Air Pollution in India: Implications of Exposure

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Air pollution is only of health interest if it is breathed by the population – exposure is what counts

Thus, of more interest to policy is “exposure apportionment” rather than “source apportionment”
What about Exposure?

- Ambient air pollution networks do not measure exposure, but indicate outdoor levels over wide areas.
- In the West, people actually breathe mostly what comes from outdoors, although less on average due to being partly blocked by housing.
- In most of India and much of Nepal and China, however, most people live in well-ventilated housing, meaning they breathe closer to ambient levels.
- In addition, unlike rich countries, Asians are affected more by local sources, sometimes heavily, meaning that their real exposures are higher than indicated by outdoor monitors.
- Local sources: stoves, garbage burning, small industry, vehicles, etc.
IF = one million ppm – all is breathed in

Worse thing you can do
## Ambient Intake Fractions in Hyderabad (Guttikunda, 2015)

ppm – grams inhaled per tonne emitted

<table>
<thead>
<tr>
<th>Source</th>
<th>Average</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Households</td>
<td>175</td>
<td>97</td>
</tr>
<tr>
<td>Construction</td>
<td>175</td>
<td>93</td>
</tr>
<tr>
<td>Waste.burn</td>
<td>140</td>
<td>74</td>
</tr>
<tr>
<td>Veh.exhaust</td>
<td>130</td>
<td>64</td>
</tr>
<tr>
<td>Gen.sets</td>
<td>123</td>
<td>53</td>
</tr>
<tr>
<td>Industries</td>
<td>65</td>
<td>17</td>
</tr>
<tr>
<td>Dust</td>
<td>18</td>
<td>4</td>
</tr>
<tr>
<td>Power plants</td>
<td>7.4</td>
<td>7.0</td>
</tr>
<tr>
<td>Brick.kilns</td>
<td>6.8</td>
<td>1.9</td>
</tr>
</tbody>
</table>
How different? Does it matter?
Yes, a factor of ~100 different!

Source – Exposure Relationships
Goal for Health

- Find a way to frame policy to control air pollution emphasizing exposure rather than just concentration
- More efficient -- more protection per unit time and effort
- Without doing so, important sources can be ignored
- And important populations left behind
India

- Embarked on industrialization while still having large traditional sectors – mixed pollution sources today
- Not the case in the West
- India now at GDP/capita of the US in late 1800s
- Need to get rid of dirty household fuels soon, while dealing with modern sources
- Has started to happen, but more emphasis needed
In which year did 80% of households begin cooking with gas?

Household air pollution, health, and climate change: cleaning the air

Jose Goldemberg, Javier Martinez-Gomez, Ambuj Sagar, and Kirk R Smith

Environmental Research Letters, 2018
India

- Concern about “social benefits” for village households using solid fuels has led to a massive program to connect them to clean gas fuel
  - 80+ million poor households connected to LPG in 3 years
  - 90% of country now connected
  - Focus now on enhancing usage
- Households also responsible for ~30% of ambient PM2.5, but not included in national air pollution action plans
- And yet, surprisingly, cleaning up households alone will be enough to allow India to reach its national air pollution standards.
Household Energy Consumption, Emissions, Pollution, and Health Impacts in India

STATE: Jharkhand
DISTRICT: Ranchi

% Households Primary Cooking Fuel
- Gas: 29.8%
- Electric: 70.2%

Estimated district annual HEC emissions:
- Particulate matter (PM2.5): 12,900 tons
- Sulfur dioxide (SO2): 1,120 tons
- Nitrogen oxides (NOx): 230 tons
- Carbon monoxide (CO): 23,600 tons
- Hydrocarbons (HC): 20,400 tons
- Black carbon (BC): 3,300 tons
- Organic carbon (OC): 5,280 tons
- Carbon dioxide (CO2): 1,134 metric tons

Estimated PM2.5 emissions @ 0.25 degree resolution:
- WH: 20%
- SH: 16%
- LG: 4%

Modelled share of HEC emissions to ambient PM2.5:
- WH: 55%
- SH: 38%
- LG: 7%

% Contribution of HEC emissions to modeled ambient PM2.5 concentrations:
- National: 29.6%
- District: 27.8%

Health impacts of outdoor air pollution include heart disease, stroke, heart attacks, respiratory diseases, lung cancer, and exacerbation of chronic respiratory diseases. The study findings help in prioritizing interventions for control of major pollutants, which can aid in reducing premature mortality associated with outdoor air pollution.

The health impact of outdoor air pollution is estimated using age-sex-specific mortality attributable to ambient PM2.5 concentrations, and 2017 life expectancy data for India. The estimated premature mortality is 0.115 premature deaths for national and 0.114 premature deaths for district.
The Contribution of Household Fuels to Ambient Air Pollution in India
A Comparison of Recent Estimates

Sourangsu Chowdhury, Zoe A. Chafe, Ajay Pillarisetti, Jos Lelieveld, Sarath Guttikunda, and Sagnik Dey
Indian annual ambient air quality standard is achievable by completely mitigating emissions from household sources

Sourangsu Chowdhury, Sagnik Dey, Sarath Guttikunda, Ajay Pillarisetti, Kirk R. Smith, and Larry Di Girolamo

Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi 110016, India; School of Public Health, University of California, Berkeley, CA 94720-7360; School of Public Policy, Indian Institute of Technology Delhi, New Delhi 110016, India; Urban Emissions, New Delhi 110019, India; Collaborative Clean Air Policy Centre, Delhi 110003, India; and Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, IL 61801

Proceedings of the National Academy of Sciences
April, 2019
If PM2.5 emissions from all household sources are completely mitigated, 187 million additional people would meet the Indian annual air-quality standard (40 μg/m³) compared with baseline (2015) when 239 million people met the standard.

At 38 μg/m³, after complete mitigation of household sources, the mean annual national population-based concentration would meet the national standard, although highly polluted areas, such as Delhi, would remain out of attainment.
Households largest single contributor to outdoor air pollution exposure in Indian

Apte and Pant, PNAS, 2019
India Burden of Disease, 2017

[Chart showing various health risks and their associated DALYs (Disability-Adjusted Life Years)]

- Child and maternal malnutrition
- Air pollution
- Dietary risks
- High systolic blood pressure
- High fasting plasma glucose
- Tobacco use
- Unsafe water, sanitation, and handwashing
- High total cholesterol
- High body-mass index
- Alcohol and drug use
- Occupational risks
- Impaired kidney function
- Unsafe sex
- Other environmental risks
- Low physical activity
- Low bone mineral density
- Sexual abuse and violence

Legend:
- HIV/AIDS and tuberculosis
- Nutritional deficiencies
- Chronic respiratory diseases
- Mental and substance use disorders
- Transport injuries
Indian Burden of Disease
2017
Indian Burden of Disease
2017
Indian Burden of Disease
2017

Remaining if households use clean fuels
Change in household fuels dominates the decrease in PM2.5 exposure and premature mortality in China in 2005-2015

Bin Zhao¹,², Haotian Zheng¹, Shuxiao Wang¹,³, Kirk R. Smith⁴,², Xi Lu¹,³, Kristin Aunan⁵, Yu Gu², Yuan Wang⁶, Dian Ding¹, Jia Xing¹,³, Xiao Fu⁷, Xudong Yang⁸, Kuo-Nan Liou², and Jiming Hao¹,³

¹School of Environment, and State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing 100084, China ²Joint Institute for Regional Earth System Science and Engineering and Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA 90095, USA ³State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing 100084, China ⁴Environmental Health Sciences, School of Public Health, University of California, Berkeley, CA 94720-7360, USA ⁵CICERO Center for International Climate Research, P.O. Box 1129 Blindern, N-0318 Oslo, Norway ⁶Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA ⁷Department of Civil and Environmental Engineering, Hong Kong Polytechnic University, Hong Kong 99907, China ⁸Department of Building Science, Tsinghua University, Beijing 100084, China
\[ IPWE = PWE_{AAP} + PWE_{HAP} \]

where \( PWE_{AAP} \) is the population-weighted exposure to AAP and \( PWE_{HAP} \) is the additional population-weighted exposure to HAP. (excluding any contribution from AAP)

\[
PWE_{AAP} = \frac{1}{P} \sum_i (P_i \cdot C_i) \\
PWE_{HAP} = \frac{1}{P} \sum_{ij} (P_{i,j,k} \cdot HAP_{j,k})
\]

\( i = \text{county} \)
\( j = \text{urban/rural} \)
\( k = \text{fuel type} \)
(a) Using central $HAP_{j,k}$ values

- Bar chart showing population distribution in million people across different categories.
- Categories range from 0-30 to >360.
- Urban and rural populations are differentiated by color (blue for urban, yellow for rural).

Million people

Energy-environment-health benefits of rural residential coal-substitution in northern China

Meng Wenjun\textsuperscript{a}, Zhong Qirui\textsuperscript{a}, Chen Yilin\textsuperscript{b}, Shen Huizhong\textsuperscript{b}, Yun Xiao\textsuperscript{a}, Kirk R. Smith\textsuperscript{c*}, Li Bengang\textsuperscript{a}, Liu Junfeng\textsuperscript{a}, Wang Xilong\textsuperscript{a}, Ma Jianmin\textsuperscript{a}, Cheng Hefa\textsuperscript{a}, Zeng Y. Eddy\textsuperscript{d}, Guan Dabo\textsuperscript{e}, Armistead G. Russell\textsuperscript{b}, Tao Shu\textsuperscript{a*}

\textsuperscript{a} College of Urban and Environmental Sciences, Laboratory for Earth Surface Processes, Sino-French Institute for Earth System Science, Peking University, Beijing 100871, China  
\textsuperscript{b} School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA30332, USA  
\textsuperscript{c} School of Public Health, University of California, Berkeley, CA 94720, USA  
\textsuperscript{d} School of Environment, Guangzhou Key Laboratory of Environmental Exposure and Health and Guangdong Key Laboratory of Environmental Pollution and Health, Jinan University, Guangzhou 510632, China  
\textsuperscript{e} School of International Development, University of East Anglia, Norwich, Norfolk, NR4 7TJ, UK
Scenario 3 – current plan
Scenario 4 – full substitution of solid household fuel

GBD 2015 Risk Factors Collaborators*

Recent CRA published 2017 in The Lancet
India
Both sexes, Age-standardized, DALYs per 100,000

1990 rank
1. Respiratory infections & TB
2. Enteric infections
3. Maternal & neonatal
4. Cardiovascular diseases
5. Chronic respiratory
6. Other infectious
7. Unintentional inj
8. Nutritional deficiencies
9. Neoplasms
10. Other non-communicable
11. Musculoskeletal disorders
12. Mental disorders
13. Digestive diseases
14. Neurological disorders
15. NTDs & malaria
16. Diabetes & CKD

2017 rank
1. Cardiovascular diseases
2. Maternal & neonatal
3. Respiratory infections & TB
4. Chronic respiratory
5. Enteric infections
6. Neoplasms
7. Unintentional inj
8. Other non-communicable
9. Musculoskeletal disorders
10. Mental disorders
11. Diabetes & CKD
12. Neurological disorders
13. Nutritional deficiencies
14. Digestive diseases
15. Sense organ diseases
16. Other infectious

Communicable, maternal, neonatal, and nutritional diseases
Non-communicable diseases
Injuries
India
Both sexes, Age-standardized, DALYs per 100,000

1990 rank
1. Child and maternal malnutrition
2. Unsafe water, sanitation, and handwashing
3. Air pollution
4. Tobacco
5. Dietary risks
6. High systolic blood pressure
7. High fasting plasma glucose
8. Alcohol use
9. High LDL cholesterol
10. Occupational risks
11. Impaired kidney function
12. Other environmental risks
13. High body-mass index
14. Low physical activity
15. Drug use
16. Low bone mineral density
17. Unsafe sex

2017 rank
1. Child and maternal malnutrition
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6. High fasting plasma glucose
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8. Alcohol use
9. High LDL cholesterol
10. High body-mass index
11. Impaired kidney function
12. Occupational risks
13. Other environmental risks
14. Low physical activity
15. Drug use
16. Unsafe sex
17. Low bone mineral density
DALYs/100,000

All causes attributable to Particulate matter pollution
Both sexes, Age-standardized
India
All causes attributable to Ambient ozone pollution
Both sexes, Age-standardized
India
All causes attributable to Ambient particulate matter pollution
Both sexes, Age-standardized
Needed a **Comparative Economic Assessment**

- Common databases and time periods
- Common models and parameters
- Common agreement on what is included and why
- Common representation of uncertainty
- Peer-reviewed systematically
- Agreed update procedures and time lines
Thanks to many colleagues in China, India, and the USA

Not all sources are equally important

Best to google “Kirk R. Smith” to find my website with publications
Burden of Disease Attributable to Major Air Pollution Sources in India

GBD MAPS Working Group
<table>
<thead>
<tr>
<th>Source Sector</th>
<th>All India (%)</th>
<th>Rural India (%)</th>
<th>Urban India (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential biomass</td>
<td>23.9</td>
<td>24.2</td>
<td>22.1</td>
</tr>
<tr>
<td>Total coal</td>
<td>15.7</td>
<td>15.5</td>
<td>17.1</td>
</tr>
<tr>
<td>Industrial coal</td>
<td>7.7</td>
<td>7.6</td>
<td>8.5</td>
</tr>
<tr>
<td>Power plant coal</td>
<td>7.6</td>
<td>7.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Open burning</td>
<td>5.5</td>
<td>5.5</td>
<td>5.6</td>
</tr>
<tr>
<td>Transportation</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Brick production</td>
<td>2.2</td>
<td>2.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Distributed diesel</td>
<td>1.8</td>
<td>1.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Anthropogenic dust(^b)</td>
<td>8.9</td>
<td>8.8</td>
<td>9.6</td>
</tr>
<tr>
<td>Total dust(^c)</td>
<td>38.8</td>
<td>38.7</td>
<td>39.5</td>
</tr>
</tbody>
</table>

GBD MAPs Study, Jan 2018
Air pollutant emissions from Chinese households: A major and underappreciated ambient pollution source

Jun Liu\textsuperscript{a}, Denise L. Mauzerall\textsuperscript{b,c,1}, Qi Chen\textsuperscript{a}, Qiang Zhang\textsuperscript{d}, Yu Song\textsuperscript{a}, Wei Peng\textsuperscript{b}, Zbigniew Klimont\textsuperscript{e}, Xinghua Qiu\textsuperscript{a}, Shiqiu Zhang\textsuperscript{a}, Min Hu\textsuperscript{a}, Weili Lin\textsuperscript{f}, Kirk R. Smith\textsuperscript{g,1}, and Tong Zhu\textsuperscript{a,h,1}

\textsuperscript{a}State Key Joint Laboratory of Environmental Simulation and Pollution Control, College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China; \textsuperscript{b}Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ 08544; \textsuperscript{c}Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544; \textsuperscript{d}Ministry of Education Key Laboratory for Earth System Modeling, Center for Earth System Science, Tsinghua University, Beijing 100084, China; \textsuperscript{e}International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria; \textsuperscript{f}Chinese Academy of Meteorological Sciences, Beijing 100081, China; \textsuperscript{g}School of Public Health, University of California, Berkeley, CA 94720-7360; and \textsuperscript{h}Beijing Innovation Center for Engineering Science and Advanced Technology, Peking University, Beijing 100871, China

Change in household fuels dominates the decrease in PM2.5 exposure and premature mortality in China in 2005-2015

Bin Zhao¹,², Haotian Zheng¹, Shuxiao Wang¹,³,⁎, Kirk R. Smith⁴, ⁺, Xi Lu¹,³, Kristin Aunan⁵, Yu Gu², Yuan Wang⁶, Dian Ding¹, Jia Xing¹,³, Xiao Fu⁷, Xudong Yang⁸, Kuo-Nan Liou², and Jiming Hao¹,³

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Proceedings National Academy Sciences (2018, Nov)
Figures a and b show the spatial distribution of PM$_{2.5}$ concentrations across China, with different colors representing various concentration levels. Figure c highlights the areas with the highest concentrations, marked as Beijing, Tianjin, Chengdu, Chongqing, Shenzhen, and Shanghai. Figure d displays the mortality cases due to PM$_{2.5}$ exposure.

Table e illustrates the mortality cases (in millions) from 2005 to 2015, split into rural and urban areas. The bars indicate the total PM$_{2.5}$-induced mortality and mortality due to household fuels for each year.
Satellite-based ambient PM$_{2.5}$

About 30% from households in India and in China based on ~10 independent estimates.
China recently

- Reduced household solid-fuel consumption was the leading contributor to the decrease in national exposure to PM$_{2.5}$ pollution (2005-2015) -- 90% of reduction
- Even though there was no explicit household control policy.
- In contrast, the emission reductions from power plants, industry, and transportation contributed less to the decrease of exposure during this period – 10%.
China today

- Clean household fuels has become part of recent air pollution control policies in northern China – wide area around Beijing – BTH region
- With a requirement for 70-80% reduction in use of household solid fuels in three years – to gas and electricity
- 4 million households by 2017
- Should be part of national policies
- Ironically, being done not because it helps the villagers, but because it helps reduce outdoor air pollution in cities
- “Type I error”
Air quality, health, and climate implications of China’s synthetic natural gas development

Yue Qin\textsuperscript{a}, Fabian Wagner\textsuperscript{a,b,c}, Noah Scovronick\textsuperscript{a}, Wei Peng\textsuperscript{a,1}, Junnan Yang\textsuperscript{a}, Tong Zhu\textsuperscript{d,e}, Kirk R. Smith\textsuperscript{f,2}, and Denise L. Mauzerall\textsuperscript{a,g,2}

\textsuperscript{a}Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ 08544; \textsuperscript{b}Andlinger Center for Energy and the Environment, Princeton University, Princeton, NJ 08544; \textsuperscript{c}International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria; \textsuperscript{d}State Key Joint Laboratory of Environmental Simulation and Pollution Control, College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China; \textsuperscript{e}Beijing Innovation Center for Engineering Science and Advanced Technology, Peking University, Beijing 100871, China; \textsuperscript{f}School of Public Health, University of California, Berkeley, CA 94720-7360; and \textsuperscript{g}Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544

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where \( PWE_{AAP} \) is the population-weighted exposure to AAP and \( PWE_{HAP} \) is the additional population-weighted exposure to HAP. (excluding any contribution from AAP)

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PWE_{AAP} = \frac{1}{P} \sum_i (P_i \cdot C_i)
\]

\[
PWE_{HAP} = \frac{1}{P} \sum_{ij} (P_{i,j,k} \cdot HAP_{j,k})
\]

\( i = \text{county} \)

\( j = \text{urban/rural} \)

\( k = \text{fuel type} \)
(a) Using central HAP\textsubscript{j,k} values

- Urban
- Rural

Million people

- 0-30
- 30-60
- 60-90
- 90-120
- 120-150
- 150-180
- 180-210
- 210-240
- 240-270
- 270-300
- 300-330
- 330-360
- >360
(a) Coal use (Mtce)
- Urban household coal use
- Rural household coal use

(b) Biomass use (Mtce)
- Household biomass
- Non-household sources

(c-f:)
(c) PM$_{2.5}$ emission (Mt)
- Household coal
- Other household fuels

(d) NMVOC emission (Mt)

(e) BC emission (Mt)

(f) OC emission (Mt)
Satellite-based ambient PM$_{2.5}$

van Donkelaar et al, EHP 2010
Formaldehyde in California in early 2000s

- Wallboard and similar indoor products were producing large human exposures to this carcinogen
- California Air Resources Board requested, but was denied authority to control indoor air pollution
  - Due to consumer-product and tobacco industry opposition
- The CARB staff, therefore, wrote control regulations based on ambient emissions
- Was not the right framing, but did the job
Formaldehyde in California: 2007*

• “Current annual average concentrations of formaldehyde in ambient air range from 3 to 4 μg/m³ across California, with indoor and in-vehicle concentrations typically many times higher.”

• “The risk from exposure to annual average concentrations of formaldehyde in ambient air is about 20 to 24 potential excess cancer cases per year.”

*PROPOSED AIRBORNE TOXIC CONTROL MEASURE TO REDUCE FORMALDEHYDE EMISSIONS FROM COMPOSITE WOOD PRODUCTS, CARB, Sacramento, March 9, 2007
Formaldehyde, Cont.

- “Within the category of area-wide sources, formaldehyde emissions from (various indoor products) in California are estimated to be about 900 tons per year.”
- “The (proposed standard) would reduce emissions of formaldehyde by about 57%.”
- Health benefit from reduction in outdoor air, however, is less than 10% of the total benefit in lower cancer risk with a total exposure approach, which is dominated by indoor exposures.
### Formaldehyde in California – Concentration versus Exposure

#### A. Mean Exposure Scenario -- Adult

<table>
<thead>
<tr>
<th>Place</th>
<th>Time (hr/d)</th>
<th>Concentration (ug/m3)</th>
<th>Weighted Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>20.82</td>
<td>17.2</td>
<td>358.1</td>
</tr>
<tr>
<td>In-vehicle</td>
<td>1.71</td>
<td>9.6</td>
<td>16.4</td>
</tr>
<tr>
<td>Outdoor</td>
<td>1.47</td>
<td>3.7</td>
<td>5.4</td>
</tr>
<tr>
<td>Total</td>
<td>24</td>
<td>-----</td>
<td>379.9</td>
</tr>
</tbody>
</table>

15.8 µg/m³
Strategies

• Type I: Ignore impact on ambient air, but get rid of indoor exposures from solid fuel – India
• Type II: Ignore impact on indoor exposures, but eliminate solid fuels to help control ambient air – China
• Type III: Use jurisdiction over ambient air to control indoor exposures – California