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Spatial–temporal patterns in anthropogenic and biomass burning emission contributions to air pollution and mortality burden changes in India from 1995 to 2014

Bin Luo et al.

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Table S1 The locations for all observation sites.

Site	Latitude/Longitude	Data record
Anantapur	14.62°N/77.65°E	2010 $PM_{2.5}$ 2009 O_3
Delhi	28.58°N/77.20°E	2011 $PM_{2.5}$
Delhi	28.63°N/77.18°E	2007 $PM_{2.5}$
Hyderabad	17.47°N/78.43°E	2003 $PM_{2.5}$
Mukteshwar	29.78°N/80.08°E	2006-2008 $PM_{2.5}$
Navi Mumbai	19.08°N/73.00°E	2005 $PM_{2.5}$
Chennai	13.04°N/80.23°E	2005 O_3
Anantapur	8.6°N/77°E	1997-1998 O_3
Ahmedabad	23.03°N/72.58°E	2002, 2011 O_3
Pune	18.5°N/73.8°E	2001-2005 O_3
Joharapur	19.3°N/75.2°E	2002-2005 O_3
Udaipur	24.58°N/73.68°E	2010-2012 O_3

Table S2. Comparison of studies for estimation of $PM_{2.5}$ concentrations and mortality.

Study	Time	Model	Pop-weighted average (μg m^{-3})	Average (μg m^{-3})	$PM_{2.5}$ Mortality in India (millions)	Resolution	Domain
Conibear et al. (2018b)	2014	WRF-Chem	57.2	/	0.99	30 km × 30 km	India
Chowdhury and Dey, (2016)	2001-2010	Satellite data with factors from GEOS-Chem model	/	46.5	0.81	0.5° × 0.5°	India
Apte et al. (2015)	2010	A combination of satellite and GEOS-Chem	28	/	/	/	India
Anenberg et al. (2010)	2000	MOZART-2	20.41	/	/	2.8° × 2.8°	Asia
Silva et al. (2016)	2005	MOZART-4	28.5	/	0.39	0.67° × 0.5°	India
Jia et al. (2021)	1998	van Donkelaar et al. (2016)	36.9	26.0	0.58	0.1°× 0.1°	India
	2015		58.3	41.4	0.91		
Sahu et al. (2020)	2015	GAM	89	/	1.61	36 km × 36 km	India
Brauer et al. (2016)	2013	Satellite & CTM estimates	46.7	/	/	0.1° × 0.1°	India
Guo et al. (2018)	2015	CMAQ	32.8	/	1.04	36 km × 36 km	India
Cohen et al. (2017)	2015	GEOS-Chem	74.3	/	1.09	56 km × 74 km	India

Table S3. Comparison of studies for estimation of O_3 concentrations and mortality.

Study	Time	Model	units	value (ppbv)	O_3 Mortality in India (millions)	Resolution	Domain
Anenberg et al. (2010)	2000	MOZART-2	pop-weighted 6mMDA1	59.64	/	2.8° × 2.8°	Asia
Silva et al. (2016)	2005	MOZART-4	pop-weighted 6mMDA1	60.5	0.16	0.67° × 0.5°	India
Brauer et al. (2016)	2013	Satellite & CTM estimates	pop-weighted 3mMDA1	74.0	/	0.1° × 0.1°	India
Liu et al. (2021)	2014	G5NR-chem	average	63.4	0.096	0.125° × 0.125°	India
Hakim et al. (2019)	2009-2010	Multi-model	area-weighted average	37.26-56.11	/	/	India
			pop-weighted average	41.38-57.5	/	/	
Conibear et al. (2018a)	2015	WRF-chem	pop-weighted ADM8h	77.2	0.37	30 km × 30 km	India
			pop-weighted 3mDMA1	94.5			
Sharma et al. (2016)	2010	WRF-CMAQ	average	44.3	/	36 km× 36 km	India

Table S4. Contributions of BB emissions changes to the seasonal area-weighted $PM_{2.5}$ and O_3 concentrations in the states of India from 1995 to 2014.

States	$PM_{2.5}$ (μg m^{-3})				O_3 (ppbv)			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Andaman and Nicobar	-0.03	1.02	0.46	0.44	-1.19	0.51	0.08	-0.68
Andhra Pradesh	0.85	0.75	-0.38	0.57	0.60	-0.20	-1.21	0.54
Arunachal Pradesh	-0.88	3.89	-0.27	0.15	-0.88	1.68	-0.87	0.07
Assam	-0.55	3.97	-0.11	-0.16	-0.37	0.68	0.11	0.29
Bihar	-0.91	0.85	-5.27	-1.78	0.12	0.20	-1.81	-0.16
Chandigarh	-0.37	-0.45	0.68	0.44	-0.14	-0.49	0.11	-0.53
Chhattisgarh	0.43	-0.89	-2.39	-0.59	0.31	-0.64	-1.50	0.00
Dadra and Nagar Haveli	/	/	/	/	/	/	/	/
Daman and Diu	/	/	/	/	/	/	/	/
Goa	0.67	-0.66	-0.33	1.09	-0.01	-0.41	-0.57	1.03
Gujarat	-0.40	-0.17	0.16	-0.20	0.02	-0.37	-0.60	-0.09
Haryana	0.41	-0.59	1.17	0.97	-0.10	-0.64	0.14	0.23
Himachal Pradesh	0.06	-0.23	0.00	-0.60	-0.70	-0.32	-0.34	-1.66
Jharkhand	-1.04	-0.30	-3.35	-2.31	-0.35	-0.29	-0.99	-0.12
Karnataka	1.19	-0.67	-0.22	-0.12	0.08	-0.45	-0.49	-0.21
Kerala	0.40	0.59	0.36	-0.68	-0.38	0.22	-0.27	-0.53
Lakshadweep	/	/	/	/	/	/	/	/
Madhya Pradesh	-0.04	-0.29	-0.11	-0.40	0.05	-0.32	-0.68	0.00
Maharashtra	0.42	-0.91	-0.93	-0.03	0.31	-0.58	-0.76	0.55
Manipur	-3.14	13.35	-0.16	0.06	-0.95	1.88	0.32	0.56
Meghalaya	0.16	0.86	-0.66	-0.08	-0.24	0.14	0.45	0.55
Mizoram	-2.32	-0.70	0.13	0.53	-0.46	0.20	-0.02	0.84
Nagaland	-3.50	9.43	-0.18	-0.27	-0.85	2.04	0.17	0.35

States	$PM_{2.5}$ (μg m^{-3})				O_3 (ppbv)			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
NCT of Delhi	0.67	-0.46	2.28	1.78	-0.31	-0.85	-0.80	-1.13
Odisha	-1.27	0.32	-1.39	1.27	-0.18	-0.20	-1.44	0.58
Puducherry	/	/	/	/	/	/	/	/
Punjab	0.56	-0.43	0.86	0.82	-0.08	-0.65	-0.14	0.72
Rajasthan	0.13	-0.06	0.34	-0.50	-0.12	-0.28	-0.10	-0.13
Sikkim	-0.64	0.92	-0.63	-0.44	-0.44	0.14	-3.28	0.75
Tamil Nadu	1.07	1.20	0.08	-0.88	-0.34	0.34	-0.44	-1.00
Telangana	1.25	0.48	-0.84	0.51	0.94	-0.61	-1.11	0.69
Tripura	-1.40	-1.46	-0.20	0.45	-0.48	0.14	0.04	0.90
Uttar Pradesh	-0.12	0.27	-0.15	-0.49	-0.08	-0.10	-0.45	-0.24
Uttarakhand	-0.09	-0.54	0.92	-0.79	-0.76	-0.46	0.38	-2.00
West Bengal	-1.46	0.48	-3.27	0.34	-0.35	-0.27	-1.36	1.14

Table S5. The contributions to premature mortality attributable to $PM_{2.5}$ per capita (avoided deaths per 100,000 people) from changes in ANTHRO and BB emissions in the states of India from1995 to 2000, 2005 and 2010-2014. The units are avoided deaths per 100,000 people.

States	Due to Anthro							Due to BB						
	2000	2005	2010	2011	2012	2013	2014	2000	2005	2010	2011	2012	2013	2014
Andaman and Nicobar	-2.91	2.23	4.38	1.13	2.75	4.54	4.49	-0.84	1.16	0.63	-0.33	0.20	-0.25	0.96
Andhra Pradesh	2.00	5.52	10.39	10.15	9.68	9.76	11.58	-0.34	0.67	0.51	0.26	0.12	0.19	0.54
Arunachal Pradesh	2.64	7.25	10.82	11.30	12.02	11.90	12.18	4.86	-1.87	-1.84	-2.51	-1.18	-0.22	1.93
Assam	2.73	5.55	8.66	9.29	9.28	9.40	10.09	0.82	-0.45	-0.42	-0.66	-0.44	-0.44	0.49
Bihar	3.52	6.67	11.69	12.32	11.15	12.17	12.04	-0.60	0.15	0.38	0.20	-0.18	0.06	-1.02
Chandigarh	11.22	25.72	55.15	43.36	41.01	52.19	44.85	-5.15	0.65	0.20	2.22	0.11	4.72	0.29
Chhattisgarh	2.90	7.63	13.18	12.60	12.27	14.14	13.14	-0.52	-0.18	0.49	0.44	0.15	0.53	-0.82
Dadra and Nagar Haveli	/	/	/	/	/	/	/	/	/	/	/	/	/	/
Daman and Diu	/	/	/	/	/	/	/	/	/	/	/	/	/	/
Goa	0.56	1.47	2.63	2.65	2.49	2.65	3.16	-0.14	0.24	-0.05	-0.15	-0.02	0.02	0.08
Gujarat	1.60	4.46	8.43	7.25	6.60	7.57	8.47	0.12	0.04	0.44	0.71	-0.03	0.25	-0.21
Haryana	3.76	6.91	12.96	11.34	10.41	12.88	11.38	-0.52	-0.40	0.18	0.33	0.05	1.00	0.36
Himachal Pradesh	0.57	4.09	8.87	7.29	6.31	8.72	7.02	-1.20	-0.36	0.41	0.36	0.01	0.92	-0.39
Jharkhand	4.56	10.20	16.18	17.20	16.26	17.01	16.84	-0.64	-0.04	0.05	0.14	0.19	0.00	-1.72
Karnataka	1.74	5.07	10.05	10.25	9.54	9.61	11.12	-0.52	0.55	-0.15	0.34	-0.23	-0.11	0.07
Kerala	1.11	2.58	6.19	6.69	6.14	5.70	7.19	-0.77	-0.20	0.30	0.39	0.08	-0.29	0.21
Lakshadweep	/	/	/	/	/	/	/	/	/	/	/	/	/	/
Madhya Pradesh	2.49	5.98	10.76	9.50	9.12	10.91	10.27	-0.57	-0.43	0.38	0.48	0.11	0.61	-0.17
Maharashtra	1.82	5.34	9.78	8.82	8.11	9.48	9.63	-0.37	0.08	0.07	0.19	-0.28	0.36	-0.32
Manipur	2.11	4.42	7.89	8.44	8.67	8.95	8.60	1.70	-3.03	3.02	-3.83	-0.85	-1.48	2.55
Meghalaya	6.36	12.25	17.46	17.53	17.60	17.34	19.58	0.79	0.10	-0.09	-0.81	-1.07	-0.40	0.10

States	Due to Anthro							Due to BB						
	2000	2005	2010	2011	2012	2013	2014	2000	2005	2010	2011	2012	2013	2014
Mizoram	1.72	4.59	8.10	8.63	9.81	9.27	10.58	5.14	-2.08	1.03	-4.99	-2.72	-2.54	-0.73
Nagaland	2.64	7.04	10.73	11.96	12.26	12.67	12.28	4.90	-2.88	0.40	-3.66	-1.68	-1.84	2.06
NCT of Delhi	4.62	8.04	17.15	15.38	14.42	17.16	15.63	0.13	-0.77	0.65	0.48	0.52	1.20	0.70
Odisha	2.67	7.30	12.17	12.41	11.11	12.35	13.51	-0.68	0.70	0.42	1.04	-0.30	0.36	-0.13
Puducherry	/	/	/	/	/	/	/	/	/	/	/	/	/	/
Punjab	2.67	5.27	10.10	8.13	7.77	9.22	8.49	-0.52	-0.01	0.04	0.55	-0.12	0.52	0.20
Rajasthan	2.29	5.32	9.49	8.14	7.32	8.97	8.74	-0.17	-0.40	0.60	0.40	-0.05	0.78	0.00
Sikkim	9.45	14.34	23.29	25.06	23.74	23.69	24.69	-0.57	0.36	-0.66	1.51	-0.84	-0.90	-0.57
Tamil Nadu	1.50	3.82	8.25	8.01	7.93	7.15	8.43	-0.57	0.20	0.33	0.58	0.26	-0.21	0.60
Telangana	1.65	6.81	12.29	11.30	10.61	11.83	12.88	-0.77	0.33	0.64	0.21	0.11	0.41	0.53
Tripura	3.19	8.09	12.84	12.35	13.76	13.18	15.40	4.17	-1.03	0.10	-2.55	-1.71	-1.11	-0.67
Uttar Pradesh	3.24	6.57	11.99	11.48	10.58	12.67	11.39	-0.52	-0.07	0.65	0.18	0.48	0.52	-0.09
Uttarakhand	1.71	4.09	8.73	7.58	6.06	9.47	7.04	-1.09	-0.10	0.91	-0.37	2.10	0.57	-0.21
West Bengal	3.15	6.99	11.92	11.92	11.33	11.85	13.25	-0.45	0.54	0.04	0.20	-0.91	0.27	-0.47

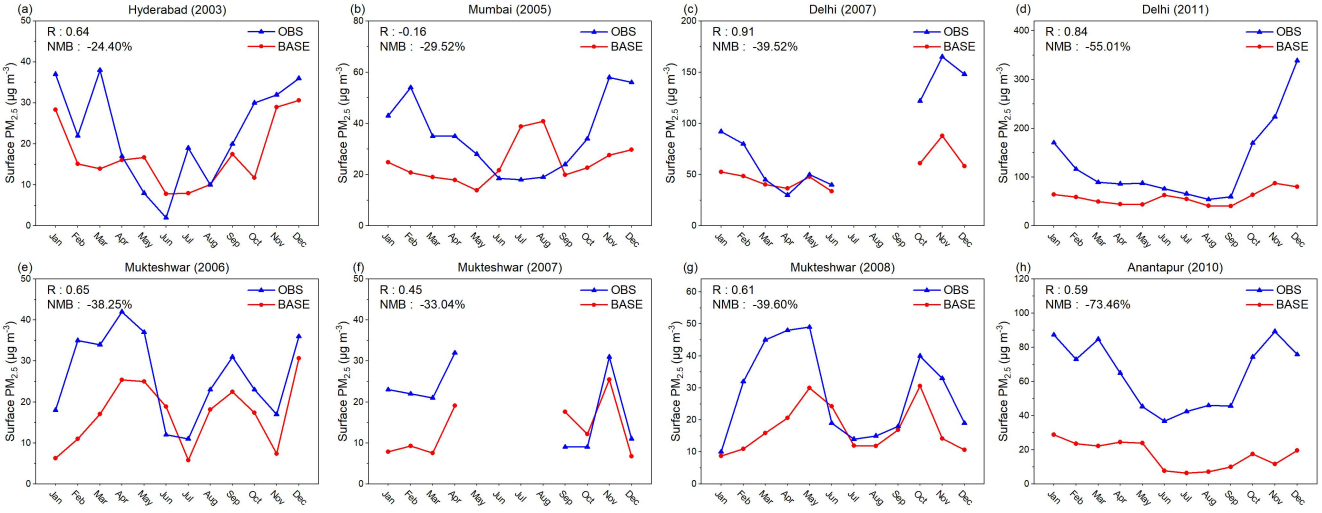
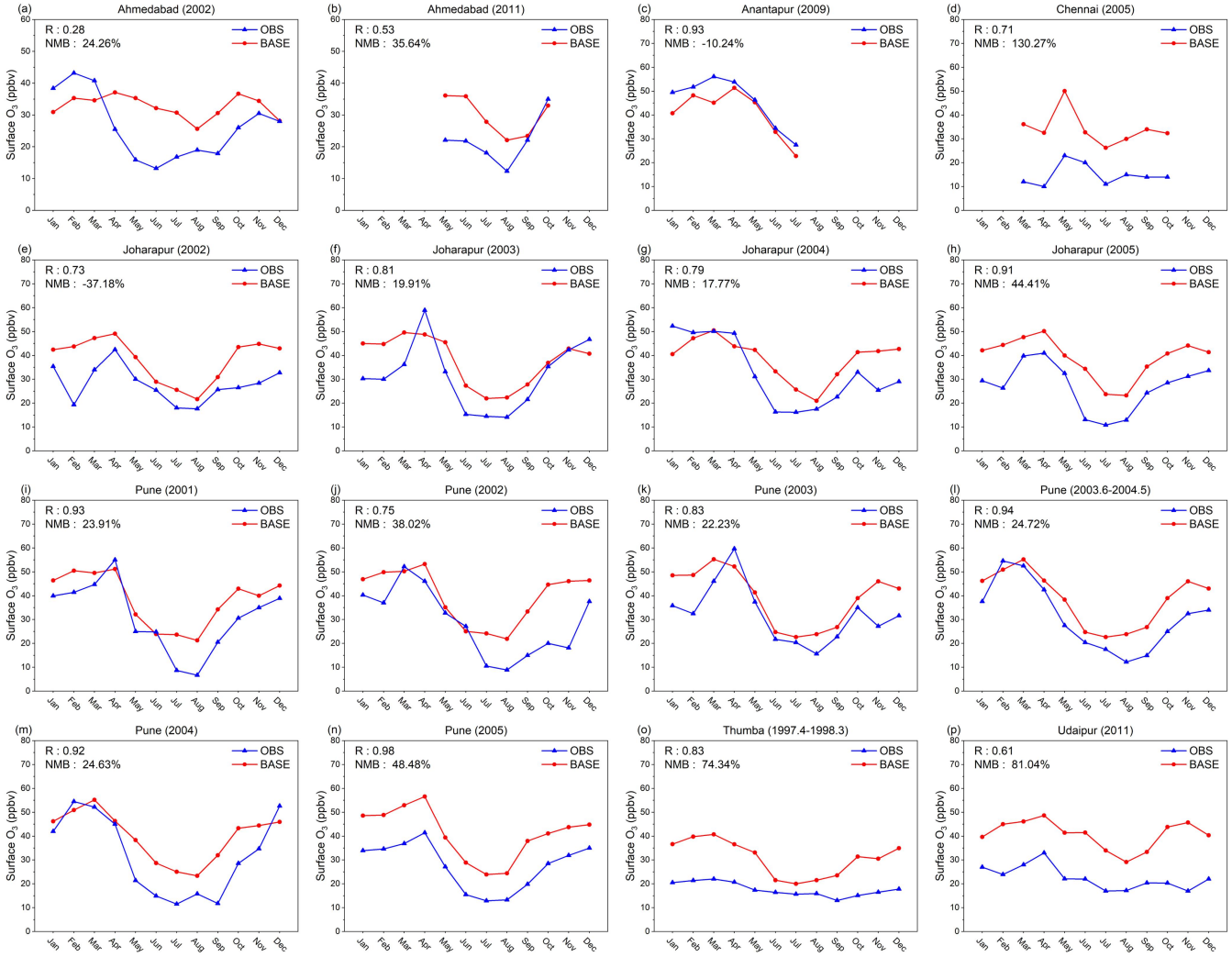


Figure S1. Comparison of the seasonal variations of surface $PM_{2.5}$ between ground-based observations (blue triangle) and the BASE simulation sampled at observation sites (red circle).



25 **Figure S2.** Comparison of the seasonal variations of surface O_3 between ground-based observations (blue triangle) and the BASE simulation sampled at observation sites (red circle).

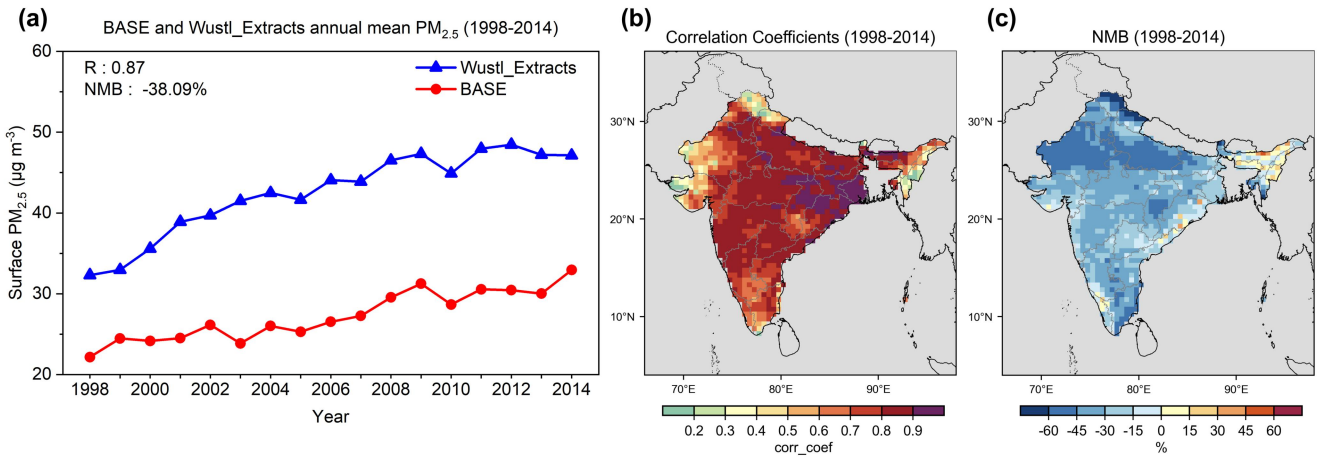
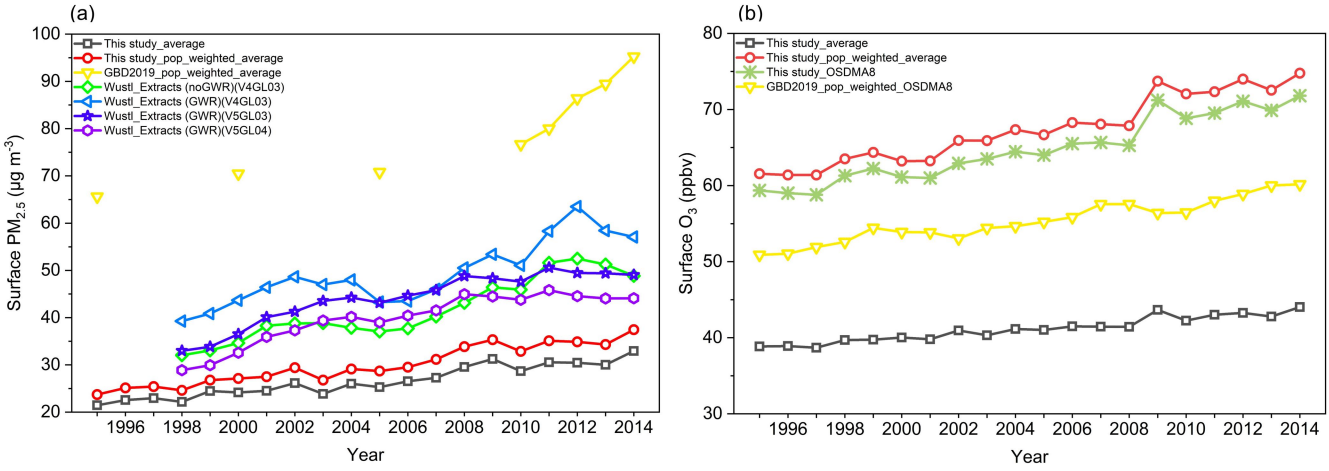


Figure S3. (a) Comparison of the interannual variations of surface $PM_{2.5}$ between Wustl_Extracts (reanalysis ground-level annual $PM_{2.5}$ concentrations from the Atmospheric Composition Analysis Group (ACAG) at Washington University in St.Louis.) (blue triangle) and the BASE simulation (red circle), and spatial distribution of (b) correlation coefficient, and (c) annual mean NMB from 1998 to 2014.



35 **Figure S4.** Compared annual $PM_{2.5}$ and O_3 concentrations with the GBD2019 datasets.

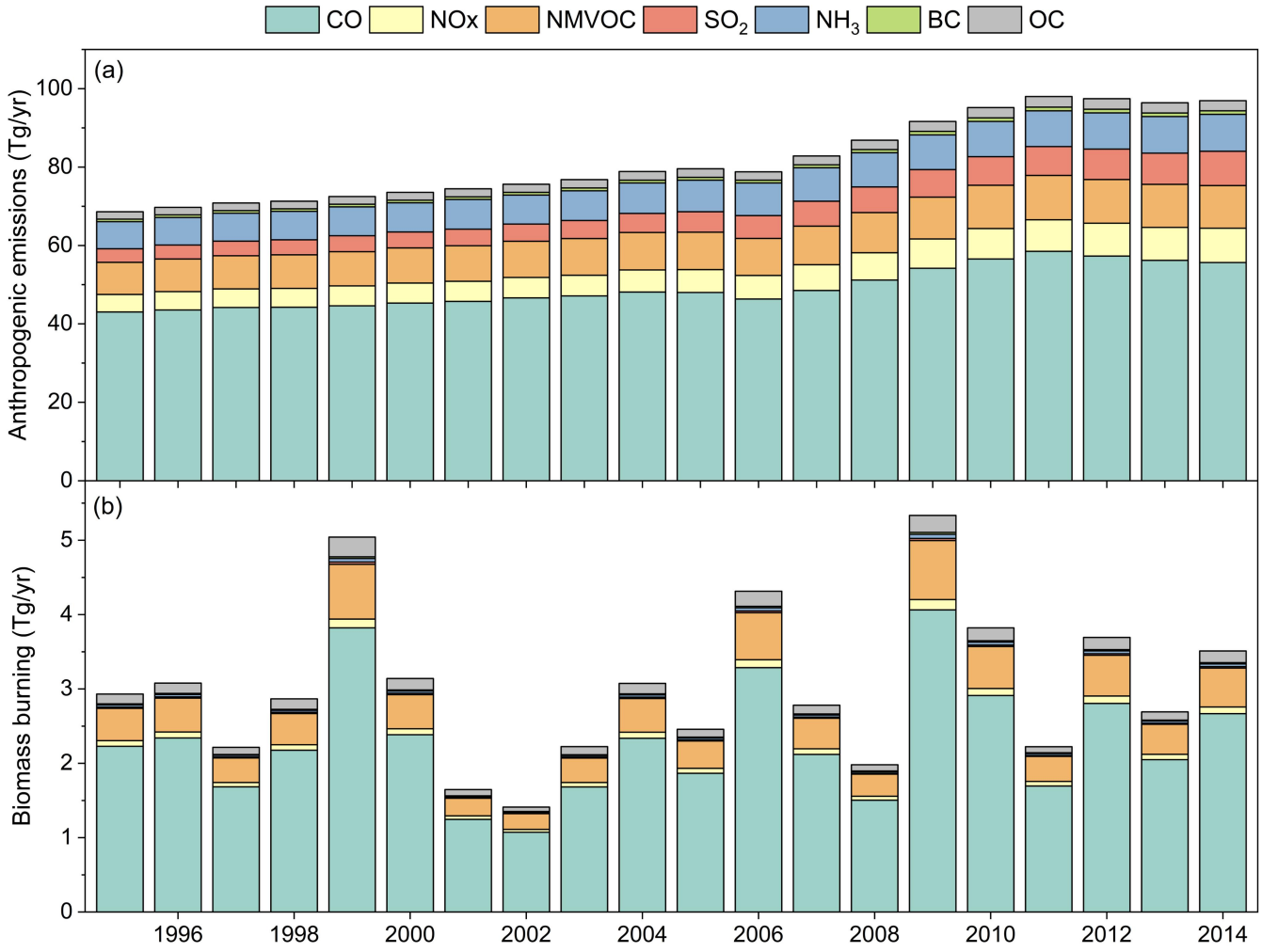


Figure S5. Annual emissions for (a) ANTHRO and (b) BB in India from 1995-2014 from the CEDS.

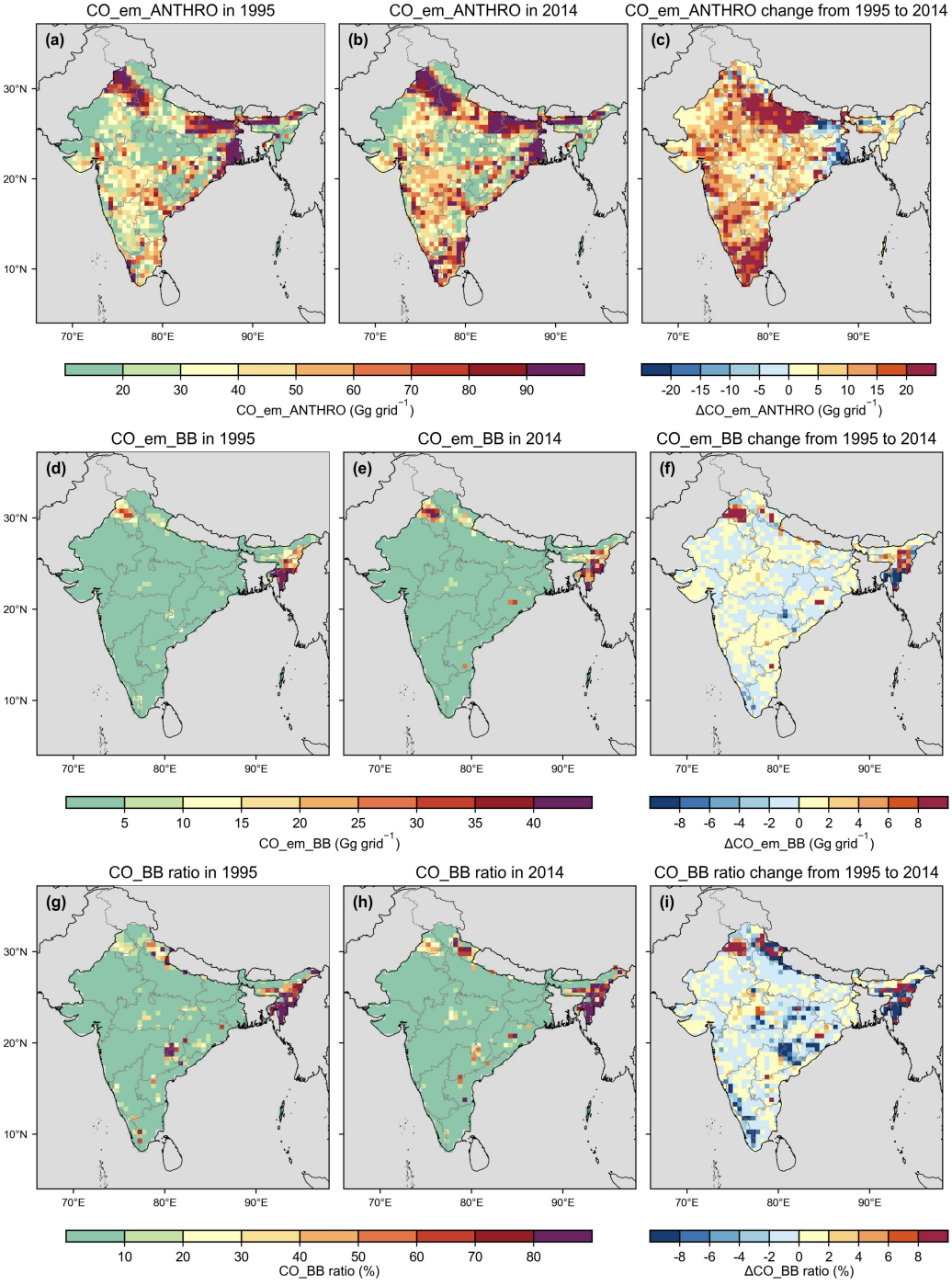
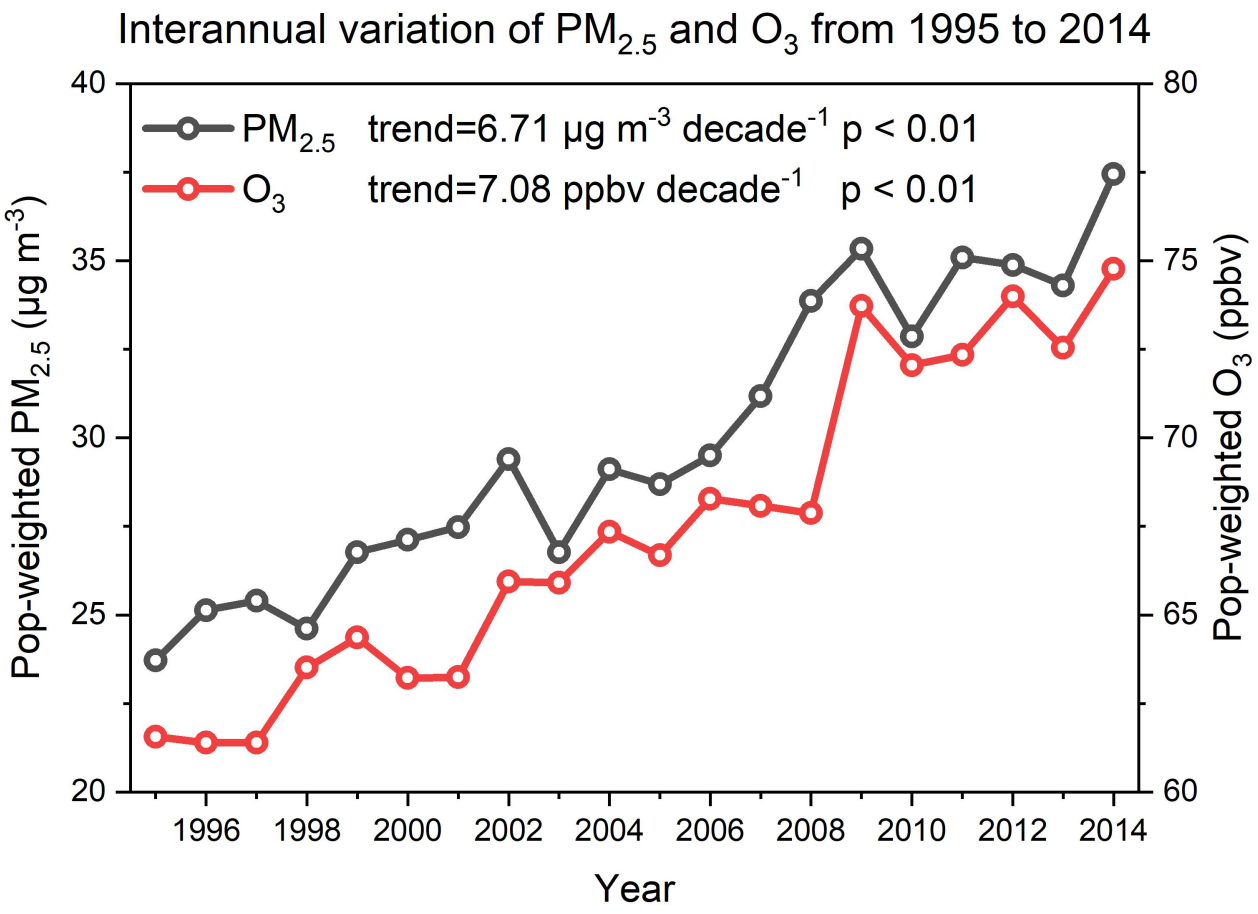


Figure S6. The spatial distribution of CO from (a) ANTHRO emissions, (b) BB emissions, and (c) the ratio of CO from BB emissions to CO from ANTHRO emissions in 1995 and 2014. The changes from 1995 to 2014 are also presented.



45 **Figure S7.** The interannual variation of pop-weighted $PM_{2.5}$ and O_3 in India from 1995 to 2014.

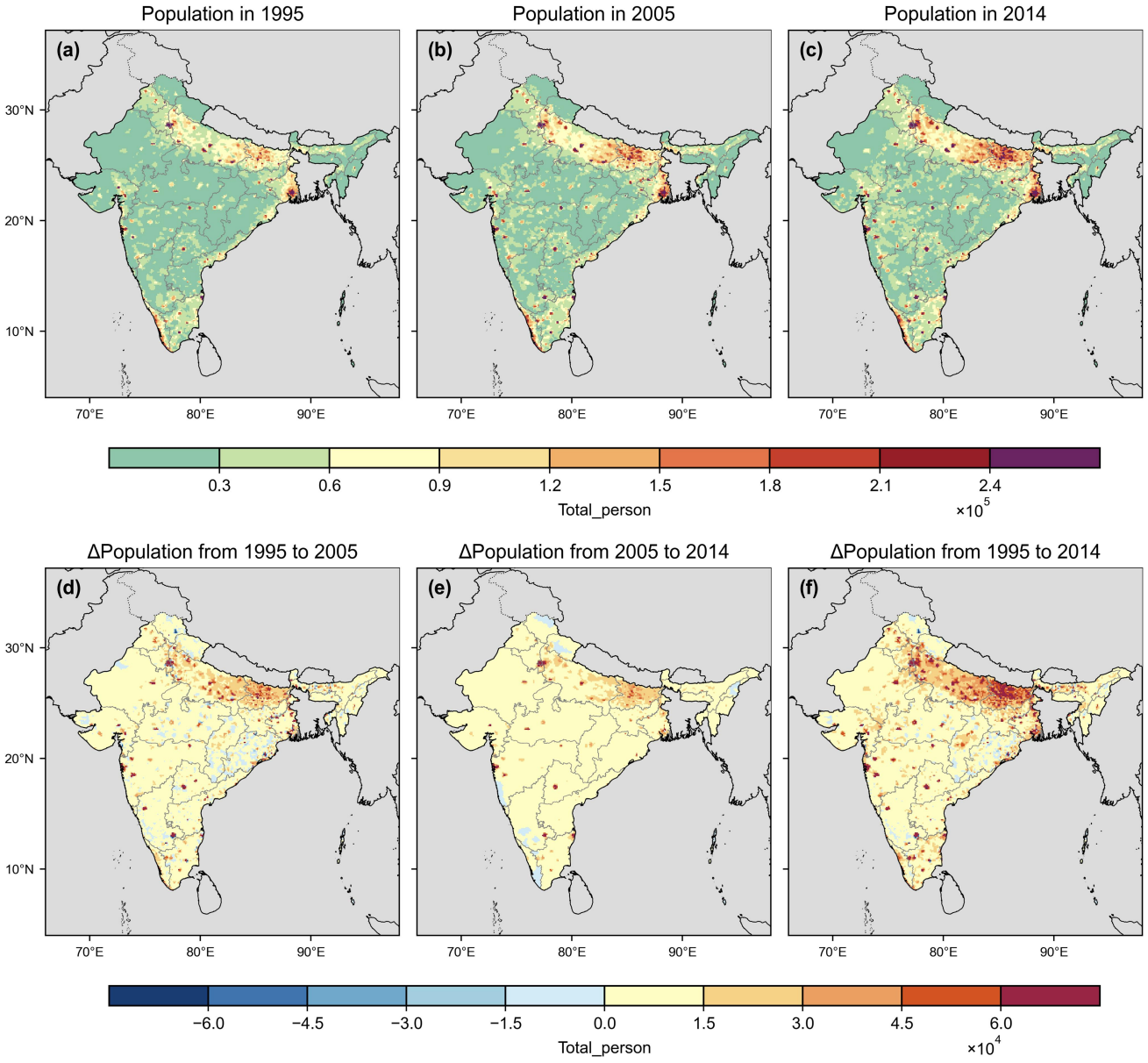


Figure S8. The spatial distribution of population in India from 1995 to 2014. The spatial distribution of population in India in (a) 1995, (b) 2005, and (c) 2014, as well as the population changes at different time periods, (d) 1995 to 2005, (e) 2005 to 2014, and (f) 1995 to 2014.

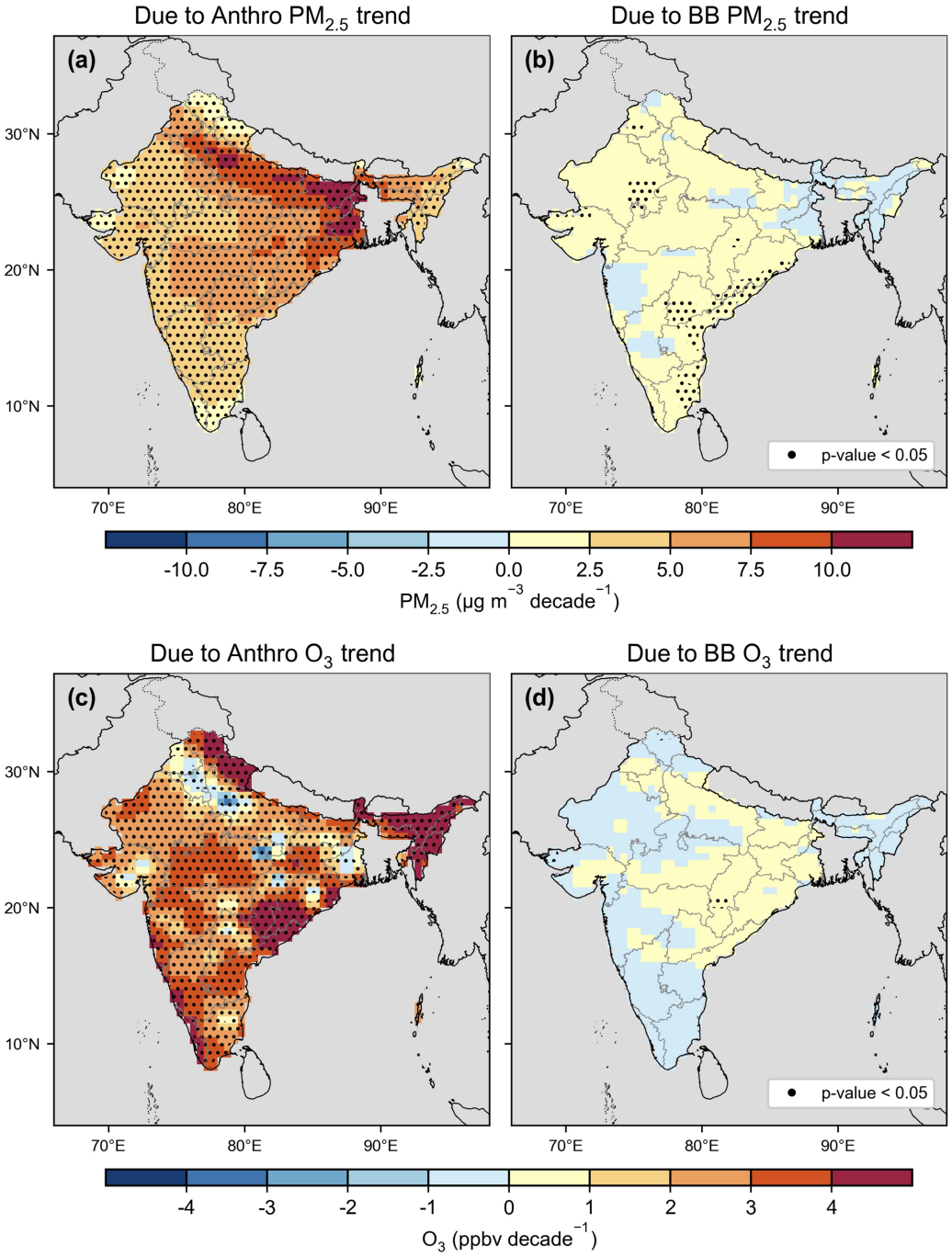


Figure S9. The contributions of (a, c) ANTHRO and (b, d) BB emissions for the trends of air quality change in India from 1995 to 2014 for (a, b) $PM_{2.5}$ and (c, d) O_3. The units are μg m^{-3} $decade^{-1}$ for $PM_{2.5}$, and ppbv $decade^{-1}$ for O_3. The black dot denotes the areas where the trend is statistically significant ($p < 0.05$).

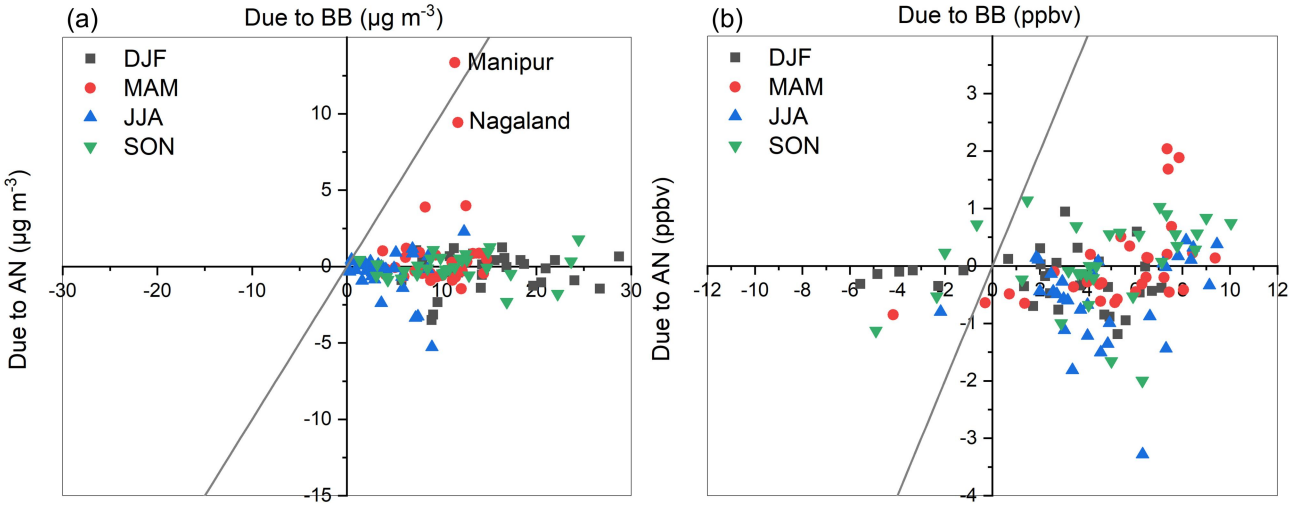


Figure S10. Contributions of ANTHRO and BB changes from 1995 to 2014 on seasonal $PM_{2.5}$ (a) and O_3 (b) changes in India administrative regions. The contributions from ANTHRO were calculated as the differences between BASE and FixAN in 2014, and the contributions from BB were calculated as the differences between BASE and FixBB in 2014. The X axis denotes the contribution from ANTHRO, while the Y axis denotes the contribution from BB. The solid line is the 1:1 ratio.

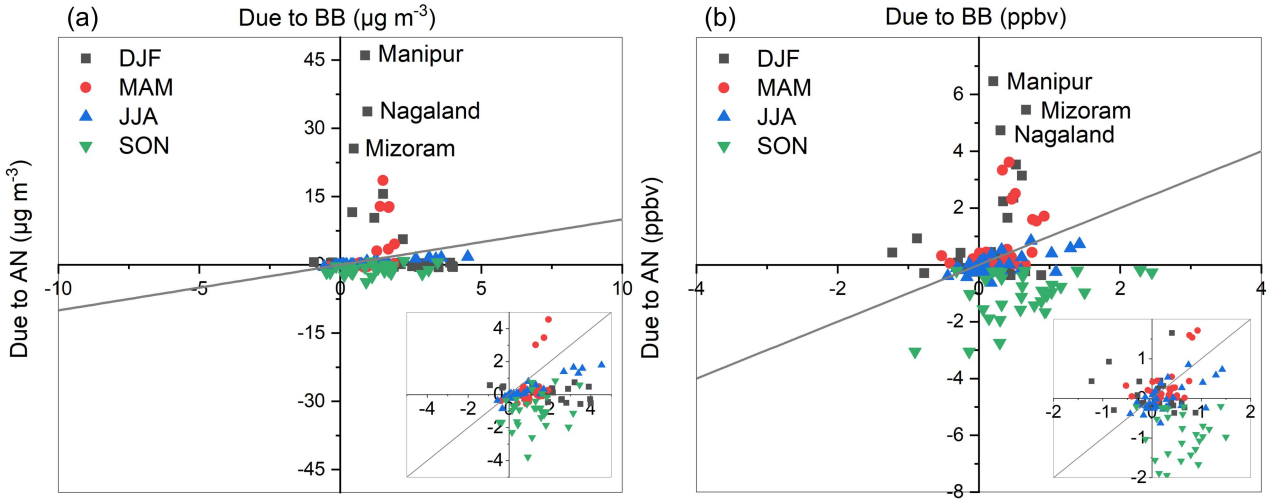


Figure S11. The same as Figure S11, but for the contributions from 1995 to 1999. The plots on the bottom right are the zoom-in results with smaller scales.

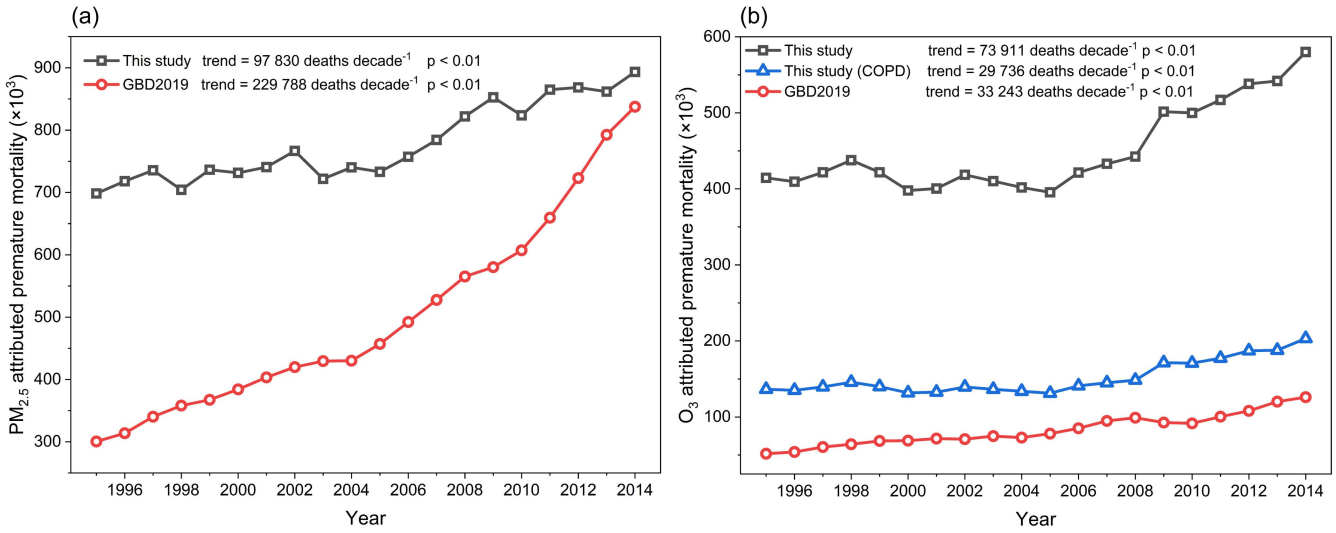


Figure S12. Comparisons of $PM_{2.5}$ and O_3 attributed premature mortality in India from 1995 to 2014 between our study and GBD2019.

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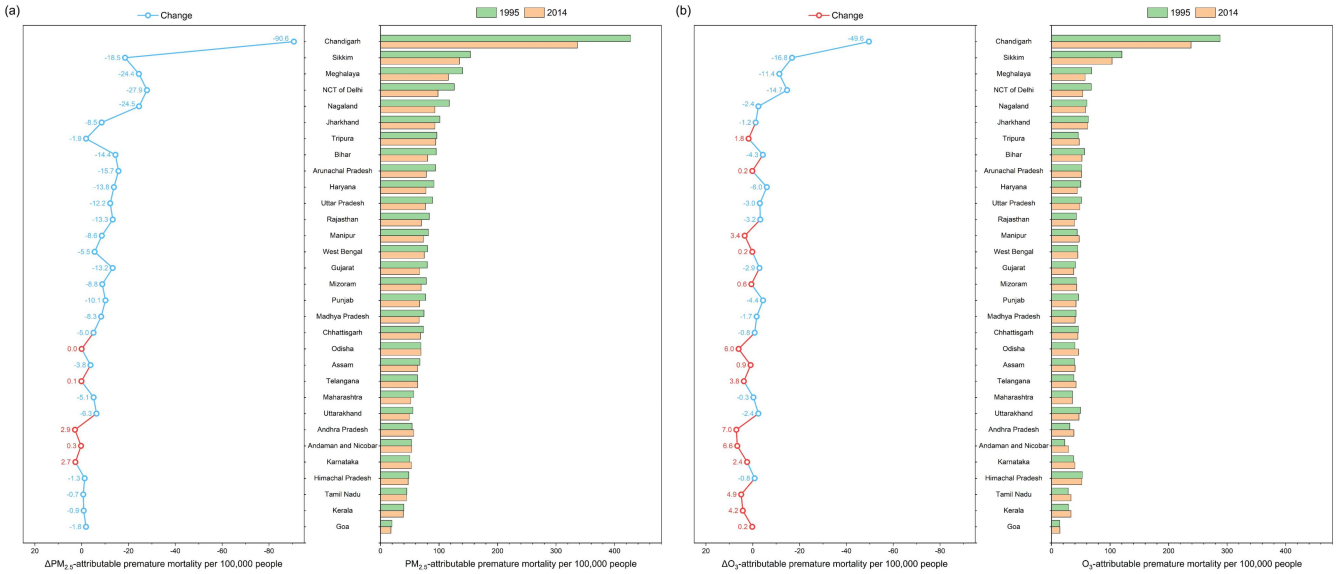

Figure S13. Premature mortality attributable to $PM_{2.5}$ (a) or O_3 (b) per capita (avoided deaths per 100,000 people) and changes in the states of India from 1995 to 2014.

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