Global, Long-term Insight into PM$_{2.5}$ Exposure using Aerosol Optical Depth

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Building on, and with the help and many, many others...

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Fine aerosol ($PM_{2.5}$) affects human health and longevity

**Diseases due to:**
- PM$_{2.5}$ air pollution
- Heart attacks
- Strokes, heart disease
- Congestive heart failure
- Lung cancer
- Chronic bronchitis
- Asthma
- Emphysema
- Scarred lung tissue
- Low birth weight

**PM$_{2.5}$-related deaths (GBD 2017)**

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Cause</td>
<td>2,580,000</td>
<td>3,080,000</td>
</tr>
<tr>
<td>Lower respiratory infections</td>
<td>425,000</td>
<td>461,000</td>
</tr>
<tr>
<td>Tracheal, bronchus, and lung cancer</td>
<td>199,000</td>
<td>256,000</td>
</tr>
<tr>
<td>Ischaemic heart disease</td>
<td>676,000</td>
<td>852,000</td>
</tr>
<tr>
<td>Ischaemic stroke</td>
<td>216,000</td>
<td>261,000</td>
</tr>
<tr>
<td>Intracerebral hemorrhage</td>
<td>277,000</td>
<td>330,000</td>
</tr>
<tr>
<td>Subarachnoid hemorrhage</td>
<td>42,900</td>
<td>50,100</td>
</tr>
<tr>
<td>Chronic obstructive pulmonary disease</td>
<td>707,000</td>
<td>819,000</td>
</tr>
<tr>
<td>Diabetes mellitus type 2</td>
<td>33,000</td>
<td>46,800</td>
</tr>
</tbody>
</table>

Modified from GRID-Arendal: [https://www.grida.no/resources/7544](https://www.grida.no/resources/7544)

[Images and diagrams related to PM$_{2.5}$ effects on health and disease]

[Images and diagrams related to PM$_{2.5}$-related deaths and disease categories]

[Images and diagrams related to PM$_{2.5}$ effects on respiratory and cardiovascular systems, and reproductive outcomes]

Groups sensitive to PM$_{2.5}$: People with heart or respiratory diseases, the elderly, pregnant women and children.

Twitter: [https://twitter.com/airlyeu/status/816953926847234048](https://twitter.com/airlyeu/status/816953926847234048)
Satellites offer more coverage than ground monitors

Only 10% of countries have more than 3 ground monitors per million people

Satellite-based Aerosol Optical Depth (AOD) retrievals have much greater coverage.
Satellite-based AOD has its own challenges...

First part of talk

• AOD accuracy varies with both retrieval/instrument and location/conditions
  • Unclear which AOD dataset is best
• AOD is not PM$_{2.5}$
  • AOD optically represents all aerosol in the entire column
  • Need a way to relate to PM$_{2.5}$ at the surface

...but offers unparalleled richness

Second part of talk
Different AOD datasets have different strengths/weaknesses

Differences result from instrumentation, methodology and sampling

Mean AOD for April 2014
How can AERONET locations tell us about unmonitored locations?

- Global network of sun photometers
- > 25 years of data
- High accuracy (AOD within ±0.01)
- Standard data source for AOD validation

*surface reflectance is a major uncertainty source for remote sensing*

Month-specific AERONET-SATELLITE AOD subset comparisons are categorized and/or weighted by:
- Land type
- Normalized Difference Vegetation Index
- Proximity
- Season

Continuous, Consistent, Global Error Definition
Global Evaluation: Use each dataset at it’s best

Combine all AOD sources weighted by NRMSD$^{-1}$, bias correction$^{-1}$, data density:

$$AOD = \frac{\sum_{n=1}^{N} \frac{1}{NRMSD_n} \left( \frac{\Delta AOD_{adj,n}}{AOD_n} \right)^{-1} \times N_{obs,n}^2 \times AOD_n}{\sum_{n=1}^{N} \frac{1}{NRMSD_n} \left( \frac{\Delta AOD_{adj,n}}{AOD_n} \right)^{-1} \times N_{obs,n}^2}$$

Hammer et al., ES&T, 2020
The aerosol column (AOD) is related to surface PM$_{2.5}$

We relate satellite-based retrievals of aerosol optical depth (AOD) to PM$_{2.5}$ using a global chemical transport model.

Chemical Transport Models (CTMs), such as GEOS-Chem, combine the equation that govern atmospheric chemistry and physics with global meteorology and emissions.

- Detailed aerosol-oxidant model
- 50-100 tracers, 100’s reactions
- Assimilated meteorology
- Resolution of between $\frac{1}{2}^\circ \times \frac{2}{3}^\circ$ (nested) to $2^\circ \times 2\frac{1}{2}^\circ$ (global)

PM$_{2.5}$ = $f(x,y,t) \cdot$ AOD

- vertical structure
- aerosol type
- meteorology
- diurnal effects
Ground monitors offer an additional source of information

Hybrid Geophysical-Statistical PM$_{2.5}$ estimates interpret the residual bias between ground monitors (GM) and geophysical PM$_{2.5}$ with a statistical framework.

Geographically Weighted Regression (GWR) provides a spatio-temporally varying, linear regression to:

$$(GM\ PM_{2.5} - SAT\ PM_{2.5}) = \sum \beta_i \text{SPEC}_i + \beta_{ED} \text{ED} + \beta_{ULT} \text{ULT}$$

ULT: Urban Land Type
ED: Local Elevation Difference with GEOS-Chem grid
SPEC: Speciated PM$_{2.5}$ concentrations
$\beta$: predictor-specific, spatially varying coefficients

*ONLY INCLUDES CROSS VALIDATED SITES*
Data offers unique and consistent long-term view
Meteorology impacted $\text{PM}_{2.5}$ during COVID-19 lockdowns

Changes in $\text{PM}_{2.5}$ during lockdown is largely associated with meteorology and transportation emissions.

Hammer et al., submitted
Case Study: Moscow Wildfire Summer 2010

- Hottest in recorded history at that time
- Widespread wildfires
- State of emergency declared
- Thousands of buildings destroyed
- Daily deaths in Moscow doubled

Cloud or Aerosol?

Needed to modified cloud filters

RGB Image

Operational

Relaxed Cloud

van Donkelaar et al., AE, 2011
Global impact of global data

Number of deaths related to risk factors in China, 2017

Global Burden of Disease - PM$_{2.5}$ causal role in 3 million deaths per year

Global years of healthy life lost (DALYs), 2019

Inform Epidemiological Studies:

- COVID-19 associations (Chakrabarty, 2020)
- Cardiovascular Disease (Chen, EHP, 2020)
- Childhood asthma (Anderson et al., 2012; Lavigne et al., 2018)
- Lung cancer (Hystad et al., 2012)
- Mortality in California (Jerrett et al., 2013)
- Diabetes (Brook et al., 2013; Chen et al., 2013; Paul et al., 2020)
- Dementia (Chen et al., 2017; Ilango et al., 2019)
- Adverse birth outcomes (Fleischer et al., 2014; Qiao et al., 2019; Wang et al., 2019; Han et al., 2020)
- Maternal Exposure and Childhood Cancer (Lavigne et al., 2017)
- Hypertension (Chen et al., 2013)
- Low PM$_{2.5}$ effects (Crouse et al., 2012; Pinault et al., 2016; Pinault et al., 2019)
- Psychological Distress (Pinault et al., 2020)
- Heart Failure (Bai et al., 2019)
Thanks!