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Decoupling the PBL Height, the Mixing Layer Height, and the Aerosol Layer Top in LiDAR Measurements over Chiang Mai, Northern Thailand

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Abstract. Accurate determination of the planetary boundary layer (PBL) height, mixing layer height (MLH), and aerosol layer top (ALT) is critical for air quality and climate studies, especially in regions with complex aerosol dynamics like Chiang Mai, northern Thailand. This study develops a novel LiDAR-based methodology that incorporates a temperature-based dynamic maximum analysis altitude (MAA) to decouple these layers, addressing the limitations of conventional methods such as the Haar Wavelet Covariance Transform (WCT). Traditional fixed-altitude approaches often misclassify the ALT as the PBL height, particularly during nighttime or transition periods, leading to significant overestimations. By dynamically adjusting the MAA based on surface temperature variations, the proposed approach effectively distinguishes the PBL from residual aerosol layers and cloud interference. Comparison against radiosonde data and WRF-Chem simulations demonstrates strong agreement, with LiDAR-derived PBL heights showing improved diurnal resolution and accuracy. However, model simulations tend to overestimate the PBL height during high aerosol events, highlighting the need for refined aerosol-radiation interaction parameterizations. This study underscores the importance of integrating thermodynamic and aerosol data for accurate boundary layer characterization and provides a robust framework for improving air quality and climate models in regions with high aerosol loading and complex topography. These findings have implications for enhancing pollutant transport analysis and advancing LiDAR-based remote sensing techniques in Southeast Asia.

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1 Introduction

The planetary boundary layer (PBL) height, mixing layer height (MLH), and aerosol layer top (ALT) are distinct atmospheric parameters essential for understanding air quality and climate dynamics. The PBL height represents the top of the lowest atmospheric layer influenced by surface interactions, encompassing layers such as the daytime mixing layer and the stable boundary layer at night (Stull, 1988). The MLH, a turbulent and well-mixed subset of the PBL, typically aligns with the PBL height under convective conditions but can diverge in stratified or stable atmospheres (Seibert et al., 2000). The ALT, marking the upper boundary of significant aerosol concentrations, often decouples from the PBL due to stratification, entrainment, or advection processes. Moreover, due to stronger vertical mixing over mountainous topography the aerosol can reach higher altitudes often resulting in significant aerosol loading above the PBL (De Wekker and Kossmann, 2015). Light Detection and Ranging (LiDAR) based techniques, despite offering high-resolution aerosol profiles, frequently face challenges in distinguishing these layers, particularly during nighttime or transitions (Ferrare et al., 2012). Emerging approaches that combine normalized relative backscatter (NRB) data with thermodynamic adjustments address these challenges, improving the accuracy of boundary layer height and ALT identification (Su et al., 2018; NASA DISCOVER-AQ Workshop, 2012). These developments are particularly relevant for regions like Southeast Asia, where high aerosol loads from industrial and biomass burning activities create complex vertical profiles.

This study focuses on enhancing LiDAR-based boundary layer characterization by refining the detection of PBL height, MLH, and ALT. Traditional algorithms, such as the Haar Wavelet Covariance Transform (WCT), often misclassify the ALT as the PBL height, especially at night or during transitional periods when aerosol gradients are less distinct. Clouds and other atmospheric complexities make these measurements more challenging. By integrating normalized relative backscatter (NRB) profiles with dynamic thermodynamic adjustments, this approach addresses ambiguities in traditional methods and improves the reliability of boundary layer determinations.

Numerous studies have significantly advanced the methods for estimating planetary boundary layer (PBL) height using LiDAR, addressing challenges posed by complex meteorological conditions, aerosol stratification, and limitations in traditional methodologies. For example, Toledo et al. (2017) explored numerical methods under sea–land breeze regimes, revealing discrepancies in residual layers that affect accurate PBL height detection, while Vishnu et al. (2017) highlighted the difficulty of applying a universal method for estimating the mixing layer height (MLH), which varies under different atmospheric conditions. Li et al. (2017) contributed to improving convective boundary layer height (CBLH) retrievals by developing a convective condensation level algorithm, and Dang et al. (2019) reviewed various aerosol LiDAR techniques and developed a robust method (Dang et al., 2019), achieving strong correlations with radiosonde data to enhance accuracy. In addition, Zhong et al.'s (2020) MLHI-RR technique, Zhang et al.'s (2020) Cluster Analysis of the Gradient Method, and Macatangay et al.'s (2021) TDMMAA method for Haar wavelet techniques improved the precision of PBL measurements, while machine learning approaches, such as Liu et al.'s (2022) MKnm algorithm, and other methods like Pan et al.'s (2022)

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MR-IP and Han et al.'s (2022) ADEILP, have addressed multilayer conditions and diurnal variations in aerosol profiles.

A critical challenge remains in fully decoupling the PBL height, MLH, and ALT, particularly in regions with high aerosol variability, such as Northern Thailand. Diverse pollution sources, including biomass burning, anthropogenic, and biogenic emissions, contribute to intricate vertical aerosol distributions. This study attempts to overcome the limitations of WCT, improving the separation of PBL, MLH, and ALT through a novel integrated NRB and surface temperature approach. The enhanced accuracy of boundary layer detection is pivotal for improving air quality and climate models, particularly in Southeast Asia, where aerosol concentrations are highly variable and challenging to characterize. This work provides new insights into the vertical aerosol distribution and its implications for air quality, aerosol-meteorology interactions, and public health in regions heavily impacted by agricultural and industrial emissions.

2 Methodology

To estimate the planetary boundary layer (PBL) height using micropulse LiDAR, normalized relative backscatter (NRB) profiles were analyzed, as NRB is proportional to aerosol concentration (Campbell et al., 2002). Conventional methods, such as the Haar WCT with a fixed maximum analysis altitude (e.g., 4 km), often yield the top of the aerosol layer rather than the actual PBL height. These methods can overestimate the PBL height during nighttime by identifying the residual layer top, and during transitional periods (morning growth or evening decay), they fail to capture diurnal PBL variations accurately (Brooks et al., 2003). Moreover, low clouds can lead to incorrect identification of either their base or top as the PBL height. To address these limitations, a robust algorithm that adapts dynamically to atmospheric conditions is necessary.

The study was conducted at the headquarters of the National Astronomical Research Institute of Thailand (NARIT) situated at the Princess Sirindhorn AstroPark in Chiang Mai, northern Thailand (18.85° N, 98.96° E, 332 mASL) a region known for its complex aerosol dynamics due to factors like its mountainous topography, biomass burning (forest and agricultural fires), anthropogenic pollution, and biogenic emissions from forested areas. The site is particularly relevant as it experiences significant seasonal variations in aerosol concentrations, influencing the vertical distribution of particulate matter. The study period, from December 2023 to February 2024, coincides with the beginning of the dry season in northern Thailand, when agricultural burning and forest fires start to contribute to heightened aerosol concentrations (Bran et al., 2024) and complicate the identification of the PBL and aerosol layers. This period provides a unique opportunity to evaluate the performance of the proposed LiDAR-based approach in a region with high aerosol loading and varying meteorological conditions. A more comprehensive description of the study site is given in Solanki et al., 2019.

In this study, a novel approach was introduced by incorporating simultaneous surface temperature observations to define a time-varying maximum analysis altitude (MAA). This dynamic parameter, unlike the fixed altitudes used in conventional methods, is calculated using Equation (1):

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$$MAA(t) = LAA + (HAA - LAA)\left(\frac{T(t)-min(T)}{max[T-min(T)]}\right) \quad (1)$$

where MAA(t) is the time-varying surface temperature-based maximum analysis altitude

LAA and HAA, represent the lowest and highest allowable maximum analysis altitudes. These are set to 0.5 and 2.5 km, respectively, based on Solanki et al. (2019)

T(t) is the observed surface temperature (in °C)

min(T) is the minimum temperature of the day (or the previous day for operational use)

max[ ] is the maximum of the expression inside the brackets

t is time, representing temporal variation for all T, with data recorded every 5 minutes

Using this dynamic MAA, the Haar WCT method (Brooks et al., 2003; Ceilo code) was employed, followed by a 6-hour moving average to smooth the data. The estimated PBL heights were then compared to radiosonde observations and WRF-Chem simulations.

Data from radiosondes launched by the Thai Meteorological Department (TMD) at the Chiang Mai International Airport (18.77° N, 98.96° E, 311 mASL; approximately 9 km in distance from the study site) were retrieved from the University of Wyoming's atmospheric sounding archive (https://weather.uwyo.edu/upperair/sounding.html). These data were interpolated to a vertical grid with 30-meter spacing from 100 m to 2 km, corresponding to the LiDAR minimum detection height or overlap region and the typical aerosol layer top (Solanki et al., 2019), respectively. PBL heights were determined using the maxima in the first derivatives of temperature, wind speed, wind direction, and potential temperature, as well as the minima in the first derivatives of dewpoint and relative humidity (Wang and Wang, 2014). The PBL height was computed as the average of estimates derived from these parameters. However, a significant limitation is that the radiosondes were launched only once daily at 7 AM local time (00 UTC), coinciding with the early morning minimum PBL height. This limitation means that diurnal variations in the PBL height, especially during its daytime growth and decay phases, cannot be captured, potentially reducing the representativeness of radiosonde-derived estimates for broader atmospheric analyses.

WRF-Chem simulations were configured and optimized for mainland Southeast Asia (Bran et al., 2024) using version 4.3.3, with the Mellor-Yamada Nakanishi and Niino (MYNN) Level 3 PBL scheme (Olson et al., 2019). The simulations used in this study (in forecast mode to reflect real operational conditions, with model output averaged over overlapping time periods in the forecast cycle) incorporated updated terrestrial data (Manomaiphiboon et al., 2017), anthropogenic emissions for northern Thailand (Jansakoo et al., 2019), and biogenic and fire emissions from MEGAN (Guenther et al., 2006) and near-real-time FINNv1.5 (Wiedinmyer et al., 2011). To project fire emissions into the future (forecast mode), the assumption of persistent fire emissions was applied (Kumar et al., 2020). Initial and boundary conditions for meteorology and chemistry were derived

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from GFS (NCEP, 2024) and CESM2-WACCM (Gettelman et al., 2019), respectively. The horizontal spatial resolution used in the WRF-Chem simulation was 9-km covering mainland Southeast Asia. Since WRF-Chem uses a hybrid, sigma-pressure, terrain-following coordinate system, the vertical resolution used in this study with 38 vertical levels varies with altitude. Near the surface (0 to ~1,100 meters AGL; 24 vertical levels), it ranges from about 45–50 meters, increasing to approximately 70–250 meters in the lower troposphere (~1,100 to 2,000 meters AGL; 4 vertical levels). From the aerosol layer top to the mid troposphere (~2,000 to 7,000 meters AGL; 4 vertical levels), the resolution becomes coarser, ranging from 500 to 2,000 meters, and further coarsens to over 2,000 meters from the mid to the upper troposphere and stratosphere (~7,000 to 20,000 meters AGL; 6 vertical levels), with finer resolution near the surface to capture smaller-scale processes and coarser resolution at higher altitudes where larger-scale dynamics dominate.

This integrated methodology ensures better alignment of LiDAR-derived PBL heights with thermodynamic and aerosol boundaries, enhancing the reliability of boundary layer characterizations.

3 Results and Discussion

Figure 1 shows the NRB signal as a colored curtain plot, where the aerosol layer top (ALT) is marked as a white line, the time-varying maximum analysis altitude (MAA) as a gray line, and the refined PBL estimate as a red line. During 00:00–06:00 LT, conventional PBL detection methods often mischaracterize the PBL height by incorrectly identifying the residual layer top or aerosol layer top as the PBL. However, during the well-mixed part of the day and under cloud-free conditions (12:00–16:00 LT on January 27), the red PBL line closely aligns with the white ALT line. This alignment indicates a well-defined mixing layer, allowing for an accurate determination of the mixing layer height (MLH). In contrast, during partly cloudy conditions (12:00–16:00 LT on January 28), conventional PBL detection algorithms misclassify the cloud base as the PBL height.

Additionally, during transitional periods, such as the morning PBL growth phase (06:00–12:00) and evening decay (16:00–00:00), mischaracterization occurs as aerosol accumulation within residual layers creates ambiguous gradients in the NRB signal. By incorporating the novel time-varying MAA (gray line) developed in this study and refining PBL estimates (red line), these limitations are addressed. The results also demonstrate improved PBL detection, as seen during the well-mixed hours under partly cloudy conditions (12:00–16:00 LT on January 28), where the red PBL line distinctly separates from the ALT (white) and follows the expected diurnal PBL development. This approach avoids overestimations caused by residual layers and enhances the reliability of boundary layer characterization, particularly in regions with complex aerosol dynamics.

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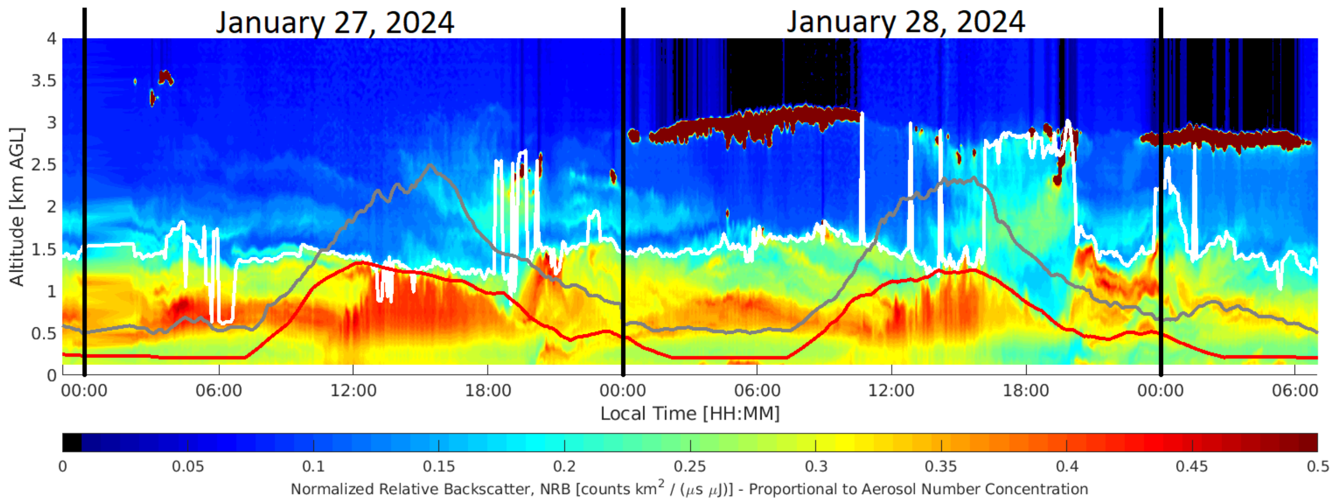

Figure 1. The normalized relative backscatter (NRB) signal from the LiDAR is shown as a colored curtain plot, illustrating variations in aerosol number concentration over time. The aerosol layer top (ALT) is marked as a white line, the time-varying maximum analysis altitude (MAA) as a gray line, and the refined planetary boundary layer (PBL) estimate is depicted in red. Data shown here were collected on January 27–29, 2024.

Figures 2 and 3 demonstrate the improved alignment of these estimates with radiosonde data and highlight discrepancies with the WRF-Chem model simulations, respectively. Radiosonde-derived PBL heights, computed using first derivatives of meteorological parameters, provide a baseline comparison but are limited to once-daily measurements at 7 AM local time, often capturing the minimum PBL height. The temperature-based MAA method offers greater temporal resolution and adaptability, enhancing its reliability in capturing diurnal variations and transitions between the PBL and the ALT.

Figure 2 illustrates the variability of the PBL height and ALT under different atmospheric conditions for December 2023, January 2024, and February 2024. The LiDAR-derived PBL height (red curve) exhibits a pronounced diurnal cycle, peaking during the day due to solar-driven convection and decreasing at night under stable conditions. The radiosonde measurements (black points) closely align with the LiDAR-derived PBL heights, providing independent validation. However, their representativeness is limited by the once-daily launch at 7 AM local time (00 UTC), coinciding with the early morning minimum PBL height. In December 2023, the LiDAR-derived PBL height ranges between 0.1 km and 1.5 km AGL, with radiosonde values exhibiting strong agreement and a correlation coefficient of r = 0.82. In January 2024, the LiDAR PBL height varies between 0.1 km and 1.6 km AGL, with excellent correlation to radiosonde measurements (r = 0.87). Similarly, in February 2024, the LiDAR-derived PBL height ranges from 0.1 km to 1.4 km AGL, maintaining a strong correlation with radiosonde data (r = 0.83), despite some divergence under complex atmospheric conditions. The ALT (green dashed line), representing the upper boundary of significant aerosol backscatter, often exceeds the PBL height during stable nighttime conditions, the presence of residual aerosol layers, or during aerosol entrainment into the free troposphere. By incorporating surface temperature variations, the proposed method effectively distinguishes the PBL height from the ALT, addressing

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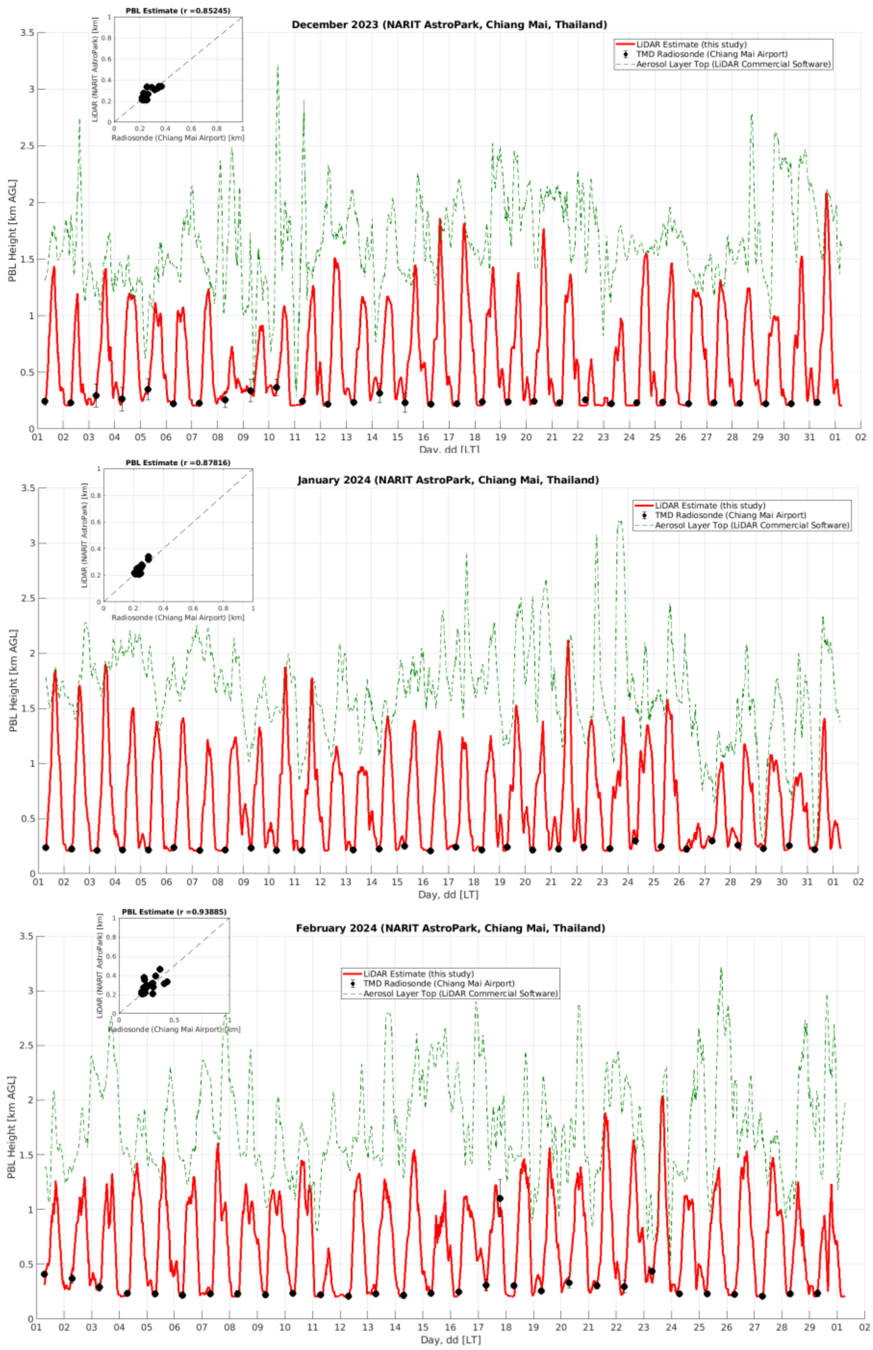

Figure 2. Comparison of planetary boundary layer (PBL) height estimates derived from this study's LiDAR retrievals (red curve), TMD radiosonde measurements at Chiang Mai Airport (black points), and aerosol layer top (ALT) heights calculated using the commercial LiDAR software (green dashed line) for December 2023 (top), January 2024 (middle), and February 2024 (bottom) at NARIT AstroPark, Chiang Mai, northern Thailand. Insets show the correlation between LiDAR-based PBL estimates and radiosonde-derived heights (r-values: 0.83–0.94).

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challenges during transitions between daytime and nighttime conditions. While the PBL height is primarily governed by thermodynamic properties and turbulent mixing, the ALT reflects aerosol stratification and distribution. These layers typically align during well-mixed daytime conditions (mixing layer height), but they diverge under stratified or complex layering scenarios, emphasizing the necessity of distinguishing between them for accurate air quality modeling and pollutant transport analysis.

Figure 3 compares PBL height estimates from LiDAR retrievals (red line) and WRF-Chem forecasts (black line) for December 2023, January 2024, and February 2024 at NARIT AstroPark in Chiang Mai, northern Thailand. While the WRF-Chem model also generally captures these patterns, it tends to overestimate PBL height during high aerosol events, attributed to the PBL estimation in the model, limitations in aerosol-radiation interaction parameterizations and the MYNN Level 3 scheme's treatment of aerosol radiative feedback (Du et al., 2020). Correlation coefficients (r = 0.85, 0.86, and 0.81 for December, January, and February, respectively) indicate strong agreement between the two methods, but the root mean square error (RMS) and percentage RMS (%RMS) increased from December (0.2769 km, 21%) to February (0.4578 km, 33%). This decline in model performance during February may also reflect the influence of persistent fire emissions on PBL dynamics (Kumar et al., 2020). These discrepancies underscore the need for model refinements to better capture aerosol effects.

These results underscore the significance of dynamic adjustments in LiDAR analyses for improved boundary layer characterization and the critical need to address limitations in both observational and modeling techniques for regions with complex atmospheric conditions.

4 Conclusions and Recommendations

This study successfully demonstrated the decoupling of the planetary boundary layer (PBL) height, mixing layer height (MLH), and aerosol layer top (ALT) using high-resolution LiDAR measurements in Chiang Mai, northern Thailand. By applying a novel temperature-based dynamic maximum analysis altitude (MAA) approach, the research overcame limitations of conventional methods, such as the Haar Wavelet Covariance Transform (WCT), which often misinterprets the ALT as the PBL height, particularly during nighttime or transitional periods. The proposed method, integrating normalized relative backscatter (NRB) profiles with surface temperature observations, improves the accuracy of PBL height estimations by accounting for variations in thermodynamic and atmospheric conditions. The results showed good agreement with both radiosonde data and WRF-Chem simulations (up to moderate aerosol loads), emphasizing the value of dynamic adjustments in refining boundary layer characterizations.

The study also highlights the complexities of aerosol layering and PBL identification in regions with high aerosol concentrations, such as Chiang Mai, where seasonal forest and agricultural burning and biomass fires contribute to significant

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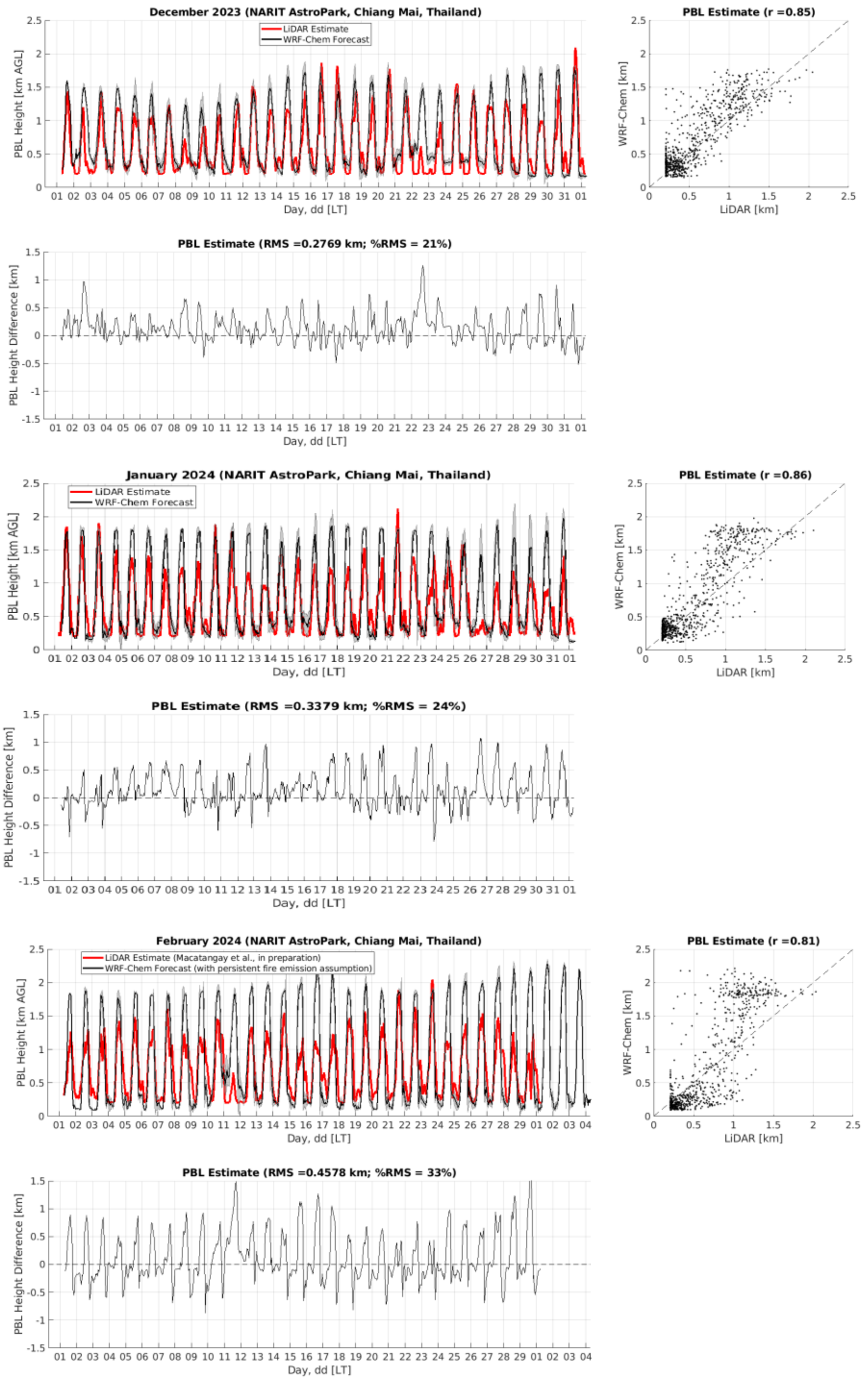

Figure 3. Comparison of planetary boundary layer (PBL) height estimates from LiDAR retrievals (red line) and WRF-Chem forecasts (black line) at NARIT AstroPark, Chiang Mai, Thailand, for December 2023 (top), January 2024 (middle), and February 2024 (bottom). Each panel includes a time series of PBL heights (top left), differences between LiDAR and WRF-Chem estimates (bottom left), and scatter plots with correlation coefficients (top right).

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atmospheric pollution. By enhancing the accuracy of LiDAR-based PBL height estimations, this research provided critical insights for improving air quality models and understanding pollutant transport, particularly in regions experiencing complex meteorological conditions.

Future research should focus on refining the dynamic MAA approach to LiDAR methodology for better handling of extreme atmospheric conditions, such as high aerosol loads and abrupt meteorological changes, while expanding its applicability to regions with diverse aerosol profiles to validate robustness. Integrating LiDAR with other remote sensing tools like radar or satellite-based sensors could enhance the accuracy and spatial resolution of PBL and aerosol layer measurements, particularly in areas with dense cloud cover or frequent atmospheric transitions. To address the limitations of once-daily radiosonde measurements, more frequent launches or the adoption of continuous vertical profiling instruments is recommended to capture diurnal variations more effectively, providing a richer dataset for model validation. Comparisons of LiDAR-derived PBL estimates with simulations from models like WRF-Chem are essential to evaluate model accuracy under high-aerosol conditions and to improve parameterizations for aerosol transport and mixing. Finally, refined PBL height estimation methods can enhance air quality forecasting systems, improving pollutant dispersion predictions and supporting more effective public health advisories and mitigation strategies in regions such as northern Thailand with significant seasonal aerosol emissions.

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.

Author Contribution

Ronald Macatangay led the conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software development, supervision, validation, visualization, writing – original draft preparation, and writing – review and editing.

Thiranan Sonkaew contributed to formal analysis, investigation, methodology, supervision, and writing – review and editing.

Sherin Hassan Bran contributed to formal analysis, investigation, methodology, software development, and writing – review and editing.

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Worapop Thongsame contributed to formal analysis and software development.

Titaporn Supasri contributed to funding acquisition, project administration, and resources.

Raman Solanki contributed to writing – review and editing.

Mana Panya contributed to resources.

Jeerasak Longmali contributed to resources.

Raman Solanki indirectly contributed to conceptualization through previous discussions on the limitations of conventional PBL estimation techniques and contributed to writing – review and editing.

Ben Svasti indirectly contributed to conceptualization, funding acquisition, methodology, project administration, resources, and supervision through a separate project entitled "The Development of a Tethered Balloon System for Vertical Profile Measurements of Meteorological Parameters and PM2.5," which provided relevant methodological insights used in comparing LiDAR and radiosonde data.

Achim Haug indirectly contributed to conceptualization, funding acquisition, methodology, resources, and supervision through a separate project entitled "The Development of a Tethered Balloon System for Vertical Profile Measurements of Meteorological Parameters and PM2.5", which provided relevant methodological insights used in comparing LiDAR and radiosonde data.

All authors reviewed and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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