Anonymous Referee RC#2

The authors appreciate the thorough assessment of our work and the key suggestions in improving our manuscript. The submitting manuscript is substantially altered addressing all the issues raised. Reviewer comments are highlighted in blue, and our responses are presented in regular font. The text in quotation marks and shown in italics denotes the text that features the submitting manuscript.

<u>Response to General Comments</u>

The manuscript by Papanikolaou and coauthors presents a 16-year analysis of CALIOP Level 2 observations of stratospheric aerosols over Europe, focusing on aerosol occurrence, vertical distribution, subtype classification and stratospheric aerosol optical depth. The topic is relevant and timely. Stratospheric aerosols produced by volcanic eruptions and wildfire-driven pyroCb events have important radiative, chemical and dynamical impacts, and the CALIOP record provides a long-term vertically resolved dataset for documenting their evolution. Europe is also an interesting receptor region for long-range transport of volcanic and wildfire plumes and benefits from complementary ground-based lidar observations within a dense European lidar network.

However, I find that the manuscript requires major revision before publication. My main concern is that the regional subdivision of Europe into 12 boxes, especially the four longitudinal sectors within each latitude band, is not sufficiently justified physically. The main aerosol sources considered in the study — Aleutian/Kuril volcanic eruptions, Nabro, Raikoke as well as North American and Siberian wildfires — are located thousands of kilometers away from Europe. By the time these plumes reach Europe in the lower stratosphere, their transport is largely controlled by large-scale quasi-zonal circulation. One would therefore not expect physically meaningful changes in aerosol optical properties from one European longitude sector to the next within the same latitude band.

Apparent differences between these longitude sectors may instead reflect CALIPSO sampling geometry, the timing of individual overpasses, small-number statistics, or the arbitrary intersection of filamentary plumes with the satellite track. The manuscript briefly acknowledges that regional variations may be affected by the intersection of plume transport and satellite orbital geometry, but this caveat is not sufficiently reflected in the interpretation. Several statements about "regional transport pathways", "localized variations", "longitudinal fingerprints" or east–west differences appear overinterpreted in the absence of trajectory analysis, event-resolved plume tracking, or statistical evidence that such longitudinal differences are robust.

As far as the latitudinal subdivision is concerned, differences between northern, central and southern Europe may be physically meaningful, given the influence of high-latitude sources, the Brewer–Dobson circulation and the latitudinal structure of transport. However, the physical meaning of the longitudinal breakdown is not demonstrated. I recommend that the authors either provide a much stronger justification for this subdivision, supported by transport diagnostics or event-based analysis, or simplify the analysis by aggregating the data zonally within latitude bands.

We thank the reviewer for this constructive comment. We agree that the long-range transport of volcanic and pyroCb plumes into Europe is governed by large-scale, quasi-zonal circulation. Upon re-evaluation, we recognize that the original 12-box subdivision —particularly the longitudinal breakdown— could introduce unnecessary complexity due to CALIPSO sampling geometry, plume filamentation, or orbital tracks, making it difficult to distinguish localized variations from broader regional pathways. Following the reviewer's recommendation and in accordance with RC#1, we have restructured our spatial analysis. We have eliminated the longitudinal subdivisions and simplified the domain into three broad latitudinal zones, with each zone extending continuously across the full longitudinal range from 10° West to 30° East:

- South Zone: 35° to 45° North

- Central Zone: 45° to 55° North
- North Zone: 55° to 65° North

This zonal aggregation resolves the issues of small-number statistics and arbitrary orbital intersections, ensuring that the documented aerosol frequencies, properties, and trends reflect robust atmospheric features. The entire manuscript and figures, along with the associated discussion sections, have been updated to reflect this new framework.

My second concern is that many conclusions drawn from the regional analysis are overinterpreted relative to the information content of the figures. The manuscript often reads as a descriptive walkthrough of multi-panel figures rather than a physically supported analysis. In several places, apparent differences between subregions are attributed to specific volcanic or wildfire sources without sufficient evidence. The attribution of European sAOD enhancements to "geographical proximity" of remote eruptions is particularly problematic, since stratospheric source-receptor relationships depend on injection altitude, season, isentropic transport or diabatic self-lofting, mixing and the timing of satellite sampling, not simply on geographical distance.

The use of occurrence counts also needs clarification. The manuscript refers to "profiles containing stratospheric aerosols", but background stratospheric aerosol is always present. The authors should specify whether they mean CALIOP-detected stratospheric aerosol features above the detection threshold, enhanced aerosol layers, or another quantity. This distinction is important because much of the discussion relies on counts of stratospheric aerosol detections.

We thank the reviewer for these remarks. We have thoroughly revised the manuscript accordingly to reduce overinterpretation, strengthen the physical context of the discussion, and use more cautious language when relating regional aerosol enhancements to specific events. We also clarified the definition of the occurrence counts throughout the manuscript, explicitly stating that they refer to CALIPSO-detected stratospheric aerosol layers above the detection threshold rather than background stratospheric aerosol.

Finally, the change-point and trend discussion should be toned down. The record is strongly event-driven, and the post-2016 period includes several major episodic perturbations, including the 2017 PNE wildfire event, Raikoke in 2019, and later North American and Siberian fire seasons. This clustering of events may produce an apparent step-like change without implying a new persistent background regime. The authors should clearly distinguish between temporary event-driven enhancement and a real change in the baseline state of European stratospheric aerosol.

It was not our intention to suggest a permanent or fundamental change in the baseline background state of the stratosphere itself. We completely agree that our study is strongly event-driven and that the apparent step-like behavior after 2016 is the result of multiple major episodic perturbations—such as the 2017 Pacific Northwest wildfires, the 2019 Raikoke eruption, and subsequent intense fire seasons—occurring in close succession. Rather than a permanent shift in the background regime, what this trend and change-point analysis captures is a distinct period where these extreme, highly pronounced events are clustered together in time. To prevent any misunderstanding, we have thoroughly toned down the discussion in the trend section and removed the part of change point analysis. We have revised the text to explicitly clarify the distinction between a temporary, event-driven enhancement and a true change in the baseline state, highlighting the increase could represent clustered series of intense perturbations rather than a new permanent stratospheric regime.

Response to Specific Comments.

l.16 To the best of my knowledge, neither Raikoke nor Siberian plumes have been reported to rise above 29 km.

Our intention was not to state that Raikoke or the Siberian wildfire plumes definitively reached altitudes above 29 km. Rather, these values represent the upper altitude limits where the CALIPSO feature detection algorithm classified features as stratospheric aerosols during those periods. However, we agree that attributing these specific high-altitude detections to Raikoke or Siberian plumes is speculative, even though some literature suggests long-range transport and self-lofting mechanism pathways can approach these altitudes (~27km) in the Northern Hemisphere (Yang et al., 2026). To prevent any misinterpretation, we have removed the phrase "especially following Raikoke's eruption and major Siberian fire seasons" from this sentence.

l.94–95: Please clarify how sAOD is calculated, including the vertical integration limits, the tropopause product used, and the effect of tropopause uncertainty.

We have updated and expanded the text to clearly specify the calculation method, the integration limits, the tropopause product used, and the potential impacts of tropopause uncertainty on our sAOD retrievals. The text has been revised as follows, lines 105-117 of the submitting manuscript:

"The primary aerosol optical properties used here include the aerosol backscatter coefficient (b_{aer}) and aerosol extinction coefficient (a_{aer}) at 532 nm, and the stratospheric aerosol optical depth (sAOD), derived by integrating each a_{aer} profile from the tropopause up to 30 km. The tropopause height (TPPH) from CALIPSO APro L2 product, used for this study, is obtained from the Modern-Era Retrospective analysis for Research Applications, version 2 (MERRA-2) meteorological reanalysis product (Gelaro et al., 2017). TPPH uncertainty in the MERRA-2 reanalyses primarily stems from high-altitude biases, poor vertical resolution in the upper troposphere/lower stratosphere (UTLS), and discrepancies in tracking sharp thermal boundaries (Weyland et al., 2025; Manney et al., 2014). The main effect of this uncertainty on the sAOD calculation is concentrated in the UTLS region; an overestimation or underestimation of the tropopause height by MERRA-2 can artificially exclude lower stratospheric aerosol layers or mistakenly include upper tropospheric feature enhancements in the integration. Given the high concentration of transported plumes near the UTLS boundary over Europe, this can introduce a minor localized variance in the absolute sAOD values, though it does not significantly alter the long-term relative trend (Xian and Homeyer, 2019). "

l.100–105: The boxes are 10° × 10° in latitude/longitude, but their physical size varies with latitude. Please clarify whether averaging is area-weighted or sampling-weighted.

We acknowledge that the original manuscript did not describe the sampling-weighting procedure used in the averaging calculations. However, the averaging methodology already accounted for the number of observations contributing to each orbit mean. In the revised manuscript, we have clarified this approach and described the sampling-weighted averaging method used across the newly defined latitudinal zones. Because the satellite orbit density and the physical dimensions of the grid cells vary with latitude, sampling-weighted averaging ensures that the calculated optical properties directly reflect the actual distribution and density of the observations within each zone, preventing under-sampled regions from disproportionately influencing the regional means. This methodology has been now included in the revised manuscript, lines 230-241: "Because CALIPSO operates in a a sun-synchronous near-polar orbit, its ground tracks converge toward higher latitudes, resulting in a greater sampling density in the northern zones. *To account for this spatial sampling asymmetry, the orbit-mean profiles, $\bar{x}_{orbit}$, were aggregated into monthly and annual means, weighted by the number of the 5-km profiles contributing to each orbit average as:*

$$\bar{x}_{monthly} = \frac{\sum_{orbits} N_{orbit}\bar{x}_{orbit}}{\sum_{orbits} N_{orbit}} \quad (1)$$

This approach ensures that the resulting values are equivalent to a direct arithmetic mean of all individual profiles within a given latitude zone and prevents regional statistics from being disproportionately influenced by variations in satellite sampling density. To characterize the overall stratospheric state, both monthly and annual averages were computed alongside their respective aerosol type contributions for each zone. Finally, a pan-European assessment was performed to represent the whole study area."

l.127–132: The limitations of CALIOP subtype classification should be discussed more fully, especially for mixed or aged aerosol layers.

We agree that the limitations of the CALIPSO subtyping algorithm regarding mixed and aged stratospheric plumes, warrant a more detailed discussion. We have expanded this section in the manuscript to explicitly address how long-range transport and atmospheric aging alter the optical properties of these layers, sometimes leading to misclassifications.

The revised text can be found in lines 179-190, as follows:

"In particular, smoke transported from the troposphere into the Upper Troposphere and Lower Stratosphere (UTLS) via self-lofting, rather than direct pyroCb activity, may still be misclassified as sulfate due to the similarly low depolarization values of both aerosol types (Tackett et al., 2023; Ansmann et al., 2021)*. Furthermore, the classification algorithm faces some limitations when dealing with aged or mixed aerosol layers during long-range transport. Long-range transported wildfire smoke has also been documented to exhibit optical signatures that closely mimic volcanic sulfate, leading to misclassifications* (Ansmann et al., 2021)*. CALIPSO stratospheric aerosol classification requires extra care for sulfate–ash mixtures that tend to be misclassified as smoke. Notably, the misclassification frequencies of smoke as volcanic ash are substantially higher during the day than at night (up to 27% at day and 1% at night) (Tackett et al., 2023). The identification of mixed plumes where smoke, volcanic sulfates, or ash coexist still requires improvements. As suggested by Tackett et al. (2023), combining CALIPSO data with SO_2 and CO measurements from other satellite sensors could provide the complementary information needed to better differentiate these mixed layers."*

l.234–237: Please define "profiles containing stratospheric aerosols". Background stratospheric aerosol is generally present, so the detection criterion needs to be clear.

Our original phrasing was inaccurate. The background stratospheric aerosols are permanently present across all profiles. We intended to refer to the number of profiles containing detected, enhanced stratospheric aerosol load rather than the baseline background state as described by Thomason et al. (2021, 2023) as was also suggested by RC#1. We have revised the text accordingly.

l.253–255: The claim that vertical broadening is largely driven by increasing pyroCb frequency should be supported quantitatively.

We agree that attributing the apparent increase in aerosol layer altitude and vertical extent specifically to increasing pyroCb frequency would require a dedicated quantitative analysis that is beyond the scope of the present study. However, in the revised manuscript, Fig. 5 has been replaced and the associated discussion has been substantially revised (lines 366–388). The previous statement linking the observed aerosol distribution primarily to increasing pyroCb activity has been removed. Instead, the revised text focuses on the observational evidence from CALIPSO and discusses major volcanic eruptions and documented wildfire events as possible contributors to the enhanced stratospheric aerosol occurrence and elevated aerosol layers during the specific period (e.g., 2017 and 2019–2022), without making a quantitative attribution to pyroCb frequency.

l.263–266: The statement that changes in C-4 “directly” reflect Siberian smoke transport is too strong without event-specific transport evidence.

This now has been removed from the revised manuscript, since we no longer have the specific subregions, but 3 latitudinal zones as suggested.

l.295–299: The interpretation of the north–south gradient in unclassified aerosol fraction as aging or mixing is plausible but speculative. Please support it with optical-property diagnostics or phrase it more cautiously.

We agree that attributing the north–south gradient in the unclassified aerosol fraction solely to aging or mixing was overly speculative without further qualification. We have revised this discussion to be much more cautious and have supported it by discussing the specific optical-property diagnostics that drive these features into the unclassified category when plumes disperse. The text has been updated as follows, in lines 475-484:

“This may reflect the transition from relatively fresh, concentrated plumes to more dispersed, aged, or mixed aerosol layers in the South. From an optical standpoint, as these layers disperse and undergo long-range transport, their particulate depolarization ratios and lidar ratio values can shift into intermediate, overlapping ranges that fail to satisfy the strict threshold criteria required by the CALIPSO algorithm for definitive categorization as pure sulfate or smoke (Tackett et al., 2023). Furthermore, the algorithm routes all weakly scattering features with a feature-integrated attenuated backscatter at 532 nm (γ’) of less than 0.0003 sr^{-1} directly into the unclassified category. Because these low-backscatter layers can belong to any aerosol type provided their integrated backscatter is sufficiently low, the gradual dilution and attenuation of the plumes during transport could drive a higher frequency of unclassified detections in the South, though further multi-sensor observations would be needed to definitively confirm the exact mixing states.”

l.306–317: The attribution of sAOD enhancements to the geographical proximity of eruptions is oversimplified for stratospheric transport.

We agree that stratospheric aerosol transport is governed by large-scale circulation processes and cannot be explained solely by the geographical proximity of the source region. In the revised manuscript, the figure and associated discussion have been substantially revised. The original statement attributing enhanced northern sAOD directly to the proximity of volcanic sources has been removed. Instead, we now discuss the influence of stratospheric transport processes, including the polar vortex and Brewer–Dobson circulation. This revision provides a more physically realistic interpretation of the observed regional sAOD patterns and avoids attributing the signal solely to source proximity. The following paragraph was added to the revised manuscript, lines 492-498:

“The enhanced sAOD observed over northern Europe cannot be explained solely by the proximity of source regions. Aerosols injected at northern extratropical latitudes are strongly influenced by the polar vortex and large-scale stratospheric circulation, which tend to confine and redistribute aerosol mass within the Northern Hemisphere (Fuglestvedt et al., 2024; Guðlaugsdóttir et al., 2025). In contrast, aerosols injected in the tropics are more efficiently dispersed by the Brewer–Dobson circulation, promoting transport across a broader hemispheric or near-global scale (Schoeberl and Ueyama, 2025). Consequently, northern extratropical perturbations may produce a stronger regional aerosol signal over Europe, even when tropical eruptions exert a larger influence on the global stratospheric aerosol burden (Toohey et al., 2025).”

l.326–331: The claim that northern regions are higher because they are closer to sources and transport pathways needs stronger dynamical support.

We thank the reviewer for this comment. We agree that the original wording did not sufficiently explain the dynamical basis for the enhanced aerosol loading observed over northern Europe. The text has been revised to clarify that the higher sAOD values in the northern regions are not solely attributed to proximity to source regions but are also related to the transport characteristics of northern extratropical injections. Previous modelling studies have shown that aerosols injected at northern high latitudes are strongly influenced by the polar vortex and large-scale stratospheric circulation, leading to preferential transport within the Northern Hemisphere *(Fuglestvedt et al., 2024; Guðlaugsdóttir et al., 2025).* In contrast, tropical injections are more efficiently redistributed by the Brewer–Dobson circulation and therefore produce a broader hemispheric or near-global dispersion of aerosol mass *(Schoeberl and Ueyama, 2025)*. As a result, extratropical eruptions can generate stronger regional aerosol signals over Europe despite tropical eruptions often having a larger global influence *(Toohey et al., 2025).* This revision, discussed in lines 492-498 provides a more physically realistic interpretation of the observed regional sAOD patterns and avoids attributing the signal solely to source proximity, consistent with the discussion in comment l.306–317.

l.346–358: The claimed “distinct longitudinal fingerprints” and eastward intensification are not convincing. Please demonstrate their robustness or avoid interpreting them as transport signatures.

We thank the reviewer for this point. We agree that the evidence presented in the original manuscript was insufficient to robustly support the interpretation of “distinct longitudinal fingerprints” or eastward intensification as transport signatures. However, as part of the major revision of our spatial framework (see General Comment Response and RC#1), we have completely removed the corresponding discussion (former lines 346–358) from the revised manuscript. Specifically, we no longer subdivide the study domain into longitudinal sub-regions. Instead, the analysis has been restructured around three broad latitudinal zones (South, Central, and North) that span the full longitudinal extent of the study area. Consequently, longitudinal variations are no longer examined or interpreted, and the associated discussion of potential transport signatures has been eliminated. This revised approach provides a more robust characterization of regional aerosol patterns while avoiding conclusions that cannot be unambiguously supported by the available observations.

l.354–358: The caveat about satellite orbital geometry is important and should be expanded, as it may explain much of the apparent regional variability.

We agree that the orbital geometry of CALIPSO is an important consideration when interpreting regional variability. The orbital geometry of polar-orbiting satellites introduces a fundamental sampling bias that can distort perceived regional variability if left unaddressed. Because CALIPSO travels in a sun-synchronous, near-polar orbit, its ground tracks naturally converge at higher latitudes. This geometric convergence results in a significantly higher spatial sampling density in the northern zones compared to the subtropics. This geometric asymmetry yields a significantly higher number of daily profiles per unit area in the northern zones compared to the southern, subtropical zones.

From a statistical standpoint, this higher sampling frequency increases the likelihood of detecting localized, low-amplitude, or short-lived aerosol filaments in the north that might be missed by the sparser track spacing further south. If left uncorrected, this uneven data density could misrepresent the true extent of regional variability and artificially bias regional means. To mitigate this orbital sampling bias and ensure that the apparent latitudinal gradient reflects physical differences in aerosol loading rather than geometric artifact, the regional optical properties in this study are computed using a sampling-weighted averaging approach. This method normalizes the data relative to the spatial distribution of the observations, effectively decoupling the satellite's track density from the derived regional trends.

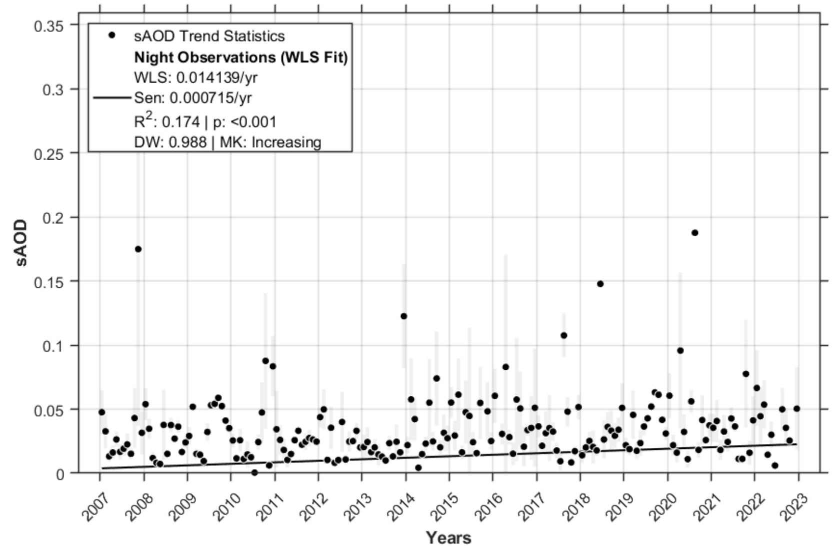
In the original manuscript, this discussion was included in the Results section 3.4, however, during the revision process, that section was removed as part of a broader restructuring of the manuscript. Nevertheless, we have expanded the discussion of the satellite's sampling geometry and its implications in the Methodology (Lines 230–241) *"Because CALIPSO operates in a sun-synchronous near-polar orbit, its ground tracks converge toward higher latitudes, resulting in a greater sampling density in the northern zones. To account for this spatial sampling asymmetry, the orbit-mean profiles,* $\bar{x}_{orbit}$*, were aggregated into monthly and annual means, weighted by the number of the 5-km profiles contributing to each orbit average as:*

$$\bar{x}_{monthly} = \frac{\sum_{orbits} N_{orbit} \bar{x}_{orbit}}{\sum_{orbits} N_{orbit}} \quad (1)$$

This approach ensures that the resulting values are equivalent to a direct arithmetic mean of all individual profiles within a given latitude zone and prevents regional statistics from being disproportionately influenced by variations in satellite sampling density. To characterize the overall stratospheric state, both monthly and annual averages were computed alongside their respective aerosol type contributions for each zone. Finally, a pan-European assessment was performed to represent the whole study area.", where we describe the averaging procedure used to mitigate orbital sampling biases, and we have also added a brief note in the Results section (Lines 345–349) *"The north-to-south gradient is evident across the study period. While this pattern largely reflects differences in aerosol transport and persistence across the three latitude bands, it may also be influenced by CALIPSO's sun-synchronous, near-polar orbital geometry, which yields a higher sampling density at northern latitudes. Consequently, the increased number of observations in the N zone enhances the likelihood of detecting localized, low-amplitude, or short-lived aerosol layers that may remain undetected in the more sparsely sampled southern regions."* to aid interpretation of the observed north–south gradient.

l.440–455 and Fig. 12: The trend is not statistically significant and should be discussed more cautiously.

In agreement with a specific comment from Reviewer #1, we have substantially revised this section. It is now entitled as Section 3.5, "Long-Term sAOD Trends over Europe". Rather than annual values, the trend analysis is now based on the complete monthly nighttime sAOD record (2007–2022), providing a more robust basis for the statistical assessment. The original Figure 12 has been replaced by a new Figure 8 (see below) showing the monthly mean sAOD time series and trend statistics. We have also incorporated discussion of previous stratospheric aerosol trend studies, including the works of Hofmann and Deshler, to place our results in the context of the existing literature. These references and their relevance to our findings are discussed in Lines 742–753 of the revised manuscript. However, the entire trend-analysis section has been rewritten (Lines 716–765).



”Figure 8: Time series of the nighttime mean monthly sAOD (2007–2022) across Europe. The shaded areas denote the SEM. The line represents the weighted least-squares (WLS; w=N/s^2, where s the uncertainty of the mean) fit and the inset panel summarizes the trend statistics, including the WLS slope, Theil–Sen slope estimate, Durbin–Watson (DW) statistic, and Mann–Kendall (MK) trend test.”

l.500–506: The interpretation of a post-2016 change-point as a change in aerosol baseline is too strong. It may simply reflect clustering of episodic events.

We completely agree with the reviewer’s comment which encompasses with specific comment by Referee #1. Volcanic eruptions and extreme wildfire injections are inherently episodic, and their atmospheric impacts are fundamentally transient. It was not our intention to claim a permanent geophysical shift or a durable new baseline regime. As the reviewer rightly points out, the post-2016 upward inflection in the CUSUM analysis is the result of a dense temporal clustering of these independent, episodic events, which could just as easily dissipate back to lower baseline levels in subsequent years. In the revised manuscript, we have removed the discussion based on the CUSUM analysis that could be interpreted as implying a sustained change in the aerosol baseline. However, we have retained the broader interpretation that periods of elevated stratospheric aerosol loading can arise from the temporal clustering of independent volcanic eruptions and wildfire events. We now emphasize that the observed variability reflects the occurrence and clustering of episodic events rather than evidence for a persistent long-term shift in the stratospheric aerosol system.

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