

# A NEW GENERATION OF GROUND-BASED MOBILE PLATFORMS FOR ACTIVE AND PASSIVE PROFILING OF THE BOUNDARY LAYER

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SPARC and CLAMPS provide high-temporal-resolution temperature, humidity, and wind profiles in the atmospheric boundary layer and are examples of possible nodes in a future observing network.

**M**uch of our current understanding of the atmosphere has been developed through intense observation, and nearly every facet of the field of atmospheric science has been shaped by the direct application of observations to real-world phenomena. A vast worldwide network of

meteorological instrumentation has been deployed to directly and indirectly sample the atmosphere on a variety of spatial and temporal scales. Operational forecasters use these observations to assess the current state of the atmosphere, while numerical weather prediction (NWP) models assimilate them to project the current state into the future. Surface meteorology stations, radiosondes, commercial aircraft, radars, satellites, ground-based remote sensing instruments, and other systems routinely provide millions of data points each day and have a return on investment that far exceeds their cost. However, the existing observation network is often insufficient to fully characterize phenomena of interest, especially in the atmospheric boundary layer, as the spatiotemporal resolution of the observations is too coarse (especially for vertical profiles) to capture many phenomena in detail. A promising solution is the increased proliferation of ground-based profilers. Collocation of a radiometric thermodynamic profiler with a Doppler wind lidar can produce profiles of temperature, humidity, and

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winds in the boundary layer just as a radiosonde would but at a far finer temporal resolution (albeit at a lower vertical resolution and with a shorter vertical range). The National Research Council, in a 2009 report, strongly advocated for an expanded network of ground-based profiling instruments to improve numerical weather prediction and operational forecasting (National Research Council 2009), while Hardesty et al. (2012) recommended a network of profilers to the National Science Foundation and the National Weather Service for operational and climatological purposes.

The benefits of profilers can be seen during field campaigns as well. Characterization of the atmospheric structure is key to most field campaigns (e.g., Wulfmeyer et al. 2015), and studies have often relied on frequent radiosonde launches to capture the temporal variability of the atmosphere during intensive observation periods (IOPs). The disadvantages of radiosondes are the same for field campaigns as they are operationally: high costs for individual observations, a finite and lengthy period to capture each profile resulting in low temporal density, horizontal drift, and significant labor required for each launch. An additional challenge for field use of radiosondes is radio frequency management: in many projects, balloons are launched at frequent intervals within a small spatial domain, and special care needs to be taken to ensure that all balloons are transmitting at different channels. These factors combine to put a practical limit on the temporal frequency at which launches can occur, and launches are usually spaced no less than one hour apart so that a balloon can profile a sufficient depth of the atmosphere while allowing enough time to prepare the subsequent sonde. Mobile remote sensing profiling facilities can alleviate these issues by providing detailed analyses of the evolution of the kinematic and thermodynamic structure and stability of the lower troposphere in close proximity to events of interest in near-real time. The integration of profiling systems into field campaigns augments the operational observing network with targeted, detailed observations analogous to how the Doppler on Wheels (DOW; Wurman et al. 1997) and Shared Mobile Atmospheric Research and Teaching (SMART; Biggerstaff et al. 2005) radars complement the operational Next Generation Weather Radar (NEXRAD) network during field campaigns.

Because of these advantages, numerous portable platforms that support ground-based profiling have been developed. Some, like the Atmospheric Radiation Measurement (ARM) mobile facilities (AMF; Miller et al. 2016), are designed for deployments that

can last for months at a time and require substantial time and effort to relocate. Others, like the Mobile Integrated Profiling System (MIPS; Karan and Knupp 2006), the Mobile Integrated Sounding System (MISS; Cohn et al. 2005), and the California State University Mobile Atmospheric Profiling System (CSU-MAPS; Clements and Oliphant 2014), are designed for rapid deployment that allows them to take observations adjacent to ephemeral phenomena like fires and severe storms.

Recently, the University of Wisconsin (UW)–Madison’s Space Science and Engineering Center (SSEC) joined with the University of Oklahoma (OU) and the National Severe Storms Laboratory (NSSL) with the goal of developing a set of facilities with common instrumentation and data processing and management routines so that joint deployments of ground-based profiling systems could easily be achieved. This resulted in the creation of the SSEC Portable Atmospheric Research Center (SPARC) and two separate versions of the Collaborative Lower Atmosphere Profiling System (CLAMPS), operated by OU and NSSL. SPARC and CLAMPS, photographs of which can be seen in Fig. 1, can be rapidly deployed to study emerging weather events but are also capable of unattended operation for weeks at a time so that longer-term datasets can be gathered. Data from SPARC and CLAMPS can be collected, processed, displayed, and uploaded in near-real time, and instrument output and diagnostics can be remotely monitored for data quality and continuity even if operators are not present. With a suite of instruments that performs best in the lowest 2–3 km of the atmosphere, SPARC and CLAMPS are ideally situated to capture small-scale evolution in the planetary boundary layer and lower levels of the free troposphere. This article serves as an introduction to SPARC and CLAMPS, outlining the various instruments that they carry and illustrating some of the contributions that they have already made to our understanding of atmospheric processes.

**INSTRUMENT PLATFORMS.** SPARC. SSEC has a long history of field deployments of ground-based atmospheric remote sensing instruments. While the original impetus for investing in mobile ground-based platforms was to calibrate and validate satellite observations, the utility of such a platform for a wide gamut of research projects was soon recognized. For two decades, SSEC operated the Atmospheric Emitted Radiance Interferometer (AERI) Winnebago (AERIbago), a motor home equipped with a suite of instrumentation for field experiments, but by 2013 the mechanical systems of the motor home were reaching

the end of their life-span and the decision was made to construct a new facility from the ground up. A truck-pulled trailer form was chosen to allow for enhanced operational flexibility and ease of repair. SPARC was first operational in July 2014.

SPARC can be powered by either a 60-A electrical connection (like those used by recreational vehicles) or an onboard propane-powered electrical generator. Onboard batteries can power the unit for approximately 20 min at full load and ensure that the instruments operate continuously while power sources or fuel tanks are being switched. Propane was chosen over diesel as the generator fuel source to prevent the production of black carbon, which could interfere with aerosol and other observations taken during air quality field experiments. A downside of the choice of propane over diesel is that more effort is required in the planning phase of field operations since the former can be purchased at any truck stop while the latter requires trips to less prevalent vendors of propane and propane accessories. SPARC can also be connected to a large external propane tank for longer deployments in a location without an electrical connection.

The interior of SPARC is approximately 20 m<sup>2</sup> (210 ft<sup>2</sup>), divided into an instrument laboratory (the instruments are described below) and an office that are separated from each other by a door. By separating the major instrumentation from the on-site scientists, instrument noise is confined and staff are free to work without disturbing the instrumentation. Each room has its own separately controlled heating and cooling system that allows the ideal ambient

temperature for both human comfort and instrument operation to be set independently. Electrically controlled jacks at each corner of the trailer allow it to be leveled even if deployed at a gently sloping location.

**CLAMPS.** The University of Oklahoma and NSSL have a long history of close-proximity observation of severe weather events with mobile radars and mobile mesonets (e.g., Biggerstaff et al. 2005; Straka et al. 1996), which have helped researchers understand many processes in mesoscale meteorology. Of course, the thermodynamics of the near-storm environment



**FIG. 1. (top) Exterior view of SPARC trailer as deployed during the Land Atmosphere Feedback Experiment (LAFE); (bottom) exterior view of CLAMPS-2 in deployed configuration.**

determine to a great degree storm mode and intensity, and Doppler radar and surface observations are ill-suited to measure temperature and moisture profiles. Therefore, to augment the existing mobile storm intercept facilities of NSSL and OU, a mobile boundary layer profiling platform was developed.

The CLAMPS units consist of a 4.9-m (16 ft)-long trailer towed by a pickup truck equipped with a ball hitch. Unlike SPARC, which was custom-designed for its duties, CLAMPS is based around an off-the-shelf trailer design that is modified to host its complement of instruments, and it was designed with efficiency and portability in mind. Smaller and lighter than SPARC, CLAMPS is more easily deployed in locations where space is at a premium and can be driven by someone with a regular driver's license as opposed to the commercial license required for a vehicle of SPARC's weight. Construction of the first unit, CLAMPS-1 [funded by a National Science Foundation (NSF) Major Research Instrumentation grant with support from OU and NSSL], was completed in May 2015, while a second, almost identical unit, CLAMPS-2 [funded by the National Oceanic and Atmospheric Administration (NOAA) as part of the Verification of the Origins of Rotation in Tornadoes Experiment–Southeast (VORTEX-SE) project] was completed in May 2016. This allows the CLAMPS units to participate in two projects simultaneously or provide multiple units to one project. The instruments, as well as an operator workspace, are located inside the CLAMPS trailers. For both units, power is provided by an onboard diesel generator, and they can also be connected to the power grid via an RV connector. The CLAMPS facilities are also outfitted to launch radiosondes and carry four helium tanks for this purpose.

**INSTRUMENTATION.** *Instruments common to SPARC and CLAMPS.* SPARC and CLAMPS were designed concurrently to be complements to each other; as such, they share a number of instruments in common. Furthermore, the processing software used to derive geophysical variables from the observations is also the same. This enables simple joint deployments of the facilities, as little effort is required to convert observations onto common spatial/temporal grids and one team can postprocess the data for the other facility with little additional effort above what needs to be done for their own system. Common data-handling routines and display systems can also be developed when instrumentation is shared.

**AERI.** AERI (Knuteson et al. 2004a,b) is a commercially available ground-based infrared Fourier transform

spectrometer that passively measures downwelling spectra over the spectral range of 550–3,500  $\text{cm}^{-1}$  (3.3–18.2  $\mu\text{m}$ ) with a temporal resolution of 30 s. The spectral resolution of these observations is better than 1  $\text{cm}^{-1}$ , which means that both atmospheric absorption bands and semitransparent windows are resolved in fine spectral detail; each spectral observation is absolutely calibrated to produce an accuracy better than 1% of the ambient radiance level. The spectral observations produced by AERI have been used in tasks as diverse as satellite calibration (e.g., Kataoka et al. 2014), radiative transfer model validation (e.g., Turner et al. 2004), retrieving cloud properties (e.g., Turner 2007; Mace et al. 1998), retrieving trace-gas concentrations (e.g., Yurganov et al. 2010), and direct observation of atmospheric radiation forcing at the surface (Feldman et al. 2015). A waterproof enclosure, automated precipitation-sensing hatch, and remote diagnostics and monitoring enable long-term unattended deployments in harsh environments, which have included locations as unique as tropical islands, transoceanic cargo ships, and polar ice caps. A short history of the AERI's development is given by Turner et al. (2016).

One of the key applications of the AERI instrument is the ability to retrieve quantitative information about the atmosphere from observed spectra. AERI has two key benefits over satellite-based sounding: first, a ground-based system has weighting functions that peak near the surface, which means that the region of the atmosphere with the greatest variability has the largest information content within a spectral observation, and second, satellite instruments must accommodate heterogeneous surfaces with varying emissivities while an upward-pointing instrument has a constant background.

The current AERI retrieval algorithm, named AERI Optimal Estimation (AERIOe; Turner and Löhnert 2014; Turner and Blumberg 2018), retrieves temperature and water vapor profiles as well as cloud properties and trace-gas concentrations by using the Line-by-Line Radiative Transfer Model (LBLRTM; Clough et al. 2005) as the forward model in an iterative optimal estimation retrieval (Rodgers 2000). AERIOe propagates the uncertainties from both the instrument and the forward model through the retrieval so that each quantity retrieved by AERIOe has a one-sigma error bar associated with it. The inclusion of cloud properties means that AERIOe can retrieve profiles up to cloud base, enabling observations that are much more temporally continuous than those from older retrieval algorithms. Since more than 90% of the AERI's information content



on temperature and humidity profiles is in the lowest 2 km (Turner and Löhnert 2014), AERI is primarily used to retrieve structure within and adjacent to the planetary boundary layer. When compared with collocated radiosonde profiles, AERI retrievals have a maximum root-mean-square difference in the lowest 2 km of the atmosphere of less than 1 K and  $0.8 \text{ g kg}^{-1}$  for temperature and water vapor mixing ratio, respectively (e.g., Blumberg et al. 2015; Wulfmeyer et al. 2015; Weckwerth et al. 2016). The retrievals are output onto a grid whose resolution increases exponentially with height, from 10 m adjacent to the surface to 300 m at 3 km AGL. The high-temporal-resolution thermodynamic profiles from AERI have been shown to have numerous applications for operational and research meteorology, including monitoring atmospheric stability during high impact weather (Feltz and Mecikalski 2002; Wagner et al. 2008), evaluating the structure of bores (Toms et al. 2017), and serving as an input into cloud property retrievals (Wagner et al. 2013).

**DOPPLER LIDAR.** The ability of pulsed active remote sensors to exploit the frequency shift of particles in motion to determine both range and velocities of meteorological scatterers along the line of sight has been known for well over a half-century (Barratt and Browne 1953), and today Doppler radars form an integral part of the operational observing network throughout the United States and beyond. Doppler lidars apply the same principle while using substantially shorter wavelengths: on the order of microns for Doppler lidars as opposed to 10 cm for the NEXRAD Weather Surveillance Radar-1988 Doppler (WSR-88D) radars used by the National Weather Service. Doppler lidars are therefore sensitive to very small scatterers like dust and other aerosols, which, unlike precipitation particles, have negligible fall speeds and are therefore useful as precise tracers of ambient air flows in the boundary layer where such scatterers are prevalent. Outside the boundary layer the aerosol concentration is much lower, which limits the effective range of the system to approximately 2 km (which can be further limited by low clouds, precipitation,

or fog). While this is generally less than the 4–6-km maximum range of 449- and 915-MHz radar wind profilers, the finer temporal resolution of Doppler lidars (2 min or less as compared to 10–30 min for radar wind profilers) means that Doppler lidars can characterize the environment in ways that radar wind profilers cannot.

Because of the demand from the wind energy sector, a number of wind-profiling lidars have become commercially available in recent years. The Halo Photonics Stream Line Doppler lidar (Pearson et al. 2009) was chosen for both SPARC and CLAMPS because of its compact form factor and ease of maneuverability, high degree of configurability, and the long-term success and reliability that the ARM program has experienced with these systems at multiple observation sites (e.g., Berg et al. 2017). CLAMPS-1 has a baseline Stream Line system, while both CLAMPS-2 and SPARC contain the Stream Line XR model with a more powerful transmitter and enhanced signal processing. The  $1.5\text{-}\mu\text{m}$  wavelength of the emitted signal is short enough to be sensitive to micron-sized scatterers but long enough that molecular scattering does not significantly interfere with the observations. Engineering principles specific to the Halo systems are discussed in Pearson et al. (2009).

Since Doppler lidars can only determine velocities along the line of sight and a zenith-pointing lidar can only measure the vertical velocity, the velocity–azimuth display (VAD) technique is used to get wind profiles. A conical scan creates a signal of line-of-sight velocities as a function of azimuth angle that is approximately sinusoidal in shape. By fitting a sine wave to the observed velocities, it is possible to retrieve all three components of the wind vector. Our

**TABLE 1. Instruments used in the CLAMPS and SPARC units.**

|                                                | CLAMPS-1                                                          | CLAMPS-2                                                          | SPARC                                                                               |
|------------------------------------------------|-------------------------------------------------------------------|-------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| <b>Remotely sensed thermodynamic profiling</b> | AERI v4,<br>HATPRO                                                | AERI v4,<br>MP-3000A                                              | AERI v2                                                                             |
| <b>Remotely sensed wind profiling</b>          | Halo Stream<br>Line                                               | Halo Stream<br>Line XR                                            | Halo Stream<br>Line XR                                                              |
| <b>Calibrated aerosol profiles</b>             |                                                                   |                                                                   | HSRL                                                                                |
| <b>Radiosonde ground station</b>               | iMet                                                              | Vaisala, <sup>a</sup> iMet                                        | Vaisala <sup>a</sup>                                                                |
| <b>Surface weather</b>                         | Vaisala WXT530<br><i>p</i> , <i>T</i> , RH at 3 m<br>Winds at 3 m | Vaisala WXT530<br><i>p</i> , <i>T</i> , RH at 5 m<br>Winds at 5 m | Vaisala HMP110<br><i>p</i> , <i>T</i> , RH at 2 m<br>RM Young 43502<br>Winds at 3 m |

<sup>a</sup> The Vaisala ground stations that used CLAMPS-2 and SPARC were originally for RS-92 radiosondes but have been recently upgraded to work with the new RS-41 radiosondes.

typical sampling mode is to perform a VAD scan at fixed time intervals using a 60° elevation and eight azimuth angles (taking approximately 30 s) with several 1-Hz zenith samples in between. The frequency of the VAD scans is selected based on the type of project with shorter intervals (2 min or less) providing more detailed information about the evolution of the horizontal winds, while longer intervals (15 min or more) result in longer continuous records of vertical velocities from which turbulence parameters can be computed more easily. Overall, the simultaneous collection of mean and turbulent wind observations when combined with thermodynamic profiles from AERI or microwave radiometers has great value for diagnosing boundary layer flows and processes (e.g., Newman et al. 2016; Bonin et al. 2015). Other scan strategies, such as range–height indicator (RHI) scans, can be easily implemented depending on the needs of the specific experiment. Key parameters like range gate length and pulse repetition frequency are easily configurable by the end user.

**IN SITU OBSERVATIONS.** For generations, detailed in situ meteorological measurements made at the surface have been considered a necessary requirement for all field experiments. Both SPARC and CLAMPS are equipped with surface meteorology stations that measure temperature, humidity, station pressure, wind speed, and wind direction. Because of limitations in onboard space as well as the frequent need to deploy and pack up rapidly, a standard 10-m tower for wind observations was deemed to be impractical for each unit, and therefore wind observations are made at a slightly lower height (see Table 1). However, for longer-term deployments additional in situ sensors, such as eddy-covariance sensors for measurements of turbulent fluxes, can be mounted on additional masts, and the data streams can easily be integrated into the data system. The mobile units also support radiosondes, with each unit hosting a ground check and receiver station; each unit also accommodates enough standard-size helium cylinders for at least a dozen launches before consumables need to be resupplied.

**Other instruments.** **HSRL.** An instrument unique to SPARC is its High Spectral Resolution Lidar (HSRL; Shipley et al. 1983; Eloranta 2005). Backscatter lidars are often deployed to measure the range-resolved backscatter induced by aerosols suspended in the atmosphere, but the backscatter signal at a given height is attenuated by both molecular and aerosol scattering of the atmosphere between the lidar and that height.

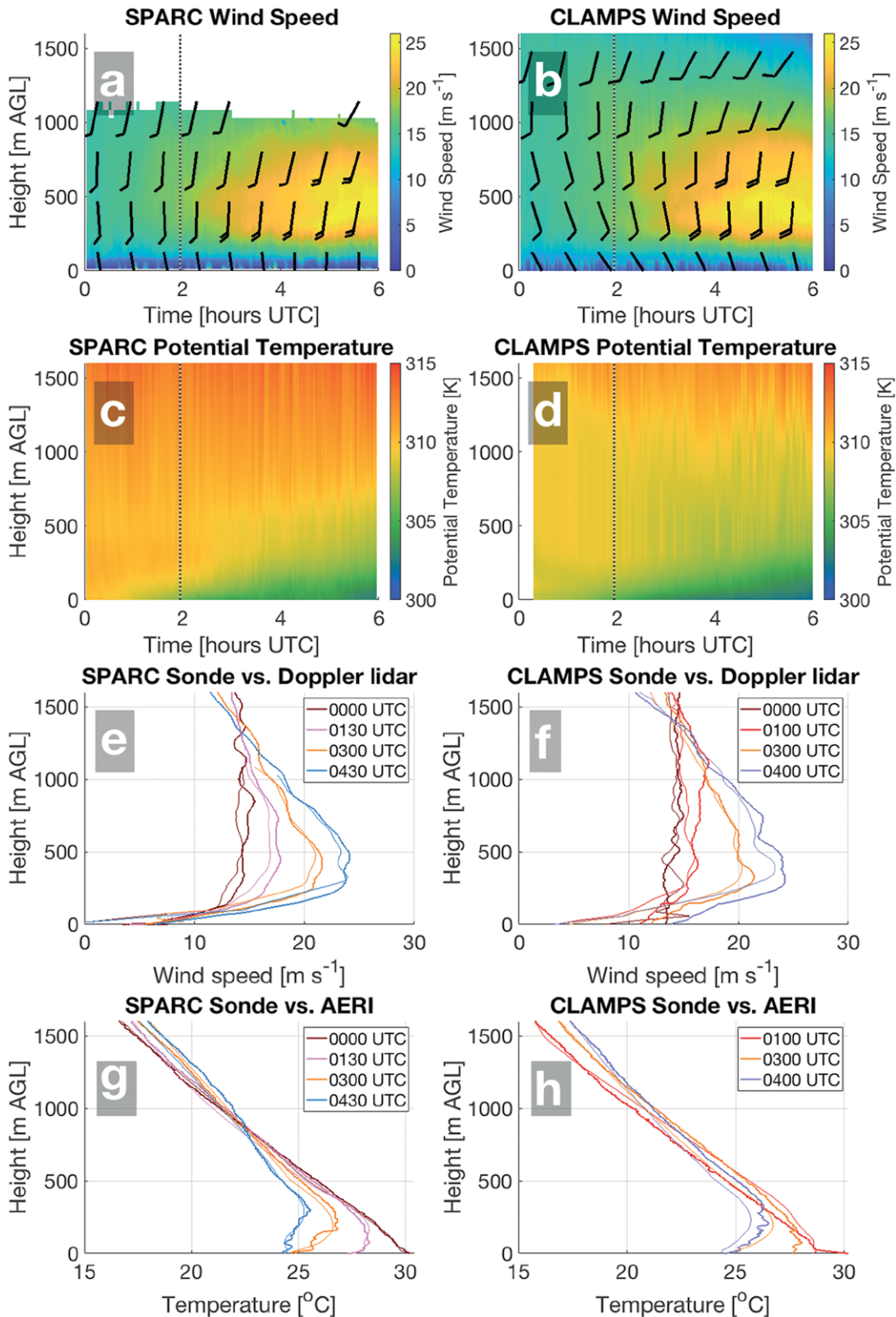
Traditional backscatter lidars that measure the back-scattered return only at the laser’s wavelength are unable to unambiguously discriminate between the two types of scattering signals: a layer with a small backscattering cross section with low extinction between the lidar and the layer or a layer that has a high backscattering cross section and larger extinction between the lidar and the layer. An HSRL is able to provide calibrated measurements of the backscatter and extinction cross section by including a detection channel that is sensitive to only the molecular scattering. The resulting measurements can be used to discern aerosol backscatter cross section, particulate optical depth, particulate depolarization, and other characteristics of aerosols. The University of Wisconsin–Madison has been a leader in the development and deployment of HSRLs, and a primary goal for SPARC was to provide a platform that allowed for field deployment of an HSRL. The SPARC HSRL was custom-built for this application, and it can be easily rolled on and off to allow for transfer to the workshop for maintenance and feature upgrades.

**Microwave radiometer.** CLAMPS augments its thermodynamic profiling capability with a multichannel microwave radiometer (MWR). CLAMPS-1 uses a version-4 Humidity and Temperature Profiler (HATPRO; Rose et al. 2005), while CLAMPS-2 includes a Radiometrics MP-3000A system (Solheim et al. 1998). Depending on the model and configuration of the MWR system, typically 14–35 spectral observations are made between 22 and 59 GHz, with one subset of channels clustered between 22.2 and 30 GHz to capture water vapor absorption and another subset spanning the oxygen absorption band from 52 to 59 GHz. Thermodynamic profiles have been retrieved from two-channel MWR systems for decades (e.g., Askne and Westwater 1986; Hewison 2007; Löhnert et al. 2008). One of the challenges of long-term operation of an MWR is maintaining its calibration (e.g., Löhnert and Maier 2012), especially for the channels in the oxygen absorption band, as these channels are typically calibrated using episodic views of liquid nitrogen. However, there has been a significant focus on improving these calibration techniques recently (e.g., Kuchler et al. 2016; Paine et al. 2014; Li et al. 2014).

While AERI has better real-world thermodynamic performance overall than an MWR in terms of both accuracy and information content (Löhnert et al. 2009; Blumberg et al. 2015), there are several synergies between the AERI and the MWR. First, clouds are much more absorptive in the infrared than the microwave,

**TABLE 2. CLAMPS and SPARC deployments. Note that the funding agency column denotes which agency funded the SPARC or CLAMPS deployment specifically, which is not necessarily the agency responsible for the project at large.**

| Project                                                          | Goal                                                                                                        | Date              | Funding agency | System(s)       | Location                                    | Publicly accessible data archive                                                        |
|------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|-------------------|----------------|-----------------|---------------------------------------------|-----------------------------------------------------------------------------------------|
| Front Range Air Pollution and Photochemistry Experiment (FRAPPE) | Characterize air pollution in an urban area in complex terrain                                              | Jul–Aug 2014      | NSF            | SPARC           | Boulder, CO                                 | NASA Langley Research Center (LARC)                                                     |
| PECAN                                                            | Observe different nocturnal severe weather processes                                                        | Jun–Jul 2015      | NSF            | SPARC, CLAMPS-1 | Central United States (mobile)              | University Corporation for Atmospheric Research (UCAR) Earth Observing Laboratory (EOL) |
| Combined HSRL and Raman Measurement Study (CHARMS)               | Facilitate intercomparison between HSRL and ARM Raman lidar                                                 | Jul–Sep 2015      | DOE/ARM        | SPARC           | ARM Southern Great Plains (SGP; Lamont, OK) | ARM                                                                                     |
| VORTEX-SE                                                        | Observe severe weather processes in southeastern United States                                              | Mar–Apr 2016      | NOAA           | CLAMPS-1        | Belle Mina, AL                              | UCAR EOL                                                                                |
|                                                                  |                                                                                                             | Feb–May 2017      | NOAA           | CLAMPS-2        | Scottsboro, AL                              | UCAR EOL                                                                                |
|                                                                  |                                                                                                             | Nov 2017–Apr 2018 | NOAA           | CLAMPS-2        | Belle Mina, AL                              | Experiment currently underway                                                           |
| Mini Mesoscale Predictability Experiment (Mini-MPEX)             | Determine how subsynoptic observations contribute to severe weather predictability                          | May–Jun 2016      | NSSL           | CLAMPS-2        | Oklahoma, Kansas, Texas (mobile)            | UCAR EOL                                                                                |
| Park Falls Shakedown                                             | Collect preliminary data in support of future deployments to the WLEF-TV, Park Falls, WI, tall tower site   | Sep 2016          | SSEC           | SPARC           | Park Falls, WI                              | UW SSEC                                                                                 |
| Environmental Profiling and Initiation of Convection (EPIC)      | Evaluate unmanned aerial systems (UAS) for profiling in convective environments                             | Sep 2016          | NSSL           | CLAMPS-2        | Medford, OK                                 | Not yet archived                                                                        |
| Rivers of Vorticity in Supercells (RiVorS)                       | Use observations of severe storm environments to evaluate current theory                                    | May–Jun 2017      | NSF and NOAA   | CLAMPS-2        | Medford, OK                                 | Not yet archived                                                                        |
| Perdigão, Portugal                                               | Study flow processes in a valley and improve wind forecasts in complex terrain for wind energy applications | May–Jun 2017      | NSF            | CLAMPS-1        | Central United States (mobile)              | Not yet archived                                                                        |
| LMOS                                                             | Evaluate the production and transport of ozone and its precursors in the Lake Michigan basin                | May–Jun 2017      | NOAA           | SPARC           | Eastern Portugal                            | UCAR EOL                                                                                |
| LAFE                                                             | Characterize fluxes and kinematic structure evolution in heterogeneous landscapes                           | Aug 2017          | NASA           | SPARC, CLAMPS-2 | Sheboygan, WI                               | NASA LARC                                                                               |
|                                                                  |                                                                                                             |                   |                |                 | ARM SGP (Lamont, OK)                        | ARM                                                                                     |



**FIG. 2. Analysis of observations during the 3 Jun 2015 LL.** Displayed observations include time–height cross sections of wind speed and potential temperature from the (a),(c) SPARC and (b),(d) CLAMPS Doppler lidar and AERIoe, respectively. The sunset time of 0157 UTC (2057 LT) is noted with a dashed vertical line. Comparisons between Doppler lidar–observed wind speeds (thin lines) and collocated radiosonde wind speeds (thick lines) are shown for (e) SPARC and (f) CLAMPS; AERIoe temperature retrievals (thin lines) are compared to radiosondes (thick lines) for (g) SPARC and (h) CLAMPS. No temperature comparison is shown for CLAMPS at 0000 UTC as the AERI system did not start collecting data until 0030 UTC that evening.

and thus the AERI has virtually no information on the thermodynamic profiles above the cloud while the MWR has some information (albeit limited by the broader microwave weighting functions). Second, combining the AERI and MWR observations results in a significantly improved retrieval of the liquid water path of the cloud (Turner 2007). The AERIoe algorithm has been updated to retrieve thermodynamic profiles and cloud properties that simultaneously agree with both the AERI and MWR observed radiances (Turner and Blumberg 2018).

**DEPLOYMENTS.** To date, CLAMPS and SPARC have jointly or independently participated in over a dozen field projects (Table 2), providing new insights on topics as diverse as instrument calibration, air quality, and mesoscale meteorology. Support for these deployments has come from NSF, NOAA, the National Aeronautics and Space Administration (NASA), the Department of Energy, and others. In this section, the benefits of synergistic deployments of our mobile platforms are highlighted by discussing results from a few selected projects.

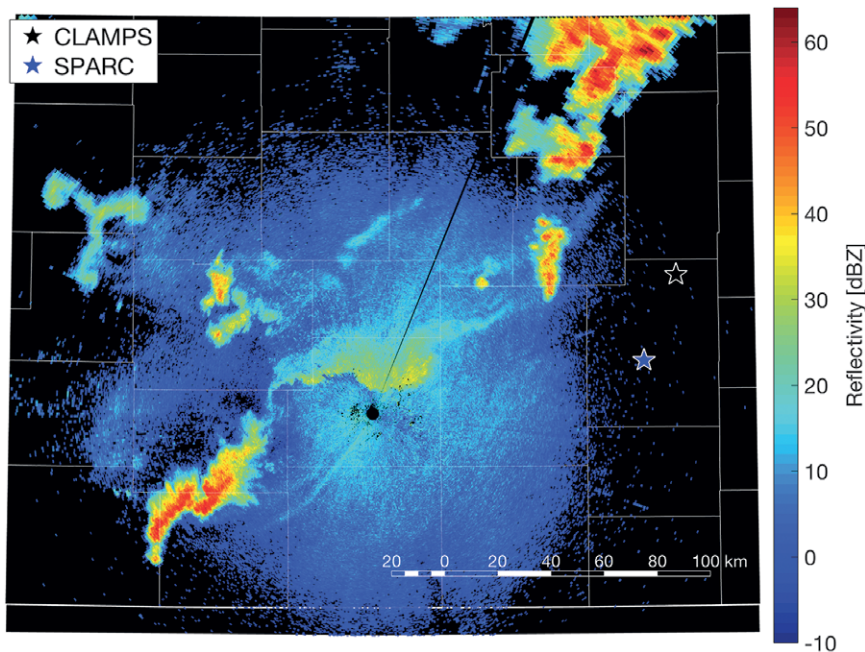
**PECAN.** While the processes that underlie daytime convection are relatively well understood, comprehension of the processes that underlie nighttime storms has been more elusive. To address these needs, the Plains Elevated Convection at Night (PECAN; Geerts et al. 2017) campaign was carried out in June and July of 2015, combining resources from NSF, NOAA, NASA, and the Department of Energy with researchers and students from over a dozen universities and laboratories. During the 45-day PECAN experiment, both the CLAMPS-1 and SPARC facilities logged over 11,000 km as the facilities were deployed in different locations from one night to the next to provide high-temporal-resolution profiles of nocturnal boundary layer structure.

The first targeted IOP during PECAN was a low-level jet (LLJ) event that began to form shortly after 0000 UTC 3 June 2015. The mobile assets were arrayed along an east–west transect perpendicular to the LLJ in order to capture the latitudinal variability of the jet structure. This led to SPARC and CLAMPS being deployed approximately 30 km apart, with SPARC at a site elevated approximately 60 m higher than CLAMPS. The lack of significant thermodynamic or kinematic gradients in the short distance between SPARC and CLAMPS for this IOP enable comparison of the performance of the two systems in largely similar environments. Selected variables from the two systems are seen in Fig. 2. The sun set at 0157

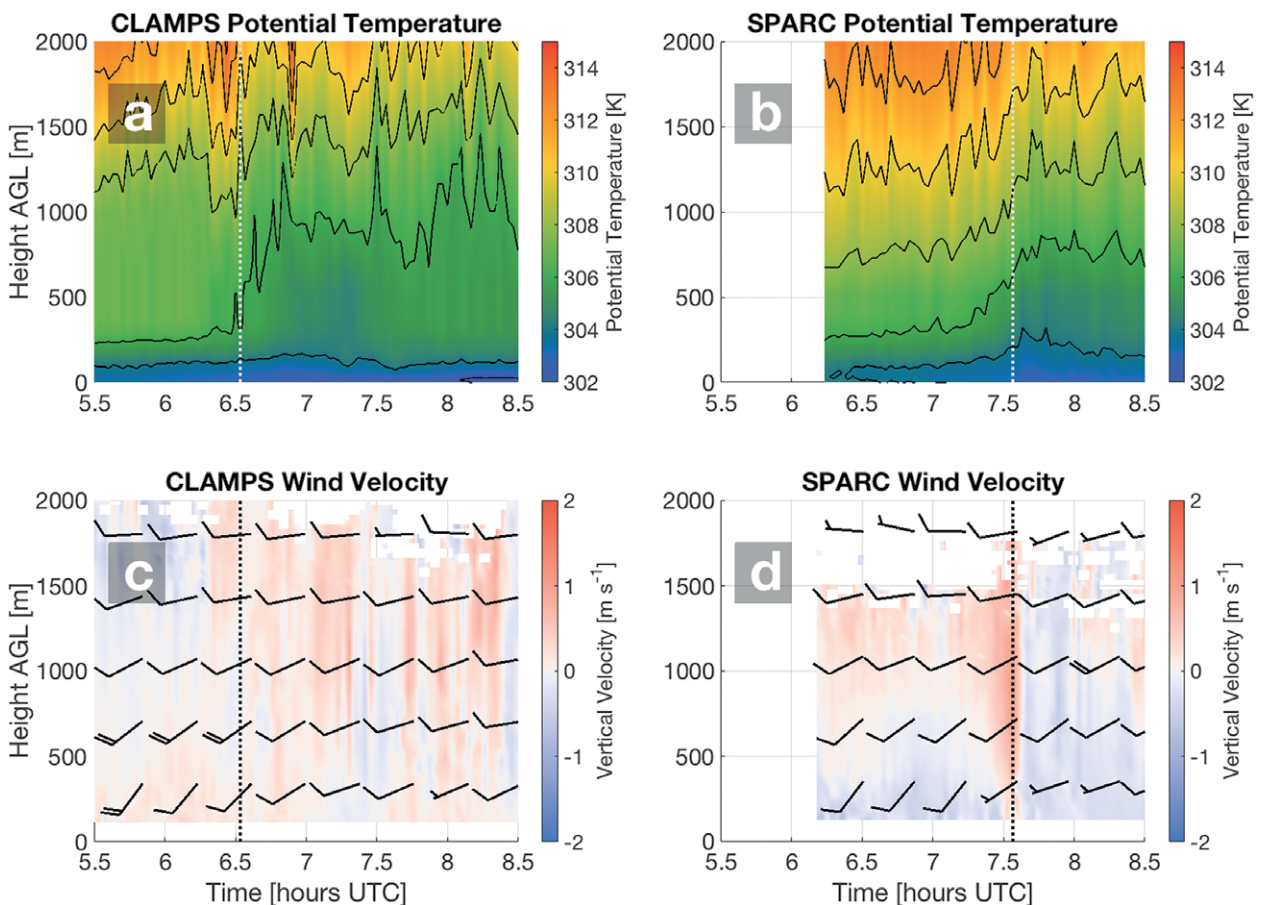
UTC [2057 local time (LT)] on a well-mixed boundary layer, and the inertial response to the decreased turbulent momentum transport following sunset created an easily identifiable LLJ, which reached speeds in excess of  $25 \text{ m s}^{-1}$  by 0500 UTC. The mobile facilities launched radiosondes throughout the evening, and comparisons between the AERIoe retrievals and the radiosondes are also shown in Fig. 2. Qualitatively, both AERI systems performed well at capturing the evolution in the magnitude and altitude of the nocturnal inversion as only subtle differences exist between the two observing systems, most notably in the timing of the LLJ and likely related to the spatial evolution of the LLJ jet in the PECAN domain.

The true value of having multiple mobile units with common instrumentation lies not in placing them in similar environments but instead in positioning them in separate locations so that they can capture the spatiotemporal variability in a given region. PECAN offered numerous opportunities to do that as well, such as occurred during bore IOPs. Since the existing synoptic observing network is both too spatially and temporally sparse to capture bores, mobile profiling units can fill in these gaps by positioning out ahead of anticipated outflow to capture the evolution of the environment with a fine temporal resolution. Figures 3 and 4 illustrate conditions associated with an environment that produced at least seven different bores or bore-like waves that were observed by fixed or mobile PECAN observation facilities during an IOP on 26 June 2015. For this deployment, CLAMPS was located approximately 35 km to the north-northeast of SPARC. The observed wave, propagating to the southeast, was too far away from Wichita, Kansas, and too close to the surface to be captured by the radar (Fig. 3), but SPARC and CLAMPS were able to capture it at different stages of its life. The time of wave passage was determined by finding the time of greatest surface pressure rise, a key characteristic of bores at the surface (e.g., Toms et al. 2017). Both CLAMPS and SPARC capture the expected semipermanent lifting of the stable surface layer that accompanies the initial wave (most easily seen as the 304-K isentrope in Figs. 4a,b), albeit at different times because of its asynchronous arrival. The initial upward pulse associated with the bore was much stronger at the SPARC location than the CLAMPS location, possibly due to SPARC's proximity to the convection that initiated the bore. Both systems seem to struggle to capture easily identifiable undulations in the wind or temperature fields after initial passage (Figs. 4c,d), indicating that this particular wave may be a gravity wave instead of a bore.

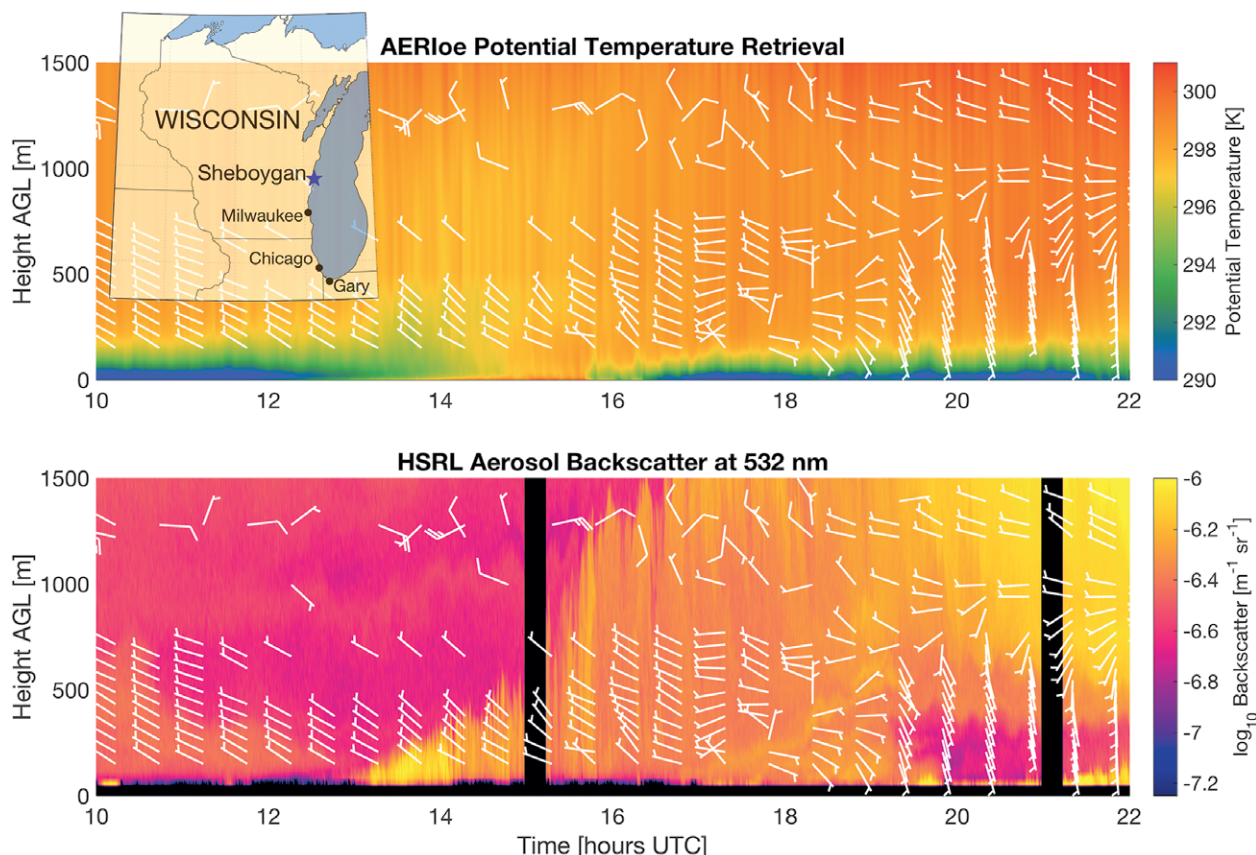




◀ **FIG. 3.** Wichita NEXRAD base reflectivity at 0532 UTC 26 Jun 2015. Black and blue stars indicate the locations of CLAMPS and SPARC, respectively, from which the observations in Fig. 4 were collected. The parallel bands of enhanced reflectivity in the south-central part of the image indicate the presence of a bore. While SPARC and CLAMPS observed a bore 1–2 h after this time, the radar was unable to see the bore when it went over the profiling facilities due to the distance away from the radar.



**FIG. 4.** Time–height cross sections of AERloe retrievals of potential temperature from (a) CLAMPS and (b) SPARC, with Doppler lidar–observed winds from (c) CLAMPS and (d) SPARC for a bore passage on 26 Jun 2015. Times are in UTC, and local times are UTC – 5 h. Horizontal winds are in  $\text{m s}^{-1}$ . The times of bore passage were determined based on surface pressure changes (not shown) and are indicated by the vertical lines on each panel. To aid readability, wind barbs are subsampled to 300-m vertical resolution and 20-min temporal resolution.



**FIG. 5. Time–height cross sections of AERloe-retrieved (top) potential temperature and (bottom) HSRL-observed backscatter during LMOS on 2 Jun 2017. Overlaid on both panels are the 2D wind vectors observed concurrently by Doppler lidar, subsampled to 30-min and 50-m resolution to enhance readability. Times are in UTC; local time is UTC – 5 h. SPARC was parked at Sheboygan, the location of which is shown in the inset.**

Having observations from multiple locations along the wave helps illustrate the nonuniform structure of these phenomena.

**Lake Michigan Ozone Study.** Many communities along the shore of Lake Michigan in the state of Wisconsin have been exceeding their ground-level ozone (GLO) attainment levels during the summer months. A unique confluence of factors enables GLO concentrations rivaling those of major cities in these smaller communities: while a small amount of heavy industry whose pollutants can be GLO precursors remains in these lakeshore communities, shoreline transport of pollutants from the industrial centers of Chicago and northwest Indiana, emissions from commercial shipping, and frequent lake breezes and boundary layer inversions over the lake all combine to create a localized environment supportive of GLO production.

The Lake Michigan Ozone Study (LMOS) was conceived to investigate the processes associated with GLO production, transport, and dispersion in greater detail through field observations and modeling. From 22

May to 22 June 2017, observations were collected from research aircraft, a NOAA research vessel, and ground sites. SPARC was deployed at Sheboygan, Wisconsin, a community with a population of approximately 50,000 people that routinely has higher GLO concentrations than isolated communities of that size typically experience. Through collocated observations from AERI, Doppler lidar, and HSRL, SPARC was able to characterize the meteorology of the environment and provide valuable insight as to the atmospheric conditions associated with ozone outbreaks.

The contributions of lake breezes to high surface ozone levels in Wisconsin shoreline communities are significant (Dye et al. 1995). While the predominant wind flow at these locations tends to transport locally produced precursors away from the shore as it prevents other precursors from reaching it, the flow reversal associated with lake breezes has the opposite effect. Furthermore, lake breezes induce inversions as a shallow layer of cold air is brought ashore where it undercuts a deeper warm layer; such an inversion inhibits further mixing that would otherwise vertically

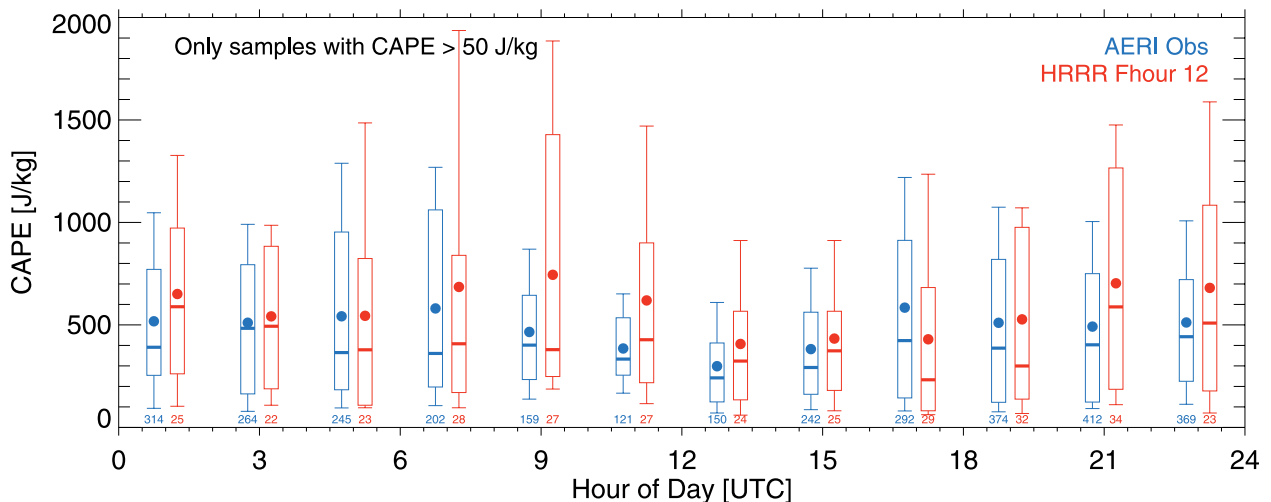
disperse the precursors. An example of a lake breeze event as observed by the instrumentation aboard SPARC is shown in Fig. 5. SPARC was located less than 50 m away from the shore of Lake Michigan, so its environment often had maritime influences. Furthermore, while the coast of Lake Michigan generally runs north–south, Sheboygan sits on a point that juts into the lake; thus, flow from the east, north, or south will contain marine characteristics. In this case, rapid cooling of the surface in the overnight hours helped facilitate the development of an inversion, clearly visible in the AERIoe time–height cross section as a warm layer overlying a shallow cold layer. Following sunrise at 1010 UTC (0510 LT), the surface began to warm, and the increase in planetary boundary layer depth can be seen in the HSRL imagery as vertical mixing can now lift aerosols to higher altitudes. With this daytime heating the inversion mixed out, but soon a lake breeze was induced, which grew from the bottom up. As the passively observing AERI can observe down to the surface while the active Doppler lidar has a minimum detection height, the thermal signature of the lake breeze is visible over an hour before its kinematic signature with a new inversion forming around 1545 UTC due to onshore advection of cooler marine air (1045 LT) and the Doppler lidar–observed winds beginning to shift around 1700 UTC (1200 LT). The HSRL imagery clearly indicates that air over the observing site originates from locations with significantly varying levels of aerosol loading depending on the direction from which that air is being advected. Air from the west is terrestrial in origin and has substantially higher levels of aerosol backscatter than air from the south and east, which originates over the lake and is much cleaner. Together, the AERI, Doppler lidar, and HSRL combine to provide a comprehensive assessment of the evolution of the boundary layer in a manner that would be impossible with traditional instrumentation.

**VORTEX-SE.** Much of the existing understanding of processes at work in tornadoes derives from field studies in the central and southern Great Plains of the United States due to the frequency of such events in that region; the relative ease to study these events with mobile radar systems (due to relatively flat and treeless regions); and the instrumentation, institutions, and personnel that have concentrated there to study them. However, several significant severe weather outbreaks occurred in the southeastern United States in recent years. In addition, there are known differences between Great Plains and southeastern tornadic environments, such as season of peak formation and

a tendency for southeastern tornadoes to form in environments with more shear and less instability than their plains counterparts (e.g., Brooks 2009). The difference in social impact of tornadoes in the two locations is also significant, with southeastern tornadoes being far more likely to cause fatalities due to higher population densities relative to the central plains. The VORTEX-SE program was instigated to investigate both the physical and societal characteristics of southeastern tornadoes with the goal of improving forecasts and outcomes. Building upon the successes of the original VORTEX (Rasmussen et al. 1994) and VORTEX-2 (Wurman et al. 2012), VORTEX-SE deployed a variety of observing systems over the course of multiple years of early spring field seasons to augment the sparse observing network in that part of the country.

Mesoscale studies like VORTEX-SE benefit greatly from the ability to capture the evolution of the structure and stability of the lower troposphere. To that end, CLAMPS-1 was deployed to north-central Alabama in March–April 2016 to provide continuous thermodynamic and wind profiles for the campaign, while CLAMPS-2 was deployed in the spring of 2017 and again in November 2017 through spring 2018. An analysis enabled by the long-term deployment of an AERI is shown in Fig. 6, which compares the diurnal distribution of convective available potential energy (CAPE) derived from the CLAMPS-1 AERI retrievals in the spring of 2016 to the 12-h forecasts from the High-Resolution Rapid Refresh model (HRRR; Benjamin et al. 2016) at that site over the 2-month deployment period. These CAPE values were computed from the AERIoe-retrieved or HRRR-modeled thermodynamic profiles using the Sounding/Hodograph Analysis and Research Program in Python (SHARPPy; Blumberg et al. 2017a). The statistic shows the 100-hPa mixed layer CAPE, considered more representative of the true environment (Craven et al. 2002), and the AERI-derived values for this convective index agree well with collocated radiosonde values (Blumberg et al. 2017b). To ensure that the analysis is not distorted by a large number of observations of marginal instability, only CAPE values of  $50 \text{ J kg}^{-1}$  or greater are included; the number of observations in each bin is indicated within Fig. 6. While it is expected that daytime hours would have a greater number of observations that meet this threshold, the still significant number of counts in the nighttime bins means that it is unlikely that the analysis is biased by small sample sizes.

The distribution of AERI-observed CAPE shows more larger values between both 0400–0800 UTC



**FIG. 6.** Diurnal distribution of calculated CAPE from CLAMPS observations and the 12-h forecasts from HRRR (valid at the displayed times) in Mar and Apr 2016 as part of VORTEX-SE. Data are binned in 2-h bins; 0000–0200, 0200–0400 UTC, etc. For all but the first two weeks of the deployment when standard time was still in effect, local time is UTC – 5 h. Dots indicate the mean value of CAPE; the boxes show upper-quartile, median, and lower-quartile values for CAPE; and the whiskers indicate the 10th and 90th percentiles. Only CAPE values greater than 50 J kg<sup>-1</sup> were included in this analysis.

(i.e., before sunrise) and 1600–2400 UTC (i.e., afternoon) time periods (blue bars in Fig. 6). The HRRR (red bars in Fig. 6) also exhibits this bimodal distribution but with elevated periods delayed 2–4 h relative to the AERI. This delay is likely due to the lack of subgridscale clouds in this version of the HRRR (version 1), which resulted in a warm bias in both the surface and boundary layer and led to lags in the forecasting of convective activity (Benjamin et al. 2016). The HRRR also tends toward larger CAPE values than AERI does, possibly because of the model not forecasting convection that actually occurred, which would leave larger residual CAPE values overnight. Such an analysis can only be performed with remote sensing systems, as traditional methods of atmospheric profiling (i.e., radiosondes) do not have the temporal resolution to capture the diurnal evolution of a derived quantity like CAPE.

**CONCLUSIONS.** The existing operational ground-based observing network has been optimized for synoptic-scale forecasting and the needs of the aviation community. The vertical and temporal variability of the winds, temperature, and humidity in the boundary layer remains unassessed when relying on operational radiosondes to characterize the vertical structure of phenomena that evolve on spatial and temporal scales smaller than a few hundred kilometers or several hours. Mobile profiling systems capture the environment near phenomena of interest with much greater detail than

would otherwise be possible, greatly enhancing our understanding of phenomena that would otherwise be difficult to characterize. To that end, the University of Wisconsin–Madison’s Space Science and Engineering Center, the University of Oklahoma, and the National Severe Storms Laboratory have collaborated in the development and deployment of a series of mobile profiler facilities that have successfully participated in numerous field studies, spanning applications that include satellite and unmanned aerial vehicle intercomparisons, mesoscale meteorology, air quality studies, and wind energy. These systems, SPARC and CLAMPS, have been shown to be valuable parts of field operations and are quite capable at both very short-term deployments (like those associated with transient phenomena like severe weather) and long-term surveillance that lasts several months. SPARC and CLAMPS were developed with the intention to be used in collaboration with a variety of groups, including academia, government, and industry. The mentors for SPARC and CLAMPS seek interested partners for the development of science plans in which these systems can help address the outstanding questions of the day.

The key role that SPARC and CLAMPS have played in field campaigns is undeniable, and there is a clear benefit to having high-temporal-resolution thermodynamic and kinematic profilers as part of the mix of observations in any study. However, the operational benefits of the instrumentation carried aboard these units need not be limited to occasional field



projects. The utility of ground-based thermodynamic and kinematic profilers has been shown through observing system simulation experiments (OSSEs) that demonstrated a positive benefit on NWP through assimilation of a simulated AERI and Doppler lidar network (Otkin et al. 2011; Hartung et al. 2011), and the benefits of near-real-time tracking of instability to operational forecasters during severe weather events has also been demonstrated (Wagner et al. 2008; Feltz and Mecikalski 2002). A permanent nationwide network of ground-based high-temporal-resolution profiling sites would bring significant benefits to all parts of the weather enterprise, informing stakeholders on issues as diverse as wind farm construction, severe weather monitoring, and the forecasting of precipitation type during winter weather events. The National Research Council (2009) has identified such a network as a high infrastructure priority. SPARC and CLAMPS are ideal prototype nodes for such a network, as these automated, effectively identical platforms can be used to test spacing, scanning strategies, communications protocols, data handling, and other issues that need addressing before the rollout of a nationwide network; they are also upgradable as new technologies become viable. The temporary erection of a profiling network in different regions could determine how operations and NWP forecasts in various climate regimes would be impacted by the presence of high-temporal-resolution boundary layer profilers, while spot deployments near NWS weather forecast offices would allow staff to gain familiarity with these state-of-the-art observational tools and provide insight into an operational network as it takes shape.

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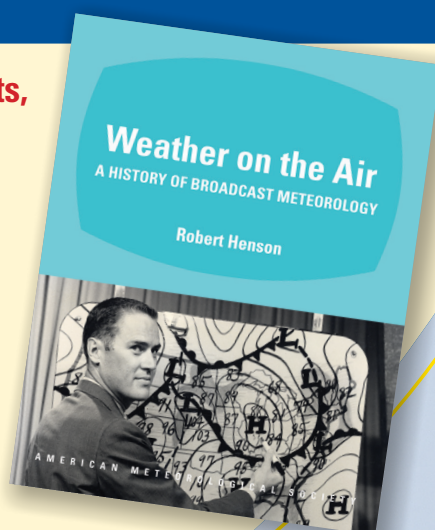
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