



Horizontal aerosol transport, not local shear, drives aerosol–boundary layer decoupling: lidar evidence from contrasting regimes in Thailand

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Abstract. Aerosol vertical structure is often inferred from lidar observations under the assumption that the dominant aerosol gradient approximates the planetary boundary layer (PBL) height. This assumption may not hold when aerosol layers decouple from boundary-layer turbulence. We investigated regime dependence of aerosol-boundary layer coupling during June 2021 to May 2022 at two contrasting sites in Thailand: an inland valley (Chiang Mai) and a coastal site (Songkhla). Results are interpreted within a regime-based framework rather than as climatology. The aerosol layer top (ALT) is compared with a thermodynamically constrained PBL height, with decoupling defined as ALT minus PBL exceeding 0.5 km and quantified using frequency, diurnal and wind-conditioned occurrence, event duration, and autocorrelation timescale. The inland site exhibits frequent (around 53%) and persistent decoupling with longer autocorrelation timescales (around 5.6 h), indicating thermodynamic control and residual-layer influence. Richardson number diagnostics show 83% of decoupled strong-wind events occur under stable stratification, and back-trajectory analysis confirms elevated aerosol layers originate from distinct source regions (median separation 502 km), attributing decoupling primarily to aerosol advection rather than in-situ shear lofting. The coastal site shows lower decoupling (around 20%), weaker diurnal contrast, and shorter persistence (around 3.1 h), reflecting mechanically regulated mixing. Decoupling frequency uncertainty is 0.9% at Chiang Mai and 9.0% at Songkhla, leaving the regime contrast robust. The stable stratification is consistent with temperature inversions widely invoked in Thailand's haze discourse, suggesting aerosol horizontal transport may co-equally drive elevated pollution layers alongside thermodynamic trapping, with implications for air quality communication and source attribution.

Keywords: lidar, decoupling, aerosols, boundary-layer, horizontal transport



1 Introduction

30 Lidar observations have become a cornerstone of atmospheric boundary-layer monitoring because they provide continuous, high-resolution vertical profiles of aerosol backscatter (Sugimoto, 1999; Lerkvaranyu et al., 2001). Most lidar-based planetary boundary layer (PBL) height retrieval methods rely on detecting strong vertical gradients in aerosol backscatter, using techniques such as the gradient method, variance method, or wavelet covariance transform (Brooks, 2003). These approaches implicitly assume that the dominant aerosol gradient is representative of the top of the turbulent boundary layer.

35 While this assumption often holds during well-developed daytime convective conditions, it frequently breaks down in aerosol-rich or stratified environments, where strong backscatter gradients may instead be associated with residual layers, elevated aerosol layers, or cloud boundaries. Numerous studies across tropical and subtropical Asia have documented the frequent occurrence of elevated and decoupled aerosol layers linked to long-range transport, biomass burning, and monsoon circulation (Satheesh et al., 2009; Wang et al., 2010; Cohen et al., 2018; Reid et al., 2025). As a result, aerosol-based PBL

40 retrievals can in some cases overestimate the thermodynamic PBL height, particularly during nighttime and transitional periods.

Recent work has therefore emphasized the importance of distinguishing between the thermodynamic PBL height, the actively mixed layer, and the aerosol layer top when interpreting lidar observations. Solanki et al. (2019) demonstrated that aerosol-gradient-based mixing layer heights in the Chiang Mai Valley are strongly influenced by residual layers and

45 biomass-burning aerosols, complicating interpretation during pollution episodes. Building on this, Macatangay et al. (2025) introduced temperature-constrained and dynamic search-altitude approaches that explicitly decouple the thermodynamic PBL height, the mixing layer height, and the aerosol layer top, providing a physically grounded framework for lidar interpretation in humid, aerosol-rich and monsoon-affected environments. This temperature-constrained retrieval algorithm, validated against radiosonde observations, is applied in the present study. Complementary evidence for the importance of

50 thermodynamic constraints is provided by recent thermodynamics-guided machine learning approaches, which embed physically meaningful predictors and diurnal structure to robustly estimate convective boundary layer height across multiple sites, demonstrating improved generalizability beyond purely data-driven or aerosol-based methods (Chu et al., 2026).

Parallel methodological developments have sought to improve nocturnal and multilayer discrimination under polluted conditions. Cluster-based gradient approaches and polarization- and sub-layer-enhanced wavelet covariance techniques have

55 been shown to reduce misclassification of residual and elevated aerosol layers, particularly during nighttime and complex stratification (Zhang et al., 2020; Han et al., 2022). Cross-platform intercomparison studies further demonstrate that aerosol backscatter lidars frequently retrieve the mixing layer height or aerosol layer top rather than the thermodynamic PBL height, emphasizing the need to align retrieval definitions with the intended physical target, especially in decoupled regimes (Kim et al., 2021; Xu et al., 2024).

60 In coastal and maritime environments, aerosol-boundary layer interactions are often governed by different physical mechanisms. Observations at tropical coastal sites such as Trivandrum, Penang, and Taiwan show that mechanical mixing



driven by persistent winds, sea-land breeze circulations, and synoptic forcing plays a dominant role in shaping aerosol vertical structure (Parameswaran et al., 2001, 2004; Hee et al., 2016; Tan et al., 2014; Wang et al., 2010). Under these conditions, aerosol layers tend to remain more vertically aligned with the mixed layer, even when surface thermodynamic forcing is weak.

Studies over the Maritime Continent further highlight the strong modulation of aerosol vertical distributions by monsoon dynamics, low-level jets, and large-scale circulation. Airborne and ground-based lidar observations document regime-dependent aerosol layering associated with monsoon transitions, El Niño conditions, and transboundary smoke transport (Campbell et al., 2016; Cohen et al., 2018; Reid et al., 2025). Similar regime dependence has been identified in aerosol-cloud-boundary-layer interactions using synergistic satellite and lidar observations (Huang et al., 2022; Huang et al., 2024).

Despite this growing body of observational and methodological work, most lidar-based PBL studies still implicitly assume that aerosol gradients provide a robust proxy for boundary-layer depth, without explicitly accounting for differences in boundary-layer forcing regimes. This raises a fundamental interpretive question: under what conditions do aerosol-based lidar retrievals provide a physically meaningful estimate of boundary-layer height, and when do they instead represent mechanically maintained or residual aerosol layers that are decoupled from boundary-layer thermodynamics?

In this study, we address this question by examining the regime dependence of aerosol-boundary layer coupling at two contrasting sites in Thailand: an inland valley site in Chiang Mai, northern Thailand, and a coastal site in Songkhla, southern Thailand. While based on two sites, these regimes are broadly consistent with continental thermodynamic and coastal mechanically influenced boundary-layer systems reported in previous studies (Solanki et al., 2019; Parameswaran et al., 2001, 2004; Hee et al., 2016; Tan et al., 2014; Wang et al., 2010). By jointly analyzing aerosol layer top, thermodynamically constrained PBL height, and their diurnal and statistical relationships, we ask whether similar instantaneous aerosol structures can arise from fundamentally different boundary-layer processes – and what implications this may have for the interpretation of lidar-derived PBL heights across monsoon-influenced regions.

The analysis covers June 2021–May 2022, the only period with simultaneous lidar observations at both sites. This single seasonal cycle limits long-term climatological interpretation, so results are presented in a regime-based framework. The two sites were chosen to represent physically distinct boundary-layer forcing regimes within the same regional climate system. The objective is not to provide statistical generalization across the whole region, but to isolate and contrast regime-dependent behavior under controlled observational consistency. Independent radiosonde validation of thermodynamic PBL height is not performed because available soundings are limited to once-daily (07:00 LT) launches, which are insufficient to resolve the full diurnal evolution central to this analysis. To move beyond correlation-based diagnostics, we introduce physically interpretable decoupling metrics to quantify the degree to which aerosol-PBL separation is intermittent or sustained, as well as the physical mechanisms that govern this behavior.



2 Methodology

2.1 Study sites

- 95 This study focuses on two contrasting sites in Thailand that differ markedly in their geographic setting, topography, and expected boundary-layer forcing: Chiang Mai in northern Thailand and Songkhla in southern peninsular Thailand (see Fig. 1). The sites are separated by approximately 1,300 km and differ markedly in topography, proximity to the coast, aerosol environment, and dominant boundary-layer drivers. Together, they provide a natural framework for examining whether, and to what degree, boundary-layer forcing regime governs aerosol-PBL coupling.

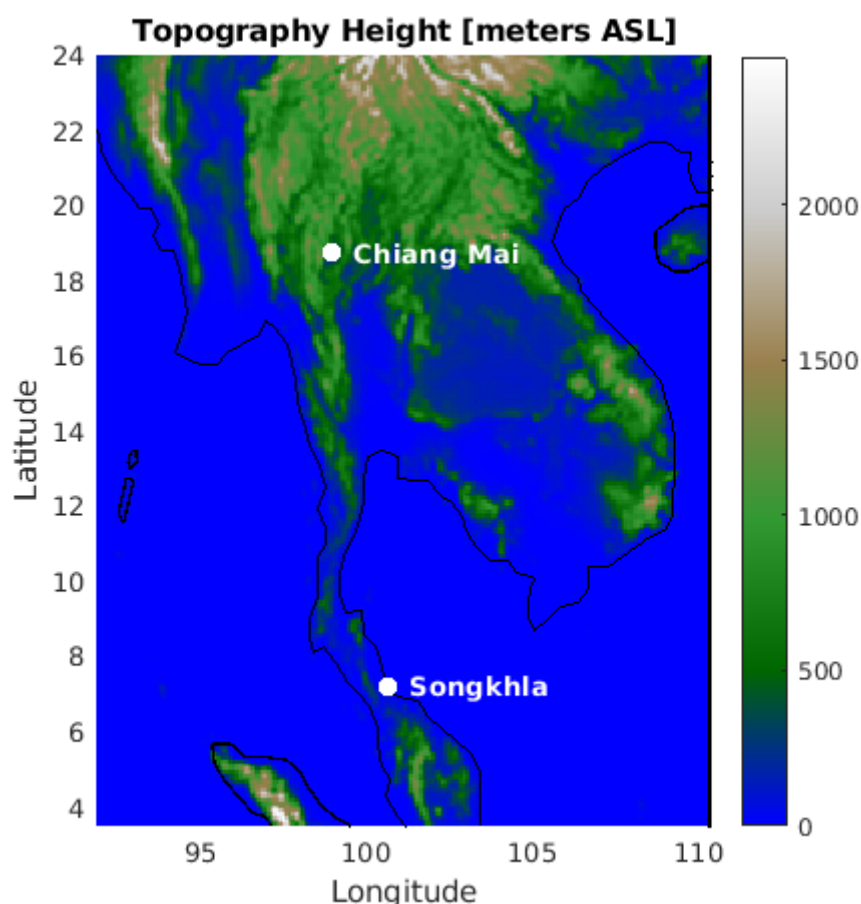


Figure 1. Map of Thailand showing the locations of the two study sites: Chiang Mai (inland valley, northern Thailand) and Songkhla (coastal, southern peninsular Thailand). Surface elevation is derived from the GTOPO30 global digital elevation model (USGS Earth Resources Observation and Science Center, 1996), processed via the WRF Preprocessing System (WPS) geogrid utility. The map highlights the contrasting topographic and geographic settings of the two study sites.



Chiang Mai (18.79° N, 98.98° E; ~310 m above mean sea level) is located in an inland basin surrounded by complex terrain. The city experiences a tropical savanna climate with three distinct seasons: a hot dry season (March–May), a wet monsoon season (June–October), and a cool dry season (November–February). Annual rainfall averages approximately 1,100–1,300 mm, concentrated in the southwest monsoon period, with mean annual temperatures around 25–26 °C (TMD, last access: 25 March 2026). Boundary-layer evolution at this site is strongly influenced by diurnal surface heating, valley-mountain breeze circulations, terrain-induced flows, and seasonal biomass-burning emissions. During the dry season, elevated aerosol loading and persistent residual layers have been reported in the region (Solanki et al., 2019), making this site a candidate for examining how seasonal aerosol loading interacts with evolving boundary-layer structure.

Songkhla (7.21° N, 100.60° E; ~10 m above mean sea level) is a coastal site located near the Gulf of Thailand, influenced by maritime air masses throughout the year. The site lies within the equatorial monsoon belt and experiences a relatively humid tropical climate with no pronounced dry season; rainfall is distributed across most months, with peaks associated with the northeast monsoon (October–January), and annual totals typically exceeding 1,800–2,000 mm. Mean annual temperatures are near 27–28 °C, with modest seasonal amplitude owing to the moderating influence of the surrounding ocean (TMD, last access: 25 March 2026). Boundary-layer structure here is shaped by persistent background winds, sea-land breeze circulations, and advective processes (Parameswaran et al., 2001, 2004), creating a boundary-layer environment that is expected to be structurally distinct from inland continental sites.

2.2 Observation period, lidar measurements, and surface meteorological data

The analysis focuses on periods when continuous elastic backscatter lidar observations are available at both sites, from June 2021 to May 2022, representing the only period with complete observational overlap available for this analysis, as other periods were affected by instrument relocation or data gaps due to instrumental issues. Using overlapping time periods helps ensure consistency in climatological background and large-scale meteorological forcing and enables characterization of diurnal and seasonal variability in aerosol-boundary layer coupling. While this period captures full wet, cool-dry, and warm-dry seasonal transitions, interannual variability in biomass burning and monsoon strength may influence the magnitude of coupling metrics.

To contextualize the representativeness of the study year, we briefly characterize the large-scale climate state during June 2021–May 2022. The period coincided with a moderate La Niña event, with the Oceanic Niño Index (ONI) ranging from approximately –0.6 to –1.0 °C across boreal autumn (September–November) 2021 through boreal spring 2022, peaking during (March–May) 2022 (ONI = –1.0 °C) (NOAA CPC, last access: 9 April 2026). In Southeast Asia, La Niña conditions are generally associated with enhanced southwest monsoon rainfall and suppressed dry-season fire activity relative to neutral or El Niño years. ERA5 (Hersbach et al., 2020) monthly mean precipitation anomalies over northern Thailand during June–October 2021 were within ± 3 % of the 1991–2020 climatological mean, and 850 hPa wind anomalies over the region were within ± 1 m s^{–1} of climatology, indicating that large-scale monsoon forcing during the wet season was broadly typical despite the La Niña background (C3S, last access: 9 April 2026).



For the dry season burning period (January–May 2022), MODIS Terra fire counts (confidence > 80%) over northern
140 Thailand (17–20°N, 97–101°E) totaled approximately 45, representing a 53% below-average burning season relative to the
2003–2021 climatological mean of 95 ± 87 detections (NASA MODIS Science Data Support Team, last access: 10 April
2026). Together, these indicators suggest that while the La Niña state may have contributed to a below-average dry-season
burning period, the anomaly (-0.58σ) remained within the range of normal interannual variability (given by the
climatological standard deviation of ± 87 fire detections), and the monsoon seasonal cycle and large-scale forcing during the
145 study year were broadly representative of recent decades.

Both sites are equipped with similar ground-based elastic backscatter lidar systems (Droplet Measurement Technologies'
Mini Micro Pulse lidar System), operating at a visible wavelength of 532 nm and providing vertically resolved profiles of
attenuated backscatter (30 m vertical resolution) with high temporal resolution (30 s). The lidar signals are processed
following standard procedures (Campbell et al., 2002), including background subtraction, afterpulse, deadtime, overlap and
150 range corrections, as well as temporal averaging to improve signal-to-noise ratios in the boundary-layer height range
(Macatangay et al., 2025). Surface meteorological measurements at both sites include near-surface air temperature, wind
speed, and wind direction, recorded at 30 s intervals and are used to characterize local boundary-layer forcing and to
distinguish periods dominated by thermodynamic versus mechanical control.

Data gaps due to instrumental issues and maintenance were excluded from the analysis. Periods affected by low clouds or
155 precipitation that attenuated the lidar signal were not explicitly removed prior to analysis. Instead, both ALT and PBL height
time series were smoothed using a 3-hour moving window, which reduces short-lived signal artifacts associated with cloud
or precipitation contamination. In addition, the retrieval algorithm inherently excludes time steps when the PBL height
cannot be reliably estimated (e.g., fully attenuated signal). Cloud occurrence below 4 km AGL and surface precipitation
frequency were tracked independently to assess potential sampling biases in the monthly statistics.

160 2.3 Identification of aerosol layer top and thermodynamic boundary-layer height

Aerosol layer tops (ALT) are identified from the processed backscatter profiles using a wavelet covariance transform
(WCT), applied as a diagnostic tool to detect dominant aerosol gradients without assuming correspondence with the
thermodynamic planetary boundary-layer (PBL) height (Brooks, 2003). In parallel, PBL height is estimated using the
temperature-constrained wavelet-based approach of Macatangay et al. (2025), in which thermodynamic information limits
165 the vertical search domain of the transform, suppressing spurious detections associated with elevated aerosol layers that are
decoupled from surface-driven turbulence.

Although both quantities are derived using WCT, they differ in both search domain and physical interpretation. ALT is
retrieved from the full backscatter profile (below 4 km AGL) and represents the strongest aerosol gradient regardless of
origin. In contrast, the thermodynamically constrained PBL height is restricted to altitudes consistent with buoyancy-driven
170 turbulence based on surface temperature evolution. As a result, discrepancies between ALT and PBL height are interpreted
as evidence of physical decoupling rather than methodological redundancy. The resulting PBL heights therefore represent



thermodynamic boundary-layer depths, distinct from both the aerosol layer top and the actively mixed layer height, enabling explicit diagnosis of aerosol-PBL coupling under varying forcing regimes.

2.4 Analysis strategy

175 The analysis compares aerosol layer tops and thermodynamically constrained PBL heights at each site across diurnal and seasonal timescales. Statistical metrics, including correlations with surface temperature and wind speed, ALT-PBL height differences, and the frequency of vertically decoupled layers, are used to characterize aerosol-boundary layer relationships under contrasting forcing regimes. All analyses are performed separately for Chiang Mai and Songkhla to preserve the physical contrast between inland valley and coastal environments.

180 In this study, aerosol-boundary layer coupling is operationally defined as sustained vertical proximity between ALT and thermodynamic PBL height, characterized by (i) small RMS differences, (ii) near-zero mean bias, and (iii) consistent diurnal phase alignment. Conversely, large RMS differences or systematic positive bias ($ALT > PBL$ height) would be consistent with vertical decoupling, the nature and persistence of which will be examined in the results.

To move beyond correlation-based diagnostics and quantify regime mechanics, physically interpretable process metrics (decoupling metrics) are introduced. These metrics are defined here and derived solely from the observational dataset described in Sect. 2.2.

Decoupling is defined when the instantaneous height difference $\Delta(ALT-PBL)$ exceeds 0.5 km. The 0.5 km threshold was chosen to exceed the typical vertical resolution of the lidar system (30 m) and the expected entrainment zone thickness under tropical convective conditions (Stull, 1988; Garratt, 1992), ensuring that identified separations reflect physical decoupling rather than retrieval ambiguity near the PBL top. To confirm that the conclusions are insensitive to this choice, decoupling metrics were recomputed at thresholds of 0.3 km and 0.7 km and compared against the primary 0.5 km results; findings are reported in Sect. 3.5. From this definition, the following metrics are computed:

1. Decoupling frequency: fraction of total observations satisfying $\Delta(ALT-PBL) > 0.5$ km.
2. Diurnal conditional frequency: decoupling fraction computed separately for daytime (07:00–19:00 LT) and nighttime (19:00–07:00 LT).
3. Wind-regime conditional frequency: decoupling fraction under weak winds (wind speed $< 1 \text{ m s}^{-1}$) and strong winds (wind speed $> 3 \text{ m s}^{-1}$). Moderate winds ($1 \leq W \leq 3 \text{ m s}^{-1}$) are not considered to avoid transitional regimes where neither thermodynamic nor mechanical forcing clearly dominates.
4. Persistence metrics: (a) Median decoupling event duration (hours), derived from contiguous periods with $\Delta(ALT-PBL) > 0.5$ km. (b) Autocorrelation e-folding timescale (hours) of $\Delta(ALT-PBL)$, defined as the first lag where the normalized autocorrelation falls below e^{-1} .

These metrics and analysis provide a direct measure of regime-dependent vertical structure and quantify whether decoupling is intermittent or dynamically sustained.



To understand the mechanisms driving aerosol-PBL decoupling, two complementary process-level analyses are applied to the subset of events satisfying $\Delta(\text{ALT-PBL}) > 0.5$ km.

The bulk Richardson number (Ri) was computed at the aerosol layer altitude (ALT, in km) for each decoupled strong-wind event to quantify the local balance between stabilising buoyancy and destabilising wind shear (Stull, 1988; Garratt, 1992): $Ri = (g/\theta)(\partial\theta/\partial z) / (\partial U/\partial z)^2$, where g is gravitational acceleration (9.81 m s^{-2}), θ is potential temperature (K), $\partial\theta/\partial z$ is the vertical gradient of potential temperature, and $\partial U/\partial z$ is the vector wind shear magnitude. Potential temperature was derived from ERA5 (Hersbach et al., 2020) temperature profiles using $\theta = T \cdot (p_0/p)^{(R_d/c_p)}$, where $p_0 = 1000 \text{ hPa}$ and $R_d/c_p = 0.2857$ (Wallace and Hobbs, 2006). Layer-wise Ri was computed between successive ERA5 pressure levels and linearly interpolated to each event's ALT. The critical thresholds follow the Miles-Howard criterion: $Ri < 0.25$ indicates that Kelvin-Helmholtz instability and shear-driven turbulence are mechanically plausible, while $Ri > 1.0$ indicates stable thermal stratification that suppresses mechanical mixing (Miles, 1961; Howard, 1961; Stull, 1988). The intermediate range ($0.25 \leq Ri \leq 1.0$) is considered transitional.

To assess whether wind shear intensity is systematically associated with greater aerosol-PBL separation, Spearman rank correlation (ρ) was computed between the vector wind shear magnitude integrated over 0–2 km AGL ($VWS_{0-2\text{km}}, \text{ s}^{-1}$) and the vertical separation between the aerosol layer and the PBL top, $\Delta(\text{ALT-PBL})$. Spearman's ρ was chosen over Pearson's r because both VWS and $\Delta(\text{ALT-PBL})$ are right-skewed and non-normally distributed (Hollander et al., 2014). A positive ρ would be consistent with shear-driven lofting (stronger shear $\rightarrow$ greater separation); a negative or near-zero ρ would indicate that shear is not the governing factor (Wilks, 2011).

HYSPLIT 48-h back-trajectories (Draxler and Rolph, 2003) were computed for events satisfying $\Delta(\text{ALT-PBL}) > 0.5$ km and surface wind speed $> 3 \text{ m s}^{-1}$. Trajectories were launched simultaneously at the aerosol-layer height (ALT) and the thermodynamic PBL height (PBL) from the observational site associated with this regime, using GDAS 1° meteorological fields (Kanamitsu, 1989; NCEP/NOAA, last access: 17 April 2026). The resulting ensemble of valid trajectory pairs was analysed using k-means clustering (MacQueen, 1967; Lloyd, 1982) applied to the 48-h endpoint positions (latitude and longitude). To evaluate whether ALT and PBL trajectories originate from statistically distinct source regions, a two-sample Hotelling T^2 test (Hotelling, 1931) was applied to the paired 48-h endpoint coordinates. In addition, per-event source separation was quantified as the Haversine great-circle distance (Sinnott, 1984) between matched ALT and PBL endpoints.

3 Results and discussion

3.1 Overview of aerosol vertical structure and boundary-layer evolution

Figure 2 presents representative one-week (January 10–16, 2022) time-height curtains of lidar attenuated backscatter for Chiang Mai and Songkhla during the study period. Despite experiencing similar large-scale climate forcing, the two sites exhibit distinct aerosol vertical structures and boundary-layer evolution.

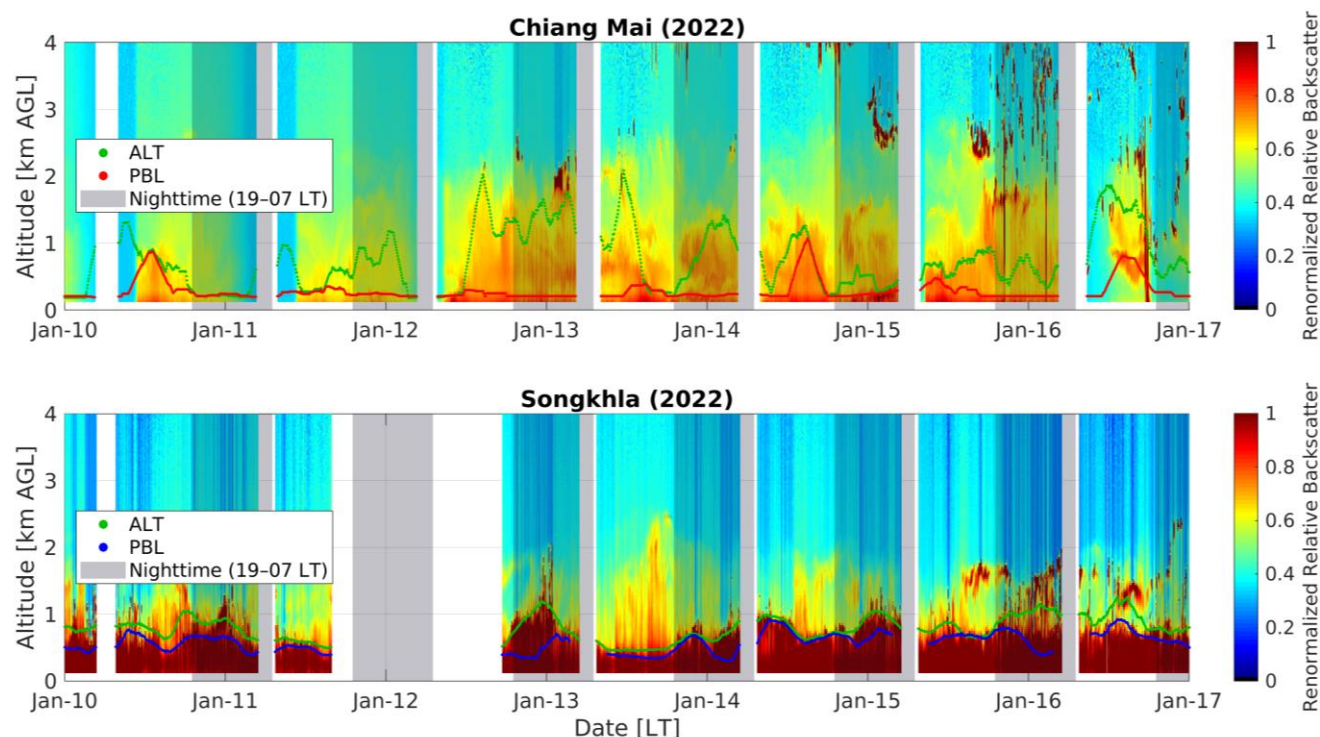


Figure 2. Representative one-week (10–16 January 2022) time-height curtains of lidar attenuated backscatter at Chiang Mai (top) and Songkhla (bottom). Each panel is independently renormalized to its site-specific 5th–97.5th percentile NRB range, such that the color scale reflects relative aerosol loading at each site rather than absolute backscatter intensity, thereby enabling meaningful visual comparison. The aerosol layer top (ALT), derived using the wavelet covariance transform (green dots), and the thermodynamically constrained planetary boundary layer (PBL) height (red and blue dots) are overlaid. Gray shading indicates nighttime hours (19:00–07:00 LT). White columns denote periods of fully attenuated signal due to condensation on the instrument enclosure window, as well as other instrumental issues.

Aerosol backscatter profiles frequently display strong vertical stratification over Chiang Mai, with elevated and residual aerosol layers persisting above the thermodynamically constrained PBL height, particularly during nighttime and morning transition periods. During daytime convective conditions, the PBL height increases rapidly in response to surface heating; however, elevated aerosol layers are often not fully entrained into the actively mixed layer. Consequently, the dominant aerosol gradient detected by wavelet-based methods frequently corresponds to the aerosol layer top rather than the thermodynamic PBL height.

In contrast, a more vertically homogeneous aerosol structure is observed in Songkhla, with weaker stratification and fewer persistent elevated layers. The aerosol backscatter typically decreases more drastically with height, and the detected aerosol layer top more closely follows the thermodynamically constrained PBL height throughout the diurnal cycle. This qualitative contrast suggests fundamental differences in aerosol-boundary layer coupling between the inland valley and coastal environments.



3.2 Temporal evolution of aerosol-boundary layer coupling

Figure 3 complements the instantaneous aerosol structures shown in Fig. 2 by illustrating the temporal evolution of aerosol layer top (ALT), thermodynamically constrained PBL height, and their difference, $\Delta(\text{ALT-PBL})$, over a representative period (June 2021) at both sites. While Fig. 2 has been renormalized to enable cross-site visual comparison, Fig. 3 provides quantitative confirmation that the observed differences in aerosol-boundary layer coupling are systematic and persist across varying meteorological conditions, including periods of cloud and precipitation.

At Chiang Mai, $\Delta(\text{ALT-PBL})$ is predominantly positive, indicating that the aerosol layer top frequently resides above the thermodynamically constrained PBL height. This separation is most pronounced during nighttime and transition periods, when the collapse of the convective boundary layer leads to the formation of residual aerosol layers aloft. Cloudy and rainy periods can locally enhance or attenuate backscatter and temporarily obscure aerosol gradients. Nevertheless, the tendency for positive $\Delta(\text{ALT-PBL})$ persists across both clear and partially cloudy periods, demonstrating that aerosol-boundary layer decoupling at Chiang Mai is a robust feature rather than a clear-sky artifact. Periods of close alignment between ALT and PBL height occur mainly during daytime convective mixing but are short-lived, suggesting that aerosol-boundary layer coupling at the inland valley site is intermittent rather than sustained over the full diurnal cycle.

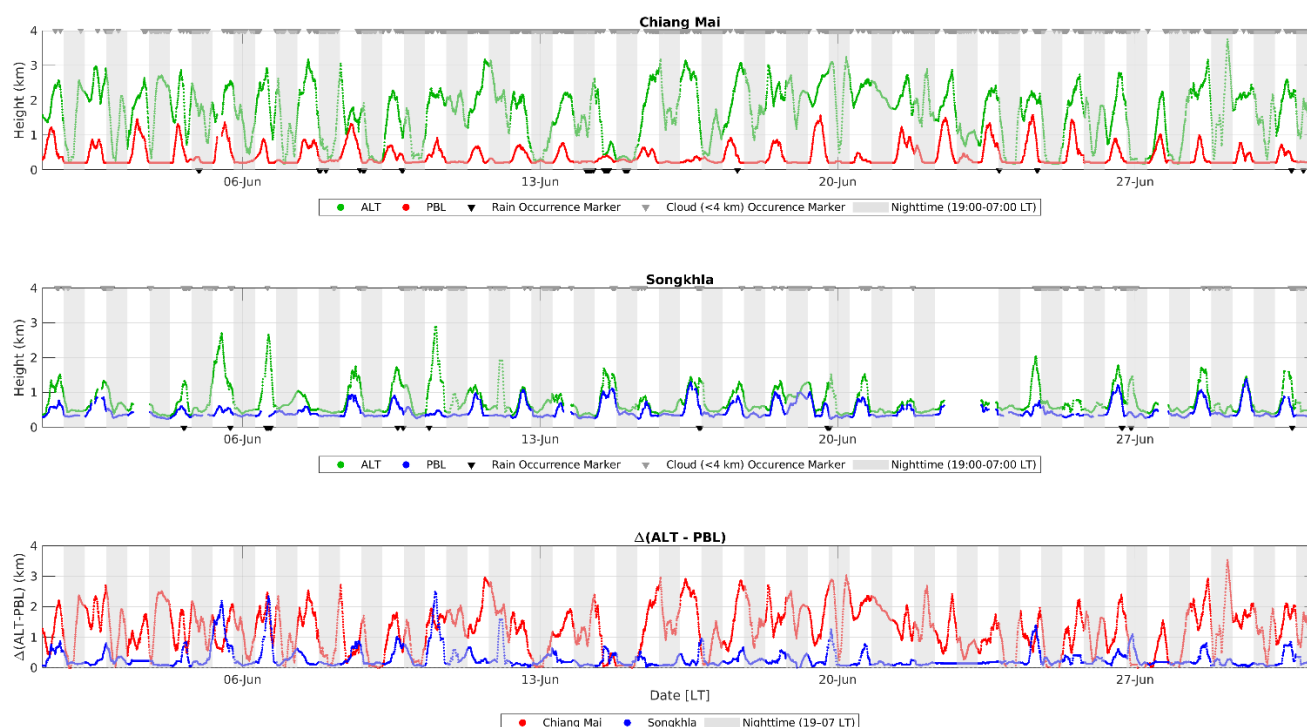


Figure 3. Time series of aerosol layer top (ALT), thermodynamically constrained PBL height, and their difference, $\Delta(\text{ALT-PBL})$, for a representative period at Chiang Mai and Songkhla (June 2021). Positive values of $\Delta(\text{ALT-PBL})$ indicate aerosol layers located above the thermodynamic PBL height. Periods influenced by clouds (< 4 km AGL) and precipitation, as well as nighttime conditions (19:00–07:00 LT), are indicated.



In contrast, $\Delta(\text{ALT-PBL})$ at Songkhla remains close to zero for most of the period shown in Fig. 3, indicating closer alignment between aerosol layer top and thermodynamically constrained PBL height. Nighttime separation is generally limited, and large deviations are infrequent even during cloudy or rainy conditions. This behavior is consistent with more continuous coupling between aerosol vertical structure and boundary-layer mixing at the coastal site, reflecting persistent mechanical forcing.

On several rainy days at Chiang Mai, the aerosol layer top (ALT) temporarily converges toward the thermodynamically constrained PBL height. This behavior is likely associated with wet scavenging of elevated or residual aerosol layers, which reduces aerosol backscatter gradients aloft and shifts the dominant gradient closer to the actively mixed layer. In contrast, rainfall events at Songkhla produce comparatively little change in ALT-PBL alignment, consistent with the already limited occurrence of persistent elevated aerosol layers under mechanically mixed coastal conditions.

3.3 Monthly statistical distributions of aerosol-boundary layer coupling

Figure 4 extends the time-resolved analysis by summarizing the monthly statistical distributions of $\Delta(\text{ALT-PBL})$ across the full study period. At Chiang Mai, distributions are consistently broad and displaced toward positive values, as quantified by the median and interquartile range (IQR) insets – median values frequently exceed +0.4 km and IQR values reach 1.0 km or more in several months, indicating that aerosol layers routinely reside well above the thermodynamically constrained PBL. This broadness reflects substantial temporal variability driven by recurrent nighttime decoupling, episodic daytime convective mixing, and frequent smoke loading during the dry season. High cloud occurrence during wet months (68–72%) further contributes to this variability by modulating boundary layer structure.

In contrast, Songkhla exhibits a narrow distribution of $\Delta(\text{ALT-PBL})$ centered near zero, indicating persistent aerosol-PBL alignment and limited variability. The reduced spread implies that large aerosol-boundary layer separations are rare and short-lived, even across different meteorological conditions, including periods of cloud cover and precipitation.

The monthly PDFs further reveal periods of partial convergence between the two sites, most notably during November and December. At Chiang Mai, this convergence occurs despite a seasonal decrease in cloud cover and precipitation, reflecting reduced surface heating and a shallower daytime boundary layer during the cool dry season. Under these conditions, elevated aerosol layers persist but are typically confined to lower altitudes, resulting in narrower $\Delta(\text{ALT-PBL})$ distributions shifted toward less positive values.

At Songkhla, the same months are characterized by increased cloud cover, precipitation, and strong background winds associated with the northeast monsoon. These conditions promote continuous mechanical mixing and maintain close alignment between aerosol layer top and thermodynamic PBL height. The resulting similarity in $\Delta(\text{ALT-PBL})$ distributions during November–December therefore reflects different physical mechanisms leading to comparable aerosol-boundary layer separation, rather than a breakdown of the inland valley-coastal contrast.

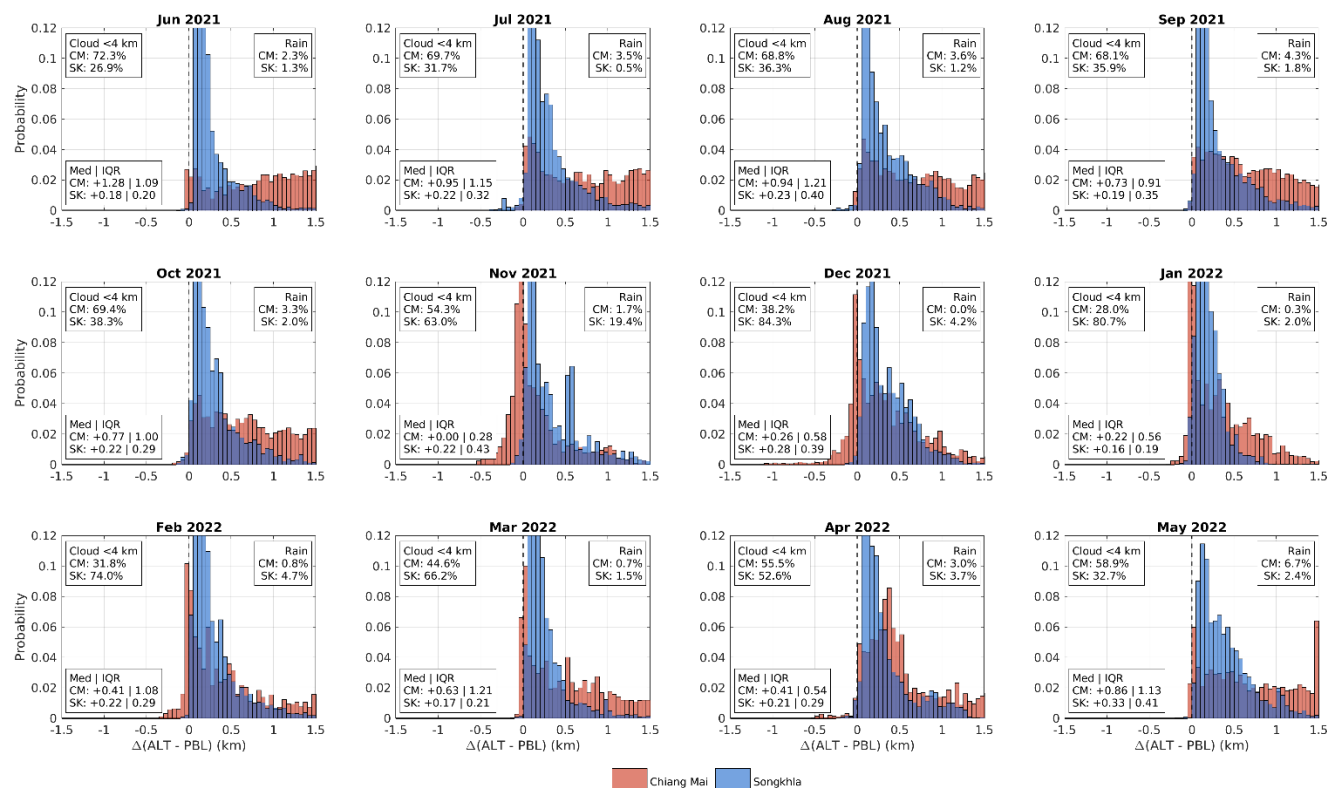


Figure 4. Monthly probability density functions (PDFs) of $\Delta(\text{ALT-PBL})$ for Chiang Mai (CM; red) and Songkhla (SK; blue) from June 2021 to May 2022. Broader distributions with larger positive medians at Chiang Mai reflect intermittent aerosol-boundary layer coupling and frequent decoupling episodes, while narrow distributions centered near zero at Songkhla indicate persistent coupling throughout the year. Three inset boxes are shown in each panel: cloud occurrence (top-left) reports the percentage of 5-minute intervals in which a cloud base was detected below 4 km AGL; rain occurrence (top-right) reports the percentage of intervals with non-zero precipitation; and distribution spread (bottom-left) reports the median and interquartile range (IQR) of $\Delta(\text{ALT-PBL})$, where IQR is the difference between the 75th and 25th percentiles and provides a robust measure of distribution width that is insensitive to tail extremes. All statistics are computed separately for each site from synchronised 5-minute retrievals and reported for direct regime comparison.

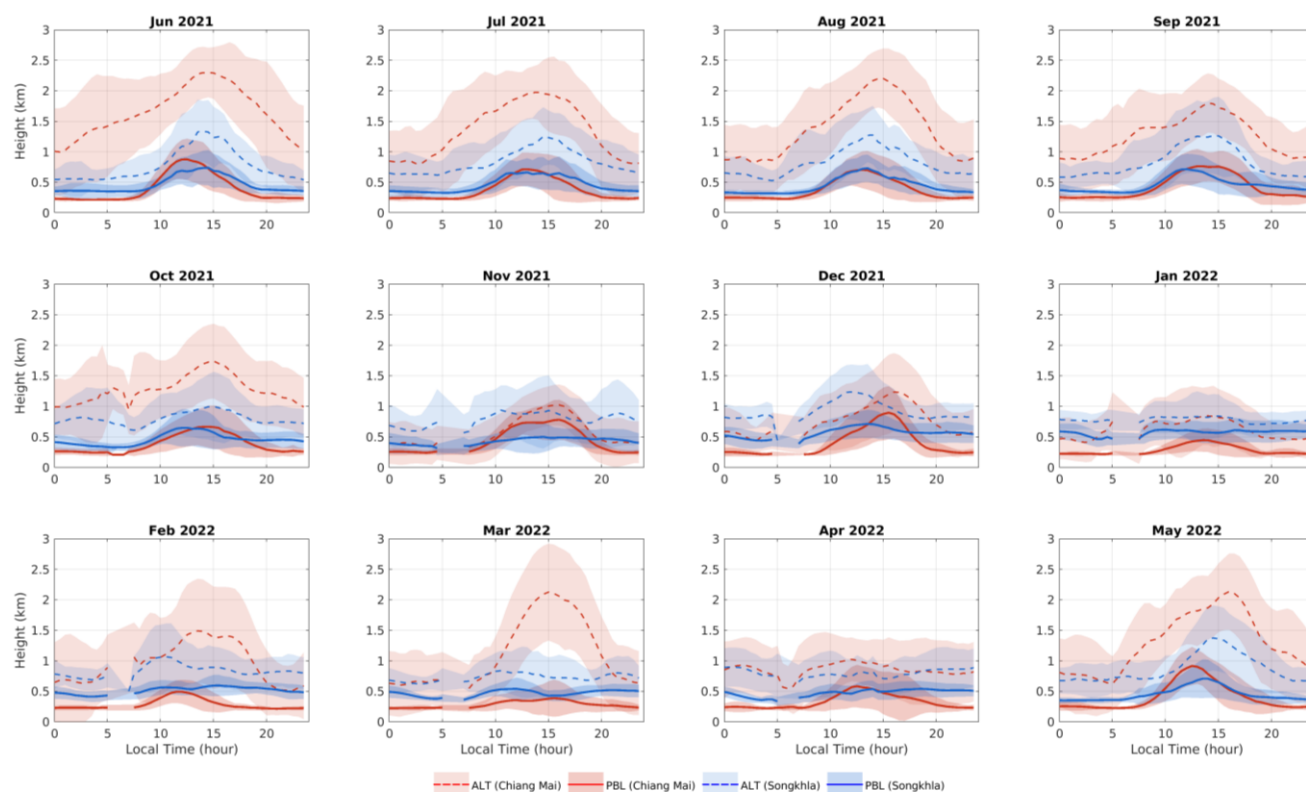
Taken together, Figs. 3 and 4 show that apparent aerosol homogeneity in instantaneous profiles – particularly during cloudy or rainy periods – does not reliably indicate aerosol-boundary layer coupling. Instead, coupling must be assessed in terms of its persistence and statistical consistency over time. The contrasting distributions shown in Fig. 4 provide quantitative evidence for regime-dependent aerosol-boundary layer behavior, motivating further examination of the diurnal processes governing coupling and decoupling at each site.

3.4 Physical controls on aerosol-boundary layer coupling

Monthly diurnal composites reveal fundamentally different coupling behavior at the two sites (Fig. 5). At Chiang Mai, ALT and PBL height evolve in phase ($r \approx 0.79\text{--}0.97$; Table S1), yet large RMS differences (0.85–1.28 km during rainy and warm dry seasons) and persistent positive biases indicate that aerosol layers frequently reside above the actively mixed layer. At



325 Songkhla, both temporal coherence and vertical proximity are maintained simultaneously – RMS differences remain small (0.21–0.44 km) and timing lags are near zero throughout the year (Table S1), indicating that diurnal phase alignment and vertical coupling co-occur rather than decouple as at the inland site.



330 **Figure 5. Monthly diurnal composites of aerosol layer top (ALT) and thermodynamically constrained PBL height for Chiang Mai and Songkhla, over the June 2021–May 2022 study period. At Chiang Mai, strong diurnal modulation of the PBL height contrasts with a weaker diurnal signal in ALT, leading to pronounced nighttime separation. At Songkhla, ALT and PBL height remain closely aligned throughout the diurnal cycle, indicating sustained aerosol-boundary layer coupling.**

The physical drivers of this contrast are reflected in surface meteorological correlations (Table S2). At Chiang Mai, PBL height is strongly temperature-dependent ($r \approx 0.68$ – 0.80) while ALT is not ($r \approx 0.23$ – 0.54), confirming that buoyancy drives boundary-layer growth but does not govern aerosol layer position. Wind speed correlations are weak at both heights ($r < 0.36$), indicating mechanical forcing plays a secondary role. At Songkhla, both ALT and PBL height show comparable and consistent wind speed dependence ($r \approx 0.15$ – 0.45), while ALT shows weak and inconsistent temperature dependence, indicating that mechanical mixing rather than surface heating governs aerosol vertical structure.

Together, these diagnostics establish that the inland valley regime is thermodynamically controlled but persistently decoupled, while the coastal regime is mechanically regulated and tightly coupled – a contrast that is directly quantified by the process-based decoupling metrics in Sect. 3.5.



340 3.5 Decoupling metrics

Table 1 presents the process-based aerosol-boundary layer decoupling metrics computed from the full one-year observational record at each site. All metrics are derived directly from the time series of $\Delta(\text{ALT-PBL})$ as described in Sect. 2.4; event durations are identified from contiguous sequences of timesteps with $\Delta(\text{ALT-PBL}) > 0.5$ km; and the autocorrelation timescale is derived by fitting an exponential decay to the autocorrelation function of $\Delta(\text{ALT-PBL})$.

345 **Table 1. Process-based aerosol-boundary layer decoupling metrics for Chiang Mai (CM) and Songkhla (SK) during June 2021–May 2022. Decoupling is defined as $\Delta(\text{ALT-PBL}) > 0.5$ km. Frequencies are unitless fractions. Duration and timescales are in hours.**

Site	Frequency	Daytime	Nighttime	Low Wind	High Wind	Median Event Duration (h)	Autocorrelation Timescale (h)
CM	0.529	0.610	0.443	0.463	0.666	3.75	5.58
SK	0.203	0.240	0.164	0.202	0.199	2.92	3.08

Sensitivity to the decoupling threshold of 0.5 km is assessed by recomputing all metrics at 0.3 km and 0.7 km. The inland-
350 coastal contrast in decoupling frequency is preserved across all thresholds (CM: 64.7%, 52.9%, and 43.8%; SK: 36.3%, 20.3%, and 11.9% at 0.3, 0.5, and 0.7 km respectively), and the autocorrelation timescale at Chiang Mai (~5.6 h) remains invariant across all three thresholds, confirming that the regime distinction and persistence structure are robust features of the data rather than artifacts of the threshold definition.

The inland valley site of Chiang Mai (CM) exhibits substantially higher decoupling frequency (~53%) compared to the
355 coastal site of Songkhla (SK; ~20%), confirming a thermodynamically dominated regime where elevated aerosol layers frequently reside above the mixing layer. Upper-bound uncertainty on decoupling frequency due to cloud and precipitation contamination is 0.9% at Chiang Mai and 9.0% at Songkhla, leaving the regime contrast robust. Decoupling in CM is more frequent during daytime (~61%) than nighttime (~44%), consistent with daytime convective growth beneath persistent residual layers. In contrast, SK shows weak diurnal contrast, indicating tighter aerosol-PBL coupling across the daily cycle.

360 Wind-conditioned statistics further highlight regime dependence. At CM, decoupling increases markedly under strong winds (~67%), which may reflect either shear-induced lofting of aerosols or the advection of a distinct elevated air mass. To distinguish between these mechanisms, HYSPLIT 48-h back-trajectories were initialized at both ALT and PBL heights for all 13,828 decoupled events under strong-wind conditions. This is analyzed further in Sect. 3.6.

365 In SK, decoupling frequency is nearly invariant across wind regimes (~20%), indicating mechanically mixed conditions where ALT and PBL remain vertically constrained regardless of wind speed. Persistence metrics reveal that decoupling events last longer inland (median ~3.8 h) than coastal (~2.9 h), and $\Delta(\text{ALT-PBL})$ exhibits a longer autocorrelation timescale



in CM (~5.6 h vs ~3.1 h in SK). This demonstrates that inland decoupling is not merely episodic but dynamically sustained, whereas coastal vertical structure adjusts more rapidly to mechanical forcing.

Overall, these results quantify regime mechanics: inland aerosol-boundary layer interactions are thermodynamically controlled and persistently decoupled, whereas coastal conditions are mechanically regulated and tightly coupled.

3.6 Shear-driven lofting and elevated advection

Two complementary analyses were used to determine whether the aerosol layers observed during decoupled, strong-wind events are produced locally by shear-driven mixing or are instead transported from a distinct source region at altitude. Wind profile analysis (Sect. 3.6.1) tests whether the atmospheric structure at the aerosol layer is mechanically unstable enough to support in-situ shear lofting. Back-trajectory analysis (Sect. 3.6.2) then tests whether the aerosol layer and the boundary layer originate from the same air mass.

3.6.1 Bulk Richardson number and wind shear diagnostics

To assess whether wind shear could mechanically lift aerosols to the observed decoupling heights, the bulk Richardson number (Ri) was computed at the aerosol layer altitude for all decoupled, strong-wind events ($n = 7,543$). Ri quantifies the balance between stabilising buoyancy forces and destabilising wind shear: values below 0.25 indicate that Kelvin-Helmholtz instability and shear-driven turbulence are plausible, while values above 1.0 indicate stable stratification that suppresses mechanical mixing. This is shown in Fig. 6.

The results provide little support for the shear-lofting mechanism (Fig. 6). Across all seasons, 83% of events have $Ri > 1.0$ at the aerosol layer, with median values ranging from 1.9 (Cool Dry) to 5.2 (Rainy), well into the stable regime. Only 3.7% of events fall below the $Ri < 0.25$ threshold. Spearman rank correlation between low-level wind shear (VWS_{0-2km}) and decoupling magnitude $\Delta(ALT-PBL)$ is negligible across all seasons ($|\rho| < 0.08$, Fig. 6b), confirming that stronger shear does not systematically produce greater aerosol-PBL separation. The cool dry season shows the weakest stratification (median $Ri = 1.9$, 6.2% shear-driven events) and the only positive shear-decoupling correlation ($\rho = +0.057$, $p < 0.001$), suggesting a minor mechanical contribution in that season, but the effect size remains small. Taken together, these results indicate that the aerosol layer sits in an environment that is too stably stratified for shear-driven lofting to be the primary formation mechanism in the majority of events.

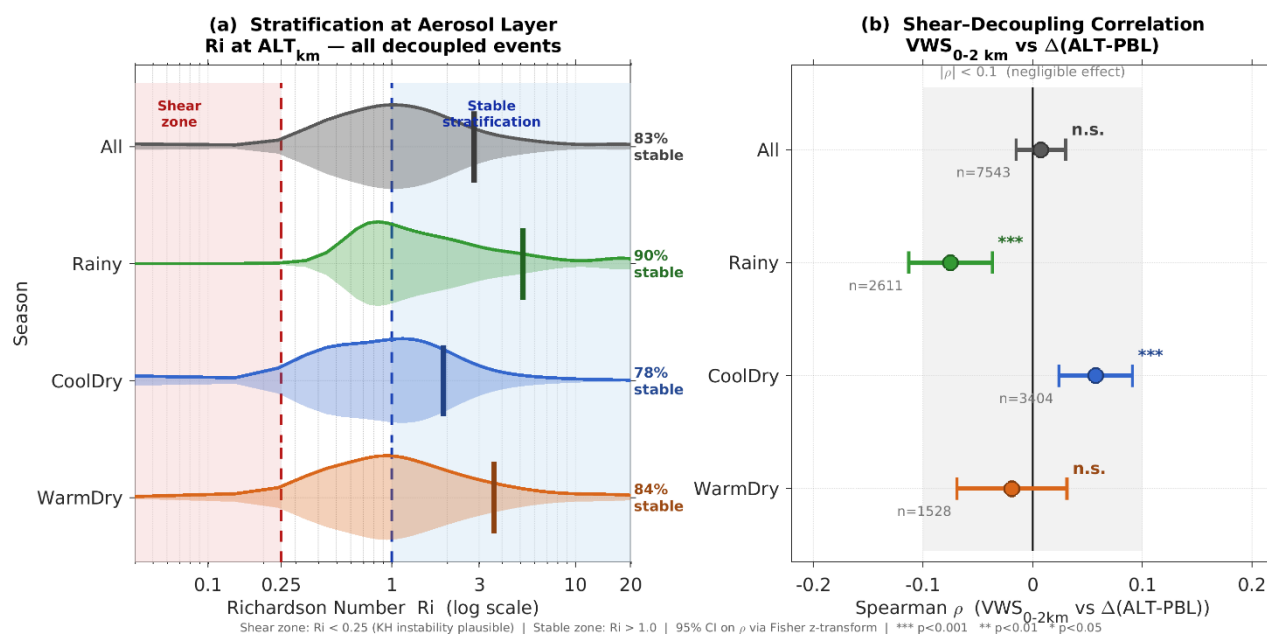


Figure 6. Wind profile diagnostics for the shear-lofting hypothesis at Chiang Mai ($n = 7,543$ decoupled strong-wind events, June 2021–May 2022). (a) Kernel density distributions of the bulk Richardson number Ri at the aerosol layer altitude, shown separately for each season and all events combined, on a logarithmic x-axis. The vertical tick inside each strip marks the seasonal median Ri . The red dashed line ($Ri = 0.25$) and blue dashed line ($Ri = 1.0$) delimit the shear-unstable, transitional, and stable regimes. The percentage of events in the stable zone is annotated for each group. (b) Spearman rank correlation (ρ) between low-level vector wind shear (VWS_{0-2km}) and decoupling magnitude $\Delta(ALT-PBL)$ for each season and all events combined. Filled circles show point estimates; horizontal bars show 95% confidence intervals (Fisher z-transform). The grey band marks the $|\rho| < 0.1$ region of negligible practical effect size. Significance stars denote two-tailed Spearman test results; sample sizes are shown for each group.

3.6.2 HYSPLIT back-trajectory cluster analysis

If the wind-profile evidence rules out local shear lofting as the dominant process, the logical alternative is that the elevated aerosol layer represents a distinct air mass that has been transported to Chiang Mai from a remote source. HYSPLIT 48-h back-trajectories were therefore initialised at both ALT and PBL heights for all 13,838 decoupled, strong-wind events to determine whether the two layers share a common origin (Fig. 7a).

If shear lofting were dominant, paired ALT and PBL trajectories from the same event would be expected to trace back to the same geographic region, since both layers would originate from a single local air mass that was subsequently separated only in the vertical. The data show the opposite. A two-sample Hotelling T^2 test applied to the 48-h trajectory endpoints reveals a statistically significant separation between the ALT and PBL source regions ($T^2 = 764.5$, $F(2, 27673) = 382.2$, $p < 0.0001$), indicating that the two air masses come from systematically different locations (Fig. 7b).

This separation is large in physical terms. The median Haversine distance between matched ALT and PBL endpoints is 502 km (IQR: 242–936 km), and 81% of trajectory pairs are separated by more than 200 km (Fig. 7c). Displacements of this magnitude are inconsistent with simple vertical shear acting on a single air parcel over 48 hours – boundary-layer shear



typically displaces air parcels by tens of kilometres over such timescales (Stull, 1988; Garratt, 1992) – and instead indicate
415 that the two layers have genuinely distinct transport histories (Draxler and Rolph, 2003; Stohl, 1998).
The cluster analysis reinforces this interpretation (Fig. 7d). K-means clustering ($K = 4$) identifies four recurring transport
regimes, and ALT and PBL trajectories are distributed unevenly among them: only 53% of event pairs share the same
cluster, compared with $\sim 25\%$ expected under independent random assignment. While this rate of co-occurrence is above
chance – meaning the ALT and PBL are not completely independent – it is low enough to confirm that different transport
420 pathways are the norm rather than the exception.

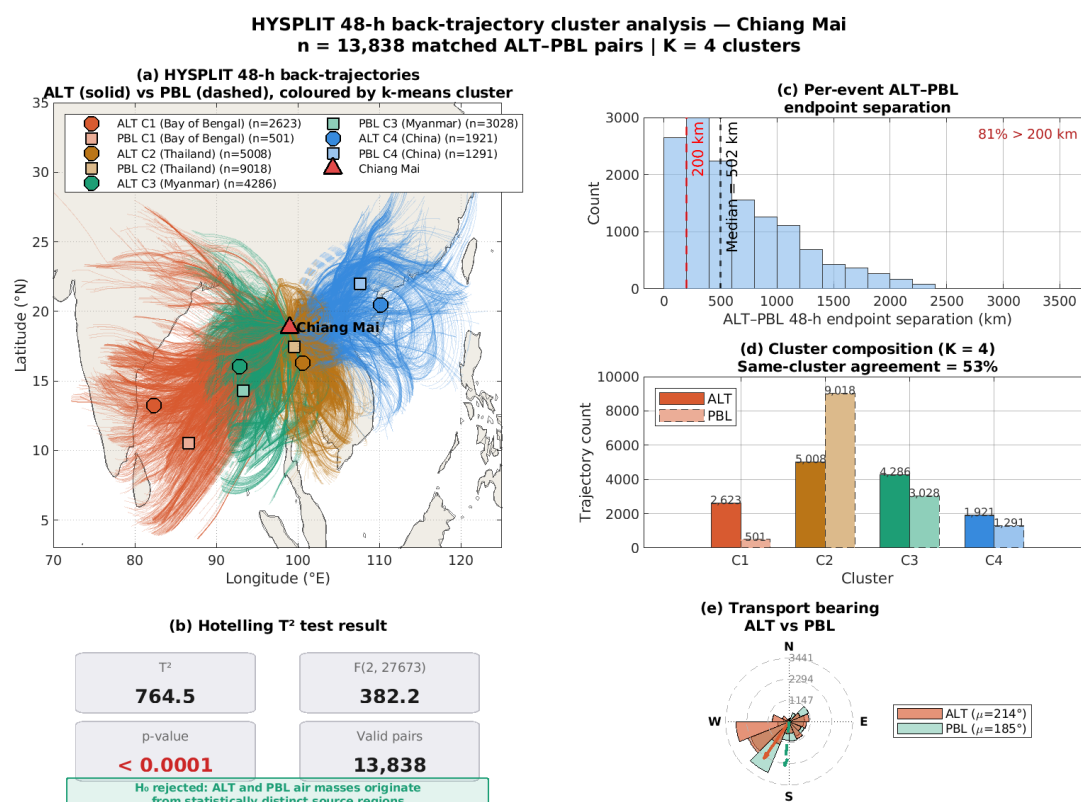


Figure 7. HYSPPLIT 48-h back-trajectory analysis for decoupling events under strong winds at Chiang Mai (n = 13,838 matched ALT-PBL pairs): (a) Trajectory map coloured by k-means cluster ($K = 4$); solid lines show ALT trajectories and dashed lines show PBL trajectories; circles and squares mark the ALT and PBL cluster centroids, respectively; (b) Two-sample Hotelling T^2 test statistics; (c) Distribution of the per-event Haversine distance between matched 48-h endpoints; the red dashed line marks 200 km and the black dashed line marks the median (502 km); (d) Cluster composition showing the count of ALT and PBL trajectories assigned to each cluster; (e) Transport bearing distributions for ALT (coral) and PBL (teal) trajectories; arrows indicate the
425 circular mean bearing.

Transport direction provides a final line of evidence (Fig. 7e). ALT trajectories arrive from a mean bearing of 214° (south-
430 southwest), placing their source regions over southern Myanmar and the Bay of Bengal, while PBL trajectories arrive from



185° (due south), reflecting more local recirculation from the Thai lowlands. The 29° directional offset is consistent with ALT air masses being carried by synoptic-scale flow that is dynamically decoupled from the near-surface wind regime.

Together, the Richardson number analysis and back-trajectory results converge on the same conclusion: elevated aerosol layers at Chiang Mai during decoupled, strong-wind conditions are primarily the product of horizontal transport rather than in-situ shear-driven lofting. While secondary aerosol formation and aerosol-radiation feedbacks may modulate aerosol loading within these layers (Satheesh et al., 2009; Cohen et al., 2018; Reid et al., 2025), they do not account for the large horizontal separation between ALT and PBL air mass origins identified here (Draxler and Rolph, 2003; Stohl, 1998). The observed decoupling is therefore attributed to dynamical processes – specifically, the advection of a distinct elevated air mass under conditions where the evolving boundary layer has subsided below it.

440 4 Conclusions and Recommendations

This study provides observational evidence, from a single seasonal cycle at two contrasting sites in Thailand, that aerosol-boundary layer coupling differs systematically between a thermodynamically dominated inland valley regime and a mechanically influenced coastal regime. Within this regime-contrast framework, we show that apparent similarity in instantaneous aerosol profiles at these two sites can mask fundamentally different coupling behavior when examined statistically and across the diurnal cycle – a result that motivates caution when interpreting aerosol-gradient-based PBL retrievals without prior characterization of boundary-layer forcing regime.

At the inland valley site, ALT and thermodynamically constrained PBL height generally evolve in phase over the diurnal cycle ($r \approx 0.79$ – 0.97), yet large RMS differences (0.85–1.28 km during rainy and warm dry seasons) and persistent positive biases indicate that aerosol layers frequently reside above the actively mixed layer. This behavior is consistent with intermittent but recurring decoupling associated with residual layers, lofted aerosol, and incomplete nocturnal mixing, particularly during dry and transitional seasons. Richardson number diagnostics show that 83% of decoupled strong-wind events occur under stably stratified conditions ($Ri > 1.0$), and HYSPLIT back-trajectory analysis confirms that elevated aerosol layers originate from statistically distinct source regions (Hotelling $T^2 = 764.5$, $p < 0.0001$; median ALT-PBL endpoint separation 502 km), attributing decoupling primarily to horizontal aerosol transport rather than in-situ shear-driven lofting.

In contrast, the coastal site exhibits consistently small vertical differences between ALT and PBL height (RMS 0.21–0.44 km), indicating more persistent coupling throughout most of the year. Mechanical mixing associated with coastal winds and sea-land breeze circulations suppresses the formation of elevated residual layers and maintains aerosol-PBL alignment. Decoupling events at Songkhla are infrequent (~20%), short-lived (median ~2.9 h), and nearly invariant across wind regimes, in contrast to the wind-sensitive and dynamically sustained decoupling at Chiang Mai (~53%, median ~3.8 h, autocorrelation timescale ~5.6 h vs ~3.1 h at Songkhla). Upper-bound uncertainty on decoupling frequency due to cloud and precipitation contamination is 0.9% at Chiang Mai and 9.0% at Songkhla, leaving the regime contrast robust.



465 The stable stratification identified here ($R_i > 1.0$ in 83% of decoupled events) is consistent with temperature inversion conditions frequently cited in public discourse on Thailand's haze episodes, but explicit inversion analysis was beyond the scope of this study and warrants dedicated investigation – particularly to disentangle local thermodynamic trapping from the horizontal transport mechanism identified here.

470 These contrasting regimes have direct implications for aerosol-gradient-based PBL detection. In thermodynamically dominated inland valley environments, aerosol layers frequently decouple from the actively mixed layer, leading to systematic overestimation of PBL height when aerosol gradients are used as a proxy. In mechanically influenced coastal environments, tighter aerosol-PBL alignment increases retrieval reliability. Critically, similar instantaneous aerosol structure does not necessarily imply physical coupling – coupling is more robustly evaluated using metrics such as temporal persistence, diurnal phase alignment, sustained vertical proximity, and decoupling diagnostics including separation frequency, autocorrelation timescale, and duration of vertically detached layers.

475 The consistency of regime-dependent behavior across seasons within the study year suggests that the inland valley-coastal contrast reflects differences in boundary-layer forcing rather than isolated events. These results raise a testable hypothesis for satellite-based PBL retrievals (e.g., CALIOP): in inland valley environments similar to Chiang Mai, aerosol backscatter gradients may systematically overestimate thermodynamic PBL depth, particularly during dry and transitional seasons. Whether this regime-dependent bias is detectable in satellite-derived PBL climatologies, and whether incorporating regime-dependent coupling diagnostics improves data assimilation and air-quality modeling in monsoon-influenced environments, 480 remain questions for dedicated multi-site and modeling studies.

Code availability

The code underlying this article will be shared on reasonable request to the corresponding author.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

485

Author contributions

490 RM contributed to conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, and writing (original draft preparation and review and editing). WT contributed to software (wavelet covariance transform implementation) and writing (review and editing). RS contributed to investigation (Songkhla site installation), methodology (PBL discussions), and writing (review and



editing). TS contributed to investigation (Songkhla site installation), methodology (PBL discussions), and writing (review and editing). CW contributed to resources (Songkhla site hosting).

Competing interests

The authors declare that they have no conflict of interest.

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