AO16: Monitoring the Evolution of Wildfire Smoke Plumes across Varying Atmospheric Altitudes using EarthCARE ATLID

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Abstract

This study tracks how extreme wildfire smoke evolves over time. A high-altitude stratospheric plume (May 2025) was compared with two lower-altitude cases: an upper-troposphere mixed plume (August 2025) and a fully trapped tropospheric plume (August 2024). The advanced Atmospheric Lidar (ATLID) on the EarthCARE satellite was utilized to observe the smoke directly without relying on Lidar Ratio assumptions. To accurately isolate the true smoke cores from clouds and background pollution, a multi-step physical filtering method was developed. The results demonstrate a clear solar-driven self-lofting effect in the pure stratospheric case, with the smoke core ascending by approximately 1.2 km (from 13.5 km to 14.7 km) within a 48-hour window. In contrast, the lower-altitude plumes were broken apart by weather systems and failed to rise. Direct High-Spectral-Resolution Lidar (HSRL) measurements revealed that the Lidar Ratio (S_p) of the smoke is highly dynamic: it ranged between 50 sr and 65 sr in the dry stratosphere, but fluctuated wildly between 30 sr and 80 sr in the lower-altitude regimes due to continuous mixing and hygroscopic growth. These findings directly challenge the historical reliance on static optical assumptions (e.g., 70 sr) and highlight the necessity of active HSRL systems in accurately capturing the true microphysical aging of aerosols.

I. Introduction

Aerosols, particularly those originating from extreme wildfire events, play an important role in the Earth's climate system by scattering and absorbing solar radiation [1]. The altitude at which these aerosols are injected heavily dictates their atmospheric lifetime and subsequent radiative forcing. In recent years, intense wildfires, such as the Canadian wildfires on May 8 and May 30, 2025, have demonstrated the capacity to inject massive amounts of smoke into the stratosphere, providing a unique opportunity to monitor the long-range transport and evolution of these plumes.

To effectively monitor such elevated smoke layers, precise vertical profiling is required. While passive satellite sensors (e.g., MODIS, VIIRS) provide high-resolution horizontal mapping of Aerosol Optical Depth (AOD), they integrate the total column extinction. This results in a "vertical blindness" that cannot distinguish between elevated smoke layers and underlying cloud decks or boundary layer pollution, making it physically impossible to determine injection heights using passive data alone. Active spaceborne lidar systems overcome this by providing necessary vertical "curtain" profiles. Historically, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission (2006–2023) was the primary tool for this using the CALIOP instrument [2]. However, as an elastic backscatter lidar, CALIOP measures the total backscattered signal but cannot independently solve the lidar equation for two unknowns: the backscatter coefficient (β) and the extinction coefficient (σ). Consequently, it relies on an assumed Lidar Ratio (LR) based on a-priori "aerosol type" classification [3]. For rapidly evolving wildfire smoke, where the LR can change from 30 sr to over 80 sr due to aging and coating, these assumptions introduce significant retrieval errors.

The European Space Agency's (ESA) EarthCARE mission, launched in 2024, overcomes this limitation with the Atmospheric Lidar (ATLID), a High-Spectral-Resolution Lidar (HSRL) [4]. ATLID operates at a UV wavelength of 355 nm and employs a high-resolution Fabry-Pérot etalon to spectrally separate the narrow Mie scattering (from aerosols) from the thermally broadened Rayleigh scattering (from atmospheric gas molecules). By using the Rayleigh signal as a known molecular reference, ATLID directly determines the attenuation of the molecular signal. This allows for the independent retrieval of the extinction coefficient and the Lidar Ratio without arbitrary assumptions [6]. Furthermore, the use of 355 nm provides a higher sensitivity to smaller fresh smoke particles compared to the

532 nm channel used by CALIOP, which is critical for capturing the early-stage evolution of wildfire plumes.

Leveraging these advanced HSRL capabilities to fully understand the impact of injection altitude, this study expands the analysis to compare the May 2025 stratospheric event with two additional scenarios: an upper troposphere-lower stratosphere (UTLS) mixed plume originating from a wildfire at approximately 57°N, 102°W in Manitoba, Canada in August 2025, and a tropospheric retention case stemming from a fire near 54°N, 109°W in Saskatchewan, Canada in August 2024.

II. Methods

A. Terminology and Optical Parameters

To ensure rigorous optical characterization within this analysis, the key concepts and Lidar-derived parameters are defined as follows:

- **Pyrocumulonimbus (PyroCb)**: A fire-induced thunderstorm that effectively serves as a chimney, pumping surface-level smoke directly into the upper atmosphere.
- **High-Spectral-Resolution Lidar (HSRL)**: An advanced Lidar system capable of separating aerosol backscatter from molecular backscatter to directly retrieve optical properties.
- **Extinction Coefficient (α_p)**: A measure of the total light attenuation from the Lidar beam per unit distance due to both scattering and absorption by particles.
- **Lidar Ratio (S_p)**: The ratio of the particle extinction coefficient to the particle backscatter coefficient, expressed in steradians (sr). It serves as an indicator of the particle's absorptive nature [5]. For instance, carbon-rich smoke typically exhibits high LR values due to its strong light-absorbing capabilities.
- **Particle Linear Depolarization Ratio (PLDR) (δ_p)**: The ratio of the cross-polarized backscatter signal to the co-polarized signal. It indicates the particle's macroscopic shape. Low values (~ 0.05) suggest spherical particles, while high values indicate non-spherical shapes.
- **Self-Lofting**: A dynamic process where black carbon particles strongly absorb solar radiation. This locally heats the surrounding air, increases the buoyancy of the plume, and causes it to dynamically ascend to higher altitudes over time.

B. Spatiotemporal Collocation and Tracking

A fundamental challenge in monitoring stratospheric aerosols is that Lidar instruments possess an extremely narrow swath. To accurately monitor the plume's movement, the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model [7] was used to predict the trajectories of the source plume. HYSPLIT is an advanced atmospheric transport and dispersion modeling system that calculates the movement of air parcels. By utilizing global meteorological data, it provides forward-trajectory simulations that track how aerosols and pollutants are transported by wind currents over time. This capability is essential for tracking the dynamic pathways of wildfire smoke as it travels across the globe.

Following this, a custom algorithm was used to calculate the coincidence between the predicted smoke pathway and the satellite orbit. An intersection is confirmed only when the satellite overpass falls within a strict spatial threshold ($< 0.5°$) and temporal window ($\pm$ 3 hours) of the moving smoke, allowing for precise spatiotemporal collocation. (Figure 1)

C. Plume Isolation and Physical Filtering Framework

A critical component of this study is isolating the target wildfire smoke from highly complex atmospheric backgrounds, boundary layer pollution, and meteorological clouds. To achieve this, a custom, multi-step algorithmic filtering framework was developed and applied to the EarthCARE Level-2 data

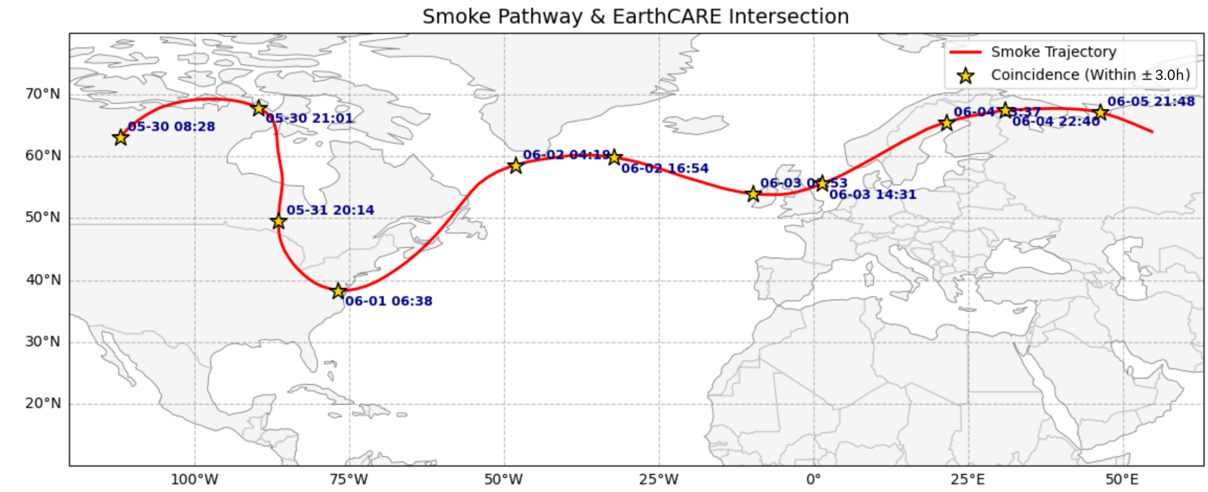


Figure 1: Spatiotemporal collocation showing the HYSPLIT trajectories and intersections with EarthCARE Orbits for May 2025 fire.

arrays. These Level-2 products represent highly processed scientific datasets that translate raw satellite backscatter signals into direct geophysical parameters. They provide high-resolution, two-dimensional spatial grids (arrays) of crucial variables—such as vertical extinction coefficients, depolarization ratios, and aerosol classifications[6].

1. Quality Control and Regime-Specific Identification

First, a strict pixel-level quality gatekeeper is enforced. Only data bins with valid `quality_status` flags (0: Good: Nominal, 1: Likely Good, but possibly degraded or low SNR, and 2: Likely Bad) are retained, while anomalous extinction spikes and negative instrument noise are systematically removed. The spatial identification of the smoke depends on its altitude regime:

- **Stratospheric Regimes:** For high-altitude plumes, the algorithm calculates the Stratospheric Aerosol Optical Depth (SAOD) by integrating the extinction coefficient exclusively from the dynamic tropopause height (z_{tropo}) up to the top of stratosphere.
- **Tropospheric and UTLS Regimes:** When plumes mix below the tropopause, the algorithm cross-references the EarthCARE aerosol classification product. Only atmospheric bins classified as target dust or smoke (classes 4, 5, and 6) or those explicitly penetrating the tropopause are included in the Plume AOD (PAOD) integration.

2. Vertical Structural Isolation (Gap Detection)

To prevent the accidental integration of lower-tropospheric clouds or boundary layer pollution, a top-down vertical continuity check is applied to every individual lidar profile. The algorithm scans downward from the highest detected aerosol layer; if a vertical clean-air gap exceeding 1.5 km is detected, the integration is immediately severed, discarding all layers below the gap.

3. Temporal Smoothing and Geometric Width Validation

Because HSRL data can contain narrow, high-intensity noise pillars, a geometric width validation is applied to the horizontal satellite track. The integrated optical depth sequences (SAOD or PAOD) are smoothed using a 1-D Gaussian filter ($\sigma = 5.0$). An automated peak-finding algorithm then locates the plume cores.

Figure 2 demonstrates the application of this identification process for the May 2025 stratospheric fire. The algorithm isolates the smoke cores (highlighted by red rectangles) from underlying dense clouds, utilizing the smoothed optical depth sequences to determine the plume's horizontal width.

4. Plume Feature Extraction

Once the valid plume is found, the algorithm extracts its key structural metrics. To avoid outliers caused by stray noise pixels, the "Robust Top" of the plume is calculated using the upper statistical percentiles (e.g. 90^{th}) of the layer tops within the validated window. Simultaneously, the core mass

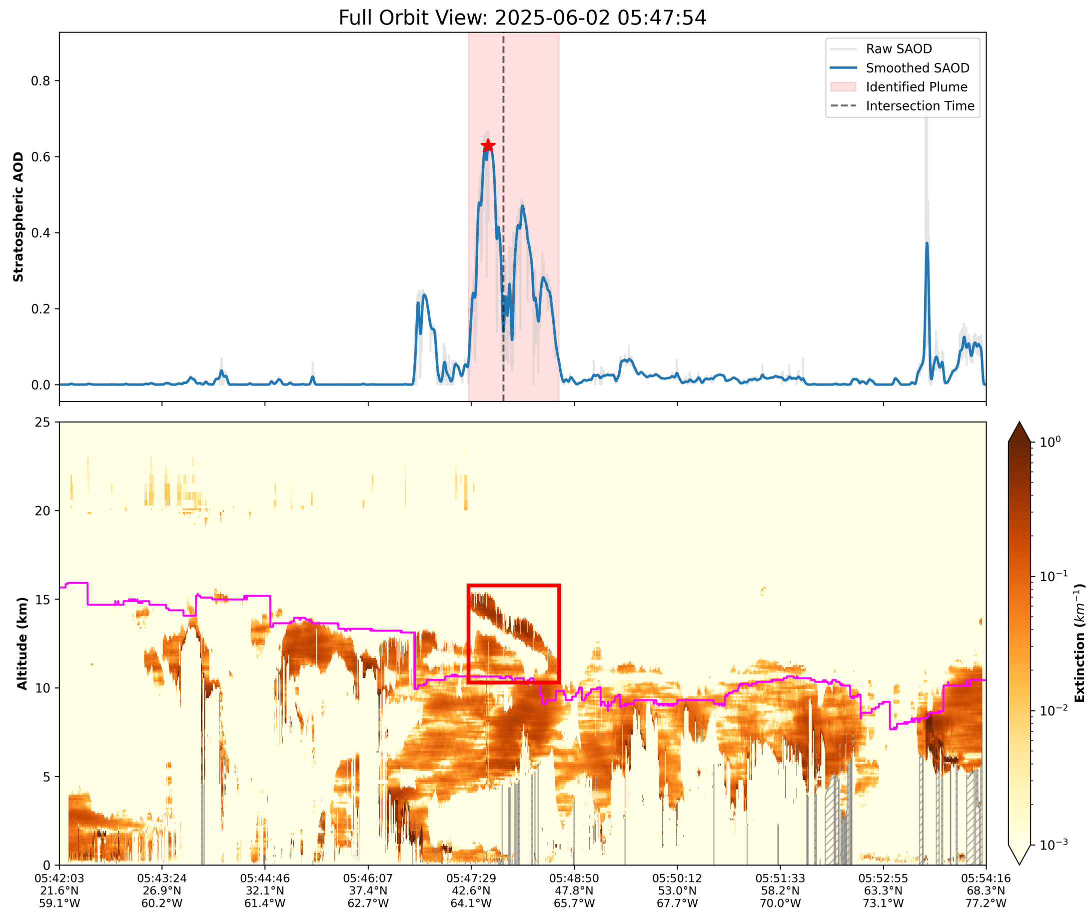


Figure 2: Example of the automated plume identification process for the May 2025 stratospheric fire. The upper panels display the smoothed horizontal optical depth sequence (blue line) used to determine the plume's horizontal boundaries (highlighted by the shaded region and red star). The lower panels present the corresponding vertical extinction coefficient profiles. The smoke cores are bounded by red rectangles, demonstrating their separation from dense clouds located below the dynamic tropopause (represented by the magenta line).

height is calculated as the extinction-weighted centroid, accurately representing where the bulk of the aerosol mass resides regardless of the plume's diffuse boundaries.

III. Results and Discussion

A. Case 1: Stratospheric Injection and Self-Lofting (May 2025)

To validate the origin and track the long-range transport of the May 2025 stratospheric smoke, HYSPLIT forward trajectories were mapped against EarthCARE orbital overpasses. As illustrated in Figure 3, the spatial overlap between the predicted smoke pathways (red lines) originating from the fire source (yellow star) and the satellite tracks provides robust confirmation of the plume's trajectory. Furthermore, the color intensity along the intersecting orbital tracks represents the retrieved Stratospheric Aerosol Optical Depth (SAOD), indicating a persistent and highly concentrated stratospheric aerosol load as it traveled eastward across the Atlantic.

The tracking of the May 2025 stratospheric smoke reveals a distinct vertical ascent over time (Figure 4). Residing entirely above the tropopause, the plume's core height steadily ascended from approximately 13.5 km on May 30 to 14.7 km by June 1. This observed ascent of approximately 1.2 km within a 48-hour window demonstrates the solar-driven self-lofting effect, a dynamic physical process fundamentally driven by the unique composition of the fire smoke.

Extreme wildfires are characterized by the incomplete combustion of massive amounts of forest

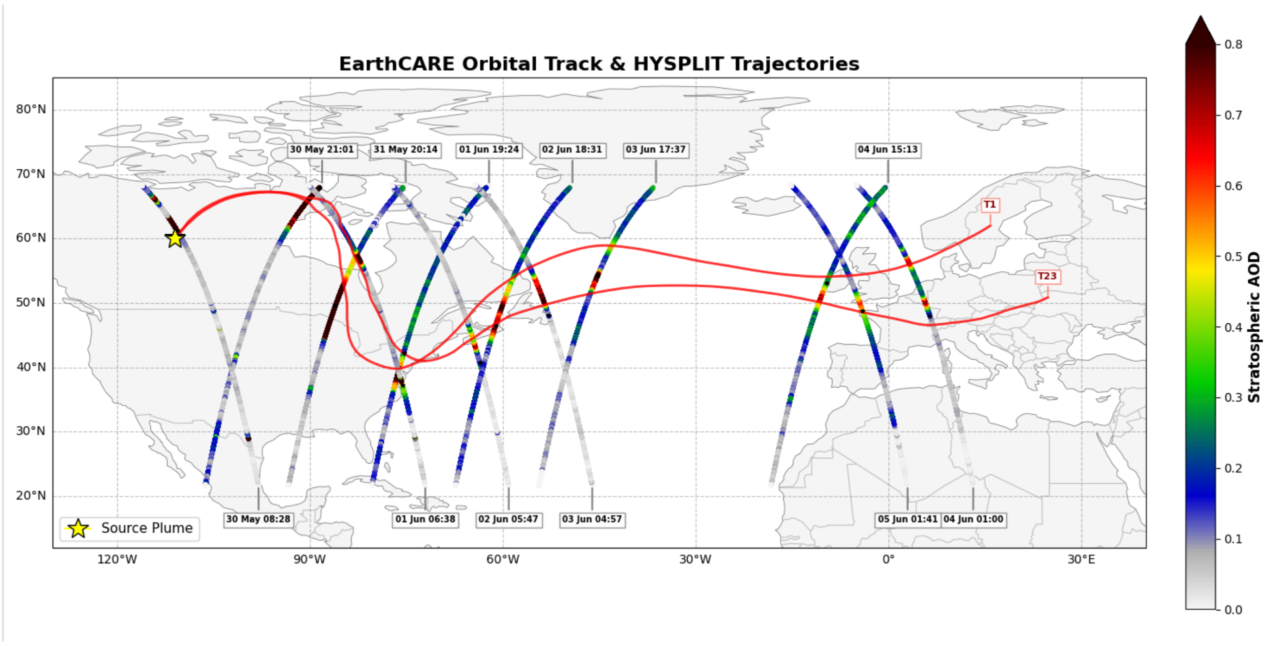


Figure 3: Spatiotemporal collocation showing the EarthCARE orbital track and HYSPLIT trajectories for the May 2025 stratospheric case. The colorbar indicates the Stratospheric Aerosol Optical Depth (SAOD), representing the vertically integrated aerosol extinction coefficient (σ_{ext}) specifically restricted to atmospheric layers above the tropopause.

biomass. This intense burning process generates dense concentrations of carbonaceous aerosols, which form the physical backbone of the visible smoke plume. Unlike highly reflective atmospheric particles (such as sulfates or sea salt) that scatter light, these carbonaceous aerosols act as potent radiation absorbers. Once injected into the clear, stable environment of the stratosphere, the black carbon vigorously absorbs incoming solar shortwave radiation. This absorbed solar energy is continuously converted into sensible heat (diabatic heating), directly warming the ambient air mass trapped within the plume. As this localized air parcel heats up, it gains thermal buoyancy, causing the entire smoke structure to act effectively as a hot air balloon, dynamically lifting itself to progressively higher altitudes over time.

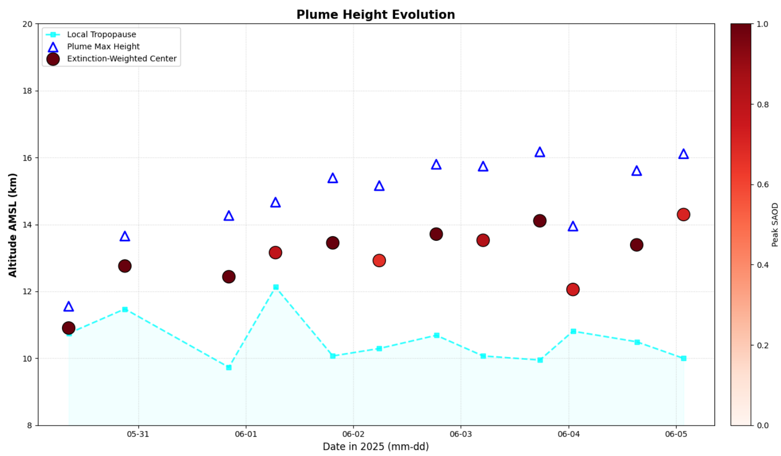
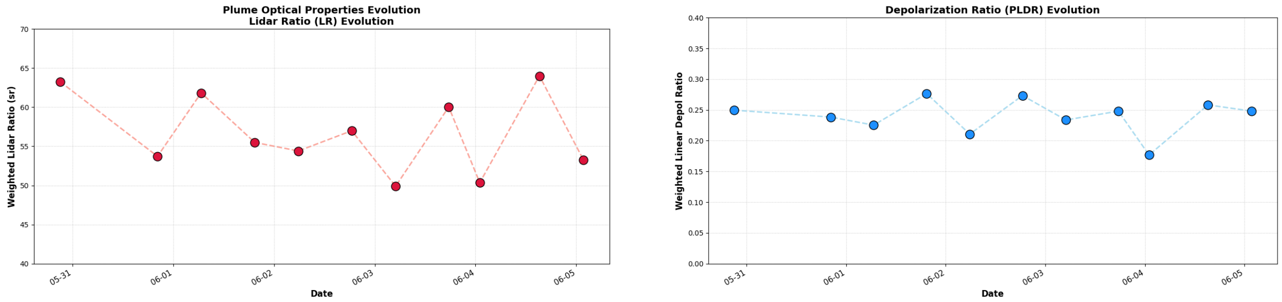


Figure 4: Plume height evolution of the May 2025 case, demonstrating the solar-driven self-lofting effect.

The optical properties further validate this self-lofting mechanism. Historically, standard elastic backscatter lidars like CALIPSO relied on an assumed, constant Lidar Ratio for biomass burning smoke (typically 70(16) sr) to retrieve extinction profiles [8, p. 10]. While the direct HSRL measurements from EarthCARE show that the S_p primarily ranges between 50 sr and 65 sr (Figure 5a)—validating the rough accuracy of the historical assumption—they crucially reveal that the Lidar Ratio is *not* a constant value. Instead, it fluctuates as the plume evolves, driven by the intense light-absorbing capabilities of black carbon that catalyze the self-lofting.

The evolution of the Particle Linear Depolarization Ratio (δ_p) indicates a dynamic, non-monotonic aging process. Following an initial decrease—which suggests a partial sphericalization of the irregular soot aggregates—the PLDR changes into a pattern of repeated, somewhat regular oscillations(Figure 5b).

This distinct oscillatory behavior is likely driven by temperature variations within the dry stratosphere. During the day, intense solar absorption by the black carbon cores triggers localized diabatic heating, causing organic coatings to evaporate and re-exposing the highly irregular soot structures (δ_p increases). Conversely, during the much cooler night, these volatile compounds re-condense onto the particle surfaces, temporarily forming more spherical liquid shells (δ_p decreases). Consequently, the smoke particles undergo continuous evaporation-condensation cycles.



(a) Lidar ratio evolution for the May 2025 stratospheric plume.

(b) Depolarization ratio evolution of the May 2025 plume, indicating a transition to spherical, aged particles.

Figure 5: Optical properties evolution of the May 2025 stratospheric plume.

B. Case 2: UTLS Interface Intrusion (August 2025)

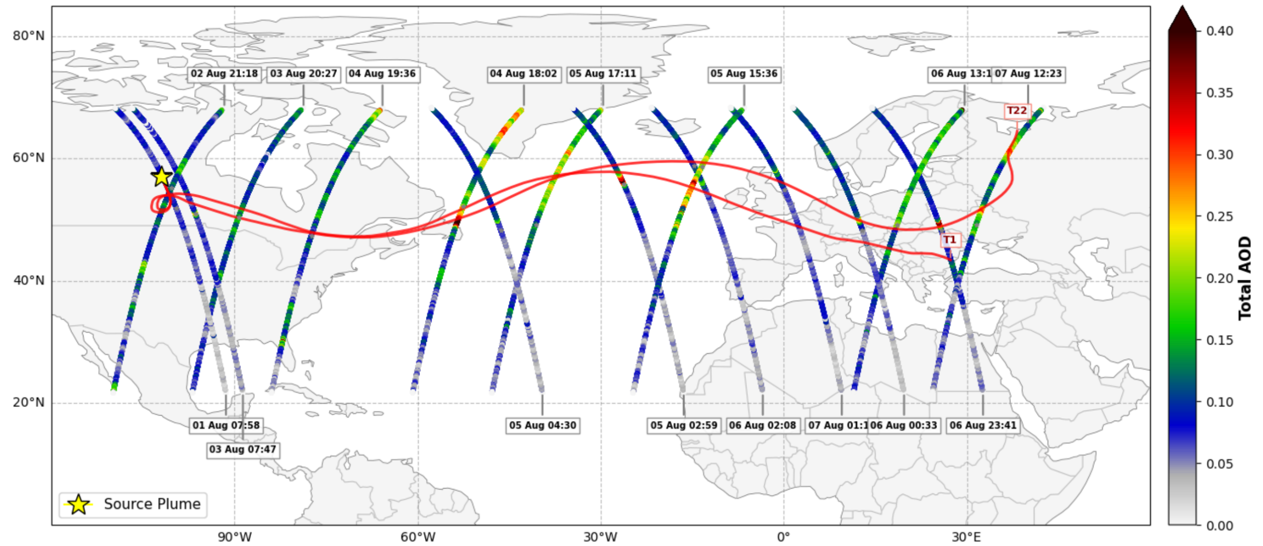


Figure 6: The early August 2025 UTLS mixed plume. HYSPLIT forward trajectories (red lines) from the fire source (yellow star) mapped against EarthCARE tracks. The colorbar indicates Total Plume Aerosol Optical Depth (PAOD)

In contrast to the May event, the August 2025 plume (Fig. 6) exhibited complex dynamics at the UTLS interface.

For the plume height evolution, while the maximum plume height closely tracked or slightly penetrated the dynamic tropopause, the extinction-weighted centroid remained significantly lower (Fig. 7) This structural gap highlights a fluctuating trend where the plume fails to sustain a steady ascent, primarily because the initial injection energy was insufficient to fully breach the stable stratosphere.

The LR, as shown in Figure 8a, exhibits variability that deviates markedly from the stability typically observed in the stratosphere. While LR occasionally peaks near 80 sr—a hallmark of highly light-absorbing carbonaceous aerosols—it also undergoes sharp decreases. This volatility directly challenges the validity of a static 70 sr assumption. It reflects the complex heterogeneity of the UTLS (Upper Troposphere-Lower Stratosphere) interface, where fresh pyrogenic plumes continuously interact and mix with ambient tropospheric aerosols.

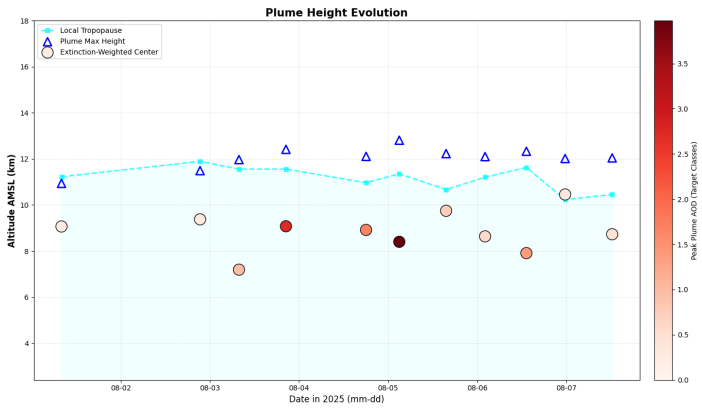
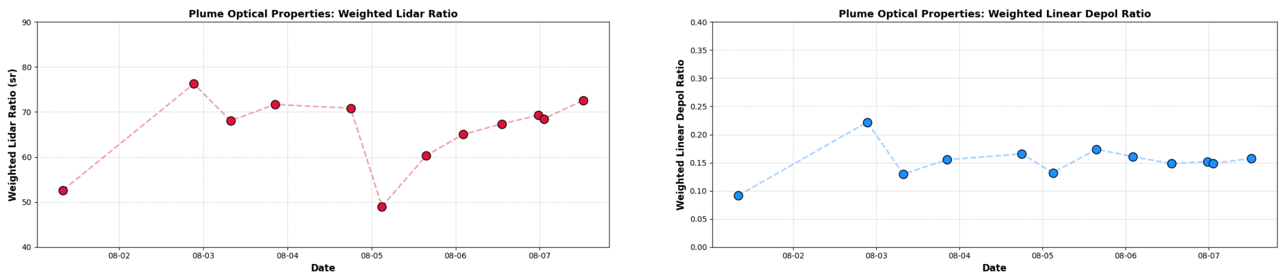


Figure 7: Height evolution of the early August 2025 UTLS mixed plume. The gap between the plume top and weighted centroid highlights intense tropospheric mixing.

Simultaneously, the PLDR (Figure 8b) displays an inconsistent aging trajectory. Following an initial high near 0.22 (indicating non-spherical, fresh smoke), the ratio drops but continues to fluctuate rather than showing a smooth monotonic decay. This pattern suggests that continuous turbulent mixing and potential tropopause folding events inject fresh particulates or alter the environmental humidity, thereby preventing a uniform structural collapse (sphericalization) of the particles.



(a) Extinction-weighted Lidar ratio evolution for the early August 2025 UTLS case.

(b) Depolarization ratio evolution for the early August 2025 UTLS case, showing inconsistent aging patterns due to mixing.

Figure 8: Optical properties evolution of the early August 2025 UTLS case.

C. Case 3: Tropospheric Retention (August 2024)

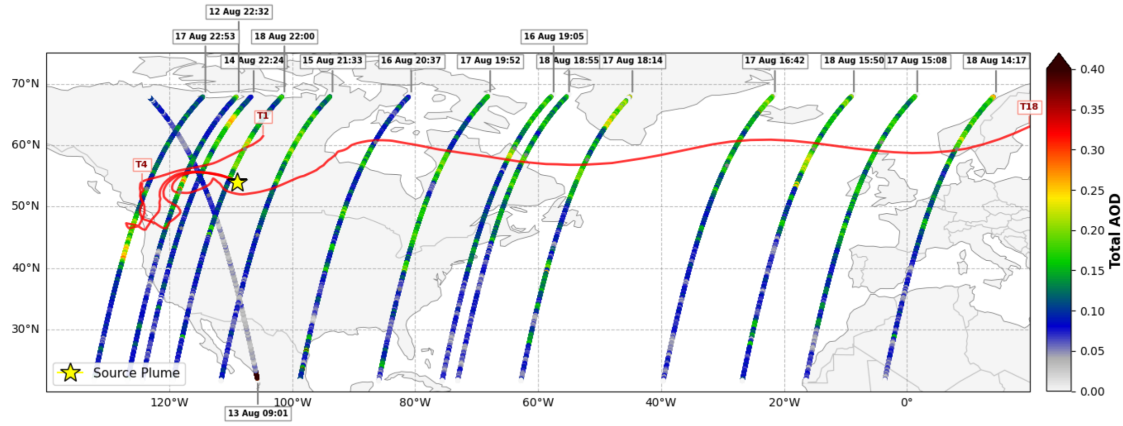


Figure 9: The mid-August 2024 case. HYSPLIT forward trajectories (red lines) from the fire source (yellow star) mapped against EarthCARE tracks. The colorbar indicates Total Plume Aerosol Optical Depth (PAOD)

The mid-August 2024 case (Fig. 9) represents a strictly tropospheric regime. The local tropopause remained high, while the absolute maximum height of the smoke plume never exceeded mid-tropospheric levels. Lacking the buoyancy from a powerful PyroCb injection, the smoke was entirely subjected to tropospheric weather dynamics, leading to a largely flat or gradually descending height trend. Widespread subsidence and turbulent dispersion physically constrained the plume (Fig. 10).

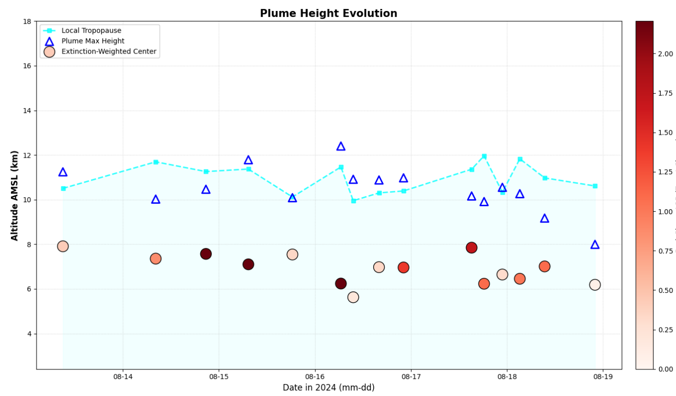
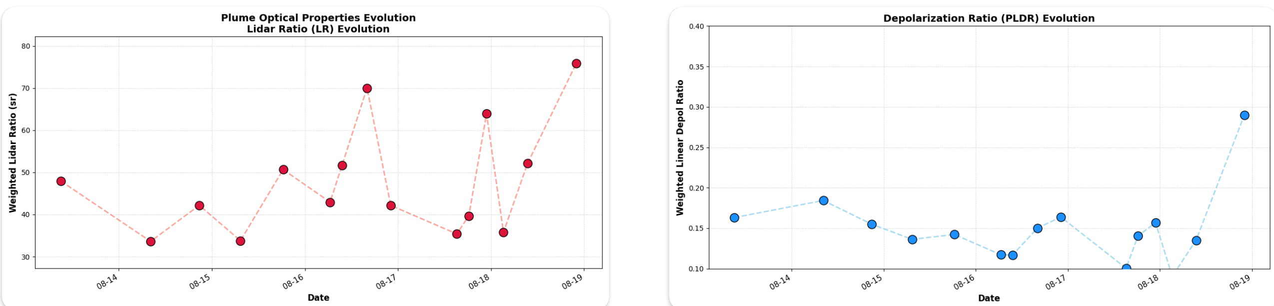


Figure 10: Height evolution of the mid-August 2024 case, depicting a plume completely retained within the lower free troposphere.



(a) Extinction-weighted Lidar ratio evolution for the mid-August 2024 tropospheric retention case.

(b) Depolarization ratio evolution for the mid-August 2024 tropospheric retention case.

Figure 11: Optical properties evolution of the mid-August 2024 tropospheric retention case.

For this purely tropospheric case, the optical transformation is even more erratic. The S_p values (Figure 11a) are notably lower and fluctuate between 35 sr and 75 sr. Applying a standard CALIPSO (70 ± 16) sr assumption here would result in severe AOD retrieval errors (up to 100 %), as the aerosol composition is constantly altered by the dense surrounding atmosphere.

Simultaneously, the PLDR (Figure 11b) remains generally low but unstable. This indicates rapid hygroscopic growth (water uptake) and cloud scavenging in the moisture-rich lower atmosphere. The soot particles are quickly coated by water and secondary aerosols, masking their irregular black carbon cores much faster and more chaotically than their counterparts in the dry stratosphere.

IV. Conclusion

This study successfully leveraged the newly launched EarthCARE satellite, specifically its High-Spectral-Resolution Lidar (ATLID), to monitor the transport, structural evolution, and optical transformation of wildfire smoke plumes. By coupling NOAA HYSPLIT forward trajectories with a rigorous, multi-step filtering algorithm, the target smoke cores were isolated from complex meteorological backgrounds and boundary-layer pollution. This spatiotemporal framework enabled the continuous tracking of specific aerosol masses across varying atmospheric regimes.

For the May 2025 stratospheric injection, the smoke resided in a stable environment free from meteorological scavenging. Here, the highly absorptive carbonaceous aerosols converted solar radiation into diabatic heating, resulting in a clear, sustained self-lofting effect. Conversely, the August 2025 UTLS and August 2024 tropospheric plumes lacked the injection energy to fully breach the stratosphere. Consequently, they were subjected to intense wind shear, tropopause folding, and widespread subsidence, which neutralized any lofting potential and led to chaotic vertical mixing and structural decoupling.

Crucially, EarthCARE's ability to directly measure the extinction coefficient without relying on assumed Lidar Ratios revealed the dynamic nature of smoke optical properties. While historical methodologies (such as CALIPSO's static $\sim$70 sr assumption for biomass smoke) roughly align with the stable stratospheric case, they fall significantly short in the UTLS and lower troposphere. In these lower regimes, continuous mixing with ambient aerosols and rapid hygroscopic growth caused the Lidar Ratio to fluctuate wildly between 30 sr and 80 sr. Furthermore, the Particle Linear Depolarization Ratio (PLDR) tracked across all cases provided clear evidence of particle aging, demonstrating how irregular soot aggregates gradually collapse into spherical droplets as they transport.

While this study derives valuable insights from EarthCARE's ATLID, it is important to acknowledge certain methodological uncertainties. First, the HYSPLIT forward trajectories are subject to cumulative meteorological errors over extended transport periods. Furthermore, although the HSRL technique explicitly retrieves Lidar Ratios, the Level-2 optical products still carry inherent uncertainties. These are primarily associated with Signal-to-Noise Ratio (SNR) limitations, which become more pronounced in optically thin stratospheric aerosol layers or heavily attenuated lower-tropospheric regions.

Additionally, the automated plume isolation framework relies on specific empirical thresholds—such as the 1.5 km vertical gap constraint (to separate boundary-layer features) and the Gaussian smoothing window ($\sigma = 5.0$)—which were selected to optimize the signal extraction. Consequently, the exact calculation of the extinction-weighted centroid exhibits some sensitivity to these filtering criteria. However, sensitivity observations suggest that while varying these thresholds can introduce minor shifts in absolute altitude values, the overarching physical trends—the stratospheric ascent and the distinct regimes of optical aging—remain consistent.

Building upon this, future research could integrate ATLID's high-resolution vertical profiles with broad-swath passive multi-spectral sensors (e.g., Sentinel-5P). Such a synergistic approach would help address current spatiotemporal tracking limitations and provide a more comprehensive understanding of the chemical and microphysical evolution of extreme wildfire smoke.

Ultimately, these findings underscore the critical advantage of spaceborne HSRL instruments. Moving beyond static assumptions allows for a much more accurate characterization of dynamic aerosol optical properties and particle microphysics. This advancement is essential for reducing uncertainties in global climate models and understanding the true radiative forcing impact of increasingly frequent extreme wildfire events.

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