Supplementary Information for Surface $PM_{2.5}$ Air Pollution in 2022 India: Emission Updates, WRF-Chem Model Evaluation, and Source Attribution

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1. Detailed WRF-Chem configuration

1.1 Physical Schemes

We configure WRF-Chem with the following physical schemes: the Rapid Radiative Transfer Model for Global Circulation Models (RRTMG) scheme for both shortwave and longwave radiation, which simulates aerosol-radiation interactions (Iacono et al., 2008); the two-moment Morrison microphysics scheme, which simulates aerosol-cloud interactions (Morrison and Pinto, 2005); and the non-local mixing YonSei University (YSU) boundary layer scheme (Hong et al., 2006).

1.2 Mapping aerosol emissions to WRF-Chem variables

Emission inventories provide aerosol emissions of POC, BC, total primary $PM_{2.5}$, and total primary PM_{10}. While EDGAR provides all four types of aerosol emissions, CEDS only includes POC and BC emissions. Total primary $PM_{2.5}$ emissions conceptually comprise primary organic aerosols (POA), BC, and other anthropogenic $PM_{2.5}$ emissions (e.g., construction and urban dust), while total primary PM_{10} emissions include $PM_{2.5}$ and coarse PM emissions. As described in **Section 2.2.1**, we apply POC and BC emissions from CEDS and use $PM_{2.5}$ and PM_{10} emissions from EDGAR.

In the selected chemical option (i.e., chem_opt=9, CBMZ_MOSAIC_4BIN_AQ), WRF-Chem reads aerosol emissions as POA, BC, other anthropogenic $PM_{2.5}$, and coarse PM. To map emissions into WRF-Chem variables, we first convert POC to POA emissions using an POC-to-POA ratio of 1.9 for India (Venkataraman et al., 2018). Since we use separate sources for total primary $PM_{2.5}$, BC, and POC, we enforce the constraint $PM_{2.5} \geq BC + POA$. This ensures that the total $PM_{2.5}$ emissions input into WRF-Chem do not exceed those estimated in the merged inventory and prevents negative emissions of other anthropogenic $PM_{2.5}$, which are calculated as $PM_{2.5} - BC - POA$. Coarse PM emissions for WRF-Chem are derived by subtracting $PM_{2.5}$ emissions from PM_{10} emissions.

When distributing aerosol species into the WRF-Chem MOSAIC aerosol bins, we use the default size distribution profiles in the WRF-Chem emission module, which distinguishes between two sources: (1) biomass burning and wildfire sources, and (2) all other sources.

1.3 Vertical distribution of emissions

Emissions are vertically distributed into WRF-Chem model by sources: (1) agricultural non-burning, residential, and transportation emission are placed at the model’s first layer; (2) industrial emissions are distributed within the model’s first three layers; (3) power sector emissions are placed within the model’s first five layers; (4) natural dust and natural biogenic VOC emissions are placed at the model’s first layer; (5) biomass burning emissions are placed vertically using WRF-Chem’s online calculated plume rise height.

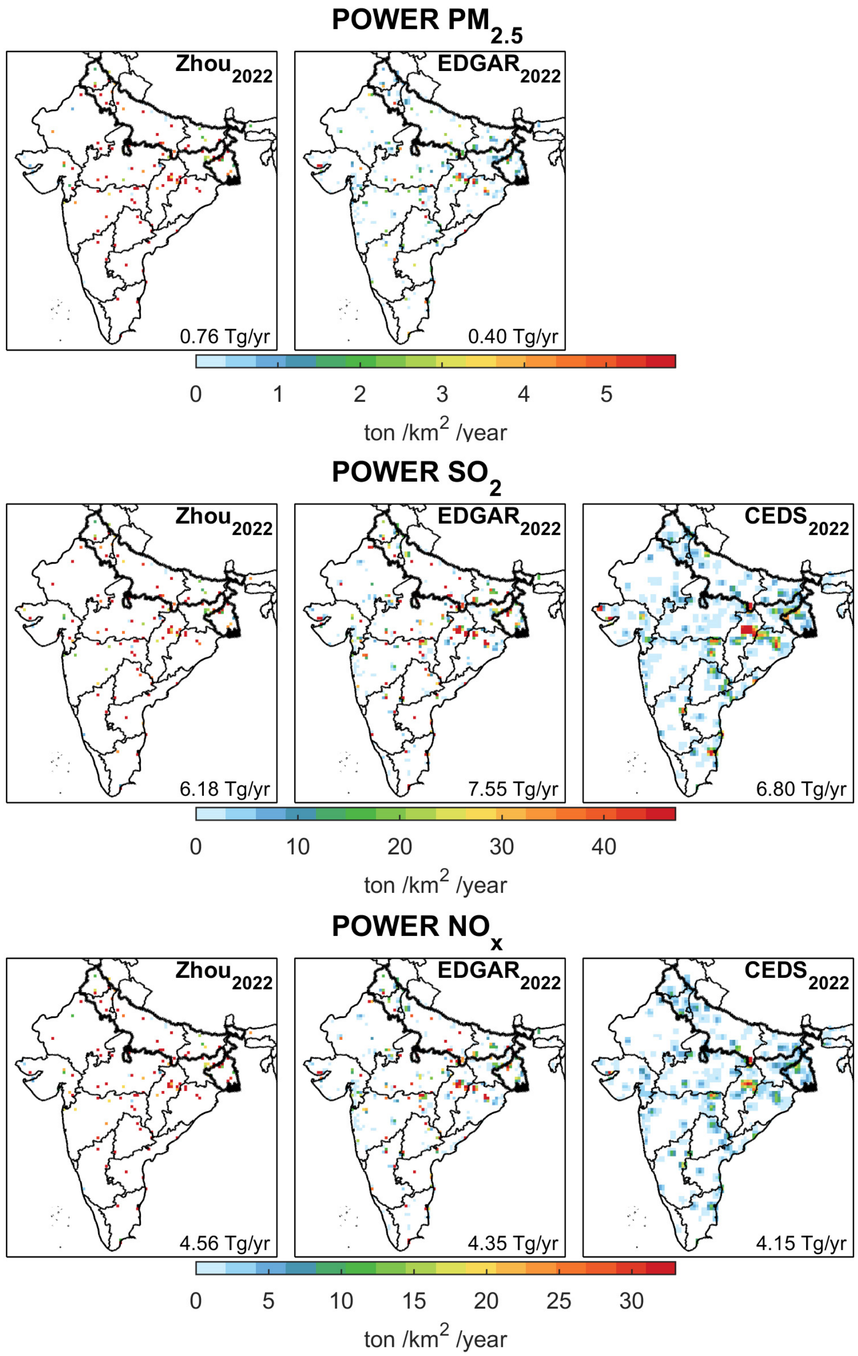

Figure S1. Spatial distribution of 2022 annual power plant emissions of $PM_{2.5}$, SO_2, and NO_x from the inventory developed in this study (Zhou), CEDS, and EDGAR. Our new inventory provides point-source emissions, whereas EDGAR and CEDS report gridded emissions at 0.1° and 0.5° resolution, respectively. For comparison, all inventories are interpolated to the 27 km WRF-Chem model grid. CEDS does not provide primary $PM_{2.5}$ emissions. Numbers inset in each panel indicate annual power plant total emissions across India, and the thick black line denotes the boundary of the Indo-Gangetic Plain (IGP).

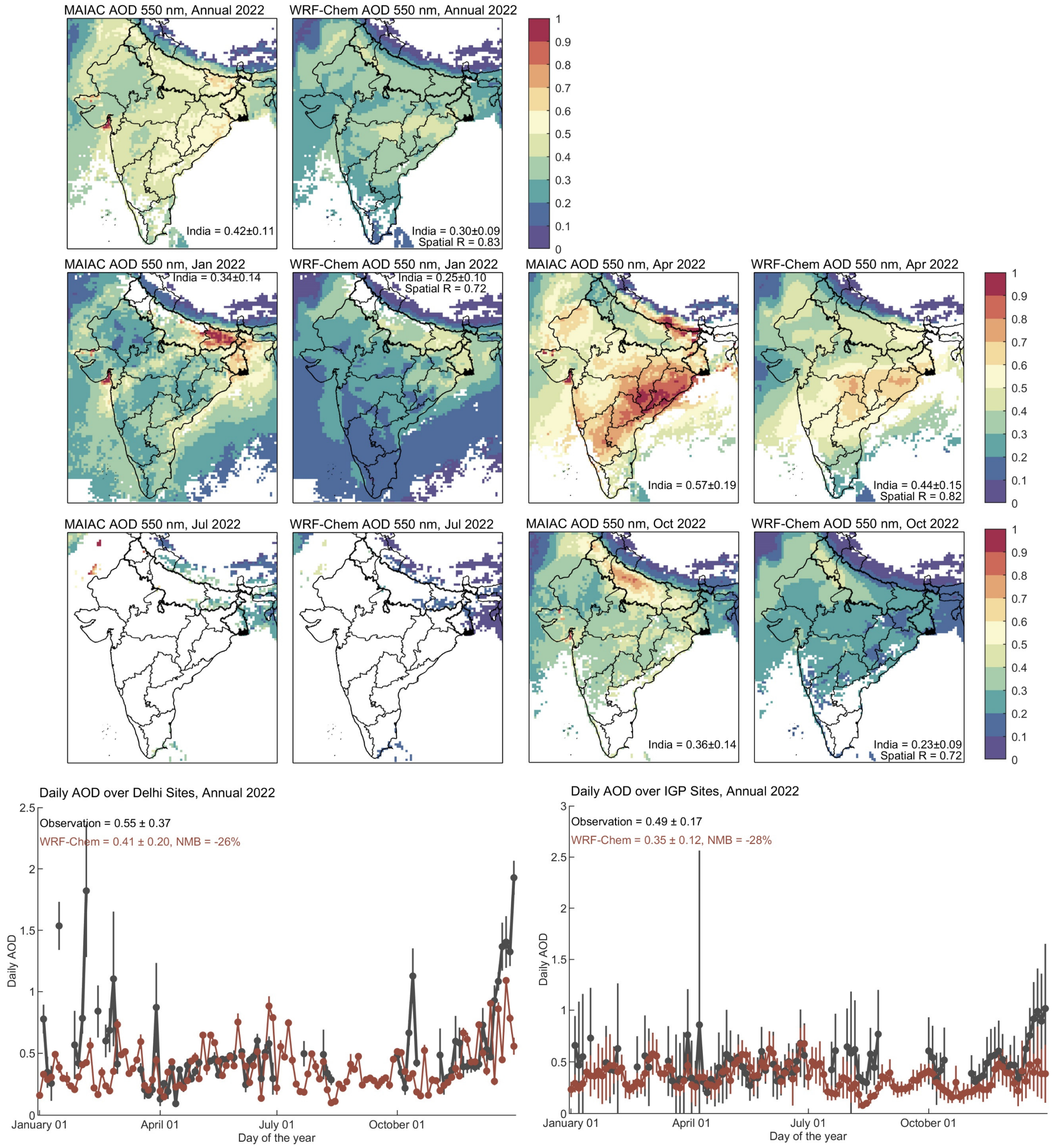

Figure S2. Comparison of WRF-Chem AOD against satellite-derived AOD at 550 nm in 2022. Daily WRF-Chem AOD is derived using mean AOD during 10:00 to 14:00 local time when same day MAIAC AOD is available. In map plots, annual and monthly comparison results are shown for grids with at least 50% valid co-sampled data. Inset numbers in each map plot show the mean ± one standard deviation across India expect for July when there are very few available values. We calculate the Pearson correlation coefficient (Spatial R) between the observed AOD at 550 nm and simulated AOD at 550 nm across India expect for July. The thick black line denotes the boundary of the Indo-Gangetic Plain (IGP) in each map plot. In timeseries plots, we sample MAIAC and WRF-Chem AOD at grids with available $PM_{2.5}$ measurements in each region, and present daily AOD data if at least 50% grids in that region have valid AOD data.

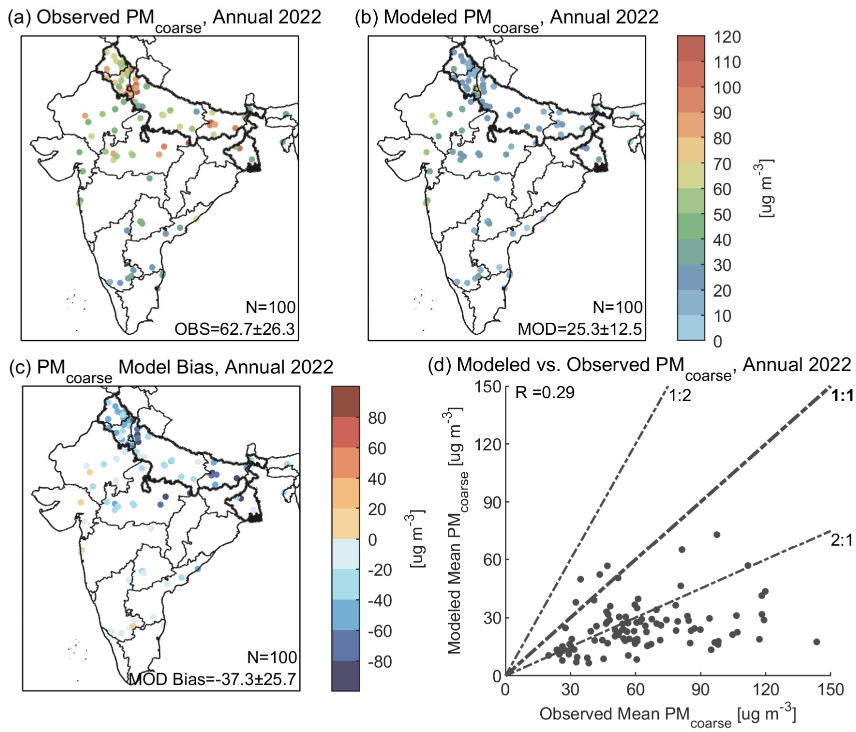

Figure S3. Comparison of observed and modeled surface PM_{coarse} concentrations in 2022 in the baseline simulation. Measurement stations with at least 80% valid hourly data during the four-month period (January, April, July, and October) are selected. Multiple measurements within a single WRF-Chem grid cell are averaged before comparison with WRF-Chem. Annual value is estimated by averaging $PM_{2.5}$ concentrations during the four-month period. In map plots, N denotes the number of grid cells used for evaluation, and the other numbers represent the mean ± one standard deviation across all grid cells. The thick black line denotes the boundary of the Indo-Gangetic Plain (IGP). In the scatter plot, R is the Pearson correlation coefficient between observed and modeled annual mean concentrations across all grid cells.

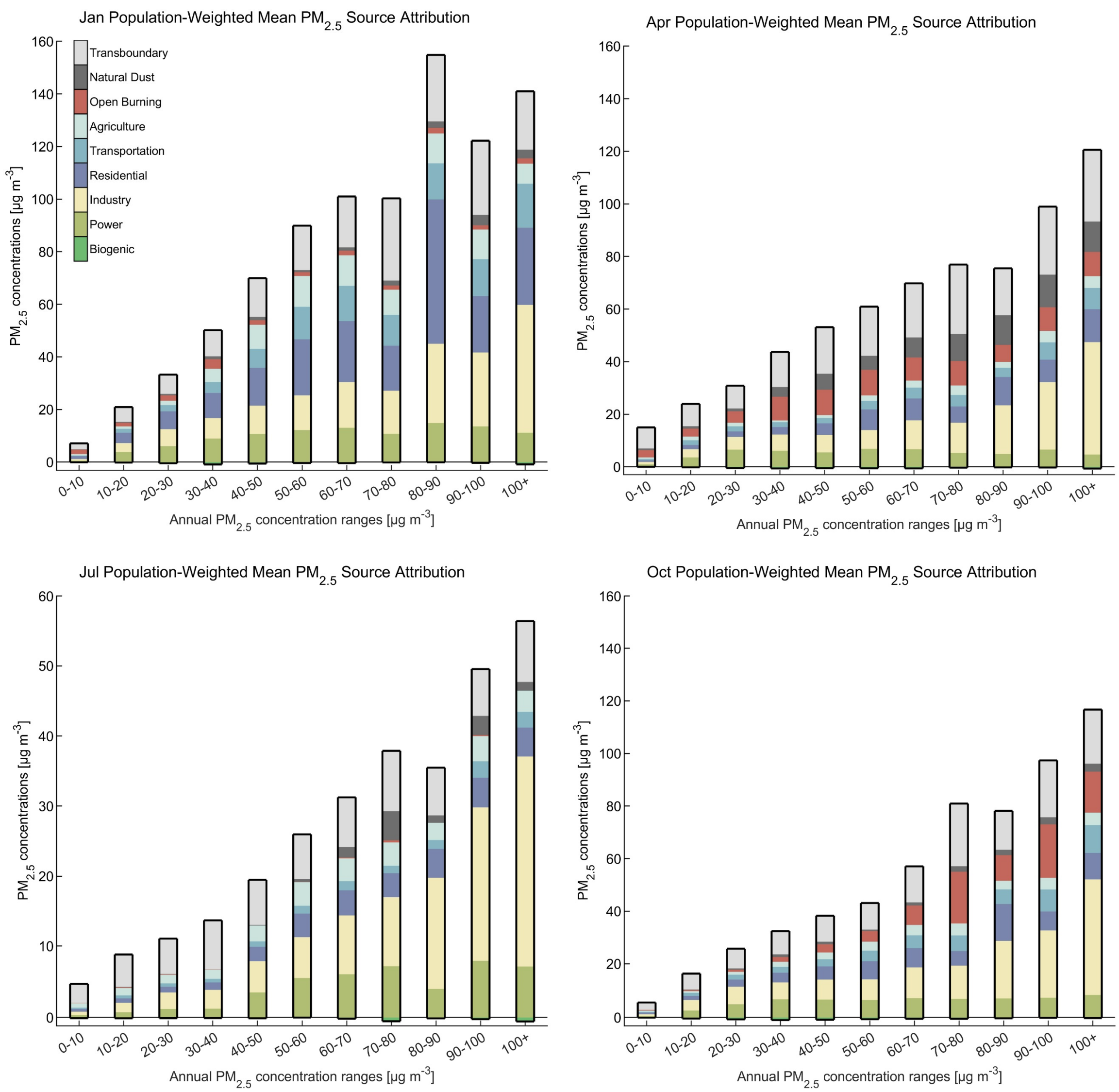

Figure S4. Monthly $PM_{2.5}$ source attribution grouped by annual mean $PM_{2.5}$ concentrations. WRF-Chem grids are aggregated by ranges of annual mean $PM_{2.5}$ concentrations, with colored bars indicating source attribution. See Main Text Figure 5c for the annual version of this figure.

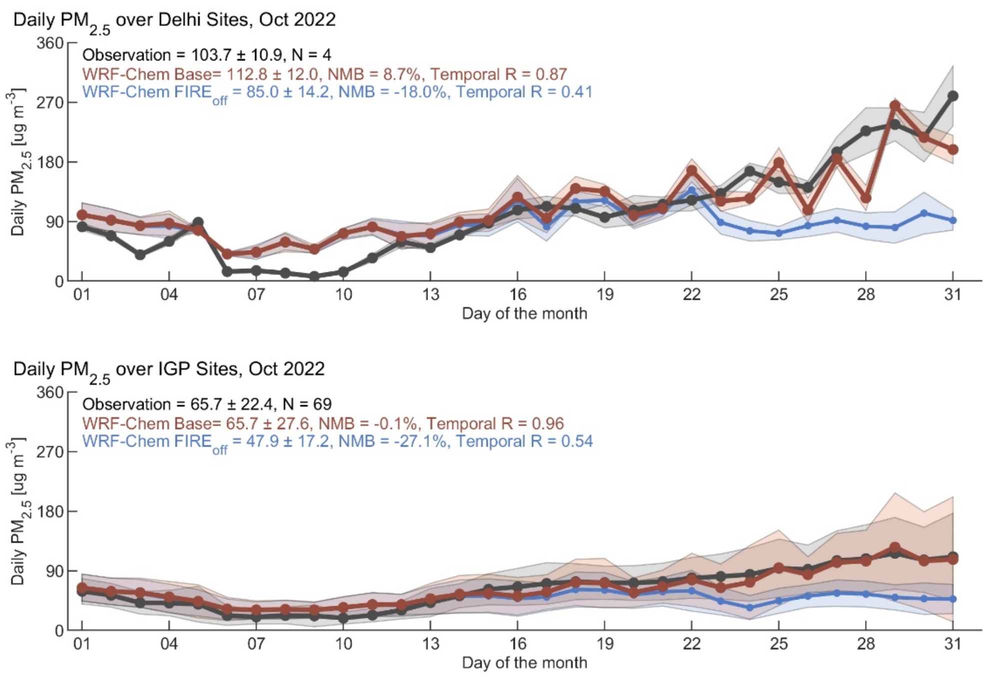

Figure S5. Comparison of observed and modeled (with and without fire emissions) surface $PM_{2.5}$ concentrations in October 2022. Measurement stations with at least 80% valid hourly data are selected. Multiple measurements within a single WRF-Chem grid cell are averaged before comparison with WRF-Chem. N denotes the number of grid cells used for evaluation. Colored lines and dots represent daily and regional mean $PM_{2.5}$ concentrations across available grid cells, with shaded areas indicating one standard deviation across daily mean $PM_{2.5}$ concentrations across those cells. Temporal R is the Pearson correlation coefficient between the red (or blue) and black lines in each panel. NMB is normalized mean bias.

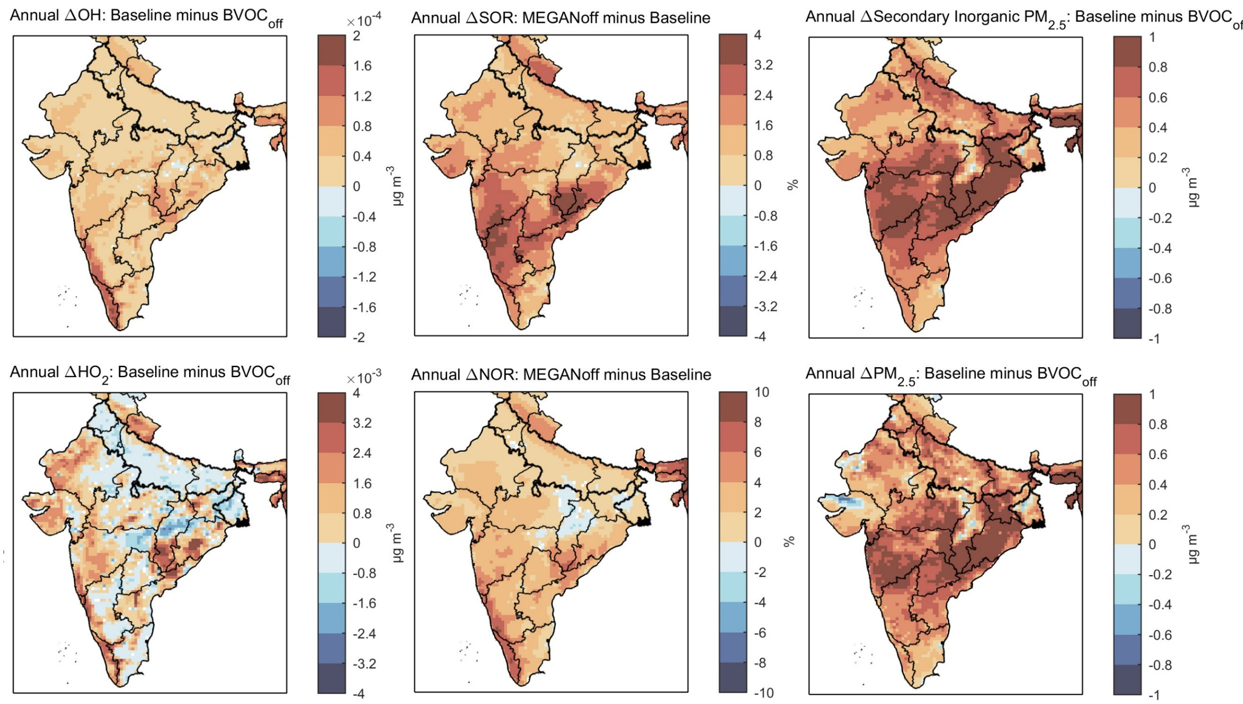

Figure S6. Impact of including BVOC emissions (via turning on the MEGAN module within India) on atmospheric chemistry. Annual results are calculated as the average of January, April, July, and October simulations. Sulfur Oxidation Ratio (SOR) and Nitrogen Oxidation Ratio (NOR) are calculated as $(SO_4^{2-} + H_2SO_4)/(SO_4^{2-} + H_2SO_4 + SO_2)$ and $(NO_3^- + HNO_3)/(NO_3^- + HNO_3 + NO_2)$, respectively. The thick black line denotes the boundary of the Indo-Gangetic Plain (IGP).

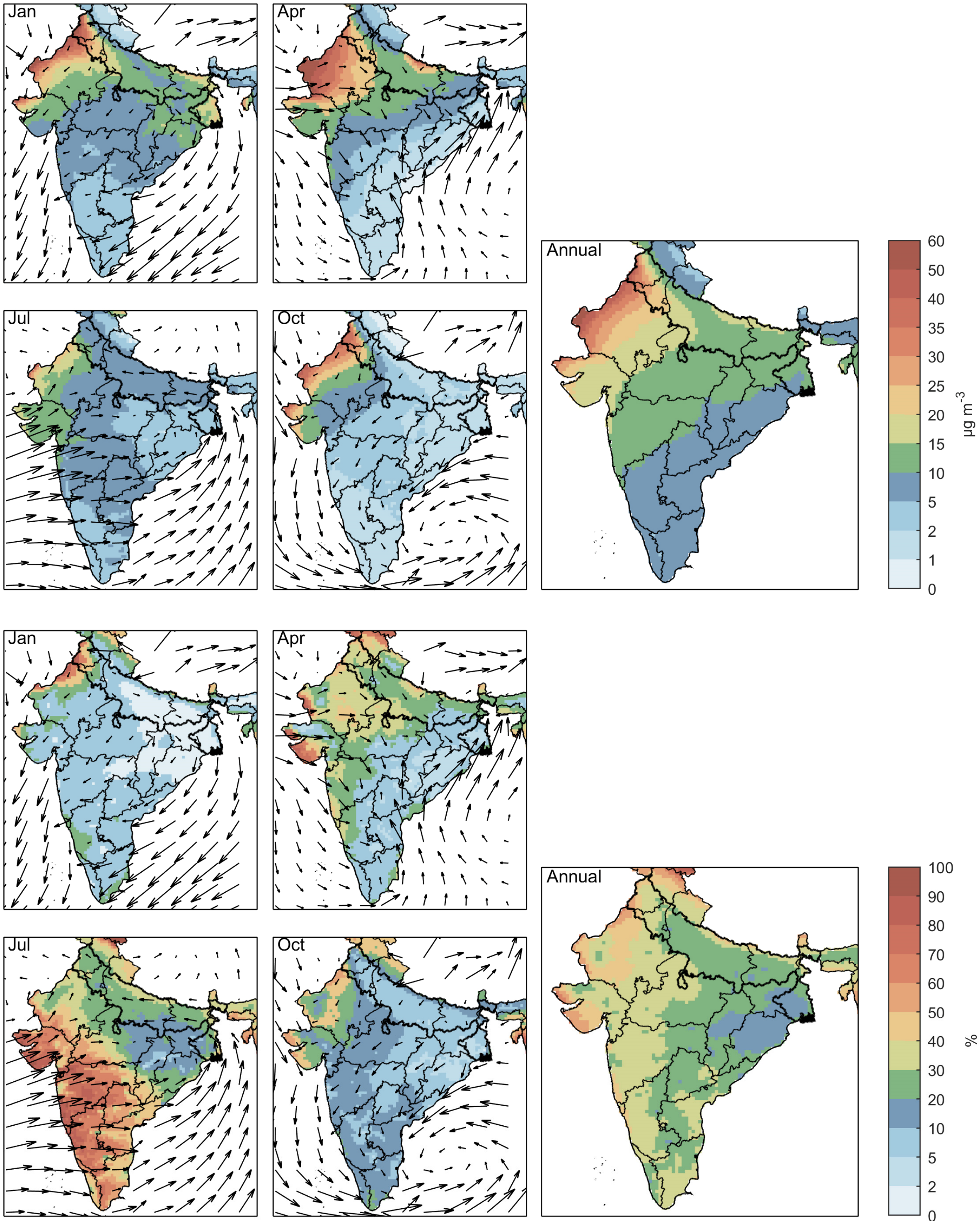

Figure S7. Absolute (upper panels) and percentage (lower panels) contribution of transboundary sources to monthly and annual $PM_{2.5}$ concentrations in 2022. Monthly mean 10-meter wind vectors are also shown to indicate near-surface transport of $PM_{2.5}$ and its precursors. The thick black line denotes the boundary of the Indo-Gangetic Plain (IGP).

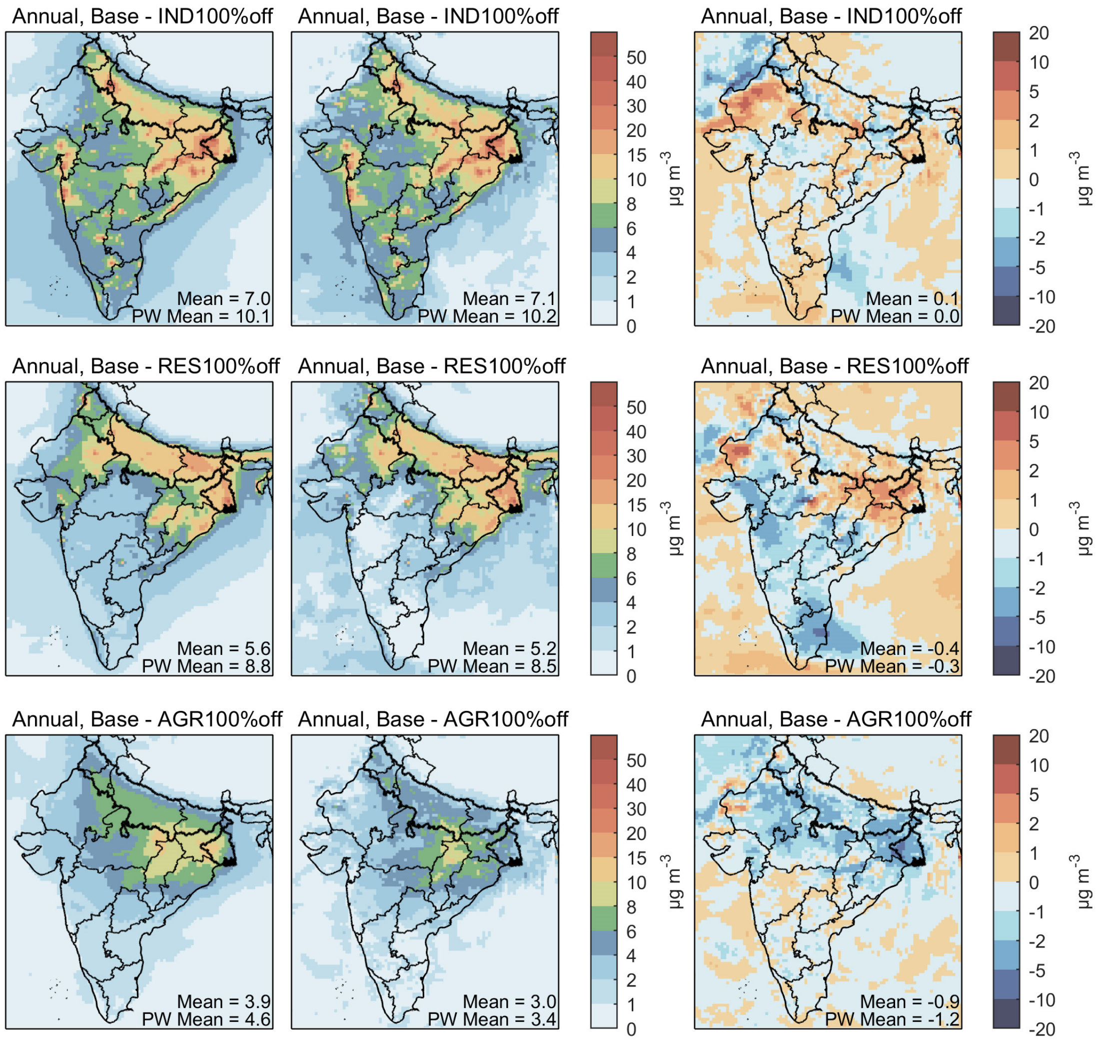

Figure S8. Comparison of $PM_{2.5}$ concentration changes between a 100% emission reduction and a fivefold scaling of 20% reductions. We show results for three sectors: industry (IND), residential (RES), and agriculture (AGR). The thick black line denotes the boundary of the Indo-Gangetic Plain (IGP).

Table S1. Uncontrolled emission factors for coal from different regions and lignite used in India's power sector

Source Region	Fuel Classification	CO_2 (g/kg fuel)	SO_2 (g/kg fuel)	NO_x as NO_2 (g/kg fuel)	$PM_{2.5}$ (g/kg fuel)
Assam	Domestic Coal	2328.98±232.90	10.84±1.08	6.04±0.60	1.81±0.18
Chhattisgarh		1204.70±272.69	6.59±0.12		11.37±1.26
Jharkhand		1493.66±408.28	6.84±2.12		9.70±2.24
Madhya Pradesh		1517.01±237.64	6.63±1.20		7.88±3.59
Maharashtra		1501.35±93.04	10.90±7.32		8.13±2.69
Odisha		1062.78±184.29	5.59±1.51		12.66±1.35
Telangana		1396.70±139.67	6.42±0.64		12.18±1.22
Uttar Pradesh		1294.35±129.44	9.18±0.92		10.62±1.06
West Bengal		1810.35±245.88	6.26±1.77		8.49±3.19
Australia	Imported Coal	2307.23±230.72	8.34±0.83		3.92±0.39
Indonesia		1250.85±125.08	5.17±0.52		1.06±0.11
South Africa		2181.98±218.20	18.52±1.85		8.61±0.86
Gujarat, Rajasthan, and Tamil Nadu	Lignite	896.52±51.27	25.54±7.22	4.00±0.40	3.30±1.70

Source Data: (Kalenga et al., 2011; Mittal et al., 2012; Yunus et al., 2014; Cheepurupalli et al., 2015; Gogoi, 2018; The Singareni Collieries Company Limited, 2018; Dwivedi and Kumar, 2022; U.S. Environmental Protection Agency)

Table S2. Average contribution of sectoral emissions to national total anthropogenic emissions for each species in India across emission inventories during 2015 to 2022*

	NO_x	SO_2	$PM_{2.5}$	BC	OC	CO	PM_{coarse}‡	NH_3
Agriculture†	5±0%	0±0%	1±0%	0±0%	0±0%	0±0%	3±0%	85±0%
Industry	19±1%	32±2%	41±5%	38±3%	30±3%	30±1%	37±5%	9±1%
Transportation	29±1%	1±0%	5±1%	13±4%	2±1%	10±1%	1±0%	0±0%
Power	39±0%	61±2%	11±1%	4±1%	4±1%	4±1%	13±9%	1±0%
Residential	8±0%	6±0%	42±2%	45±1%	64±3%	57±1%	46±14%	5±0%

*Results in this table are derived from three global emission inventories: CEDS version 2024-07-08, EDGAR version 8.1, and Hemispheric Transport of Air Pollution (HTAP) version 3.1. Please see Methods for details of how each emission inventory is utilized.

†This excludes agricultural waste burning.

‡PM_{coarse} emissions are estimated by subtracting $PM_{2.5}$ emissions from PM_{10} emissions.

Table S3. A summary of India's power sector emission inventories from this study and previous studies

Inventory	Year of Inventory	Total Coal-based Capacity (GW)	Total Coal-based Generation (TWh/year)	Total Emissions (Tg/year)			Emission Factors (g/kWh)		
				$PM_{2.5}$	SO_2	NO_x (as NO_2)	$PM_{2.5}$	SO_2	NO_x (as NO_2)
This Study*	2022	210.6†	1121.7	0.76	6.18	4.56	0.68	5.51	4.07
(Velamuri et al., 2024)*	2022	210.0	1160.4	0.31	4.70	3.48‡	0.27	4.05	3.00‡
(Singh et al., 2024)*	2019	175.0	948.6	0.58	6.52	4.85	0.61	6.88	5.11
(Cropper et al., 2021)*	2018	208.0	1093.2	0.57	4.86	4.57‡	0.52	4.45	4.18‡
(Guttikunda and Jawahar, 2014)*	2010-2011	120.7	689.0	0.58	2.1	2.99‡	0.84	3.05	4.34‡
EDGAR (v8.1) (Crippa et al., 2018)¶	2022	-	-	0.40	7.55	4.35	-	-	-
CEDS (v2024-07-08) (Hoesly et al., 2018)¶	2022	-	-	-	6.80	4.15	-	-	-
HTAP (v3.1) (Guizzardi et al., 2025)¶	2020	-	-	0.66	7.26	2.99	-	-	-
(Venkataraman et al., 2024)¶	2019	-	-	1.70	5.11	2.47	-	-	-
(Venkataraman et al., 2018)¶	2015	-	-	1.07	3.70	2.26	-	-	-

*Inventories only include coal-fired power plants.

¶Inventories include coal, gas, and oil-fired power plants, with coal plants dominating total emissions.

†This value matches the total generation capacity of coal and lignite documented by the Central Electricity Authority (CEA) of India in July 2022.

‡These inventories provide NO_x emissions without specifying the partition between NO and NO_2. We assume a composition of 95% NO and 5% NO_2 for the NO_x emissions reported in these inventories and convert them to NO_2 emissions

Table S4. Summary of model performance of annual $PM_{2.5}$ simulation against surface measurements in each state[†]

	WRF-Chem Mean ($\mu g/m^3$)	Observation Mean ($\mu g/m^3$)	Mean Bias ($\mu g/m^3$)	Normalized Mean Bias (%)	Temporal Correlation*	Number of model grids
Andhra Pradesh	30.3±4.7	30.8±5.0	-0.4±5.4	0.35±18.87	0.9	4
Assam	35.8	48.2	-12.5	-25.46	0.54	2
Bihar	55.4±7.9	77.1±11.5	-21.7±11.2	-26.79±15.27	0.89	10
Chandigarh	44.2	47.7	-3.5	-7.3	0.65	1
Delhi	100.2±13.5	100.7±9.2	0.6±16.9	1.61±16.55	0.81	4
Foreign	69.0±30.6	75.1±31.4	-6.2±5.5	-8.25±6.09	0.86	5
Gujarat	66.5	47.5	19	50.92	0.54	3
Haryana	63.6±14.6	73.6±12.6	-10.1±10.9	-13.37±16.92	0.8	14
Karnataka	26.9±7.8	25.7±4.6	1.2±6.2	5.14±22.97	0.88	11
Kerala	20.6	17.9	2.7	14.8	0.6	1
Maharashtra	54.3±11.0	40.2±5.7	14.1±6.1	34.07±13.97	0.74	5
Madhya Pradesh	48.5±10.3	50.5±13.3	-2.0±6.9	-1.81±14.05	0.88	10
Nagaland	25.1	27	-2	-7.22	0.56	1
Punjab	58.3±12.9	48.9±9.0	9.4±17.8	24.41±42.20	0.77	7
Rajasthan	58.7±7.8	51.6±7.3	7.1±12.0	17.05±29.38	0.8	8

[*]We first average results for all model grid within a given region, and then estimate the temporal Pearson correlation coefficient between observed and simulated daily $PM_{2.5}$, consistent with **Figure 3 e** and **g**.

Table S5. Source contribution to 2022 annual population-weighted mean $PM_{2.5}$ nationwide and in each state

(dominant domestic source is highlighted in red)

	Domestic Sources (see the note after this table for full names of each source)								**Transboundary Sources**
	POW	**IND**	**RES**	**TRA**	**AGR**	**FIRE**	**DST**	**BOVC**	
National	6.1 (13%)	8.6 (18%)	7.3 (15%)	3.8 (8%)	3.7 (8%)	3.6 (8%)	1.9 (4%)	-0.5 (-1%)	12.8 (27%)
Andhra Pradesh	5.9 (21%)	6.7 (24%)	3.5 (12%)	1.4 (5%)	1.6 (6%)	1.4 (5%)	0.5 (2%)	-0.5 (-2%)	7.6 (27%)
Arunachal Pradesh	0.9 (6%)	1.7 (12%)	2.1 (15%)	0.5 (3%)	0.6 (4%)	3.6 (25%)	0.2 (1%)	-0.2 (-1%)	4.9 (34%)
Assam	1.9 (7%)	3.1 (11%)	7.9 (28%)	1.2 (4%)	1.3 (4%)	6.0 (21%)	0.3 (1%)	-0.7 (-2%)	7.7 (27%)
Bihar	7.0 (13%)	7.9 (14%)	12.5 (23%)	5.5 (10%)	4.8 (9%)	3.9 (7%)	0.5 (1%)	-0.4 (-1%)	13.7 (25%)
Chhattisgarh	13.5 (24%)	11.4 (20%)	7.0 (12%)	2.4 (4%)	6.0 (11%)	5.6 (10%)	1.1 (2%)	-0.4 (-1%)	10.3 (18%)
Delhi	7.8 (8%)	33.9 (33%)	12.9 (12%)	11.6 (11%)	5.9 (6%)	8.5 (8%)	2.1 (2%)	-0.4 (-0%)	21.0 (20%)
Goa	3.3 (13%)	5.4 (21%)	2.0 (8%)	1.5 (6%)	0.8 (3%)	2.1 (8%)	0.9 (3%)	-0.3 (-1%)	10.7 (41%)
Gujarat	4.1 (7%)	14.2 (25%)	6.2 (11%)	3.1 (6%)	2.3 (4%)	1.7 (3%)	7.2 (13%)	-0.3 (-1%)	17.9 (32%)
Haryana	6.1 (9%)	10.8 (16%)	6.8 (10%)	6.2 (9%)	5.0 (8%)	9.3 (14%)	2.5 (4%)	-0.4 (-1%)	20.4 (31%)
Himachal Pradesh	1.7 (7%)	3.4 (15%)	3.2 (14%)	1.3 (6%)	1.8 (8%)	1.9 (8%)	0.7 (3%)	-0.4 (-2%)	8.8 (39%)
Jammu and Kashmir	1.0 (4%)	1.8 (7%)	4.2 (18%)	1.2 (5%)	1.5 (6%)	0.4 (2%)	0.7 (3%)	-0.3 (-1%)	13.2 (56%)
Jharkhand	10.6 (18%)	13.9 (24%)	7.6 (13%)	4.3 (7%)	6.7 (11%)	4.3 (7%)	0.6 (1%)	-0.5 (-1%)	11.5 (19%)
Karnataka	4.9 (17%)	8.0 (28%)	2.1 (7%)	2.2 (8%)	1.5 (5%)	2.3 (8%)	0.8 (3%)	-0.5 (-2%)	7.9 (27%)
Kerala	3.2 (13%)	6.0 (25%)	3.5 (14%)	2.6 (11%)	0.9 (4%)	1.1 (5%)	0.4 (2%)	-0.4 (-1%)	6.9 (28%)
Ladakh	0.2 (2%)	0.3 (2%)	0.6 (5%)	0.4 (4%)	0.9 (8%)	0.1 (1%)	0.2 (2%)	-0.0 (-0%)	9.1 (77%)
Madhya Pradesh	7.5 (17%)	5.9 (13%)	3.6 (8%)	3.1 (7%)	4.6 (10%)	4.7 (10%)	2.8 (6%)	-0.4 (-1%)	13.5 (30%)
Maharashtra	6.4 (16%)	9.3 (23%)	2.9 (7%)	2.5 (6%)	2.4 (6%)	3.7 (9%)	1.8 (5%)	-0.7 (-2%)	12.0 (30%)
Manipur	2.2 (8%)	3.7 (13%)	3.1 (11%)	0.8 (3%)	1.6 (6%)	7.2 (26%)	0.3 (1%)	-0.8 (-3%)	9.9 (35%)
Meghalaya	2.3 (9%)	3.5 (13%)	4.6 (17%)	1.5 (6%)	1.6 (6%)	4.8 (18%)	0.3 (1%)	-0.9 (-3%)	9.2 (34%)
Mizoram	2.2 (9%)	2.3 (9%)	2.0 (8%)	0.6 (2%)	1.3 (5%)	4.0 (16%)	0.3 (1%)	-0.6 (-3%)	12.9 (52%)
Nagaland	1.8 (6%)	3.0 (10%)	4.6 (16%)	1.1 (4%)	1.4 (5%)	10.1 (34%)	0.3 (1%)	-0.7 (-2%)	7.7 (26%)

Odisha	8.8 (19%)	10.0 (22%)	8.2 (18%)	2.5 (5%)	4.9 (11%)	3.6 (8%)	0.5 (1%)	-0.8 (-2%)	8.3 (18%)
Punjab	3.4 (6%)	7.1 (12%)	6.2 (10%)	4.8 (8%)	3.6 (6%)	10.4 (17%)	1.5 (2%)	-0.4 (-1%)	23.5 (39%)
Rajasthan	4.4 (7%)	5.1 (8%)	7.5 (12%)	4.6 (8%)	4.1 (7%)	2.2 (4%)	10.3 (17%)	-0.4 (-1%)	22.2 (37%)
Sikkim	1.4 (8%)	2.1 (12%)	3.0 (17%)	1.2 (7%)	1.2 (7%)	1.3 (8%)	0.3 (1%)	-0.4 (-3%)	7.2 (42%)
Tamil Nadu	4.6 (21%)	5.2 (24%)	1.9 (9%)	1.5 (7%)	1.1 (5%)	0.9 (4%)	0.4 (2%)	-0.3 (-1%)	6.6 (30%)
Telangana	7.5 (21%)	7.7 (21%)	4.7 (13%)	1.8 (5%)	2.2 (6%)	2.5 (7%)	1.1 (3%)	-0.7 (-2%)	9.1 (25%)
Tripura	2.2 (6%)	2.3 (7%)	9.0 (25%)	1.9 (5%)	1.9 (5%)	3.7 (11%)	0.1 (0%)	-1.1 (-3%)	15.4 (43%)
Uttar Pradesh	6.5 (11%)	9.4 (16%)	10.2 (18%)	6.3 (11%)	5.2 (9%)	4.7 (8%)	1.0 (2%)	-0.4 (-1%)	14.7 (26%)
Uttarakhand	2.1 (7%)	3.4 (12%)	6.0 (21%)	1.8 (6%)	1.7 (6%)	5.1 (17%)	0.6 (2%)	-0.5 (-2%)	8.9 (31%)
West Bengal	7.8 (14%)	11.2 (20%)	15.3 (27%)	4.5 (8%)	5.0 (9%)	2.2 (4%)	0.3 (1%)	-0.3 (-1%)	10.9 (19%)

Abbreviations and their corresponding full names: POW=Power, IND=Industry, RES=Residential, TRA=Transportation, AGR=Agriculture, FIRE= Smoke from Open Burning, DST=Natural Dust, BVOC=Biogenic.

Table S6. Source contribution to 2022 national annual population-weighted mean $PM_{2.5}$ component concentrations

(dominant domestic source is highlighted in red)

	Domestic Sources (see the note after this table for full names of each source)								**Transboundary Sources**
	POW	**IND**	**RES**	**TRA**	**AGR**	**FIRE**	**DST**	**BOVC**	
Organic	0.42	2.64	6.60	0.83	0.12	1.44	0.05	0.03	3.10
BC	0.01	0.93	0.58	0.17	0.01	0.21	0.00	0.00	0.28
Dust	0.99	2.09	0.13	0.61	0.15	1.45	1.84	0.00	5.05
Sulfate	2.80	1.63	-0.01	0.38	0.32	0.10	-0.01	-0.29	1.96
Nitrate	0.81	0.61	-0.01	1.28	2.00	0.29	-0.01	-0.08	1.12
Ammonium	1.11	0.69	-0.01	0.57	0.97	0.15	0.00	-0.12	0.91
Sodium and Chloride	-0.03	-0.01	0.00	-0.03	0.09	0.00	0.00	0.00	0.42

Abbreviations and their corresponding full names: POW=Power, IND=Industry, RES=Residential, TRA=Transportation, AGR=Agriculture, FIRE=Smoke from Open Burning, DST=Natural Dust, BVOC=Biogenic.

Reference:

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