TRAMP Nocturnal Mixing from Micropulse LIDAR Measurements (TNMPL)
Final Report

A Report to the Texas Environmental Research Consortium

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Executive Summary

The primary goals of the TRAMP Nocturnal Mixing from Micropulse LIDAR Measurements **(***TNMPL) project were to continuously determine the depth of the planetary boundary layer (PBL) and infer the degree of mixing in the nocturnal urban boundary layer and how this impacts the sources and sinks for radicals in the urban atmosphere of Houston during the TexAQS II study.*

In order to address this research need, we deployed a ground-based scanning micropulse lidar (MPL) at the UH-Moody Tower during the TexAQS II intensive throughout September 2006. The PBL would be measured vertically above the lidar and along a single vertical plane between Moody Tower and downtown Houston. The choice of this scanning plane provides for co-located measurements with the Differential Optical Absorption Spectrometer (DOAS). The observations from these lidar measurements shall be available to all participants of the 2006 campaign, including the air quality modelers who need to validate urban boundary layer heights which are known to be a critical parameter for many components of their modeling. It would also serve the scientific interests of a number of TRAMP investigators, including those who are investigating nocturnal mixing and the role of this process on nighttime chemistry.

Four separate activities were proposed for TNMPL:

- Supervision of implementation of the necessary infrastructure at the Moody Towers
- Coordination of the scanning MPL measurement activities at Moody Tower
- Coordination of working groups to exploit and interpret lidar data sets obtained at the Moody Tower,
- Contribution to publications in peer reviewed journals

However, only the first two of these activities which pertained to the actual deployment received funding. The scanning Micropulse lidar was deployed in a trailer on the roof of Moody Tower collocated with the DOAS approximately 60 meters AGL. The MPL scanning assembly was programmed to repeatedly execute a measurement cycle of approximately 20 minutes length consisting of twenty-two fixed angles from vertical to horizontal with emphasis on small elevation angles for compatibility with the DOAS light paths. The micropulse lidar was operational for greater than 95% of the time from Sept. 1 through Sept. 29.

We have retrieved PBL depth using the vertical profile data, day and night, for essentially the entire time period except when the lidar was strongly attenuated by low cloud or precipitation. This data is provided as ASCII data files and also as daily images of lidar profiles with an estimate of the PBL indicated graphically. Because funding has not yet been provided for analysis, the PBL depths reported here are considered preliminary and have not been fully validated. The results show the expected diurnal variation with boundary layer growth beginning near sun-rise. We see day-time maximum PBL heights generally up to 3 km, but sometimes (especially in overcast conditions) we observe suppressed conditions with PBL depth not exceeding 500 meters. As the boundary layer descends after sunset it can be difficult to unambiguously distinguish residual aerosol

from the nighttime PBL. Nevertheless, our preliminary results show nocturnal PBL to be quite low, sometimes less than 100 meters.   Slant profiles will improve this determination. The slant-path retrieval promises much finer vertical resolution which is important for the very low nocturnal mixing depths, but also requires specialized treatment to properly account for horizontal aerosol gradients between the tower and the Houston downtown area.

In general, we have found the Houston area to exhibit highly variable aerosol concentrations with complex vertical and horizontal structure. For example, we indicate relatively clean free troposphere and reduced aerosol vertical structure associated with marine air masses from Sept. 16-18 and 23-24. In contrast, on most other days we show significant residual aerosol both throughout and above the boundary layer. Frequently residual aerosol is present in distinct layers having high spatial coherence suggestive of recirculation of local emissions rather than long range transport.

Preliminary Analysis and Data Description:

We have determined instrument corrections applicable to the instrument throughout the time period. These corrections are described in reference 1 below. After application of the instrument corrections, the lidar profiles were analyzed to determine PBL depth. The PBL typically has higher concentrations of aerosols compared to the free troposphere and such that lidar backscatter profiles typically exhibit a significant negative gradient at the PBL top. Several previous studies have used wavelet correlation transform techniques to identify boundary layer top from vertical lidar profiles (references 2-5). However, Brooks (reference 6) notes that these approaches are subject to bias stemming from signal gradients either above or below the boundary layer. While Brooks has demonstrated an alternate technique for marine boundary layers to account for such gradients, the applicability of this technique has not been demonstrated under complex atmospheric conditions common in Houston due to both urban and coastal interactions. The residual layers and elevated aerosol layers apparent in Figure 1 exemplify the presence of vertical gradients above the boundary layer as described by Brooks.

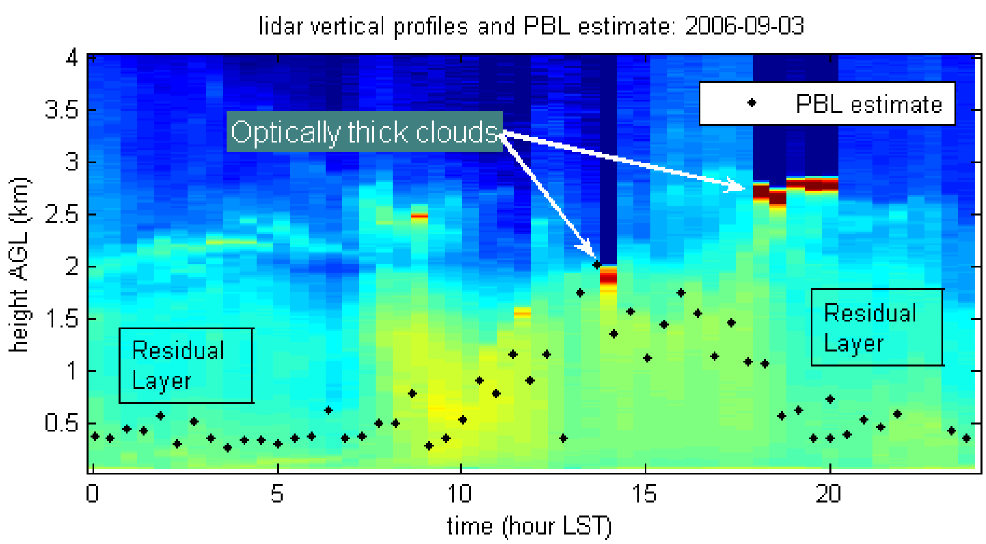

Figure 1. PBL detected via wavelet covariance transform

As evident from figure 1, this wavelet approach shows some skill in identifying the PBL, but requires further refinement and validation under these challenging conditions. In the interim we have estimated PBL through visual examination of the lidar profiles. All days of deployment have been manually processed to yield PBL height versus time in LST hours. The results are provided as ASCII data and image files contained within the file “TNMPL_PBL.v1.zip” which is provided as a support file for this document.

The ASCII files contain comma-separated columns in the following format:

```
yyyy, mm, dd, HH_LST, PBL_km
2006, 9, 3, 0.0623, 0.05662
2006, 9, 3, 0.3115, 0.05662
…
```

Images similar to figure 1 have been generated showing time-series of vertical lidar profiles along with the PBL estimates. The image files are “portable network graphics” (PNG) format.

In addition, daily images have been generated displaying lidar profiles corresponding to each discrete mirror angle. Examination of these images permits identification of Houston metropolis signatures (abrupt decrease in lidar signal beyond 5-6 km), detection of point sources, and qualitative evaluation of homogeneity or stability. These images have been provided to TERC/HARC as part of this project.

Conclusions and recommendations:

As noted previously, while the wavelet technique has demonstrated skill for boundary layer detection under relatively uniform marine conditions, the Houston environment is temporally, vertically, and horizontally complex. In order to provide continuous high-quality measurements of PBL, it is important to validate this remote sensing technique against direct measurements. The following extensions of the current work would provide this validation, and would also yield improvements to the technique directly applicable to the nocturnal case:

- Compare to PBL derived from UH sonde profiles (Rappenglück)
- Refine / automate wavelet algorithm to use variable dilation scheme
    - Reduces sensitivity to non-zero gradients above and below the PBL top
    - Quantitative determination of transition zone between BL and free atm.
- Extend algorithm to slant-path profiles
    - Finer resolution more appropriate to nocturnal PBL depth
    - Explore heat-island / urban influence on PBL
    - Identify spatial inhomogeneities, aerosol point sources along scan path.

In addition to determination of the PBL depth, a key focus of TNMPL is to assess the impact of the PBL depth and the nocturnal mixing on the sources and sinks for radicals in the urban atmosphere of Houston. In this respect, aerosol extinction profiles retrieved from calibrated lidar measurements have the potential to improve the interpretation of the long-path integrated column DOAS observations. The following actions would be required to retrieve aerosol extinction profiles from the lidar measurements, and utilize them with the DOAS measurements:

- Address temperature-related collimation issues
- Calibrate lidar using independent AOD measurement (Lefer) or versus in-situ aerosol optical measurements of scattering/backscattering coefficients (Atkinson))

- Use backward Klett lidar retrieval of aerosol extinction profiles (Flynn)
- Use aerosol extinction profiles in forward radiative transfer model to improve DOAS molecular species retrievals

There are also significant benefits to be gained by integrating the lidar profiles with meteorology, especially wind measurements from sondes or other wind profilers.

- Detect low level nocturnal jets
- Back trajectory analysis to identify potential sources of elevated aerosol regions.
- Investigate impact of on-shore/off-shore coastal air patterns
- Categorize local airmass according to wind direction to characterize as marine or regional continental background.

References:

1. Full-time, Eye-Safe Cloud and Aerosol Lidar Observation at Atmospheric Radiation Measurement Program Sites: Instrument and Data Processing. JR Campbell, DL Hlavka, EJ Welton, CJ Flynn, DD Turner, JD Spinhirne, VS Scott, IH Hwang, J. Atmos. Oceanic Technol., 19, 431-442, 2002.
2. Davis, K. J., D. H. Lenschow, S. P. Oncley, C. Kiemle, G. Ehret, and A. Giez, 1997: Role of entrainment in surface–atmosphere interactions over a boreal forest. *J. Geophys. Res.*, **102,** 29 219–29 230.
3. Russell, L. M., D. H. Lenschow, K. K. Laursen, P. B. Krummel, S. T. Siems, A. R. Bandy, D. C. Thompson, and T. S. Yates, 1998: Bidirectional mixing in an ACE 1 marine boundary layer overlain by a second turbulent layer. *J. Geophys. Res.*, **103,** 16 411– 16 432.
4. Cohn, S. A., and W. M. Angevine, 2000: Boundary-layer height and entrainment zone thickness measured by lidars and wind profiling radars. *J. Appl. Meteor.*, **39,** 1233–1247.
5. Davis et. al, 2000: An Objective Method for Deriving Atmospheric Structure from Airborne Lidar Observation. *Journal of Atmospheric and Oceanic Technology* **17**, 1455-1468.
6. Brooks, 2003: Finding Boundary Layer Top: Application of Wavelet Covariance Transform to Lidar Backscatter Profiles. *Journal of Atmospheric and Oceanic Technology* **20**, 1092-1105.

Preliminary Data Deliverable:

ASCII and image files of preliminary PBL estimates have been provided to TERC/HARC as part of this project.