

Supporting information for

Contrasting absorption and transport regimes of black and brown carbon across the western, central, and eastern Himalayas

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Text S1. Aerosol Sampling and Chemical Measurements

Total suspended particulate (TSP) samples were collected on 47 mm Whatman quartz fiber filters (QM/A) using a custom-built sampler operating at a flow rate of 17 L min⁻¹ with a 7-day integrated sampling period. Field blank samples were also collected during the sampling period to correct for potential contamination arising from both sampling operations and post-sampling filter handling. The quartz fiber filters were pre-baked at 900 °C for 3 hours before sampling to fully remove residual organic carbon. After sampling, all exposed filters were stored at approximately -20 °C to minimize volatilization and degradation of organic compounds.

Ion chromatography (IC) was used to determine K⁺ concentrations in TSP samples. Levoglucosan was quantified using high-performance anion exchange chromatography coupled with pulsed amperometric detection (HPAEC-PAD), following previously reported methods (Engling et al., 2006; Zhang et al., 2013). The method detection limits for K⁺ and levoglucosan were both 4 ppb.

Text S2. CALIPSO Satellite datasets

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), launched in April 2006, is a joint NASA–CNES mission. It carries the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) as its primary instrument, which is a dual-wavelength (532 nm and 1064 nm) polarization-sensitive lidar (Hunt et al., 2009; Winker et al., 2007; Winker et al., 2009). CALIOP enables retrieval of global vertical distributions of aerosols and clouds, making it well suited for aerosol studies in regions with sparse ground-based observations, such as the polar regions and the Tibetan Plateau (Liu et al., 2008).

This study uses two CALIPSO Level 2 products, namely the Aerosol Profile (APRO) and the Vertical Feature Mask (VFM), version V4.51, obtained from the NASA Langley Research Center Atmospheric Science Data Center (<https://asdc.larc.nasa.gov/>). The APRO product provides vertical profiles of aerosol optical properties. In this study, the total attenuated backscatter coefficient at 532 nm is used to characterize the combined contribution of aerosol and molecular backscatter.

The 532 nm vector depolarization ratio (VDR), defined as the ratio of perpendicular to parallel polarized backscatter intensities, is sensitive to particle shape, with lower values indicating more spherical particles. The color ratio (CR), defined as the ratio of the 1064 nm to 532 nm backscatter coefficients, provides information on particle size, with lower values generally indicating smaller particles. The VFM product classifies atmospheric features into aerosols, clouds, and clear air conditions. The Feature Subtype further classifies aerosol types, including clean marine, dust, polluted continental, and smoke (Kim et al., 2018).

Text S3. Meteorological conditions and regional aerosol regimes

Figure S1 shows the spatial distributions of aerosol optical depth (AOD, <https://giovanni.gsfc.nasa.gov/giovanni/>) around the three sites during the pre-monsoon seasons of 2021-2023, with wind fields from representative pollution episode overlaid. Elevated AOD extended over extensive regions south of the Himalayas, including South Asia and Southeast Asia. At Purang (western Himalayas), regions with elevated AOD were mainly located northwest of the site and along the upper reaches of the Indus River valley. Pollution episodes at Purang were associated with enhanced westerly transport. Yadong (central Himalayas) is located within a region characterized by persistently elevated AOD. Aerosol enhancements at Yadong were associated with strong southwesterly transport, which may introduce anthropogenic aerosols from the Indo-Gangetic Plain (IGP). These air masses undergo orographic uplift and subsequent accumulation due to topographic forcing. In Zayü (eastern Himalayas), high-AOD regions extend in a tongue-shaped pattern and penetrate the interior of the transverse mountains from the southeast. The wind field during representative pollution episodes shows a distinct westerly airflow extending deep into the plateau.

Text S4. Potential source contribution function method

The potential source contribution function (PSCF) is a receptor model that incorporates meteorological information to identify potential source regions through a probability field (Cheng et al., 1993). PSCF is a conditional probability function giving the probability that an air parcel with a certain level of pollutant concentration arrives

at a receptor site after passing through a specific upwind source area (Hwang and Hopke, 2007).

The PSCF approach assumes that when a back trajectory passes through a grid cell (i, j), that region may have contributed pollutants transported to the receptor site along the trajectory. The PSCF value for grid cell (i, j) is defined as:

$$PSCF = \frac{m_{ij}}{n_{ij}} \quad (S1)$$

where n_{ij} represents the total number of trajectory endpoints (or trajectory segments) located within grid cell (i,j), and m_{ij} represents the number of those trajectories associated with pollutant concentrations exceeding a predefined threshold.

Table S1. Geographic information of aerosol sampling sites across the western, central, and eastern Himalayas

Sampling sites	Latitude (°N), Longitude (°E)	Sampling period	Site Description
Purang	30.32°N, 81.17°E, 3952 m a.s.l.	March–May 2021	Located in the western part of the southern slopes of the Himalayas, near the Taklamakan Desert and the Indus River Plain
Yadong	27.52°N, 88.97°E, 3314 m a.s.l.	March–May 2022	Located in the central part of the southern slopes of the Himalayas, adjacent to Bangladesh and northeastern India
Zayü	28.50°N, 97.02°E, 1520 m a.s.l.	March–May 2023	Located in the eastern part of the southern slopes of the Himalayas, adjacent to India and Myanmar

Table S2. Contributions of 24-h forward and backward air-mass trajectory clusters at 0, 6, 12, and 18 h for Purang, Yadong, and Zayü, respectively.

Sites	Trajectories	Main trajectory directions	0 h	6 h	12 h	18 h
Purang	Forward	TP	100%	100%	100%	100%
		Valley	/	/	/	/
	Backward	TP	5.4%	/	/	1.1%
		Valley	94.6%	100%	100%	98.9%
Yadong	Forward	TP	69.6%	70.7%	70.7%	98.9%
		Valley	30.4%	29.3%	29.3%	1.1%
	Backward	TP	6.5%	10.9%	10.9%	6.5%
		North–south valley	83.7%	77.2%	61.9%	85.9%
		Transverse-oriented valley	9.8%	11.9%	27.2%	7.6%
Zayü	Forward	TP	100%	100%	100%	98.9%
		Valley	/	/	/	1.1%
	Backward	TP	/	4.4%	5.4%	5.4%
		Valley	100%	95.6%	94.6%	94.6%

Table S3. Contributions of clustered 72-h backward air-mass trajectories to $B_{\text{abs}}(\text{BC})_{370}$ and $B_{\text{abs}}(\text{BrC}_{\text{pri}})_{370}$ at Purang, Yadong, and Zayü, respectively.

Sites	Clusters	Trajectory Contributions	$B_{\text{abs}}(\text{BC})_{370}$ (Mm^{-1})	$B_{\text{abs}}(\text{BrC}_{\text{pri}})_{370}$ (Mm^{-1})
Purang	C1	47.8%	6.1	1.7
	C2	37.5%	7.6	2.2
	C3	11.9%	6.4	2.1
	C4	2.6%	4.6	1.3
Yadong	C1	65.2%	47.4	21.6
	C2	16.2%	51.7	22.9
	C3	7.3%	45.9	24.0
	C4	6.5%	43.5	20.1
	C5	4.5%	57.6	20.4
Zayü	C1	61.9%	37.6	1.8
	C2	15.4%	32.4	1.4
	C3	14.5%	26.7	1.6
	C4	8.0%	26.1	1.6

Table S4. Values of $B_{\text{abs}}(\text{BC})_{370}$, $B_{\text{abs}}(\text{BrC}_{\text{pri}})_{370}$, and $B_{\text{abs}}(\text{BrC}_{\text{sec}})_{370}$ during representative aerosol pollution episodes at Purang, Yadong, and Zayü (Mm^{-1}).

Sites	Polluted periods	$B_{\text{abs}}(\text{BC})_{370}$	$B_{\text{abs}}(\text{BrC}_{\text{pri}})_{370}$	$B_{\text{abs}}(\text{BrC}_{\text{sec}})_{370}$
Purang	16 March 2021	12.5	3.5	10.0
Yadong	12 April 2022	75.2	31.8	7.7
Zayü	8 May 2023	34.9	2.2	0.7

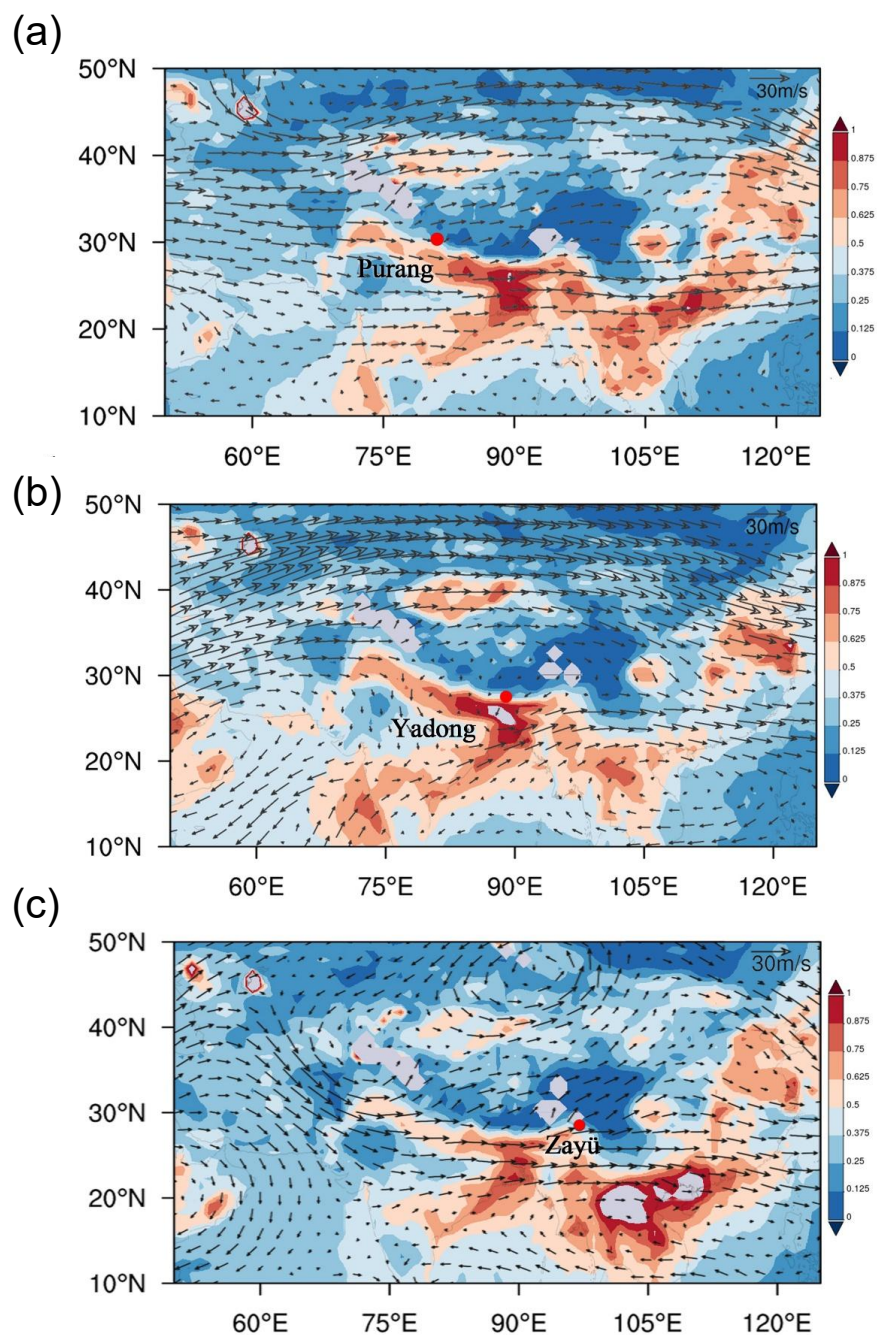


Figure S1. Spatial distributions of aerosol optical depth (AOD) and 500-hPa circulation patterns during representative aerosol pollution episodes in the pre-monsoon season: 16 March 2021 (Purang), 12 April 2022 (Yadong), and 8 May 2023 (Zayü).

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