Source influence on emission pathways and ambient PM-2.5 pollution in India (2015-2050)

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The *genesis* of air pollution and climate change is an *emission source*.
Estimating emissions

Building from globally consistent emission datasets, needs inclusion of regional details, in fuels, technology divisions and energy-use practices, with refined spatial resolution – essential for health burden estimation.

- NATCOM emissions mostly at national level (Tier I).

- Many energy use sectors not well quantified.
Improving emission estimation
Inventory methodology: Tiers of details

**Tier 1**
Global tech / fuel / EF

**Tier 2**
- Country specific fuel characteristics
- Technology based EF

**Tier 3**
- Detailed activity/technology levels
- Measured regional EF

### Source Categories
- **Industry**
  - Thermal power
  - Heavy industry
  - Light industry

- **Transport**
  - On-road gasoline
  - On-road diesel
  - Railways/Shipping/Aviation

- **Residential**
  - Cooking biofuels
  - Cooking LPG/kero
  - Lighting kero lamps

- **Agriculture**
  - Agriculture residue burning
  - Agriculture diesel use

- **Informal**
  - Brick production
  - Food processing

### Technologies
- **PC boiler, Stokers, oil-fired boilers, gas turbines, coke ovens, refineries**
- **2-wheelers, 3-wheelers, Cars, LDV, HDV, Buses, CNG vehicles, Super-emitters, age distribution**
- **Traditional biomass stoves, LPG stoves, kerosene stoves, kerosene wick lamps**
- **Open field burning, Different agricultural residues, diesel tractors, diesel pumps**
- **Bull’s Trench Kiln – Fixed and moving chimney, Clamps, Zig-zag firing, VSBKs, wood-boilers**
Improving spatial proxies

**NEW SPATIAL PROXIES**

- LPS – Lat/Lon
- Light industry – Urban pop.
- Road (g)+Railway–Urban pop.
- Road (d) – Road network
- Residential cooking – cooking-fuel based user fraction (Census & NSS)
- Res. lighting – Rural pop.
- Tractors and pumps – Irrigated area
- Brick prod. – Brick-walled houses
- Informal industry – food and agro-processing (flattened rice, khoya, drying spices, tea, coffee...)

**OLD REPORTED SPATIAL PROXIES**

Population based proxies were used for area source categories
No distinction in sources for distributing emissions

Sadavarte and Venkataraman, 2014 AE; Pandey et al., 2014 AE; Pandey and Venkataraman, 2014 AE
Constraining emissions with satellite-based estimates

Magnitude and spatial distribution corrected to capture prominent features of top-down satellite-based emissions.

Sadavarte and Venkataraman, 2014 AE; Pandey et al., 2014 AE; Pandey and Venkataraman, 2014 AE
Harmonizing satellite based (e.g. GFED-4s) and bottom-up emissions from agricultural residue burning

Annual Agri. residue burning PM2.5 emissions:
- IITB (bottom-up): 1030 Gg y\(^{-1}\)
- GFED (top down): 201 Gg y\(^{-1}\)
- Difference ratio IITB/GFED = 5.1

Uncertainties:
- Inventory: Assumed “fraction of residue burned in field” and “waste to grain ratio”
- Satellite based: Satellite detected “burned area” and assumed “biomass density”
- Both: Emission factors

\[ F_{i,k} = \sum_k (CPR_{i,k} \times RPR_{i,k} \times fB_{i,k} \times DMF_{i,k} \times BE_{i,k}) \]

- \( F_{i,k} \) = Amount of crop residue burned in district ‘i’ of crop type ‘k’ (kg/yr)
- \( CPR_{i,k} \) = total crop produced in district ‘i’ (from state level food production data)
- \( RPR_{i,k} \) = Waste to grain ratio
- \( fB_{i,k} \) = fractional amount of residue burnt in the field
- \( DMF_{i,k} \) = Dry matter fraction
- \( BE_{i,k} \) = Burning efficiency

Published reports/FAI/Literature
Census/ NSS/ NCAP survey & measurements/BAHS
Detecting missing sources – anthropogenic dust – using ground measurements

AFCID: coal fly ash, mineral matter from combustion, fugitive dust (re-suspended road dust, and dust from construction).

Including AFCID improves measured vs modelled total dust globally ($R^2$ from 0.06 to 0.66; SPARTAN sites).

Simulations including AFCID reduce the bias in total dust measured over Asia from -17% to -7%.

AFCID = Anthropogenic, Fugitive, Combustion and Industrial Dust

Annual mean PM2.5 total dust concentrations ($\mu g/m^3$)

(GEOS-Chem simulated; SPARTAN campaign measurements (inner circle))
Present-day emission magnitudes

Residential biomass, open burning and informal industry emit 2/3rd of present day primary PM-2.5. Major sources of emissions of BC, OC, CH$_4$, NMVOC and CO.

Electricity generation, industry (using coal) and transport emit high NO$_x$ and SO$_2$, which form secondary PM-2.5

Sadavarte and Venkataraman, 2014 AE; Pandey et al., 2014 AE; Pandey and Venkataraman, 2014 AE

("Others" category includes residential lighting (kerosene lamps), informal industry (food and agro-product processing), trash burning and fugitive dust)
Demand or activity projected from annualized growth rates by sector, for 2015-30 and 2030-50, developed from literature.

- Building sector grows 5.7 times, almost 80% of built environment to be constructed.
- Electricity generation grows 4.2 times.
- Growth rates differ in industrial sectors, highest in cement, overall 3.4 times.
- Residential growth tracks population projection at 1.25% per year, grows ~1.4 times.
- Agricultural growth tracks food production, grows ~2 times.

[NITI Aayog 2015; MoEFCC, 2011; Firoz, 2014; Maithel et al., 2012; Ray et al., 2009; PNG regulatory board, 2013; Murthy, 2014]
### Shifts in technologies and practices

**Power plant**
- Share of renewable energy (40% by 2030) as targeted in India’s NDC; negligible flue gas desulphurization from a slow adoption of recent regulation (MoEFCC, 2015).

**Industry**
- Modest increases in energy efficiency (62-84%) under the Perform Achieve and Trade (PAT) scheme (Level 2, IESS, Niti Aayog, 2015).

**Transport**
- Promulgated growth in public vehicle share (25-30%) (NTDPC, 2013; Guttikunda and Mohan, 2014; NITI Aayog, 2015); slow shifts to BS-VI standards (MoRTH, 2016 ICRA, 2016).

**Bricks & Informal Ind.**
- Modest increases in non-fired-brick walling materials (30-45%) (UNDP, 2009; Maithel, personal communication, 2016); slow shift to zig-zag fired brick kilns / clean tech in informal industry.

**Residential**
- Modest shift (55% in 2030 and 70% in 2050) to energy efficient technologies and fuels (Level 2, IESS, Niti Aayog, 2015).

**Open burning**
- No shift away from agricultural residue burning.

### S3 - Future policies

**Power plant**
- Large shift (75-80%) to non-fossil power generation (Anandarajah and Gambhir 2014; Shukla and Chaturvedi 2012; Level 4, IESS, Niti Aayog, 2015); 80-95% use of flue gas desulphurization.

**Industry**
- Near complete shift to high efficiency (85-100%) industrial technologies (Level 4, IESS, Niti Aayog, 2015).

**Transport**
- Large shifts to public vehicles (40-60%) (NITI Aayog, 2015), BS-VI syandards, efficient engine technology (MoP, 2015), electric/CNG vehicle share (20-50%) (NITI Aayog, 2015).

**Bricks & Informal Ind.**
- Large share of non-fired brick walling materials (40-70%), complete move to zig-zag fired / VSBK kilns; gasifiers / clean technologies in informal industries (65-80%).

**Residential**
- Large shifts (90% in 2030 and 100% in 2050) to LPG/PNG/electric cooking (Level 4, IESS, Niti Aayog, 2015), (100% in 2030) electric and solar lighting (National Solar Mission 2010).

**Open burning**
- Shift away from (35% phase out by 2030) and complete phase-out (2050) of agricultural residue burning to mulching/deep-sowing technologies/practices (Gupta, 2014).
Projected growth in PM-2.5 emissions from 9.1 Tgy\(^{-1}\) (2015):

REF: 2015 emission regulations
- 12.0 Tg (2030) and 18.5 Tg (2050)

S2: Minor gains from modest shifts to non-coal power (NDC, 2015); biomass stoves to LPG/gasifiers
- 9.5 Tg (2030) and 11.5 Tg (2050)

S3: Major gains from major shift to non-coal power and industry; complete shift from biomass stoves; complete phase-out of open burning (agricultural residue)
- 3.8 Tg (2030) and 3.0 Tg (2050)
Air quality impacts

- Emission inventory
- Air quality modelling/measurements
- Mitigation strategies
- Clean air
Simulations over subcontinent (GEOS-Chem; 50 km x 67 km)

- 11.2% NMB of model simulated concentrations and in-situ measurements
- 33% NMB of model simulated vs satellite detected AOD
- Species seasonal cycle OK; wintertime underestimation

In-situ (circles) v/s GEOS-Chem

Model AOD vs MODIS AOD

Concentrations (µg/m³)

Chemical species

PM$_{2.5}$ at Bhopal

Sulphate at Bhopal

Nitrate at Bhopal

BC at Ahmedabad

Venkataraman et al., 2017, ACPD
Air pollution is widespread; a national problem, not limited to urban centres.

Largest modelled concentrations occur in north India.

Promulgated regulations (S2), inadequate to achieve air quality gains in 2030/2050.

Aggressive action (S3) can yield significant reductions in 2030/2050.
Wide differences among modelled concentrations across states. In 2015 all exceed WHO or US-NAAQS and most exceed Indian annual PM-2.5 standard (40 µg m⁻³).

Under promulgated regulations (S2), growth in industrial and energy demand, neutralizes gains in emission reductions, yielding no air quality benefits in 2030, with modest worsening in 2050.

Venkataraman et al., 2017, ACPD
State-level population weighted PM-2.5 concentrations: present day and under ambitious action scenario (S3)

- Large shifts away from residential biomass stoves and agricultural open burning, along with large shifts away from industrial coal use, necessary for future improvements in air quality.
- Modelled concentration in about 10 states still exceed the ambient PM-2.5 standard in 2050, but most fall below it.
Present-day and future source contributions, S2: North India

- In 2015, residential biomass use and agricultural residue burning have largest influence on outdoor air pollution in north India.
- Followed by power plant/industrial coal and anthropogenic dust (mainly coal fly-ash).
- In 2050, under S2, while power plant/industry influence grows, residential and agricultural emissions do not reduce enough.
- More accurate capturing of spatial gradients from local sources like transport, needs nested higher resolution simulations.

<table>
<thead>
<tr>
<th>State</th>
<th>2015 (µg m⁻³)</th>
<th>2050 S2 (µg m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUNJAB</td>
<td>92.2</td>
<td>97.0</td>
</tr>
<tr>
<td>DELHI</td>
<td>137.9</td>
<td>138.5</td>
</tr>
<tr>
<td>UTTAR PRADESH</td>
<td>118.6</td>
<td>123.6</td>
</tr>
<tr>
<td>BIHAR</td>
<td>124.0</td>
<td>126.8</td>
</tr>
</tbody>
</table>
Present-day and future source contributions, S2: Peninsular India

- In 2015, residential biomass use influence in peninsular India as well.
- Industrial/power plant coal and anthropogenic dust have next largest influence; open burning not significant.
- In 2050, under S2, power plant/industry influence grows sharply from influence of power and cement plants.
- Factor of ~1.5 increase in modelled PM-2.5 concentrations in Andhra Pradesh and Odisha.
Future source contributions, S3: North India

- Under S3, ambient PM-2.5 concentrations fall by factor of ~1.5-2; residential and agricultural residue burning contribution falls to 1-2%.
- Industrial and power plant coal / anthropogenic dust (urban fugitive), followed by transportation and distributed diesel, become relatively more important.
- Balance from “total dust”, “natural dust” and “others” (urban fugitive dust / trash burning).
Future source contributions, S3: Peninsular India

- GUJARAT (55.4 µg m⁻³)
- MAHARASHTRA (47.1 µg m⁻³)
- ANDHRA PRADESH (47.5 µg m⁻³)
- ODIHSA (57.8 µg m⁻³)

Under S3, ambient PM-2.5 concentrations fall only slightly by factors of ~1.2; residential contribution falls to 1-2%.

However, Industrial coal / anthropogenic dust, becomes significantly important, in peninsular states.

Cement, Iron and steel sector growth neutralizes PAT gains – further sectoral analysis needed - fugitive emissions from crushing / grinding operations, etc.
Perspective

- Simulations on a regional domain reveal air pollution is a pan-India problem.
- Large regional background pollution, underlying local sources.
- Regional background (residential biomass, open burning, coal-industry/power), local sources (transportation, brick kilns, diesel generators, trash burning).
- Residential biomass dominates outdoor air pollution (in addition to large HAP exposures, not examined here).
- To mitigate air pollution, India needs stringent targets, beyond ones promulgated, for a three-pronged switch away from:
  - traditional biomass technologies
  - open burning of agricultural residues
  - coal-burning in industrial / power
- Residential clean energy solutions are essential, including “ultra-low-emission gasifier stoves,” LPG/PNG/ electric stoves, and electric/solar lighting.
- Shifts away from agricultural residue burning to mulching/deep-sowing practices essential to improving north India air quality.

Thank you,
Questions welcome!
Extra slides
OPM2.5 sectoral distribution

Total emissions

- OPM$_{2.5}$ 2013: 3220 Gg
- OPM$_{2.5}$ 2030 Sc1: 6315 Gg
- OPM$_{2.5}$ 2030 Sc2: 4933 Gg
- OPM$_{2.5}$ 2030 Sc3: 1937 Gg
- OPM$_{2.5}$ 2050 Sc1: 12436 Gg
- OPM$_{2.5}$ 2050 Sc2: 7204 Gg
- OPM$_{2.5}$ 2050 Sc3: 1866 Gg
Total emissions

- OPM$_{2.5}$ 2030 Sc1: 6315 Gg
- OPM$_{2.5}$ 2030 Sc2: 4933 Gg
- OPM$_{2.5}$ 2030 Sc3: 1937 Gg
Total emissions
- OPM$_{2.5}$ 2050 Sc1: 12436 Gg
- OPM$_{2.5}$ 2050 Sc2: 7204 Gg
- OPM$_{2.5}$ 2050 Sc3: 1866 Gg
Ongoing activities
**Field Network**

**CarbOnaceous AerosoL Emissions Source Apportionment & ClimatE Impacts**

**Ministry of Environment, Forest and Climate Change**

**National Committee**

**National Project Co-ordinator and Lead Institute**

**IIT Bombay**

**Associate Institutions**

**Field Institutions**

- **IIT Hyderabad**
  - IITM Pune
- **Bose Inst Darjeeling**
  - NEIST Jorhat
- **IISER Mohali**
  - University of Kashmir
- **IISER Bhopal**
  - BIT Mesra
- **NARL Gadanki**

**WP1:** Source measurements and emission inventory.

**WP2:** Regional source identification and apportionment.

**WP3:** RCM and GCM multi-model ensemble simulations.
The Delhi/NCR story: Source contribution to emissions and PM-2.5

- **PM\textsubscript{2.5} emissions Delhi**:
  - PM\textsubscript{2.5} 51.6 kT/yr

- **PM\textsubscript{2.5} emissions NCR**:
  - PM\textsubscript{2.5} 550.3 kT/yr

- NCR = National capital region: Delhi + a few districts of Haryana, Rajasthan and UP.

- **Note**: Emissions of precursor gases SO\textsubscript{2}, NO\textsubscript{x} and NMVOC also input to model.

- Others includes - trash burning, fugitive dust, residential lighting (kerosene lamps), informal industry (food and agro-product processing)

- Residential, “other” (trash burning, fugitive dust, etc) and open burning (agricultural) categories account about 70% of PM2.5 emissions over Delhi and the larger NCR region.

- Relatively coarse model grid (50 km x 67 km) makes is difficult to capture concentration gradients on finer spatial scales.

- To better capture vehicular / distributed diesel, need nested inventory and simulations at say 1 km x 1 km resolution or finer, over high pollution areas, within regional domain.
# Summary of available emission inventories

<table>
<thead>
<tr>
<th>Name</th>
<th>Time-Period</th>
<th>Sources</th>
<th>Resolution</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global</strong></td>
<td></td>
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</tr>
<tr>
<td>AEROCOM</td>
<td>1750 - 2000</td>
<td>Anthropogenic, Natural</td>
<td>1 x 1 deg</td>
<td>BC, OM, SO2, dust, sea-salt, volcanic SO2</td>
</tr>
<tr>
<td>EDGAR v4.2</td>
<td>1970 - 2008</td>
<td>Anthropogenic, Biomass burning</td>
<td>0.5 x 0.5 deg</td>
<td>CO2, CH4, N2O, NOx, CO, NMVOC, SO2</td>
</tr>
<tr>
<td>RETRO</td>
<td>1960 - 2000</td>
<td>Anthropogenic, Biomass burning</td>
<td>0.5 x 0.5 deg</td>
<td>CO2, CH4, N2O, NOx, CO, NMVOC, SO2</td>
</tr>
<tr>
<td>Bond et al., 2004</td>
<td>2000</td>
<td>Anthropogenic</td>
<td>-</td>
<td>BC and OC</td>
</tr>
<tr>
<td><strong>Regional</strong></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>GAINS</td>
<td></td>
<td>Anthropogenic</td>
<td>0.5 x 0.5 deg</td>
<td></td>
</tr>
<tr>
<td>REAS</td>
<td>1980-2020</td>
<td>Anthropogenic</td>
<td>0.5 x 0.5 deg</td>
<td>CO2, CH4, CO, NOX, NMVOC, BC, OC, SO2</td>
</tr>
<tr>
<td>TRACE-P</td>
<td>2000</td>
<td>Anthropogenic</td>
<td>0.5 x 0.5 deg</td>
<td></td>
</tr>
<tr>
<td>INTEX-B</td>
<td>2006</td>
<td>Anthropogenic</td>
<td>0.5 x 0.5 deg</td>
<td>PM2.5, PM10, BC, OC, SO2, NOx, CO, NMVOC</td>
</tr>
<tr>
<td>Lu and Streets, 2011</td>
<td>1996-2010</td>
<td>Anthropogenic</td>
<td>0.5 x 0.5 deg</td>
<td>BC, OC and SO2</td>
</tr>
</tbody>
</table>
Present day emission uncertainties

Technology-linked methodology reduces uncertainty compared to Tier-I estimates for 1996. Large uncertainty in emission factors, because of lack of measurements. Large uncertainty in activity data in sectors like residential, brick production and agricultural sectors.