Development of a Mathematical Model for the Determination of the Atmospheric Boundary Layer Height Using Artificial Intelligence

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Abstract

The Atmospheric Boundary Layer Height (ABLH) is critical for meteorological applications and climate change studies. While numerous methods exist for ABLH determination, none are both reliable and feasible. This study develops an AI-based model for ABLH determination, employing machine learning techniques. Various methods including the mountain method and clustering algorithms are explored, along with different similarity functions. The unsupervised mountain method with Manhattan similarity emerges as the most practical, requiring no ABLH reference and offering reduced computation time. Evaluation metrics, including root mean square error, support the effectiveness of the proposed method across different atmospheric conditions.

Keywords: Atmospheric Boundary Layer Height, Unsupervised Learning, Mountain Clustering, Artificial Intelligence, Radiosonde, LIDAR.

Introduction

Background:

- The atmospheric boundary layer (ABL) is crucial for air quality dynamics, hosting a significant portion of atmospheric mass, including aerosols. [1]
- Accurate determination of the atmospheric boundary layer height (ABLH) is essential for emission control and air quality forecasting.[2]
- Challenges arise in ABLH determination under complex atmospheric conditions, such as multiple aerosol layers or cloud presence, impacting large-scale models like WRF and LOTOS-EUROS [3, 4].

Purpose:

- Enhance understanding of air quality dynamics in the Aburrá Valley through the Medellín Air Quality Initiative (MAUI).
- Improve models like WRF and LOTOS-EUROS using local data and insights gained from MAUI.
- Develop intelligent methodologies, leveraging insights into backscattering phenomena, to refine physical-mathematical models.

Hypothesis:

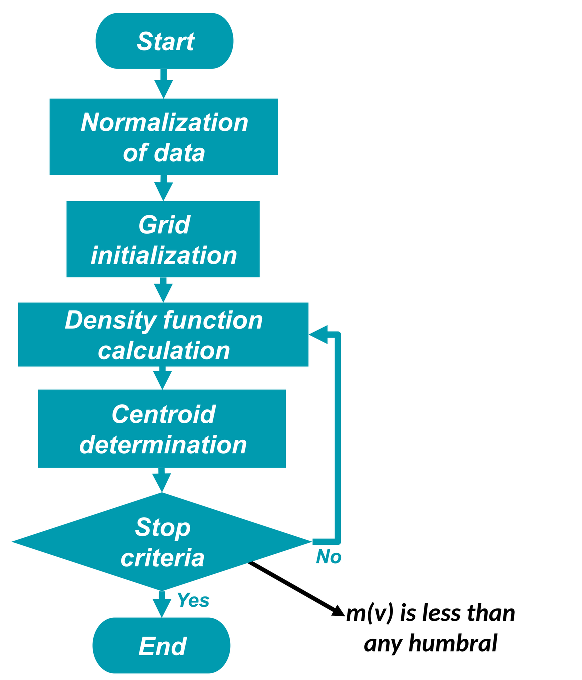
- Mathematical methods can enhance the precision of ABLH determination from LIDAR signals, reducing uncertainties in air quality assessments.
- Integration of advanced instrumentation, such as the 4DAir LIDAR system, within the MAUI project framework can mitigate uncertainties in ABLH determination.
- Through intelligent methodologies and advanced instrumentation, MAUI can contribute to more accurate air quality assessments and forecasting in the Aburrá Valley region.

Materials and Methods

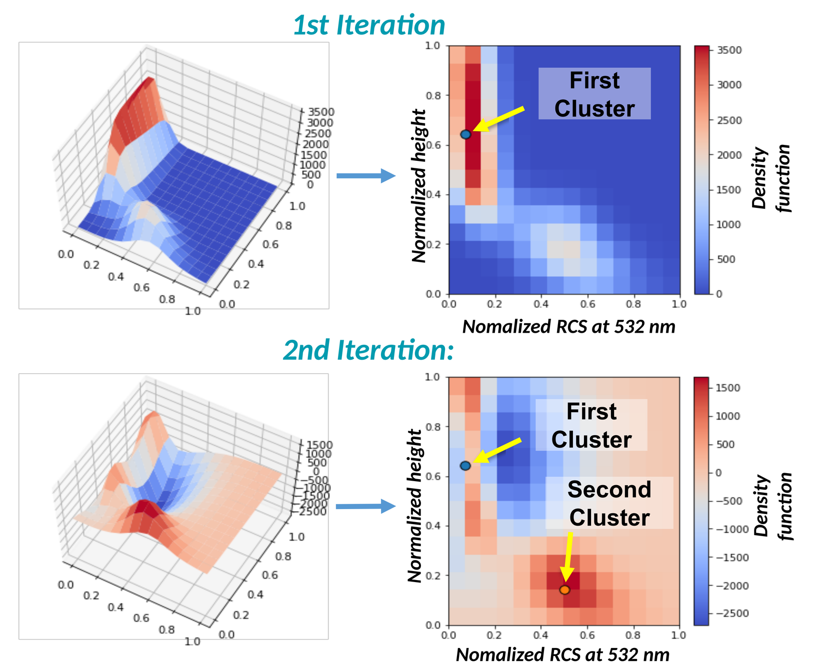
1. Exploratory Dataset [5]:
   - Dataset from MiniMPL LIDAR in Brest on February 24, 2018.
   - 288 profiles with 5-minute temporal and 30-meter spatial resolution.
   - Measurement height ranges from 100 to 2500 meters.
   - Two input variables: standardized corrected range signal at 532 nm and altitude.
2. Generalization Dataset [5]:
   - Dataset from MiniMPL LIDAR in Brest from July 12 to December 31, 2018.
   - 83 days with 288 profiles each.
   - Two input variables: attenuated backscatter coefficient at 532 nm and altitude.
   - Reference ABLH determined using radiosonde profiles.

Mountain Method: A simple approach to identify cluster centers based on a density measure called the mountain function. It involves creating a grid on an n-dimensional hypercube, where the vertices represent potential cluster centers. A mountain function is then constructed to quantify data density at each vertex. Cluster centers are selected by sequentially modifying the mountain function until a stopping criterion is met. This method is suitable for low-dimensional problem spaces.

$$m(\mathbf{v}) = \sum_{i=1}^{N} \exp\left(-\frac{\|\mathbf{v}-\mathbf{x}_i\|^2}{2\sigma^2}\right) \qquad \mathbf{c}_j = (D_i(\mathbf{x}_i)), \qquad m_{\text{new}}(\mathbf{v}) = m(\mathbf{v}) - m(\mathbf{c}_j)\exp\left(-\frac{\|\mathbf{v}-\mathbf{c}_i\|^2}{2\beta^2}\right)$$



(a) Logical process of the Mountain Method.



(b) Density function for the iterative cluster determination.

Figure 1. Mountain Method.

Results

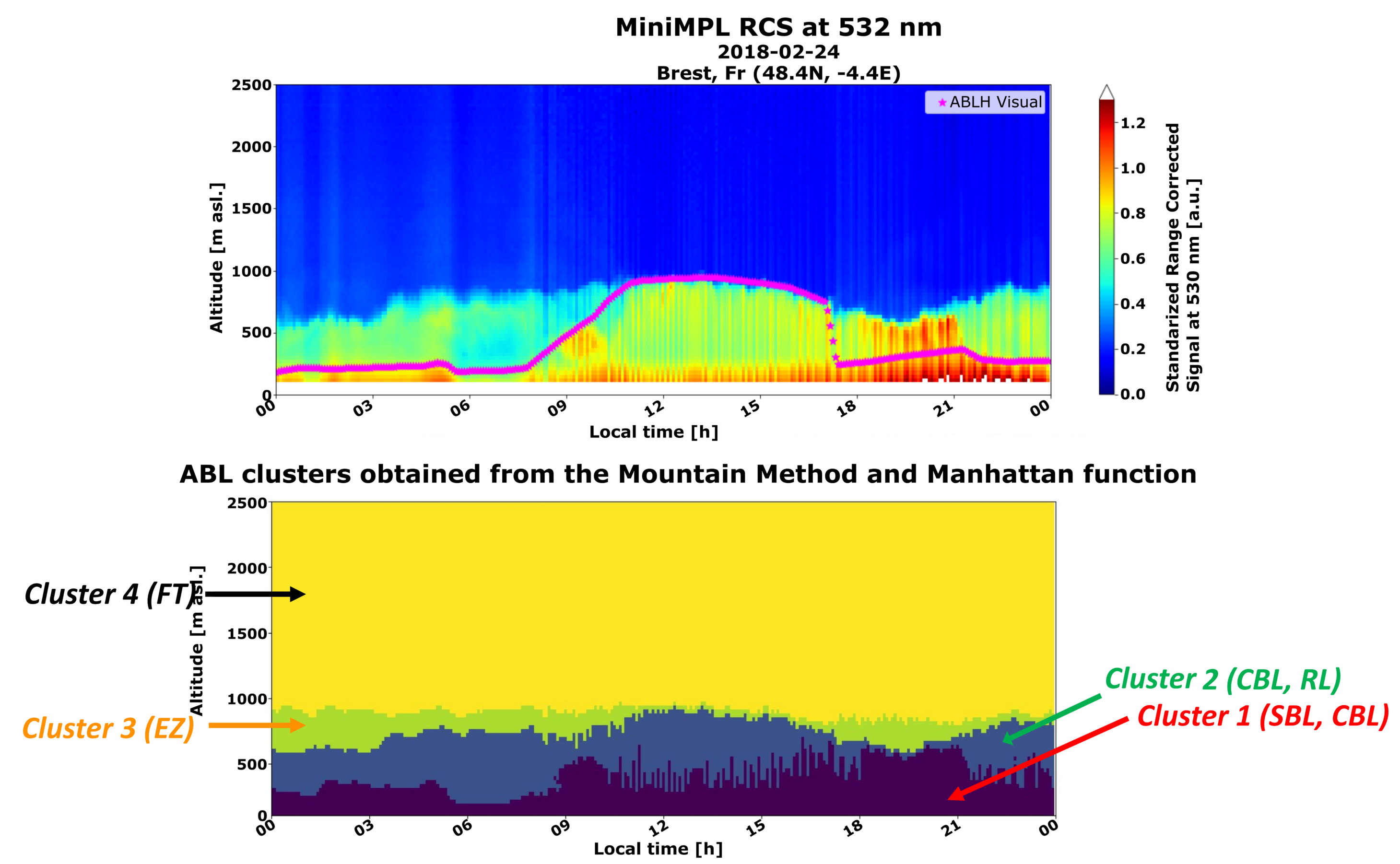


Figure 2. Clusters determined with the Mountain Method for a clear day.

Validation: Quantitative analysis shows the mountain method underestimating ABLH due to complex atmospheric conditions, with an RMSE of 55.42% and 500m. The method lacks information in regions where radiosonde measurements are below the LIDAR system's height overlap (213m).

Discussion

Evaluation: Despite cloud cover complexities, qualitative analysis indicates stable performance. The method accurately determines ABLH heights under various atmospheric conditions. However, it struggles with cloud presence, leading to errors.

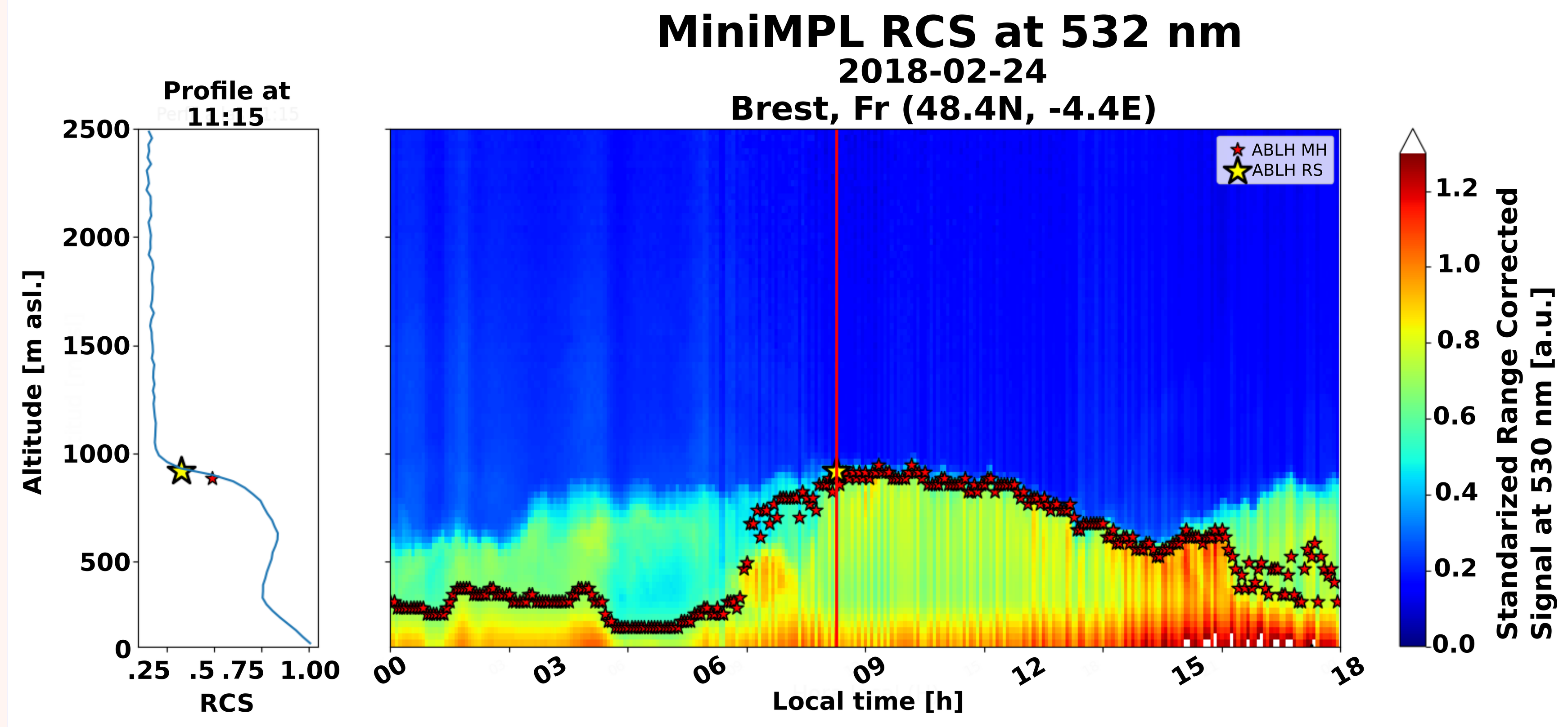


Figure 3. Result of the implementation of the Mountain Method with Radiosonde reference.

Conclusion

- The mountain method, a non-stochastic approach, proves to be a robust and consistent technique for determining the Atmospheric Boundary Layer Height (ABLH) from LIDAR data.
- Multiple layer detection for more complex segmentation of the ABL, into stable boundary layer (SBL), convective boundary layer (CBL), enhancement zone (EZ) and free troposphere (FT).
- Its reliability and versatility make it a promising tool for ABL studies, regardless of atmospheric complexity.
- Future research should focus on optimizing key parameters of the method for particular applications (as MAUI Project).

References

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