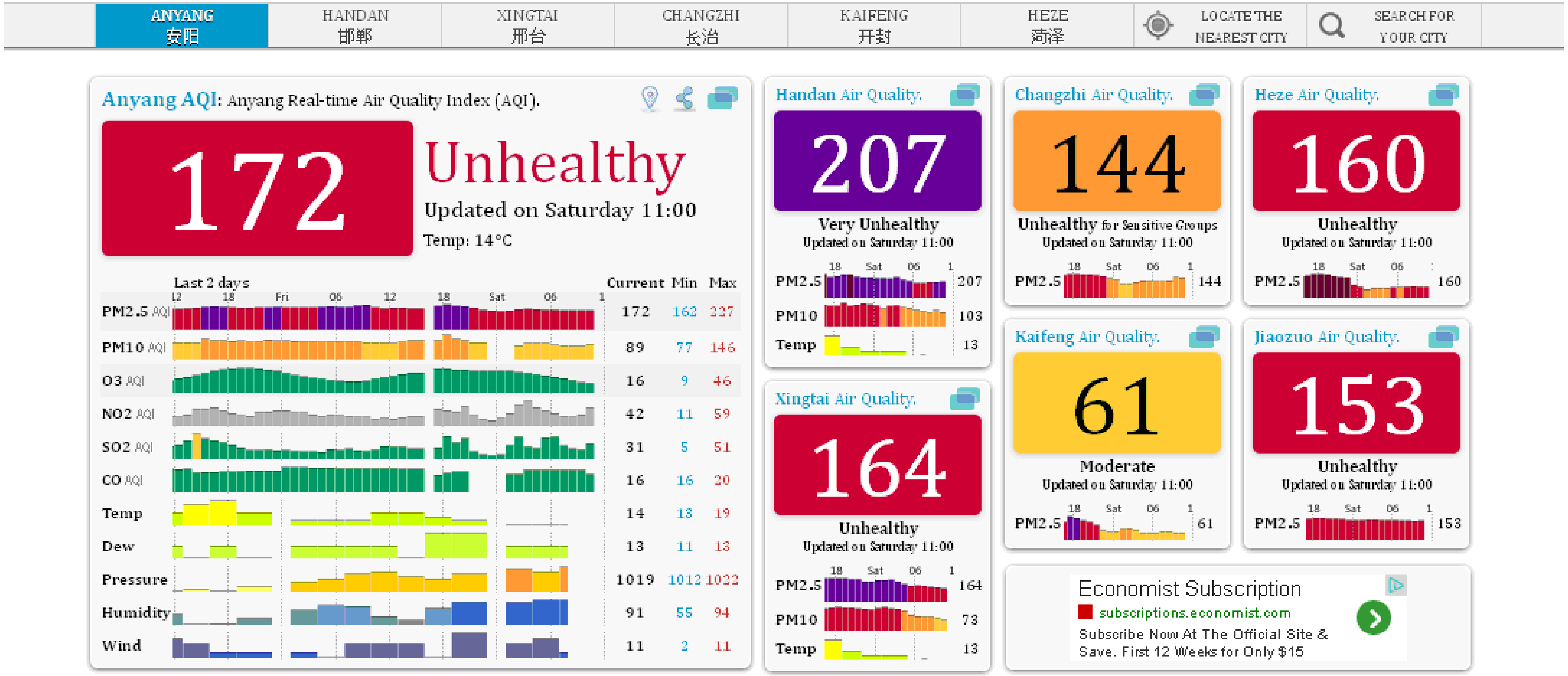
More Beijing

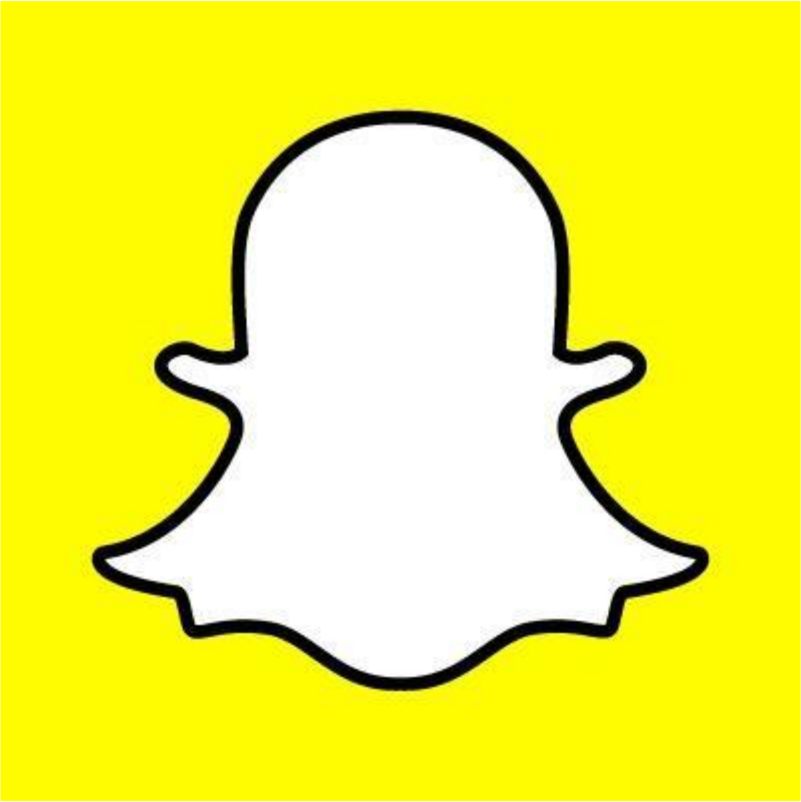
What about Data?

- Real time AQI exists, available for hundreds of cities
- Reports concentrations of various air pollutants, including $PM_{2.5}$
- But…

AQI	Air Pollution Level	Health Implications
0 - 50	Good	Air quality is considered satisfactory, and air pollution poses little or no risk
51 -100	Moderate	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
101-150	Unhealthy for Sensitive Groups	Members of sensitive groups may experience health effects. The general public is not likely to be affected.
151-200	Unhealthy	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects
201-300	Very Unhealthy	Health warnings of emergency conditions. The entire population is more likely to be affected.
300+	Hazardous	Health alert: everyone may experience more serious health effects

Anyang Air Pollution: Real-time Air Quality Index (AQI)





Another Caveat…

- Public data only available from 2013 and on
- What about pre-2013?

Research

Global Estimates of Ambient Fine Particulate Matter Concentrations from Satellite-Based Aerosol Optical Depth: Development and Application

Aaron van Donkelaar,[1] Randall V. Martin,[1,2] Michael Brauer,[3] Ralph Kahn,[4] Robert Levy,[4] Carolyn Verduzco,[1] and Paul J. Villeneuve[5,6]

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BACKGROUND: Epidemiologic and health impact studies of fine particulate matter with diameter < 2.5 μm ($PM_{2.5}$) are limited by the lack of monitoring data, especially in developing countries. Satellite observations offer valuable global information about $PM_{2.5}$ concentrations.

OBJECTIVE: In this study, we developed a technique for estimating surface $PM_{2.5}$ concentrations from satellite observations.

METHODS: We mapped global ground-level $PM_{2.5}$ concentrations using total column aerosol optical depth (AOD) from the MODIS (Moderate Resolution Imaging Spectroradiometer) and MISR (Multiangle Imaging Spectroradiometer) satellite instruments and coincident aerosol vertical profiles from the GEOS-Chem global chemical transport model.

RESULTS: We determined that global estimates of long-term average (1 January 2001 to 31 December 2006) $PM_{2.5}$ concentrations at approximately 10 km × 10 km resolution indicate a global population-weighted geometric mean $PM_{2.5}$ concentration of 20 μg/m³. The World Health Organization Air Quality $PM_{2.5}$ Interim Target-1 (35 μg/m³ annual average) is exceeded over central and eastern Asia for 38% and for 50% of the population, respectively. Annual mean $PM_{2.5}$ concentrations exceed 80 μg/m³ over eastern China. Our evaluation of the satellite-derived estimate with ground-based *in situ* measurements indicates significant spatial agreement with North American measurements ($r = 0.77$; slope = 1.07; $n = 1057$) and with noncoincident measurements elsewhere ($r = 0.83$; slope = 0.86; $n = 244$). The 1 SD of uncertainty in the satellite-derived $PM_{2.5}$ is 25%, which is inferred from the AOD retrieval and from aerosol vertical profile errors and sampling. The global population-weighted mean uncertainty is 6.7 μg/m³.

CONCLUSIONS: Satellite-derived total-column AOD, when combined with a chemical transport model, provides estimates of global long-term average $PM_{2.5}$ concentrations.

KEY WORDS: aerosol, aerosol optical depth, AOD, particulate matter, $PM_{2.5}$. *Environ Health Perspect* 118:847–855 (2010). doi:10.1289/ehp.0901623 [Online 16 March 2010]

et al. 2006; Liu et al. 2005) or to filter the AOD (e.g., Gupta et al. 2006). Some studies have employed light detection and ranging (LIDAR) instruments to capture the vertical aerosol distribution at specific locations (e.g., Engel-Cox et al. 2006; Schaap et al. 2008). Schaap et al. (2008) noted that locally derived AOD–$PM_{2.5}$ relationships cannot be extended easily to other regions because of variation in meteorology and aerosol composition. Unique, local, time-dependent AOD–$PM_{2.5}$ relationships are necessary to infer global estimates of $PM_{2.5}$. Ground-based measurements of aerosol vertical profiles and properties have insufficient coverage to estimate global AOD–$PM_{2.5}$ relationships.

Global chemical transport models (CTMs) resolve atmospheric composition at a resolution of hundreds of kilometers horizontally by hundreds of meters vertically, with a temporal frequency of tens of minutes. Liu et al. (2004) first estimated surface-level $PM_{2.5}$ from MISR observations by using CTM output to represent local AOD–$PM_{2.5}$ conversion factors over the contiguous United

Research

A Section 508–conformant HTML version of this article is available at http://dx.doi.org/10.1289/ehp.1409481.

Satellite-Based Spatiotemporal Trends in $PM_{2.5}$ Concentrations: China, 2004–2013

Zongwei Ma,[1,2] Xuefei Hu,[2] Andrew M. Sayer,[3,4] Robert Levy,[4] Qiang Zhang,[5] Yingang Xue,[6] Shilu Tong,[7] Jun Bi,[1] Lei Huang,[1] and Yang Liu[2]

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Background: Three decades of rapid economic development is causing severe and widespread $PM_{2.5}$ (particulate matter ≤ 2.5 μm) pollution in China. However, research on the health impacts of $PM_{2.5}$ exposure has been hindered by limited historical $PM_{2.5}$ concentration data.

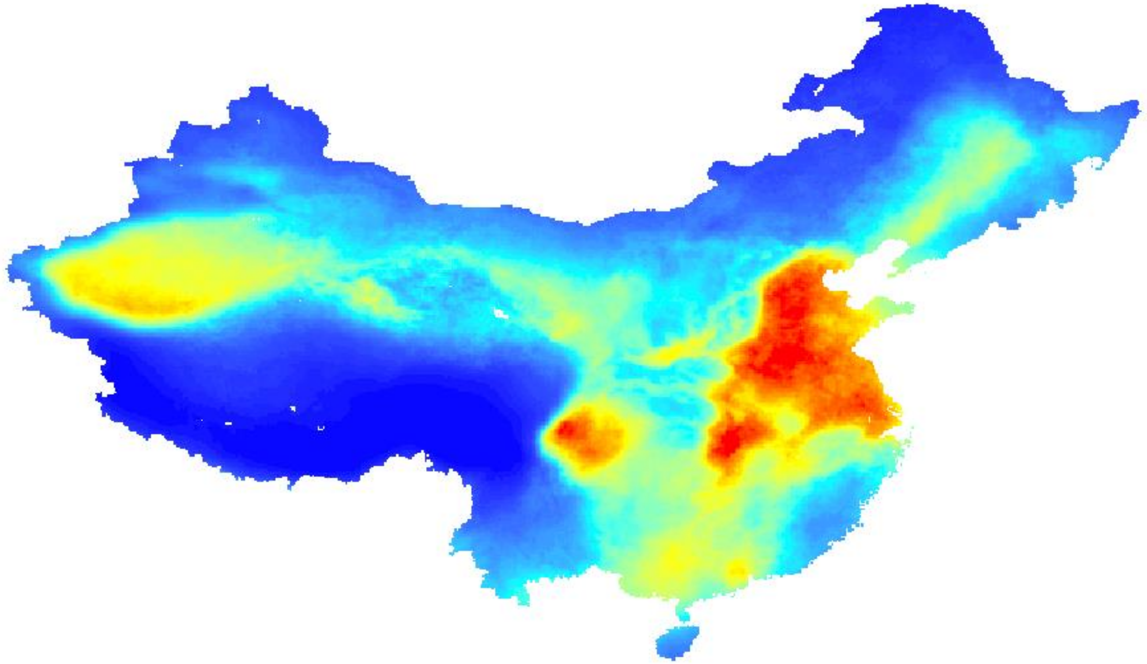
Objectives: We estimated ambient $PM_{2.5}$ concentrations from 2004 to 2013 in China at 0.1° resolution using the most recent satellite data and evaluated model performance with available ground observations.

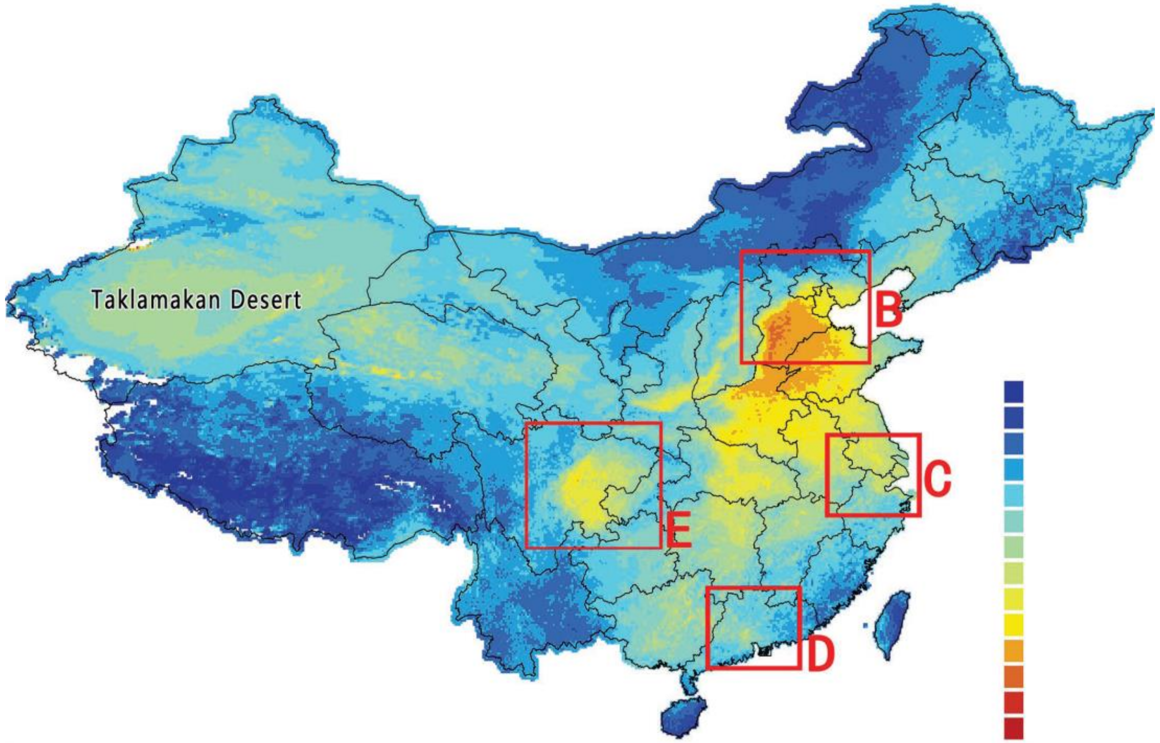
Methods: We developed a two-stage spatial statistical model using the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 aerosol optical depth (AOD) and assimilated meteorology, land use data, and $PM_{2.5}$ concentrations from China's recently established ground monitoring network. An inverse variance weighting (IVW) approach was developed to combine MODIS Dark Target and Deep Blue AOD to optimize data coverage. We evaluated model-predicted $PM_{2.5}$ concentrations from 2004 to early 2014 using ground observations.

China from 2006 to 2010. However, their ANN was trained partially using $PM_{2.5}$ and satellite data from the United States, which may have introduced substantial prediction error.

Taking advantage of the newly available national $PM_{2.5}$ measurements for China, Ma et al. (2014) estimated $PM_{2.5}$ levels for 2013 in China using satellite AOD and a geographically weighted regression (GWR) model. Using an early version of the Dark Target (DT) algorithm (Remer et al. 2005), this study adopted a relatively coarse spatial

Comparison with GFDL Model





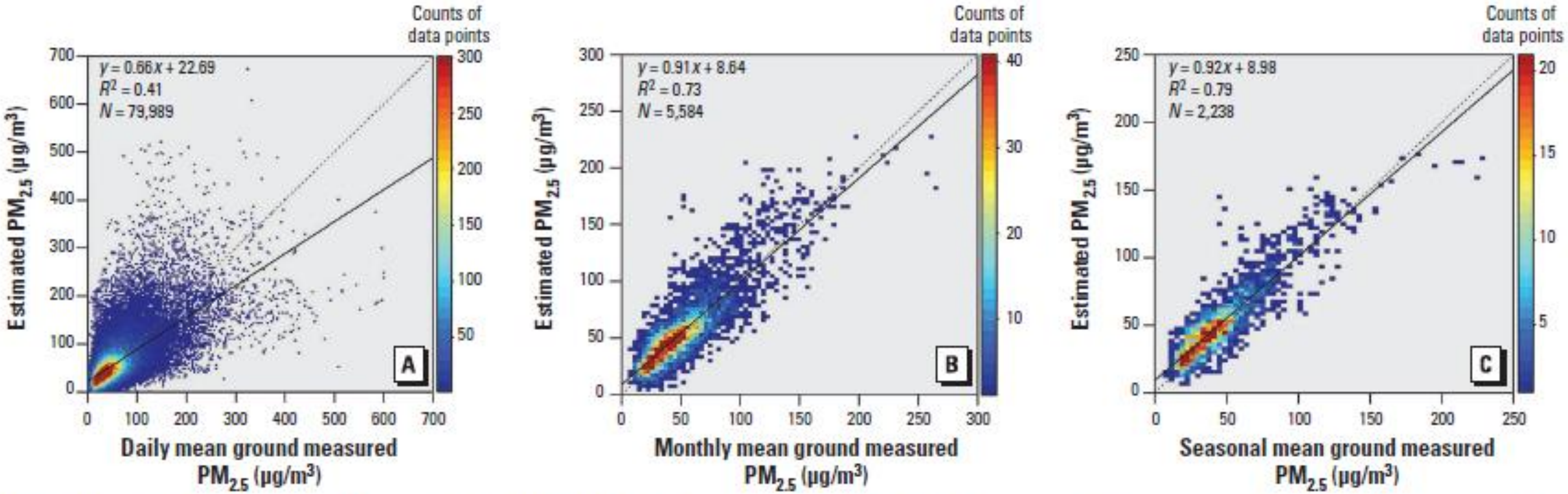


Figure 5. Evaluation of historical $PM_{2.5}$ estimations (2004–2012 and January–June 2014) at daily (*A*), monthly (*B*), and seasonal (*C*) levels. Because there were few ground $PM_{2.5}$ data for mainland China before 2013, we also estimated $PM_{2.5}$ for the first half of 2014 using the 2013 model and compared the results with the ground measurements to validate the accuracy of the historical estimations.

Piecing Together the Puzzle

International Journal of
Environmental Research and Public Health

MDPI

Review

Fine Particulate Matter Concentrations in Urban Chinese Cities, 2005–2016: A Systematic Review

Mike Z. He [1,2,*], Xiange Zeng [3], Kaiyue Zhang [4,5] and Patrick L. Kinney [6]

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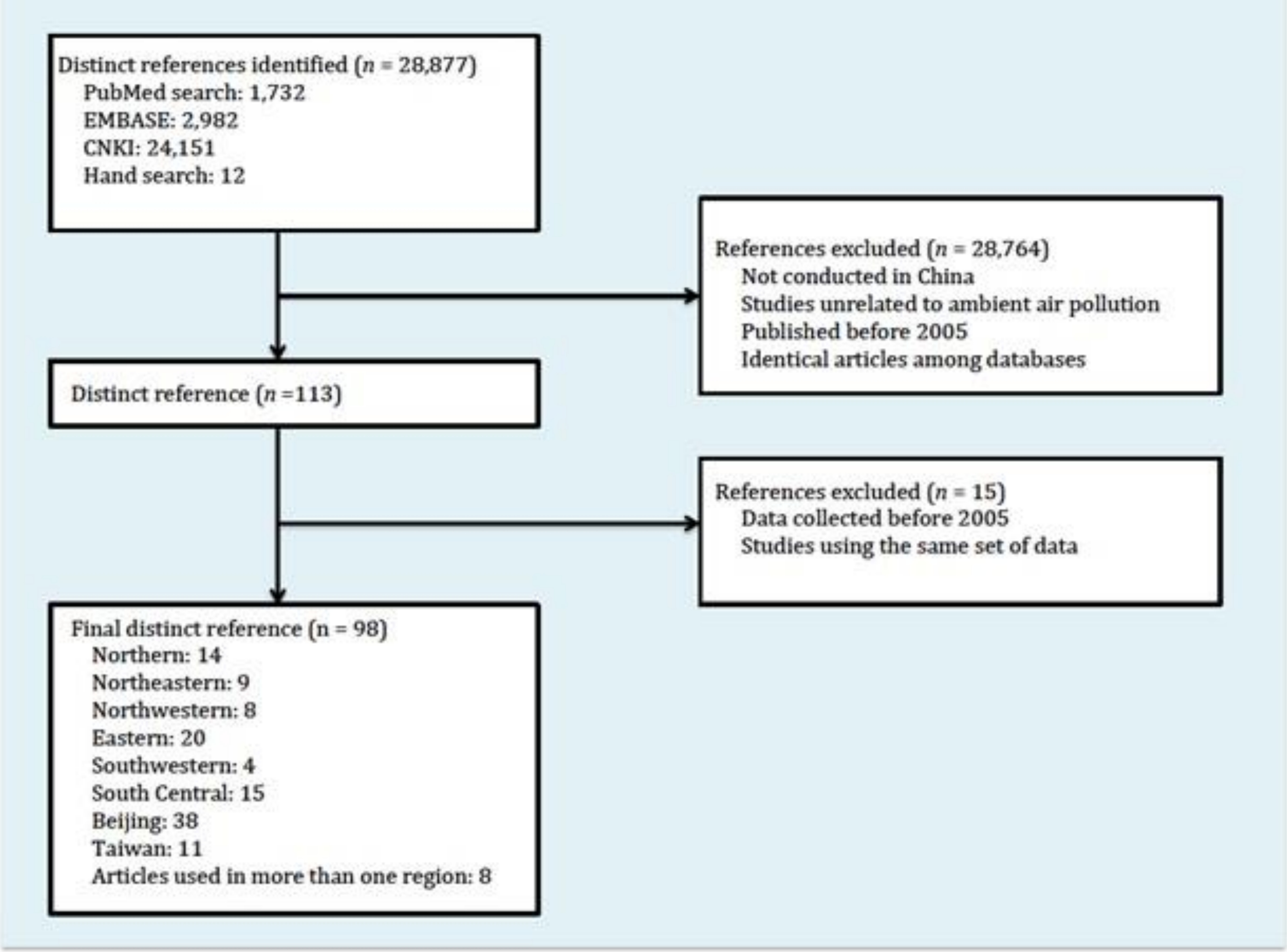
A Grueling Process…Not Fun



But it Exists!

Table 1. Summary of geographic regions.

Region	$[PM_{2.5}]$ ($\mu g/m^3$)	Number of Measurements	% Above Annual Limit [1]	% Above 24-h Limit [2]
Northeastern	66.50 ± 27.96	61	91.80%	34.43%
Northern	76.10 ± 38.69	53	100%	50.94%
Northwestern	85.41 ± 59.19	42	100%	14.29%
Eastern	55.41 ± 18.16	121	86.78%	20.66%
South Central	50.23 ± 21.00	136	75.74%	16.91%
Southwestern	48.72 ± 13.63	51	90.20%	11.76%
Beijing	94.42 ± 23.83	98	100%	77.55%
Taiwan	30.49 ± 1.81	12	8.33%	0%
Overall Average	**60.64 ± 33.27**	**574**	**87.80%**	**32.06%**

[1] Annual limit is 35 $\mu g/m^3$. [2] 24-h limit is 75 $\mu g/m^3$.

Table 2. Summary of three economic regions.

Region	$[PM_{2.5}]$ ($\mu g/m^3$)	Number of Measurements	% Above Annual Limit [1]	% Above 24-h Limit [2]
BTH	93.73 ± 25.89	123	100%	78.05%
Yangtze River	55.86 ± 17.62	59	93.22%	28.1%
Pearl River	47.23 ± 14.86	38	65.79%	13.16%
Overall Average	**71.99 ± 30.20**	**220**	**92.27%**	**53.64%**

[1] Annual limit is 35 $\mu g/m^3$. [2] 24-h limit is 75 $\mu g/m^3$.

How might Climate Change affect Air Pollution?

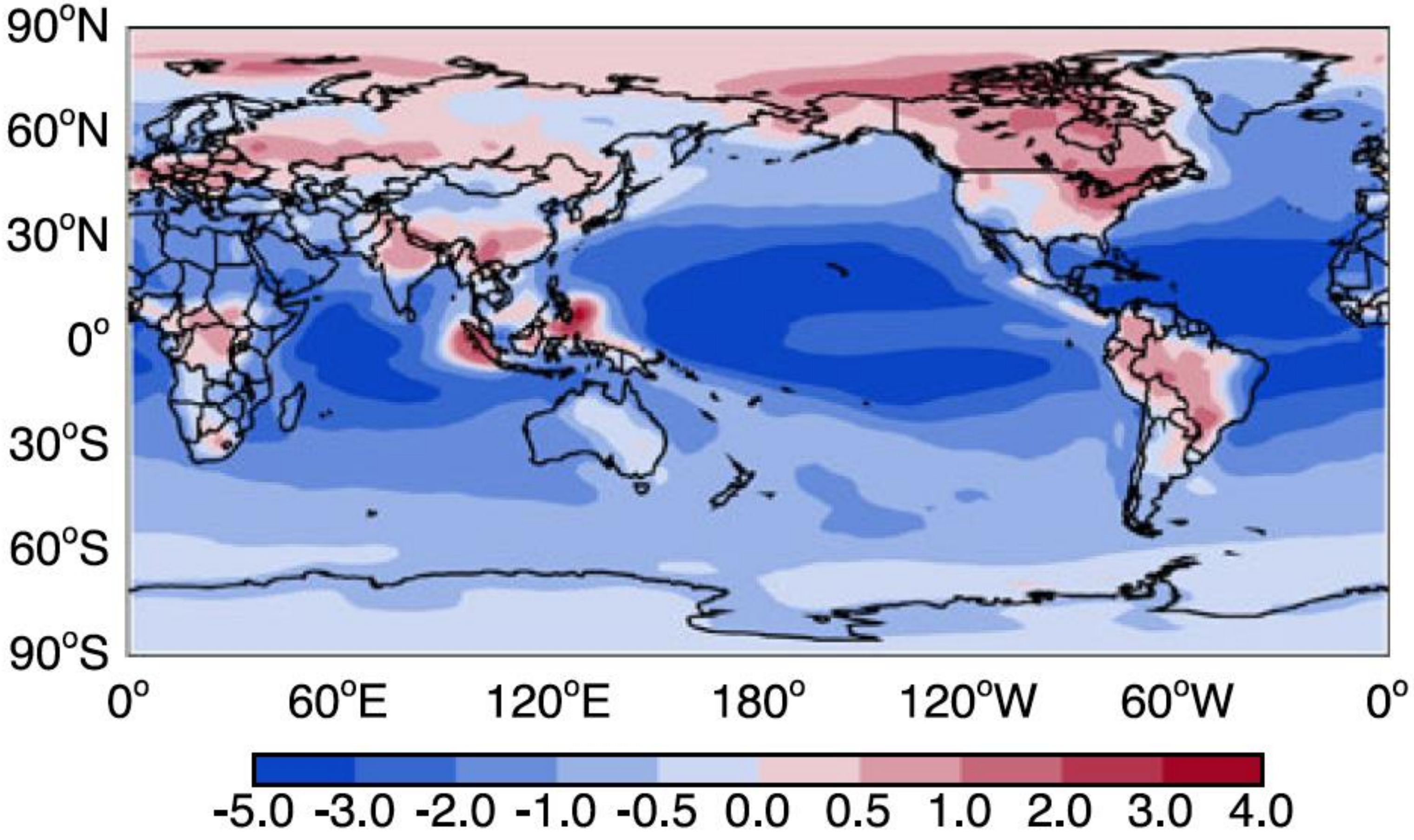
- Formation reactions for secondary pollutants generally happen faster at high temp and with greater sunlight
- Biogenic emissions increase at higher temp

- Some particle species may volatilize at higher temperatures

- Regional air mass patterns over time and space may change, altering stagnation and clearance events
- The mixing height of the lower atmosphere may change, affecting dilution of pollution emitted at the surface

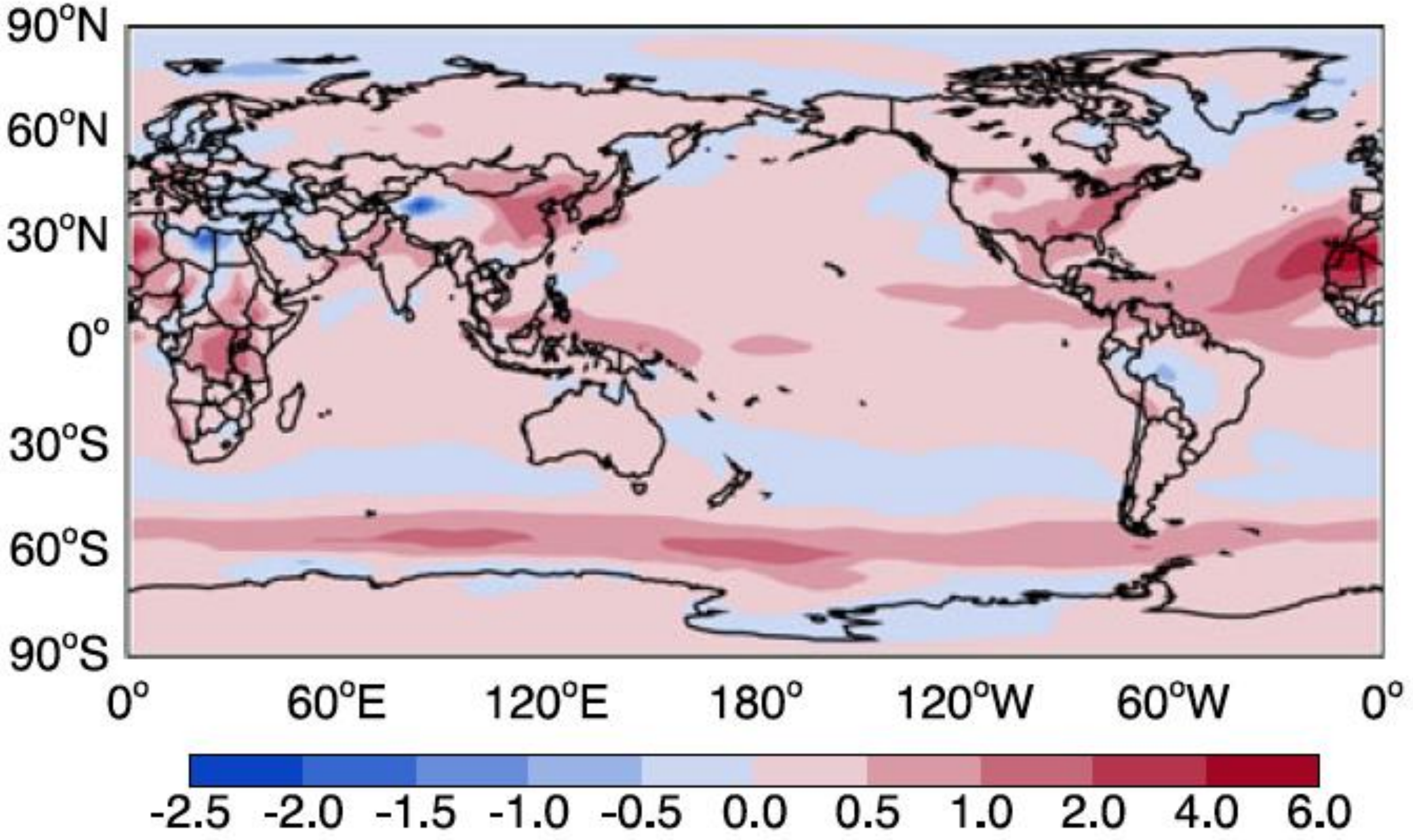
→ Use Coupled Climate/Air Quality Models to Investigate

Climate-induced Changes in Ozone (ppb) from late 20th to late 21st Century



Fang et al., Climatic Change, 2013

Climate-induced Changes in $PM_{2.5}$ ($\mu g/m^3$) from late 20th to late 21st Century



Fang et al., Climatic Change, 2013

Key Inputs and Assumptions in Assessing Future Climate-Air Quality-Health Impacts

- Baseline and Future Time Windows
- Climate models
  - Which models?
  - At what spatial scale? Downscaling?
- Greenhouse gas emission scenarios
  - SRES (older IPCC reports); RCPs (newer IPCC reports)
- Air pollution models and emission scenarios
  - Which models? Downscaling?
- Exposure-response functions
- Population projections
- Baseline mortality rates by region and over time

Take-Home Messages

- Air pollution is bad; $PM_{2.5}$ and ozone priority
- Many historical and current research that document health effects of $PM_{2.5}$, currently a huge concern
- Climate change will make it harder to achieve future air quality goals – the "climate penalty"
- We lack climate/air quality/health information at fine spatial scales relevant to local decision makers
- To the extent possible, air pollution and climate mitigation should be planned in a coordinated way

Questions?