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Stable Boundary Layer Education (STABLE) Final Campaign Summary

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ARM CLIMATE RESEARCH FACILITY

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Executive Summary

The properties of, and the processes that occur in, the nocturnal stable boundary layer are not well understood, making it difficult to represent adequately in numerical models. The nocturnal boundary layer often is characterized by a temperature inversion and, in the Southern Great Plains region, a low-level jet. To advance our understanding of the nocturnal stable boundary layer, high temporal and vertical resolution data on the temperature and wind properties are needed, along with both large-eddy simulation and cloud-resolving modeling.

The Stable Boundary Layer Education (STABLE) campaign was designed to collect a set of data at the University of Oklahoma that could be used in these studies. The Meteorology Department at the University of Oklahoma has a Halo Streamline Doppler wind lidar; this lidar is able to scan in three-dimensions and thus provide profiles of horizontal winds, vertical motions, and other variables. The U.S. Department of Energy's Atmospheric Radiation Measurement program located an Atmospheric Emitted Radiance Interferometer (AERI) at the University of Oklahoma during this period. The AERI observes downwelling radiance, and these spectra can be inverted to provide profiles of temperature and humidity in the lowest 3 km of the atmosphere. Furthermore, the University of Oklahoma Meteorology Department has a small unmanned aerial system that is flown at irregular intervals over the campus to provide in situ measurements of temperature, humidity, and wind. The combination of regular high-temporal-resolution AERI thermodynamic profiles and Doppler lidar wind profiles, together with the in situ observations from the unmanned aerial system, provide an interesting data set for investigating a wide range of boundary-layer processes.

One key aspect of this project is to let undergraduate and graduate students drive the experiment. Graduate students in the Meteorology Department at the University of Oklahoma have developed new retrieval algorithms for the AERI data, devised new scanning strategies and analysis techniques for the Doppler lidar, and are flying the unmanned aerial system. The students have used the data sets to evaluate the accuracy of different boundary-layer parameterization schemes that are used within the Weather and Forecast Model. These instruments and data sets have played an important role in several undergraduate and graduate classes at the University of Oklahoma, in both lectures and individual research projects.

Acronyms and Abbreviations

AERI	Atmospheric Emitted Radiance Interferometer
ARM	Atmospheric Radiation Measurement
BLISS	Boundary Layer Sensing and Simulation (working group)
CIN	convective inhibition
NWS	National Weather Service
SGP	Southern Great Plains
STABLE	Stable Boundary Layer Education (campaign)
UTC	Coordinated Universal Time

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Figures

1.0 Background

The Stable Boundary Layer Education (STABLE) field campaign was conducted at the National Weather Center on the University of Oklahoma campus in Norman, Oklahoma, from November 1, 2011 until November 8, 2013. The experiment consisted of two primary instruments: 1) a Doppler lidar from the School of Meteorology at the University of Oklahoma and 2) an Atmospheric Emitted Radiance Interferometer (AERI) from the Atmospheric Radiation Measurement (ARM) program. The focus of the experiment was to provide the opportunity for undergraduate and graduate students to become more familiar with the AERI and Doppler lidar instruments, the data they collect, and how these data can be used to study the structure and evolution of the stable nocturnal boundary layer.

2.0 Notable Events or Highlights

Data collected during the STABLE campaign covered a wide range of atmospheric conditions, and because of its separation by nearly 160 km to the north, nicely complemented data collected at the ARM Southern Great Plains (SGP) site. Students at the University of Oklahoma used data collected from both the STABLE campaign and the SGP site to study the passage of cold fronts, the structure and evolution of undular bores, the development the nocturnal low-level jet, the evolution of the boundary layer during convective events, and an elevated heat-burst event.

Graduate students in the University of Oklahoma Boundary Layer Sensing and Simulation (BLISS) working group analyzed the passage of the bore above Norman, which was well captured by the AERI and Doppler lidar (Figure 1). The BLISS students demonstrated that these ground-based remote sensors were able to characterize the rapid evolution of the nocturnal boundary layer. This was an important finding for investigators developing the observational strategy for the Plains Elevated Convection at Night field campaign, and led to a proposal to deploy AERIs at each of the fixed Plains Elevated Convection at Night Integrated Sounding Array stations. Furthermore, it also illustrated that plan position indicator scans needed to be collected at much higher temporal resolution to resolve the possible waves in the wind field; this change was made and a new event was captured in August 2014. Two senior undergraduate students analyzed this new data set extensively; the results are being captured in a paper that is about to be submitted for publication (Toms et al. 2015).

The STABLE instruments captured data during another dramatic event that occurred on May 20, 2013: the F4/F5 tornado that devastated the city of Moore, Oklahoma, which is just 10 miles north of Norman. National Weather Service (NWS) forecasters have long desired high-temporal-resolution profiles of temperature and humidity in the boundary layer to monitor the evolution of the pre-convective and convective environment. The AERI is one possible technology that might be able to meet that need. Observations from the ARM-provided AERI in Norman provided a unique data set to study the evolution of the boundary layer in this tornadic storm. BLISS graduate students, as well as staff in the NWS Storm Prediction Center, have analyzed the storm's evolution using both the AERI-retrieved thermodynamic profiles and the convective indices that have been computed from these profiles (Figure 2). Conversations with the forecasters at the Storm Prediction Center suggested that a network of AERI instruments providing these thermodynamic profiles in real-time would be very valuable for the operational forecaster.

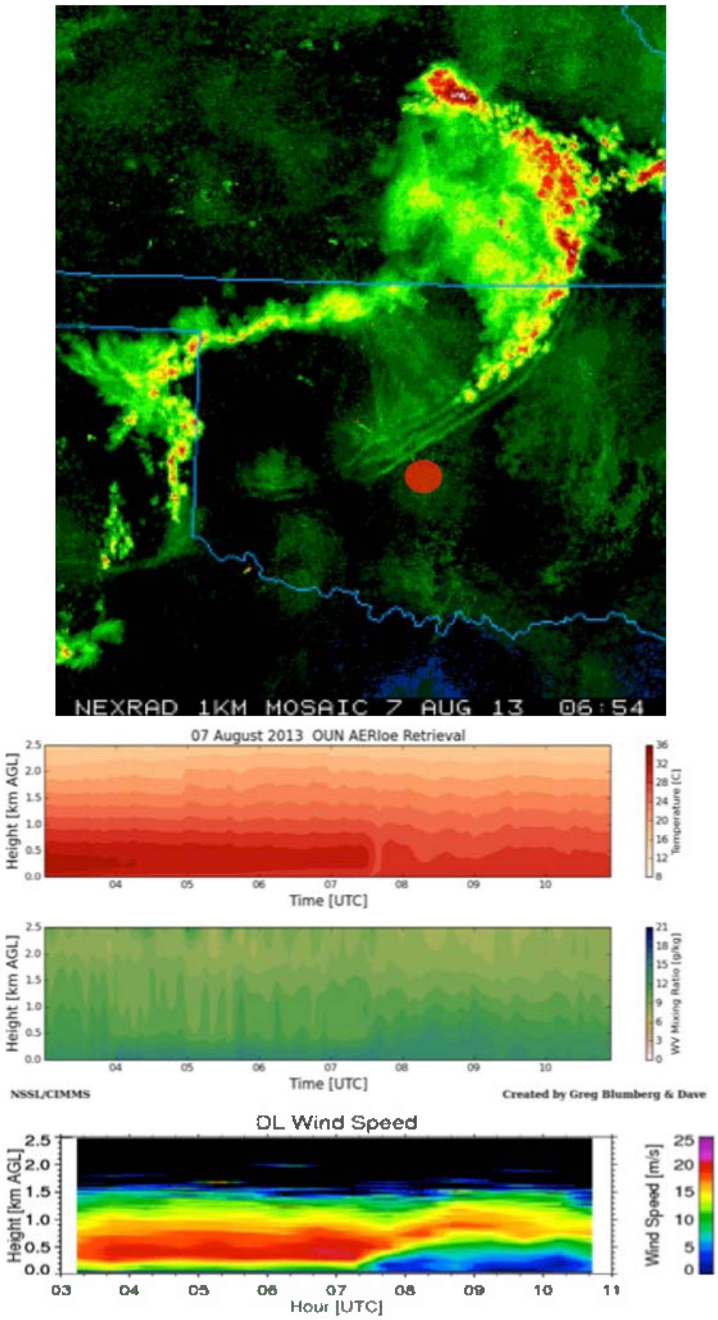

Figure 1. (top panel) Radar reflectivity mosaic from the NWS WSR-88D network on August 7, 2013, at 0654 Coordinated Universal Time (UTC) showing a propagating undular bore moving south-southeast that is just about to pass over Norman, Oklahoma (red dot). The bore was triggered by outflow from the convective system in north-central Oklahoma/south-central Kansas. The other panels show time-height cross sections of potential temperature, water vapor mixing ratio, and horizontal wind speed where the first two were retrieved from the AERI using the algorithm by developed by Turner and Löhnert (2014), and the last panel was derived using a velocity-azimuth display-analysis of plan position indicator scans at 60 degrees elevation that were collected every 15 minutes. The temperature data show the presence of a nocturnal inversion that corresponds with a low-level jet from 0300 to 0715 UTC. At approximately 0715 UTC, the first wave of the bore passes overhead, resulting in enhanced mixing in the lowest 1 km and an isothermal layer. The temperature data after the passage of the bore show a wave-like feature between 300 and 700 m above ground level, and there are hints of such structure in the Doppler lidar wind data. Note also that there are enhancements in the water-vapor field associated with the passage of each wave of the bore; these enhancements were associated with lifting, and cloud condensation occurred at the peak of each wave.

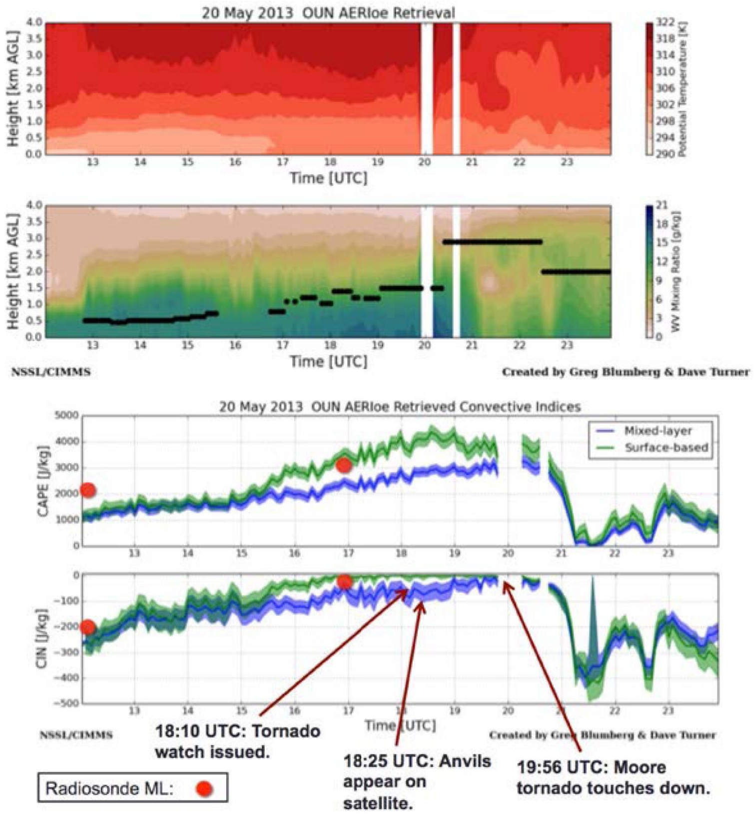

Figure 2. Time-height cross sections of potential temperature (derived from the temperature) and water vapor mixing ratio retrieved from the AERI located in Norman, Oklahoma, during the May 20, 2013, tornadic storm event. The bottom panels show the convective available potential energy and convective inhibition (CIN) that were derived from the AERI-retrieved profiles, as well as the values derived from two collocated radiosonde launches (red dots). Both the mixed-layer and surface-layer convective available potential energy and CIN values are shown. The water vapor image shows that there was a significant increase in low-level water vapor after 1800 UTC, which led to a rapid decrease in CIN. Note that the CIN went to zero right as the tornado touched down in Moore (which is about 15 miles north-northwest of where the AERI was located).

The AERI observations made during the STABLE campaign were very important for exposing undergraduate and graduate students at the University of Oklahoma to this new way to characterize the temperature and water-vapor structure (and hence stability) of the lower troposphere. The new insight gained by the students led to the development of the Lower Atmospheric Boundary Layer Experiments that were carried out at the ARM SGP site in 2012 and 2013 (Klein et al. 2015). These early observations also provided the motivation for the work by Tim Bonin, a recent Ph.D. graduate student at the University of Oklahoma and member of the BLISS team, who evaluated the role of stability classifications on the development of turbulence associated with the nocturnal low-level jet (Bonin et al. 2015).

3.0 Lessons Learned

One of the challenges with truly understanding the evolution of the stable nocturnal boundary layer is collecting representative observations that are not affected by local influences. For security reasons, and to allow easier access to the instruments for class tours, the Doppler lidar and AERI were installed on the roof of the National Weather Center building on the University of Oklahoma campus. While the data collected were certainly illustrative of what is possible from these instruments and show the promise of these data sets to help us advance our understanding of the evolution of the boundary layer, this location was suboptimal for observing low-level features in the nocturnal boundary layer.

4.0 Results

Results from the STABLE field campaign are discussed in Section 2.0.

5.0 Public Outreach

The STABLE campaign provided an excellent opportunity to familiarize operational forecasters in the NWS Norman Weather Forecast Office and staff at the Storm Prediction Center with the AERI instrument, and its capability to help characterize the atmosphere in rapidly evolving conditions. Furthermore, the instrument and the data it collects, as well as its complementary nature with other observations, was emphasized in both undergraduate- and graduate-level classes (e.g., METR 3613 Meteorological Measurement Systems and METR 5103 Boundary Layer Meteorology, respectively).

6.0 STABLE Publications

6.1 Journal Articles/Manuscripts

Blumberg, WG. 2013. "Developing a Statistical Thermodynamic Retrieval for Ground-Based Infrared Spectrometers." M.S. Thesis, School of Meteorology, University of Oklahoma. pp. 110.

Blumberg, WG, TJ Wagner, DD Turner, and J Correia. 2015. "Validation and use of AERI-retrieved thermodynamic profiles to characterize convective environments." *Weather and Forecasting*, in preparation.

Toms, B, J Tomaszewski, DD Turner, and SE Koch. 2015. "Analysis of a gravity wave train and its influence on the nocturnal boundary layer." *Weather and Forecasting*, in preparation.

Wulfmeyer, V, RM Hardesty, DD Turner, A Behrendt, M Cadeddu, P Di Girolamo, P Schluesel, J Van Baelen, and F Zus. 2015. "A review of the remote sensing of lower-tropospheric thermodynamic profiles and its indispensable role for the understanding and the simulation of water and energy cycles." *Reviews of Geophysics* 53(3): 819-895, doi:10.1002/2014RG000476.

6.2 Meeting Abstracts/Presentations/Posters

Blumberg, WG and DD Turner. 2014. "Benefits of Ground-Based AERI Retrievals in Operational Forecasting." International Geoscience and Remote Sensing Symposium (IGARSS) 2014, Quebec City, Canada.

Toms, B, J Tomaszewski, DD Turner, and SE Koch. 2015. "Analysis of a Gravity Wave Train and Its Influence on the Nocturnal Boundary Layer using Direct and Indirect Measurement Systems." To be presented at the 2016 AMS Annual Meeting, New Orleans, Louisiana.

Turner, DD. 2014. “A Future Ground-Based Network of Thermodynamic Boundary Layer Profilers: The Infrared Spectrometer Option.” National Weather Center Colloquium, Norman, Oklahoma.

Turner, DD and WG Blumberg. 2014. “A Future Ground-Based Network of Thermodynamic Boundary Layer Profilers: The Infrared Interferometer Option.” World Weather Open Science Conference, Montreal, Canada.

7.0 References

Bonin, TA, WG Blumberg, PM Klein, and PB Chilson. 2015. “Thermodynamic and turbulence Characteristics of the Southern Great Plains nocturnal boundary layer under differing turbulent regimes.” *Boundary-Layer Meteorology* 157: 401-420, doi:10.1007/s10546-015-0072-2.

Klein, PM, TA Bonin, JF Newman, DD Turner, PB Chilson, CE Wainwright, WG Blumberg, S Mishra, M Carney, EP Jacobsen, and RK Newsom. 2015. “LABLE: A multi-institutional, student-led, atmospheric boundary layer experiment.” *Bulletin of the American Meteorological Society*, doi:10.1175/BAMS-D-13-00267.1.

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

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