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

RR > 1  Risk increase
RR = 1  No effect
RR < 1  Risk decrease

American Cancer Society Study

Pope and Dockery, 2006
Current evidence suggests that \( \text{PM}_{2.5} \) has a stronger relationship with mortality than does \( \text{O}_3 \).

Slope = Concentration-Response Factor
# 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 µg/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 µg/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.)

![Graph showing PM$_{10}$ levels over time]

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 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.

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.
Harvard Six-Cities Study (Dockery et al., 1993):
First long-term cohort study of chronic mortality.
~8000 adults followed over many years.
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.

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.

By PHILIP J. HILTS
Special to The New York Times
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

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

- **Attributable fraction**
- **Baseline mortality**
- **Annual deaths**
- **Concentration-response factor**
- **Change in concentration**
- **Population exposed**
- **Baseline mortality rate**

\[ y_0 \text{ is fraction of population that has health effect in a year.} \]

\[ \text{Pop is not necessarily the total population.} \]

\[ \text{If } \beta \Delta X \text{ is small, then } 1-e^{-\beta \Delta X} \approx \beta \Delta X \]
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\(_{2.5}\).

\[
RR = \frac{0.03}{10} = 0.003 \text{ per µgm}^{-3}
\]

\[
\beta = \frac{RR}{(1+RR)} = \frac{0.003}{(1.003)} = 0.00299 \text{ per µgm}^{-3}
\]

\[
\Delta X = 1 \text{ µgm}^{-3}
\]

\[
Pop = 195 \text{ million (adult population, > 30 yrs old)}
\]

\[
y_0 = 0.012 \text{ (per year, for adults from all causes of death)}
\]

\[
\Delta \text{Mort} = \frac{(0.00299 (\text{µgm}^{-3})^{-1}) (1 \text{ µgm}^{-3}) (195 \times 10^6) (0.012 \text{ yr}^{-1})}{1 = 7000 \text{ deaths reduced per year}}
\]
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°)

6,946 million
3,839 million
Baseline Mortality Rates

Baseline Mortality Rates, deaths per year per 100,000 (GBD 2010, country level, AllAges > gridded to 0.67°x0.5°)

IHD

COPD

Stroke

LC
What are sources of pollutant concentrations ($\Delta X$)?

- Observations
- Satellites
- Models
- Data Fusion
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.)
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

- US Census Data
- Population Estimates
  - Air Quality Modeling
  - Population Exposure Projections
  - Air Quality Monitoring
  - Baseline & Projected Incidence Rates

- Population Projections

BenMAP Input

User Input Choice

Result from Inputs

Adverse Health Effects

Economic Benefits

Valuation Functions

EPA-452/R-19-003
June 2019
<table>
<thead>
<tr>
<th></th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Avoided premature death among adults</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Krewski et al. (2009)</td>
<td>33 (22 to 43)</td>
<td>44 (30 to 58)</td>
<td>48 (32 to 63)</td>
</tr>
<tr>
<td>Lepeule et al. (2012)</td>
<td>74 (37 to 110)</td>
<td>99 (49 to 150)</td>
<td>110 (54 to 160)</td>
</tr>
<tr>
<td>Ozone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smith et al. (2009)</td>
<td>6 (3 to 9)</td>
<td>6 (3 to 9)</td>
<td>7 (4 to 11)</td>
</tr>
<tr>
<td>Jerrett et al. (2009)</td>
<td>23 (8 to 38)</td>
<td>23 (8 to 38)</td>
<td>28 (9 to 46)</td>
</tr>
<tr>
<td><strong>PM$_{2.5}$-related non-fatal heart attacks among adults</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peters et al. (2001)</td>
<td>37 (9 to 64)</td>
<td>48 (12 to 84)</td>
<td>50 (12 to 88)</td>
</tr>
<tr>
<td>Pooled estimate</td>
<td>4 (2 to 11)</td>
<td>5 (2 to 14)</td>
<td>5 (2 to 14)</td>
</tr>
<tr>
<td><strong>All other morbidity effects</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hospital admissions—</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cardiovascular (PM$_{2.5}$)</td>
<td>9 (4 to 16)</td>
<td>12 (5 to 22)</td>
<td>13 (5 to 23)</td>
</tr>
<tr>
<td>Hospital admissions—</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>respiratory (PM$_{2.5}$ &amp; O$_3$)</td>
<td>19 (6 to 40)</td>
<td>23 (7 to 48)</td>
<td>25 (8 to 53)</td>
</tr>
<tr>
<td>ED visits for asthma (PM$_{2.5}$ &amp; O$_3$)</td>
<td>54 (3 to 150)</td>
<td>55 (5 to 150)</td>
<td>65 (5 to 180)</td>
</tr>
<tr>
<td>Exacerbated asthma (PM$_{2.5}$ &amp; O$_3$)</td>
<td>14,000 (11,000 to 35,000)</td>
<td>14,000 (11,000 to 34,000)</td>
<td>17,000 (13,000 to 41,000)</td>
</tr>
<tr>
<td>Minor restricted-activity days (PM$_{2.5}$ &amp; O$_3$)</td>
<td>48,000 (28,000 to 67,000)</td>
<td>52,000 (32,000 to 71,000)</td>
<td>58,000 (36,000 to 80,000)</td>
</tr>
<tr>
<td>Acute bronchitis (PM$_{2.5}$)</td>
<td>42 (10 to 94)</td>
<td>56 (13 to 130)</td>
<td>60 (14 to 130)</td>
</tr>
<tr>
<td>Upper resp. symptoms (PM$_{2.5}$)</td>
<td>770 (140 to 1,400)</td>
<td>1,000 (190 to 1,900)</td>
<td>1,100 (200 to 2,000)</td>
</tr>
<tr>
<td>Lower resp. symptoms (PM$_{2.5}$)</td>
<td>540 (200 to 870)</td>
<td>720 (270 to 1,200)</td>
<td>770 (290 to 1,200)</td>
</tr>
<tr>
<td>Lost work days (PM$_{2.5}$)</td>
<td>3,700 (3,100 to 4,200)</td>
<td>4,600 (3,900 to 5,400)</td>
<td>5,000 (4,300 to 5,800)</td>
</tr>
<tr>
<td>School absence days (O$_3$)</td>
<td>8,400 (3,000 to 19,000)</td>
<td>8,200 (2,900 to 18,000)</td>
<td>9,700 (3,400 to 22,000)</td>
</tr>
</tbody>
</table>

*Values rounded to two significant figures.*
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$^{-3}$)

Silva et al. (2013)
### Global and regional mortality per year

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

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

1 in 19 deaths globally!  
1 in 45 deaths globally!

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**
  - Global total: 290,000 deaths/year

- **Industry**
  - Global total: 323,000 deaths/year

- **Land Transportation**
  - Global total: 212,000 deaths/year

- **Residential & Commercial**
  - Global total: 675,000 deaths/year

Silva et al. (EHP, 2016)
Ozone from N. American and European emissions causes more deaths outside of those regions than within.

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

Silva et al. Nat Clim Ch, 2017

- OZONE
  - 2030: 3,000 (95% CI: -30,000, 47,000)
  - 2100: 44,000 (95% CI: -195,000, 237,000)

- PM$_{2.5}$
  - 2030: 56,000 (95% CI: -34,000, 164,000)
  - 2100: 215,000 (95% CI: -76,000, 595,000)
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 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.
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).
INTERVENTION MODEL FOR AIR POLLUTION

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

Christopher Tessum | Jason Hill | Julian Marshall

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

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

Annual deaths

Concentration-response factor

Change in concentration

Population exposed

Baseline mortality rate
Health impact function

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

- Annual avoided mortalities
- Concentration-response factor
- Change in concentration
- Population exposed
- Baseline mortality rate

\( \beta \) – from re-analysis of ACS cohort: Krewski et al. (2009) for \( \text{PM}_{2.5} \), Jerrett et al. (2009) for ozone.

\( \text{Pop} \) – from LANDSCAN database at very fine resolution, adjusted for adult population.

\( y_0 \) – from WHO country- or region-level data.

\( \text{Pop} \) and \( y_0 \) fields were gridded using a GIS.
Health impact function

\[ \Delta \text{Mort} = y_0 \times AF \times \text{Pop} \]

\[ \Delta \text{Mort} = y_0 \times (1 - \exp^{-\beta \Delta X}) \times \text{Pop} \]

- Baseline mortality rate
- Exposed Population
- \( \Delta X = \text{Change in concentration} \)
- \( \beta = \text{Concentration-response factor} \)

- Respiratory diseases (RESP)
  (inc. COPD – chronic obstructive pulmonary disease)
- Cardiovascular diseases
  (inc. IHD – ischemic heart disease, STROKE – cerebrovascular disease)
- Lung Cancer (LC)
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.
- Measurements of chemical components
- Spatially-distributed measurements (cheap sensors)
- Satellite observations
- Computer models
• Which pollutants to emphasize, averaging times
• Risk functions
• Biological mechanisms
American Cancer Society Study (Pope et al., 2002) >500,000 adult volunteers followed.
Global Burden: Ozone-related mortality

Global and regional mortality per year

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</tr>
<tr>
<td>Former Soviet Union</td>
<td>10,600</td>
<td>66</td>
</tr>
<tr>
<td>Middle East</td>
<td>16,200</td>
<td>68</td>
</tr>
<tr>
<td><strong>India</strong></td>
<td><strong>118,000</strong></td>
<td><strong>212</strong></td>
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<tr>
<td><strong>East Asia</strong></td>
<td><strong>203,000</strong></td>
<td><strong>230</strong></td>
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<td>Southeast Asia</td>
<td>33,300</td>
<td>119</td>
</tr>
<tr>
<td>South America</td>
<td>6,970</td>
<td>38</td>
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<tr>
<td>Africa</td>
<td>17,300</td>
<td>73</td>
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<tr>
<td>Australia</td>
<td>469</td>
<td>29</td>
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<tr>
<td><strong>Global</strong></td>
<td><strong>472,000</strong></td>
<td><strong>149</strong></td>
</tr>
</tbody>
</table>

(*): Exposed population (age 30 and older)

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

Silva et al. (2013)