To Referee #2

Dear Reviewer:

Hello!

Thank you very much for your careful reading of our manuscript and for the constructive and detailed comments. Your suggestions helped us identify weaknesses in the scientific framing, methodological description, physical interpretation, and presentation of the results.

In response, we added threshold-sensitivity and daily-sample statistical analyses, presented the paired PM_{10}–extinction regression and its limitations, clarified the physical interpretation of potential-temperature gradients and time standards, refined the EAL identification procedure, standardized depolarization terminology and figure labels, and moderated the radiative and regional-impact discussion.

We have responded to each comment point by point below. Reviewer comments are reproduced in bold, and representative text from the revised manuscript is shown in blue italics for ease of reference.

We sincerely appreciate the time and effort you devoted to reviewing our work.

Reviewer #2 (Comments to Author):

The manuscript titled "Elevated Aerosol Layers within the Daytime Mixed Layer Over Ecologically Sensitive Areas of Northwest China: Diurnal Variation, Formation Mechanisms and Regional Effects" addresses an important and relatively understudied topic: the high-resolution diurnal vertical structure of aerosols over the complex terrains of Northwest China (specifically the Hexi Corridor). The identification of Elevated Aerosol Layers (EALs) during the daytime and their quantification via lidar observations provides valuable insights into regional air quality budgets, boundary layer dynamics, and localized radiative forcing. The paper falls well within the scope of Atmospheric Chemistry and Physics. However, the manuscript still needs revised and improved; there are several critical issues that should be addressed before publication.

Major Comments

(1) The study identifies frequent elevated aerosol layers within the daytime mixed layer over the Hexi Corridor and further suggests that their formation is jointly controlled by positive potential temperature anomalies and negative relative humidity anomalies. However, the current EAL identification method remains relatively empirical, especially regarding the physical meaning of the "continuous positive gradient" and the 20% threshold. The authors are encouraged to provide a sensitivity test of different threshold combinations.

Response: We agree. Section 2.2.1 now gives an operational definition of the continuous positive gradient in the aerosol extinction coefficient profile and explains the sequence used to exclude dust events and identify EALs. We also added Fig. S1, which systematically varies the dust-event exclusion threshold and the positive-gradient observation-proportion threshold at both sites. The selected combination (50% dust-event exclusion and 20% positive-gradient proportion) lies within a comparatively stable part of the classification curves and was chosen to minimize classification fluctuations while retaining consistency between sites.

The corresponding revised text is as follows:

"For the remaining non-dust observations, elevated aerosol layers were identified based on the spatiotemporal continuity of the positive-gradient

structure in the aerosol extinction coefficient profiles. In this study, a "continuous positive gradient" refers to a fitted aerosol extinction coefficient profile that increases persistently with height from the first valid value above the lidar blind zone to the altitude of the aerosol-layer peak, with this increasing structure required to be continuous in both height and time."

"The selection of the 50% and 20% thresholds was based on the stability of event classification. Specifically, different threshold combinations were systematically evaluated, and the variability of the resulting classifications was analysed, as shown in Fig. S1. The optimal combination—defined as that which minimized classification fluctuations and maximized consistency—was ultimately selected as the determination criterion."

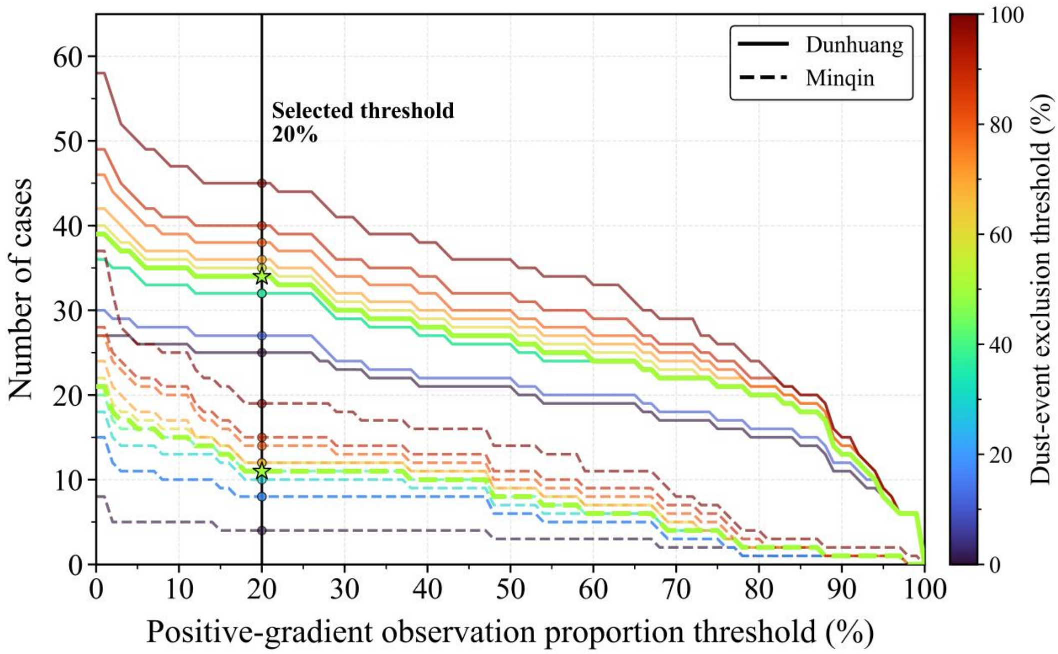

Fig. S1. Sensitivity of elevated aerosol layer classification to threshold combinations at Dunhuang and Minqin. Solid and dashed lines represent the Dunhuang and Minqin sites, respectively, and line colour denotes the dust-event exclusion threshold. The black vertical line marks the selected positive-gradient observation-proportion threshold of 20%, while the star markers indicate the final threshold combination of 50% for dust-event exclusion and 20% for elevated aerosol layer identification. The selected thresholds correspond to relatively stable classification results across different threshold combinations.

(2) The authors suggest that EAL occurrence is associated with positive potential temperature anomalies and negative relative humidity anomalies, which is physically plausible. However, the current evidence is mainly based on composite anomaly fields, and a daily-sample statistical comparison between EAL and non-

EAL days is still lacking. I suggest site-specific statistics, such as mean differences, bootstrap 95% confidence intervals, and non-parametric significance tests, together with a boxplot or scatter-boxplot showing day-to-day variability.

Response: We added Fig. S3 to show all daily samples, medians, interquartile ranges, outliers, sample sizes, and non-parametric test results separately for Dunhuang and Minqin. The daily comparison supports the composite pattern: EAL days are generally warmer in potential-temperature anomaly and drier in relative-humidity anomaly. The differences are significant for potential temperature at both sites (Dunhuang $p < 0.001$; Minqin $p = 0.027$) and for relative humidity at Dunhuang ($p = 0.009$); the Minqin relative-humidity difference is directionally consistent but does not reach the 0.05 level ($p = 0.069$). Because the groups are small and strongly unbalanced at Dunhuang (32 EAL days versus 7 non-EAL days), we did not interpret bootstrap confidence intervals as robust. Instead, the figure reports the complete daily distributions and non-parametric tests, which make the sample-size limitation transparent.

The corresponding revised text is as follows:

"To further support the composite anomaly analysis, daily samples were statistically compared under conditions with and without elevated aerosol layers within the main height range and occurrence period of elevated aerosol layers (Fig. S3). The results show that daily potential temperature anomalies were generally higher, whereas daily relative humidity anomalies were generally lower, under conditions with elevated aerosol layers at both Dunhuang and Minqin sites."

"The non-parametric test results indicate statistically distinguishable differences between the two groups, with significance levels varying between variables and sites. These daily statistics provide additional support that the dry and warm thermodynamic conditions associated with elevated aerosol layers are also evident in day-to-day variability."

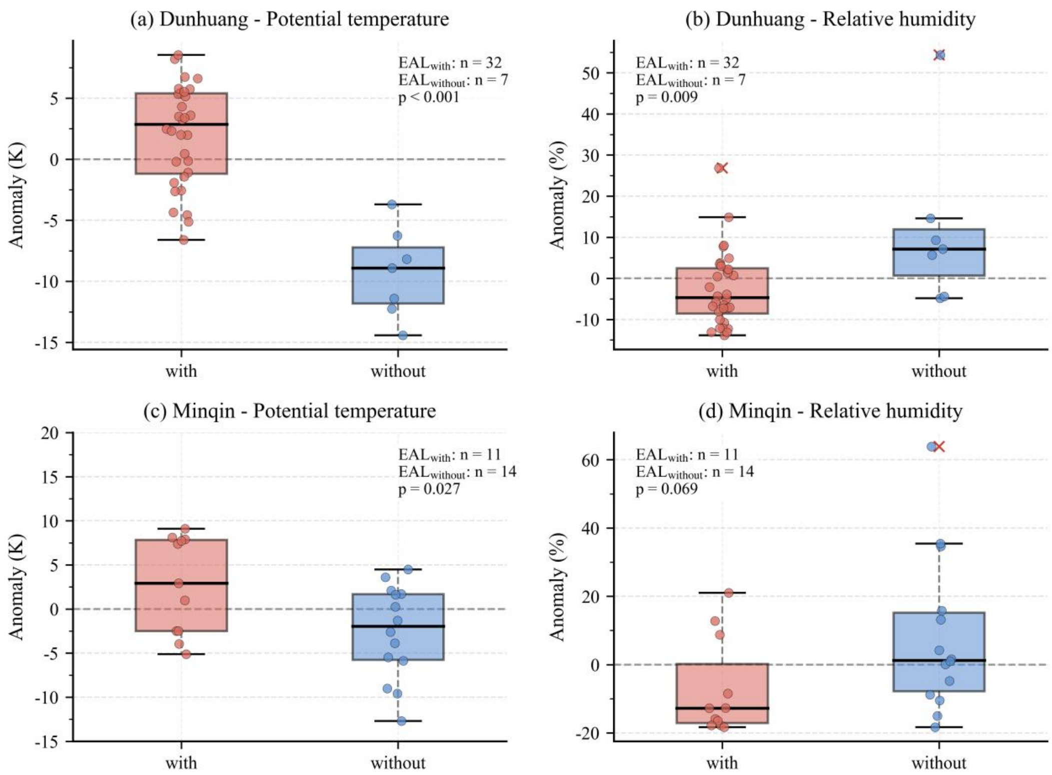

Fig. S3. Boxplots of daily potential temperature and relative humidity anomalies at the Dunhuang and Minqin sites under conditions with and without elevated aerosol layers (EALs). The black lines represent the medians, circles indicate individual daily values, the box edges denote the 25th and 75th percentiles (Q1 and Q3), and the whiskers represent non-outlier data points. Outliers (values beyond Q3 + 1.5 × IQR or below Q1 − 1.5 × IQR) are marked with red crosses. Under a normal distribution, the whiskers encompass approximately 99% of the data. Reported p values are based on non-parametric tests comparing EAL and non-EAL days.

(3) The authors establish an empirical relationship between near-surface lidar extinction coefficients and ground-level PM10 concentrations, and then use this relationship to estimate PM10 concentrations within the EAL. Since the conversion can be affected by particle size distribution, relative humidity, and aerosol type, the authors are encouraged to present the paired samples and fitted relationship more clearly and to describe the EAL values cautiously as empirical estimates.

Response: We agree. Figure S2 now displays all temporally collocated pairs and the fitted line. Section 2.2.1 states the temporal resolutions, the near-600 m sampling bins, the number of paired samples (n = 4,357), the correlation coefficient (r = 0.80), the regression equation, and the units. Throughout the revised manuscript, the aloft quantity is described as an extinction-derived PM_{10}-equivalent mass concentration. We also added an explicit caveat that the regression is empirical and site/campaign specific, and that negative values predicted under very low-extinction conditions fall outside the physically meaningful range of the relationship.

The corresponding revised text is as follows:

"The 1 min MPL-derived extinction coefficients were matched with the 5 min ground-level PM10 observations at the corresponding observation times during the intensive observation period. As shown in Fig. S2, a significant positive correlation was found between PM10 mass concentration and the aerosol extinction coefficient (α) (r = 0.80, n = 4357)."

"$PM_{10} = 914.65 \times \alpha - 56.26$, where α is the aerosol extinction coefficient in km^{-1}, and PM_{10} represents the PM_{10}-equivalent mass concentration estimated from aerosol extinction coefficients using an empirical relationship, expressed in $\mu g/m^3$."

"Regression-derived PM_{10}-equivalent estimates should be interpreted empirically, and values predicted below zero under very low-extinction conditions are treated as outside the physically meaningful range of the relationship."

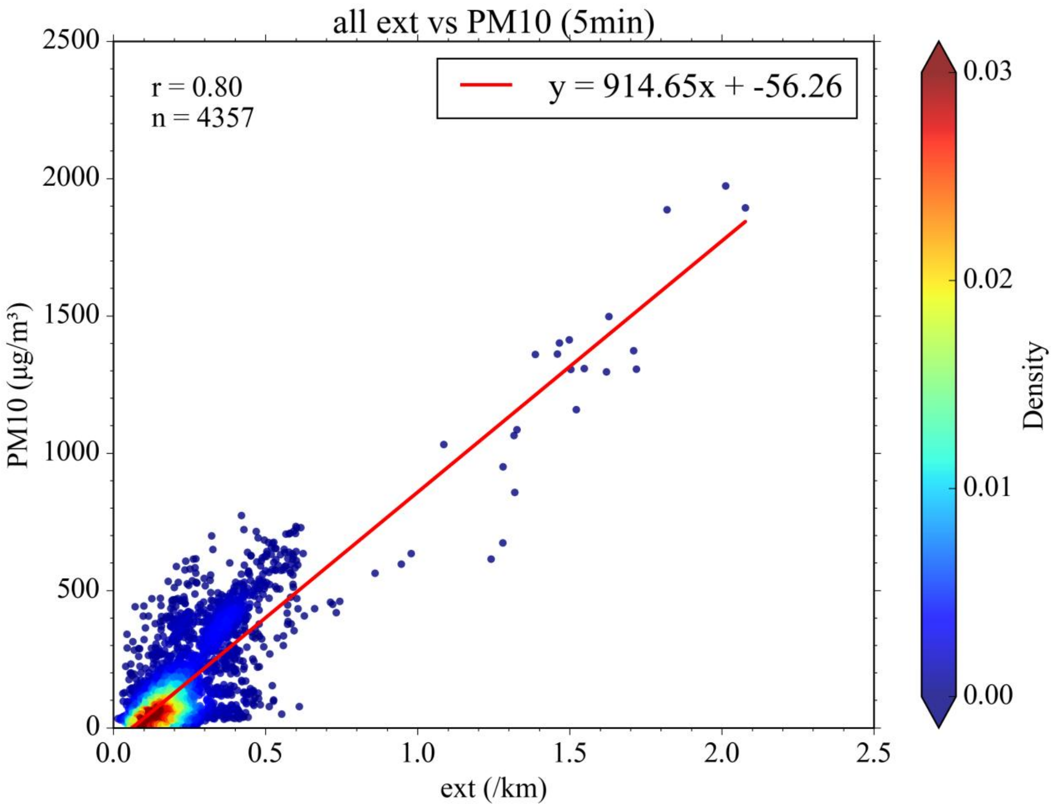

Fig. S2. Relationship between ground-level PM_{10} mass concentration and the temporally collocated MPL-derived aerosol extinction coefficient from the lowest two valid sampling bins near ~600 m during the intensive observation period. The red line represents the linear regression used to derive Eq.

(1). Regression-derived PM_{10}-equivalent estimates should be interpreted empirically, and values predicted below zero under very low-extinction conditions are treated as outside the physically meaningful range of the relationship.

(4) The discussion of radiative effects and potential impacts on snow and glaciers in the Qilian Mountains is scientifically interesting, but the current conclusions appear somewhat overextended. The radiative results are mainly based on two representative SBDART case simulations and are insufficient to demonstrate that EALs generally form a "heating pump" or significantly accelerate regional glacier/snow melting. The authors are encouraged to revise this part as a potential implication.

Response: We agree that two case simulations cannot establish a general regional cryospheric response. We removed the term "heating pump", explicitly described the SBDART results as simulations of two representative EAL events, and reframed the snow/glacier discussion as a potential implication rather than a demonstrated regional effect. The transport discussion is also now conditional on favourable wind regimes, and the limitation paragraph calls for longer-term observations and model simulations before generalization.

The corresponding revised text is as follows:

"Simulated shortwave radiative forcing results for two elevated aerosol layer events—observed on 21 April 2012 at Dunhuang and on 14 June 2010 at Minqin—are presented (Fig. 13a)."

"Furthermore, the EALs enhance the atmospheric shortwave heating rate (up to 0.7 K/day), indicating a potential impact on regional snowmelt/glacier retreat."

"This case-specific result does not exclude the possibility of regional impacts under other wind regimes. Under such conditions, daytime mountain–valley circulations may facilitate the transport of elevated aerosol layers from the Dunhuang region toward the Qilian Mountains. This process may contribute to localized pollution and has potential implications for snow/glacier environments in the Qilian Mountains."

Specific Comments

(1) In the abstract, the phrase "This study first identifies..." should be weakened. EALs are not a completely new aerosol phenomenon. The novelty would be more

appropriately described as a systematic analysis of the diurnal variation and potential mechanisms of EALs based on high-resolution ground-based observations in ecologically sensitive areas of the Hexi Corridor.

Response: We agree that elevated aerosol layers in general are not a newly discovered phenomenon. However, the novelty of this study lies in identifying and systematically characterizing an elevated aerosol layer embedded within the daytime mixed layer, rather than an elevated layer located above the boundary layer or within the residual/free tropospheric layer. To our knowledge, this specific daytime mixed-layer structure has rarely been explicitly identified and investigated over the Hexi Corridor using high-resolution ground-based lidar observations. We have therefore revised the Abstract to distinguish this specific phenomenon from EALs in general and to avoid implying that all elevated aerosol layers are newly discovered.

The corresponding revised text is as follows:

"This study first identifies the elevated aerosol layer (EAL) embedded within the daytime mixed layer over the Hexi Corridor, northwest China, defined as a high-concentration layer above the surface but within the mixed layer. Based on intensive observation campaigns conducted in 2010 and 2012, we analyze the diurnal variation, formation mechanisms, air quality and radiative effects of EALs."

(2) Lines 150–160 should provide more details on the EAL identification method. The authors should specify the variable used for the "continuous positive gradient", the minimum vertical thickness, minimum duration, smoothing method, and the criteria for excluding clouds and dust contamination.

Response: We expanded Section 2.2.1 to specify the profile variable, analysis period, blind-zone starting height, vertical and temporal continuity requirement, dust-screening criterion, and threshold-sensitivity analysis. The fitted variable is the aerosol extinction coefficient. A separate fixed minimum thickness or duration is not imposed; instead, the method requires a persistent increase from the first valid range bin above the 600 m blind zone to the layer peak, continuity in both height and time, and occurrence in more than 20% of observations during 13:00–21:00 BJT. Dust-contaminated days are excluded when more than 50% of observations have depolarization ratio > 0.20. Cloud features are identified during the standard MPL preprocessing and retrieval procedure described by Xie et al. (2017) and Zhou et al. (2018), and the EAL analysis is applied to the resulting aerosol profiles.

The corresponding revised text is as follows:

"MPL observations are corrected and preprocessed using the algorithm proposed in previous studies (Xie et al., 2017; Zhou et al., 2018). Subsequently, aerosol optical properties, including the extinction coefficient, backscattering coefficient, particle depolarization ratio, cloud top and base heights, and cloud thermodynamic phase, are retrieved."

"For both sites, if the proportion of observations identified as dust aerosols exceeded 50% on a given day, that day was classified as a dust event and subsequently excluded from further analysis. For the remaining non-dust observations, elevated aerosol layers were identified based on the spatiotemporal continuity of the positive-gradient structure in the aerosol extinction coefficient profiles."

(3) Lines 164–168 present the empirical regression between PM10 and aerosol extinction coefficient. The authors should provide units and scatter plots. Since the regression equation has a negative intercept, the treatment of possible negative concentrations under low-extinction conditions should also be explained.

Response: We added Fig. S2, specified the units of α (km^{-1}) and PM_{10}-equivalent mass concentration (μg/m^3), and described the collocation and regression sample size. The Supplement caption now explicitly states that negative regression outputs under very low-extinction conditions are outside the physically meaningful range and are not interpreted as physical concentrations.

The corresponding revised text is as follows:

"where α is the aerosol extinction coefficient in km^{-1}, and PM_{10} represents the PM_{10}-equivalent mass concentration estimated from aerosol extinction coefficients using an empirical relationship, expressed in μg/m^3."

"Regression-derived PM_{10}-equivalent estimates should be interpreted empirically, and values predicted below zero under very low-extinction conditions are treated as outside the physically meaningful range of the relationship."

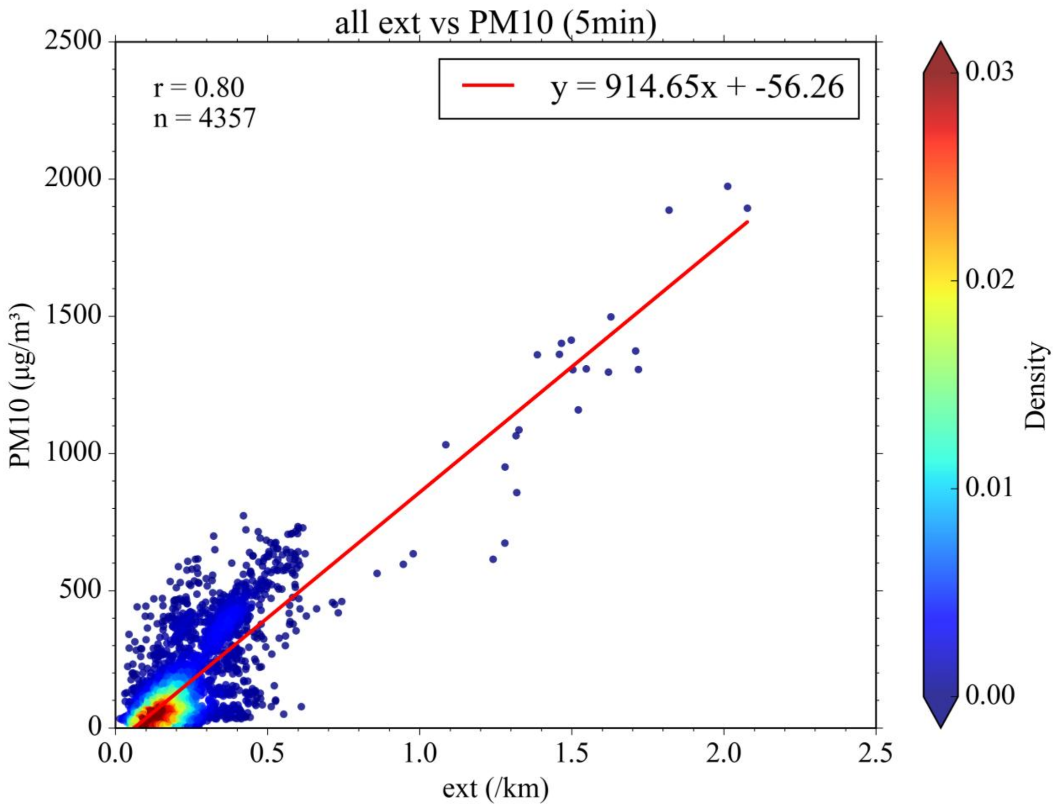

Fig. S2. Relationship between ground-level PM_{10} mass concentration and the temporally collocated MPL-derived aerosol extinction coefficient from the lowest two valid sampling bins near ~600 m during the intensive observation period. The red line represents the linear regression used to derive Eq. (1). Regression-derived PM_{10}-equivalent estimates should be interpreted empirically, and values predicted below zero under very low-extinction conditions are treated as outside the physically meaningful range of the relationship.

(4) Lines 357–360 state that a weakened potential temperature gradient indicates increased atmospheric stability. This physical interpretation should be reconsidered. In general, a stronger positive vertical gradient of potential temperature indicates stronger static stability.

Response: We agree and corrected the physical interpretation. The revised text distinguishes reduced stability and enhanced mixing within the daytime boundary layer from the stable layer near the boundary-layer top that caps further vertical dispersion.

The corresponding revised text is as follows:

"In addition, the weakened potential temperature gradient within the daytime boundary layer indicates reduced static stability and enhanced vertical mixing, which favoured the upward transport of aerosols from the lower atmosphere. The stable stratification near the boundary layer top further limited upward

dispersion, thereby promoting aerosol accumulation and the formation of the elevated aerosol layer."

(5) Figures 7 and 9 are key case studies. The authors should clarify whether the time is Beijing Time or local solar time. Since Dunhuang and Minqin are located in northwest China, the difference may affect interpretation of the diurnal peak.

Response: All times in the case studies are Beijing Time (BJT). We added "BJT" to the relevant times in the text and retained the discussion that the longitudinal difference and local-solar-time offset may partly contribute to the earlier Minqin peak.

The corresponding revised text is as follows:

"When elevated aerosol layers were present from 15:00 to 20:00 BJT, a high aerosol extinction coefficient (~0.27 km^{-1}) was observed at approximately 1 km."

"At Minqin, the average aerosol extinction coefficient remained relatively low for most of the observation period, except during the fully developed boundary layer stage (14:00–20:00 BJT), when it increased significantly to 0.23 km^{-1}."

"This earlier occurrence of the peak at Minqin may be partly related to geographical differences between the two regions, including the longitudinal difference and the resulting local-time effect, which can influence the timing of boundary layer development."

(6) In Lines 540–555, when comparing PM10 concentrations within EALs with severe haze or dust events in other regions, the authors should emphasize that these values are equivalent mass concentrations estimated from extinction coefficients rather than directly measured concentrations.

Response: We revised the terminology throughout Section 3.3 and the Abstract/Conclusions. The aloft values are now explicitly identified as PM_{10}-equivalent mass concentrations estimated from aerosol extinction coefficients, whereas the surface values are direct observations.

The corresponding revised text is as follows:

"During elevated aerosol layer episodes, the near-surface average PM10 concentration decreased to 40.8 ± 30.4 μg/m^3, whereas the average PM10-equivalent mass concentration estimated from the aerosol extinction coefficient at the peak of the elevated aerosol layers reached 203.3 ± 106.6 μg/m^3."

"This estimated concentration approaches levels observed during severe haze events."

(7) The discussion on snow, glaciers, and water resources in the Qilian Mountains should be moderated. Without deposition fluxes, snow-sample black carbon/dust concentrations, or snow-albedo observations, "accelerate snowmelt/glacier retreat" should be revised to a potential implication for snow and glacier energy balance.

Response: We agree that the present observations do not quantify aerosol deposition, snow impurity concentration, albedo change, or melt response. We therefore frame the result as a potential implication inferred from the simulated shortwave heating and the possible transport pathway, rather than as direct evidence of accelerated melt. The Abstract and the case-specific transport discussion now use explicitly cautious language.

The corresponding revised text is as follows:

"Furthermore, the EALs enhance the atmospheric shortwave heating rate (up to 0.7 K/day), indicating a potential impact on regional snowmelt/glacier retreat."

"This process may contribute to localized pollution and has potential implications for snow/glacier environments in the Qilian Mountains."

(8) The phrase "heating pump" in the abstract and conclusion is vivid but not sufficiently rigorous. It is suggested to replace it with "enhanced shortwave heating within the aerosol layer" or "a daily-scale atmospheric heating effect".

Response: The term "heating pump" has been removed from the Abstract and Conclusions. The revised manuscript directly reports the simulated enhancement of atmospheric shortwave heating rate.

The corresponding revised text is as follows:

"Furthermore, the EALs enhance the atmospheric shortwave heating rate (up to 0.7 K/day), indicating a potential impact on regional snowmelt/glacier retreat."

(9) The manuscript should use either "depolarisation ratio" or "depolarization ratio" consistently throughout the text.

Response: We checked the full manuscript, figure captions, and labels and standardized the spelling to "depolarization ratio" throughout.

The corresponding revised text is as follows:

"Time–height cross-sections of (a) normalised relative backscatter (NRB) and (b) linear volume depolarization ratio (Dep) derived from MPL observations."

(10) The linear depolarization ratio shown in Figure 6 is inconsistent with the linear volume depolarization ratio indicated in the figure caption.

Response: The label in Fig. 6 has been changed to "Linear Volume Depolarization Ratio", consistent with the caption and the retrieved quantity.

The corresponding revised text is as follows:

"Fig. 6. Hourly averaged vertical profiles of aerosol extinction coefficient (solid lines) and linear volume depolarization ratio (dashed lines) during the experimental periods at Dunhuang (red lines) and Minqin (blue lines)."

We trust that these revisions have addressed the reviewer's concerns and have improved the clarity and scientific robustness of the manuscript.

Thank you again for your constructive review.