AC2 to RC2 Anonymous Referee #1

We would like to thank the Reviewer for his/her thorough and detailed review. AC replies (regular font) for each comment (bold font) are provided below.

General Comments: (overall quality)

The manuscript integrates the ground-based and satellite observational data with atmospheric transport models (FLEXPART) to demonstrate the impact of volcanic eruptions on different aerosol concentrations observed at different ground-based atmospheric monitoring stations. The inversion model developed in this manuscript provides an innovative solution for developing a volcanic hazard warning model for aviation when source information is incomplete, synergistically bridging ACTRIS research infrastructures, satellite missions and modeling. Although only a study is presented that targets the eruption of the Etna volcano on March 12, 2021, the results obtained demonstrate the capability of the model to estimate volcanic ash emissions from lidar and FLEXPART data.

The manuscript is quite clean from an editorial point of view, well structured and is appropriate for ACP. However, a few questions should be addressed, and I would appreciate further discussion in the manuscript.

Specific comments:

1. Page 2, Lines 60-65 (Introduction): I recommend that you add a phrase or two to improve the description of the volcanic particles radiative effects, both direct and indirect. Also, you must include some key references for that.

AC. We would like to thank the reviewer for this suggestion. In the revised manuscript we add this paragraph "Moreover, volcanic particles can influence the planetary radiative balance through both direct and indirect effects, introducing significant uncertainties in plume dispersion and lifetime. The direct effect involves the scattering and absorption of solar and terrestrial radiation, where fine ash and sulfate aerosols contribute to surface cooling or atmospheric warming depending on particle composition, size distribution, and injection plume height (Robock, 2000; Sicard et al., 2025). The indirect effect relates to the role of volcanic particles in cloud micro- and macro-physical properties. Ash particles can act as cloud condensation nuclei (CCN), facilitating water droplet formation and, under specific pressure and temperature conditions, as ice nuclei (IN) (Guerrieri et al., 2023). These processes can alter cloud optical and microphysical properties, enhance cloud reflectivity, affect cloud lifetimes and increase the uncertainties in radiative transfer. Additionally, volcanic ice clouds can hide possible ash layers and pose a severe threat to aviation safety. Atmospheric transport models often struggle to account for these complex interactions, leading to uncertainties in plume evolution, trajectory forecasts, and deposition estimates. Furthermore, the absence of significant physical processes and dependence on empirical relations and data from previous eruptions further contributes to substantial uncertainties in estimates of the erupted mass."

2. Page 3, Lines 75-79 (Introduction): Do you know of previous studies on volcanic particles (volcanic ash, sulfate) that have advanced the integration of data from remote sensing measurements and atmospheric transport modeling? I recommend that you provide an

overview of what has been done before in terms of integrating observational data from ground, satellite and atmospheric transport models.

AC. We appreciate the reviewer's suggestion. In the revised manuscript, we have included an overview of previous studies that have advanced the integration of remote sensing observations (both ground-based and satellite instruments) with atmospheric transport models for volcanic ash and sulfate aerosol dispersion. The revised text is incorporated into the Introduction as follows:

"Over the past two decades, significant progress has been made in integrating remote sensing data into atmospheric transport models to enhance the forecasting of volcanic emissions and their dispersion. Satellite observations from both polar orbiting and geosynchronous thermal infrared instruments have been used to retrieve ash mass loadings (Clarisse et al., 2010; Pavolonis et al., 2013; Prata and Prata, 2012). Additional sensors, including Moderate Resolution Imaging Spectrometer (MODIS), Second Generation Spin-stabilised Enhanced Visible and Infra-Red Imager (SEVIRI), Atmospheric Infra-Red Sounder (AIRS), Ozone Monitoring Instrument (OMI), Multi-angle Imaging Spectroradiometer (MISR), and CALIOP lidar on board of the CALIPSO have provide valuable data in volcanic ash detection and retrievals (Eckhardt et al., 2008; Francis et al., 2012). A comprehensive discussion on the application of satellite remote sensing for volcanic ash monitoring in aviation hazard mitigation is provided by (Prata, 2009).

In addition, ground-based lidar networks, such as the European Aerosol Research Lidar Network (EARLINET), have played a crucial role in validating the accuracy of transport model outputs and improving dispersion simulations, by providing high-resolution vertical profiles of volcanic aerosols (Pappalardo et al., 2004).

Advancements in atmospheric transport and dispersion modeling have further facilitated the integration of these observational datasets. Models like the Numerical Atmospheric-dispersion Modelling Environment (NAME; Jones et al., 2007) which is used operationally by the London Volcanic Ash Advisory Centre (LVAAC), the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Stein et al., 2015) and the FLEXible PARTicle dispersion model (FLEXPART) (Eckhardt et al., 2008; Kristiansen et al., 2010, 2014; Stohl et al., 2011) have been extensively used for volcanic ash forecasting, often incorporating satellite and lidar data to refine model inputs and improve predictive accuracy.

The integration of remote sensing data into atmospheric transport models has been significantly advanced through inversion algorithms. In previous studies (Eckhardt et al., 2008; Kristiansen et al., 2010), inversion algorithms were developed using satellite column retrievals and tested to estimate the vertical distribution of sulphur dioxide (SO2) emission rates for quasi-instantaneous volcanic eruptions such as the 2007 Jebel at Tair and the 2008 Kasatochi eruptions. Seibert et al., (2011) examined the uncertainties of the various configurations for the 2008 Kasatochi case study and expanded the method to estimate the uncertainty of the retrieved source emissions (a-posteriori uncertainties).

The inversion algorithm was further used by Stohl et al., (2011) for volcanic ash emission rates as a function of altitude and time. While Kristiansen et al., (2012) improved the volcanic ash inversion techniques using various inputs to better constrain the 2010 Eyjafjallajökull eruption.

In Amiridis et al., (2023), it is demonstrated that volcanic ash early warning systems can be significantly enhanced from the assimilation of Aeolus wind fields. Notably, these improvements are most pronounced over under-sampled geographical regions, such as the Mediterranean Sea, as volcanoes are often situated in remote areas lacking surface-based observation networks. Moreover, the study indicates that the positive effect of Aeolus wind data assimilation is more pronounced in the middle and upper troposphere (mostly between 7 and 15 km), compared to the lower troposphere. This may highlight under-sampling issues, since the in situ observations (like radiosondes) traditionally used for data assimilation, exhibit lower vertical resolution in the upper troposphere (Rennie et al., 2021). Considering that volcanic ash plumes are typically injected in upper-tropospheric and lower-stratospheric heights, their transport is largely influenced by upper tropospheric winds hence accuracy in dispersion modelling is advanced from high accuracy wind fields assimilation.

Building on these advancements, our study further investigates improvements in ash emission estimations by developing an inversion method that integrates Aeolus wind data, ground-based lidar observations, and transport model simulations. This approach aims to enhance the accuracy of volcanic emission source terms and reduce uncertainties in dispersion forecasting."

3. Page 4, Lines 95-102 (The Case of 12 March–14 March 2021 Etna Volcanic Eruption): The authors should show the relevant meteorological maps for the period with significant volcanic activity from February - March 2021 (500, 300, 200 and 100 hPa circulation) to support the conclusions on volcanic particles transport. Even if FLEXPART ingests the upper air data from ECMWF, a cross-validation with "real meteorological data" (including AEOLUS data) will make the case more convincing. Consider adding a paragraph to the results section to further explore the transport and dispersion of volcanic ash particles.

AC. We thank the reviewer's valuable suggestion. We add the following paragraph to the results section. Unfortunately, we were unable to extend model simulations to earlier periods due to data availability constraints, as the European Centre for Medium-Range Weather Forecasts (ECMWF) provided data only for this specific timeframe (from 12 to 14 March 202). These datasets were produced explicitly to investigate the potential improvements attributed to the assimilation of Aeolus wind profiles.

"The transport and dispersion of volcanic ash particles are strongly influenced by upper-air circulation patterns, which play a crucial role in determining the trajectory and lifetime of the volcanic plume. To assess the sensitivity of the volcanic ash transport to the driving meteorology, two simulations were performed using the WRF regional model over the study period. These simulations were driven by two versions of the ECMWF-IFS global model: one incorporating Aeolus wind profile assimilation ("w") and one without Aeolus assimilation ("w/o") (see Sect. 3.3). To evaluate the influence of upper-level circulation on volcanic ash transport, wind maps at 100, 200, 300, and 500 hPa, were generated, for the period of significant volcanic activity (Figure A 3-A 5).

Given that lidar observations estimated the volcanic plume's center of mass at approximately 10 km, the analysis primarily focused on the 300 hPa level (~9.6 km), which closely corresponds to this altitude (Figure 4). Analyzing the WRF regional model wind vectors at upper-tropospheric levels (300 hPa, ~9.6 km) at 18:00 UTC (approximately 11 hours after the Etna eruption), the general atmospheric circulation remained predominantly zonal over the Mediterranean, with westerly winds prevailing throughout the troposphere. Over the Anatolian Plateau and the Eastern Mediterranean Sea, these winds transition into northwesterlies, favoring the direct transport of the Etna plume towards Greece and the Eastern Mediterranean.

A comparison of the two simulations ("w" and "w/o" Aeolus assimilation) indicates that the overall atmospheric pattern remains consistent, with the subtropical and polar jet streams dominating the circulation. However, notable differences in wind speed are evident, as highlighted in the wind speed difference map for the WRF 18-hour forecast (Figure 4).

The color shading in Figure 4 (c) illustrates the differences between the two WRF runs on 12 March 2021 (18:00 UTC). This comparison indicates significant strengthening of winds at 300 hPa when

Aeolus wind profiles are assimilated (Figure 4 c), with maximum difference values reaching approximately 8 m/s. Additionally, slight differences in wind vector direction ("w" Aeolus (green) and "w/o" Aeolus (black)) are observed, particularly over the Ionian Sea (from W to NW) and the Eastern Mediterranean between Crete and Cyprus (from WNW to NW), where the two jet streams merge.

Similar wind speed tendencies are observed at 200 hPa (Figure A 4). In contrast, at 500 hPa (Figure A 5), the influence of Aeolus assimilation is less pronounced, indicating that the most significant differences occur at higher altitudes where jet stream dynamics dominate.

At 100hPa (Figure A 3), a strong westerly jet stream is evident across Europe and North Africa, indicating fast-moving winds that could contribute to long-range transport of volcanic particles. The corresponding wind speed difference map (Figure A 3 c) shows high differences mainly along the jet stream axis, suggesting that Aeolus assimilation plays a crucial role in improving the representation of high-altitude wind fields critical for long-range ash transport.

These findings highlight the importance of accurate upper-air circulation representation in volcanic ash transport modeling. The inclusion of Aeolus wind profiles in the ECMWF-IFS model leads to a more refined depiction of wind patterns, particularly at upper tropospheric and lower stratospheric levels, which are crucial for accurately forecasting the dispersion of volcanic emissions."

Regarding the second part of the comment a cross-validation with "real meteorological data", in this study, the meteorological simulations are conducted using the WRF-ARW model, which relies on initial and boundary conditions derived from two versions of ECMWF-IFS data. One version incorporates assimilated Aeolus Rayleigh-clear and Mie cloudy horizontal line-of-sight (HLOS) L2B wind profiles (the "w" Aeolus experiment), while the other excludes Aeolus data (the "w/o" Aeolus experiment). These meteorological fields subsequently drive the FLEXPART simulations, ensuring a comprehensive representation of atmospheric transport mechanisms.

The generated wind maps from both simulations (with and without Aeolus assimilation) indicate that the wind direction in both cases facilitates the long-range transport of volcanic particles from Etna to Greece (and more specific to Antikythera). This result underscores the importance of upper-level circulation in volcanic ash dispersion and supports the study's conclusions regarding its role in atmospheric transport processes.

The IFS analysis with and without Aeolus assimilation is considered good enough for the objectives of this study. The primary focus is the development of the inversion algorithm using ground-based data, rather than the verification of the IFS wind fields. Since Aeolus wind data are already incorporated into the meteorological fields, the study inherently accounts for their impact on atmospheric circulation. Consequently, a detailed verification of the IFS data is beyond the scope of this work.

4. Page 4, Lines 113-117 (Methods and Data): The authors should include a description of the general aspects of climate and atmospheric synoptic scale circulation for the region where is located PANGEA-NOA observatory.

AC. We thank the reviewer for the comment. We have now included a description of the general aspects of climate and synoptic-scale atmospheric circulation in the Eastern Mediterranean region.

"The Mediterranean region, particularly its Eastern basin, serves as a confluence of air masses originating from Europe, Asia, and Africa. In this region, anthropogenic emissions from large urban centers interact with natural emissions from the Saharan and Middle Eastern deserts, smoke from frequent wildfires, and volcanic particles from eruptions, notably from Mt. Etna and Icelandic volcanoes. Additionally, the atmosphere over the Eastern Mediterranean contains background marine aerosols and pollen particles from oceanic and vegetative sources. Aerosols exert a variety of effects on regional weather and climate, impacting solar radiation, visibility, and human health, and they pose significant concerns for aviation safety (WMO, 2024).

The Eastern Mediterranean is characterized by a Mediterranean climate, with hot, dry summers and mild, wet winters. This seasonal variability is driven primarily by the interaction between mid-latitude westerlies and subtropical high-pressure systems (Lensky et al., 2018). During winter, the region experiences frequent passage of extratropical cyclones originating from the North Atlantic and Mediterranean storm tracks, bringing precipitation and colder temperatures. In contrast, summer conditions are dominated by the expansion of the subtropical height, leading to stable atmospheric conditions and minimal rainfall (ECMWF, 2010).

Synoptic-scale circulation in the Eastern Mediterranean plays a crucial role in shaping weather patterns and atmospheric dynamics. The atmospheric circulation over the eastern Mediterranean is dominated by persistent northerly and westerly winds, favoring the advection of volcanic products from Etna to Greece (Kampouri et al., 2020; Scollo et al., 2013). Research has identified several dominant synoptic types that influence the region, including cyclonic systems, anticyclonic patterns, and blocking heights (Rousi et al., 2014). These circulation patterns significantly impact the transport of aerosols, moisture, and pollutants, affecting regional air quality and climate variability. Furthermore, the region's proximity to large-scale circulation features such as the subtropical jet stream and the African monsoon system contributes to complex seasonal interactions (Lensky et al., 2018)."

5. Page 6 Table 1 (Ash mass calculation using remote sensing data): I recommend that you add a sentence or two to justify the values selected in the table for lidar ratio and "volume to extinction conversion factor". Also, you must include some key references for that.

AC. We thank the reviewer for this suggestion. We revised the text accordingly and added the following paragraph with the respective references both in the text but also included here for convenience:

The lidar ratio of coarse mode volcanic ash at 532 nm is reported to range between 40 and 60 sr in the literature (see for example Groß et al., 2012; table 3 for particle extinction and backscatter values in Floutsi et al., 2023 and Gasteiger et al., 2011). For the fine mode aerosols, we use a mean value of 60 sr following the values reported in the literature for particles of sulphuring nature (see for example Floutsi et al., 2023; Müller et al., 2007). We also account for a lidar ratio retrieval uncertainty of ~30% to capture the measurement range (Ansmann et al., 2012; Giannakaki et al., 2015; Groß et al., 2013). The particle density values ρ follow from OPAC model for coarse mode mineral component and water soluble component for ash and sulfate particles respectively (Hess et al., 1998; Koepke et al., 2015). For the water soluble component, we assume values at relative humidity of 0% which is considered representative for the altitudes of the volcanic layers. The coarse mode component is not considered as hudrophylic. Finally, the extinction to mass conversion factors cv are taken from Ansmann et al., (2011a) for ash and fine mode particles respectively.

6. Page 12, Figure 2b (Results): It is unclear to me what meas the blue vertical lines. Profiles of NaN (no valid volume linear depolarization ratio)? Missing data in the time periods analyzed? Common time periods for lidar - photometer? Comment on this aspect.

AC. We thank the reviewer for the comment. The blue vertical lines indicate negative values, which arise due to a low signal-to-noise ratio (SNR). They do not represent meaningful atmospheric features and they are masked before data averaging over the entire time interval, hence they do not influence the analysis. We added the following sentence to Figure 2 caption to make this clearer:

"The blue vertical lines on (b) indicate negative values, which arise due to a low signal-to-noise ratio (SNR) of the measurements, and they are masked before data averaging and final retrievals."

7. Page 13, Lines 346-348: It is unclear to me why a-posterior MER has this behavior. Please give a short explanation for clarification.

AC. We would like to thank the reviewer for this question. The inversion process incorporates ground-based lidar observations from the Polly^{XT} system, which provides direct measurements of the volcanic ash plumes vertical structure. These lidar observations, being highly sensitive to the vertical distribution of ash, help refine the emission estimates, particularly within the altitude range where the plume was observed (8–12 km), ensuring that the final estimates better reflect the actual emission patterns.

Additionally, the a-priori MER estimates were initially derived from empirical relationships based on VONA-reported plume heights (see Appendix Table A1, added for further clarification). These empirical methods often overestimate emissions, particularly in the initial stages of the eruption when plume dynamics are highly variable. The inversion process corrects for this by adjusting emissions to match the lidar observations, leading to lower and more consistent a-posteriori MER values. As a result, the a-posteriori MER shows a more physically realistic and concentrated vertical distribution, predominantly between 8 and 12 km, in contrast to the a-priori estimates, which exhibit a wider spread, including lower altitudes where the plume was not actually observed. This suggests that the inversion effectively filters out unrealistic emissions, yielding a more refined and accurate vertical profile.

Moreover, it is important to highlight that during the eruption, the plume undergoes a dynamic evolution, rising and collapsing at different stages. This complex evolution is not fully captured by the model, which does not explicitly simulate the transient rise and fall of the plume. Instead, the model adjusts the a-posteriori MER at each height over time, increasing or decreasing emission rates to best match the available observations. While this approach provides a more constrained and consistent representation of emissions, some rapid fluctuations in plume height and intensity may not be fully resolved within the model framework. Finally, we emphasize that the most significant refinement in the inversion algorithm occurs between 08:00–08:45 UTC, at the peak of the eruption.

In the revised manuscript we added a paragraph to clarify better the MER behavior. The text now reads "The eruption dynamics involve a complex evolution of the volcanic plume, with phases of rising and collapsing. However, this dynamic behavior is not explicitly resolved in the a-posteriori simulations, which do not capture rapid fluctuations in plume height and intensity. Instead, the inversion algorithm adjusts the a-posteriori MER at each altitude over time, dynamically increasing or decreasing emission rates to achieve the best agreement with available observations. The most significant refinement occurs between 08:15–08:45 UTC, within the 8–12 km altitude range, where lidar observations provide direct constraints on the plume's vertical structure. As a result, the inversion optimizes the emission estimates primarily within this altitude range, ensuring the highest degree of agreement between observed and a-posteriori emissions."

8. Page 21, Lines 513-515 (Conclusions and discussion) Discuss how the method could be adjusted for other EARLINET/ACTRIS stations with similar lidar configurations and/or for the Earth Observation missions (current and future), detailing the data requirements and necessary adjustments.

AC. We thank the reviewer for the insightful comment. In the revised manuscript we added the following paragraph. “However, their applicability to the proposed methodology depends on the operation of a backscatter-depolarization lidar, which constitutes the primary requirement. In cases where direct measurements of essential parameters, such as lidar ratios, are unavailable, values from the scientific literature can be used. A more advanced configuration, incorporating Raman lidar capabilities, would enhance the accuracy of retrieved backscatter and lidar ratio coefficients. Additionally, for daytime measurements, a co-located sun photometer would facilitate direct estimation of the conversion factors required in the inversion process. Beyond ground-based applications, the methodology is also applicable to spaceborne aerosol lidars, which provide vertical profiles of the backscatter coefficient and particle linear depolarization ratio, both fundamental parameters for the inversion process. Furthermore, the methodology presented herein can be applied to current or future satellite missions that employ lidar measurements (e.g. the EarthCARE mission).”

9. What were the main technical challenges in modeling long-range transported of volcanic ash and sulfate particles?

AC. We would like to thank the reviewer for this question. Modeling the long-range transport of volcanic particles, especially in real time and during the initial phase of an eruption when little observational data is available (Eckhardt et al., 2008), presents several technical challenges due to their distinct physical and chemical properties of ash and sulfate particles.

Simulations of volcanic eruptions are strongly dependent on the accuracy of the eruption source term, such as 1) injection plume height, 2) the mass eruption rate (MER), 3) the vertical distribution of the ash and SO_2 in the eruption column and 4) the duration of the eruption, all of which significantly influence particle dispersion (Beckett et al., 2022; Mastin et al., 2009).

Various methods exist for estimating the source term of a volcanic eruption. The most common approach is based on plume height observations, e.g., from weather radar, or ECV calibrated cameras which are then applied to empirical relationships linking the total MER to the eruption plume height (Mastin et al., 2009). However, these empirical relationships have large uncertainties, as a wide range of total mass emissions can correspond to the same plume height.

Beyond source term assumptions, there are several other factors contribute to uncertainties in volcanic particles transport modelling. These include uncertainties in the dispersion model itself, and the meteorological input data that drive the simulations. Volcanic ash and SO_2 transport are highly dependent on wind fields, and errors in numerical weather prediction models, in upper-tropospheric wind shear can lead to significant uncertainties in forecasted trajectories (Harvey et al., 2020). Additionally, processes such as particle aggregation, gravitational settling, and wet/dry deposition affect ash lifetime and spatial distribution, yet they remain challenging to accurately parameterize in dispersion models (Dacre et al., 2011; Durant et al., 2010).

For volcanic ash, another important source of uncertainty is the assumptions made for particle size distribution in model simulations. Fine ash particles (diameter $< 63\ \mu m$) can remain in the atmosphere for many hours or days and can be transported far from the source, but their size distribution varies significantly between different volcanoes and eruptions (Kristiansen et al., 2012; Moxnes et al., 2014).

In the case of SO_2 emissions, interactions with hydroxyl radicals (OH) in the atmosphere result in the formation of sulfate aerosols, introducing additional challenges related to chemical transformation and microphysical processes (Schmidt et al., 2012; Textor et al., 2004). Sulfate particles, due to their smaller size and longer atmospheric residence time, are prone to long-range transport, but their interactions with clouds and solar radiation by scattering introduce further uncertainties in atmospheric modeling forecasts (Zhu et al., 2020). Addressing these challenges requires improved observational constraints, such as satellite and lidar data assimilation, to refine both ash and sulfate dispersion models (Amiridis et al., 2023; Kristiansen et al., 2010).

10. How fast is the inversion scheme presented in this study and what is the confidence level of the data provided?

AC. We would like to thank the reviewer for this question. The inversion scheme presented in this study is computationally efficient, with each simulation being processed within a few minutes. Once lidar data become available, the algorithm rapidly optimizes the volcanic ash emission profile by integrating observational constraints with dispersion modeling. This efficiency makes the method highly suitable for near-real-time applications, which are critical for aviation safety and early warning systems.

The confidence level of the provided data depends on several factors, including the accuracy of the eruption source terms (e.g., injection plume height, eruption duration), the a priori estimation of ash mass emission rates based on empirical equations, the quality of meteorological input data driving the simulations, and the constraints applied in the optimization process. Validation against ground-based lidar observations demonstrates a minimal difference of approximately 2% between the a posteriori simulated and observed ash mass concentrations. Furthermore, the assimilation of Aeolus wind data significantly enhances the accuracy of the transport model by improving wind field representation, particularly at higher altitudes. While the inversion-derived emission estimates provide a high-confidence dataset for dispersion forecasting, uncertainties persist due to potential biases in observational data and assumptions in source term estimation. To further enhance validation, additional independent datasets, such as satellite observations, ground-based remote sensing, or in situ measurements along the plume's trajectory, should be incorporated in future studies.

Technical corrections

1. Update the figures 2- 4 with larger fonts to make them more visible.

AC. Done. In the revised manuscript we replace Figures 2-4.

2. Figures 4-5: Change the "μgr" in the figure captions to "μg"

AC. Done. We have changed 'μgr' to 'μg' in the caption of Figure 4 and updated Figure 5 accordingly. The revised caption for Figure 5 now reads: "Figure 5: FLEXPART time-height cross-sections on 12 March 2021, 18:30 – 21:30 UTC, over the PANGEA observatory in Antikythera, Greece. (a) time-height plot of a-priori FLEXPART volcanic ash concentrations (μg/m^3), over Antikythera "w/o" Aeolus wind assimilation over Antikythera, Greece (zero values); (b) time-height plot of a-priori FLEXPART volcanic ash concentrations (μg/m^3) over Antikythera "w" Aeolus wind assimilation; (c) time-height plot of a-posteriori FLEXPART volcanic ash concentrations (μg/m^3) over Antikythera "w" Aeolus wind assimilation over Antikythera, Greece ("w/o" are not calculated)." Additionally, we have updated 'μgr' to 'μg' in the Figure 5 plot as well.

3. Figures 6-7: Change the "ug" in the figure captions to "μg"

AC. Done. In the revised manuscript, we have changed "ug" to "µg" in Figures 6 and 7. Additionally, as requested by **Referee 1**, we have combined Figures 6 and 7. In the revised text, Figure 7 is now presented as Figure 6 d.

4. Please specify in the text the reference point (a.s.l or a.g.l) for the altitude values in figures 3, 6, 7 and 8.

AC. Done. In the revised manuscript, we have specified the reference point (a.s.l. or a.g.l.) for the altitude values in Figures 3, 6, and 7. However, there is no Figure 8 in our manuscript.

References

Amiridis, V., Kampouri, A., Gkikas, A., Misios, S., Gialitaki, A., Marinou, E., Rennie, M., Benedetti, A., Solomos, S., Zanis, P., Vasardani, O., Eleftheratos, K., Paschou, P., Georgiou, T., Scollo, S., Mona, L., Papagiannopoulos, N., Retscher, C., Parrinello, T., and Straume, A. G.: Aeolus winds impact on volcanic ash early warning systems for aviation, Sci. Rep., 13, 7531, https://doi.org/10.1038/s41598-023-34715-6, 2023.

Ansmann, A., Tesche, M., Seifert, P., Groß, S., Freudenthaler, V., Apituley, A., Wilson, K. M., Serikov, I., Linné, H., Heinold, B., Hiebsch, A., Schnell, F., Schmidt, J., Mattis, I., Wandinger, U., and Wiegner, M.: Ash and fine-mode particle mass profiles from EARLINET-AERONET observations over central Europe after the eruptions of the Eyjafjallajökull volcano in 2010, J. Geophys. Res. Atmospheres, 116, https://doi.org/10.1029/2010JD015567, 2011.

Ansmann, A., Seifert, P., Tesche, M., and Wandinger, U.: Profiling of fine and coarse particle mass: case studies of Saharan dust and Eyjafjallajökull/Grimsvötn volcanic plumes, Atmospheric Chem. Phys., 12, 9399–9415, https://doi.org/10.5194/acp-12-9399-2012, 2012.

Beckett, F., Rossi, E., Devenish, B., Witham, C., and Bonadonna, C.: Modelling the size distribution of aggregated volcanic ash and implications for operational atmospheric dispersion modelling, Atmospheric Chem. Phys., 22, 3409–3431, https://doi.org/10.5194/acp-22-3409-2022, 2022.

Clarisse, L., Prata, F., Lacour, J., Hurtmans, D., Clerbaux, C., and Coheur, P.: A correlation method for volcanic ash detection using hyperspectral infrared measurements, Geophys. Res. Lett., 37, 2010GL044828, https://doi.org/10.1029/2010GL044828, 2010.

Dacre, H. F., Grant, A. L. M., Hogan, R. J., Belcher, S. E., Thomson, D. J., Devenish, B. J., Marenco, F., Hort, M. C., Haywood, J. M., Ansmann, A., Mattis, I., and Clarisse, L.: Evaluating the structure and magnitude of the ash plume during the initial phase of the 2010 Eyjafjallajökull eruption using lidar observations and NAME simulations, J. Geophys. Res., 116, D00U03, https://doi.org/10.1029/2011JD015608, 2011.

Durant, A. J., Bonadonna, C., and Horwell, C. J.: Atmospheric and Environmental Impacts of Volcanic Particulates, Elements, 6, 235–240, https://doi.org/10.2113/gselements.6.4.235, 2010.

Eckhardt, S., Prata, A. J., Seibert, P., Stebel, K., and Stohl, A.: Estimation of the vertical profile of sulfur dioxide injection into the atmosphere by a volcanic eruption using satellite column measurements and inverse transport modeling, 2008.

ECMWF: European Centre for Medium-Range Weather Forecasts (ECMWF) (2010). Synoptic-scale variability in the Mediterranean. ECMWF Technical Report., 2010.

Floutsi, A. A., Baars, H., Engelmann, R., Althausen, D., Ansmann, A., Bohlmann, S., Heese, B., Hofer, J., Kanitz, T., Haarig, M., Ohneiser, K., Radenz, M., Seifert, P., Skupin, A., Yin, Z., Abdullaev, S. F., Komppula, M., Filioglou, M., Giannakaki, E., Stachlewska, I. S., Janicka, L., Bortoli, D., Marinou, E., Amiridis, V., Gialitaki, A., Mamouri, R.-E., Barja, B., and Wandinger, U.: DeLiAn – a growing collection of depolarization ratio, lidar ratio and Ångström exponent for different aerosol types and mixtures from ground-based lidar observations, Atmospheric Meas. Tech., 16, 2353–2379, https://doi.org/10.5194/amt-16-2353-2023, 2023.

Francis, P. N., Cooke, M. C., and Saunders, R. W.: Retrieval of physical properties of volcanic ash using Meteosat: A case study from the 2010 Eyjafjallajökull eruption, J. Geophys. Res. Atmospheres, 117, 2011JD016788, https://doi.org/10.1029/2011JD016788, 2012.

Gasteiger, J., Groß, S., Freudenthaler, V., and Wiegner, M.: Volcanic ash from Iceland over Munich: mass concentration retrieved from ground-based remote sensing measurements, Atmospheric Chem. Phys., 11, 2209–2223, https://doi.org/10.5194/acp-11-2209-2011, 2011.

Giannakaki, E., Pfüller, A., Korhonen, K., Mielonen, T., Laakso, L., Vakkari, V., Baars, H., Engelmann, R., Beukes, J. P., Van Zyl, P. G., Josipovic, M., Tiitta, P., Chiloane, K., Piketh, S., Lihavainen, H., Lehtinen, K. E. J., and Komppula, M.: One year of Raman lidar observations of free-tropospheric aerosol layers over South Africa, Atmospheric Chem. Phys., 15, 5429–5442, https://doi.org/10.5194/acp-15-5429-2015, 2015.

Groß, S., Freudenthaler, V., Wiegner, M., Gasteiger, J., Geiß, A., and Schnell, F.: Dual-wavelength linear depolarization ratio of volcanic aerosols: Lidar measurements of the Eyjafjallajökull plume over Maisach, Germany, Volcan. Ash Eur. Erupt. Eyjafjallajöekull Icel. April-May 2010, 48, 85–96, https://doi.org/10.1016/j.atmosenv.2011.06.017, 2012.

Groß, S., Esselborn, M., Weinzierl, B., Wirth, M., Fix, A., and Petzold, A.: Aerosol classification by airborne high spectral resolution lidar observations, Atmos Chem Phys, 13, 2487–2505, https://doi.org/10.5194/acp-13-2487-2013, 2013.

Harvey, N. J., Dacre, H. F., Webster, H. N., Taylor, I. A., Khanal, S., Grainger, R. G., and Cooke, M. C.: The Impact of Ensemble Meteorology on Inverse Modeling Estimates of Volcano Emissions and Ash Dispersion Forecasts: Grímsvötn 2011, Atmosphere, 11, 1022, https://doi.org/10.3390/atmos11101022, 2020.

Hess, M., Koepke, P., and Schult, I.: Optical Properties of Aerosols and Clouds: The Software Package OPAC, Bull. Am. Meteorol. Soc., 79, 831–844, https://doi.org/10.1175/1520-0477(1998)079<0831:OPOAAC>2.0.CO;2, 1998.

Jones, A., Thomson, D., Hort, M., and Devenish, B.: The U.K. Met Office's Next-Generation Atmospheric Dispersion Model, NAME III, in: Air Pollution Modeling and Its Application XVII, Boston, MA, 580–589, 2007.

Kampouri, A., Amiridis, V., Solomos, S., Gialitaki, A., Marinou, E., Spyrou, C., Georgoulias, A. K., Akritidis, D., Papagiannopoulos, N., Mona, L., Scollo, S., Tsichla, M., Tsikoudi, I., Pytharoulis, I., Karacostas, T., and Zanis, P.: Investigation of Volcanic Emissions in the Mediterranean: "The

Etna–Antikythera Connection,” Atmosphere, 12, 40, https://doi.org/10.3390/atmos12010040, 2020.

Koepke, P., Gasteiger, J., and Hess, M.: Technical Note: Optical properties of desert aerosol with non-spherical mineral particles: data incorporated to OPAC, Atmospheric Chem. Phys., 15, 5947–5956, https://doi.org/10.5194/acp-15-5947-2015, 2015.

Kristiansen, N. I., Stohl, A., Prata, A. J., Richter, A., Eckhardt, S., Seibert, P., Hoffmann, A., Ritter, C., Bitar, L., Duck, T. J., and Stebel, K.: Remote sensing and inverse transport modeling of the Kasatochi eruption sulfur dioxide cloud, J. Geophys. Res. Atmospheres, 115, 2009JD013286, https://doi.org/10.1029/2009JD013286, 2010.

Kristiansen, N. I., Stohl, A., Prata, A. J., Bukowiecki, N., Dacre, H., Eckhardt, S., Henne, S., Hort, M. C., Johnson, B. T., Marenco, F., Neininger, B., Reitebuch, O., Seibert, P., Thomson, D. J., Webster, H. N., and Weinzierl, B.: Performance assessment of a volcanic ash transport model mini-ensemble used for inverse modeling of the 2010 Eyjafjallajökull eruption, J. Geophys. Res. Atmospheres, 117, 2011JD016844, https://doi.org/10.1029/2011JD016844, 2012.

Kristiansen, N. I., Arnold, D., and Stohl, A.: Procedures for volcano inversions using FLEXPART, 2014.

Lensky, I. M., Dayan, U., and Helman, D.: Synoptic Circulation Impact on the Near-Surface Temperature Difference Outweighs That of the Seasonal Signal in the Eastern Mediterranean, J. Geophys. Res. Atmospheres, 123, 11,333-11,347, https://doi.org/10.1029/2017JD027973, 2018.

Mastin, L. G., Guffanti, M., Servranckx, R., Webley, P., Barsotti, S., Dean, K., Durant, A., Ewert, J. W., Neri, A., Rose, W. I., Schneider, D., Siebert, L., Stunder, B., Swanson, G., Tupper, A., Volentik, A., and Waythomas, C. F.: A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions, J. Volcanol. Geotherm. Res., 186, 10–21, https://doi.org/10.1016/j.jvolgeores.2009.01.008, 2009.

Moxnes, E. D., Kristiansen, N. I., Stohl, A., Clarisse, L., Durant, A., Weber, K., and Vogel, A.: Separation of ash and sulfur dioxide during the 2011 Grímsvötn eruption, J. Geophys. Res. Atmospheres, 119, 7477–7501, https://doi.org/10.1002/2013JD021129, 2014.

Müller, D., Ansmann, A., Mattis, I., Tesche, M., Wandinger, U., Althausen, D., and Pisani, G.: Aerosol-type-dependent lidar ratios observed with Raman lidar, J. Geophys. Res. Atmospheres, 112, https://doi.org/10.1029/2006JD008292, 2007.

Pappalardo, G., Amodeo, A., Mona, L., Pandolfi, M., Pergola, N., and Cuomo, V.: Raman lidar observations of aerosol emitted during the 2002 Etna eruption, Geophys. Res. Lett., 31, 2003GL019073, https://doi.org/10.1029/2003GL019073, 2004.

Pavolonis, M. J., Heidinger, A. K., and Sieglaff, J.: Automated retrievals of volcanic ash and dust cloud properties from upwelling infrared measurements, J. Geophys. Res. Atmospheres, 118, 1436–1458, https://doi.org/10.1002/jgrd.50173, 2013.

Prata, A. J.: Satellite detection of hazardous volcanic clouds and the risk to global air traffic, Nat. Hazards, 51, 303–324, https://doi.org/10.1007/s11069-008-9273-z, 2009.

Prata, A. J. and Prata, A. T.: Eyjafjallajökull volcanic ash concentrations determined using Spin Enhanced Visible and Infrared Imager measurements, J. Geophys. Res. Atmospheres, 117, 2011JD016800, https://doi.org/10.1029/2011JD016800, 2012.

Rennie, M. P., Isaksen, L., Weiler, F., De Kloe, J., Kanitz, T., and Reitebuch, O.: The impact of AEOLUS wind retrievals on ECMWF global weather forecasts, Q. J. R. Meteorol. Soc., 147, 3555–3586, https://doi.org/10.1002/qj.4142, 2021.

Rousi, E., Mimis, A., Stamou, M., and Anagnostopoulou, C.: Classification of circulation types over Eastern mediterranean using a self-organizing map approach, J. Maps, 10, 232–237, https://doi.org/10.1080/17445647.2013.862747, 2014.

Schmidt, A., Carslaw, K. S., Mann, G. W., Rap, A., Pringle, K. J., Spracklen, D. V., Wilson, M., and Forster, P. M.: Importance of tropospheric volcanic aerosol for indirect radiative forcing of climate, Atmospheric Chem. Phys., 12, 7321–7339, https://doi.org/10.5194/acp-12-7321-2012, 2012.

Scollo, S., Coltelli, M., Bonadonna, C., and Del Carlo, P.: Tephra hazard assessment at Mt. Etna (Italy), Nat. Hazards Earth Syst. Sci., 13, 3221–3233, https://doi.org/10.5194/nhess-13-3221-2013, 2013.

Seibert, P., Kristiansen, N. I., Richter, A., Eckhardt, S., Prata, A. J., and Stohl, A.: Uncertainties in the inverse modelling of sulphur dioxide eruption profiles, Geomat. Nat. Hazards Risk, 2, 201–216, https://doi.org/10.1080/19475705.2011.590533, 2011.

Stein, A. F., Draxler, R. R., Rolph, G. D., Stunder, B. J. B., Cohen, M. D., and Ngan, F.: NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System, Bull. Am. Meteorol. Soc., 96, 2059–2077, https://doi.org/10.1175/BAMS-D-14-00110.1, 2015.

Stohl, A., Prata, A. J., Eckhardt, S., Clarisse, L., Durant, A., Henne, S., Kristiansen, N. I., Minikin, A., Schumann, U., Seibert, P., Stebel, K., Thomas, H. E., Thorsteinsson, T., Tørseth, K., and Weinzierl, B.: Determination of time- and height-resolved volcanic ash emissions and their use for quantitative ash dispersion modeling: the 2010 Eyjafjallajökull eruption, Atmospheric Chem. Phys., 11, 4333–4351, https://doi.org/10.5194/acp-11-4333-2011, 2011.

Textor, C., Graf, H.-F., Timmreck, C., and Robock, A.: Emissions from volcanoes, in: Emissions of Atmospheric Trace Compounds, vol. 18, edited by: Granier, C., Artaxo, P., and Reeves, C. E., Springer Netherlands, Dordrecht, 269–303, https://doi.org/10.1007/978-1-4020-2167-1_7, 2004.

WMO: State of the Global Climate 2023, United Nations, Erscheinungsort nicht ermittelbar, 2024.

Zhu, Y., Toon, O. B., Jensen, E. J., Bardeen, C. G., Mills, M. J., Tolbert, M. A., Yu, P., and Woods, S.: Persisting volcanic ash particles impact stratospheric SO2 lifetime and aerosol optical properties, Nat. Commun., 11, 4526, https://doi.org/10.1038/s41467-020-18352-5, 2020.