

Reviewer #1:

- This is a review for “Vertical Retrieval of AOD using SEVIRI data, Case Study: European Continent” by Pashayi et al. In this paper, AOD is determined at several altitudes from SEVIRI/MSG data using machine learning (ML) methods trained on vertical aerosol profiles from the CALIOP lidar satellite. Validation is performed using CALIOP and independent EARLINET ground lidar data. The article is well written and generally clear.

We sincerely appreciate your thoughtful and constructive feedback on our manuscript titled "*Vertical Retrieval of AOD using SEVIRI Data: A Case Study over the European Continent.*" We are grateful for the time and effort you dedicated to reviewing our work and for your positive assessment of its clarity and presentation.

Your insights and suggestions are invaluable to us, and we are committed to addressing your comments thoroughly to further enhance the quality and scientific rigor of our manuscript. We greatly value your expertise and guidance in helping us refine our research for publication.

- However, I find the scientific interest of the study to be very limited, at least in the way findings are presented. Indeed, results are limited to a large number of scores calculated by validating the vertical variation of the AOD retrieved at certain single pixel locations, thus showing no maps or vertical profiles estimated by the presented methodology.

Thank you for your insightful suggestion emphasizing the importance of incorporating spatial and temporal visualizations of the retrieved multi-layer AOD values to better demonstrate the applicability of our methodology. In response to your feedback, we have added a new subsection, "*4.3 Qualitative Validation,*" which includes the following enhancements (Page 27 line 1 to Page 33 line 1):

1. **Spatial Maps:** We have incorporated maps illustrating the spatial trends of the multi-layer AOD retrievals and their comparison with CALIOP AOD retrievals on four specific days across various seasons in 2019.
2. **Temporal Analysis:** We have conducted and presented detailed analyses of two significant aerosol events: (i) a major dust intrusion event from March 13–18, 2022, and (ii) a volcanic eruption event on August 14, 2023, as the sub-hourly estimated multi-layer AOD values.

These additions provide illustrative examples that highlight the spatial and temporal capabilities of our proposed methodology. We believe these enhancements substantially improve the manuscript and effectively address your concerns.

- Furthermore, the temporal variation (daily and diurnal) of the retrieved aerosol variables is not discussed, nor shown, in the paper. I find this highly surprising, mainly because the authors state in the abstract that "These estimations are achieved with spatial and temporal resolutions of $3 \text{ km} \times 3 \text{ km}$ and 15 minutes, respectively, over Europe". In my opinion, this statement needs to be proven in order to properly evaluate the contribution of this paper, as SEVIRI's main asset is that it is a high temporal resolution imager that provides images of the entire disk of the Earth every 15 minutes.

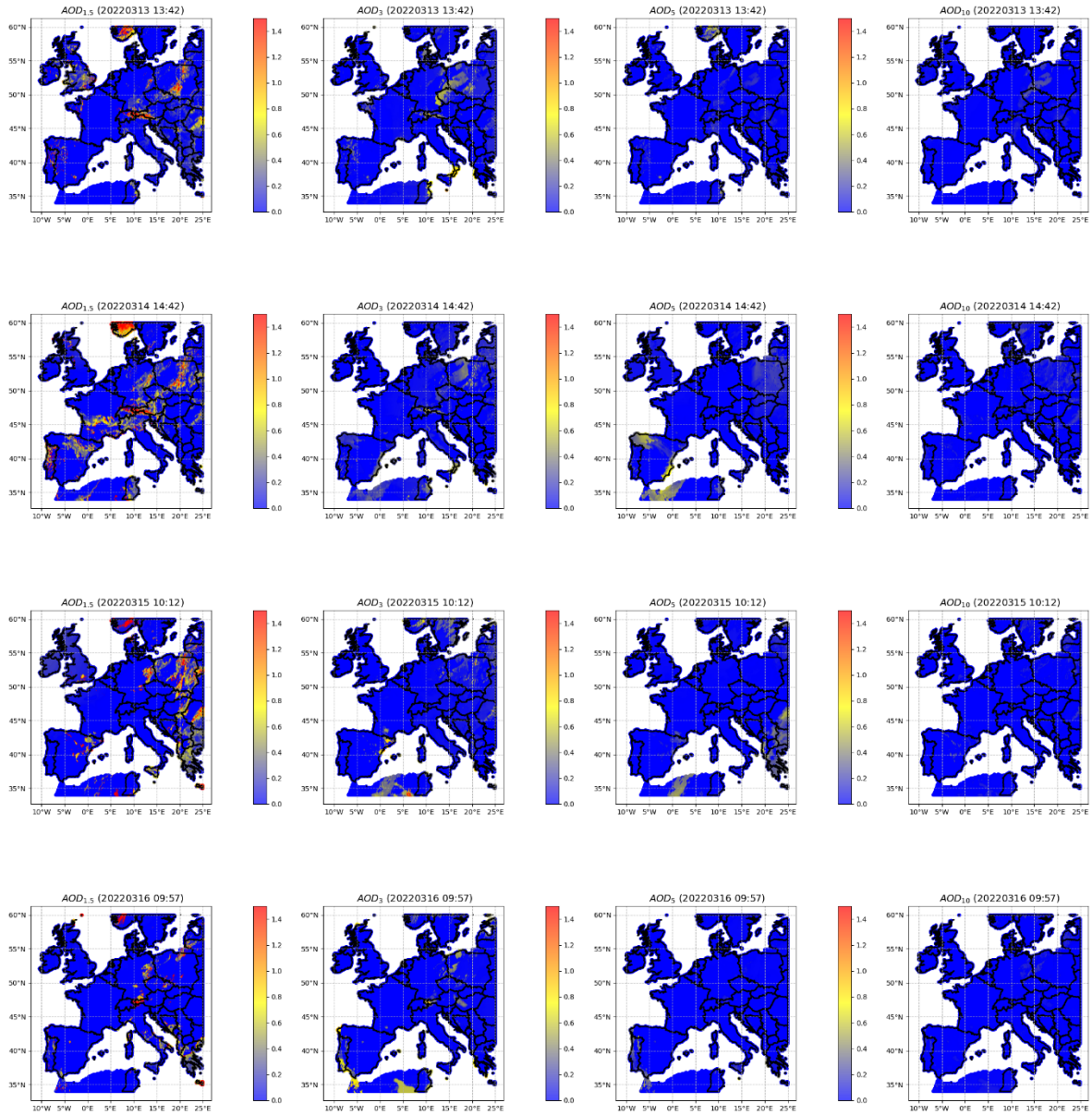
Thank you for your valuable feedback. We have carefully considered your suggestion regarding the inclusion of the temporal variation of the estimated multi-layer AOD values. In response, we conducted a detailed regional-scale analysis focusing on two significant aerosol events: (i) a major dust intrusion from March 13 to March 18, 2022, and (ii) a volcanic eruption on August 14, 2023. To demonstrate the spatial and temporal capabilities of the proposed methodology, we have included spatial distribution maps at key time intervals during these events. These maps effectively illustrate the temporal evolution of aerosols across four altitude layers. This analysis, along with the corresponding visualizations, has been incorporated into the manuscript as *Figures 10 and 11* within the new subsection “4.3 Qualitative Validation.” Additionally, we have compiled sub-hourly estimations of multi-layer AOD values into an animation, provided as Supplementary Video S1 and S2, which visualizes how aerosols dynamically evolve over time. We believe these additions address your concerns and further substantiate the temporal capabilities of our methodology (Page 29 line 1 to Page 33 line 1).

“The subsequent approach for qualitative validation of the model on a regional scale involved analyzing two aerosol events. The first event examined was a substantial Saharan dust plume that traversed Western and Central Europe between March 13 and 18, 2022. SEVIRI scenes captured during this event, illustrated in Fig. 10, were visualized at specific hours to assess how well the aerosol vertical dispersion behaviour aligned with the dynamic characteristics of the event.

On March 13, at 13:42 UTC, the event is characterized by concentrated aerosol presence at 1.5 km over southern Europe, particularly Spain, Italy, and the Mediterranean, with progressive dispersion at higher altitudes reaching central Europe. By March 14 at 14:42 UTC, the dust plume expands further into central and northern Europe at 1.5 km, while mid-altitudes (AOD_3 and AOD_5) show notable aerosol presence over the Iberian Peninsula and central Europe, reflecting the dust's horizontal transport. At 10 km, concentrations remain low, indicating limited vertical penetration. Comparing these two days reveals a clear intensification and northward progression of the plume. On March 15, at 10:12 UTC, $AOD_{1.5}$ shows sustained high concentrations over southern Europe, with increased impact in southeastern Europe, including the Balkans. At mid-levels, the plume spreads further into central and eastern Europe, reaching countries like Germany and Poland, while at 10 km, faint concentrations persist over parts of southern and central Europe. By March 16 at 09:57 UTC, the plume shows signs of dissipation, with reduced intensity at 1.5 km across Spain, Greece, and the Mediterranean, and weaker signals at mid-altitudes over central Europe. On March 17 at 08:27 UTC, the dust plume is confined mainly to southern Europe at lower altitudes, while mid-altitudes exhibit limited spread and intensity, and 10 km shows negligible influence.

Finally, the spatial distributions on March 18 at 14:42 UTC, as shown in the figure, reveal a significant reduction in aerosol concentrations at all altitudes. At 1.5 km, the AOD values remain notable over southern Spain and the western Mediterranean, but are much weaker compared to earlier days. At 3 km, the dust plume is localized over the Iberian Peninsula, with faint traces extending towards southeastern Europe. Higher altitudes, represented by AOD_5 and AOD_{10} , exhibit very low concentrations, indicating minimal vertical transport of the dust on the final day of the event. This vertical behaviour, compared to earlier days, reflects the dissipation phase of the Saharan dust plume, as atmospheric processes like mixing, dilution, and deposition progressively weaken its intensity. Additionally, during the Saharan dust event, sub-hourly estimated multi-layer AOD values for the European continent (from 07:12 to 16:12

daily on March 18, 2022) were compiled into an animation that includes 37 SEVIRI scenes over Europe, as shown in Supplementary Video S1.



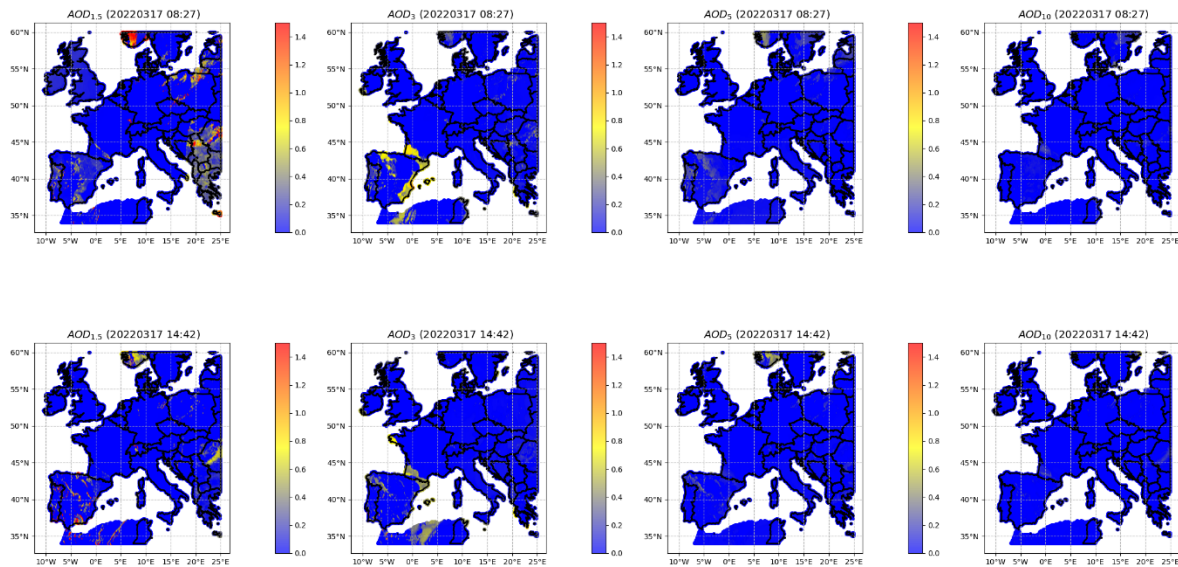


Figure 10. Spatial distributions of SEVIRI- estimated multi-layer AOD values during the Saharan dust event from March 13 to 18, 2022, at selected times.

The other event in this approach is the Mount Etna eruption, located on the eastern coast of Sicily, Italy, one of the most active volcanoes in the world and a prominent feature in the Mediterranean region. On August 14, 2023, Mount Etna erupted in a significant volcanic event that released vast quantities of ash and aerosols into the atmosphere. This eruption produced an ash plume reaching up to 8,200 meters above the crater and spreading southward over the Mediterranean. The event provided another opportunity to visualize the aerosol vertical dispersion behaviour aligned with the dynamic characteristics of the event. The AOD spatial distribution maps in Fig.11 revealed distinct layers of aerosol, with a clear upward transport of particles, especially in the lower to mid-level layers (1.5 km to 3 km) at 7:27, suggesting strong vertical convective activity driven by the eruption's intensity. As time progressed, the AOD values in the upper layers increased, particularly at the 5 km altitude around 8:27, signalling a greater vertical transport of aerosols. This upward transport continued throughout the day, with the highest values observed at 10 km by 9:57, suggesting the plume had reached greater altitudes. By 13:42, the AOD values in the 10 km layer were at their peak, reflecting the maximum extent of vertical transport before the aerosols began to disperse more horizontally. After this point, the plume's vertical extent started to decrease (15:57), likely due to the long-distance transport of the aerosols across the Mediterranean region. This multi-layer analysis highlights the dynamic behaviour of volcanic aerosols, providing valuable insight into their dispersal patterns. An animation of sub-hourly SEVIRI multi-layer AOD estimations during the eruption (from 07:27 to 15:57) was also generated, represented as Video. S2 in supplementary, providing a detailed view of the plume's evolution over time.

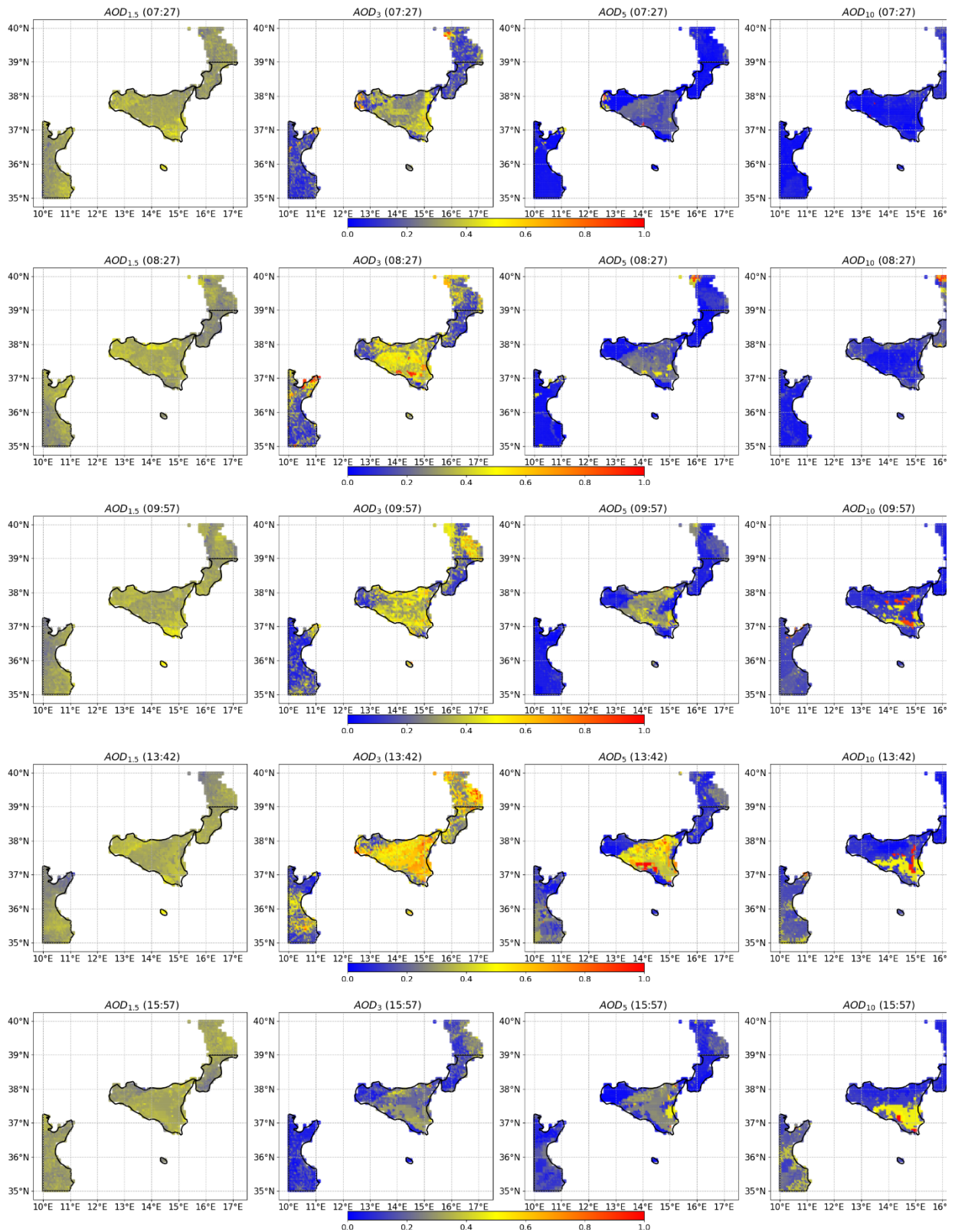
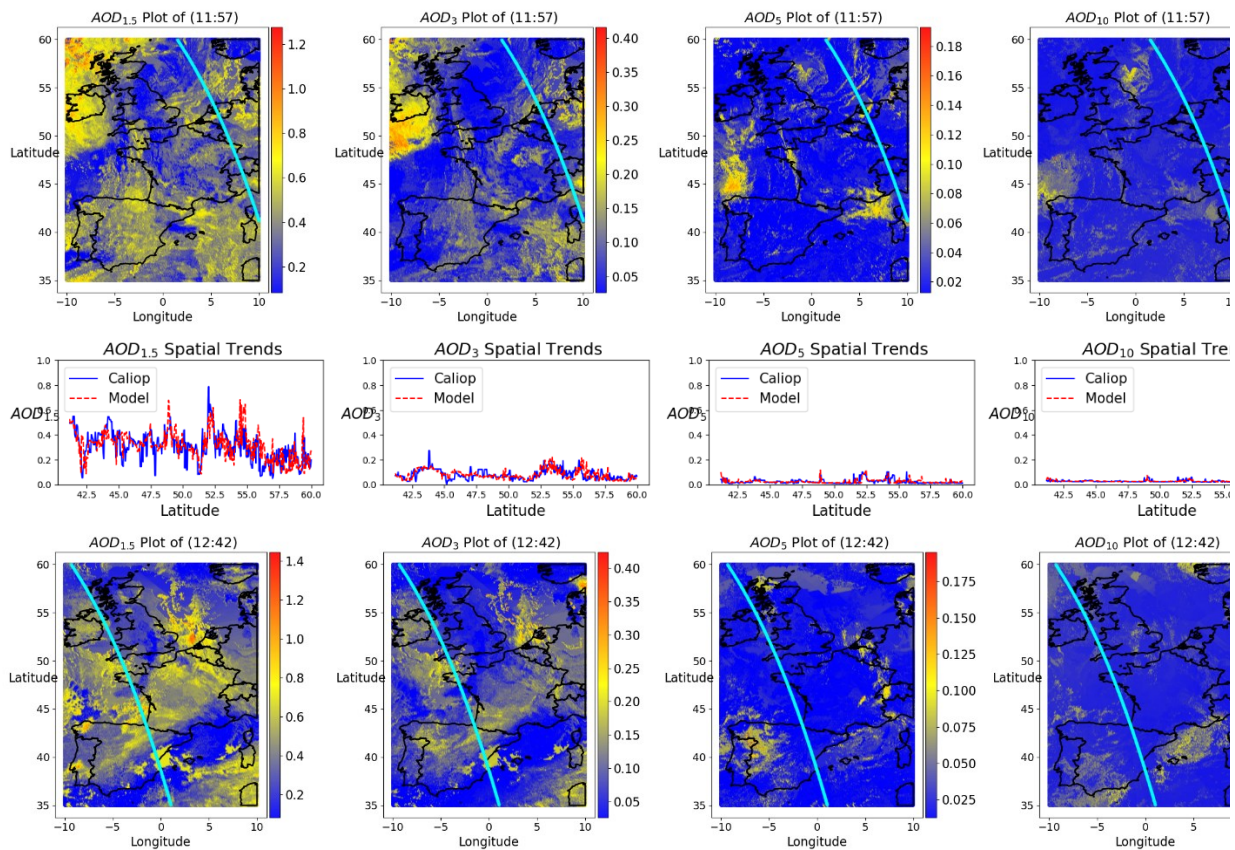


Figure 11. Spatial distributions of estimated multi-layer AOD values during the Volcanic Eruption on August 14, 2023, at selected times.

I suggest including examples of maps and time series of vertical AOD variations across space and time, as well as their validation with reference data, as this is in my eyes the main interest of the proposed methodology for the scientific community.

We greatly appreciate your suggestion to include spatial and temporal validation to better highlight the main scientific interest of the proposed methodology. In response, we have incorporated maps under the subsection “4.3 Qualitative Validation” that demonstrate the spatial trends of estimated multi-layer AOD values and their comparison with CALIOP AOD retrievals. These maps provide a visual means for readers to assess the consistency between the estimated multi-layer AOD values and the CALIOP reference data, thereby strengthening the validation and relevance of our methodology (Page 27 line 1 to Page 29 line 1).

“Conducting the qualitative validation for an entire scene within the first approach is challenging due to the spatial and temporal resolution constraints of CALIOP. To address this limitation, SEVIRI scene pixels corresponding to CALIOP overpasses with temporal differences of less than four minutes were compared on the specified days. The results, illustrated in Fig. 9, indicate that the spatial trends of the estimations generally align well with the trends of CALIOP AOD retrievals in regions with both high and low AOD values across the four seasons. This alignment highlights the model's ability to provide reliable AOD estimates with enhanced temporal resolution, effectively complementing CALIOP AOD retrievals.



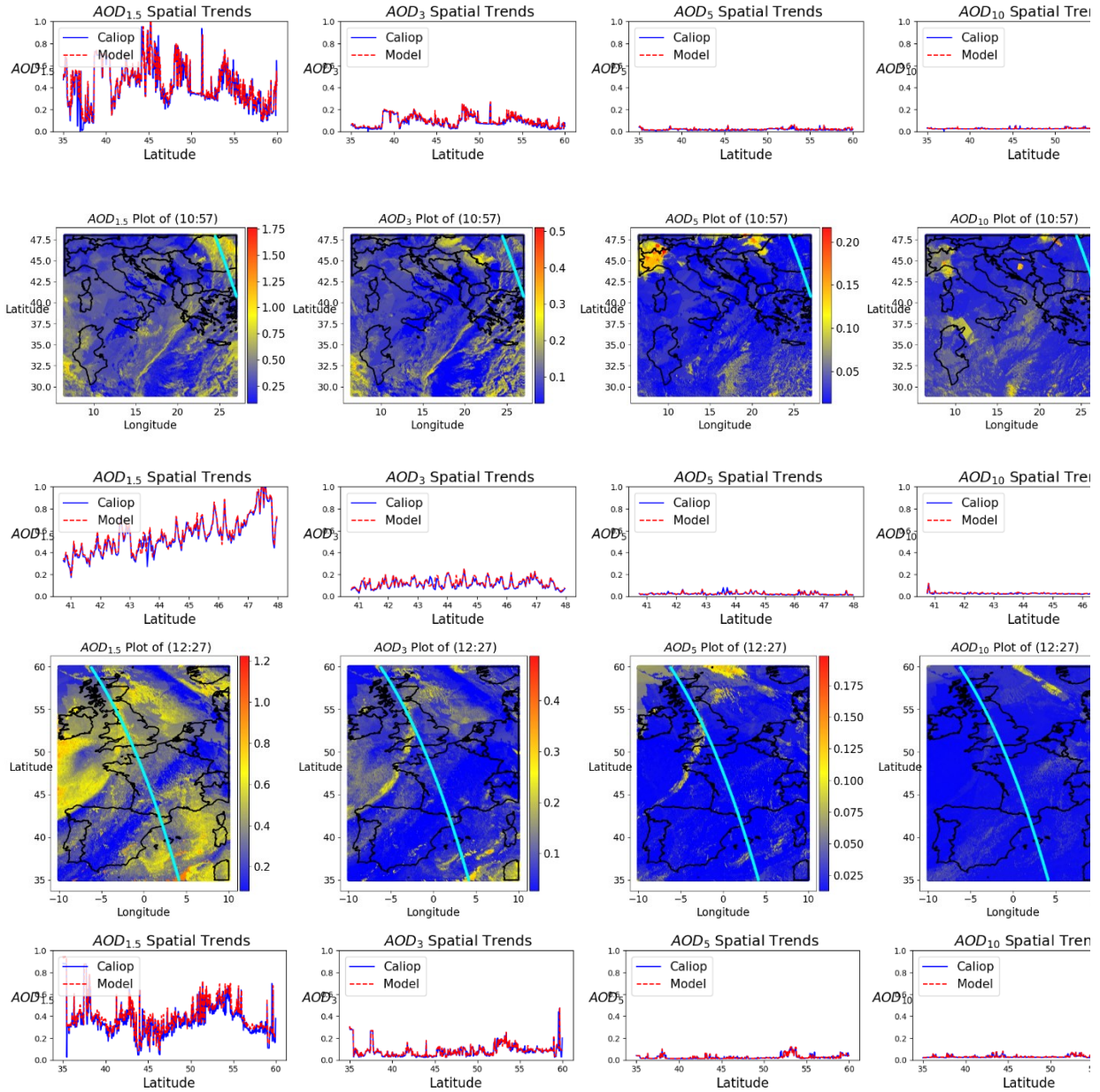


Figure 9. Spatial distributions and trends of SEVIRI-retrieved multi-layer AOD values compared to CALIOP retrievals for four specific days in March 3 (11:57), April 30 (12:42), June 13 (10:57), and October 31 (12:27) across various seasons in 2019.

- I strongly suggest going beyond the statistical analysis, which is extensively presented in this paper, to discuss more the physical interpretation of the results. This applies not only to the results in general but also to other parts of the paper, such as the analysis of the importance of different variables in vertical AOD retrieval.

Thank you for your valuable feedback. While statistical modeling provides important insights, we acknowledge the need to complement these analyses with a thorough understanding of the underlying meteorological and physical

mechanisms. In response, we have revised Sections “4.1.1” and “4.1.2” to include a more comprehensive physical interpretation of the results.

These revisions emphasize the importance of different variables and their contributions to multi-layer AOD retrievals, offering a more holistic perspective on the physical relevance of key features identified by the machine learning models. Specifically, we discuss the sensitivities of SEVIRI spectral bands, the influence of meteorological parameters (e.g., wind speed and humidity), and the role of land cover types. Additionally, we highlight how these factors shape the model’s performance, extending the analysis beyond statistical metrics to capture the physical underpinnings of the retrieval process (Page 16 line 9 to Page 20).

“4.1.1 Feature Importance

According to established radiative transfer theory (Tsang et al., 1984; Zege et al., 1991), the spectral signal captured by a satellite sensor at the TOA is intricately shaped by various factors, including the composition, size distribution, and altitude of aerosols, as well as atmospheric molecules such as water vapor. These factors have a direct impact on the retrieval of AOD values. Consequently, SEVIRI reflectance and brightness temperature across Bands 1 to 11 (B_1 to B_{11}) were identified as critical features for this analysis. The relationship between AOD and all candidate features—including spatial features such as latitude (lat) and longitude (lon), temporal features including year, month, and day, as well as meteorological data like P, T, Ws, and Wd, and LC—was investigated through a correlation analysis. This analysis, illustrated in Fig. 5, utilized the PCC as the chosen filtering method. The findings underscored that the majority of selected features in this study exhibited significance levels exceeding 1%.

As illustrated the PCC results (Fig. 5), aerosol dynamics in the 0–1.5 km layer of the study area are strongly influenced by geographic and temporal factors, characteristic of surface-dominated conditions. High correlations of AOD with lon (23.92%) and lat (22.41%) highlight the impact of location-specific emissions and regional transport patterns, while significant correlations with day (11.59%) and month (6.19%) indicate the role of diurnal and seasonal cycles driven by emissions, meteorological changes, and boundary layer dynamics. Thermal infrared sensitivity also plays a role, as indicated by the strong correlations with B_7 (3.73%) and B_8 (3.07%), the highest among SEVIRI bands. This suggests a potential link between surface temperature variations and AOD in the lower atmosphere. Moreover, the correlation with B_1 (3.06%) points to aerosols interacting with visible light, likely from urban/industrial emissions, biomass burning, and potentially dust. Meanwhile, meteorological factors such as Ws (1.31%), Wd (1.22%), T (1.16%), and P (1.1%) are relatively weak compared to geographic and temporal factors. Finally, LC (0.54%) shows the weakest correlation, suggesting a limited direct influence on AOD, potentially masked by stronger influences from emissions, transport, and meteorological factors.

In the 1.5–3 km layer of area of interest, aerosol dynamics remain strongly correlated with lon (23.15%) and lat (21.39%), though slightly decrease compared to the 0-1.5 km layer. This suggests a transition towards atmospheric stability and a more synoptic-scale patterns. Day (11.29%) and month (5.86%) still exhibit notable correlations, reflecting the ongoing impact of diurnal and seasonal cycles on AOD, albeit slightly weaker than in the lower layer. The visible band B_1 (3.86%) shows the strongest correlation among SEVIRI bands, potentially reflecting a change in aerosol composition or properties compared to the lower layer. This could be due to an increased influence of

transported aerosols, potentially with different spectral characteristics. B_7 (3.48%) remains strongly correlated, suggesting continued sensitivity to thermal characteristics. Enhanced transport influence is evident, as Wd (1.34%) shows a stronger correlation than Ws (1.29%), emphasizing the role of transport pathways in AOD distribution at this altitude. Additionally, the correlation with P (1.3%) points to an emerging link between atmospheric stability and aerosol accumulation in this layer. This aligns with other studies' discussion on PBLH and its role in controlling pollutant dispersion, as PBLH is influenced by factors like temperature and stability. LC correlation slightly increases to 0.63%, still remaining relatively weak overall.

In the 3–5 km layer of research area, correlations with lon (19.42%) and lat (17.32%) decrease further, indicating a reduced influence of local sources and an increased dominance of long-range transport and large-scale atmospheric circulation patterns. Correlations with day (9.87%) and month (6.1%) also weaken, suggesting a shift from surface-driven cycles to broader atmospheric processes. The high correlation with B_1 (5.38%) points to a prominent presence of aerosols interacting with visible light. Strong correlations with B_7 (4.73%) indicate effect of thermal characteristics on AOD at this level. Wd (1.18%), Ws (1.1%), T (1.09%), and P (0.99%) correlations remain at similar levels as the previous layer, suggesting continued influence of transport and stability.

In the 5–10 km layer of target region, free tropospheric dynamics dominate aerosol behaviour, geographic correlations with lon (22.92%) and lat (21.46%) show a slight increase compared to the 3-5 km layer, potentially indicating the influence of large-scale transport patterns in the free troposphere. Day (8.59%) and month (4.91%) correlations further weaken, reinforcing the diminishing impact of surface-driven cycles. B_1 (5.25) still showing the highest correlation, indicating aerosols that interact with visible light and are likely transported from lower altitudes or distant sources. B_7 (4.6%) also maintains a strong correlation, indicating a potential sensitivity to upper-level atmospheric dynamics. Notably, P (1.41%) now shows the strongest correlation among meteorological variables, surpassing Wd (1.13%), T (1.1%), and Ws (0.84%). This emphasizes the critical role of atmospheric stability in controlling AOD distribution in the free troposphere. Despite meteorological data showing low statistical importance (below 2%) in estimating AOD across all altitude layers, they have significant physical relevance in processes unique to each layer. LC (0.42%) shows the weakest correlation across all layers, further suggesting its limited direct influence on AOD at this altitude.”

“4.1.2 Meteorological data and Land cover Feature selection

As previously noted, LC, T, P, Ws, and Wd are key features in AOD estimation. To further understand their impact on machine learning model performance in SEVIRI multi-layer AOD values, we conducted 16 cases of experiments with varied meteorological and LC feature combinations, validated using CALIOP AOD retrievals. Our analysis, depicted in Fig. 6 and supplementary Tables S1-S2, is summarized using statistical metrics like R^2 , R, RMSE, and MAE.

Our findings indicate that, for most cases across annual and seasonal datasets, combining these features with B_1 has negligible impact on the 1.5 km layer. In contrast, integrates Ws and Wd with SEVIRI bands (Case 5), consistently yields the highest R^2 and lowest RMSE values across both annual and seasonal datasets. Incorporating these features significantly enhances R^2 values across models, with substantial increases ranging from 0.75 to 0.99 and 0.89 to 0.99 observed in R^2 , and decreases ranging from 0.075 mg/m³ to 0.009 mg/m³ and 0.033 mg/m³ to 0.002 mg/m³ in RMSE,

for both XGB and RF models from Case 1 to Case 5 in the 10 km layer. These statistical values underscore the crucial role of W_s and W_d in influencing the spatial and temporal properties of atmospheric aerosols, particularly in the 10 km layer. Physically, W_s and W_d are known to be primary drivers of aerosol transport across various spatial scales. High W_s can lift dust and other particulate matter into the atmosphere, while W_d affects the regional and long-range advection of aerosols. This mechanism is particularly impactful in the 5-10 km altitude range, where aerosols experience less drags and can be transported over long distances with minimal settling, especially in dry conditions (Pérez et al., 2006a, b; Georgoulias et al., 2016; Nicolae et al., 2019).

However, integrating T and P features, as seen in cases 3, 4, and 9, notably enhances AOD accuracy at 3, 5, and 10 km altitudes. This improvement is attributed to P reflecting changes in aerosol vertical layers, influencing aerosol diffusion capacity, while T is closely linked to atmospheric aerosol distribution by altering air movement dynamics. T affects atmospheric stability by controlling the thermal stratification of air masses; higher T can destabilize the atmosphere, promoting vertical mixing and lifting of aerosols. However, the impact of T on aerosol concentration diminishes with altitude, especially in stable layers where thermal inversion limits upward transport (Pérez et al., 2006a, b; Choobari et al., 2014; Xu et al., 2024). P , on the other hand, can reflect shifts in the PBL height, which influences the vertical distribution of aerosols. A higher PBL allows more aerosols to disperse vertically, enhancing their presence in layers such as AOD_5 , while a lower PBL restricts aerosols closer to the surface. Despite these influences, T and P are generally less effective than wind-related factors (cases 6, 7, and 8), particularly in upper layers, because wind-driven advection predominantly controls the lateral movement of aerosols, especially during seasonal changes when wind dynamics vary substantially (Nicolae et al., 2019; Georgoulias et al., 2016; Ortiz-Amezcuca et al., 2017; Granados-Muñoz et al., 2016). However, T and P impact PBL dynamics, but these effects may be limited in certain seasons due to more stable atmospheric conditions, where lower T and P fluctuations are less conducive to vertical mixing. For example, case 12 including T and P may show less impact on AOD_5 and AOD_{10} layers in winter, when aerosols tend to stay close to the surface due to limited vertical convection. In contrast, warmer seasons promote vertical convection, enhancing the influence of T and P in predicting AOD values across altitude layers. Additionally, the proposed learning models can capture complex, nonlinear relationships among features, but it may not always prioritize individual variables unless they strongly affect the target variable. As a result, even if T or P is expected to influence AOD, their impact may be overshadowed by more influential W_s and W_d (cases 13, 14, 15, and 16).

Conversely, LC plays a more localized role in AOD estimation, particularly in lower layers ($AOD_{1,5}$), as it impacts the sources and types of aerosols present near the surface. However, the effect of LC diminishes with altitude due to decreased influence on vertical transport; aerosols released from surface sources are progressively diluted as they disperse upwards. This observation is confirmed by our findings that cases with LC (e.g., Cases 2, 8, 13, 14, and 16) did not consistently outperform those with purely meteorological features, especially in higher layers (AOD_5 and AOD_{10}). Physically, this limitation arises from the fact that the vertical distribution of aerosols across different atmospheric layers over Europa troposphere is more heavily influenced by continental and regional transport patterns, atmospheric stability, and meteorological conditions than localized land cover characteristics (Zhao et al., 2019).

In conclusion, the validation of our models using CALIOP AOD retrievals highlights the robustness of our findings, particularly the critical role of W_s and W_d in enhancing AOD estimation accuracy. The consistency of these findings across the RF and XGB models, evaluated at different temporal scales (annual and seasonal), highlights the critical role of W_s and W_d in AOD estimation at both the 5 km and 10 km layers. Consequently, we prioritize W_s and W_d , along with B_i , as the preferred input features for our models due to their demonstrated impact on improving AOD estimation accuracy.”

- To avoid writing a lengthy paper, some details about the methodology can be omitted (for example, I would only consider the RF method if it is the best of the two).

We appreciate your suggestion to streamline the methodology section for improved clarity and conciseness. While we acknowledge the merit of focusing on the best-performing model, we believe it is important to retain both models (RF and XGB) in the manuscript. To address this, we have reduced the detailed descriptions of model architectures and hyperparameter tuning, concentrating instead on their comparative performance. To further streamline the presentation and reduce redundancy, we have omitted Table 4 and Table S3, as their content is effectively covered through other figures and analyses. Including both models allows us to provide a more comprehensive evaluation, demonstrating the robustness of the methodology across different approaches. This comparison also highlights the adaptability of the proposed methodology in varying contexts, which we believe is valuable for the scientific community. By balancing detail with conciseness, we have ensured that the manuscript remains accessible while maintaining its depth and rigor.

- We sincerely hope that these revisions address your concerns and improve the clarity and impact of the manuscript. We thank you again for your time and insightful comments, which have been invaluable in refining our work.