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Transported aerosols regulate the pre-monsoon rainfall over north-east India: a WRF-Chem modelling study

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Table S1: Model performance statistics for meteorological parameters

	Bangalore	Delhi	Guwahati	Kolkata	Mumbai	Patna
Temperature						
RMSE (°C)	2.58	2.23	2.88	4.02	2.61	1.89
IOA	0.91	0.94	0.75	0.79	0.80	0.95
ME (°C)	-2.32	-0.34	-1.97	-3.16	-1.99	-0.74
Relative humidity						
RMSE (%)	9.33	8.71	11.21	15.68	10.49	11.63
IOA	0.97	0.92	0.79	0.79	0.85	0.91
ME (%)	0.06	0.53	3.09	12.09	3.99	5.98
Wind speed						
RMSE ($m\ s^{-1}$)	1.47	1.91	1.84	1.90	1.44	2.11
IOA	0.49	0.59	0.40	0.48	0.83	0.55
ME ($m\ s^{-1}$)	0.51	-0.22	-0.35	0.07	-0.71	1.22
Wind direction						
RMSE (°)	44.06	108.48	146.95	64.29	76.91	104.87
IOA	0.79	0.72	0.47	0.43	0.68	0.75
ME (°)	-18.48	10.28	6.07	22.41	14.23	-26.17

Table S2: Model performance statistics for chemical species compared against MERRA2

NOR-I						
	BC					
	BANGALORE	DELHI	KOLKATA	MUMBAI	PATNA	GUWAHATI
RMSE ($\mu g\ m^{-3}$)	1.49	20.03	27.31	47.12	7.12	1.04
IOA	0.44	0.13	0.03	0.01	0.28	0.48
ME ($\mu g\ m^{-3}$)	0.74	13.81	21.71	32.84	3.81	0.00
	Dust					
RMSE ($\mu g\ m^{-3}$)	18.85	122.19	32.02	82.17	64.17	33.40
IOA	0.41	0.33	0.35	0.35	0.35	0.26
ME ($\mu g\ m^{-3}$)	-15.13	-76.40	-30.09	-76.21	-50.50	-31.91
	Organic Carbon					
RMSE ($\mu g\ m^{-3}$)	2.57	34.63	49.02	87.04	12.12	4.64
IOA	0.71	0.24	0.07	0.02	0.51	0.50
ME ($\mu g\ m^{-3}$)	0.73	24.55	38.29	60.88	3.87	-1.41
	Sulfate					
RMSE ($\mu g\ m^{-3}$)	1.66	4.36	2.43	3.34	7.48	4.12
IOA	0.42	0.56	0.68	0.36	0.35	0.30
ME ($\mu g\ m^{-3}$)	-0.16	3.19	0.58	2.87	5.11	-2.22
NOR						

	BC					
	BANGALORE	DELHI	KOLKATA	MUMBAI	PATNA	GUWAHATI
RMSE ($\mu g\ m^{-3}$)	0.69	7.13	15.14	24.16	2.86	0.77
IOA	0.64	0.29	0.06	0.02	0.51	0.61
ME ($\mu g\ m^{-3}$)	0.48	5.76	13.21	19.76	2.16	0.11
	Dust					
RMSE ($\mu g\ m^{-3}$)	18.43	120.49	29.71	74.03	57.77	20.48
IOA	0.40	0.23	0.36	0.38	0.33	0.39
ME ($\mu g\ m^{-3}$)	-14.52	-61.58	-26.64	-65.36	-40.90	-18.49
	Organic carbon					
RMSE ($\mu g\ m^{-3}$)	1.44	11.21	25.73	44.48	5.34	3.64
IOA	0.81	0.51	0.14	0.04	0.70	0.61
ME ($\mu g\ m^{-3}$)	0.44	8.61	22.04	36.26	0.02	-2.02
	Sulfate					
RMSE ($\mu g\ m^{-3}$)	1.56	3.48	1.88	3.99	3.30	3.04
IOA	0.38	0.45	0.73	0.31	0.60	0.30
ME ($\mu g\ m^{-3}$)	-0.30	1.63	0.12	3.61	1.27	-1.62

Table S3: Model performance statistics for chemical species compared against observation stations. RMSE and ME units in μg m^{-3}.

		NOR			NOR-I		
		RMSE	IOA	ME	RMSE	IOA	ME
DELHI	NO	24.82	0.35	-23.28	23.86	0.36	-22.48
	NO_2	30.22	0.17	28.47	35.58	0.14	33.22
	PM_{10}	37.87	0.48	-19.65	73.84	0.37	-47.57
	$PM_{2.5}$	15.72	0.62	-10.12	21.15	0.62	15.14
KANPUR	NO	42.17	0.43	-36.42	42.38	0.43	-36.65
	NO_2	54.22	0.25	-53.52	59.32	0.22	-58.60
	$PM_{2.5}$	24.10	0.48	-20.02	17.70	0.43	-9.34
	SO_2	20.44	0.45	18.49	10.97	0.53	8.90
PATNA	NO	12.18	0.35	-10.69	12.14	0.35	-10.67
	NO_2	8.79	0.55	-0.60	8.49	0.57	0.06
	$PM_{2.5}$	55.62	0.22	-55.28	49.78	0.21	-48.48
SILIGURI	NO	5.77	0.25	-5.64	5.77	0.24	-5.64
	NO_2	14.17	0.42	-9.90	16.94	0.22	-16.76
	PM_{10}	22.28	0.52	-19.53	30.07	0.44	-27.76
	$PM_{2.5}$	14.51	0.52	-12.90	14.27	0.52	-12.94

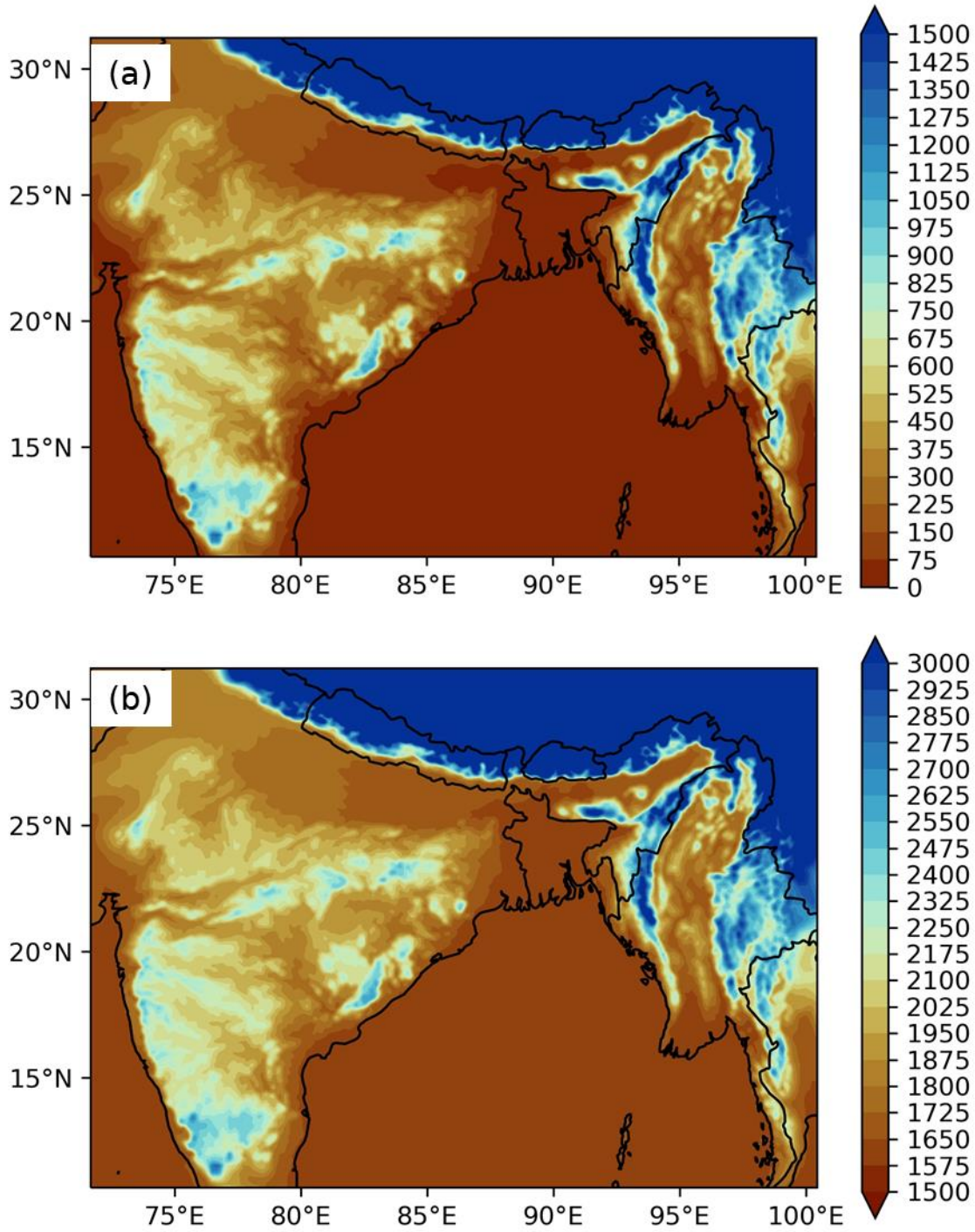

Figure S1: Spatial distributions of geopotential heights (m) of model level a) 0 (near surface) b) 15

Table S4: Region-wise PM_{10} concentration (µg m^{-3}) in different scenarios at different atmospheric heights

	No_EMISS_NE		Only_EMISS_NE		NOR-I		(No_EMISS_NE/ (No_EMISS_NE + Only_EMISS_NE))*100%	
Model level	0	15	0	15	0	15	0	15
Region 1	18.18	32.67	6.49	1.01	30.25	42.99	73.70	97.00
Region 2	12.78	21.70	6.33	1.14	26.64	33.75	66.86	95.02
Region 3	5.25	7.33	3.43	0.90	12.69	12.39	60.48	89.03
Region 4	21.62	36.01	16.03	0.88	40.12	47.38	57.43	97.62
Average	14.46	24.43	8.07	0.98	27.43	34.13	64.18	96.14

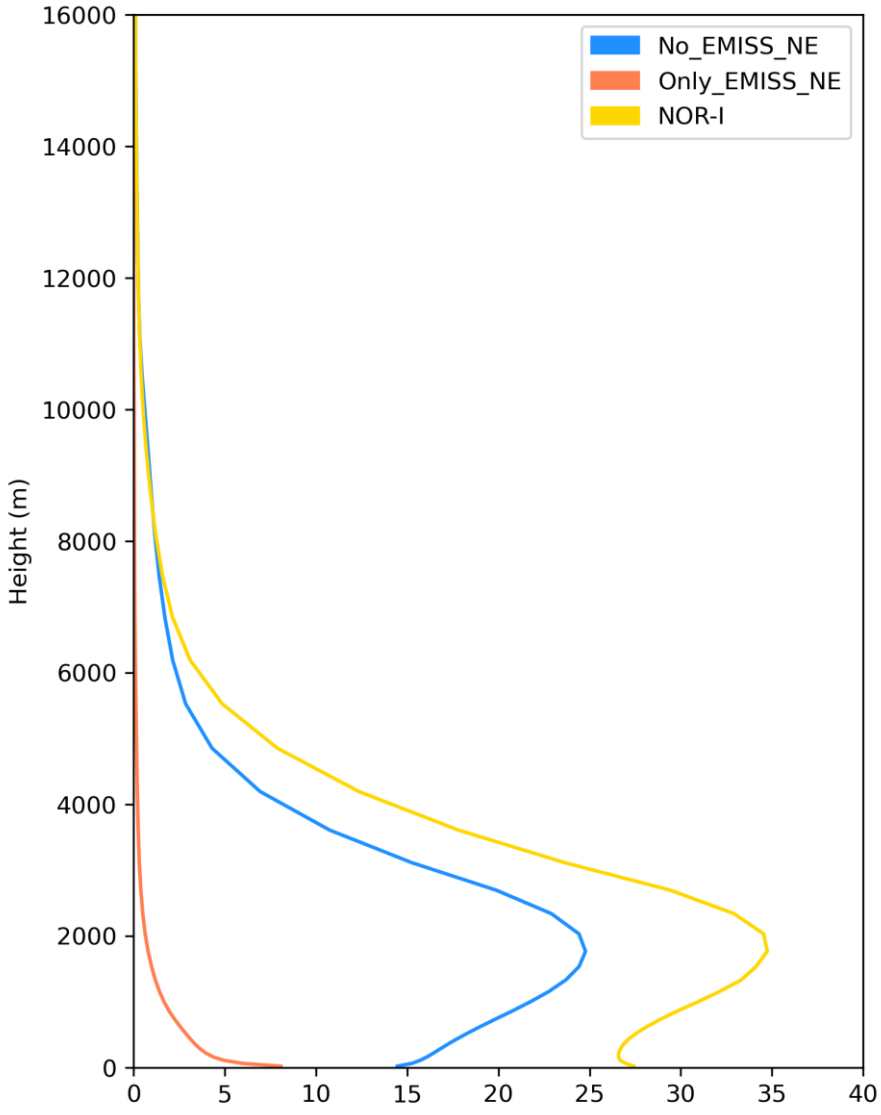

Figure S2: Regional average vertical profile of PM_{10} concentration (µg m^{-3}) in different scenarios

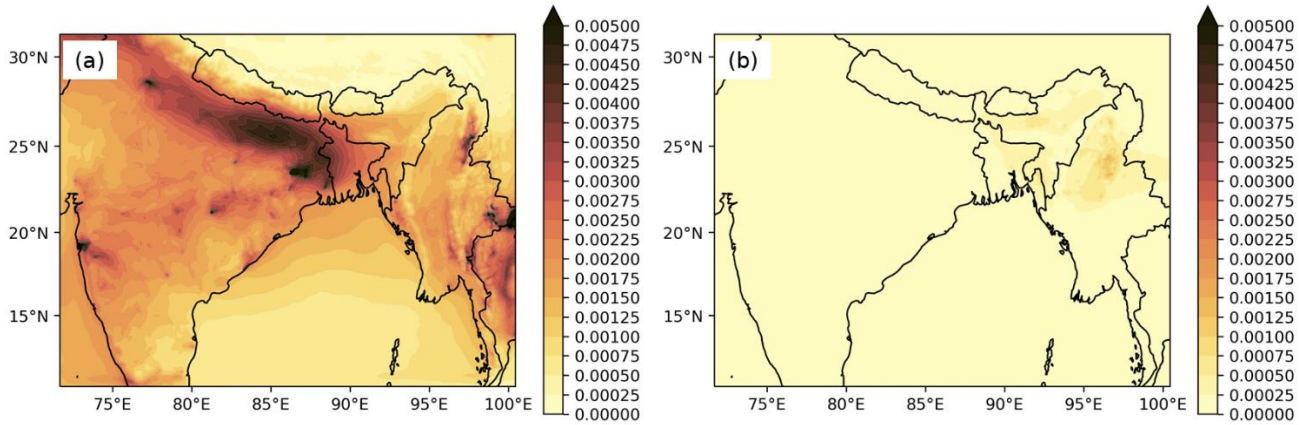

Figure S3: Spatial distribution of column integrated BC mass (g m^{-2}) in a) No_EMISS_NE b) Only_EMISS_NE

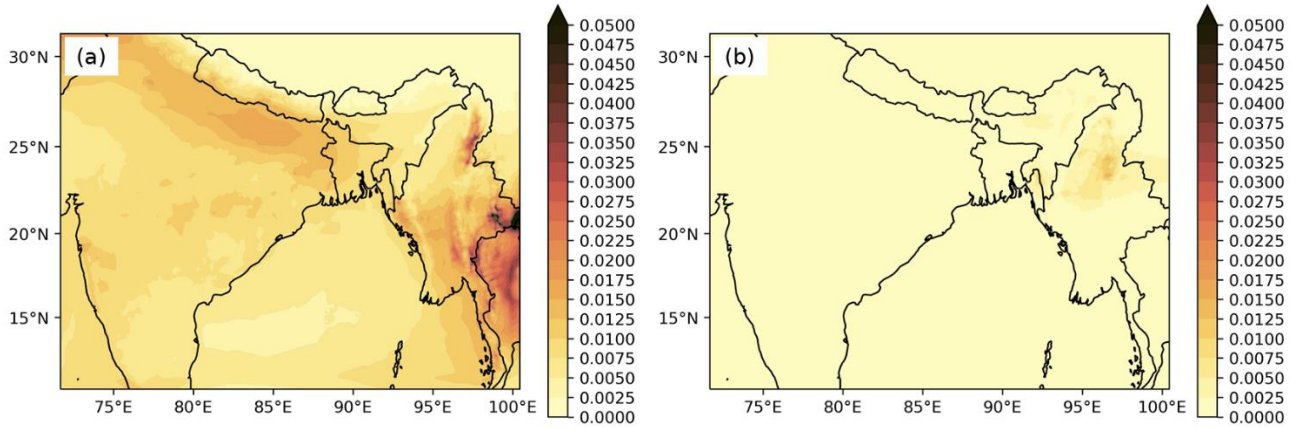

Figure S4: Spatial distribution of column integrated organic carbon mass (g m^{-2}) in a) No_EMISS_NE b) Only_EMISS_NE

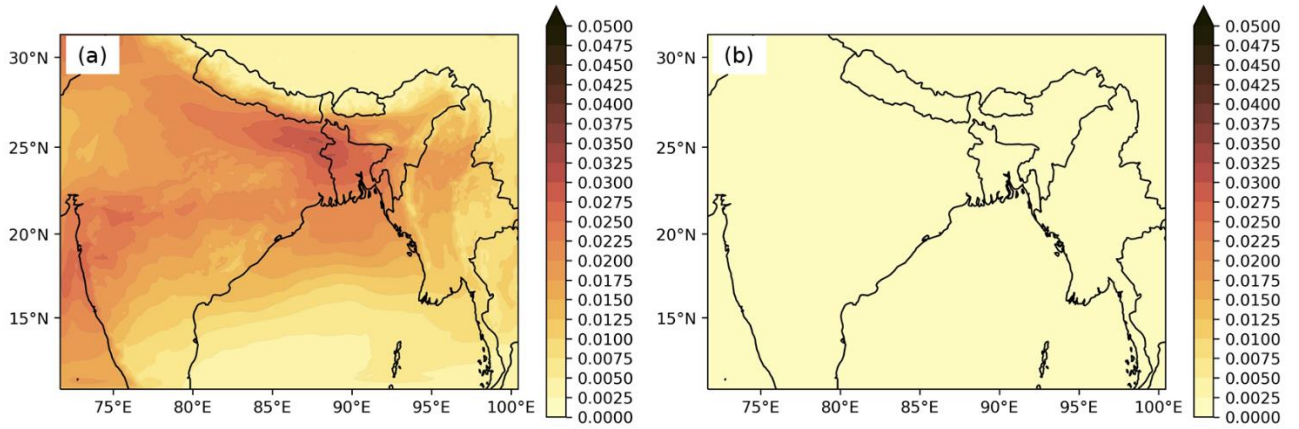

Figure S5: Spatial distribution of column integrated sulfate mass (g m^{-2}) in a) No_EMISS_NE b) Only_EMISS_NE

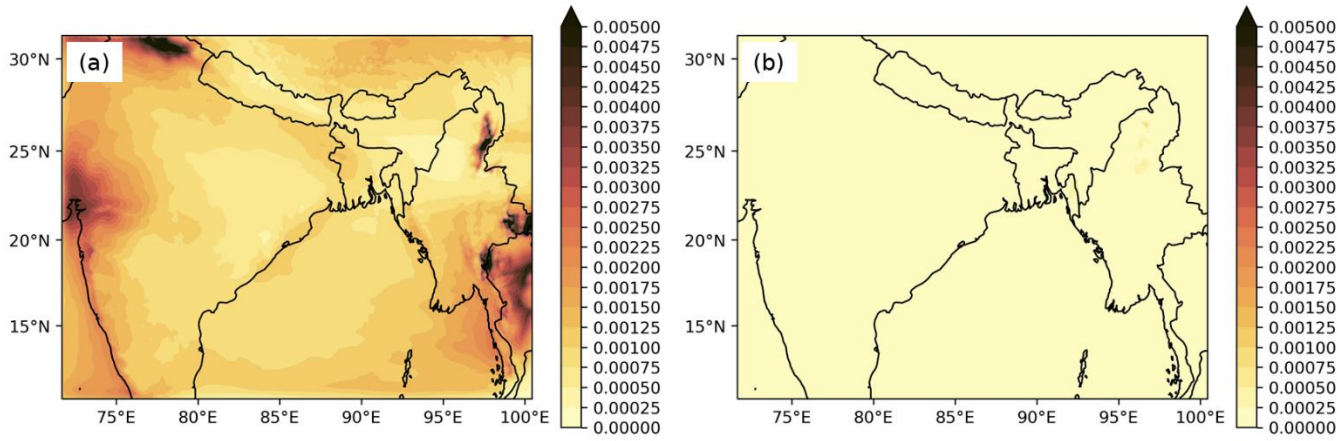

Figure S6: Spatial distribution of column integrated nitrate mass (g m^{-2}) in a) No_EMISS_NE b) Only_EMISS_NE

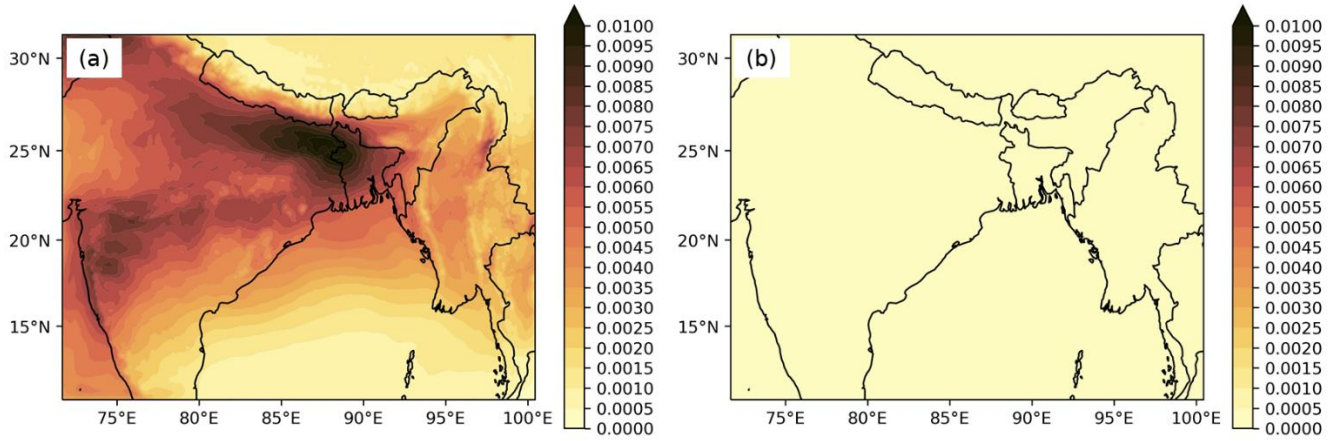

Figure S7: Spatial distribution of column integrated ammonium mass (g m^{-2}) in a) No_EMISS_NE b) Only_EMISS_NE

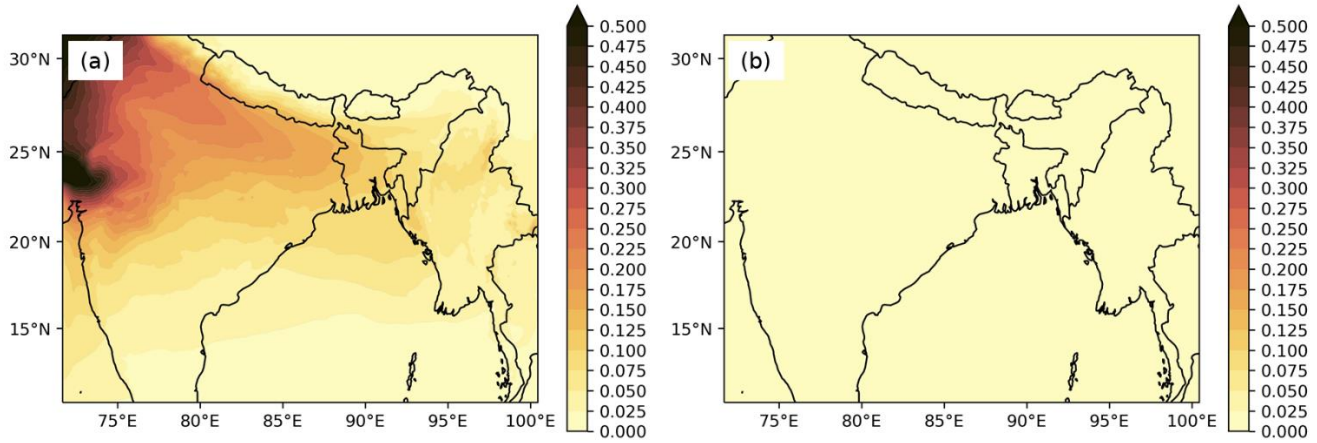

Figure S8: Spatial distribution of column integrated dust mass (g m^{-2}) in a) No_EMISS_NE b) Only_EMISS_NE

Aerosol effects of local and transported aerosols on radiative forcing

At surface,

Net total RF = $NOR\text{-}I_{((SWDNB+LWDNB)-(SWUPB+LWUPB))}$ - $NOCHEM_{((SWDNB+LWDNB)-(SWUPB+LWUPB))}$

Net indirect RF = $NOFEED\text{-}I_{((SWDNB+LWDNB)-(SWUPB+LWUPB))}$ - $NOCHEM_{((SWDNB+LWDNB)-(SWUPB+LWUPB))}$

Net direct + semi-direct RF = $NOR\text{-}I_{((SWDNB+LWDNB)-(SWUPB+LWUPB))}$ – $NOFEED\text{-}I_{((SWDNB+LWDNB)-(SWUPB+LWUPB))}$

Net direct RF = $NOR\text{-}I_{((SWDNBC+LWDNBC)-(SWUPBC+LWUPBC))}$ – $NOFEED\text{-}I_{((SWDNBC+LWDNBC)-(SWUPBC+LWUPBC))}$

Net semi-direct RF = (Direct + semi-direct RF) – Net direct RF

At TOA,

Net total RF = $NOR\text{-}I_{((SWDNT+LWDNT)-(SWUPT+LWUPT))}$ - $NOCHEM_{((SWDNT+LWDNT)-(SWUPT+LWUPT))}$

Net indirect RF = $NOFEED\text{-}I_{((SWDNT+LWDNT)-(SWUPT+LWUPT))}$ - $NOCHEM_{((SWDNT+LWDNT)-(SWUPT+LWUPT))}$

Net direct + semi-direct RF = $NOR\text{-}I_{((SWDNT+LWDNT)-(SWUPT+LWUPT))}$ – $NOFEED\text{-}I_{((SWDNT+LWDNT)-(SWUPT+LWUPT))}$

Net direct RF = $NOR\text{-}I_{((SWDNTC+LWDNTC)-(SWUPTC+LWUPTC))}$ – $NOFEED\text{-}I_{((SWDNTC+LWDNTC)-(SWUPTC+LWUPTC))}$

Net semi-direct RF = (Direct + semi-direct RF) – Net direct RF

Thus, Net atmospheric RF = Total RF_{TOA} – Total $RF_{SURFACE}$

Similarly, the short-wave (SW) or long-wave (LW) was similarly found by using either or SW or LW radiation instead of combined radiations. NOR-I was replaced by No_EMISS_NE or Only_EMISS_NE while NOFEED was replaced by No_EMISS_NE_NOFEED or Only_EMISS_NE_NOFEED to find contributions of local and transported aerosols.

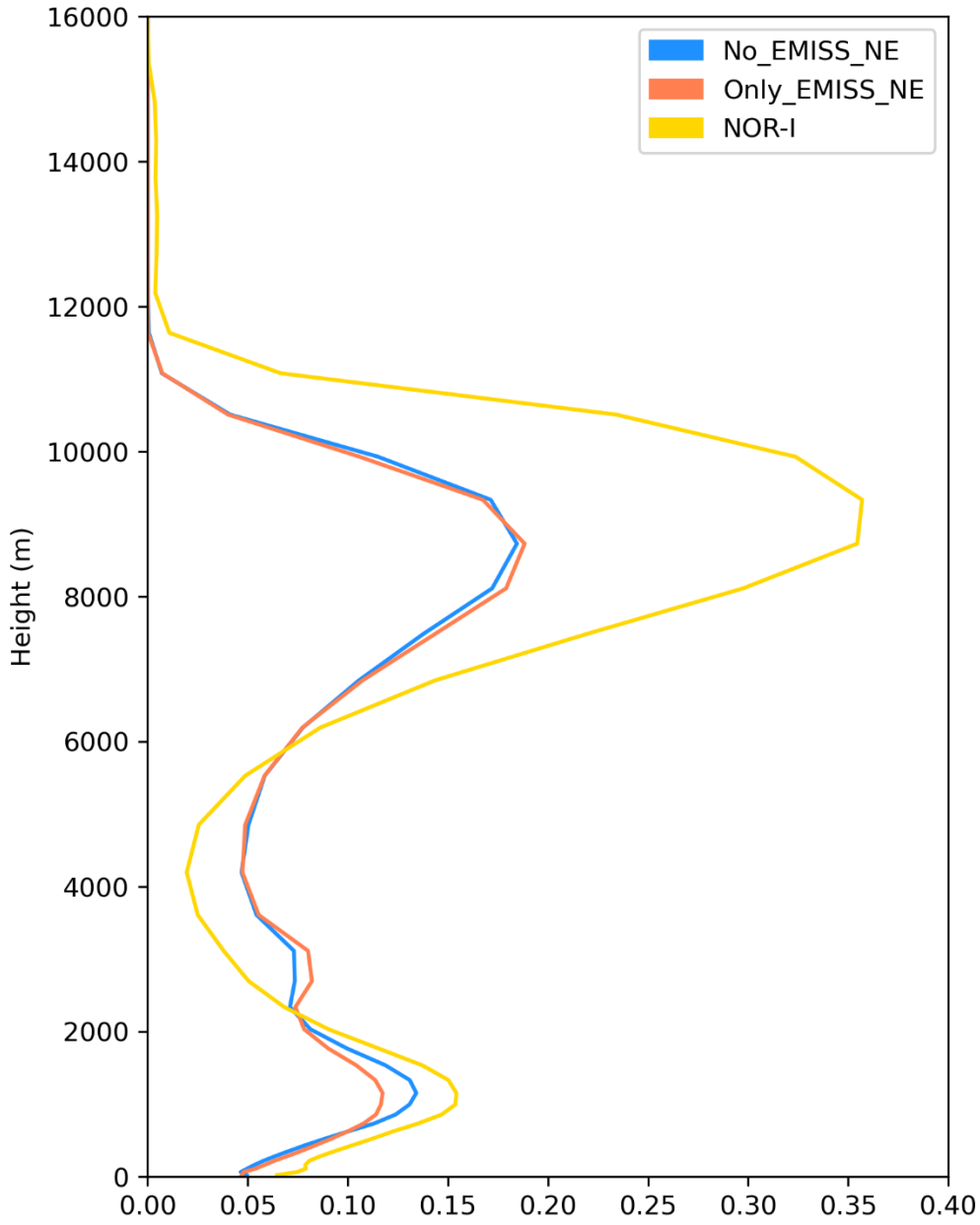

Figure S9: Regional average vertical profile of cloud cover in different scenarios

Table S5: Changes in total rainfall (mm) due to different aerosol effects in different scenarios

		Total aerosol effect	Direct + Semi-direct	Indirect
NOR-I	Region 1	-100.60	-13.21	-87.39
	Region 2	-71.93	-1.34	-70.59
	Region 3	-102.60	-2.49	-100.11
	Total	-275.13	-17.04	-258.09
No_EMISS_NE	Region 1	-29.81	-18.37	-11.44
	Region 2	-21.52	-5.88	-15.64
	Region 3	-21.73	0.30	-22.04
	Total	-73.06	-23.95	-49.11
Only_EMISS_NE	Region 1	-26.81	-6.23	-20.57
	Region 2	2.48	-0.17	2.65
	Region 3	-0.12	-2.01	1.89
	Total	-24.45	-8.42	-16.04

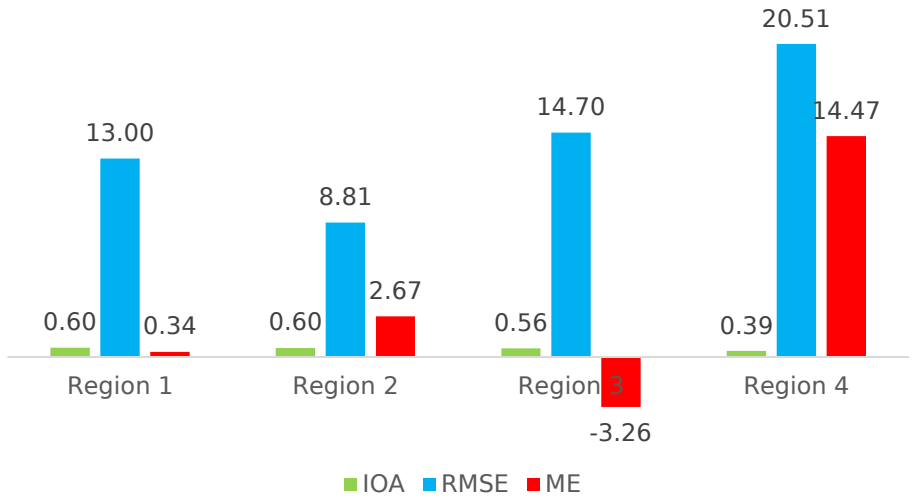

Figure S10: Region wise rainfall evaluation statistics with NOR-I. RMSE and ME in mm day^{-1}

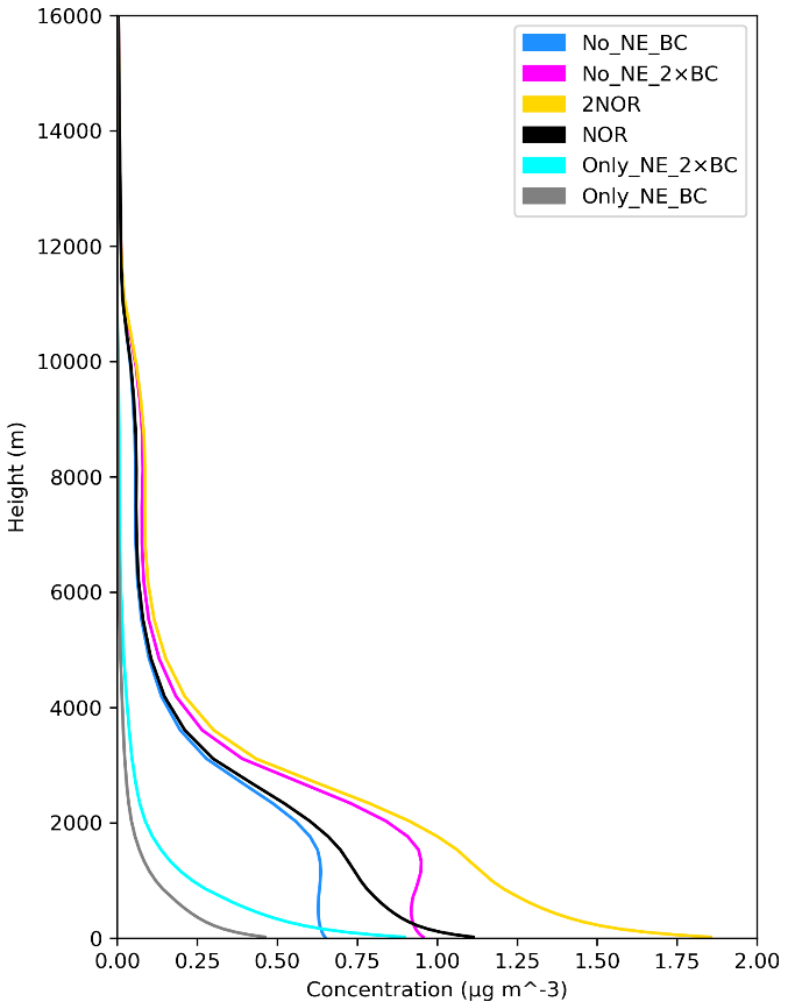

Figure S11: Regionally averaged vertical profiles of BC concentration (μg m^{-3}) in different scenarios

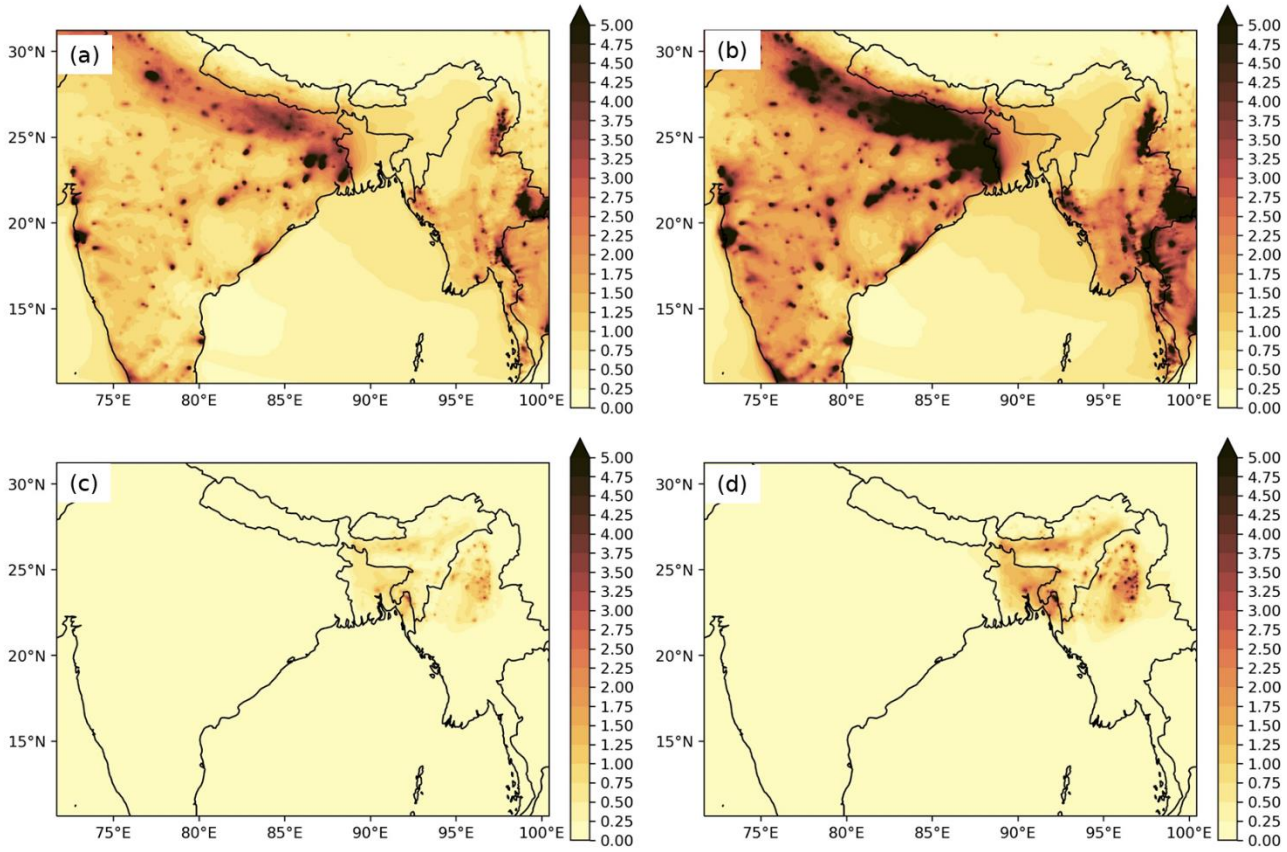

Figure S12: Spatial distributions of near surface (model level 0) BC concentration (µg m^{-3}) in a) No_NE_BC b) No_NE_2×BC c) Only_NE_BC d) Only_NE_2×BC

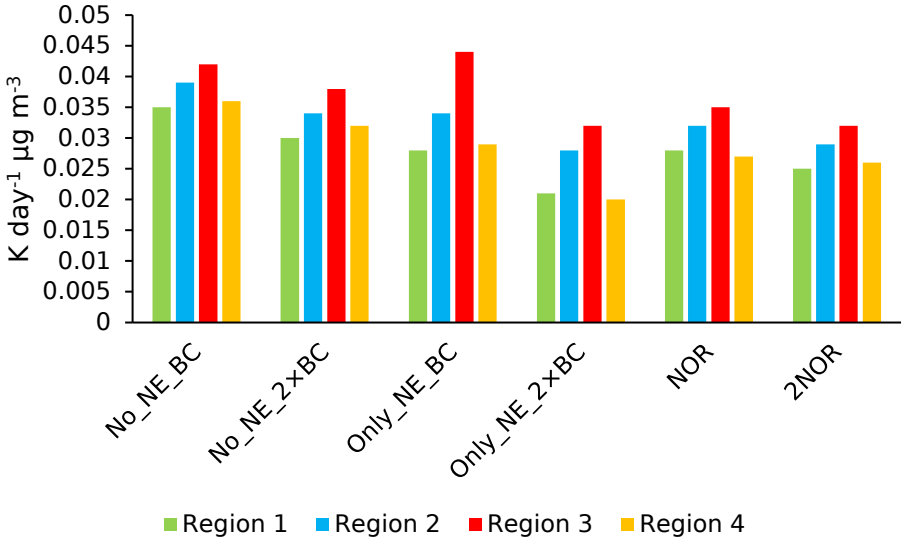

Figure S13: Region-wise HE in different scenarios

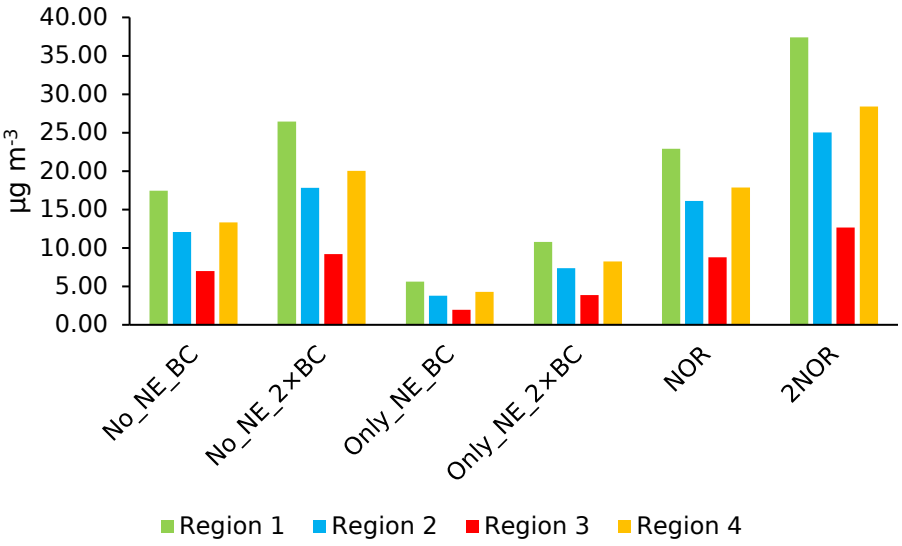

Figure S14: Column integrated BC concentration

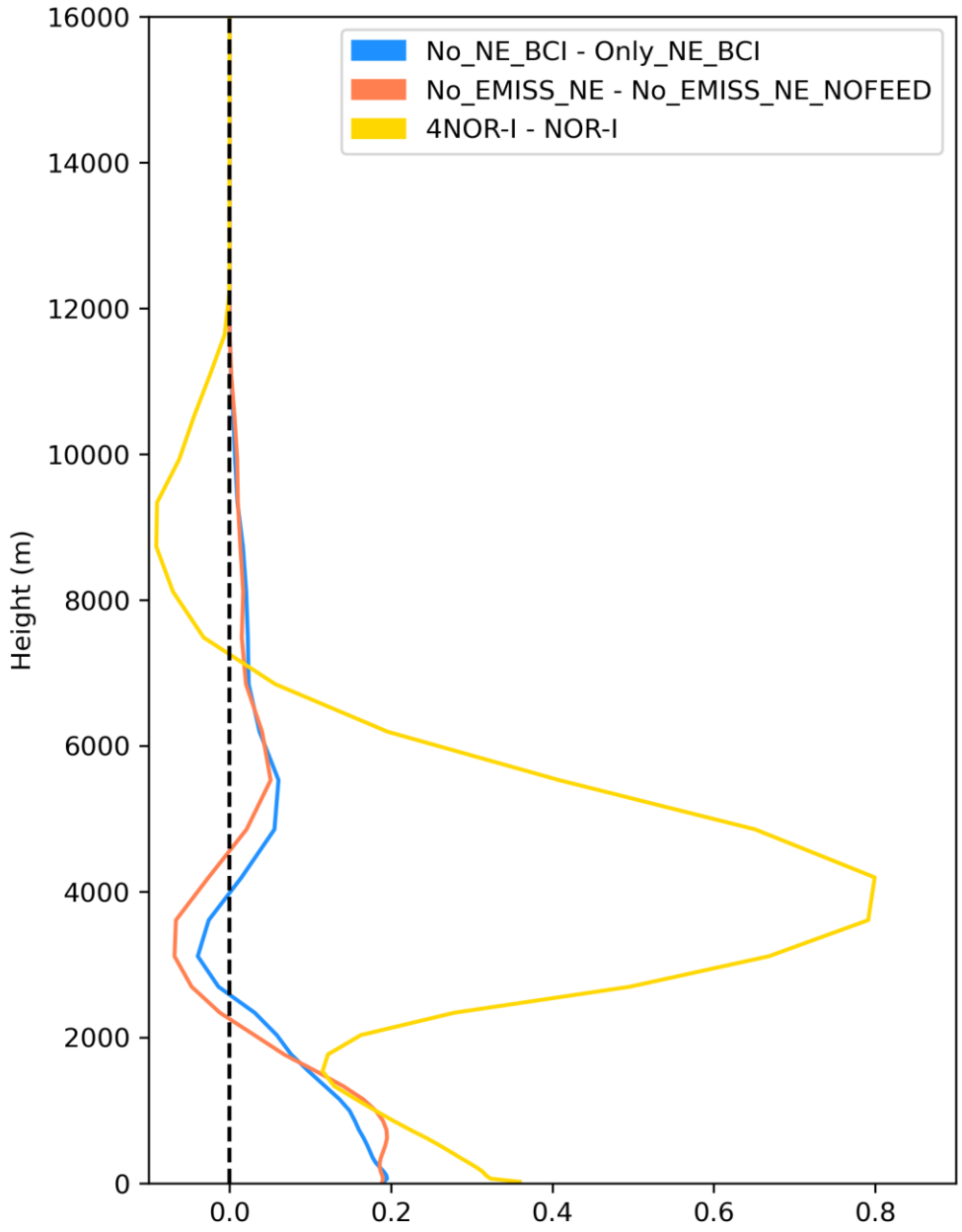

Figure S15: Regionally averaged vertical profiles of water vapor mixing ratio (g kg^{-1}) perturbations

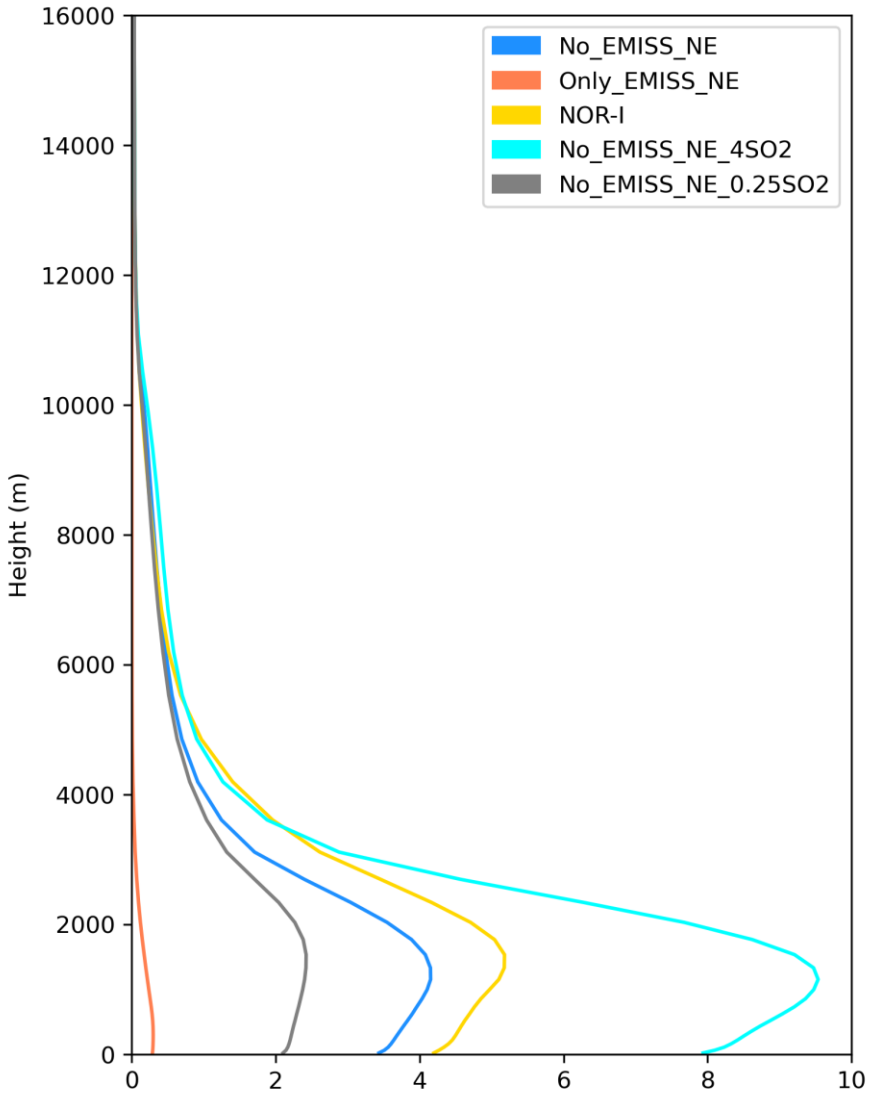

Figure S16: Regional average vertical profile of sulfate aerosol concentration (μg m^{-3}) in different scenarios

Table S6: Amount of rainfall (mm) aerosol effects increase (inc) or decrease (dec) RAIN under different rainfall intensities

	inc_0_5	inc_5_10	inc_>10	dec_0_5	dec_5_10	dec_>10
Total aerosol effect (NOR-I – NOCHEM)	6.17	9.99	137.16	-6.50	-10.61	-411.34
Direct + semi-direct effect (NOR-I – NOFEED-I)	6.62	10.17	116.92	-7.07	-10.51	-133.16
Indirect effect (NOFEED-I – NOCHEM)	6.52	10.24	141.62	-6.48	-10.57	-399.41
Total aerosol effect with BC increase (4NOR-I – NOCHEM)	5.13	8.81	275.47	-6.52	-10.10	-337.23
Direct + semi-direct effect with BC increase (4NOR-I – NOFEED-I)	5.55	9.66	339.33	-6.95	-10.78	-143.17
BC increase (4NOR-I – NOR-I)	5.63	9.73	343.76	-6.58	-10.45	-131.41

Table S7: Percentage (%) of simulation time aerosol effects increase (inc) or decrease (dec) RAIN under different rainfall intensities

	inc_0_5	inc_5_10	inc_>10	dec_0_5	dec_5_10	dec_>10
Total aerosol effect (NOR-I – NOCHEM)	21.05	4.51	12.32	21.06	4.80	19.23
Direct + semi-direct effect (NOR-I – NOFEED-I)	22.37	4.61	10.85	24.18	4.78	11.38
Indirect effect (NOFEED-I – NOCHEM)	21.44	4.63	12.38	20.58	4.78	18.85
Total aerosol effect with BC increase (4NOR-I – NOCHEM)	17.83	3.97	13.92	23.69	4.58	16.63
Direct + semi-direct effect with BC increase (4NOR-I – NOFEED-I)	17.79	4.36	16.51	24.08	4.87	12.74
BC increase (4NOR-I – NOR-I)	18.45	4.39	16.55	23.57	4.72	12.34