



Measurement report: Mesoscale heterogeneity in the intensive optical properties of long-range-transported Shinmoedake-related volcanic aerosol observed with dual-site polarization Raman–Mie lidars

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Abstract. Long-range transport can substantially modify volcanic particles; however, it remains unclear whether volcanic
25 aerosol in a common eruptive source context retains a consistent optical identity across neighboring remote receptors. We
investigated elevated aerosol particles observed over Anqing and Shouxian in eastern China during the July 2025 Shinmoedake
activity using eruption records, continuous 10-min Himawari-9 Ash RGB imagery, Sentinel-5P/TROPOspheric Monitoring
Instrument SO₂ observations, Hybrid Single-Particle Lagrangian Integrated Trajectory backward trajectories, and observations
from same-design multi-wavelength polarization Raman–Mie lidars. Independent source and transport evidence places both
30 receptor layers within a common Shinmoedake-related regional source–transport context after approximately 3–4 d; however,
neither layer can be assigned uniquely to a specific eruption pulse. Under strictly matched sampling (26 paired 10-min profiles
within the height range of 2.036–2.966 km), median 355-nm backscatter was similar at Anqing and Shouxian (i.e., 3.33 and
3.19 Mm⁻¹ sr⁻¹, respectively), whereas marked differences occurred in polarization and spectral behavior. Median particle
depolarization ratios at 355 nm were 0.019 at Anqing and 0.101 at Shouxian, whereas those at 532 nm were 0.052 and 0.076,
35 respectively. The median backscatter Ångström exponent was +2.10 at Anqing and -0.35 at Shouxian, with the depolarization
wavelength ratio $\delta_{532}/\delta_{355}$ being >1 in every matched Anqing profile and <1 in every matched Shouxian profile. The contrast



is inconsistent with a simple wavelength-independent difference in aerosol optical signal, and receptor-scale meteorological and regional aerosol constraints do not support simple explanations based on greater humidity, boundary layer mixing, or enhanced sulfate at Anqing. Instead, the observations are consistent with transport history-dependent differences in particle optical state among Shinmoedake-related volcanic aerosol sampled at the two receptors. Size-selective removal and differential aging or mixing are plausible contributors; however, the available observations do not uniquely constrain their relative roles. Overall, aged volcanic aerosol associated with a common regional transport event can exhibit substantial mesoscale optical heterogeneity. Therefore, joint interpretation of multi-wavelength lidar observables with independent source–transport constraints is important for far-field volcanic aerosol characterization.

1 Introduction

Explosive volcanic eruptions inject ash particles and gases such as sulfur dioxide (SO_2) into the troposphere, producing aerosol populations that can affect aviation, atmospheric radiation, cloud processes, and surface air quality far beyond the source region (Kristiansen et al., 2024; Schoeberl et al., 2024; Zhuo et al., 2024; Dodangodage et al., 2025; Stenchikov et al., 2025). Coarse ash is removed efficiently through sedimentation and deposition, whereas fine ash and secondary particles formed from volcanic gases can remain airborne for days and be transported over continental distances (Kahn et al., 2024; Hedelt et al., 2025; Lemus et al., 2025). Therefore, far-field remote sensing must characterize not only whether volcanic material reaches a receptor but also the optical state of the particle population that survives transport. This is important for hazard assessment, model evaluation, and optical-to-mass interpretation, all of which depend on assumptions about particle size, shape, density, composition, and mixing state (Ansmann et al., 2011, 2012).

The downstream optical state reflects both the emitted particle population and processing experienced along the transport path. Gravitational settling and size-selective removal preferentially deplete larger nonspherical ash particles; aggregation modifies the effective particle size and settling velocity; oxidation of co-emitted SO_2 and subsequent condensation can increase secondary fine-particle contributions; and coagulation, dilution, entrainment, and mixing with regional background aerosol can alter the particle size distribution, morphology, refractive properties, and mixing state (Brown et al., 2012; Muser et al., 2020; Bruckert et al., 2023; Li et al., 2024; Pardini et al., 2024). Receptor conditions can further modulate the measured optical response: relative humidity can modify scattering through water uptake, while boundary layer entrainment can introduce locally or regionally sourced aerosol. Consequently, optical differences among downwind sites can arise from source–time or source–height variability, nonidentical transport pathways, differential aging and removal, and contemporaneous receptor meteorology rather than from transport duration alone.

Multi-wavelength polarization Raman–Mie lidar is advantageous for examining these differences, as extinction and backscatter constrain the aerosol optical magnitude and spectral response; the linear particle depolarization ratio (PDR) responds to nonsphericity; and the lidar ratio (LR) and Ångström exponents provide complementary information on the optically dominant particle population (Floutsi et al., 2024; Gebauer et al., 2024; Haarig et al., 2025; Filioglou et al., 2026). Published volcanic



aerosol observations span a broad optical parameter space: ash-rich Eyjafjallajökull layers exhibited PDR values of approximately 0.35–0.38 at 355 and 532 nm; aged Eyjafjallajökull aerosol showed substantially lower depolarization after several days of transport; and long-lived Raikoke aerosol over central China included a weakly depolarizing component with PDR at 532 nm below 0.05 (Groß et al., 2012; Papayannis et al., 2012; Jing et al., 2023). The same fine-to-coarse partition also affects spectral behavior: a relatively stronger short-wavelength contribution from weakly depolarizing fine particles can produce $\delta_{355} < \delta_{532}$ together with a positive backscatter Ångström exponent, whereas a larger coarse or nonspherical contribution can weaken or reverse the backscatter spectral slope, while increasing short-wavelength depolarization (Groß et al., 2012).

A persistent issue is spatial representativeness. Most far-field lidar studies characterize transported volcanic aerosol at a single receptor, while multi-station observations often combine different instrument designs, calibration states, retrieval configurations, observation times, and sampled altitudes (Bellini et al., 2024; Hedelt et al., 2025; Kampouri et al., 2025). Such observations are essential for documenting dispersion; however, they do not offer sufficient information on how much station-to-station variability is atmospheric and how much is methodological (Pappalardo et al., 2013). If intensive and wavelength-dependent particle properties vary over mesoscale distances—even when a loading-sensitive observable, such as backscatter, is similar—a single lidar profile might not represent a broader transport feature or model grid cell. Consequently, the transfer of aerosol typing or optical-to-mass relationships from one location to another might carry an additional spatial representativeness uncertainty.

Testing this spatial variability requires a configuration that minimizes methodological and sampling differences. The receptor observations should be matched in time and altitude; the lidar systems and retrieval chain should be as comparable as possible; and source association should be established independently of the optical variables used to characterize the aerosol. The latter avoids circular reasoning, in which an expected depolarization signature is first used to define a layer as volcanic and then reused to infer the optical properties of volcanic aerosol. More generally, multisource satellite observations have been used to identify and characterize atmospheric emission sources by integrating complementary trace-gas and contextual information (Zhang et al., 2025). Consequently, eruption records, source region satellite observations, co-emitted gas information, and receptor-oriented trajectories provide the source–transport context, while the lidar measurements are used to quantify particle optical state.

In this context, the June–July 2025 Shinmoedake activity constitutes a natural experiment. Same-design multi-wavelength polarization Raman–Mie lidars at Anqing and Shouxian in eastern China, separated by approximately 202 km and located approximately 1,330 km from the volcano, sampled elevated aerosol during overlapping periods. We combined the documented July 3–4 eruptive activity, continuous Himawari-9 Ash RGB observations, Sentinel-5P/TROPOspheric Monitoring Instrument (TROPOMI) SO₂ observations, Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) trajectories, and strictly matched dual-lidar measurements. The primary objective was to determine whether source-related aerosol sampled synchronously at the two receptors exhibits a spatially consistent or contrasting intensive and spectral optical state when instrument design, time, and altitude are controlled. Subsequently, we evaluated whether the observed contrast can



be explained by a simple difference in aerosol amount or contemporaneous receptor conditions or whether nonidentical source and transport histories must also be considered. For this comparison, source attribution was treated as a prerequisite rather than
105 a separate scientific endpoint. In the following, all times reported are in Universal Time (UTC) unless otherwise stated.

2 Data and methods

2.1 Shinmoedake source records and satellite observations

Shinmoedake (31.9094° N, 130.8864° E) in the Kirishima volcanic complex of southern Kyushu was eruptively active during June–July 2025. We compiled the source chronology from Japan Meteorological Agency (JMA) volcanic information, Tokyo
110 Volcanic Ash Advisory Center (Tokyo VAAC) advisories, and Geological Survey of Japan/AIST (GSJ/AIST) reports (JMA, 2025; Tokyo VAAC, 2025; GSJ/AIST, 2025). The chronology defines the four documented E1–E4 eruption pulses during July 3–4 and provides the source–time framework used to interpret the satellite observations and backward trajectories. Reported aviation cloud top flight levels were converted to kilometers using 1 flight level = 0.03048 km for graphical comparison.

115 Near-source volcanic cloud structure was examined based on Himawari-9 Advanced Himawari Imager (AHI) infrared observations. AHI provides 10-min full-disk imagery, with nominal sampling of approximately 2 km for the infrared channels used here (Bessho et al., 2016). The JMA-style Ash RGB composite was constructed from B11 (8.6 μm), B13 (10.4 μm), and B15 (12.4 μm): red = BT12.4 - BT10.4; green = BT10.4 - BT8.6; and blue = BT10.4 (JMA/MSJ, 2020). During the procedure, identical display stretches for all scenes were used. Under this Ash RGB convention, volcanic ash is typically displayed in
120 reddish, pinkish, or magenta tones, volcanic SO₂ in green to yellow-green tones, and overlap of ash and SO₂ in yellow. The hues remain qualitative and can also be influenced by cloud and thermal conditions. The continuous 10-min sequence from July 3 to 5 was used to assess temporal coherence of the source region volcanic cloud. Four representative frames are shown in Fig. 1.

Regional volcanic gas evolution was characterized through Sentinel-5P/TROPOMI SO₂ vertical column density (VCD) and
125 effective plume height retrievals (Liu et al., 2006, 2007; Nowlan et al., 2011; Xia et al., 2021, 2024). SO₂ VCD and effective plume height were retrieved simultaneously from ultraviolet measurements using an optimal estimation method (OEM). The state vector included SO₂ abundance, effective plume altitude, and ozone profile parameters, and the retrieved daily fields were used to follow the regional gas plume from southern Kyushu toward eastern China (Fig. 2).

The volcanic SO₂ vertical distribution was represented by a Gaussian profile centered at the retrieved effective plume height
130 with a prescribed full width at half maximum of 0.5 km (Efremenko et al., 2017) and an initial plume height of 1 km. Radiative transfer calculations used the Vector Linearized Discrete Ordinate Radiative Transfer—or VLIDORT—model at 0.02 nm spectral resolution (Spurr, 2006). Retrievals used TROPOMI Band 3 measurements within the range of 310.5–326.0 nm; observations with solar zenith angles $\geq 70^\circ$ were excluded; and the near-nadir spatial resolution was approximately 5.5×3.5 km².



135 The July 3–8 TROPOMI VCD and effective height fields were used to describe the regional evolution and broad vertical regime of co-emitted SO₂. The effective height represents the center altitude of the assumed Gaussian SO₂ profile. Gas and particles can evolve differently during multi-day transport; hence, the TROPOMI fields were used as one source–transport constraint together with the eruption record, Himawari observations, and HYSPLIT trajectories. The limitations of this interpretation are presented in the Discussion.

140 2.2 Ground-based multi-wavelength polarization Raman–Mie lidar observations and retrieval products

The receptor sites are Anqing (30.6231° N, 116.9672° E) and Shouxian (32.4347° N, 116.7955° E), separated by approximately 202 km in Anhui Province, eastern China. Both stations operate the same design of multi-wavelength polarization Raman–Mie lidar with the same acquisition configuration and processing/retrieval algorithms. The systems operate continuously in a vertically pointing mode from environmentally controlled cabins. This common configuration reduces methodological
145 heterogeneity between the two sites; however, it does not establish exact instrumental equivalence. Each lidar uses an Nd:YAG laser emitting simultaneously at 355, 532, and 1,064 nm with single-pulse energies of 40, 125, and 250 mJ, respectively, at 20 Hz and beam divergence <0.75 mrad. Backscatter is collected by a 254-mm Cassegrain telescope with a 0.3-mrad receiver field of view and separated into eight channels: parallel- and perpendicular-polarized elastic channels at 355 and 532 nm, one elastic channel at 1,064 nm, nitrogen Raman channels at 386 and 607 nm, and a water-vapor Raman channel at 407 nm. Native
150 profiles have 1 min temporal resolution (40 s acquisition and 20 s idle time) and 7.5 m range resolution.

Ten consecutive 1-min profiles and four adjacent range bins were averaged before retrieval, giving an effective resolution of 10 min × 30 m. Background signals were removed, and the returns were range-corrected before inversion. This averaging improves the Raman signal-to-noise ratio but does not remove systematic uncertainties associated with calibration, overlap correction, channel cross-talk, or wavelength-dependent response (Ansmann et al., 1992; Baars et al., 2016; Engelmann et al.,
155 2016). Aerosol extinction coefficients at 355 and 532 nm (α_{355} and α_{532}) were retrieved from the corresponding nitrogen Raman signals near 386 and 607 nm using the standard Raman lidar approach. Aerosol backscatter coefficients (β_{355} and β_{532}) were obtained from the elastic and Raman returns with molecular and aerosol transmission corrections relative to a low-aerosol reference region (Ansmann et al., 1992; Baars et al., 2016). Calibrated polarization signals were first converted to volume linear depolarization ratio and then to PDR (δ_{355} and δ_{532}) using particle and molecular backscatter and molecular depolarization
160 (Freudenthaler et al., 2009; Freudenthaler, 2016). LR was calculated as $LR_{\lambda} = \alpha_{\lambda}/\beta_{\lambda}$. Backscatter and extinction Ångström exponents were calculated as $AE_{\beta} = \ln(\beta_{355}/\beta_{532})/\ln(532/355)$ and $AE_{\alpha} = \ln(\alpha_{355}/\alpha_{532})/\ln(532/355)$, respectively. Wavelength dependence of PDR and LR were calculated as $R_{\delta} = \delta_{532}/\delta_{355}$ and LR_{532}/LR_{355} , respectively. Positive Ångström exponents indicate larger coefficients at 355 nm compared with those at 532 nm.

Calibration and quality assurance followed the China Meteorological Administration (CMA) three-wavelength aerosol–lidar
165 framework and technical specification supplied with the lidar data. Procedures included effective range verification, receiver uniformity and linearity tests, Rayleigh signal fitting, polarization channel gain calibration, inter-channel cross-talk tests, and overlap factor calibration against a reference lidar. CMA acceptance criteria include system linearity ≥95%, Rayleigh fit



relative deviation $\leq 15\%$, inter-wavelength and parallel-to-perpendicular polarization cross-talk $\leq 1\%$, elastic-to-Raman contamination $\leq 0.01\%$, and overlap factor relative difference $\leq 50\%$ within the range of 0.2–0.5 km. Both systems underwent
170 routine calibration in June 2025, approximately one month before the observations, and passed the CMA requirements. Their common optical design, channel configuration, acquisition settings, and retrieval chain result in smaller methodological differences relative to those from a comparison of dissimilar lidars. Nevertheless, no event-specific side-by-side intercomparison was available; hence, the analysis did not assume perfect instrumental equivalence, and the inter-site interpretation was based on coordinated behavior across multiple wavelength and polarization diagnostics rather than on a
175 single parameter.

Retrieval uncertainty was evaluated separately from calibration acceptance. In the processing framework, signal and background uncertainties are propagated through repeated noise perturbations, and the ensemble spread provides a retrieval-uncertainty estimate. Backscatter propagation also includes uncertainty in elastic and Raman signals, Raman-derived extinction, spectral dependence, and reference-region aerosol contribution. For the 2–5-km range relevant here, CMA
180 validation requirements provide conservative performance limits of approximately 30% for Raman backscatter and 40% for Raman extinction, with representative relative PDR uncertainties of approximately 25% at 355 nm and 10% at 532 nm. AE_β , AE_α , and R_δ inherit uncertainty from their component retrieval.

2.3 Elevated aerosol layer segmentation and matched sampling

Elevated aerosol structures were delineated with time–height masks based on δ_{532} . Before segmentation, δ_{532} was smoothed
185 with a 3×3 median filter in time and height, after which a two-threshold core/edge procedure identified coherent structures. Core and edge thresholds at Anqing were 0.055 and 0.040, respectively, whereas those at Shouxian were 0.060 and 0.050, respectively. Candidate pixels were connected by binary closing and 8-neighbor connected-component analysis. The Anqing mask used a one-bin closing radius in time and height and retained components with at least 20 connected pixels and 3 core pixels; the Shouxian mask used a one-bin closing radius in time, no closing in height, and retained components with at least
190 40 connected pixels and 3 core pixels. Holes were filled. These settings serve only to segment coherent structures and are not aerosol type or source attribution thresholds. The resulting masks span July 7, 11:55–20:15 UTC and approximately 1.44–3.39 km at Anqing and 16:05–21:15 UTC and approximately 2.04–2.97 km at Shouxian.

For the inter-site comparison, sampling was synchronously matched in time and restricted to a common altitude domain to minimize differences in observation period and layer depth. The segmentation-assisted sample covered July 7, 2025, 16:05–
195 20:15 UTC and 2.036–2.966 km, yielding 26 paired 10-min profiles. At each site and time, a layer median was calculated from finite retrievals within the station-specific event mask and common height interval; subsequently, site medians were calculated across the 26 profiles. For strictly positive parameters (δ_{355} , δ_{532} , β_{355} , β_{532} , LR_{355} , and LR_{532}), profile-wise Shouxian/Anqing ratios were also summarized by their median. Consecutive profiles are temporally correlated; hence, the sequence was used to describe the magnitude and persistence of the contrast rather than as 26 independent statistical realizations.



200 Because δ_{532} was used to construct the primary event masks, and given that it also contributes to the subsequent optical state analysis, an additional depolarization-independent sensitivity test was performed, in which the alternative aerosol layer mask was derived only from β_{355} . The same 26 paired 10-min sampling times and the same matched altitude domain were retained. Owing to the small offset between the native height grids, the range bins within this domain spanned 2.040–2.940 km at Anqing and 2.036–2.966 km at Shouxian. For each 10-min profile, a first-order linear trend was fitted to $\ln(\beta_{355})$ as a function of height within the matched domain, and the residual field was used to identify local backscatter enhancements relative to the broad vertical background. The residuals were robustly standardized using the median and median absolute deviation within the matched time–height domain at each site and then smoothed with a 3×3 median filter. Pixels with standardized residual $z \geq 0$ were treated as edge candidates and those with $z \geq 1$ as core pixels. Subsequently, a 3×3 binary closing and 8-neighbor connected-component analysis were applied; components containing at least 20 pixels and at least 3 core pixels were retained, and internal holes were filled. The same standardized thresholds and morphological settings were used at both sites. No δ_{355} , δ_{532} , or depolarization ratio entered this alternative layer definition, and the thresholds were fixed in standardized backscatter anomaly space rather than tuned to reproduce the primary mask. This backscatter-defined analysis was used only as a sensitivity test of the depolarization-based segmentation; the original δ_{532} event masks were retained for the primary matched comparison and for characterizing the complete temporal–vertical evolution of the elevated aerosol structures.

215 2.4 HYSPLIT source–receptor analysis

Receptor-oriented transport was analyzed with 96-h HYSPLIT backward trajectories (Cohen et al., 2015; Rolph et al., 2017) using the GFSQ meteorological archive and OMEGA vertical motion. Trajectories were initialized at 2.2, 2.6, and 3.0 km over each receptor at multiple times within the lidar-observed elevated-aerosol periods. Hourly release times were used to sample the multi-hour evolution of the observed layer and avoid basing the source proximity assessment on a single arbitrarily selected profile. Figure 3 shows the 2.6- and 3.0-km subsets, which most closely represent the elevated receptor layer; hence, for each listed release time, two trajectories are plotted—one from each starting altitude. The 96-h integration length was chosen to extend the July 7 receptor observations back through the documented July 3–4 eruptive period, with additional temporal margin, and it is not interpreted as the transport time.

For every trajectory, the great-circle distance to Shinmoedake was calculated at each backward time step. We retained the minimum source distance, time and altitude of closest approach, and elapsed time between that closest-approach time and receptor release time. This elapsed interval is the trajectory-based source-proximity-to-receptor transport time used below; the reported medians of 84 h for Anqing and 89 h for Shouxian were calculated from this quantity for the selected trajectories entering the 300-km visualization envelope—not from the fixed 96 h integration duration. The 300-km envelope was used only to display trajectories that enter the broader southern Japan source region. HYSPLIT was interpreted as an air-parcel transport diagnostic and combined with eruption timing, Himawari source region imagery, and TROPOMI SO_2 evolution.



2.5 ERA5 meteorological and CAMS aerosol context constraints

Meteorological context was characterized using the fifth-generation ECMWF atmospheric reanalysis (ERA5). ERA5 pressure- and single-level reanalysis fields were used to characterize contemporaneous meteorological conditions at the receptor sites (Hersbach et al., 2020). Pressure-level variables were geopotential Φ , relative humidity, temperature, zonal and meridional wind, and pressure vertical velocity ω . Boundary layer height was taken from the single-level product. Geopotential was converted to geopotential height as $H = \Phi/g_0$. At each hour, pressure-level fields were averaged within $\pm 0.25^\circ$ of each site, interpolated with height, and averaged over 2–3 km. Horizontal wind speed was calculated from u and v . Negative ω denotes ascent in pressure coordinates. These fields were used to test for obvious contemporaneous receptor-scale differences.

The aerosol background and regional aerosol distribution were assessed using the Copernicus Atmosphere Monitoring Service (CAMS) global atmospheric composition reanalysis (EAC4). CAMS reanalysis was used as coarse context for the regional aerosol and trace gas environment (Inness et al., 2019). The available file covers July 3, 00:00 to July 7, 21:00 UTC at three-hourly resolution on a 0.75° grid and includes SO_2 , sulfate aerosol, mineral dust, organic matter, black carbon, and sea salt on 60 hybrid model levels. Because the auxiliary meteorological variables needed to convert the hybrid coordinate to geometric height were unavailable, we used the maximum mass mixing ratio across all levels at the nearest grid point to each station. These column maxima are neither vertically integrated burdens nor concentrations matched to the 2–3-km lidar layer; therefore, CAMS was used only to identify broad contemporaneous receptor-scale contrasts—not to infer layer composition or microphysical processing.

3 Results

3.1 Source activity, satellite evolution, and source-to-receptor transport

Shinmoedake underwent repeated eruptive activity during July 3–4, 2025 (Fig. 1a). E1 began at 04:49 UTC on July 3 with a reported volcanic cloud top of approximately 6.71 km; E2 occurred at approximately 13:40 UTC on July 3 with a reported top of approximately 3.35 km; E3 at 23:10 UTC with approximately 3.05 km; and E4 at 07:40 UTC on July 4 with approximately 5.18 km (JMA, 2025; Tokyo VAAC, 2025). On July 7, the Anqing lidar detected elevated aerosol from 11:55 to 20:15 UTC over a range of approximately 1.44–3.39 km, whereas the Shouxian lidar detected an elevated aerosol layer from 16:05 to 21:15 UTC over a range of approximately 2.04–2.97 km. The records overlap from 16:05 to 20:15 UTC (Fig. 1a).

The continuous Himawari-9/AHI record shows a temporally coherent ash-sensitive feature near Shinmoedake on July 3 (Fig. 1b–e). In the representative frames at 07:30, 08:00, 08:30, and 09:30 UTC after E1, a pink-to-violet/lavender feature remains identifiable west of the volcano while its elongated structure evolves downstream. Its persistence across successive 10-min images supports ash-sensitive source region activity during the documented eruptive period rather than an interpretation based on an isolated frame (JMA/MS, 2020). The Himawari sequence does not by itself connect those source region particles to



eastern China or identify which E1–E4 injection contributed to either receptor layer. Hence, it was used together with TROPOMI and HYSPLIT to establish the broader source–transport context.

TROPOMI further constrain the regional evolution of co-emitted SO₂ from July 3 to 8 (Fig. 2). The VCD and effective height fields are interpreted as volcanic gas transport and broad vertical regime information rather than a particulate ash map or precise reconstruction of the aerosol layer. On July 3, enhanced SO₂ was concentrated around southern Kyushu and adjacent waters, with effective heights mainly in the lower-to-middle troposphere and local values near 2–4 km. The enhancement broadened into the East China Sea–Ryukyu sector on July 4 and formed an elongated feature east and southeast of southern Japan on July 5. By July 6, a western branch extended toward approximately 118–120° E; on July 7, it reached eastern China and the vicinity of Anqing and Shouxian. Effective heights in substantial parts of this western branch were approximately 1–3 km, broadly consistent with lower tropospheric transport and the receptor layer/trajectory initialization regime. By July 8, the field became more fragmented.

The HYSPLIT trajectories provide the receptor-oriented dynamical constraint, with Fig. 3 showing 96-h trajectories initialized at 2.6 and 3.0 km that enter the 300-km visualization envelope around Shinmoedake. Thirteen Anqing and ten Shouxian trajectories in this displayed subset entered the envelope. Their closest approaches occurred from July 3, 22:00 to July 4, 19:00 UTC for Anqing and from July 3, 18:00 to July 5, 12:00 UTC for Shouxian. Median source-proximity-to-receptor elapsed times were 84 and 89 h; median minimum source distances were approximately 88 and 130 km; and median trajectory altitudes at closest approach were approximately 3.34 and 3.78 km for Anqing and Shouxian, respectively. The combined source proximity window therefore spanned late July 3 to 5, consistent with approximately 3–4 d lower-to-middle tropospheric air parcel transport from southern Japan to Anhui. The two trajectory bundles differ in timing, geometry, and vertical history, and the overlapping lidar observations do not indicate that one unchanged air parcel passed sequentially over both sites. Instead, the eruption chronology, Himawari imagery, TROPOMI SO₂ evolution, and receptor-oriented trajectories provide complementary constraints on source activity and regional transport.

Overall, these constraints support an event-scale interpretation in which both elevated layers are associated with the same broad Shinmoedake-related regional source–transport episode. They do not uniquely identify contributions from individual E1–E4 injections or establish continuous particulate tracking from the volcano to either receptor. Therefore, the lidar comparison concerns two source-related aerosol populations sampled under different air parcel histories.

3.2 Temporal–vertical evolution and optical properties of Shinmoedake-related transported aerosol over Anqing and Shouxian

The two lidar records resolve different temporal–vertical structures and optical patterns within the elevated aerosol (Figs. 4 and 5). At Anqing, the segmented structure extended from 11:55 to 20:15 UTC over approximately 1.44–3.39 km. The strongest signal occurred mainly in a lower branch near 1.5–2.1 km during approximately 12:30–14:30 UTC; after approximately 16:45 UTC, a more persistent branch appeared near 2.3–2.9 km. Backscatter and extinction at 355 nm are generally stronger than those at 532 nm in both branches, producing predominantly positive Ångström exponents; the full-



event masked median AE_β is +2.45 (Fig. 6). Anqing also shows very weak 355-nm depolarization over most of the segmented
295 layer. The full-event masked medians are $\delta_{355} = 0.019$ and $\delta_{532} = 0.053$, with $R_\delta = \delta_{532}/\delta_{355}$ generally >1 (Fig. 4). Together with
the positive spectral exponents, these measurements define a weakly depolarizing, strongly wavelength-dependent lidar optical
pattern.

At Shouxian, the segmented structure extended from 16:05 to 21:15 UTC over approximately 2.04–2.97 km (Fig. 5). It formed
a more coherent band centered near 2.4–2.8 km during the early and middle part of the event, descended to approximately 2.0–
300 2.6 km around 19:30–20:30 UTC, and rose slightly toward the end. Its spectral ordering differs from that at Anqing: β_{532} is
often comparable to or larger than β_{355} , with a similar tendency in extinction. The full-event masked median AE_β is -0.38 (Fig.
6). The Shouxian layer has larger 355-nm depolarization than that at Anqing in the masked sample, with full-event medians
 $\delta_{355} = 0.103$ and $\delta_{532} = 0.069$. $R_\delta < 1$ through most of the segmented layer. LR at both wavelengths is moderate and variable,
without a wavelength contrast as systematic as that in PDR and spectral exponents.

305 Therefore, the full time–height fields show contrasting lidar optical patterns: Anqing has stronger short-wavelength backscatter
and extinction, positive spectral exponents, very weak δ_{355} , and $R_\delta > 1$, whereas Shouxian shows weaker or reversed backscatter
spectral dependence, larger δ_{355} , and predominantly $R_\delta < 1$. These coordinated differences are not equivalent to a wavelength-
independent scaling of aerosol signal. Because the full-event masks span different time–height domains and use δ_{532} in the
segmentation, the quantitative inter-site comparison below focuses on synchronously matched samples and the corresponding
310 mask-free sensitivity analysis.

3.3 Contrasting optical properties under synchronously matched dual-lidar observations

The segmentation-assisted comparison is based on 26 paired 10-min profiles from 16:05 to 20:15 UTC on July 7, 2025, within
the common 2.036–2.966 km altitude range (Sect. 2.3; Fig. 7; Table 1). The largest masked difference occurs in δ_{355} : site
medians are 0.019 at Anqing and 0.101 at Shouxian, with a median profile-wise Shouxian/Anqing ratio of 5.17. Median δ_{532}
315 is 0.052 and 0.076 at Anqing and Shouxian, respectively, with a profile-wise ratio of 1.51. Therefore, the masked depolarization
contrast depends strongly on wavelength. Backscatter shows why a single wavelength does not capture the inter-site difference.
Median β_{355} values at Anqing and Shouxian are similar (3.33 and 3.19 $\text{Mm}^{-1} \text{sr}^{-1}$, respectively; profile-wise ratio of 0.97),
whereas median β_{532} values are not (1.51 and 3.58 $\text{Mm}^{-1} \text{sr}^{-1}$, respectively; profile-wise ratio of 2.91). Median LR_{355} is 48.8
and 58.7 sr, and LR_{532} is 52.0 and 67.7 sr at Anqing and Shouxian, respectively. The spectral diagnostics also separate the sites:
320 median AE_β is +2.10 at Anqing and -0.35 at Shouxian; median AE_α is +1.85 and -0.72; and median R_δ is +2.63 and +0.73.
Therefore, the principal difference is wavelength dependent and normalized rather than a simple change in 355-nm backscatter
magnitude.

The wavelength ordering persists through most or all of the matched sequence (Fig. 8). In the masked sample, all 26 Anqing
profiles have $\delta_{532} > \delta_{355}$ and $\beta_{355} > \beta_{532}$. All 26 Shouxian profiles have $\delta_{532} < \delta_{355}$, while 22 of 26 have $\beta_{532} > \beta_{355}$, with the
325 remaining four being close to the 1:1 line. In the AE_β – R_δ space, all Anqing point estimates have $AE_\beta > 0$ and $R_\delta > 1$, whereas
23 of 26 Shouxian profiles have $AE_\beta < 0$, while all have $R_\delta < 1$. The profiles are temporally correlated, and the derived



quantities inherit retrieval uncertainty; hence, these counts describe persistence of the measured ordering rather than independent hypothesis tests.

The depolarization-independent backscatter-defined sensitivity analysis further shows that the principal inter-site contrast does not depend on using δ_{532} to define the sampled aerosol structure (Fig. S1; Table S1). With the alternative detrended- β_{355} anomaly mask, median δ_{355} is 0.019 at Anqing and 0.094 at Shouxian, compared with 0.019 and 0.101 in the primary comparison, respectively. The respective median δ_{532} values are 0.046 and 0.072. Median β_{355} is 3.71 and $3.10 \text{ Mm}^{-1} \text{ sr}^{-1}$ at Anqing and Shouxian, respectively; conversely, median β_{532} remains strongly contrasted at 1.59 and $3.57 \text{ Mm}^{-1} \text{ sr}^{-1}$, respectively. The opposing spectral behavior is also retained: median AE_β is $+2.14$ at Anqing and -0.45 at Shouxian, while median R_δ is $+2.41$ and $+0.79$, respectively. All 26 Anqing profiles remain in the $\text{AE}_\beta > 0$ and $R_\delta > 1$ regime; all 26 Shouxian profiles have $R_\delta < 1$, and 23 of 26 have $\text{AE}_\beta < 0$. Thus, replacing the δ_{532} -based event masks with an independent backscatter anomaly layer definition changes the magnitude of some quantities but preserves the principal opposing spectral–polarimetric behavior.

For concise reference, we refer to these combinations as the Anqing and Shouxian optical states, i.e., observational lidar states rather than unique microphysical classes. Anqing combines β_{355} comparable with that of Shouxian with a much weaker δ_{355} , lower β_{532} , positive spectral exponents, and $R_\delta > 1$; Shouxian combines stronger δ_{355} , higher β_{532} and LR, weak-to-negative spectral exponents, and predominantly $R_\delta < 1$. Therefore, the matched comparison provides descriptive evidence for mesoscale variability in particle optical state after substantially reducing differences associated with temporal and vertical sampling. Possible contributions from source–time variability, transport path-dependent removal, aging, and mixing are evaluated in the Discussion.

4 Discussion

4.1 Common source–transport context and mesoscale optical contrast

The event context is established based on independent source and transport evidence before interpreting the lidar observables, as PDR is not unique to volcanic emissions (Tesche et al., 2009; Pisani et al., 2012; Wang et al., 2020, 2023; Spinosa et al., 2025). The eruption chronology documents four Shinmoedake pulses during July 3–4; Himawari identifies temporally coherent ash-sensitive source region activity; TROPOMI follows the regional evolution of co-emitted SO_2 ; and HYSPLIT links the lidar-defined receptor periods to air parcels that pass through the broader southern Japan source region. Together, these constraints support a common event-scale Shinmoedake-related source–transport context, with the relative contributions of E1–E4 being indistinguishable at the receptors. Nevertheless, the Anqing and Shouxian trajectory ensembles differ in source proximity timing, minimum distance, altitude, and three-dimensional pathway. Therefore, the two lidar records are best interpreted as source-related aerosol populations sampled within a common event context albeit after nonidentical source and transport histories.



This distinction is important, as the matched lidar observations show that a common event context does not imply a uniform optical state. The two sites sample the same 4-h interval and common altitude domain; nevertheless, their wavelength-dependent and normalized observables separate strongly. Therefore, the contrast is not an artefact of comparing different observation times, instrument designs, or layer depths, which are common confounding factors in multi-site volcanic aerosol comparisons.

Median β_{355} values at Anqing and Shouxian are nearly identical (3.33 and 3.19 $\text{Mm}^{-1} \text{sr}^{-1}$, respectively). Conversely, median δ_{355} changes from 0.019 to 0.101, median AE_{β} from +2.10 to -0.35, and median R_{δ} from +2.63 to +0.73. The depolarization-independent backscatter mask sensitivity test changes the magnitude of some layer statistics; however, it preserves the opposite wavelength ordering and separation in the AE_{β} - R_{δ} space. Therefore, the robust inference is a marked difference in lidar-observed particle optical state rather than a wavelength-independent change in backscatter magnitude.

The coordinated behavior of AE_{β} and R_{δ} provides qualitative constraints on the relative optical contributions of different particle populations. A weakly depolarizing fine-particle component contributing proportionally more strongly at shorter wavelengths can reduce δ_{355} relative to δ_{532} and favor positive AE_{β} and $R_{\delta} > 1$. Conversely, a larger relative contribution from coarse or nonspherical particles can increase δ_{355} , weaken or reverse the backscatter spectral dependence, and produce $R_{\delta} < 1$. The Anqing–Shouxian contrast is consistent with these different optical mixtures; however, the lidar data do not uniquely retrieve particle size distribution, mineralogy, chemical composition, morphology, or mixing state, and regional background aerosol may contribute to either mixture (Floutsi et al., 2024; Gebauer et al., 2024; Haarig et al., 2025; Nishizawa et al., 2026).

Both receptor states fall within the broad range reported for transported volcanic aerosol; however, direct comparison among studies is limited by wavelength, retrieval configuration, transport age, and aerosol mixture (Table 2). Shouxian $\delta_{355} = 0.101$ lies near the lower end of the range of approximately 0.10–0.25 reported for aged Eyjafjallajökull aerosol, whereas Anqing $\delta_{355} = 0.019$ is comparable to the weakly depolarizing end of long-lived Raikoke observations and far below the approximately 0.35–0.38 values of ash-rich Eyjafjallajökull layers (Groß et al., 2012; Papayannis et al., 2012; Jing et al., 2023). Event-specific 2025 Shinmoedake conference reports have focused on near-source ash mineral/glass composition (Miyagi et al., 2025) and satellite/model analysis of SO_2 evolution (Takagi and Shimbori, 2025). These studies provide complementary source information; however, they do not provide synchronous far-field dual-site particle optical profiles. Therefore, the present same-design, time–height-matched lidar comparison adds a spatial dimension by documenting substantial optical state variability over 202 km within one regional transport episode.

4.2 Plausible controls on the inter-site optical contrast

A simple wavelength-independent difference in aerosol amount cannot explain the observations. This is because β_{355} is nearly identical at the two sites, whereas δ_{355} , β_{532} , and the spectral ordering differ. Large methodological differences are also less likely, as the two lidars share the same optical design and retrieval chain, and both passed the same CMA calibration requirements shortly before the event; nevertheless, residual wavelength- or polarization-dependent offsets cannot be excluded. ERA5 does not support an obvious contemporaneous meteorological explanation at the receptors: relative humidity in the 2–



3-km layer is not systematically higher over Anqing during the matched interval, and boundary layer heights remain only a few hundred meters at both sites—well below the lidar layer (Fig. 9). Likewise, CAMS does not show an anomalously large contemporaneous sulfate maximum at Anqing; during July 7, 12:00–21:00 UTC, the Shouxian/Anqing mean column-maximum ratios were approximately 1.24 for SO₂ and 1.19 for sulfate. These receptor-scale fields make a purely local humidity, boundary layer, or sulfate explanation less evident; however, they do not constrain processing earlier along the transport pathways.

The different trajectory geometries provide a physically plausible framework for earlier processing without identifying a unique cause. Air parcels reaching Anqing and Shouxian approach southern Japan at partly different times, distances, and altitudes and follow nonidentical three-dimensional paths. Combined with the four eruption pulses with different reported cloud top heights, the two receptors could have sampled different initial source–time or source–height subsets. During subsequent transport, gravitational settling preferentially removes larger ash particles; aggregation changes effective particle size and settling velocity (Brown et al., 2012); oxidation of co-emitted SO₂ produces secondary sulfate; and coagulation, condensation, and mixing with regional background aerosol can increase the weakly depolarizing fine-particle contribution and alter refractive properties or apparent particle shape (Muser et al., 2020; Bruckert et al., 2023). The similar median source-proximity-to-receptor transport times (i.e., 84 and 89 h for Anqing and Shouxian, respectively) show that elapsed time alone is not sufficient to explain the contrast; emission conditions, injection height, meteorological history, size-selective removal, secondary-particle formation, and background mixing remain nonexclusive controls (Bruckert et al., 2023, 2025; Li et al., 2024).

Therefore, the most defensible interpretation is a family of source- and pathway-dependent effects that can alter the fine-to-coarse optical partition rather than a unique transport history mechanism. The Anqing state is optically consistent with a larger fine or weakly depolarizing contribution, whereas the Shouxian state retains a stronger nonspherical or coarse-particle contribution. The available observations cannot partition how much of this contrast was inherited from different eruption pulses or injection heights and how much developed through removal, aging, secondary formation, or mixing during transport. Figure 11 summarizes this evidence hierarchy: the eruption record, satellite observations, and HYSPLIT provide the common event context; the matched lidars establish the contrasting optical states; and the schematic diagram represents the event-scale interpretation and range of plausible processes rather than continuous particulate tracking or a microphysical retrieval.

4.3 Implications for spatial representativeness, aerosol identification, and limitations

The first implication concerns aerosol identification and source attribution. A fixed depolarization threshold would classify the Anqing and Shouxian layers differently, even though independent eruption, satellite, and trajectory evidence places both within the same event-scale Shinmoedake-related source–transport context. Therefore, low depolarization does not by itself exclude a volcanic-related source after multi-day processing, whereas elevated depolarization is not unique to volcanic aerosol, as mineral dust and other nonspherical particles can have overlapping PDR values. Consequently, source attribution should rely on independent source–transport evidence, with lidar observables used subsequently to characterize particle optical state.



The second implication is spatial representativeness. Optical-to-mass conversion depends on particle size distribution, shape, density, and associated optical assumptions (Ansmann et al., 2011, 2012). Although in this study, aerosol mass was not retrieved, similar β_{355} at the two receptors together with different spectral–polarimetric behavior shows why an optical relationship inferred at one site may not transfer directly to another. The 202-km separation is one spatial realization rather than a decorrelation length; however, it identifies a representativeness issue at a scale relevant to regional observations and model evaluation.

The third implication is methodological. Combining AE_β and R_δ with the underlying wavelength-specific backscatter and depolarization separates the two receptor states more clearly than any single channel. Importantly, removing δ_{532} -based height–bin selection reduces the PDR contrast; however, it retains the opposing median wavelength ordering. Therefore, the primary segmentation affects the exact magnitude of some retrieved layer statistics but does not generate the opposing wavelength dependence observed at the two receptors. Therefore, for aged volcanic aerosol, spectral backscatter behavior and dual-wavelength depolarization should be interpreted jointly and together with independent source–transport constraints. R_δ is best regarded as an optical mixture-sensitive indicator rather than a direct retrieval of composition, morphology, or particle size distribution.

Several limitations constrain the generality of these findings. The analysis covers one eruptive period and two receptor sites; hence, the 202-km separation does not define a characteristic spatial scale. The 26 consecutive 10-min profiles are also temporally correlated; they document the persistence of the contrast but are not independent statistical realizations. Quantifying a horizontal decorrelation scale would require repeated paired events, denser lidar networks, or airborne observations. Residual inter-instrument differences are a second limitation. Both systems share the same design and processing chains and passed CMA calibration before the event; however, no quantitative side-by-side intercomparison was available. Coordinated behavior across several channels argues against a simple common scaling offset; nevertheless, wavelength- or polarization-dependent systematic differences cannot be excluded. The mask-free analysis removes direct δ_{532} -based height–bin selection; however, it retains the event–time selection. Finally, the receptor layers lack in situ measurements of particle size, morphology, mineralogy, or chemical composition, and the Shinmoedake-related and regional background contributions cannot be quantitatively partitioned. HYSPLIT represents air parcel motion rather than particle microphysics; ERA5 constrains contemporaneous receptor meteorology rather than full pathway history; and the CAMS column-maximum diagnostic is neither height matched nor a volcanic ash tracer. Therefore, the proposed roles of size-selective removal, secondary aerosol, nonsphericity, and mixing remain process hypotheses consistent with the lidar observations rather than uniquely demonstrated mechanisms.

Overall, this case shows that aerosol within a common regional source–transport episode need not exhibit a uniform far-field lidar optical state. The contrast is expressed most clearly in wavelength-dependent and normalized properties and only weakly apparent in 355-nm backscatter alone. Therefore, far-field volcanic aerosol studies should combine multi-wavelength optical measurements with independent source–transport constraints and explicitly consider spatial representativeness, selection sensitivity, and measurement uncertainty.



5 Conclusions

This study examined far-field Shinmoedake-related aerosol with same-design multi-wavelength polarization Raman–Mie lidars at Anqing and Shouxian, together with eruption records, Himawari-9 imagery, TROPOMI SO₂ retrievals, HYSPLIT backward trajectories, and atmospheric reanalysis. The combined evidence supports an event-scale Shinmoedake-related source–transport context after approximately 3–4 d of air-parcel transport; it does not resolve contributions from individual E1–E4 eruptions or establish continuous particulate tracking from the volcano to the receptors.

Under strictly matched sampling conditions (26 paired 10-min profiles within the height range of 2.036–2.966 km), the two receptors exhibited a pronounced contrast in particle optical state despite comparable short-wavelength backscatter. Median β_{355} values at Anqing and Shouxian were nearly identical (3.33 and 3.19 Mm⁻¹ sr⁻¹, respectively), whereas strong differences were observed in wavelength dependent and intensive optical properties. Anqing showed very weak depolarization at 355 nm (median $\delta_{355} = 0.019$), positive AE_{β} (+2.10), and $\delta_{532}/\delta_{355} > 1$ for all matched profiles, indicating an optical state dominated by fine or weakly depolarizing contributions. Conversely, Shouxian exhibited stronger depolarization (median $\delta_{355} = 0.101$), negative AE_{β} (-0.35), and $\delta_{532}/\delta_{355} < 1$, suggesting a relatively larger contribution from nonspherical or coarse-mode particles. These results demonstrate that similar aerosol loading does not necessarily imply similar particle optical characteristics after long-range transport.

The measurements do not uniquely identify the mechanism responsible for this contrast. ERA5 and the available CAMS diagnostic provide no obvious contemporaneous receptor-scale explanation, while the differing trajectory histories and repeated eruptions permit nonexclusive contributions from source–time/source–height variability, size-selective removal, aging, secondary-particle evolution, and mixing with regional background aerosol. Residual wavelength- and polarization-dependent inter-instrument differences and uncertainty in derived optical ratios remain additional constraints on interpretation. Compared with that derived from observations referring to different volcanoes, transport ages, or receptor times, this synchronous two-site case demonstrates that substantial optical state variability can also occur spatially within a single regional source–transport episode. The 202-km separation is one spatial realization rather than a decorrelation length, and the 26 consecutive profiles are temporally correlated descriptive samples. Therefore, far-field volcanic aerosol characterization should combine multi-wavelength polarization and spectral measurements with independent source–transport information, while explicitly addressing selection sensitivity, spatial representativeness, and measurement uncertainty.

Code and data availability

Measurement data in this study are available in the data repository maintained by Mendeley Data <https://data.mendeley.com/datasets/xwxb53dfnh/1> (Wang et al., 2026). Additional code related to this paper may be requested from the authors.



Author contributions

Yujia Chen, Congzi Xia, and Cheng Liu conceived the study and supervised the research. Zhuang Wang conducted the primary data analysis, performed the visualization and synthesis of the multi-source observations, and prepared the original manuscript. Yizhi Zhu, Congzi Xia, Kaidi Zhang, Shanshan Liu, and Xintong Chen contributed to data analysis, methodological implementation, and interpretation of the results. Xinfeng Lin, Nian Qiu, Shaowei Yan, Jiaqi Chen, Nan Ge, Guanyin Yang, and Zhenzhen Hua were responsible for lidar operation and maintenance and contributed to lidar data acquisition, quality control, and data processing. Yujia Chen, Chengzhi Xing, Chengxiao Liu, Yanfeng Huo, Xiaoyun Sun, Hao Zhang, Chune Shi, and Cheng Liu contributed to the interpretation and discussion of the results and reviewed and edited the manuscript. All authors discussed the results, contributed to the scientific interpretation of the study.

Competing interests

The authors declare that they have no competing interests.

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515 References

- Ansmann, A., Seifert, P., Tesche, M., and Wandinger, U.: Profiling of fine and coarse particle mass: case studies of Saharan dust and Eyjafjallajökull/Grimsvötn volcanic plumes, *Atmos. Chem. Phys.*, 12, 9399-9415, 10.5194/acp-12-9399-2012, 2012.
- Ansmann, A., Wandinger, U., Riebesell, M., Weitkamp, C., and Michaelis, W.: Independent measurement of extinction and backscatter profiles in cirrus clouds by using a combined Raman elastic-backscatter lidar, *Appl. Opt.*, 31, 7113-7131, 10.1364/AO.31.007113, 1992.
- 520 Ansmann, A., Tesche, M., Groß, S., Freudenthaler, V., Seifert, P., Hiebsch, A., Schmidt, J., Wandinger, U., Mattis, I., Müller, D., and Wiegner, M.: The 16 April 2010 major volcanic ash plume over central Europe: EARLINET lidar and AERONET photometer observations at Leipzig and Munich, Germany, *Geophys. Res. Lett.*, 37, 10.1029/2010gl043809, 2010.
- Ansmann, A., Tesche, M., Seifert, P., Groß, S., Freudenthaler, V., Apituley, A., Wilson, K. M., Serikov, I., Linné, H., Heinold, B., Hiebsch, A., Schnell, F., Schmidt, J., Mattis, I., Wandinger, U., and Wiegner, M.: Ash and fine-mode particle mass profiles from EARLINET-AERONET observations over central Europe after the eruptions of the Eyjafjallajökull volcano in 2010, *J. Geophys. Res.*, 116, 10.1029/2010jd015567, 2011.
- 525 Baars, H., Kanitz, T., Engelmann, R., Althausen, D., Heese, B., Komppula, M., Preißler, J., Tesche, M., Ansmann, A., Wandinger, U., Lim, J.-H., Ahn, J. Y., Stachlewska, I. S., Amiridis, V., Marinou, E., Seifert, P., Hofer, J., Skupin, A., Schneider, F., Bohlmann, S., Foth, A., Bley, S., Pfüller, A., Giannakaki, E., Lihavainen, H., Viisanen, Y., Hooda, R. K., Pereira, S. N., Bortoli, D., Wagner, F., Mattis, I., Janicka, L., Markowicz, K. M., Achtert, P., Artaxo, P., Pauliquevis, T., Souza, R. A. F., Sharma, V. P., van Zyl, P. G., Beukes, J. P., Sun, J., Rohwer, E. G., Deng, R., Mamouri, R.-E., and Zamorano, F.: An overview of the first decade of Polly^{NET}: an emerging network of automated Raman-polarization lidars for continuous aerosol profiling, *Atmos. Chem. Phys.*, 16, 5111-5137, 10.5194/acp-16-5111-2016, 2016.
- 535 Bellini, A., Diémoz, H., Di Liberto, L., Gobbi, G. P., Bracci, A., Pasqualini, F., and Barnaba, F.: ALICENET-an Italian network of automated lidar ceilometers for four-dimensional aerosol monitoring: infrastructure, data processing, and applications, *Atmospheric Measurement Techniques*, 17, 6119-6144, 10.5194/amt-17-6119-2024, 2024.
- Bessho, K., Date, K., Hayashi, M., Ikeda, A., Imai, T., Inoue, H., Kumagai, Y., Miyakawa, T., Murata, H., Ohno, T., Okuyama, A., Oyama, R., Sasaki, Y., Shimazu, Y., Shimoji, K., Sumida, Y., Suzuki, M., Taniguchi, H., Tsuchiyama, H., Uesawa, D., Yokota, H., and Yoshida, R.: An Introduction to Himawari-8/9—Japan's New-Generation Geostationary Meteorological Satellites, *Journal of the Meteorological Society of Japan. Ser. II*, 94, 151-183, 10.2151/jmsj.2016-009, 2016.
- 540 Boselli, A., Scollo, S., Leto, G., Sanchez, R. Z., Sannino, A., Wang, X., Coltelli, M., and Spinelli, N.: First Volcanic Plume Measurements by an Elastic/Raman Lidar Close to the Etna Summit Craters, *Frontiers in Earth Science*, 6, 10.3389/feart.2018.00125, 2018.
- 545 Brown, R. J., Bonadonna, C., and Durant, A. J.: A review of volcanic ash aggregation, *Physics and Chemistry of the Earth, Parts A/B/C*, 45-46, 65-78, <https://doi.org/10.1016/j.pce.2011.11.001>, 2012.
- Bruckert, J., Chopra, S., Siddans, R., Wedler, C., and Hoshyaripour, G. A.: Aerosol dynamic processes in the Hunga plume in January 2022: does water vapor accelerate aerosol aging?, *Atmos. Chem. Phys.*, 25, 9859-9884, 10.5194/acp-25-9859-2025, 2025.
- 550 Bruckert, J., Hirsch, L., Horváth, Á., Kahn, R. A., Kölling, T., Muser, L. O., Timmreck, C., Vogel, H., Wallis, S., and Hoshyaripour, G. A.: Dispersion and Aging of Volcanic Aerosols After the La Soufrière Eruption in April 2021, *Journal of Geophysical Research: Atmospheres*, 128, 10.1029/2022jd037694, 2023.
- Cohen, M. D., Stunder, B. J. B., Rolph, G. D., Draxler, R. R., Stein, A. F., and Ngan, F.: NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System, *Bulletin of the American Meteorological Society*, 96, 2059-2077, 10.1175/bams-d-14-00110.1, 2015.
- 555 Dodangodage, R., Bernath, P. F., Wyatt, M., and Boone, C.: Atmospheric Chemistry Experiment (ACE) satellite observations of aerosols and SO₂ emissions from the 2024 Ruang volcanic eruption, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 333, 10.1016/j.jqsrt.2024.109333, 2025.
- Efremenko, D. S., Loyola, R. D. G., Hedelt, P., and Spurr, R. J. D.: Volcanic SO₂ plume height retrieval from UV sensors using a full-physics inverse learning machine algorithm, *International Journal of Remote Sensing*, 38, 1-27, 10.1080/01431161.2017.1348644, 2017.
- 560 Engelmann, R., Kanitz, T., Baars, H., Heese, B., Althausen, D., Skupin, A., Wandinger, U., Komppula, M., Stachlewska, I. S., Amiridis, V., Marinou, E., Mattis, I., Linné, H., and Ansmann, A.: The automated multiwavelength Raman polarization and



- water-vapor lidar PollyXT: the neXT generation, *Atmospheric Measurement Techniques*, 9, 1767-1784, 10.5194/amt-9-1767-2016, 2016.
- 565 Filioglou, M., Luoma, K., Asmi, E., Le, V., Haikarainen, K., Brus, D., Mielonen, T., Komppula, M., Virtanen, A., Sippula, O., Pullinen, I., Buchholz, A., Miettinen, P., Kommula, S., Peltokorpi, S., Hao, L., Köster, K., Saarto, A., Pätsi, S., van Zyl, P. G., Breidenkamp, L., and Vakkari, V.: Depolarization ratio of smoke and volcanic ash aerosol particles at 1565 nm using a HALO Doppler lidar, *Atmospheric Chemistry and Physics*, 26, 11525-11542, 10.5194/acp-26-11525-2026, 2026.
- 570 Floutsi, A. A., Baars, H., and Wandinger, U.: HETEAC-Flex: an optimal estimation method for aerosol typing based on lidar-derived intensive optical properties, *Atmospheric Measurement Techniques*, 17, 693-714, 10.5194/amt-17-693-2024, 2024.
- Freudenthaler, V.: About the effects of polarising optics on lidar signals and the $\Delta 90$ calibration, *Atmospheric Measurement Techniques*, 9, 4181-4255, 10.5194/amt-9-4181-2016, 2016.
- 575 Freudenthaler, V., Esselborn, M., Wiegner, M., Heese, B., Tesche, M., Ansmann, A., Müller, D., Althausen, D., Wirth, M., Fix, A., Ehret, G., Knippertz, P., Toledano, C., Gasteiger, J., Garhammer, M., and Seefeldner, M.: Depolarization ratio profiling at several wavelengths in pure Saharan dust during SAMUM 2006, *Tellus B: Chemical and Physical Meteorology*, 61, 10.1111/j.1600-0889.2008.00396.x, 2009.
- Gebauer, H., Floutsi, A. A., Haarig, M., Radenz, M., Engelmann, R., Althausen, D., Skupin, A., Ansmann, A., Zenk, C., and Baars, H.: Tropospheric sulfate from Cumbre Vieja (La Palma) observed over Cabo Verde contrasted with background conditions: a lidar case study of aerosol extinction, backscatter, depolarization and lidar ratio profiles at 355, 532 and 1064 nm, *Atmos. Chem. Phys.*, 24, 5047-5067, 10.5194/acp-24-5047-2024, 2024.
- 580 Groß, S., Freudenthaler, V., Wiegner, M., Gasteiger, J., Geiß, A., and Schnell, F.: Dual-wavelength linear depolarization ratio of volcanic aerosols: Lidar measurements of the Eyjafjallajökull plume over Maisach, Germany, *Atmos. Environ.*, 48, 85-96, 10.1016/j.atmosenv.2011.06.017, 2012.
- 585 Geological Survey of Japan, AIST (GSJ/AIST): Shinmoe-dake, Kirishima Volcano Group (2025), Research Institute of Earthquake and Volcano Geology, Geological Survey of Japan, AIST, <https://www.gsj.jp/en/hazards/volcano/kirishima2025-e.html>, last access: 1 October 2026, 2025.
- Haarig, M., Engelmann, R., Baars, H., Gast, B., Althausen, D., and Ansmann, A.: Discussion of the spectral slope of the lidar ratio between 355 and 1064 nm from multiwavelength Raman lidar observations, *Atmospheric Chemistry and Physics*, 25, 7741-7763, 10.5194/acp-25-7741-2025, 2025.
- 590 Hedelt, P., Reichardt, J., Lauermann, F., Weiß, B., Theys, N., Redondas, A., Barreto, A., Garcia, O., and Loyola, D.: Analysis of the long-range transport of the volcanic plume from the 2021 Tajogaite/Cumbre Vieja eruption to Europe using TROPOMI and ground-based measurements, *Atmospheric Chemistry and Physics*, 25, 1253-1272, 10.5194/acp-25-1253-2025, 2025.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J. N.: The ERA5 global reanalysis, *QJRM*, 146, 1999-2049, 10.1002/qj.3803, 2020.
- 600 Inness, A., Ades, M., Agustí-Panareda, A., Barré, J., Benedictow, A., Blechschmidt, A. M., Dominguez, J. J., Engelen, R., Eskes, H., Flemming, J., Huijnen, V., Jones, L., Kipling, Z., Massart, S., Parrington, M., Peuch, V. H., Razinger, M., Remy, S., Schulz, M., and Suttie, M.: The CAMS reanalysis of atmospheric composition, *Atmos. Chem. Phys.*, 19, 3515-3556, 10.5194/acp-19-3515-2019, 2019.
- Japan Meteorological Agency, Meteorological Satellite Center (JMA/MSC): Himawari Ash RGB Quick Guide, Version 1.0, https://www.jma.go.jp/jma/jma-eng/satellite/VLab/RGB_QG.html, last access: 1 October 2026, 2020.
- 605 Japan Meteorological Agency (JMA): Volcanic information reports for Kirishimayama (Shinmoedake), July 2025, Japan Meteorological Agency, <https://www.data.jma.go.jp/vois/data/report/volinfo/volinfo.php?id=551&info=VG>, last access: 28 August 2026, 2025.
- Jing, D., He, Y., Yin, Z., Liu, F., Yi, Y., and Yi, F.: Evolution of aerosol plumes from 2019 Raikoke volcanic eruption observed with polarization lidar over central China, *Atmos. Environ.*, 309, 10.1016/j.atmosenv.2023.119880, 2023.
- 610 Kahn, R. A., Limbacher, J. A., Junghenn Noyes, K. T., Flower, V. J. B., Zamora, L. M., and McKee, K. F.: Evolving Particles in the 2022 Hunga Tonga—Hunga Ha'apai Volcano Eruption Plume, *Journal of Geophysical Research: Atmospheres*, 129, 10.1029/2023jd039963, 2024.



- Kampouri, A., Amiridis, V., Georgiou, T., Solomos, S., Gialitaki, A., Tschla, M., Rennie, M., Scollo, S., and Zanis, P.: Volcanic emission estimates from the inversion of ACTRIS lidar observations and their use for quantitative dispersion modeling, *Atmospheric Chemistry and Physics*, 25, 7343-7368, 10.5194/acp-25-7343-2025, 2025.
- Kokkalis, P., Papayannis, A., Amiridis, V., Mamouri, R. E., Veselovskii, I., Kolgotin, A., Tsaknakis, G., Kristiansen, N. I., Stohl, A., and Mona, L.: Optical, microphysical, mass and geometrical properties of aged volcanic particles observed over Athens, Greece, during the Eyjafjallajökull eruption in April 2010 through synergy of Raman lidar and sunphotometer measurements, *Atmospheric Chemistry and Physics*, 13, 9303-9320, 10.5194/acp-13-9303-2013, 2013.
- Kristiansen, N. I., Witham, C. S., and Beckett, F. M.: A modelling approach for quantifying volcanic sulphur dioxide concentrations at flight altitudes and the potential hazard to aircraft occupants, *Journal of Applied Volcanology*, 13, 10.1186/s13617-024-00144-x, 2024.
- Lemus, J., Rossi, E., Fries, A., Latt, J., and Bonadonna, C.: Particle Aggregation and Settling - Driven Gravitational Instabilities: A Combined Impact on Volcanic Ash Sedimentation, *Journal of Geophysical Research: Solid Earth*, 130, 10.1029/2024jb030855, 2025.
- Li, C., Peng, Y., Asher, E., Baron, A. A., Todt, M., Thornberry, T. D., Evan, S., Brioude, J., Smale, P., Querel, R., Rosenlof, K. H., Zhou, L., Xu, J., Qie, K., Bian, J., Toon, O. B., Zhu, Y., and Yu, P.: Microphysical Simulation of the 2022 Hunga Volcano Eruption Using a Sectional Aerosol Model, *Geophys. Res. Lett.*, 51, 10.1029/2024gl108522, 2024.
- Liu, X., Chance, K., Sioris, C. E., and Kurosu, T. P.: Impact of using different ozone cross sections on ozone profile retrievals from Global Ozone Monitoring Experiment (GOME) ultraviolet measurements, *Atmos. Chem. Phys.*, 7, 3571-3578, 10.5194/acp-7-3571-2007, 2007.
- Liu, X., Chance, K., Sioris, C. E., Kurosu, T. P., Spurr, R. J. D., Martin, R. V., Fu, T. M., Logan, J. A., Jacob, D. J., Palmer, P. I., Newchurch, M. J., Megretskaia, I. A., and Chatfield, R. B.: First directly retrieved global distribution of tropospheric column ozone from GOME: Comparison with the GEOS - CHEM model, *Journal of Geophysical Research: Atmospheres*, 111, 10.1029/2005jd006564, 2006.
- Miyagi, I., Konoo, T., Matsumoto, K., Ikenaga, Y., Oikawa, T., Furukawa, R., Iwahashi, K., Araya, N., Takarada, S., Kusano, Y., Tomiya, A., and Saito, G.: Mineral and glass chemical composition of volcanic ash from the eruptions of Shinmoedake, Kirishima volcano on July 2-4, 2025, *Programme and Abstracts, The Volcanological Society of Japan 2025 Fall Meeting*, 2025, https://doi.org/10.18940/vsj.2025.0_182, 2025.
- Mona, L., Amodeo, A., D'Amico, G., Giunta, A., Madonna, F., and Pappalardo, G.: Multi-wavelength Raman lidar observations of the Eyjafjallajökull volcanic cloud over Potenza, southern Italy, *Atmospheric Chemistry and Physics*, 12, 2229-2244, 10.5194/acp-12-2229-2012, 2012.
- Muser, L. O., Hoshyaripour, G. A., Bruckert, J., Horváth, Á., Malinina, E., Wallis, S., Prata, F. J., Rozanov, A., von Savigny, C., Vogel, H., and Vogel, B.: Particle aging and aerosol-radiation interaction affect volcanic plume dispersion: evidence from the Raikoke 2019 eruption, *Atmos. Chem. Phys.*, 20, 15015-15036, 10.5194/acp-20-15015-2020, 2020.
- Nishizawa, T., Kudo, R., Oikawa, E., Higurashi, A., Jin, Y., Sugimoto, N., Sato, K., and Okamoto, H.: Algorithms to retrieve aerosol optical properties using lidar measurements on board the EarthCARE satellite, *Atmos. Meas. Tech.*, 19, 729-744, 10.5194/amt-19-729-2026, 2026.
- Nowlan, C. R., Liu, X., Chance, K., Cai, Z., Kurosu, T. P., Lee, C., and Martin, R. V.: Retrievals of sulfur dioxide from the Global Ozone Monitoring Experiment 2 (GOME-2) using an optimal estimation approach: Algorithm and initial validation, *Journal of Geophysical Research*, 116, 10.1029/2011jd015808, 2011.
- Papayannis, A., Mamouri, R. E., Amiridis, V., Giannakaki, E., Veselovskii, I., Kokkalis, P., Tsaknakis, G., Balis, D., Kristiansen, N. I., Stohl, A., Korenskiy, M., Allakhverdiev, K., Huseynoglu, M. F., and Baykara, T.: Optical properties and vertical extension of aged ash layers over the Eastern Mediterranean as observed by Raman lidars during the Eyjafjallajökull eruption in May 2010, *Atmos. Environ.*, 48, 56-65, 10.1016/j.atmosenv.2011.08.037, 2012.
- Pappalardo, G., Mona, L., D'Amico, G., Wandinger, U., Adam, M., Amodeo, A., Ansmann, A., Apituley, A., Alados Arboledas, L., Balis, D., Boselli, A., Bravo-Aranda, J. A., Chaikovskiy, A., Comeron, A., Cuesta, J., De Tomasi, F., Freudenthaler, V., Gausa, M., Giannakaki, E., Giehl, H., Giunta, A., Grigorov, I., Groß, S., Haeffelin, M., Hiebsch, A., Iarlori, M., Lange, D., Linné, H., Madonna, F., Mattis, I., Mamouri, R. E., McAuliffe, M. A. P., Mitev, V., Molero, F., Navas-Guzman, F., Nicolae, D., Papayannis, A., Perrone, M. R., Pietras, C., Pietruczuk, A., Pisani, G., Preißler, J., Pujadas, M., Rizi, V., Ruth, A. A., Schmidt, J., Schnell, F., Seifert, P., Serikov, I., Sicard, M., Simeonov, V., Spinelli, N., Stebel, K., Tesche, M., Trickl, T., Wang, X., Wagner, F., Wiegner, M., and Wilson, K. M.: Four-dimensional distribution of the 2010 Eyjafjallajökull volcanic cloud over Europe



- observed by EARLINET, *Atmos. Chem. Phys.*, 13, 4429–4450, 10.5194/acp-13-4429-2013, 2013.
- 665 Pardini, F., Barsotti, S., Bonadonna, C., de' Michieli Vitturi, M., Folch, A., Mastin, L., Osorio, S., and Prata, A. T.: Dynamics, Monitoring, and Forecasting of Tephra in the Atmosphere, *Reviews of Geophysics*, 62, 10.1029/2023rg000808, 2024.
- Pisani, G., Boselli, A., Coltelli, M., Leto, G., Pica, G., Scollo, S., Spinelli, N., and Wang, X.: Lidar depolarization measurement of fresh volcanic ash from Mt. Etna, Italy, *Atmos. Environ.*, 62, 34–40, 10.1016/j.atmosenv.2012.08.015, 2012.
- Rolph, G., Stein, A., and Stunder, B.: Real-time Environmental Applications and Display sYstem: READY, *Environ. Model. Software*, 95, 210–228, 10.1016/j.envsoft.2017.06.025, 2017.
- 670 Sakai, T., Uchino, O., Nagai, T., Liley, B., Querel, R., Morino, I., Jin, Y., Fujimoto, T., Oikawa, E., and Oshima, N.: Stratospheric Aerosol Backscatter and Depolarization Ratio Observed With Ground - Based Lidar at Tsukuba, Japan, and Lauder, New Zealand, *Journal of Geophysical Research: Atmospheres*, 130, 10.1029/2024jd041329, 2025.
- Sassen, K., Zhu, J., Webley, P., Dean, K., and Cobb, P.: Volcanic ash plume identification using polarization lidar: Augustine eruption, Alaska, *Geophys. Res. Lett.*, 34, 10.1029/2006gl027237, 2007.
- 675 Schoeberl, M. R., Wang, Y., Taha, G., Zawada, D. J., Ueyama, R., and Dessler, A.: Evolution of the Climate Forcing During the Two Years After the Hunga Tonga-Hunga Ha'apai Eruption, *Journal of Geophysical Research: Atmospheres*, 129, 10.1029/2024jd041296, 2024.
- Spinosa, S., Boselli, A., Mereu, L., Leto, G., Sanchez, R. Z., and Scollo, S.: Remote sensing measurements of fresh volcanic ash during the Mount Etna emission of February 21, 2019, *Remote Sensing Applications: Society and Environment*, 37, 10.1016/j.rsase.2024.101413, 2025.
- Spurr, R. J. D.: VLIDORT: A linearized pseudo-spherical vector discrete ordinate radiative transfer code for forward model and retrieval studies in multilayer multiple scattering media, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 102, 316–342, 10.1016/j.jqsrt.2006.05.005, 2006.
- 685 Stenchikov, G., Ukhov, A., and Osipov, S.: Modeling the Radiative Forcing and Atmospheric Temperature Perturbations Caused by the 2022 Hunga Volcano Explosion, *Journal of Geophysical Research: Atmospheres*, 130, 10.1029/2024jd041940, 2025.
- Tesche, M., Ansmann, A., Müller, D., Althausen, D., Engelmann, R., Freudenthaler, V., and Groß, S.: Vertically resolved separation of dust and smoke over Cape Verde using multiwavelength Raman and polarization lidars during Saharan Mineral Dust Experiment 2008, *Journal of Geophysical Research: Atmospheres*, 114, 10.1029/2009jd011862, 2009.
- 690 Tokyo Volcanic Ash Advisory Center (Tokyo VAAC): Volcanic Ash Advisories archive for 2025, Japan Meteorological Agency, https://www.data.jma.go.jp/vaac/data/Archives/2025_vaac_list.html, last access: 28 August 2026, 2025.
- Takagi, A. and Shimbori, T.: Confirmation of time decay of sulfur dioxide concentrations using satellite data and JMA Local Analysis, and activity of Shinmoedake in 2025, Programme and Abstracts, The Volcanological Society of Japan 2025 Fall Meeting, 2025, https://doi.org/10.18940/vsj.2025.0_75, 2025.
- 695 Wang, Z., Shi, C., Zhang, H., Chen, Y., Chi, X., Xia, C., Wang, S., Zhu, Y., Zhang, K., Chen, X., Xing, C., and Liu, C.: Measurement report: Dust and anthropogenic aerosols' vertical distributions over northern China dense aerosols gathered at the top of the mixing layer, *Atmospheric Chemistry and Physics*, 23, 14271–14292, 10.5194/acp-23-14271-2023, 2023.
- Wang, Z., Liu, C., Xie, Z., Hu, Q., Andreae, M. O., Dong, Y., Zhao, C., Liu, T., Zhu, Y., Liu, H., Xing, C., Tan, W., Ji, X., Lin, J., and Liu, J.: Elevated dust layers inhibit dissipation of heavy anthropogenic surface air pollution, *Atmospheric Chemistry and Physics*, 20, 14917–14932, 10.5194/acp-20-14917-2020, 2020.
- 700 Wang, Z., “Mesoscale heterogeneity in the intensive optical properties of long-range transported Shinmoedake-related volcanic aerosol observed with dual-site polarization Raman-Mie lidars”, *Mendeley Data*, V1, <https://data.mendeley.com/datasets/xwxb53dfnh/1>, 2026.
- 705 Xia, C., Liu, C., Cai, Z., Wu, H., Li, Q., and Gao, M.: Tracking SO₂ plumes from the Tonga volcano eruption with multi-satellite observations, *iScience*, 27, 10.1016/j.isci.2024.109446, 2024.
- Xia, C., Liu, C., Cai, Z., Zhao, F., Su, W., Zhang, C., and Liu, Y.: First sulfur dioxide observations from the environmental trace gases monitoring instrument (EMI) onboard the GeoFen-5 satellite, *Science Bulletin*, 66, 969–973, 10.1016/j.scib.2021.01.018, 2021.
- 710 Xing, C., Liu, C., Li, Q., Wang, S., Tan, W., Zou, T., Wang, Z., and Lu, C.: Observations of HONO and its precursors between urban and its surrounding agricultural fields: The vertical transports, sources and contribution to OH, *Sci. Total Environ.*, 915, 10.1016/j.scitotenv.2023.169159, 2024.
- Zhang, C., Wang, Z., and Liu, C.: Pinpointing and characterizing large anthropogenic emitters of atmospheric reactive nitrogen



in China using multisource satellite observations, *Environmental Science & Technology*, 59, 25994-26005, <https://doi.org/10.1021/acs.est.5c08881>, 2025.
Zhuo, Z., Fuglestedt, H. F., Toohey, M., and Krüger, K.: Initial atmospheric conditions control transport of volcanic volatiles, forcing and impacts, *Atmospheric Chemistry and Physics*, 24, 6233-6249, 10.5194/acp-24-6233-2024, 2024.

Figures:

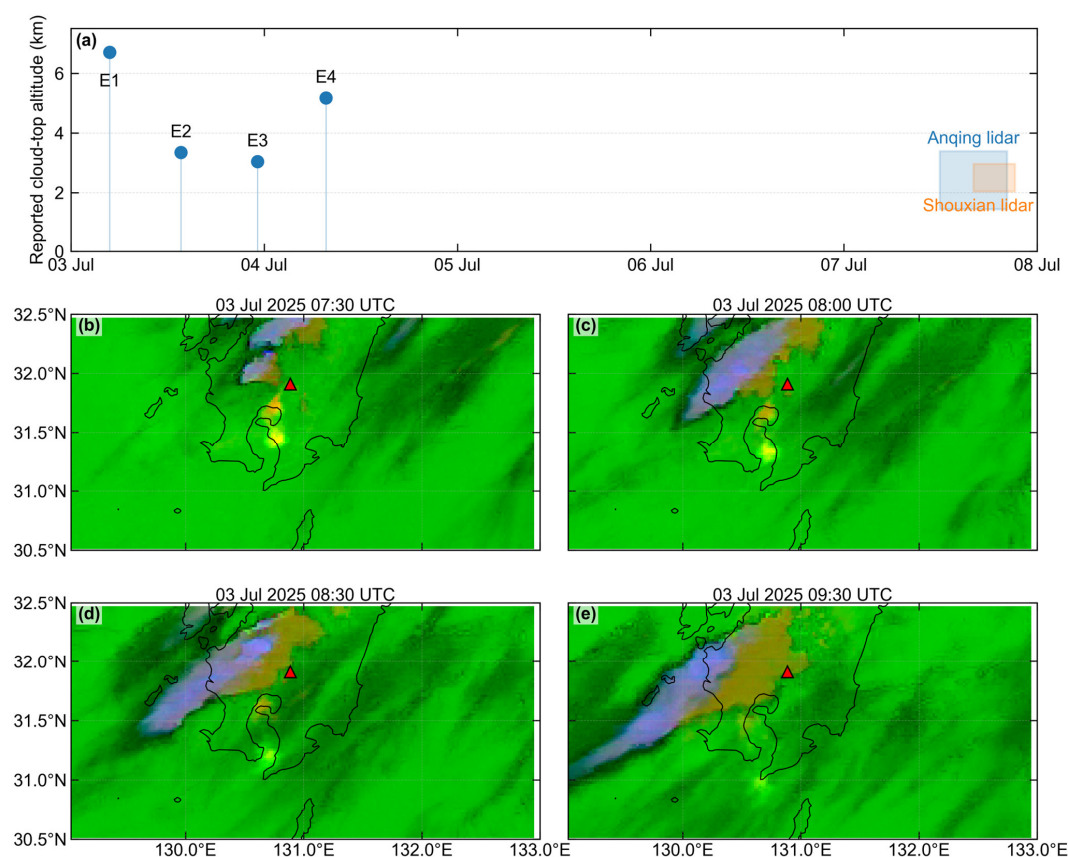
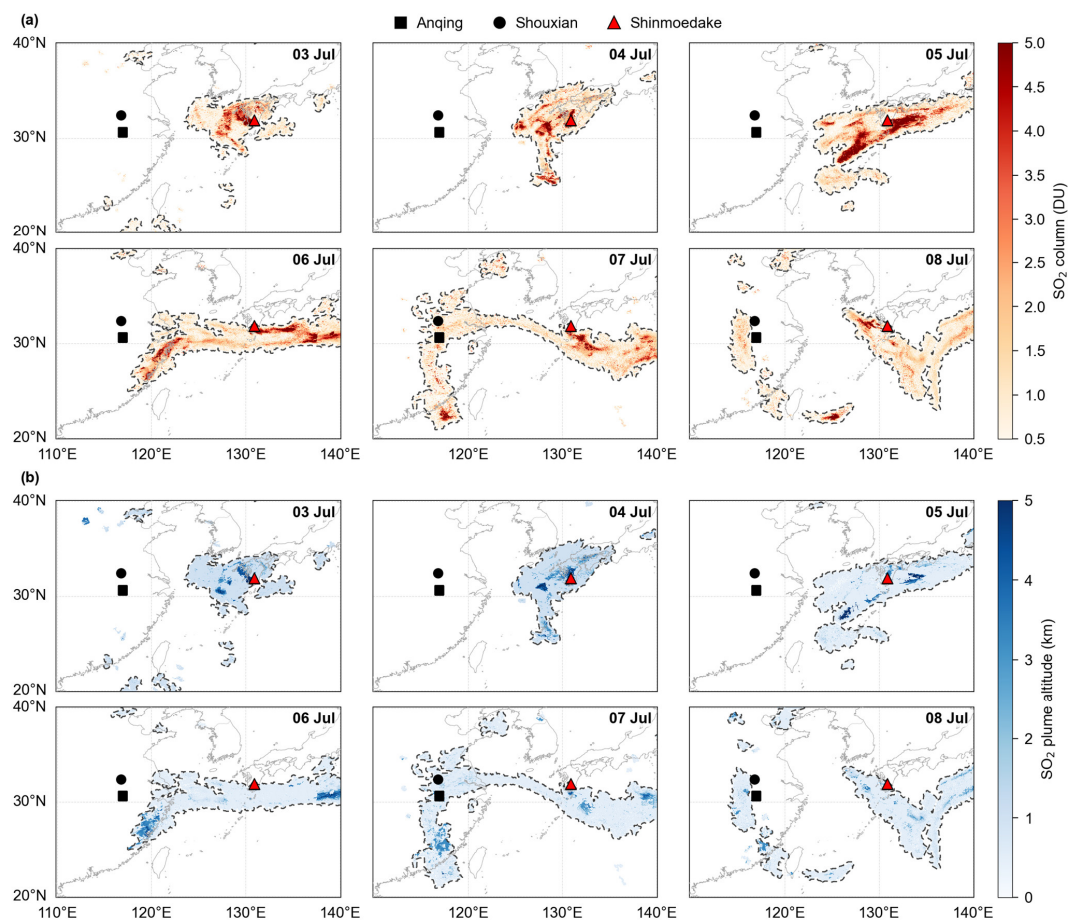


Figure 1: Shinmoedake eruption chronology and short-term evolution of an ash-sensitive source–region volcanic cloud based on Himawari-9 Advanced Himawari Imager (AHI) observations. (a) Reported volcanic cloud top altitudes for E1–E4 eruption pulses; shaded boxes mark the lidar-observed layer ranges at Anqing and Shouxian. (b–e) Representative frames from the continuous 10-min AHI Ash RGB record at 07:30, 08:00, 08:30, and 09:30 UTC on July 3, 2025, following E1.



725 **Figure 2: Evolution of TROPOMI-retrieved SO₂ vertical column density and effective**
plume height over East Asia from July 3 to 8, 2025. (a) SO₂ vertical column density (VCD; Dobson units, DU). (b) Optimal estimation
method (OEM)-retrieved effective SO₂ plume height (km), representing the center altitude of the assumed Gaussian SO₂ vertical
profile rather than the plume top or base. Black dashed contours show the candidate daily SO₂ feature used for visualization; source
730 **attribution does not rely on the contour boundary as a quantitative threshold. In each panel, the black square and black circle mark**
Anqing and Shouxian, respectively, and the red filled triangle marks Shinmoedake.

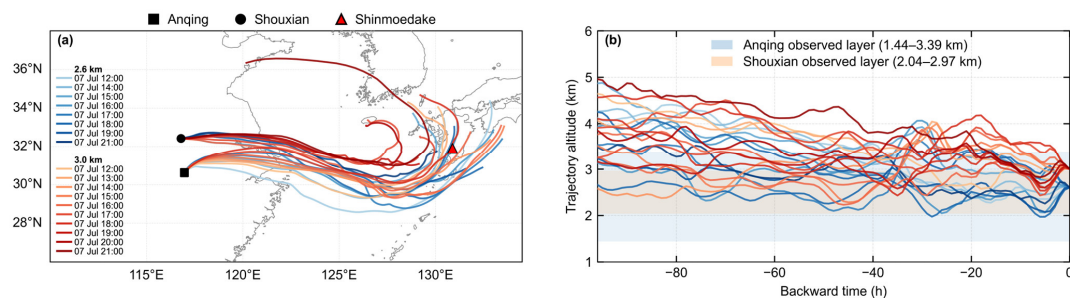
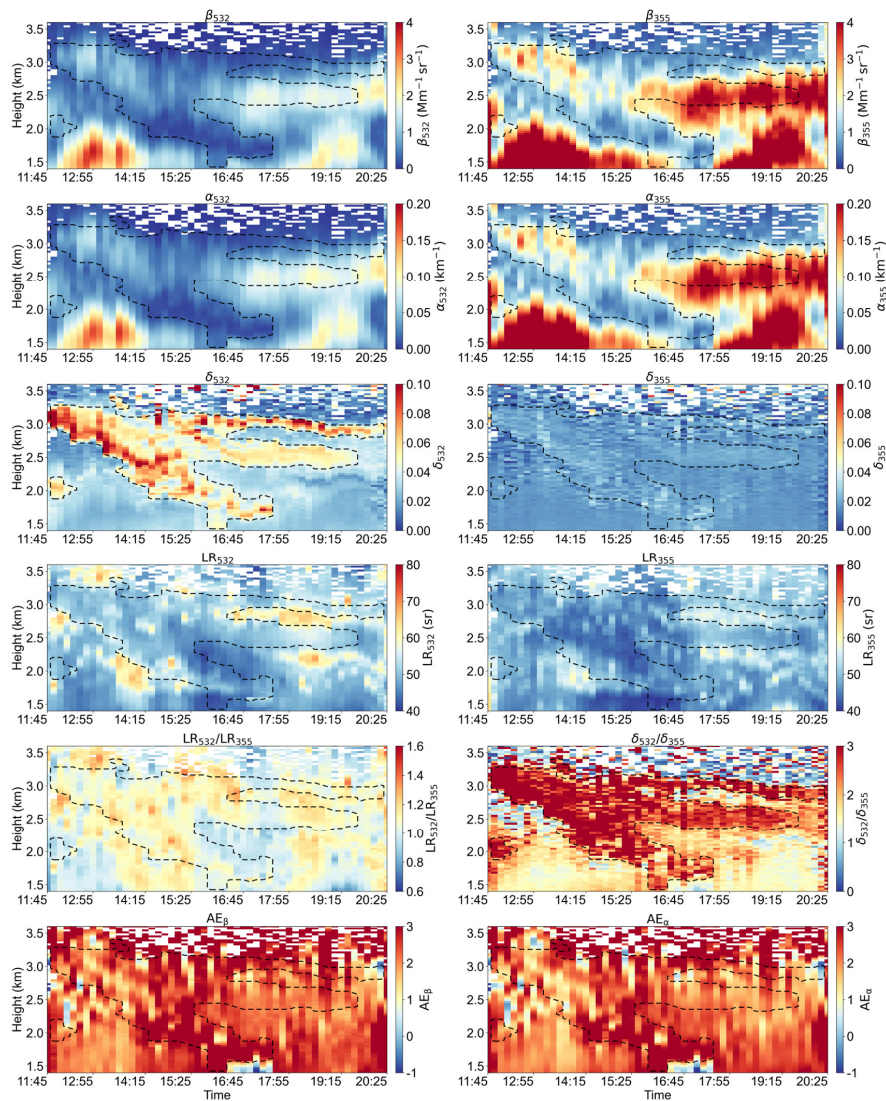
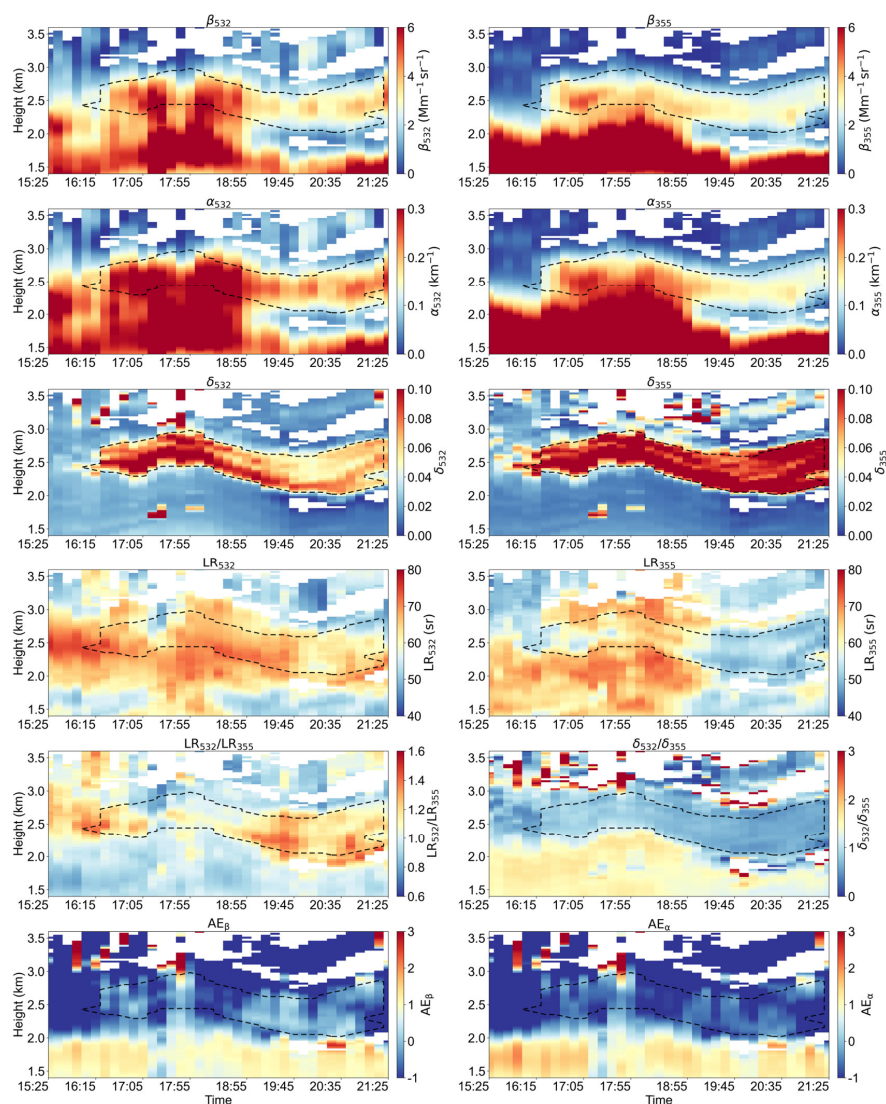


Figure 3: Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) backward trajectory analysis for the elevated aerosol layers observed at Anqing and Shouxian on July 7, 2025. (a) 96-h backward trajectories initialized at 2.6 and 3.0 km over Anqing and Shouxian. The corresponding initialization times are listed in the color-coded legends within the panel. The black square and black circle mark Anqing and Shouxian, respectively, and the red filled triangle marks Shinmoedake. (b) Vertical histories of the same trajectories, with each trajectory retaining the same color as that in panel (a). The blue and orange shaded bands indicate the lidar-observed elevated-aerosol layer height ranges at Anqing (1.44–3.39 km) and Shouxian (2.04–2.97 km), respectively.



740 **Figure 4: Time–height evolution of aerosol optical properties measured by the multi-wavelength polarization Raman–Mie lidar at Anqing during the transported aerosol episode. Rows from top to bottom show the 532- and 355-nm backscatter coefficients, extinction coefficients, particle depolarization ratios, lidar ratios, wavelength ratios (LR_{532}/LR_{355} and PDR_{532}/PDR_{355}), and backscatter and extinction Ångström exponents. Black dashed contours mark the event mask described in Sect. 2.3; white regions denote missing or invalid retrievals.**



745 Figure 5: Same as in Fig. 4 but for Shouxian.

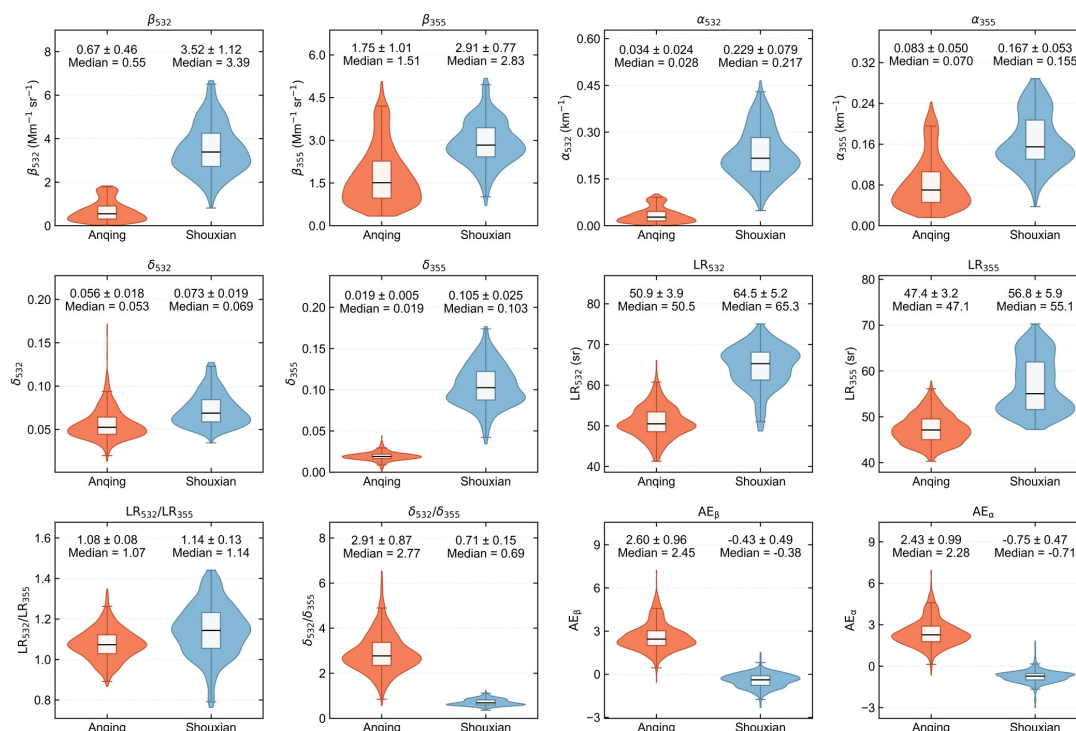
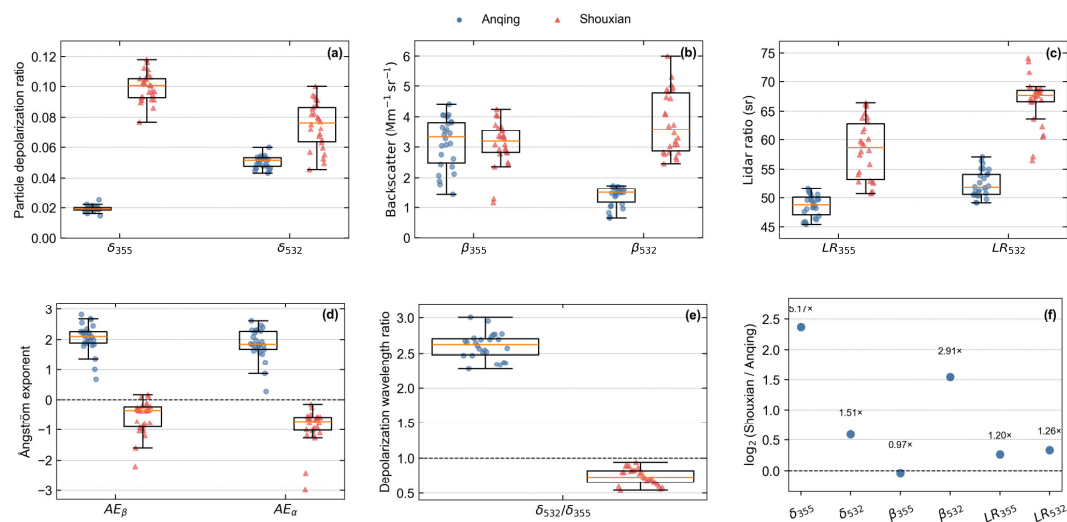
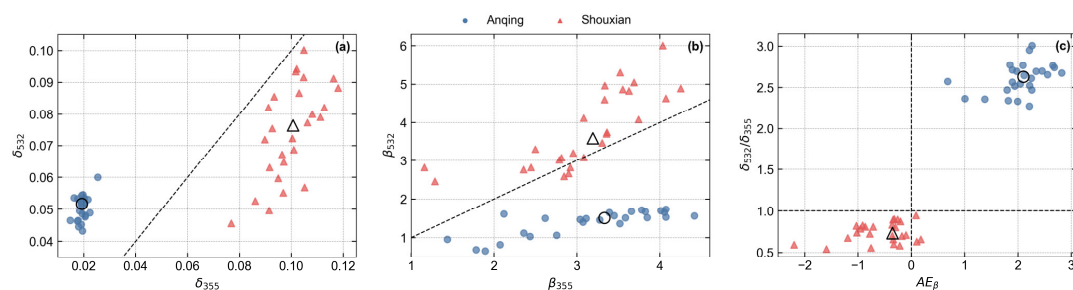


Figure 6: Lidar-retrieved optical properties of the transported aerosol at Anqing and Shouxian. Violin plots show the distributions of the 532- and 355-nm backscatter and extinction coefficients, particle depolarization ratios, lidar ratios, wavelength ratios $\text{LR}_{532}/\text{LR}_{555}$ and $\text{PDR}_{532}/\text{PDR}_{555}$, and the backscatter and extinction Ångström exponents. Only valid retrievals within the event masks identified by the black dashed contours in Figs. 4 and 5 are included. Orange and blue violins represent Anqing and Shouxian, respectively. Embedded boxplots show the interquartile range and median, with whiskers extending to 1.5 times the interquartile range; numbers above the distributions denote the arithmetic mean ± 1 standard deviation and the median.



755 **Figure 7:** Inter-site comparison under strict time–height matching using the station-specific event masks. The comparison is based on 26 paired 10-min profiles during July 7, 2025, 16:05–20:15 UTC, restricted to 2.036–2.966 km. Points are 10-min layer medians and boxes show the median and interquartile range across matched profiles. (a) Particle depolarization ratio, (b) aerosol backscatter coefficient, (c) lidar ratio, (d) backscatter and extinction Ångström exponents, (e) $R_\delta = \delta_{532}/\delta_{355}$, and (f) summary of $\log_2(\text{Shouxian}/\text{Anqing})$ for strictly positive optical parameters.



760 **Figure 8:** Dual-wavelength optical state comparison during the strictly matched, segmentation-assisted interval. (a) δ_{532} versus δ_{355} , (b) β_{532} versus β_{355} , and (c) AE_β versus $R_\delta = \delta_{532}/\delta_{355}$. Each small symbol is one paired 10-min layer median point estimate, and large open symbols are site medians.

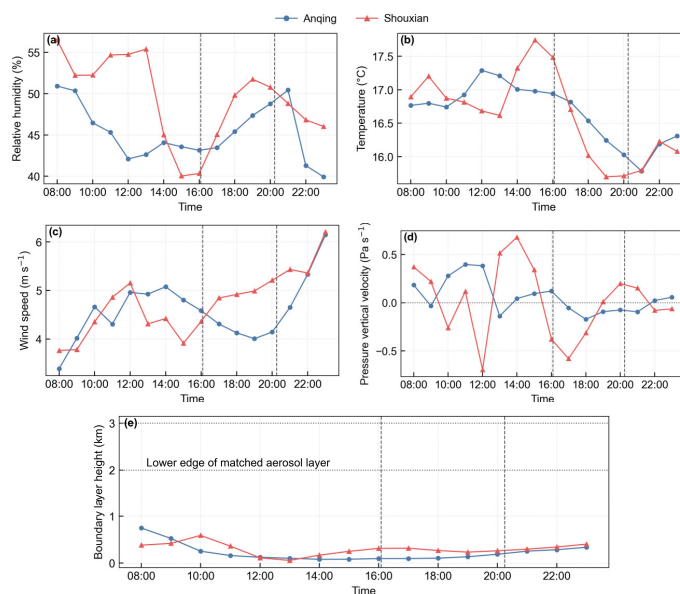


Figure 9: ERA5 meteorological environment of the 2–3-km receptor layer over Anqing and Shouxian on July 7, 2025. (a) Relative humidity, (b) temperature, (c) horizontal wind speed, (d) pressure vertical velocity (negative values denote ascent in pressure coordinates), and (e) boundary layer height. Vertical dashed lines mark the strictly matched lidar interval.

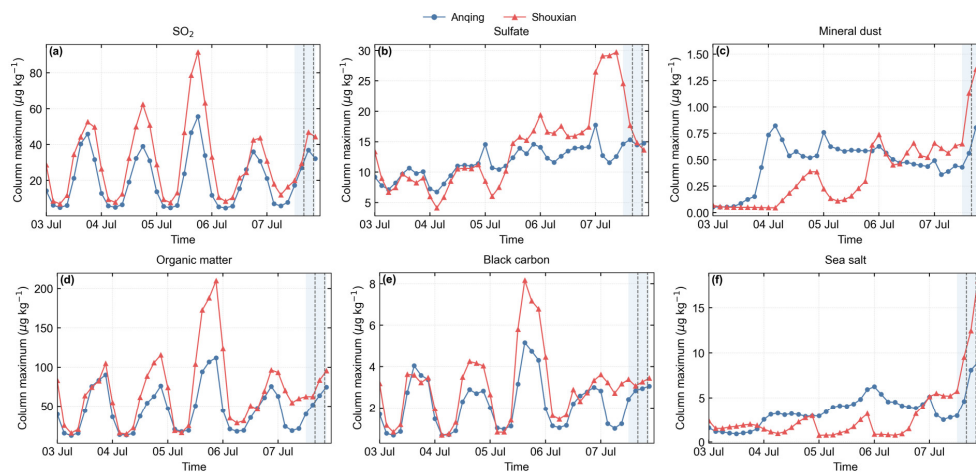


Figure 10: Copernicus Atmosphere Monitoring Service (CAMS) regional aerosol context at Anqing and Shouxian from July 3 to 7, 2025. Panels show the maximum mass mixing ratio across the available CAMS hybrid column for (a) SO₂, (b) sulfate, (c) mineral dust, (d) organic matter, (e) black carbon, and (f) sea salt. In each panel, the shaded interval marks July 7, 12:00–21:00 UTC, and dashed lines mark the strict lidar comparison interval.

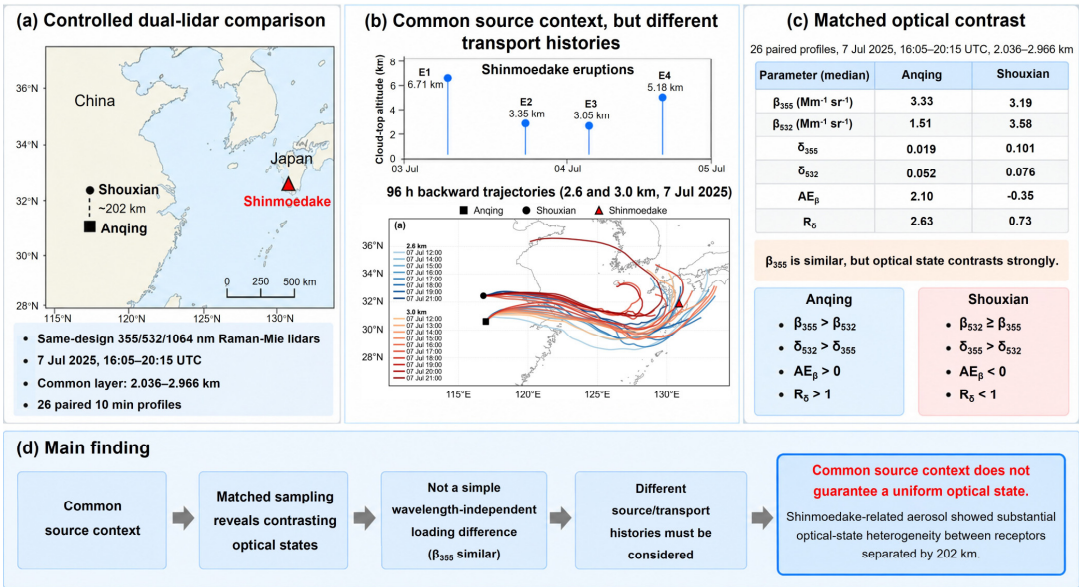


Figure 11: Conceptual synthesis of the Shinmoedake-related source–transport context and receptor optical states.

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790 **Tables:**

Table 1: Segmentation-assisted matched optical properties at Anqing and Shouxian. The Anqing and Shouxian columns give site medians from the 26 matched 10-min profiles during July 7, 2025, 16:05–20:15 UTC and 2.036–2.966 km. The final column gives Shouxian minus Anqing.

Parameter	Anqing	Shouxian	Difference
δ_{355}	0.019	0.101	+0.082
δ_{532}	0.052	0.076	+0.024
β_{355} (Mm ⁻¹ sr ⁻¹)	3.33	3.19	-0.14
β_{532} (Mm ⁻¹ sr ⁻¹)	1.51	3.58	+2.07
LR ₃₅₅ (sr)	48.8	58.7	+9.9
LR ₅₃₂ (sr)	52.0	67.7	+15.7
AE _{β}	+2.10	-0.35	-2.45
AE _{α}	+1.85	-0.72	-2.57
R _{δ} = $\delta_{532}/\delta_{355}$	+2.63	+0.73	-1.90

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Table 2: Lidar-derived optical parameters reported for selected volcanic aerosol events.

Study / event	Transport / state	Particle depolarization ratio	Lidar ratio (sr)	Reference
Eyjafjallajökull (2010), central Europe	Fresh ash-rich layer	$\delta_{355} \approx 0.35\text{--}0.38$ $\delta_{532} \approx 0.35\text{--}0.38$	LR ₃₅₅ $\approx 50\text{--}60$ LR ₅₃₂ $\approx 45\text{--}55$	Groß et al. (2012) Ansmann et al. (2010)
Augustine (2006), Alaska	Fresh tropospheric ash plume	$\delta_{694} \approx 0.10\text{--}0.15$	Not reported	Sassen et al. (2007)
Eyjafjallajökull (2010), Mediterranean transport	Aged ash after ~6–7 d	$\delta_{355} \approx 0.10\text{--}0.25$	LR ₃₅₅ $\approx 55\text{--}67$ LR ₅₃₂ $\approx 76\text{--}89$	Papayannis et al. (2012)
Eyjafjallajökull (2010), Athens and Italy	Aged transported volcanic aerosol	$\delta_{532} \approx 0.07\text{--}0.25$	LR ₃₅₅ $\approx 38\text{--}89$ LR ₅₃₂ $\approx 44\text{--}92$	Kokkalis et al. (2013) Mona et al. (2012)
Etna eruptions (2013), Italy	Fresh volcanic ash plume	$\delta_{355} \approx 0.30\text{--}0.50$	LR ₃₅₅ $\approx 50\text{--}80$	Boselli et al. (2018)
Raikoke (2019), East Asia	Long-lived volcanic aerosol	$\delta_{532} < 0.05$	Not reported	Jing et al. (2023)
Shinmoedake-related (2025), eastern China	Long-range transported, source-related aerosol	Anqing $\delta_{355} < 0.05$	Anqing LR ₃₅₅ $\approx 40\text{--}58$	This study
		$\delta_{532} \approx 0.01\text{--}0.17$	LR ₅₃₂ $\approx 41\text{--}66$	
		Shouxian $\delta_{355} \approx 0.03\text{--}0.18$	Shouxian LR ₃₅₅ $\approx 47\text{--}70$	
		$\delta_{532} \approx 0.03\text{--}0.13$	LR ₅₃₂ $\approx 49\text{--}75$	