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3D assimilation and radiative impact assessment of aerosol black carbon over the Indian region using aircraft, balloon, ground-based, and multi-satellite observations

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Supplementary Information

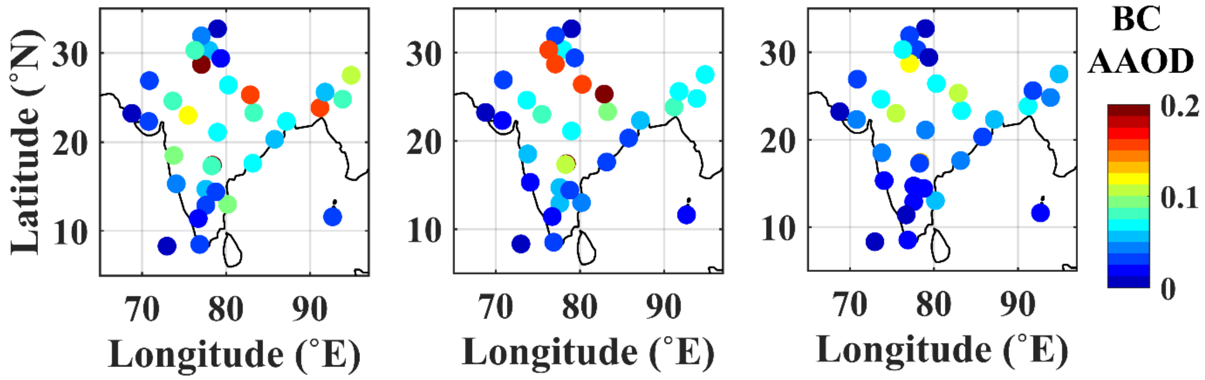

Figure S1. Variation of BC AAOD at the ARFINET measurement sites for (a) DJF, (b) MAM, and (c) ON seasons.

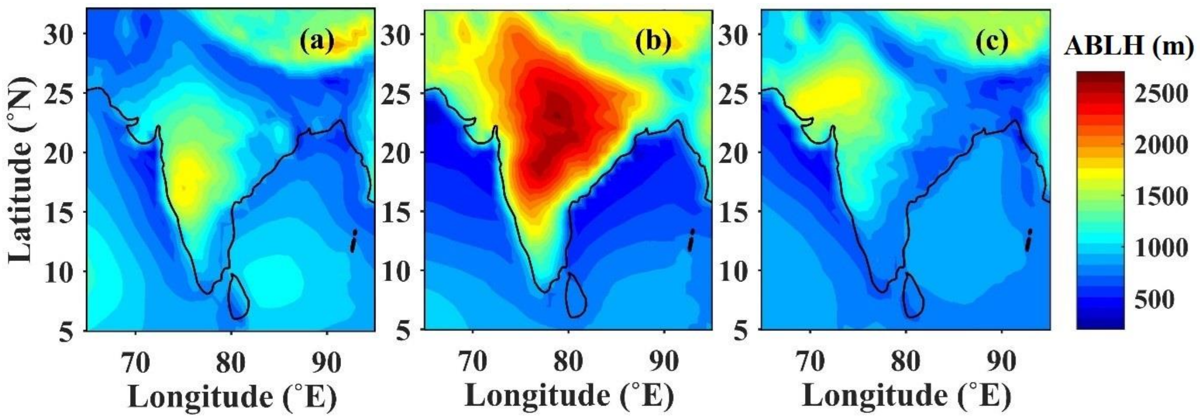

Figure S2. Seasonal mean atmospheric boundary layer height (ABLH) from MERRA-2 reanalysis for (a) DJF, (b) MAM, and (c) ON seasons.

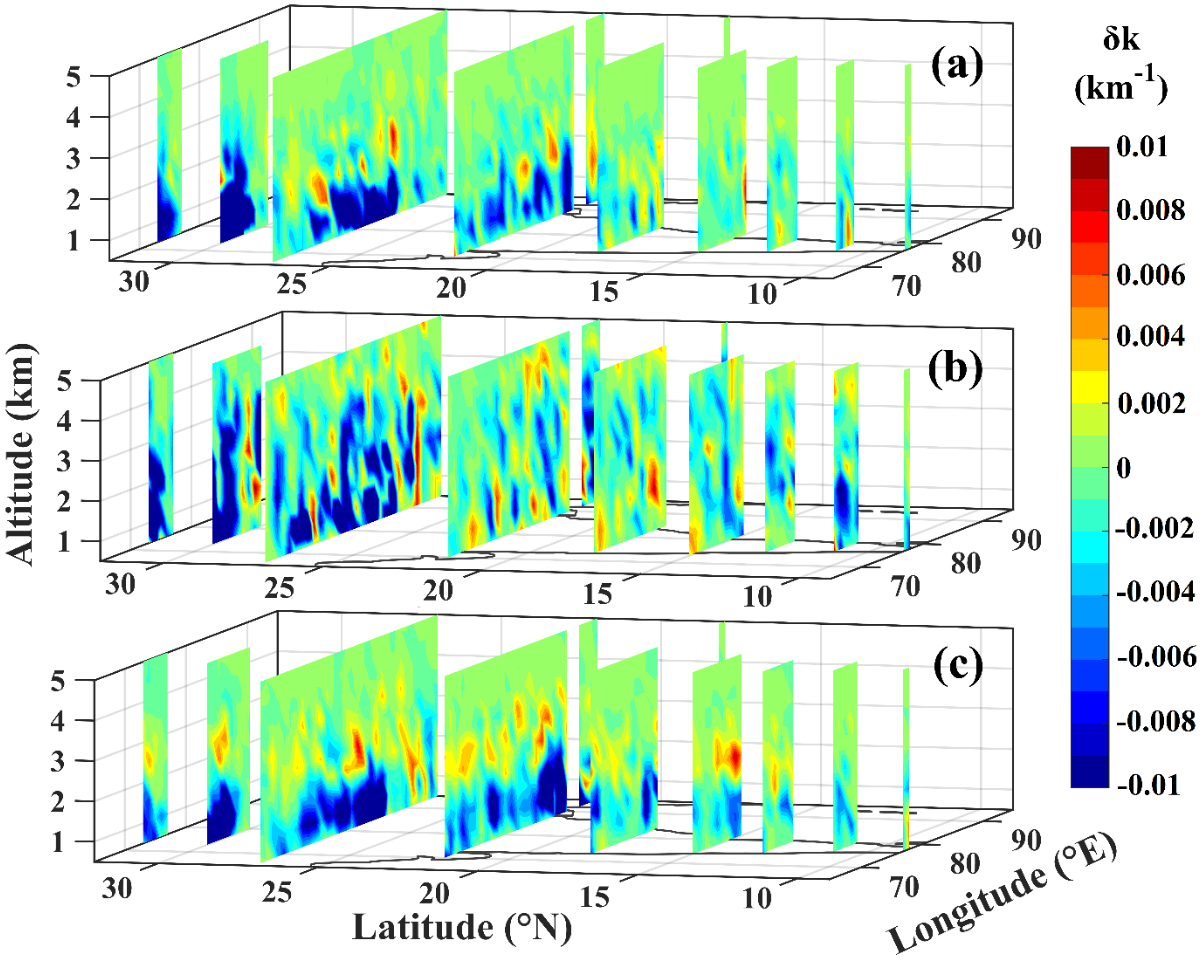

Figure S3. Variation in δk during (a) DJF, (b) MAM, and (c) ON seasons.

Examination of Background covariance structure of 3D-Var assimilation technique

The background error covariance in 3D-Var assimilation technique is derived either from climatological data or forecasts (Lewis et al., 2006). We have estimated the covariance matrix from climatological data (Eq. 3) as it effectively captures the spatial covariance structure (Pathak et al., 2019). Due to the relatively short data availability duration, it can be safely assumed that there are no discernible increasing or decreasing trends in the absorbing aerosol loading during the assimilation period. Thus, the deviations in monthly mean BC absorption coefficient across different years is considered as anomalies which are further employed for covariance estimation. The square root of diagonal elements of covariance matrix provides the estimates for the uncertainties in the background data at respective locations, while off-diagonal elements signify the cross-covariance values, which provide valuable insights on how the aerosol emissions from a grid influence the neighboring grids, and vice versa. It should be noted here that the present methodology does not employ any external estimates of the uncertainties in the background data.

Careful examination of the spatial covariance (off-diagonal components) within the error covariance matrix is performed. Two representative locations are selected, one each from North India and the other from Peninsular India, at an altitude of 2 km amsl, for MAM season. The results, representatives of which are shown in Figure S4, indicate that the covariance matrix adequately captures the spatial covariance for nearby locations as shown in

Figure. S4. In the top panel of Figure. S4, around the source region from peninsular India (marked by black diamond symbols), the covariance is high at an altitude of 2 km, indicating that the nearby grids are getting strongly influenced by the source region. Similarly, in the bottom panel of Figure S4, where a source from north India is considered, high covariance is observed over the Indo-Gangetic Plain at an altitude of 2 km. A similar pattern of high covariance is observed for other source locations as well.

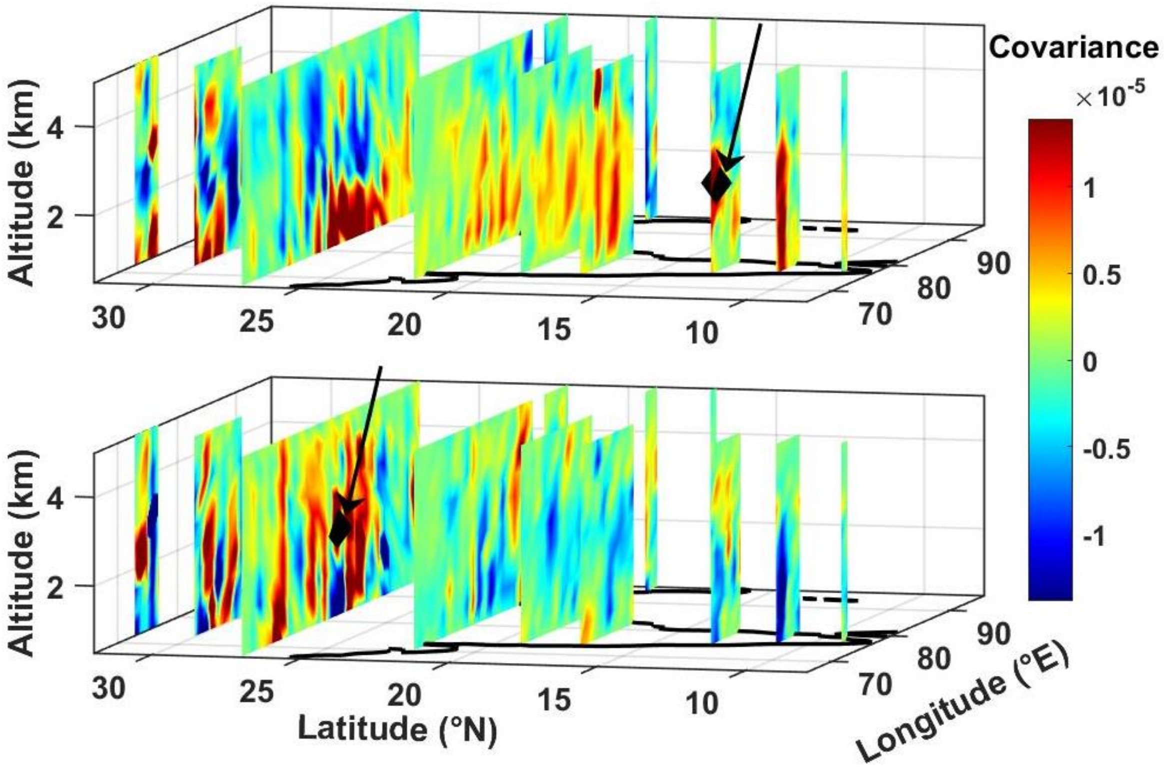

Figure S4. Spatial variation of the covariance between a single grid (marked with black diamond and arrow) and rest of the grids for peninsular (top panel) and northern (bottom panel) India.

- Lewis, J. M., Lakshmivarahan, S., and Dhall, S.: Dynamic data assimilation: a least squares approach, Vol. 104, Encyclopedia of Mathematics and its Applications, Cambridge University Press, Cambridge, 2006.

- Pathak, H. S., Satheesh, S. K., Nanjundiah, R. S., Moorthy, K. K., Lakshmivarahan, S., and Babu, S. S.: Assessment of regional aerosol radiative effects under the SWAAMI campaign–Part 1: Quality-enhanced estimation of columnar aerosol extinction and absorption over the Indian subcontinent, Atmospheric Chemistry and Physics, 19, 11865-11886, https://doi.org/10.5194/acp-19-11865-2019, 2019.

Table S1. Details of the surface measurement stations under ARFINET.

Sl. No.	Station name	Station code	Latitude (°N)	Longitude (°E)	Altitude (m amsl)
1	Agartala	AGR	91.2	23.8	13
2	Ahmedabad	AMD	23	75.5	53
3	Anantapur	ATP	14.7	77.6	335
4	Bhubaneswar	BBR	20.3	85.8	58
5	Bengaluru	BLR	12.9	85.8	920

6	Chennai	CHN	13	80.2	6
7	Dibrugarh	DBR	27.5	94.9	108
8	Dehradun	DDN	30.3	78	640
9	Delhi	DEL	28.7	77.1	300
10	Goa	GOA	15.3	74.1	8
11	Hyderabad (urban)	HDN	17.4	78.4	542
12	Hyderabad (suburban)	HDT	17.3	78.3	542
13	Hanle	HNL	32.7	79	4500
14	Imphal	IPH	24.8	93.9	786
15	Jaisalmer	JSL	26.9	70.9	225
16	Kadappa	KDP	14.4	78.8	138
17	Kharagpur	KGP	22.3	87.2	61
18	Kanpur	KNP	26.4	80.3	126
19	Kullu	KLU	31.9	77.1	1279
20	Naliya	NAL	23.2	68.6	26
21	Nagpur	NGP	21.1	79	310
22	Nainital	NTL	29.4	79.4	2084
23	Ooty	OTY	11.4	76.7	2240
24	Patiala	PTL	30.3	76.3	257
25	Pune	PUN	18.5	73.8	560
26	Rajkot	RKT	22.3	70.8	134
27	Ranchi	RNC	23.3	83.3	651
28	Shillong	SHN	25.6	91.8	1525
29	Thiruvananthapuram	TVM	8.5	76.9	10
30	Udaipur	UDP	24.6	73.7	423
31	Varanasi	VNS	25.3	82.9	81
32	Vishakhapatnam	VSK	17.6	83.2	45