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Lower Atmospheric Boundary Layer Experiment (LABLE) Final Campaign Report

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DISCLAIMER

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Executive Summary

The Lower Atmospheric Boundary Layer Experiment (LABLE) included two measurement campaigns conducted at the Atmospheric Radiation Measurement (ARM) Southern Great Plains site in Oklahoma during 2012 and 2013. LABLE was designed as a multi-phase, low-cost collaboration among the University of Oklahoma, the National Severe Storms Laboratory, Lawrence Livermore National Laboratory, and the ARM program. A unique aspect was the role of graduate students in LABLE. They served as principal investigators and took the lead in designing and conducting experiments using different sampling strategies to best resolve boundary-layer phenomena.

A variety of novel atmospheric profiling techniques were used to study turbulent phenomena in the lowest 2 km of the atmosphere over heterogeneous terrain. During both campaign periods, several instruments from the University of Oklahoma and Lawrence Livermore National Laboratory were deployed at the ARM Southern Great Plains site. The collected observations were analyzed together with selected data sets from the observational ARM *in situ* and remote sensing instruments. The available instruments overall complement each other with respect to resolution and height coverage, and the data provide a near-complete picture of the dynamic and thermodynamic structure of the atmospheric boundary layer.

The campaigns have provided new insights about the structure of the nocturnal boundary layer and the development of low-level jets, the interaction of low-level jets with mesoscale disturbances such as frontal boundaries, and the spatial variability of turbulence parameters in the atmospheric boundary layer. An overview paper describing the LABLE experiment in detail has been submitted and conditionally accepted (pending minor revisions) for publication in the *Bulletin of the American Meteorological Society*. Additional journal articles are being prepared, including one article that focuses on a dust storm that occurred during the 2012 campaign. Two Ph.D. dissertations based on LABLE observations are expected to be finished in Spring 2015 and an M.S. thesis was defended in summer 2014.

Acronyms and Abbreviations

AERI	Atmospheric Emitted Radiance Interferometer
ARM	Atmospheric Radiation Measurement
BLISS	Boundary Layer Integrated Sensing and Simulation
CBL	convective boundary layer
DL	Doppler lidar
LABLE	Lower Atmospheric Boundary Layer Experiment
LLJ	low-level jet
LLNL	Lawrence Livermore National Laboratory
MODIS	Moderate Resolution Imaging Spectrometer
NSSL	National Severe Storms Laboratory
OU	University of Oklahoma
SBL	stable boundary layer
SGP	Southern Great Plains
UTC	Coordinated Universal Time

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1.0 Background

Graduate students and professors in the Boundary Layer Integrated Sensing and Simulation (BLISS) group within the School of Meteorology at the University of Oklahoma (OU), together with scientists from the National Oceanic and Atmospheric Administration National Severe Storms Laboratory (NSSL) and the Lawrence Livermore National Laboratories (LLNL), conducted the first Lower Atmospheric Boundary Layer Experiment (LABLE) campaign from September 18 to November 13, 2012. The second LABLE campaign took place from June 12 to July 3, 2013. The key instruments deployed and used for the LABLE campaigns are listed in Table 1.

Table 1. Key Instruments for LABLE.

ARM Instruments		Guest Instruments	
1.	Doppler lidar (Halo Streamline)	1.	OU Doppler lidar (Halo Streamline, LABLE I & II)
2.	915 MHz radar wind profiler	2	Leosphere Windcube 200 Doppler lidar (on loan from Leosphere for LABLE I)
3.	Raman lidar	3.	OU Metek Sodar (LABLE I)
4.	Sonic anemometers on 60-m tower	4.	Galion Doppler lidar (rented for LABLE II)
5.	Sonic anemometer on 2-m tower	5	Leosphere Windcube v2 profiling Doppler lidar (deployed by LLNL during LABLE II)
6.	AERI		
7.	Radiosondes		
AERI = Atmospheric Emitted Radiance Interferometer LABLE = Atmospheric Boundary Layer Experiment LLNL = Lawrence Livermore National Laboratory OU = Oklahoma University			

LABLE was conducted at the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site, located in north-central Oklahoma. All LABLE instruments were deployed at the SGP central facility near Lamont (36.606°N, 97.485°W). The SGP site boasts a wide range of *in situ* and remote sensing instrumentation (Mather and Voyles 2013), and its central facility site is one of the most heavily instrumented atmospheric research sites in the world. Since the SGP site is approximately two hours north of the OU campus and easily accessible, the ARM site was a natural location for LABLE. During LABLE I, OU and NSSL deployed four additional instruments (a Halo Streamline scanning Doppler lidar, a Leosphere Windcube 200 vertically pointing lidar, a Metek sodar, and a Scintec SLS 20 scintillometer) that complemented the ARM instruments. During LABLE II, two scanning Doppler lidars (Halo Streamline and Galion) and one profiling lidar (Leosphere Windcube v2) were deployed.

The LABLE experiments had four primary scientific objectives:

- compare observations of mean and turbulent motions from Doppler wind lidars and sodars, and to characterize their mean accuracy and sensitivity over a range of different environmental conditions (e.g., convective boundary layer [CBL] vs. stable boundary layer [SBL], high vs. low wind speed conditions)

- assess the accuracy and reliability of temperature profiles retrieved from radiance observations made by the Atmospheric Emitted Radiance Interferometer (AERI) using the new *AERIoe* retrieval algorithm
- obtain a better understanding of the structure and turbulent processes within the nocturnal boundary layer (NBL) and their interaction with larger-scale weather patterns
- investigate how turbulent statistics, such as variance and skewness profiles of vertical motions vary with upwind land-surface conditions.

Another unique objective of LABLE was to provide experience for graduate students in observational atmospheric boundary layer (ABL) studies covering all aspects from the design of a field campaign to the scientific analysis of the collected data sets. Three OU graduate students, Tim Bonin, Jennifer Newman, and Charlotte Wainwright, were involved in all phases of the experiment and played a leading role in the siting, deployment and operation of the instruments as well as in data quality control, processing, and analysis. Three additional OU graduate students, Eric Jacobsen, Nathan Anderson, and Greg Blumberg, and a post-doctoral candidate Subhashree Mishra assisted in the deployment and data analysis.

A detailed description of the instrument setup, lidar scanning strategies and analysis procedures, and examples of first results addressing the first three objectives listed in the previous paragraph are included in a paper that is expected to appear in the *Bulletin of the American Meteorological Society* (Klein et al. 2014). This paper also documents the routine observations from the ARM site that are important for the LABLE objectives.

2.0 Notable Events or Highlights

One of the many interesting meteorological phenomena that occurred during LABLE was an intense dust storm on October 18, 2012. The MODIS true-color image collected at 18:15 Coordinated Universal Time (UTC) shows the dust plume stretching from southwestern Nebraska to north-central Oklahoma. This storm had surface wind speeds of over 20 m s^{-1} (50 miles per hour), resulting in visibility as low as 3 m. This storm led to numerous accidents involving 27 vehicles along Interstate Highway 35, which links Oklahoma City to Kansas City. Ultimately this highway was closed for several hours until the storm abated. A paper summarizing this event is being prepared (Mishra et al. 2014).

A dynamically distinctive event occurred over central Oklahoma on October 4, 2012 during LABLE I. A fast-moving atmospheric bore, which was generated by outflow from a convective event in northwestern Kansas, resulted in a large-amplitude wave packet that passed over the SGP site; this packet of waves persisted for over two hours with the amplitudes gradually decreasing with time. Bores are one of the mechanisms that can trigger elevated convection; this is one of the phenomena that will be studied intensely in the upcoming 2015 Plains Elevated Convection at Night (PECAN) experiment. While the environment was too dry for convection to be initiated in this event, two undergraduate students at the University of Oklahoma are analyzing the thermodynamic and kinematic structure of this event using Doppler lidar, AERI retrievals, and other datasets as their senior Capstone project to better understand how the ambient environment is modified by the passage of these events.

3.0 Lessons Learned

The campaign was very successful overall and the collected data sets provide the basis for two Ph.D. dissertations and an M.S. thesis. Several journal articles are being prepared for submission.

The combined analysis of high-resolution Doppler-lidar wind profiles and AERI temperature profiles has been proven to be very useful for studying the diurnal evolution of the ABL.

During LABLE II, there were testing-synchronized scanning strategies with three Doppler lidars of similar design (two Halo Streamline and one Galion lidar). Synchronizing these scans proved to be a challenge. In the future, such studies should be much easier, as Halo is developing new software that will enable the user to control the scans of multiple lidars from one central unit.

The scintillometer, a Scintec SLS20 (Scintec 2006), experienced technical problems during LABLE I. Only a limited data set was collected and the data will require intensive post processing before they can be used for scientific analysis. Therefore, the observations from this instrument were not submitted to the ARM archive.

4.0 Results

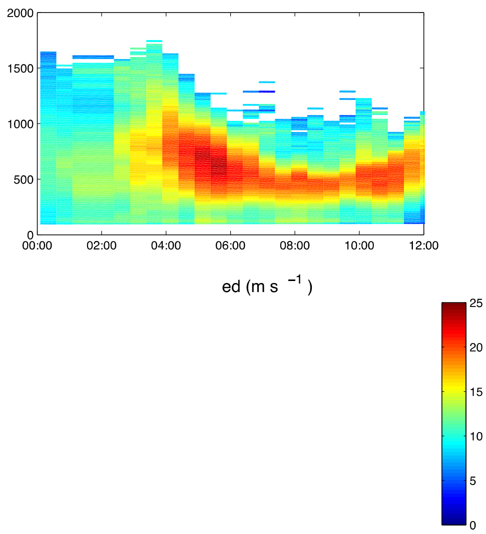
There was generally found good agreement between mean wind speeds and directions measured by *in situ* sensors on the ARM tower, the OU sodar, and Doppler lidars, which allow us to aggregate data from different instruments into profiles that capture the atmospheric boundary layer structure in the lowest 2-3 km at high resolution (Klein et al. 2014).

The *AERIoe* retrievals (Turner and Löhnert 2014) accurately capture the near-surface temperature gradients, i.e., the thermodynamic structure of the surface layer can be studied at high temporal resolution (Klein et al. 2014).

The LABLE data sets provide new insights about the evolution of nocturnal low-level jets (LLJs), which are a prominent feature of the boundary layer at night in the SGP. During the LABLE I campaign period, LLJs with peak winds of at least 10 m s^{-1} were observed on 20 nights. An example is shown in Figure 1. The LLJs typically developed shortly after sunset and dissipated in the early morning hours. However, the exact onset and dissipation time of the LLJs varied greatly on each individual night, often depending on synoptic conditions (Klein et al. 2014, Bonin et al. 2014).

The Doppler lidar and *AERIoe* profile observations provide new insights into the interplay between the dynamic, thermodynamic, and turbulence structure in the nocturnal boundary layer. The time of LLJ onset appears to play a critical role in the decay or persistence of turbulent mixing after sunset (Klein et al. 2014).

The LABLE observations allow us to systematically evaluate the skill of Doppler lidars in measuring turbulence statistics, which is important for a number of applications such as wind resource assessments and air quality studies (Newman et al. 2014, 2013).



c)

Figure 1. The evolution of the horizontal wind speed (a,c,e) and vertical velocity variance profiles (b,d,f) from the OU Doppler Lidar (DL) (a,b), the ARM DL (c,d), and sonic anemometers installed on a 60-m tower (e,f) on the morning of 17 October 2012. In panels (e) and (f), the blue, red, and black lines indicate values at 4-m, 25-m, and 60-m above ground level, respectively.

Doppler lidar vertical motion data (from both the Leosphere Windcube 200 and OU Halo systems, examples shown in Figure 2) and water vapor mixing ratio from the Raman lidar from LABLE-1 are being used to demonstrate that these systems have the ability to measure water vapor fluxes over the SGP site, which is the first time this has been demonstrated with ground-based Raman and Doppler lidars (Wulfmeyer et al. 2014).

To investigate how the inhomogeneous surface conditions around the SGP site affect the boundary layer, Nathan Anderson, a graduate student at OU, analyzed how the vertical velocity variance and skewness profiles observed by two Doppler lidars that were separated by 300 m changed as a function of wind speed and direction, surface fluxes, and other variables (Anderson 2014).

In summary, the LABLE campaigns provided invaluable data sets for multiple student projects and it is we expected several additional journal articles to be published in the near future. Work is also under way to quantify the water vapor flux at the top of the CBL over a range of conditions. Future work will also focus on additional case studies of cold fronts and gravity waves, incorporating data from ARM's K-, X-, and C-band radars, which provide valuable scans over the site to potentially complement observations.

Data from both LABLE I and LABLE II have been uploaded to the intensive operational period (IOP) portion of the ARM data archive.

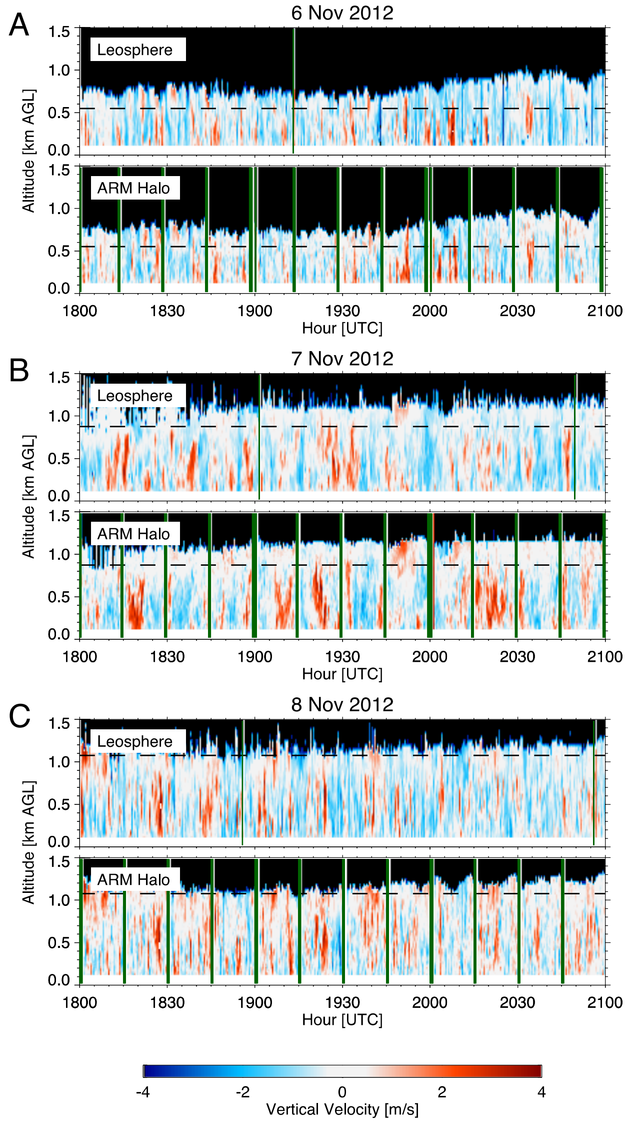


Figure 2. Time-height cross-sections of vertical velocity measured by the Leosphere (top) and ARM DLs (bottom), which were located 300-m apart, during the afternoons of November 6, 7, and 8 2012 (panels A, B, and C, respectively). The horizontal dashed line indicates the height of the convective mixed layer, as determined from the radiosonde launched at 1730 UTC on each day.

5.0 Public Outreach

For the 2013 campaign we rented a Doppler lidar from Sgurr Energy. Sgurr Energy described the use of the instrument in the campaign in its press release published February 12, 2014 http://www.sgurrenergy.com/sgurrenergys-galion-lidar-used-in-wind-turbulence-measurement-campaign/.

At OU, no specific campaign website was developed but the LABLE campaigns were described on the website of the BLISS group which can be found at oubliss.som.ou.edu.

During the 2012 LABLE campaign, OU undergraduate students participated in a field trip to the ARM SGP site as part of the class METR 3613 "Meteorological Measurements".

6.0 LABLE Publications

The LABLE observations formed the basis of a number of student presentations in a variety of conferences and meetings

6.1 Journal Articles and Manuscripts

The following papers are in press or in preparation. The targeted journals are included in the listing.

Klein PM, TA Bonin, JF Newman, DD Turner, PB Chilson, CE Wainwright, WG Blumberg, S Mishra, M Carney, EP Jacobsen, S Wharton, and RK Newsom. In press. "LABLE: A multi-institutional, student-led, atmospheric boundary-layer experiment." *Bulletin of the American Meteorological Society*.

Newman JF, TA Bonin, PM Klein, S Wharton, and PB Chilson. 2014. "Optimizing multi-lidar scanning strategies for wind energy turbulence measurements." Written, not submitted.

Mishra S, T Jones, and DD Turner. 2014. "An observational and model analysis of a dust storm over the Great Plains - I-35 on 18th October 2012." (The targeted journal is *Monthly Weather Review*.)

Wulfmeyer V, C Senff, S Pal, and DD Turner. 2014. "Can water vapor Raman and Doppler lidars measure latent heat flux profiles in the convective boundary layer?" (The targeted journal is *Boundary-Layer Meteorology*.)

6.2 Meeting Abstracts/Presentations/Posters

LABLE topics that were presented at meetings are listed below.

Newman JF, TA Bonin, P Klein, S Wharton, and PB. Chilson. 2014. "Optimizing lidar scanning strategies for wind energy turbulence measurements." Preprints, *21st Symposium on Boundary Layers and Turbulence*, Leeds, United Kingdom, Amer. Meteor. Soc., 17A.5, Oral presentation, June 12, 2014.

Bonin TA, PM Klein, PB Chilson, JF Newman, WG Blumberg, and DD Turner. 2014. "Analysis of turbulence and thermodynamics associated with low-level jets." *21st Symposium on Boundary Layers and Turbulence*, Leeds, United Kingdom, Amer. Meteor. Soc., 7B.4, Oral presentation, June 10, 2014.

Newman JF, TA Bonin, P Klein, S Wharton, and PB Chilson. 2013. "Optimizing lidar scanning strategies for wind energy measurements." Oral presentation at AGU Fall Meeting, San Francisco, California.

Klein P, J Newman, T Bonin, and S Wharton. 2013. “Lidar measurements of wind and turbulence for wind-energy applications.” Oral presentation on August. 7, 2013 at the North American Wind Energy Academy Symposium, Boulder, Colorado.

Turner DD, WG Blumberg, N Anderson, and A Dzambo. 2014. “Characterizing the structure of the boundary layer with the AERI and Doppler lidar.” Poster presented at the 2014 ASR PI Meeting, Potomac, Maryland.

6.3 Student Theses and Dissertations

The thesis that was based on the LABLE campaign is listed below.

Anderson N. 2014. *Vertical velocity turbulence profiles measured by two horizontally separated Doppler lidars*. Master’s Thesis, School of Meteorology, University of Oklahoma.

7.0 References

Mather JH and JW Voyles. 2013. “The ARM climate research facility.” *Bulletin of the American Meteorological Society*, 94: 377-392. doi:10.1175/BAMS-D-11-00218.1

Scintec AG. 2006. Scintec Surface Layer Scintillometer, User Manual, 100 pp.

Turner DD and U Löhnert. 2014. “Information content and uncertainties in thermodynamic profiles and liquid cloud properties retrieved from the ground-based Atmospheric Emitted Radiance Interferometer (AERI).” *Journal of Applied. Meteorology and Climatology*, 53(3):752-771. doi:10.1175/JAMC-D-13-0126.1

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