Reviewer #2:

- This paper presents an awkward title, "Vertical Retrieval of AOD...". There seems to be a misunderstanding regarding the term "vertical retrieval." AOD (Aerosol Optical Depth) is generally understood as a columnar quantity, representing the total extinction of light from the surface to the top of the atmosphere. The concept of "vertical retrieval" is unclear. Upon reading the paper, it appears that the authors are referring to the retrieval of AOD in layers at specific altitudes, with each layer having a thickness of 60 m, which corresponds to the vertical resolution of CALIOP data. If this is the case, a more appropriate title would be something like "Retrieval of Extinction at Four Layers Using...".

We sincerely thank you for dedicating your time to review our paper and providing valuable feedback. Your comment regarding the title and the term "vertical retrieval" is particularly insightful, and we appreciate the opportunity to clarify and address this concern.

Indeed, as you noted, the focus of our study is on estimating columnar AOD values within specific altitude layers: 0–1.5 km, 1.5–3 km, 3–5 km, and 5–10 km. We understand how the original title might have led to ambiguity, potentially suggesting retrievals at a finer vertical resolution or full vertical profiles.

To resolve this and better reflect the scope of our work, we have revised the title of the manuscript to "Multi-layer Retrieval of Aerosol Optical Depth in the Troposphere Using SEVIRI Data: A Case Study over the European Continent." Additionally, throughout the manuscript, we have replaced the term "SEVIRI AOD profiles" with "SEVIRI multi-layer AOD values" where applicable to ensure consistency and clarity.

We believe these changes effectively address your comment and improve the overall precision of the manuscript.

- From what I gather, the paper does not conduct a true retrieval of the aerosol extinction profile, as provided by CALIOP. If they are only retrieving AOD for a few layers, it raises the question—what is the purpose of this retrieval? Who will use such data? most climate models have vertical resolution coarser than 500m. so, layered AOD at 60 m at a few altitudes seems not useful.

You raise an important point regarding the nature of our manuscript's approach, and we appreciate your thoughtful feedback. In response to your question about the significance of AOD retrieval at specific altitudes (1.5 km, 3 km, 5 km, and 10 km) with high temporal resolution about 15 minutes, we have revised the Introduction section to better clarify the purpose and relevance of this approach as follows (Page 4 line 27 to Page 5 line 5):

"In this study, we introduce a model for sub-hourly multi-layer AOD retrieval over Europe continent troposphere by integrating SEVIRI-based information with CALIOP aerosol profile products. To achieve this, two well-established machine learning models—XGBoost (XGB) and Random Forest (RF)— utilized for retrieving AOD values in four distinct layers, approximately every 15 minutes, with a spatial resolution of 3 km × 3 km. The four tropospheric layers analyzed in this study are 0–1.5 km, 1.5–3 km, 3–5 km, and 5–10 km, denoted as $AOD_{1.5}$, AOD_3, AOD_5, and AOD_{10}, respectively. The selection of these layers for multi-layer AOD retrieval is based on the distinct aerosol transport mechanisms observed at these altitudes. The 0-1.5 km layer captures aerosols from local sources transported upwards by updrafts from the cloud base, a process called pumping. The 1.5-3 km layer, where thermal bubbles often initiate, allows examination of aerosols, potentially from mid-range sources, that are lifted into the cloud with the rising bubble. The 3-5 km layer captures aerosols transported over longer distances that enter the cloud through entrainment at the cloud edges as the bubble ascends. The 5-10 km layer is designed to capture the influence of long-range transported aerosols on cloud properties at higher altitudes. This multi-layer approach enables analysis of how local to long-range aerosol transport contributes to aerosol-cloud interactions (Zhang et al., 2021; Lebo, 2014; Marinescu et al., 2017)."

Due to significant flaws in the methodology and validation, I recommend rejecting this paper. Below are my major comments:

- **Introduction**: The introduction fails to acknowledge recent advancements in aerosol layer height retrieval from instruments like EPIC and TROPOMI. I recommend referencing recent literature, such as https://doi.org/10.1016/j.rse.2021.112674 and the references therein.

  We sincerely thank you for introducing these valuable references to our attention regarding recent advancements in aerosol layer height retrieval, particularly from instruments like EPIC and TROPOMI. We have reviewed these studies thoroughly and have incorporated them into our literature review, considering their objectives, key achievements, and limitations in the context of our work.

  In response to your suggestion, we have revised the Introduction section to include a discussion of these recent advancements, ensuring that our manuscript aligns with the latest developments in the field of aerosol layer height retrieval (Page 2 line 23 to Page 3 line 25).

"Recent advancements have sought to overcome these limitations through the use of passive satellite sensors with varying temporal resolutions, such as the Tropospheric Monitoring Instrument (TROPOMI), which provide near-daily global coverage with a spatial resolution 3.5 × 7 km (improved 3.5 × 5.5 km in 2019) and was launched in 2017 on Sentinel-5P satellite (Veefkind et al., 2012); the Earth Polychromatic Imaging Camera (EPIC), offering a continuous daytime view every 60 to 100 minutes with a spatial resolution of about 8x8km since its lunch on February 11, 2015, onboard the Deep Space Climate Observatory (DSCOVR) satellite (Marshak & Knyazikhin, 2017); the Global Ozone Monitoring Experiment-2 (GOME-2) on Meteorological Operational Satellite Program (MetOp-C), with a three-day revisit cycle and a spatial resolution of approximately 40 × 40 km since 2018; and the Moderate Resolution Imaging Spectroradiometer (MODIS), onboard Terra (launched in 1999) and Aqua (launched in 2002), provides daily global coverage with spatial resolutions ranging from 0.25 to 1 km (Lyapustin et al., 2011).

The relevant researches focus on various methods specifically aimed at retrieving aerosol layer height (ALH) rather than AOD at different altitudes. One prominent method, Oxygen (O_2) A and B band Absorption Spectroscopy, utilizes the differential absorption of sunlight by O_2 molecules at different altitudes (Zeng et al., 2018; Xu et al., 2017; Xu et al., 2019). Elevated aerosol layers scatter sunlight back to space, shortening the atmospheric path length and decreasing O_2 absorption. By analyzing spectral characteristics in the O_2 A and B bands, researchers infer ALH. However, retrieval sensitivity is enhanced over darker surfaces and higher AOD, making it challenging over bright surfaces or under low aerosol loading. For instance, Nanda et al. (2020) employed TROPOMI observations with an optimal estimation scheme in the O_2 A band, assuming a uniformly distributed aerosol layer. Similarly, the algorithm developed using EPIC/DSCOVR data leverages atmospheric window bands and Differential Optical Absorption Spectroscopy (DOAS) ratios, integrating MODIS and GOME-2 surface reflectance data. For retrievals over vegetated areas, the algorithm favours the O_2 B band due to its lower surface reflectance (Xu et al., 2019). Another study combined O_2 A and B band data from Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) and GOME-2 for enhanced ALH sensitivity, especially near boundary layers (Hollstein & Fischer, 2014).

Additional retrieval method, Stereoscopic techniques—employed by the Multi-angle Imaging SpectroRadiometer (MISR), launched in 2000— utilize multi-angle observations to geometrically determine plume heights. MISR offers a spatial resolution of approximately 275 meters and a temporal resolution of around once every 7 days, making it especially useful over reflective surfaces, as it relies on geometric data rather than surface reflectance (Muller et al., 2002; Zakšek et al., 2013; Fisher et al., 2014; Val Martin et al., 2018).

Passive satellite-based ALH retrieval techniques, while offering global coverage, often simplify the aerosol vertical distribution by assuming a single homogeneous layer (Zeng et al., 2018; Xu et al., 2017; Xu et al., 2019). This simplification can lead to inaccurate representations of complex aerosol profiles, especially in cases of multi-layered events. In addition, these passive satellite-based methods face further constraints due to the low spatial resolution of instruments like EPIC and GOME-2, as well as low temporal resolution of sensors such as TROPOMI, GOME-2, and MISR. These constrains on resolution reduce the effectiveness of these retrievals in capturing fine-scale, rapidly evolving aerosol distribution events, such as smoke plumes from fires."

- **Methodology**: The method has significant flaws, particularly in the use of machine learning as a "black box." The authors fail to explain the underlying physics of how SEVIRI would contain information about the aerosol vertical distribution—specifically, at what wavelengths and why? The method pairs CALIOP layered AOD with meteorological data and SEVIRI radiance for training but lacks a clear justification for this approach.

  Thank you for your valuable suggestion, which we believe greatly enhances the clarity and depth of our methodology. We have carefully considered your feedback and have revised the Methodology section to address your concerns. To provide a clearer understanding of how SEVIRI data contributes to the retrieval of aerosol vertical distribution, we have added several sentences at the beginning of Section 3. Specifically, we now discuss the impact of aerosols at the relevant altitudes and how different SEVIRI bands, meteorological data, and land cover types provide critical information for the machine learning models. Additionally, we have highlighted the importance of spatial and temporal features such as latitude, longitude, year, month, and day, and how these factors influence the retrieval process. These revisions help clarify the rationale behind pairing CALIOP layered AOD with SEVIRI radiance and meteorological data, providing a more robust justification for this approach (Page 9 line 2 to Page 10 line 30).

  "As noted, hyperspectral measurements in the oxygen bands enable aerosol vertical distribution retrieval by analyzing photon path length changes due to scattering at different altitudes. SEVIRI's spectral bands, however, are primarily designed for cloud and land surface observations and do not specifically cover the oxygen bands. The SEVIRI bands closest to the oxygen bands are B_1 (635 nm) and B_2 (810 nm), which are in the visible spectrum and respond to scattering by vertically distributed aerosols. The near-infrared and shortwave infrared (SWIR) bands (B_3, B_4, B_7, B_9, and B_{10}) are indirectly influenced by aerosol vertical distribution, as the accuracy of AOD retrievals using these bands can be affected by aerosol layering. While these bands may not directly provide vertical profile information, they could yield complementary data that, when combined with other wavelength retrievals, enhances the understanding of aerosol vertical distribution (Wu et al., 2017; Li et al., 2020). B_5 and B_6 offer insights into water vapor profiles, which can be incorporated into aerosol retrieval algorithms. By accounting for water vapor influence, these bands indirectly improve the accuracy of aerosol vertical distribution estimates. The ozone band (B_8) contributes to atmospheric chemistry and aerosol formation insights but does not directly reveal vertical distribution, while B_{11}'s lower scattering efficiency limits its sensitivity to vertical variations in aerosols for direct retrieval. As a result, SEVIRI's bands provide a range of potential avenues for studying aerosol vertical distribution, with both direct and indirect contributions. Although SEVIRI's bands offer valuable data for meteorological observations such as cloud monitoring, surface temperature and water vapour, its spectral design is not optimized for detailed monitoring of air quality or climate through atmospheric gases and aerosols, as is TROPOMI. Thus, physical approaches for detailed multi-layer aerosol retrieval, especially for multi-layer AOD, remain challenging with SEVIRI's current spectral configuration.

Meteorological data significantly influence the vertical distribution of aerosols, with varying impacts depending on aerosol type, transport dynamics, and atmospheric conditions. Wind speed and direction drive both horizontal and vertical aerosol transport, with higher wind speeds over oceans enhancing sea salt aerosol concentrations (Kaufman et al., 1997; Yu et al., 2006; Chin et al., 2007; Tesche et al., 2009). Temperature and pressure also play critical roles; temperature inversions inhibit vertical mixing, trapping aerosols in distinct layers, while convective activity from surface heating mixes aerosols in the boundary layer, creating a more homogeneous distribution. Stable high-pressure systems promote surface accumulation by limiting mixing, whereas low-pressure systems enhance upward transport, extending aerosol atmospheric lifetimes (Tesche et al., 2009). The complexity of these interactions suggests a significant challenge for multi-layer AOD retrieval using physical approaches, as accurate modelling requires accounting for diverse meteorological influences and variations in aerosol type, transport, and vertical distribution.

Geographical location, land cover, and temporal factors significantly influence the vertical distribution of aerosols across Europe. Coastal regions tend to have elevated sea salt aerosols due to ocean surface wind activity, while continental areas, especially in winter, experience higher anthropogenic aerosol concentrations from sources like fossil fuel combustion and industrial emissions. Additionally, the latitude and prevailing wind patterns, such as easterly winds, play a role in the long-range transport of aerosols, affecting distribution both horizontally and vertically. Land cover also contributes to these dynamics: forests emit biogenic volatile organic compounds (VOCs), which can form secondary organic aerosols, while urban and agricultural areas introduce anthropogenic aerosols from activities like traffic, industrial emissions, and fertilizer use.

Temporal variations, including seasonal and diurnal changes, further complicate aerosol distribution. For example, during winter, stable high-pressure systems trap aerosols in the planetary boundary layer (PBL), while in summer, warmer temperatures enhance photochemical activity, leading to increased ozone and sulfate concentrations. Diurnal fluctuations are also evident, particularly in urban areas, where traffic and industrial activities create peaks in anthropogenic emissions during the day.

These combined effects underscore the complexity of aerosol behaviour, emphasizing the necessity for an approach that integrates all relevant variables and effectively captures their interactions and influence on vertical aerosol distribution and multi-layer AOD retrieving. Machine learning-based methodology, capable of managing large datasets and discerning intricate relationships between these variables, presents a promising solution for accurate multi-layer AOD retrieval."

- **Cross-validation**: The cross-validation approach is problematic. The data used for training and validation likely have significant auto-correlation in space or time. I suggest separating the datasets by year, for example, using the first two years of data for training and the third year for validation.

Thank you for your insightful suggestion regarding the cross-validation approach. We fully agree that ensuring temporal independence between training and testing datasets is crucial for avoiding potential issues related to autocorrelation. To address this, we have revised our data partitioning strategy to ensure better temporal generalization of the models. Specifically, the dataset was split by year, with the data from 2017 and 2018 used for model training, while the 2019 data was reserved exclusively for testing. This approach helps mitigate temporal autocorrelation and ensures more robust model evaluation.

In line with this updated approach, we have thoroughly revised the "3.3 Model Training and Evaluation" subsection. Additionally, all figures (Figures 6, 7, 8) and tables (Tables 3, 4, S1, S2) representing the results of the trained and tested models have been updated accordingly, and the related text has been modified to reflect these changes.

- **Validation and Results**: The paper should provide a map of retrieved AOD at each hour and validate these results with AERONET sites. Additionally, the paper should present an extinction profile from their retrieval and compare it with either ground-based lidar measurements or other aerosol profile measurements, such as those from aircraft.

Thank you for your valuable suggestion regarding the validation and results. To address the ambiguity related to the retrieval of profiles, we have revised the manuscript to clarify that we are estimating multi-layer AOD values rather than retrieving full aerosol extinction profiles. This change has been applied throughout the manuscript to ensure consistency and clarity.

Regarding the validation aspect, we acknowledge the importance of using reliable datasets. However, due to the nature of our approach—multi-layer AOD values estimation—AERONET station measurements cannot be comprehensively utilized for validation across all altitude layers. Instead, we have validated our results using EARLINET ground-based lidar AOD retrievals for the four specified altitude ranges. These validations are presented in Figure 8 and Table 4 (Page 24 line 1 to Page 27 line 1).

For further validation, we have conducted a detailed spatial comparison of the estimated multi-layer AOD values with CALIOP AOD retrievals on four specific days across different seasons in 2019, as illustrated in Fig. 9 (Page 27 line 1 to page 29 line 1). Additionally, to enhance both temporal and spatial validation, we have included two significant aerosol events: a major dust intrusion and a volcanic eruption. These events are analyzed in detail and presented in Fig. 10, Fig. 11, Video S1, and Video S2 (Page 29 line 1 to 33 line 1). The spatial and temporal exploration of these events provides additional validation of the estimated multi-layer AOD values, further reinforcing the robustness of the proposed methodology.

- We sincerely hope that these revisions address your concerns and enhance the clarity and overall impact of the manuscript. We greatly appreciate your time and thoughtful feedback, which have been instrumental in refining our work. Thank you once again, Reviewer 2, for your invaluable comments and suggestions.