Supplement of

Spatial-temporal patterns of anthropogenic and biomass burning contributions on air pollution and mortality burden changes in India from 1995 to 2014

Bin Luo et al.

Correspondence to: Yuqiang Zhang (yuqiang.zhang@sdu.edu.cn), Likun Xue (xuelikun@sdu.edu.cn)

Table S1. Comparison of studies for estimation of PWC (Population weighted concentration) and $PM_{2.5}$ mortality.

Study	Time	Model	PWC (μg m^{-3})	Average (μg m^{-3})	$PM_{2.5}$ Mortality in India (millions)	Resolution	Domain
Conibear et al. (2018)	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	/	/	/	Global
Anenberg et al. (2010)	2000	MOZART-2	20.41	/	/	2.8° × 2.8°	Global
Silva et al. (2016)	2005	MOZART-4	28.5	/	0.39	0.67° × 0.5°	Global
Jia et al. (2021)	1998	van Donkelaar et al. (2016)	36.9	26.0	0.58	0.1°× 0.1°	Global
	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°	Global
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	Global

Table S2. 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	6mMDA8 (pop-weighted)	59.64	/	2.8° × 2.8°	global
Silva et al. (2016)	2005	MOZART-4	6mMDA8 (pop-weighted)	60.5	0.16	0.67° × 0.5°	global
Brauer et al. (2016)	2013	Satellite & CTM estimates	3mMDA1 (pop-weighted)	74.0	/	0.1° × 0.1°	Global
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	37.26-56.11	/	/	India
			pop-weighted	41.38-57.5	/	/	
Conibear et al. (2018)	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 S3. Contributions of biomass burning 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 S4. 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

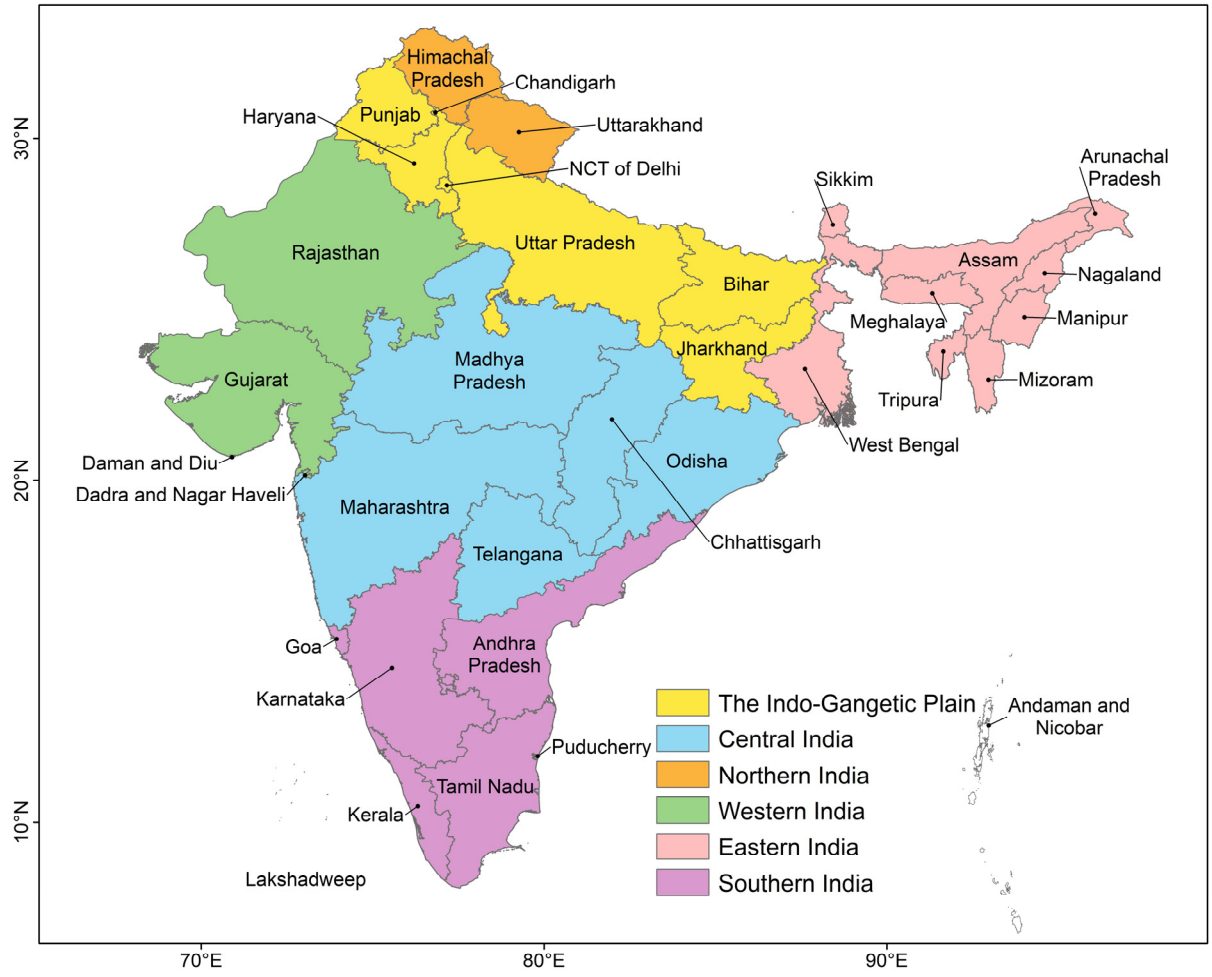


Figure S1. A map of India marked into six regions based on meteorological conditions and aerosol variability (adapted from David et al. 2018).

20

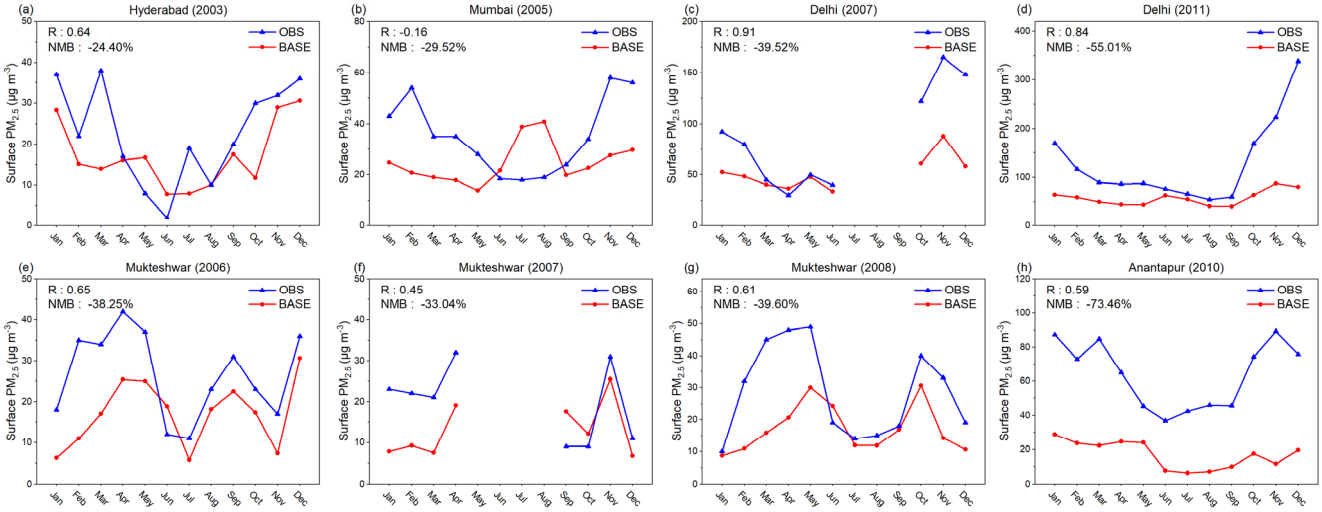


Figure S2. Comparison of the seasonal variations of surface $PM_{2.5}$ between ground-based observations (blue triangle) and the BASE simulation sampled at observation sites (red circle).

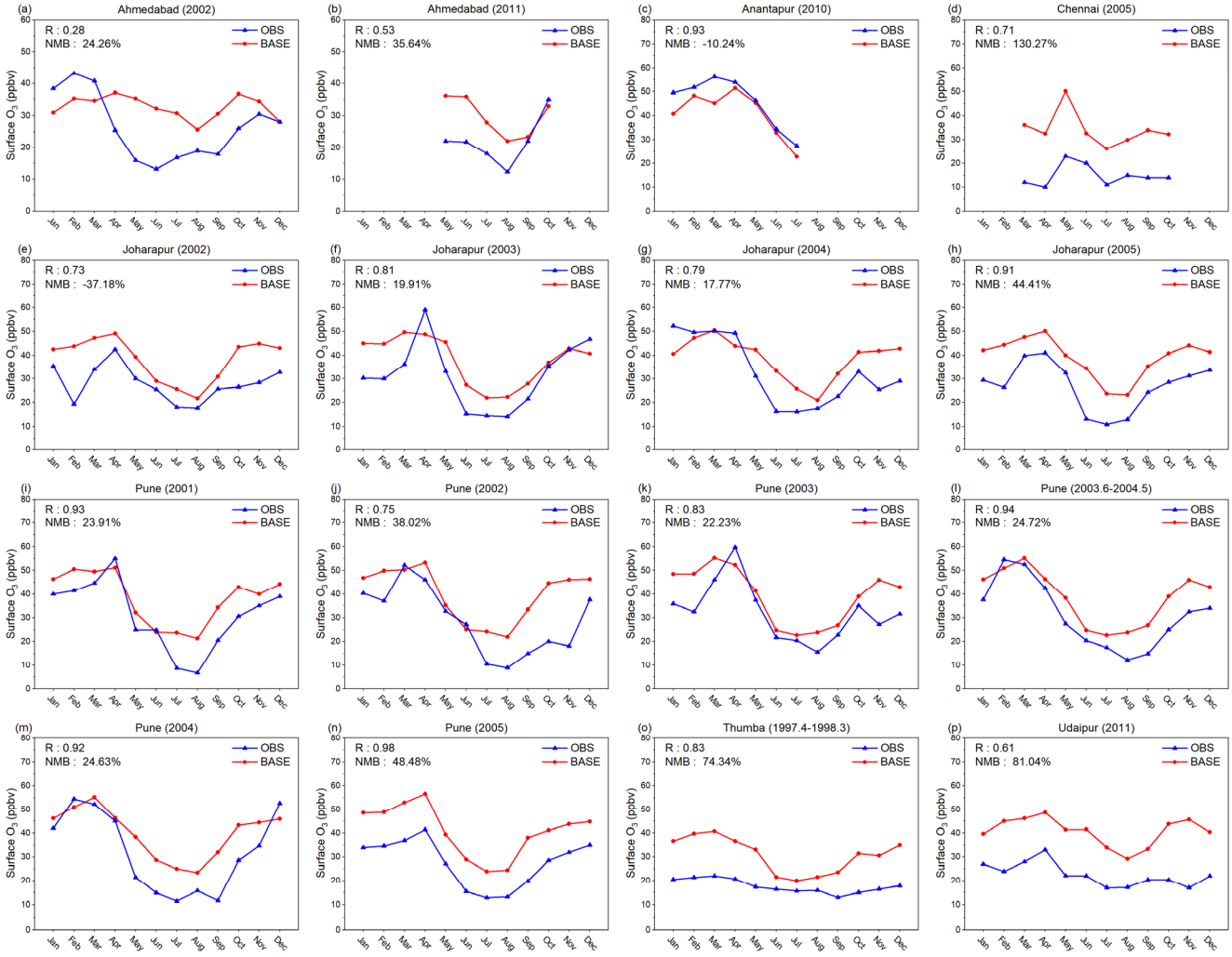
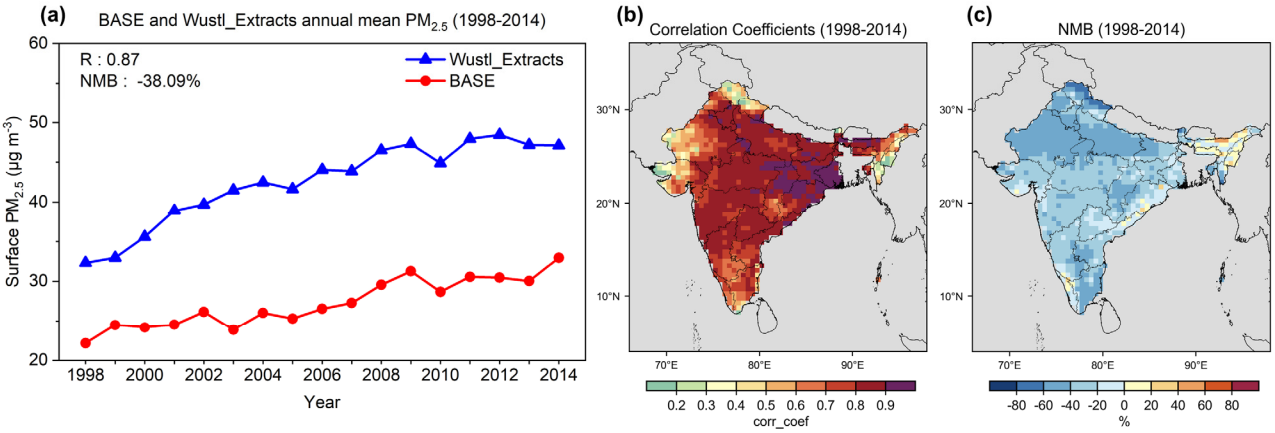


Figure S3. Comparison of the seasonal variations of surface O_3 between ground-based observations (blue triangle) and the BASE simulation sampled at observation sites (red circle).



30 **Figure S4.** (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.

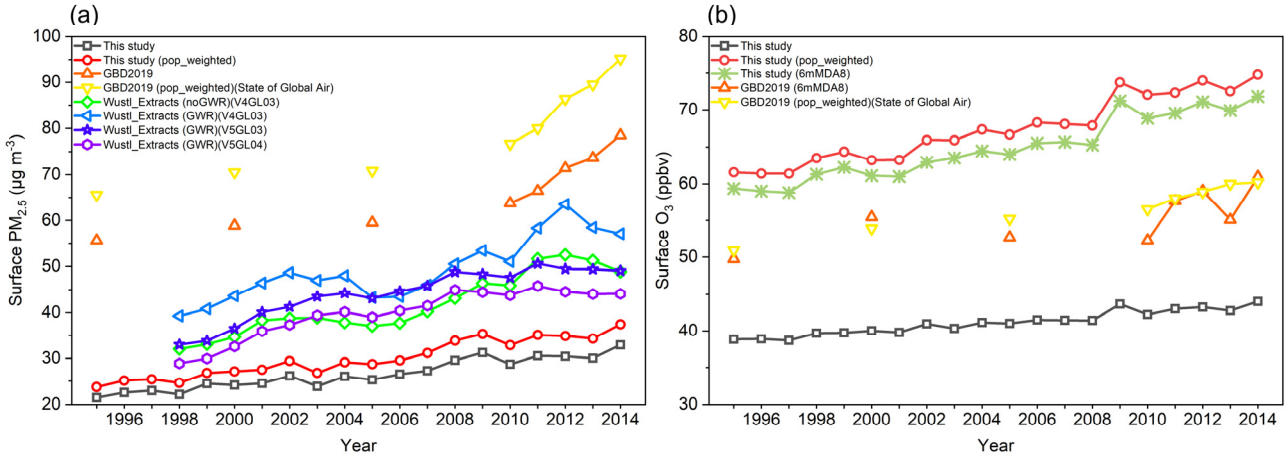


Figure S5. Compared annual $PM_{2.5}$ and O_3 concentrations with the GBD2019 datasets.

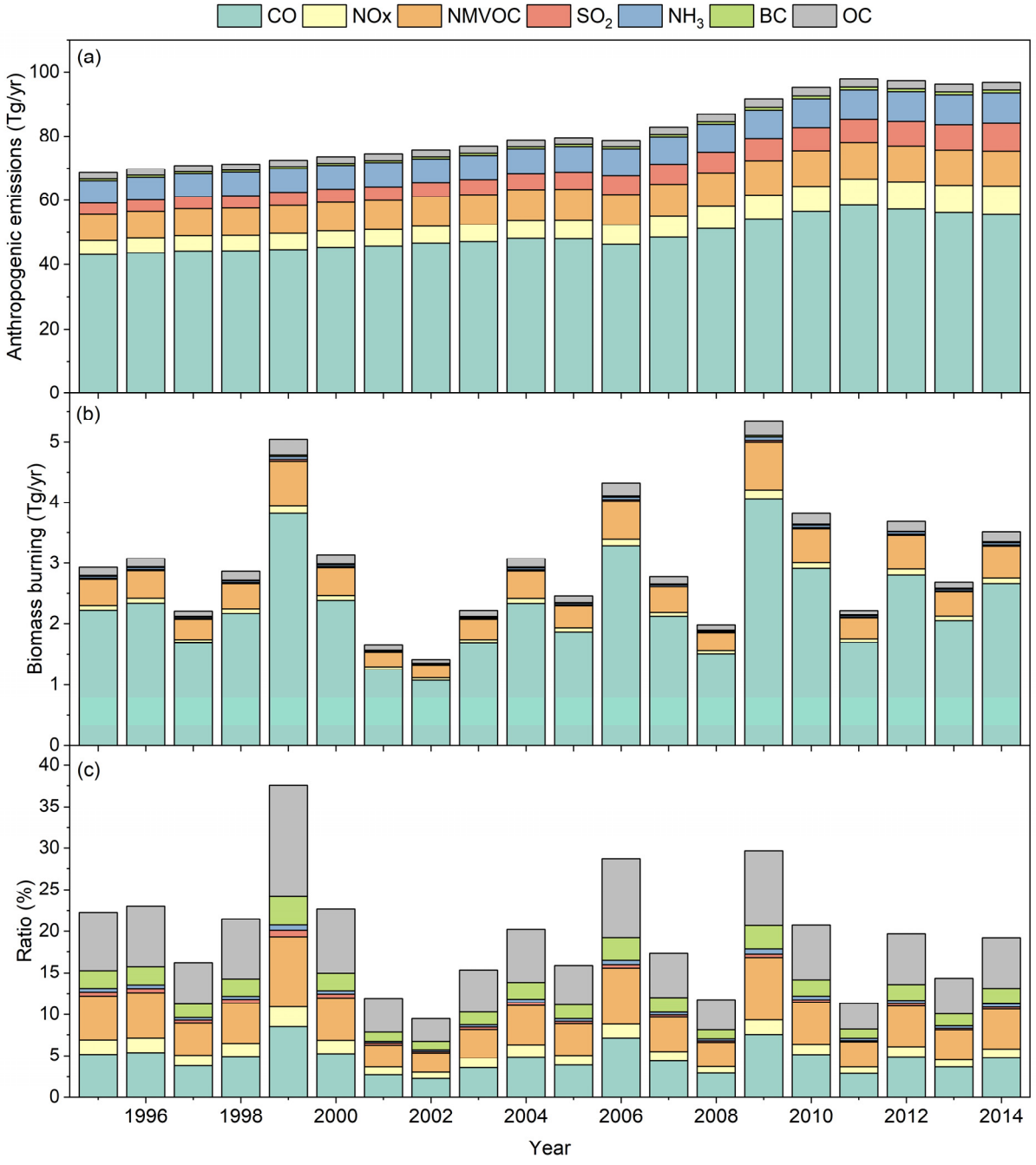


Figure S6. Annual emissions for (a) anthropogenic, (b) biomass burning and (c) the ratio of biomass burning to anthropogenic emissions in India from 1995-2014 from the CEDS.

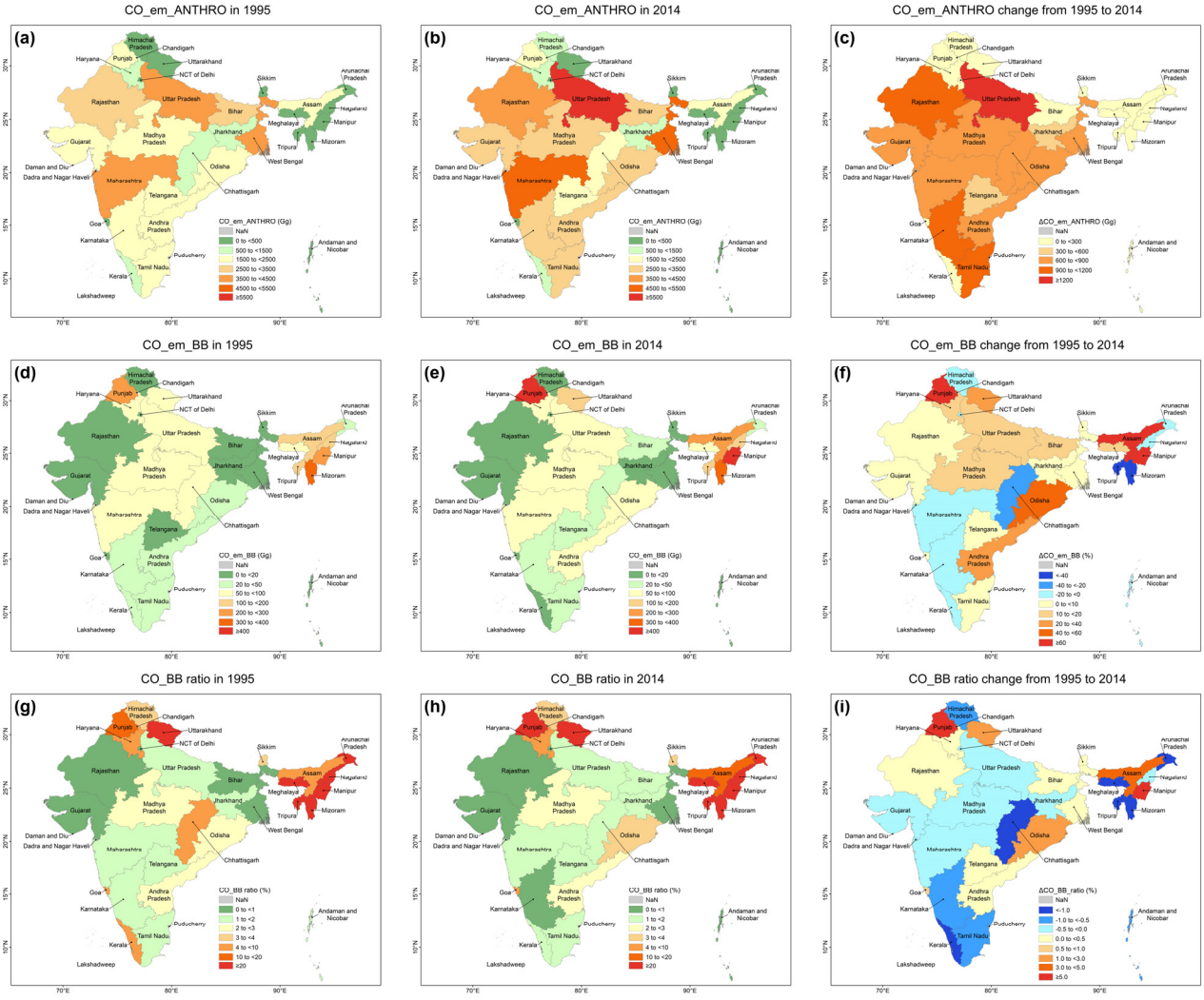


Figure S7. The spatial distribution of CO from (a) anthropogenic emissions, (b) biomass burning emissions, and (c) the ratio of CO from biomass burning emissions to CO from anthropogenic emissions in 1995 and 2014. The changes from 1995 to 2014 are also presented.

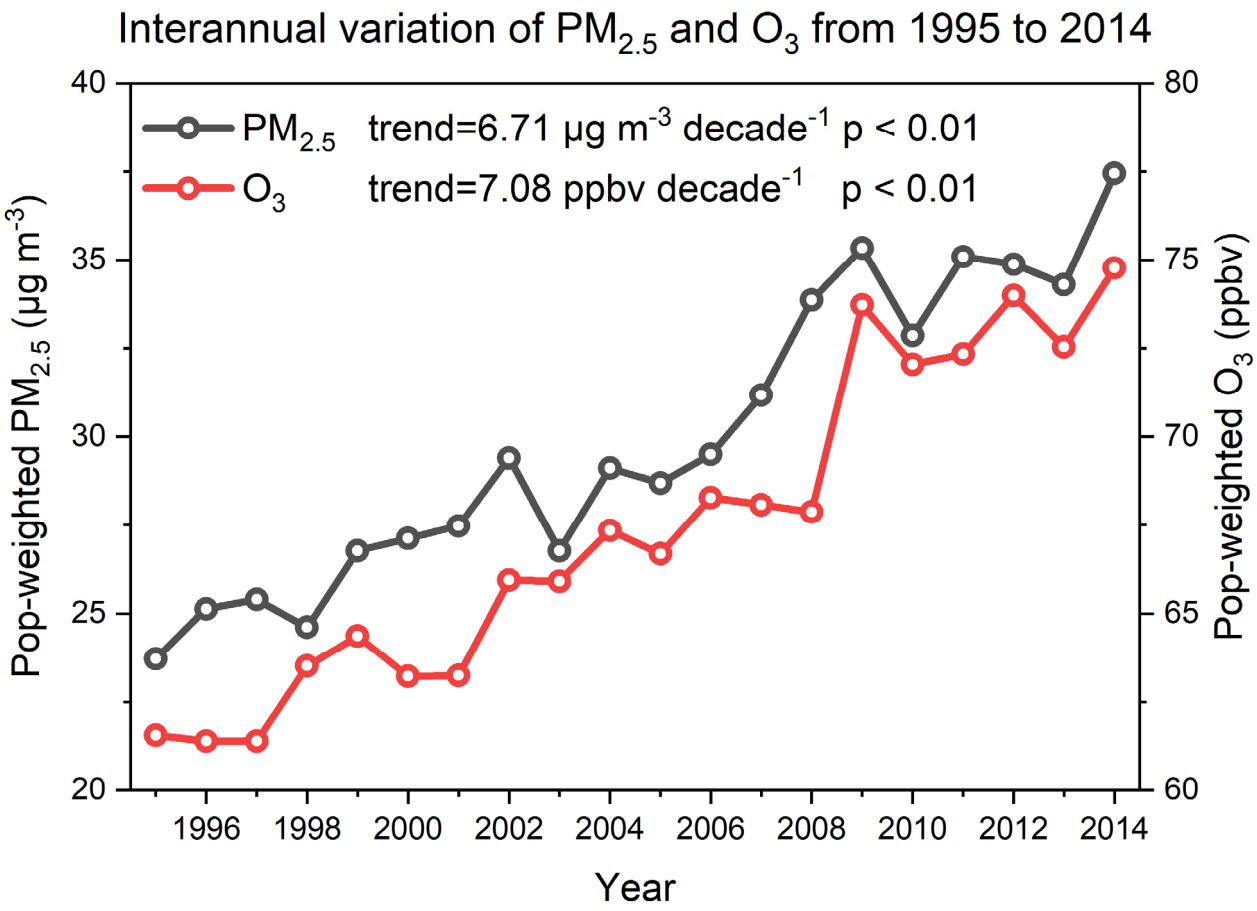
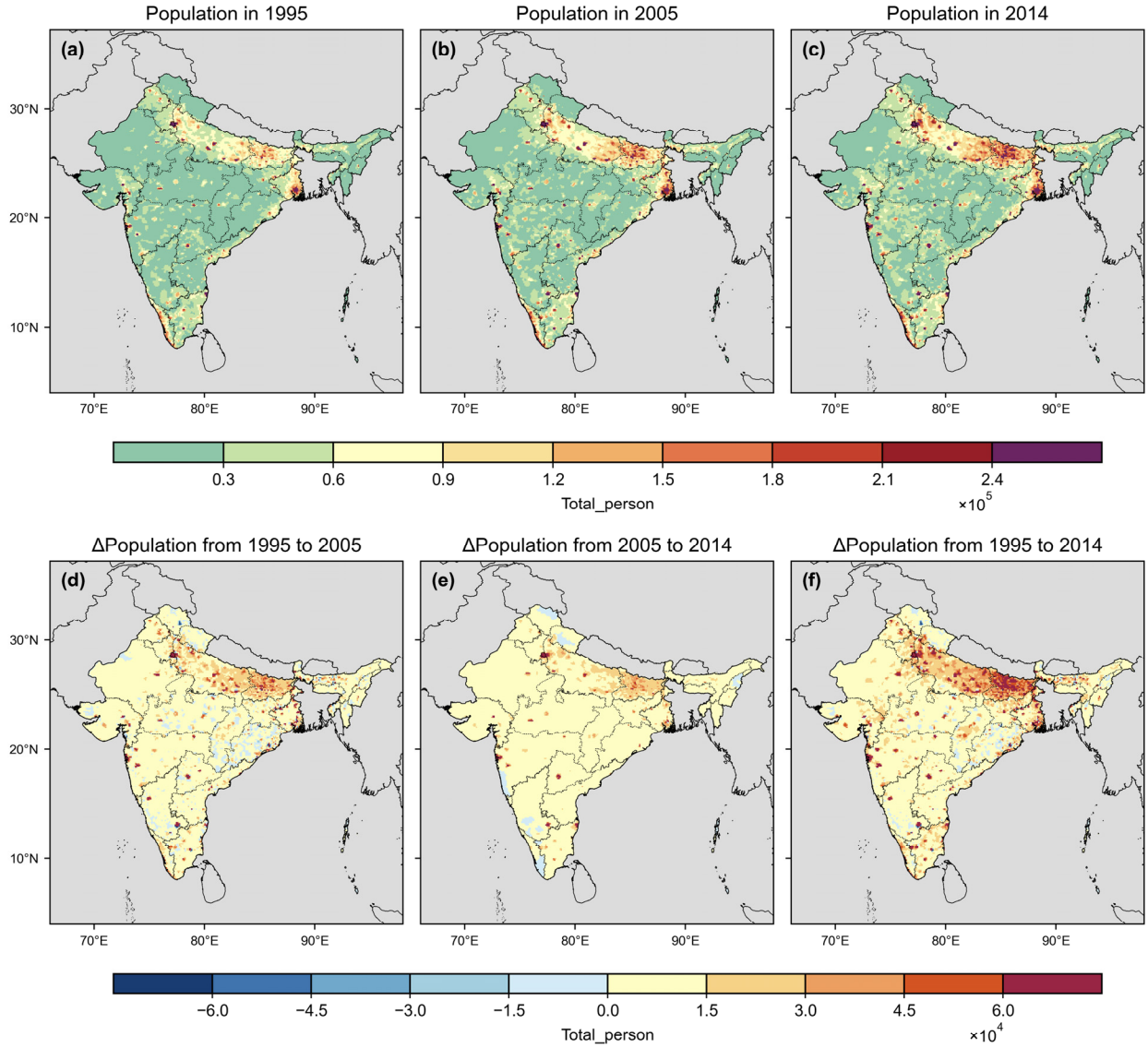
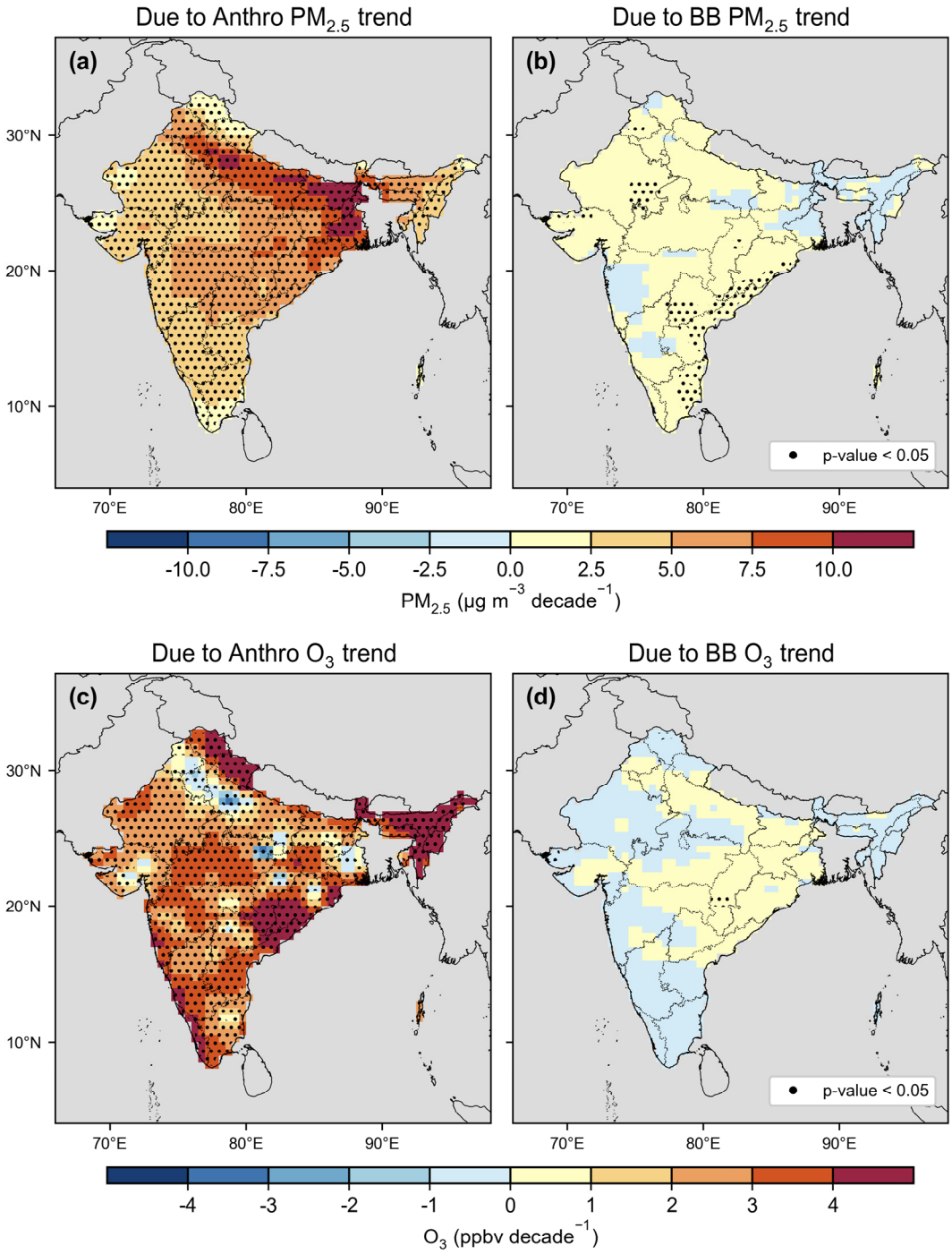


Figure S8. The interannual variation of pop-weighted $PM_{2.5}$ and O_3 in India from 1995 to 2014.



50

Figure S9. 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.



55

Figure S10. 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.

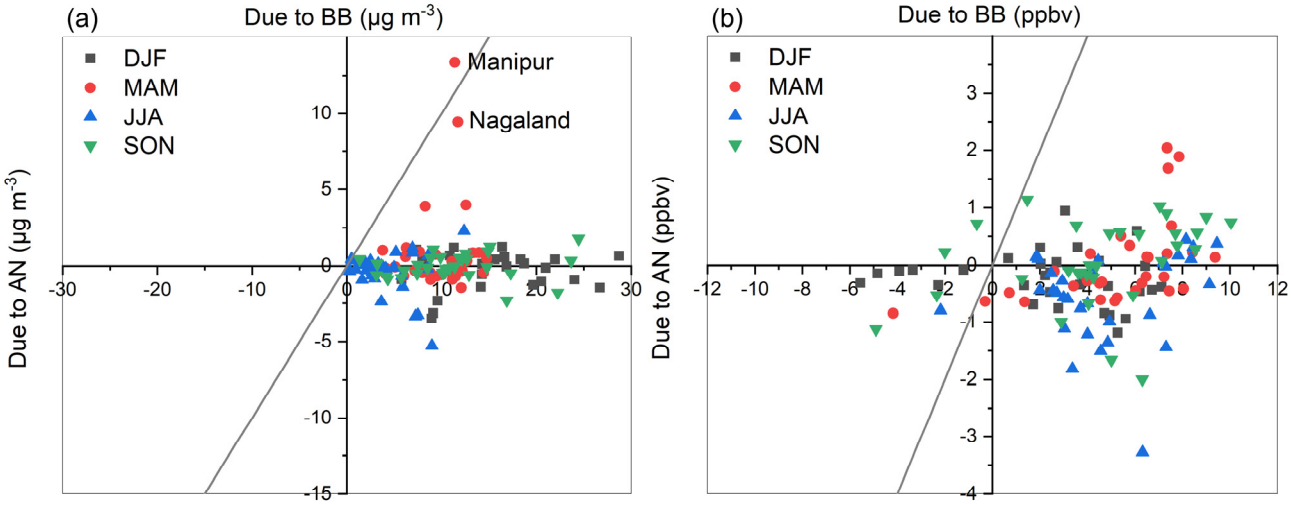


Figure S11. Contributions of ANTHRO and BB changes from 1995 to 2014 on seasonal $PM_{2.5}$ (a) and O_3 (b) changes in India administrative regions. The contributions from ANTHRO were calculated as the differences between BASE and FixAN in 2014, and the contributions from BB were calculated as the differences 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.

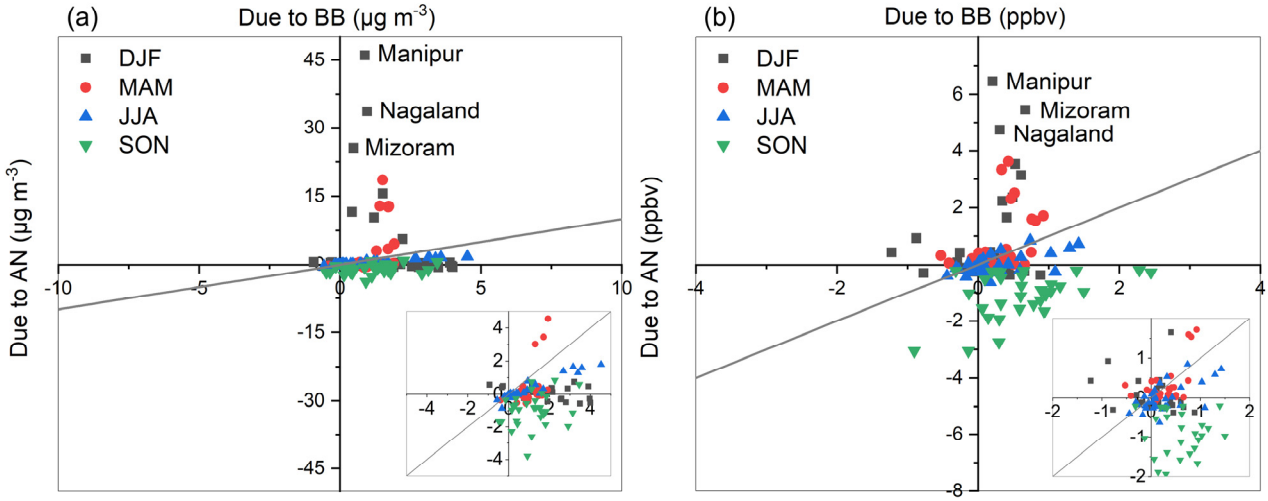


Figure S12. The same as Figure S11, but for the contributions from 1995 to 1999. The plots on the bottom right are the zoom-in results with smaller scales.

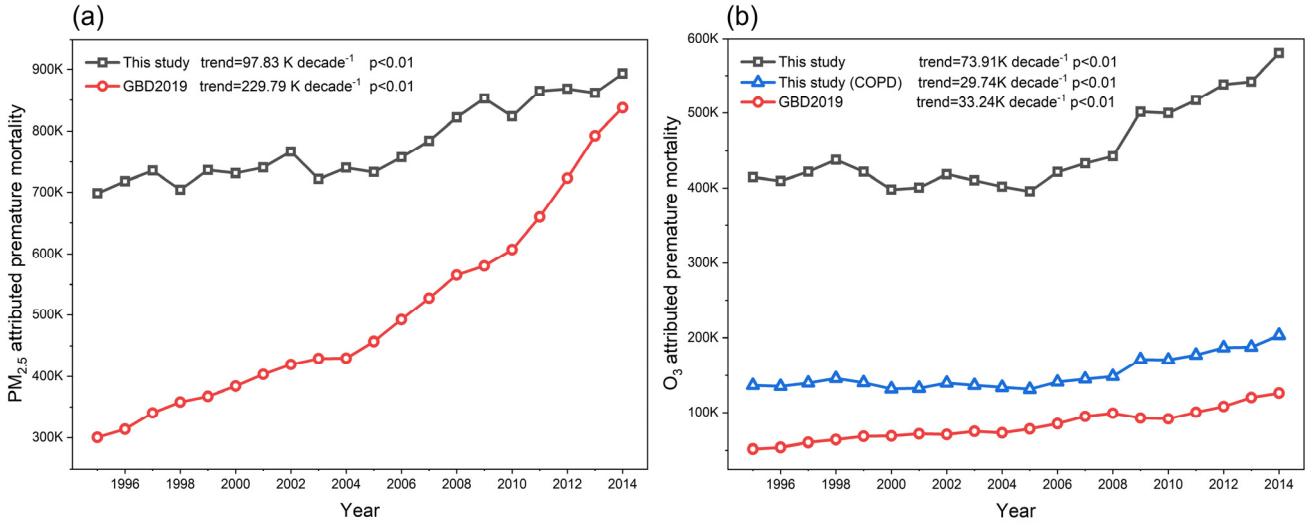


Figure S13. Comparisons of $PM_{2.5}$ and O_3 attributed premature mortality in India from 1995 to 2014 between our study and GBD2019.

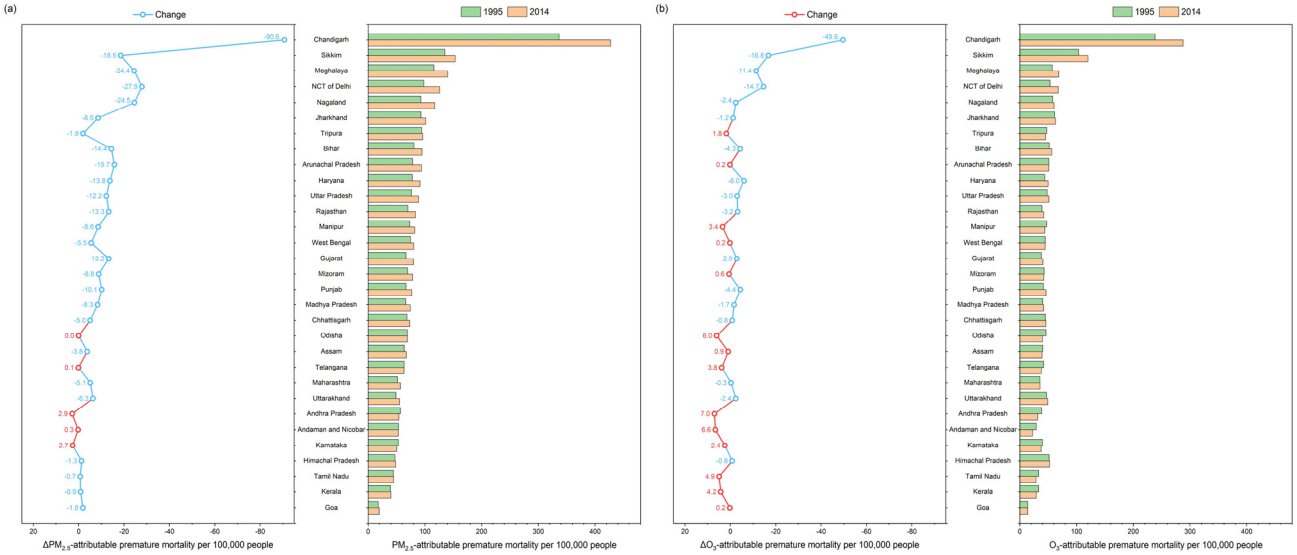


Figure S14. Premature mortality attributable to $PM_{2.5}$ (a) or O_3 (b) per capita (avoided deaths per 100,000 people) and changes in the states of India from 1995 to 2014.

REFERENCES

Anenberg, S. C., Horowitz, L. W., Tong, D. Q., and West, J. J.: An Estimate of the Global Burden of Anthropogenic Ozone and Fine Particulate Matter on Premature Human Mortality Using Atmospheric Modeling, Environ Health Perspect, 118, 1189–1195, https://doi.org/10.1289/ehp.0901220, 2010.

Apte, J. S., Marshall, J. D., Cohen, A. J., and Brauer, M.: Addressing Global Mortality from Ambient $PM_{2.5}$, Environ. Sci. Technol., 49, 8057–8066, https://doi.org/10.1021/acs.est.5b01236, 2015.

Brauer, M., Freedman, G., Frostad, J., van Donkelaar, A., Martin, R. V., Dentener, F., Dingenen, R. van, Estep, K., Amini, H., Apte, J. S., Balakrishnan, K., Barregard, L., Broday, D., Feigin, V., Ghosh, S., Hopke, P. K., Knibbs, L. D., Kokubo, Y., Liu, Y., Ma, S., Morawska, L., Sangrador, J. L. T., Shaddick, G., Anderson, H. R., Vos, T., Forouzanfar, M. H., Burnett, R. T., and Cohen, A.: Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013, Environ. Sci. Technol., 50, 79–88, https://doi.org/10.1021/acs.est.5b03709, 2016.

Chowdhury, S. and Dey, S.: Cause-specific premature death from ambient $PM_{2.5}$ exposure in India: Estimate adjusted for baseline mortality, Environment International, 91, 283–290, https://doi.org/10.1016/j.envint.2016.03.004, 2016.

Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C. A., Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C. J. L., and Forouzanfar, M. H.: Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015, The Lancet, 389, 1907–1918, https://doi.org/10.1016/S0140-6736(17)30505-6, 2017.

Conibear, L., Butt, E. W., Knote, C., Arnold, S. R., and Spracklen, D. V.: Residential energy use emissions dominate health impacts from exposure to ambient particulate matter in India, Nat Commun, 9, 617, https://doi.org/10.1038/s41467-018-02986-7, 2018.

David, L. M., Ravishankara, A. R., Kodros, J. K., Venkataraman, C., Sadavarte, P., Pierce, J. R., Chaliyakunnel, S., and Millet, D. B.: Aerosol Optical Depth Over India, Journal of Geophysical Research: Atmospheres, 123, 3688–3703, https://doi.org/10.1002/2017JD027719, 2018.

van Donkelaar, A., Martin, R. V., Brauer, M., Hsu, N. C., Kahn, R. A., Levy, R. C., Lyapustin, A., Sayer, A. M., and Winker, D. M.: Global Estimates of Fine Particulate Matter using a Combined Geophysical-Statistical Method with Information from Satellites, Models, and Monitors, Environ. Sci. Technol., 50, 3762–3772, https://doi.org/10.1021/acs.est.5b05833, 2016.

Guo, H., Kota, S. H., Chen, K., Sahu, S. K., Hu, J., Ying, Q., Wang, Y., and Zhang, H.: Source contributions and potential reductions to health effects of particulate matter in India, Atmospheric Chemistry and Physics, 18, 15219–15229, https://doi.org/10.5194/acp-18-15219-2018, 2018.

Hakim, Z. Q., Archer-Nicholls, S., Beig, G., Folberth, G. A., Sudo, K., Abraham, N. L., Ghude, S., Henze, D. K., and Archibald, A. T.: Evaluation of tropospheric ozone and ozone precursors in simulations from the HTAPII and CCMI model intercomparisons – a focus on the Indian subcontinent, Atmospheric Chemistry and Physics, 19, 6437–6458, https://doi.org/10.5194/acp-19-6437-2019, 2019.

Jia, B., Gao, M., Zhang, X., Xiao, X., Zhang, S., and Lam Yung, K. K.: Rapid increase in mortality attributable to $PM_{2.5}$ exposure in India over 1998–2015, Chemosphere, 269, 128715,

https://doi.org/10.1016/j.chemosphere.2020.128715, 2021.

Liu, L., Hu, L., Liu, Y., and Wang, H.: Modeling of the health impacts of ambient ozone pollution in China and India, Atmospheric Environment, 267, 118753, https://doi.org/10.1016/j.atmosenv.2021.118753, 2021.

Sahu, S. K., Sharma, S., Zhang, H., Chejarla, V., Guo, H., Hu, J., Ying, Q., Xing, J., and Kota, S. H.: Estimating ground level $PM_{2.5}$ concentrations and associated health risk in India using satellite based AOD and WRF predicted meteorological parameters, Chemosphere, 255, 126969, https://doi.org/10.1016/j.chemosphere.2020.126969, 2020.

Sharma, S., Chatani, S., Mahtta, R., Goel, A., and Kumar, A.: Sensitivity analysis of ground level ozone in India using WRF-CMAQ models, Atmospheric Environment, 131, 29–40, https://doi.org/10.1016/j.atmosenv.2016.01.036, 2016.

Silva, R. A., Adelman, Z., Fry, M. M., and West, J. J.: The Impact of Individual Anthropogenic Emissions Sectors on the Global Burden of Human Mortality due to Ambient Air Pollution, Environmental Health Perspectives, 124, 1776–1784, https://doi.org/10.1289/EHP177, 2016.