To Referee #1

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 substantially strengthened the Introduction, reorganized the mechanism discussion in Section 3.2, clarified the elevated-aerosol-layer identification procedure, added supporting analyses in the Supplement, moderated case-dependent regional-impact statements, and standardized the figures, captions, terminology, equations, and references.

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 #1 (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 terrain of Northwest China, specifically the Hexi Corridor. The identification and lidar-based characterization of daytime elevated aerosol layers provide useful information on regional air quality, boundary-layer dynamics, and radiative effects. The manuscript falls within the scope of Atmospheric Chemistry and Physics, but several critical issues should be addressed before publication.

Major Comments

(1) The Introduction contains much general background on aerosol-related studies, while the discussion of current research bottlenecks remains insufficient. I would suggest placing more emphasis on the key knowledge gaps in existing studies. In addition, the novelty of this work is not clearly highlighted. The authors should more explicitly state the main innovation and scientific contribution of this study.

Response: We agree that the original Introduction did not sufficiently distinguish the unresolved scientific problem from the general aerosol background. We therefore refocused the Introduction on three connected gaps: the observational imbalance between abundant surface/column measurements and scarce high-resolution vertical profiles; the limited understanding of diurnal boundary-layer aerosol structure in arid and semi-arid complex terrain; and the lack of a physically integrated assessment of formation mechanisms, air-quality implications, and radiative effects. We also revised the study-scope statement to emphasize the specific object of this work—elevated aerosol layers embedded within the daytime mixed layer over the Hexi Corridor—and the combined observational, mechanistic, and impact-oriented contributions.

The corresponding revised text is as follows:

"Compared with the abundance of ground-level observations and column-integrated aerosol properties measurements, continuous, high-resolution observations of aerosol vertical distribution remain scarce. This observational

imbalance limits our ability to connect surface aerosol variations with column-integrated optical properties through the intermediate vertical structure, particularly on diurnal timescales (Li et al., 2020; Cheng et al., 2020a; Yorks et al., 2023; Bellini et al., 2025).”

“Although substantial progress has been made in understanding the diurnal variation of aerosol vertical distributions, important knowledge gaps remain. These gaps are particularly pronounced in arid and semi-arid regions with complex terrain, where high-resolution profile observations are scarce and the diurnal characteristics of boundary-layer aerosol vertical structure remain largely unexplored (Yorks et al., 2023; Parajuli et al., 2020). Consequently, the thermodynamic and dynamical mechanisms governing these variations, together with their regional air-quality and radiative impacts, remain poorly understood (Su et al., 2020b).”

“In this study, the phenomenon of elevated aerosol layers embedded within the daytime mixed layer was investigated in terms of identification, occurrence, vertical characteristics, associated meteorological conditions, and potential air-quality and shortwave radiative effects, based on intensive observations at Minqin in 2010 and Dunhuang in 2012 over the Hexi Corridor.”

(2) Section 3.2 contains excessive descriptive narration of meteorological evolution. Much of the text provides step-by-step qualitative descriptions of temperature, potential temperature, wind, and humidity fields, resembling a case report rather than a concise mechanism analysis. Additionally, the two case studies presented for Dunhuang and Minqin show highly similar thermodynamic evolution, yet both are described in extensive detail. Although Section 3.2 aims to explain formation mechanisms, much of the discussion remains case-specific. Some summary conclusions and key points should be provided.

Response: We agree and have reorganized Section 3.2 to separate the common physical mechanism from site-specific features. The Dunhuang case is retained as the more complete illustration of the daytime uplift–accumulation sequence. The Minqin discussion is shortened and now concentrates on differences that add physical information, particularly the humid stable layer, the likely frontal inversion, and the stronger terrain-induced circulation. We also added an explicit synthesis paragraph after the case and composite analyses. This paragraph identifies the common mechanism and clarifies that the temperature–humidity anomalies indicate meteorological conditions favourable for EAL occurrence rather than a fully validated deterministic prediction rule.

The corresponding revised text is as follows:

“In general, elevated aerosol layers at Minqin were also associated with daytime thermal forcing, upward aerosol transport, and terrain-induced circulation, suggesting a broadly similar thermodynamic coupling mechanism to that identified at Dunhuang.”

“In contrast to Dunhuang, a pronounced abrupt change in relative humidity occurred at the upper boundary of the unstable stratification, where a persistent high-relative-humidity zone was present. Rather than directly implying that water vapour itself inhibited aerosol uplift, the coexistence of enhanced relative humidity and stable stratification suggests that this layer likely acted as a cap, limiting further upward dispersion of aerosols.”

“Overall, the representative cases and composite anomalies indicate that elevated aerosol layer formation at both sites was associated with a common daytime uplift–accumulation mechanism. Positive potential temperature anomalies and negative relative humidity anomalies within the daytime boundary layer favoured sensible heating, reduced static stability, and enhanced vertical mixing, while stable stratification near the boundary layer top limited further upward dispersion and promoted aerosol accumulation aloft. Terrain-induced local circulations further modulated the horizontal transport of the elevated aerosol layers.”

“When both indicators are satisfied simultaneously, this can be identified as a meteorological condition favourable for the occurrence of elevated aerosol layers, although additional long-term observations and model simulations are still needed to further evaluate its predictive applicability.”

(3) Given that the observational data used in this study were collected more than a decade ago (2010–2012), their representativeness for present-day atmospheric conditions may be limited. Changes in emissions, aerosol composition, and regional atmospheric environments over the past decade could affect the occurrence and characteristics of elevated aerosol layers. I suggest the authors discuss this limitation in the conclusion.

Response: We agree. A dedicated limitation paragraph has been added to the Conclusions. It explicitly distinguishes campaign-period results from a present-day climatology, identifies the environmental factors that may have changed since 2010–2012, and explains which parts of the interpretation are more likely to remain physically transferable. The revised text also identifies long-term observations and modelling as necessary next steps.

The corresponding revised text is as follows:

"It should be noted that the intensive observations used in this study were conducted in 2010 at Minqin and in 2012 at Dunhuang. Therefore, the occurrence frequencies, dominant aerosol types, PM10-equivalent mass concentrations, and radiative effects reported here should be interpreted as representative of the specific campaign periods rather than as a present-day climatology of the Hexi Corridor."

"Over the past decade, changes in anthropogenic emissions, dust activity, aerosol composition, land-surface conditions, and regional atmospheric environments may have affected the occurrence and characteristics of elevated aerosol layers. Nevertheless, the thermodynamic mechanism identified in this study, including daytime surface heating, dry lower-atmospheric conditions, upward transport of near-surface aerosols, and accumulation below stable stratification, is physically based and may remain applicable under similar meteorological and source conditions."

"Additional long-term field observations and model simulations across other parts of the Hexi Corridor and the adjacent Qilian Mountains are needed to further investigate the present-day occurrence, long-term evolution, composition changes, and regional impacts of elevated aerosol layers."

(4) In the abstract, the authors claim that these EALs form a daily-scale heating pump that transports pollutants via mountain–valley breezes to the Qilian

Mountains, accelerating glacier melt. However, in Section 3.2 the authors state that the influence of the Dunhuang case on the Qilian Mountains was negligible. This seems contradictory.

Response: We agree that the original wording conflated a case-specific transport pathway with a general regional implication. The term "heating pump" has been removed. Section 3.2 now makes clear that the transport of an EAL toward the Qilian Mountains depends on the background wind direction and is not expected in every event. For the representative Dunhuang case, southwesterly flow was not directed toward the mountains, so the influence was likely limited. The revised manuscript separately notes that northeasterly flow occurs frequently and may permit mountainward transport under other conditions. The Conclusion now uses the conditional phrase "under favourable wind regimes".

The corresponding revised text is as follows:

"However, for the case illustrated in Fig. 8, southwesterly winds prevailed during the formation of the elevated aerosol layer, indicating that the transport pathway was not directed toward the Qilian Mountains. Therefore, the influence of this particular EAL event on the Qilian Mountains was likely limited. 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."

"Under favorable wind regimes, daytime mountain–valley circulations may further transport these elevated aerosol layers toward the adjacent Qilian Mountains."

(5) Line 155: "This classification is based on the gradient characteristics of the vertical profiles. If a continuous positive gradient is observed and the corresponding proportion of observations exceeds 20%, an elevated aerosol layer is considered to be present." What does positive grade refer to here? This is currently ambiguous.

Response: We have rewritten the identification procedure in Section 2.2.1. The revised text now specifies that the gradient is calculated for the aerosol extinction coefficient profile, defines the vertical interval from the first valid range bin above the 600 m lidar blind zone to the layer peak, requires continuity in both height and time, and explains how the 20% observation-proportion threshold is applied within the 13:00–21:00 BJT analysis window. We also added Fig. S1 to document the sensitivity of the classification to the two threshold choices.

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."

"If the proportion of observations satisfying this continuous positive-gradient criterion within this time window exceeded 20%, an elevated aerosol layer was considered to be present. 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."

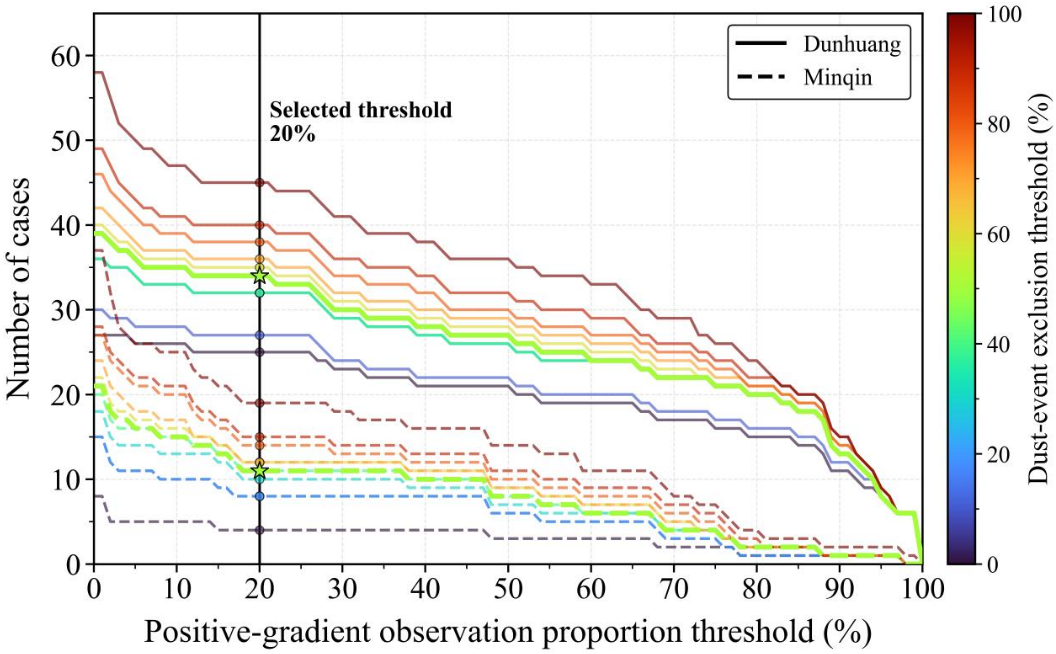

Fig. S1. Sensitivity of elevated aerosol layer classification to threshold combinations at Dunhuang and Minqin. Solid and dashed lines represent the Dunhuang and Minqin sites, respectively, and line colour denotes the dust-event exclusion threshold. The black vertical line marks the selected positive-gradient 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.

Minor Comments

(1) Line 85: supply literatures.

Response: Relevant references have been added to support the statements concerning the scarcity of high-resolution profile observations and the remaining uncertainty in the mechanisms and impacts of diurnal aerosol vertical variability in arid and semi-arid complex-terrain regions.

The corresponding revised text is as follows:

"These gaps are particularly pronounced in arid and semi-arid regions with complex terrain, where high-resolution profile observations are scarce and the diurnal characteristics of boundary-layer aerosol vertical structure remain largely unexplored (Yorks et al., 2023; Parajuli et al., 2020). Consequently, the thermodynamic and dynamical mechanisms governing these variations, together with their regional air-quality and radiative impacts, remain poorly understood (Su et al., 2020b)."

(2) Line 150: "following the method of (Zhou et al., 2021; Zhou et al., 2018)", this expression seems to be non-standard.

Response: The sentence has been rewritten in standard citation form and the references have been placed at the end of the statement.

The corresponding revised text is as follows:

"Consistent with previous dust aerosol identification criteria, a depolarization ratio greater than 0.20 was used as the threshold for identifying dust aerosols (Zhou et al., 2018; Zhou et al., 2021)."

(3) Line 165: "PM10", indicate the subscripts correctly. Is there any reference source for Equation 1? Provide more information.

Response: We corrected the PM_{10} subscript throughout the manuscript and expanded the derivation and interpretation of Eq. (1). The equation is not adopted from an external reference; it is a site-specific empirical regression derived from 4,357 temporally collocated samples of 1 min MPL extinction coefficient and 5 min ground-level PM_{10} during the intensive observation period. Figure S2 has been added to show the paired samples and fitted line. We now consistently describe the retrieved quantity aloft as an extinction-derived PM_{10}-equivalent mass concentration rather than a direct PM_{10} measurement.

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). A linear regression based on these collocated observations yielded the following empirical equation:"

"$PM_{10} = 914.65 \times \alpha - 56.26$,"

"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* $\mu g/m^3$*."*

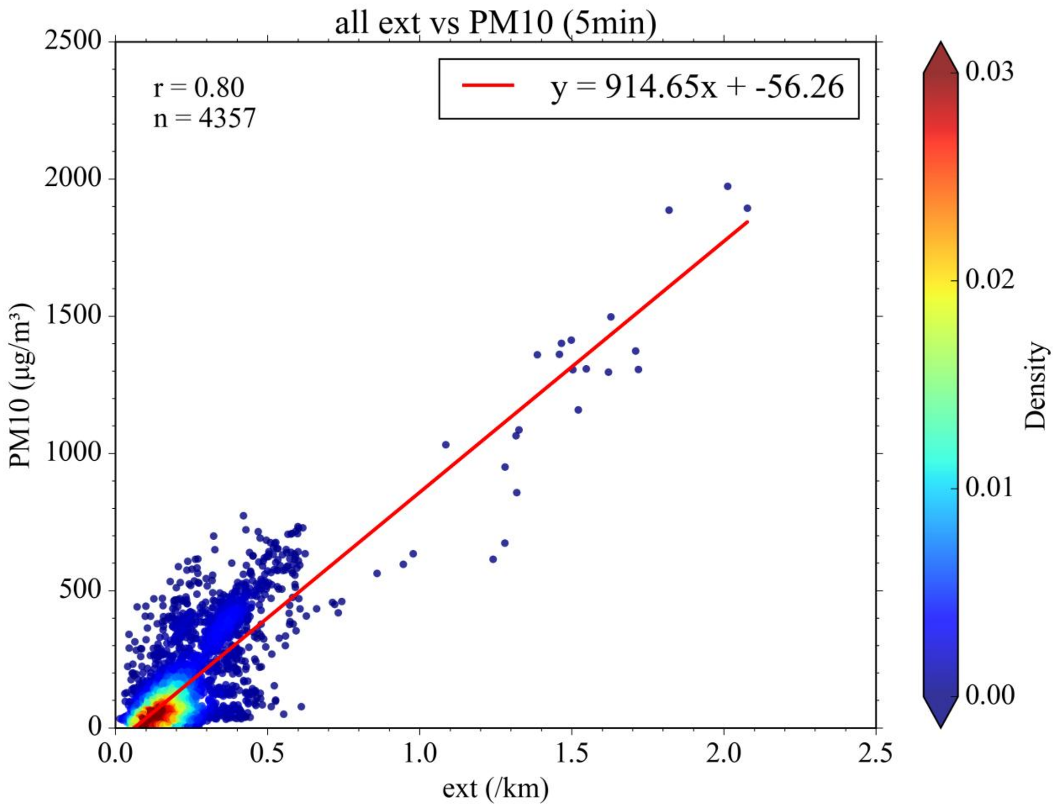

Fig. S2. Relationship between ground-level PM_{10} mass concentration and the temporally collocated MPL-derived aerosol extinction coefficient from the lowest two valid sampling bins near ~600 m during the intensive observation period. The red line represents the linear regression used to derive Eq. (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) Line 225: Were formulas 2–6 developed by the authors, or are they based on existing references?

Response: We clarified that Eqs. (2)–(6) follow the formulations of Li et al. (2025) and were not newly developed in this study.

The corresponding revised text is as follows:

"Here, the shortwave radiative forcing (SRF) and shortwave heating rate are calculated under clear-sky conditions (Jangid et al., 2024). Following the formulations of Li et al. (2025), Eqs. (2)–(6) can be expressed as follows:"

(5) Line 300: The legend for Figure 5 is not standardized; provide a detailed description. Similar cases include Fig. 9 and Fig. 10.

Response: We replaced abbreviated captions such as “Same as Fig. 4” and “Same as Fig. 7” with independent, complete captions that specify the site, date, variables, panels, data sources, contours, and annotations.

The corresponding revised text is as follows:

“Fig. 5. Time series of observations obtained from a micro-pulse lidar (MPL) and a sun photometer during the intensive observation period at Minqin in 2010. Time–height cross-sections of (a) normalised relative backscatter (NRB) and (b) linear volume depolarization ratio (Dep) derived from MPL observations. (c) Time series of aerosol optical depth (AOD) retrieved from AERONET at 500 nm (red dots) and from MPL at 527 nm, along with the Ångström exponent (AE) at 440–870 nm (green dots). All identified elevated aerosol layers are indicated by shaded regions, and the representative case selected for detailed discussion is highlighted with black dashed lines.”

“Fig. 9. Time series of aerosol vertical distribution and meteorological parameters at Minqin on 14 June 2010. (a) Time–height cross-sections of aerosol extinction coefficient and (b) depolarization ratio derived from MPL lidar, with potential temperature contours (black lines) and boundary layer height (red lines) from ERA5. (c) Wind vectors measured by an automatic meteorological station (model WXT520), and (d) temperature, relative humidity, and pressure.”

“Fig. 10. Thermal and dynamical fields at Minqin on 14 June 2010. (a–c) Vertical cross-sections of relative humidity with unstable stratification (demarcated by the white enclosed area) along the transect indicated by the red line in Fig. 1. Black solid lines represent isotherms, while black dashed lines denote the location of the observation site. (d–i) Meteorological fields at the 600 hPa and 800 hPa levels, with geopotential height contours, during the experimental period over the Minqin region. White regions indicate elevated mountain terrain.”

(6) The fonts in the figures are inconsistent. For example, Figure 1 seems to be Times New Roman, whereas Figure 2 seems to be Calibri.

Response: All figures were checked and reformatted so that panel labels, axes, tick labels, legends, annotations, and colour-bar labels use Times New Roman consistently.

We also checked font sizes for readability and consistency across the complete figure set.

(7) Some references appear inconsistent or incomplete. Please carefully check all references.

Response: We performed a complete cross-check of the in-text citations and reference list. Author names, publication years, journal titles, volumes, page ranges or article numbers, DOI information, punctuation, and ordering were corrected where necessary. We also checked that every in-text citation has a corresponding reference-list entry and that no uncited references remain.

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.