Evolution of India's $PM_{2.5}$ Pollution Between 1998 and 2020 Using Global Reanalysis Fields Coupled with Satellite Observations and Fuel Consumption Patterns

Supplementary Information

Data files referred in the main manuscript are the following

1. $PM_{2.5}$ mass concentrations aggregated at the grid level for the Indian Subcontinent domain covering 67-99 degrees in longitude and 7-39 degrees in latitude at 0.1-degree spatial resolution
2. $PM_{2.5}$ mass concentrations aggregated at the state level (30 states and 6 union territories in India)
3. $PM_{2.5}$ mass concentrations aggregated at the district level (640 districts)
4. $PM_{2.5}$ source apportionment data at state and district level

All the data is available as xlsx files
@ https://doi.org/10.5281/zenodo.7115052

The following sections provide

1. A summary of source contribution assessment at the city level (also available as xlsx @ https://doi.org/10.5281/zenodo.7115052)
2. A compilation of resources for energy and emissions analysis in India

Supplementary Table S1: Summary of estimated source contributions including the contribution of sources outside the city airsheds. A = all transport (road, rail, aviation, and shipping) ; B = residential; C = industries (without brick kilns); D = all dust (construction and resuspension due to vehicle movement); E = open waste burning; F= diesel generator sets; G = brick manufacturing; H = sea salt; and I = outside/regional contribution (Guttikunda et al., 2019; UEinfo, 2020)

This table was published in
National Clean Air Programme (NCAP) for Indian cities: Review and outlook of clean air action plans
Atmospheric Environment, 2020, https://doi.org/10.1016/j.aeaoa.2020.100096
A CSV file is included in the Supplementary Folder for model use.

	City	A	B	C	D	E	F	G	H	I	Study year
1	Agartala	17.5%	14.9%	4.3%	15.3%	8.3%	2.7%	2.1%		34.9%	2019
2	Ahmedabad-Gandhi Nagar	14.9%	6.6%	12.4%	17.7%	8.4%	6.5%	0.7%		32.8%	2019
3	Allahabad	18.6%	12.5%	6.2%	14.9%	4.0%	4.1%	3.2%		36.6%	2019
4	Asansol-Durgapur	12.5%	7.1%	8.5%	16.2%	4.9%	4.2%	13.9%		32.7%	2019
5	Aurangabad	10.8%	4.3%	18.7%	10.7%	12.0%	6.7%	1.9%		34.9%	2019
6	Dharwad-Hubli	21.6%	5.6%	9.2%	14.7%	8.5%	1.7%	0.7%		38.0%	2019
7	Dhanbad-Bokaro	12.2%	4.1%	12.5%	29.2%	2.6%	3.0%	4.3%		32.2%	2019
8	Gaya	23.1%	10.0%	0.9%	17.3%	3.6%	4.4%	4.7%		36.1%	2019
9	Guwahati-Dispur	36.5%	6.8%	5.2%	27.0%	6.8%	1.7%	0.8%		15.1%	2019
10	Gwalior	12.7%	9.3%	12.2%	12.9%	4.8%	2.5%	4.2%		41.4%	2019
11	Hyderabad	16.5%	4.8%	14.8%	18.6%	12.9%	6.8%	0.2%		25.3%	2019
12	Jamshedpur	19.5%	6.6%	25.8%	15.0%	3.0%	3.7%	2.2%		24.1%	2019
13	Jodhpur	19.9%	6.1%	6.6%	25.5%	3.8%	2.1%	0.0%		36.0%	2019
14	Kolkata-Howarh	13.5%	8.6%	17.6%	12.5%	12.8%	9.4%	6.7%		19.0%	2019
15	Kota	16.7%	8.0%	19.5%	12.5%	4.7%	1.4%	0.5%		36.6%	2019
16	Lucknow	13.0%	24.3%	4.3%	13.9%	7.5%	3.3%	3.5%		30.1%	2019
17	Madurai	23.4%	3.5%	13.6%	19.0%	15.0%	3.6%	0.0%		22.0%	2019
18	Mumbai	16.4%	3.2%	15.0%	12.6%	3.8%	1.9%	2.3%	12.1%	32.6%	2019
19	Nashik	12.1%	6.6%	15.8%	13.2%	8.7%	3.6%	0.9%		39.1%	2019
20	Panjim-Vasco-Margao	22.6%	0.6%	4.5%	12.6%	2.8%	2.6%	0.0%	17.0%	37.3%	2019
21	Puducherry-Cuddalore	9.7%	1.2%	27.8%	6.7%	8.9%	7.8%	0.6%	7.3%	30.0%	2019
22	Rajkot	19.0%	5.1%	20.9%	16.4%	6.9%	2.2%	0.0%		29.6%	2019
23	Shimla	17.4%	11.8%	0.2%	11.8%	5.5%	1.0%	0.0%		52.2%	2019
24	Srinagar	9.8%	41.3%	0.8%	8.2%	6.4%	7.4%	1.8%		24.4%	2019
25	Surat	16.4%	1.7%	31.4%	10.3%	9.8%	3.3%	0.3%	5.6%	21.2%	2019
26	Thiruvananthapuram	37.0%	5.5%	9.4%	17.4%	6.6%	5.4%	0.0%	3.2%	15.4%	2019
27	Tiruchirapalli	19.0%	3.9%	28.2%	16.2%	7.9%	4.4%	0.0%		20.5%	2019
28	Vadodara	20.8%	4.7%	8.0%	17.2%	7.6%	5.8%	0.6%		35.4%	2019
29	Vijayawada-Guntur-Tenali	22.7%	3.5%	11.7%	19.7%	9.3%	5.9%	1.4%		25.8%	2019
30	Visakhapatnam	19.3%	3.3%	23.5%	10.9%	8.1%	2.3%	0.0%	4.8%	27.8%	2019
31	Agra	13.9%	23.8%	0.2%	10.7%	12.4%	2.7%	0%		35.9%	2017
32	Amritsar-Tarn Taran	10.5%	10.6%	7.3%	7.1%	6.1%	3.1%	2.1%		52.7%	2017
33	Bengaluru	26.5%	9.8%	2.1%	23.0%	16.1%	4.0%	2.5%		15.6%	2017
34	Bhopal	14.1%	10.2%	2.8%	17.1%	8.7%	4.9%	0.0%		41.8%	2017
35	Bhubaneswar	17.0%	15.9%	0.6%	20.8%	5.7%	3.6%	4.0%		32.0%	2017
36	Chandigarh-Patiala-Ambala	10.6%	11.4%	1.3%	12.6%	8.9%	2.6%	1.3%		50.8%	2017
37	Chennai	24.5%	3.6%	12.8%	23.5%	15.5%	1.6%	3.1%	1.8%	13.3%	2017
38	Coimbatore	18.3%	6.4%	11.1%	13.7%	14.1%	2.4%	1.0%		32.5%	2017
39	Dehradun	14.2%	14.3%	1.3%	4.4%	19.6%	3.8%	0.4%		41.7%	2017
40	Indore	26.9%	8.1%	2.4%	22.7%	7.8%	2.0%	2.0%		27.8%	2017
41	Jaipur	24.1%	13.4%	2.4%	17.5%	8.4%	2.2%	1.7%		29.9%	2017
42	Kanpur	13.7%	33.8%	6.5%	8.9%	8.8%	4.1%	1.2%		22.5%	2017
43	Kochi	20.2%	9.5%	4.1%	16.3%	3.8%	4.5%	3.8%	16.5%	20.9%	2017
44	Ludhiana-Phillaur	16.3%	7.8%	7.9%	12.3%	9.2%	2.6%	2.8%		40.7%	2017
45	Nagpur	17.2%	6.8%	26.7%	10.9%	11.6%	1.8%	3.2%		21.4%	2017
46	Patna	14.8%	14.6%	11.2%	12.1%	12.9%	5.4%	9.3%		19.2%	2017
47	Pune-Pimpri Chinchwad	24.0%	5.8%	9.8%	23.4%	6.4%	2.8%	2.6%		24.7%	2017
48	Raipur-Durg-Bhillai	17.2%	11.8%	22.8%	11.5%	6.2%	2.8%	1.4%		25.8%	2017
49	Ranchi	21.1%	18.0%	1.1%	14.1%	12.2%	1.3%	3.2%		28.5%	2017
50	Varanasi	13.5%	20.9%	0.2%	8.2%	16.2%	3.3%	6.1%		31.2%	2017

REFERENCES

Guttikunda, S.K., Nishadh, K.A., Jawahar, P., 2019. Air pollution knowledge assessments (APnA) for 20 Indian cities. Urban Climate 27, 124-141.

UEinfo, 2020. Resource Links: Energy, Emissions and Air Pollution Analysis in India. https://www.urbanemissions.info.

Raw & Processed Data Repositories for Energy and Emissions Analysis in India

The links were last accessed in March 2022 at the time of the submission of this manuscript.

A. Official national and state level portals; guidelines, acts, and rules documents

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National Clean Air Programme (NCAP)

- Draft NCAP proposal (2018)
- Final NCAP proposal (2019)
- City by city approved action plans are available here or here
- NCAP budget and pollution tracker (by CarbonCopy)
- A review of the 102 approved action plans – conducted by Urban Emissions and CEEW, July 2020. Final publication here.
- A review of 10 approved action plans – conducted by NRDC, January 2020

Official portals

- Ministry of Environment, Forests, and Climate Change (MoEFCC)
- National Green Tribunal (NGT)
- Environment Pollution (Protection & Control) Authority (EPCA)
- Central Pollution Control Board (CPCB)
- State Pollution Control Boards
    - [Andhra Pradesh] [Arunachal Pradesh] [Assam] [Bihar] [Chhattisgarh] [Goa] [Gujarat] [Haryana] [Himachal Pradesh] [Jharkhand] [Karnataka] [Kerala] [Madhya Pradesh] [Maharashtra] [Manipur] [Meghalaya] [Mizoram] [Nagaland] [Odisha] [Punjab] [Rajasthan] [Sikkim] [Tamil Nadu] [Telangana] [Tripura] [Uttar Pradesh] [Uttarakhand] [West Bengal]
- Pollution Control Committees
    - [Andaman & Nicobar Islands] [Chandigarh] [Dadra, Nagar Haveli, Daman, & Diu] [Delhi] [Jammu & Kashmir] [Ladakh] [Lakshadweep] [Puducherry]
- National Environmental Engineering Research Institute (CSIR-NEERI)

Acts and Rules

- Air (Prevention and Control of Pollution) Act, 1981, amended 1987
    - Air (Prevention and Control of Pollution) Rules, 1982
    - Air (Prevention and Control of Pollution) Rules, 1983
- Environment (Protection) Act, 1986 and Rules thereunder
- National Green Tribunal Act, 2010
- National Ambient Air Quality Standards, amended 2009

Environmental Standards

- 17 major polluting industries
    - Aluminium Smelter, Caustic Soda, Cement, Copper Smelter, Distilleries, Dyes & Dye Intermediates, Fertiliser, Integrated Iron & Steel, Tanneries, Pesticides,

Petrochemicals, Drugs & Pharmaceuticals, Pulp & Paper, Oil Refineries, Sugar, Thermal Power Plants, Zinc Smelter

- Effluent emission standards are listed @CPCB and @MoEFCC. Here is a summary for the heavy industry
    - [Bricks] [Cement] [Coal mines] [Coal washeries] [Copper, Lead, and Zinc smelting] [Fertilizers] [Glass] [Iron and Steel] [Paper and Pulp] [Pesticides] [Petrochemicals] [Sewage Treatment] [Sugar] [Tanneries] [Textiles] [Thermal power plants]

B. Ambient air quality monitoring

- 101 style blog piece on air monitoring in India
- Guidelines and technical specifications
    - 2003 – guidelines for ambient air monitoring
    - 2015 – technical specifications for continuous ambient air quality monitoring stations (CAAQMS)
    - 2018 – technical specifications for continuous emissions monitoring (CEMS)
- Number of monitoring states recommended by state and by district (based on the guidelines published by CPCB, 2003)
- National Ambient Monitoring Program (NAMP) – manual monitoring network operated and maintained by CPCB, India
    - Table of monitoring stations (as of July 2020)
    - Annual summary of air quality and number of monitoring days (2013, 2014, 2015, 2016, 2017, 2018)
    - Monthly AQI bulletins
    - Compiled NAMP air quality data (as excel) for 2011-2015
- Continuous Ambient Air Quality Monitoring System (CAAQMS) – real-time monitoring network operated and maintained by CPCB, India
    - How to access real-time and archived CAAQMS data?
- System of Air Quality and Weather Forecasting And Research (SAFAR) – real-time monitoring network operated and maintained by IITM, Pune, India
- A global summary of outdoor ambient air quality data by WHO (2018)
    - A review piece of WHO data included for India (2018)
- openaq.org – aggregator of official real-time monitoring data across the globe (blog piece on how to access data)
- IQair – aggregator of official and unofficial data across the globle
- Breezo.in – aggregator of official real-time monitoring data in India
- AirVeda – unofficial network of low-cost sensors
- AQI.in – unofficial network of low-cost sensors
- Purple Air – unofficial network of low-cost sensors
- Clarity – unofficial network of low-cost sensors
- Full resource links with illustrations

C. Satellite retrievals and tools

- Indian National Satellite System (INSAT) series
    - RAPID portal to visualize real-time INSAT products (IMD, Delhi)
    - Satellite derived PM2.5 (by ISRO, Dehradun)
    - Radar maps (IMD, Delhi)
    - Customized satellite maps for the Indian Subcontinent (IMD, Delhi)
- Geostationary Environment Monitoring Spectrometer (GEMS) – hourly air quality over East Asia and part Indian Subcontinent (new)
- Multi-Angle Imager for Aerosols (MAIA) (new)
- Tropospheric Monitoring Instrument (TROPOMI) – NO2, SO2, Ozone, HCHO, and CH4
- Active fire counts database from VIIRS satellite
- Active burned area product from MODIS satellite
- Fires visualization portal by NASA
- ACE-FTS and MAESTRO – 50+ gaseous species
- Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)
- Global Ozone Monitoring Experiment (GOME-2) – total column SO2, O3, NO2, and cloud parameters
- Measurement of Pollution in the Troposphere (MOPITT) – CO and CH4
- Total Ozone Mapping Spectrometer (TOMS) – Ozone
- Ozone Monitoring Instrument (OMI) – near real time SO2, O3, and AOD
- Moderate Resolution Imaging Spectroradiometer (MODIS)
    - near real time Aerosol Optical Depth (AOD)
    - Leaf Area Index (LAI) data sets were generated by reprocessing the MODIS version 6 LAI products for 2000 to 2019at multiple resolutions
- Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) – multiple gases
- Optical Spectograph and Infrared Imaging System (OSIRIS) – O3 and NO2
- Multi-angle Imaging Spectrometer (MISR) – dust storms and aerosols
- Global Precipitation Measurements (GPM)
- Data centers and access methods
    - World Data Center (WDC)
    - Earth Data (NASA)
    - Data access methods (NASA)
    - Copernicus open access hub (ESA)
    - Aura Validation Data Center (AVDC, NASA)
    - The Wisconsin Horizontal Interpolation Program for Satellites (WHIPS)
    - Atmospheric Tool Box (ATB) for Sentinel-5P products
    - Google Earth Engine (GEE) for Sentinel-5P products

D. Global & regional health impact analysis and tools

- Visualization portal for 1990-2018 global burden of disease estimates (IHME-GBD)
    - Resource links to methodology and inputs
- Visualization portal for State of the Global Air (SOGA) by Health Effects Institute (HEI)
    - India factsheet and more
- India state-level disease burden initiative by ICMR and PHFI (2019)
    - State-level reports (PHFI)
- Burden of disease attributable to major sources of air pollution in India (GBDMAPS-India) by HEI
- Air Quality Life Index (AQLI) by U.Chicago
- Health impacts analysis tools
    - Household Air Pollution Intervention Tool (HAPIT)
    - Air pollution health effects online tool by TERI
    - CO-Benefits Risk Assessment (COBRA) health impacts screening and mapping tool by USEPA
    - Environmental BENefits MAPping and analysis program (BENMAP) by USEPA
    - AirCounts tool by Abt Associates
    - Tool for health risk assessment of air pollution – AirQ+ by WHO
    - FAst Scenario Screening Tool (FASST) by EU
    - Greenhouse gas – Air pollution INteractions and Synergies (GAINS) by IIASA
    - The Long-range Energy Alternatives Planning – Integrated Benefits Calculator (LEAP-IBC) by SEI
    - Simple Internative Models for better air quality (SIM-air) by Urban Emissions

E. Compiled statistics, maps, and other geospatial databases

Compiled national and state level statistics

- Census India (2011)
- Indiastats.com (paid statistics service)
- Statista.com (paid statistics service)
- Statistical Year Book (SYB) of India by MoSPI
- Energy Statistics of India by MoSPI
- Directorate of Statistics by state
    - [Andhra Pradesh] [Assam] [Bihar] [Chandigarh] [Chhattisgarh] [Delhi] [Goa] [Gujarat] [Haryana] [Himachal Pradesh] [Jammu & Kashmir] [Jharkhand] [Karnataka] [Kerala] [Madhya Pradesh] [Maharashtra] [Manipur] [Meghalaya] [Mizoram] [Nagaland] [Odisha] [Puducherry] [Punjab] [Rajasthan] [Sikkim] [Tamil Nadu] [Telangana] [Tripura] [Uttarakhand] [Uttar Pradesh] [West Bengal]

Compiled GIS data and maps

- Community created maps of India by datameet
- Openstreetmaps (GIS)
- Mapcruzin.com (GIS)

- Global Human Settlements (GHS) – urban built areas
- Land cover data 1992-2015 (ESA)
- Gridded Population
    - Global database GPW from SEDAC
    - Global database Landscan from ORNL
    - India database for 2011-2050 at 0.25° resolution from Urban Emissions

F. Compiled databases on energy, emissions, meteorology, and reanalysis fields

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Compiled energy databases

- India energy dashboard by Niti Aayog
- India Energy Security Scenarios (IESS) by Niti Aayog
- GHG Platform India (GPI) by multiple agencies
- International Energy Agency (IEA)
- Greenhouse gas – Air pollution INteractions and Synergies (GAINS) by IIASA

Compiled emission databases

- MIX regional emissions database for Asia
- REAS regional emissions database for Asia
- EDGAR global emissions inventory
- CAMS global emissions inventory
- ECCAD global compilation of emissions and ancillary data
- SAFAR India emissions inventory by Indian Institute of Tropical Meteorology (contact)
- SMoG-India emissions inventory by Indian Institute of Technology, Bombay
- OMI-HTAPv2.2 SO2 global emissions inventory 2005-2019 (NASA)
- Greenhouse gas – Air pollution INteractions and Synergies (GAINS) by IIASA
- MEGAN global biogenic emissions
- Forest and agricultural fires
    - Fire emissions Inventory from NCAR (FINN) by UCAR
    - Global fire emissions database (GFED)
    - Global fire emissions database (IS4FIRES)
    - Blended global fire emissions database (GBBEPx V3) by NOAA
    - Global quick fire emissions database (QFED) by NASA
    - Global fire assimilation system (GFAS) by ECMWF

Compiled meteorological fields

- Indian Meteorological Department (IMD)
- Climate Explorer by KNMI for stationwise data
- NCEP global reanalysis fields (long-term achives)
- Global Forecast System (GFS) fields (short-term archives)
- Windy (open visualization portal)
- Earth Nullschool (open visualization portal)
- Compiled meteorological data for Indian districts (from Urban Emissions)

Compiled modelled reanalysis fields

- MOZART global model by UCAR
- CAM-chem global community earth system model by UCAR
- CAMS global reanalysis model by ECMWF
- MERRA-2 global reanalysis model by NASA
- SAANS India reanalysis model by IIT-Delhi
- Global PM2.5 reanalysis by WUSTL
    - Extracted India database for 1998-2018 from Urban Emissions

G. Compiled statistics on Indian energy sectors

Industry

- Annual Survey of Industries (ASI) by the Ministry of Statistics and Programme Implementation (MoSPI)
- Annual reports by MOSPI
- Annual reports by the Ministry of Steel
- Annual reports by the Ministry of Chemicals and Fertilizers
- Annual reports by the Ministry of Mines
- Annual reports by the Cement Manufacturers Association
- Annual reports by the Ministry of Micro, Small, and Medium Enterprises
- Annual reports by the Ministry of Textiles
- Annual reports by the Ministry of Coal
- Annual reports by the Ministry of Petroleum and Natural Gas
- Annual reports by the Department of Heavy Industry
- Annual reports by the Department of Animal Husbandry and Dairy
- Annual reports by the Department of Fisheries
- Annual reports by the Department of Pharmaceuticals
- Annual reports by the Department of Chemical and Petro-chemicals

Power Plants

- Official portals
    - Ministry of Power (MoP)
    - Ministry of Petroleum and Natural Gas (MoPNG)
    - Ministry of New and Renewable Energy (MNRE)
    - Ministry of Coal (MoC)
    - Central Electrical Authority (CEA) daily reports
    - National Power Portal (NPP) dashboard
    - Merit order dispatch of Electricity for Rejuvenating Income and Transparency (MERIT) by MoP
- Other portals
    - Coal India Limited (CIL)
    - Gas Authority of India Limited (GAIL)

    - Solar Energy Corporation of India (SECI)
    - National energy policy (Niti Aayog)
    - India Energy Review (IEA)
- Wikipedia
    - Electricity sector in India
    - Energy policy in India
    - Renewable energy in India
    - Solar power in India
- Regulations
    - Central Electricity Regulatory Corporation – current regulations
    - India Electricity Act (2003)
    - Environmental Standards for Ambient Air, Automobiles, Fuels, Industries and Noise (CPCB, 2000)
    - Industry effluent emission standards (CPCB)
    - Online monitoring of industrial emissions & effluent (CPCB)
- Power plants list
    - Global power plants database (WRI)
    - Global power plants database (GEO)
    - Global power plants database (Carbon Brief)
    - Existing power plants in India (Wikipedia)
    - Existing and proposed power plants in India (GEM-wiki)
    - Existing power companies in India (GEM-wiki)
    - Plant and unit level generation data (CEEW)
    - Hourly load curves 2012-2015 (CEEW)
    - Electricity generation and carbon tracker – dashboard by Brookings India
- Regional Load Dispatch Centers
    - Northern (NRLDC)
    - Sorthern (SRLDC)
    - Eastern (ERLDC)
    - Western (WRLDC)
    - NorthEastern (NERLDC)
- State Load Dispatch Centers
    - [Andhra Pradesh] [Assam] [Chhattisgarh] [Delhi] [Gujarat] [Himachal Pradesh]
    - [Karnataka] [Kerala] [Madhya Pradesh] [Maharashtra] [Odisha] [Punjab]
    - [Rajasthan] [Tamil Nadu] [Uttar Pradesh] [Uttarakhand] [West Bengal]
- **Non-governmental institutions**
    - Brookings India
    - Center for Science and Environment (CSE)
    - Center for Study of Science Technology and Policy (CSTEP)
    - Council for Energy Environment and Water (CEEW)
    - GHG Platform India (GPI)
    - Institute for Energy Economics and Financial Analysis (IEEFA)

Transport (road)

- National Transport Development Policy Committee (NTDPC) report – Moving India to 2032

- Annual reports by the Ministry of Road Transport and Highways
- Annual reports by the Ministry of Petroleum and Natural Gas
- Urban transport reports by the Ministry of Housing and Urban Affairs
- AMRUT/JNNURM city development reports
- Smart Cities Mission – city development reports
- Google directions API for traffic speeds (paid service)
    - Google mobility statistics during COVID-19
- Tom Tom traffic index (paid service)

Transport (rail, aviation, and shipping)

- Shipping – full resource links
- Aviation global emissions inventory by EDGAR
- Departures and arrivals information by AirSewa
- Railway train schedules
- Departures and arrivals information by flightstats (paid service)
- Cargo tonnage by rail and aviation by indiastats.com (paid service)

Open waste burning

- Global trash burning emissions inventory by UCAR
- waste management in India (database)
- Gridded open waste burning emissions in India (2019)