RECOMMENDATIONS FOR IN SITU AND REMOTE SENSING CAPABILITIES IN ATMOSPHERIC CONVECTION AND TURBULENCE

BART GEERTS, DAVID J. RAYMOND, VANDA GRUBIŠIĆ, CHRISTOPHER A. DAVIS, MARY C. BARTH, ANDREW DETWILER, PETRA M. KLEIN, WEN-CHAU LEE, PAUL M. MARKOWSKI, GRETCHEL L. MULLENDORE, AND JAMES A. MOORE

Recommendations for instruments and capabilities needed to advance the study of atmospheric convection and turbulence are presented.

Much progress has been made in atmospheric observational capabilities in recent decades, especially in atmospheric remote sensing. Yet the ability of the research community to obtain the necessary observations for substantial progress in understanding turbulent and convective environments has stagnated, because the availability and capacity of airborne and ground-based platforms and sensors have not grown in proportion to technological advances. More highly resolved in situ and remotely sensed observations are needed for scientific advancement in understanding and prediction of turbulent and convective processes and their impacts. Such measurements are required to study the dynamical, thermodynamical, cloud microphysical, chemical, electrical, and aerosol characteristics in environments ranging from turbulent boundary layers, shallow to deep moist convection, organized mesoscale convective systems, and supercell storms to tropical cyclones. These observations are required also to better understand exchanges of heat and momentum between the atmosphere and the underlying surface, both onshore and offshore. The issue is not a stalemate in technological innovations. There are many constraints to observing these processes, both for manned and unmanned airborne platforms and for surface-based platforms. These include safety, intermittency of occurrence, remoteness, accessibility, instrument performance limitations due to
turbulence or attenuation, difficulty in obtaining sufficient temporal and spatial coverage, and, ultimately, a lack of resources to deploy platforms or to install and maintain observing networks.

To address this challenge, and to assist the National Science Foundation (NSF) in defining the necessary next-generation technologies and observing capabilities, a workshop was held on 22–24 May 2017 at the National Center for Atmospheric Research (NCAR). This workshop is referred to as the Community Workshop on Developing Requirements for In Situ and Remote Sensing Capabilities in Convective and Turbulent Environments (C-RITE). Similar NSF-sponsored workshops have been convened by NCAR recently, including those on thermodynamic profiling technologies (Carbone et al. 2012), radar systems (Bluestein et al. 2014), airborne microwave radiometry (Zuidema et al. 2016), and the use of unmanned aerial systems for atmospheric research (Vömel et al. 2018). The focus of the C-RITE workshop was on experimental capabilities that currently exist or are under development and on ways to overcome or mitigate obstacles for advancing observational work. A subset of the instruments and capabilities recommended herein are mentioned by the National Research Council (NRC) in reports concerning mesoscale networks of observing systems (NRC 2009) and on the role of weather information in meeting critical national needs (NRC 2010).

The primary goal of this paper is to highlight gaps in our observational capabilities, gaps that the C-RITE workshop identified as obstacles obstructing scientific progress. This essay also aims to identify instruments, platforms, or measurement strategies that can fill those gaps, and specify their accessibility to the NSF research community. A secondary, but nonetheless important, outcome of this essay is to reaffirm the utility of current observational facilities for addressing key science goals.

The C-RITE workshop is summarized in the following section. Next, a list of recommendations that the C-RITE Program Organizing Committee (POC) distilled from the workshop is presented, before we conclude the paper.

**THE C-RITE WORKSHOP.** The two-and-a-half-day-long NSF-sponsored C-RITE workshop was attended by 145 participants. The workshop was international in scope and included representation from 27 universities in the United States and elsewhere, five international companies or agencies, two U.S. commercial firms, and three U.S. government agencies. Travel was supported for 20 early career scientists, graduate students, and postdocs to attend and participate in the meeting.

As mandated by NSF, the C-RITE workshop focused on existing and desired in situ and remote sensing capabilities in turbulent and convective environments. The main goals were i) to identify the scientific needs for future observing capabilities that will enable advancement in understanding processes, interactions among processes, and simulations for understanding them; ii) to match these science requirements with the inventory of existing atmospheric observing facilities currently available; iii) to identify gaps in the current facility inventory; and thus iv) to identify a facility suite that will meet the requirements for future observing capabilities.

The C-RITE POC chose to organize the workshop around four major scientific topics, encompassing the realm of atmospheric convection and turbulence: boundary layer flows and turbulence (including diverse topography and land use), free-tropospheric flows and turbulence (including mountain winds), dynamics and thermodynamics of convection (deep and shallow and continental and maritime), and physical processes in convection (aerosols, cloud physics, chemistry, radiation, and lightning).

The workshop devoted half a day to each of these four major topics. The participant pool was distributed in three parallel breakout sessions, to encourage more focused discussion about specific subtopics. For instance, the three subtopics of choice for the participants to explore during the half day on (thermo-) dynamics of convection were shallow convection, deep continental convection, and deep maritime convection. For each subtopic, information was gathered during the workshop from a combination of invited plenary talks and breakout discussions. The POC summarized these discussions for each of the four major topics in a report to NSF (Geerts et al. 2017). This report also links to an extensive record of the workshop discussions and other reference material. These discussions were the basis for the POC to prioritize existing and planned instrument capabilities, to identify critical missing instruments, platforms, or deployment strategies (gaps), and, finally, to develop a series of recommendations. These recommendations are summarized below.

**RECOMMENDATIONS.** Recommendations from the workshop are organized as follows. First, we address existing facilities that we consider to be particularly important to retain. Second, new desired developments are discussed, requiring an investment that is significant but does not rise to the level
of a major enhancement. Third, important facilities requiring extensive development and/or major, sustained funding are indicated. Fourth, there are highly desired measurements for which technological solutions are in a nascent stage.

The list of instruments and capabilities presented below is designed to be comprehensive, except for the fourth category, which merely illustrates items on what could be a long wish list. The list of recommendations should not be perceived as exhaustive, nor rank ordered. The recommendations are intended to provide the atmospheric research community and NSF with the most significant information developed at the workshop. By itself, this information may be inadequate to set definitive priorities. There are undoubtedly worthy instrumentation projects that have escaped the attention of the C-RITE workshop participants and the C-RITE POC. We hope that NSF will judge such projects based on their merits, irrespective of whether they have appeared in this report. While the focus here is on the study of turbulence and convection, all instruments and platforms have broader applications across the field of atmospheric science.

A common thread is the need for higher temporal and higher spatial resolution sampling than is currently available with in situ and remote sensors. As computational power has grown steadily, numerical simulations have outpaced observational systems in their ability to capture fine details, for example, the transition from linear waves into turbulence; the effect of aerosol, cloud, and precipitation processes on convective cold pool development and storm evolution; or the effect of finescale turbulence on precipitation growth. Instruments are being developed to address this need for higher resolution (e.g., phased-array radar and advanced cloud radars), but much room remains for further progress.

In terms of accessibility to the NSF-supported community, special attention is paid to whether or not facilities are (or should be) part of the NSF Lower Atmosphere Observing Facilities (LAOF) pool and, thus, can be requested as part of an observationally focused NSF proposal.

Existing facilities. Many currently existing facilities are important to retain and support since well-designed deployments that include these facilities can yield new insights in convection and turbulence. We present here only those that rise to a level of major significance.

Airborne instruments. Three aircraft platforms currently exist in the NSF atmospheric science fleet, the NSF/NCAR Gulfstream V [GV; also known as the High-Performance Instrumented Airborne Platform for Environmental Research (HIAPER)], the NSF/NCAR C-130, and the University of Wyoming King Air (UWKA). All three of these aircraft, and their base-funded remote and in situ instrument arrays, are central to the NSF atmospheric science program. The GV is in high demand for a variety of projects, especially those in remote locations; the C-130 is uniquely capable of carrying a heavy payload; and the UWKA provides a less expensive and more agile platform for more localized weather phenomena. The current inventory of airborne instrumentation available on these three aircraft, particularly the radars, lidars, and in situ cloud physics, trace gas, aerosol, radiation, turbulence, and flux probes, are indispensable. Sondes dropped from these or other aircraft continue to be irreplaceable for obtaining finely resolved vertical profiles over broad reaches of the oceans and in some cases over land. Though expensive, dropsondes provide the only way to obtain 3D mesoscale arrays or grids of comprehensive kinematic and thermodynamic profile information at high vertical resolution over the ocean. Further miniaturization of dropsondes is desired, to reduce both costs and restrictions for drops over land.

Profiling systems. Balloon-borne radiosondes released from land or from aboard ships are similarly important, and remain essential, for instance, in obtaining detailed time–height transects through passing convective systems or in assembling frequent tropospheric profiles from remote locations. Current technology for launching soundings is inexpensive, compact, and highly mobile. Some radiosondes are equipped to also collect good data on the way down (following separation from the balloon), but this capability needs to be improved and standardized. Consistency in radiosonde launch procedures, data processing, and quality assurance, as well as temperature and humidity intercomparisons for sondes from diverse vendors against a reference sonde, are critical for obtaining high-quality datasets that can advance the science. Even though NCAR’s Earth Observing Laboratory (EOL) no longer provides stand-alone radiosonde systems as part of the LAOF pool, EOL is in a strong position to assume a role in such intercomparisons and achievement of consistency as part of the field campaigns it supports. Surface-based continuously operating tropospheric profiling systems, including wind profilers, centimeter-wave Doppler radars, Doppler lidars, Raman and other lidars, atmospheric interferometers, and passive microwave...
radiometers provide a valuable complement to radiosonde observations, but do not replace them. Unfortunately, none of these continuously operating tropospheric profiling systems currently are part of the LAOF pool, except for wind profilers.

**Scanning radars.** The highly mobile and versatile Doppler-on-Wheels (DOW) radars, including the rapid scan DOW, are central to the study of convection and turbulence. In several campaigns these radars have been arranged in a larger array including non-LAOF mobile radars (Bluestein et al. 2014), to obtain more complete 3D depictions of storm motions and precipitation characteristics. The NCAR S-band/Ka-band Dual Polarization, Dual Wavelength Doppler Radar (S-PolKa) should be retained in the LAOF pool. Operational weather radar networks such as the Weather Surveillance Radar-1988 Doppler (WSR-88D) radar array, operated by the National Weather Service, and the Terminal Doppler Weather Radar, operated by the Federal Aviation Administration, are invaluable for the monitoring of convection and turbulence. While S-PolKa is similar to the WSR-88D radars, S-PolKa has capabilities that the WSR-88D network does not have, including enhanced polarimetric capabilities, dual-frequency capability, and researcher-controlled scan strategy (e.g., RHIs and sector scans).

**Surface networks.** Mesoscale networks of surface observations, in the United States typically coordinated at the state level (e.g., in Oklahoma) or by private enterprise (e.g., Earth Networks; www.earthnetworks.com), play an essential role in the study of both the boundary layer and deep convection. Aside from the usual surface meteorological parameters, additional mesonet station measurements are possible and encouraged, specifically for the study and prediction of air quality, clouds, surface energy fluxes, and turbulence. Some permanent networks include towers for near-surface meteorological and flux profiles, and even remotely sensed lower-tropospheric wind and thermodynamic profiling capabilities. NCAR’s Next Generation Surface Flux System (CentNet) can be deployed as a temporary network of O(100) stations. Atmospheric research would benefit considerably from the development of an operational network of tropospheric thermodynamic and wind profiling systems, something the National Research Council advocated in a recent report (NRC 2009).

**Minor enhancements or additions.** We now address existing facilities or proven technologies that through some minor enhancements or additions could lead to significant research breakthroughs, especially if made available more readily to researchers via inclusion in the LAOF instrument pool, according to the discussions at the C-RITE workshop. We discuss capabilities in the same sequence as before, starting with airborne instruments. Again, the list is not exhaustive and is biased toward the LAOF pool.

**Airborne instruments.** NCAR’s HIAPER Cloud Radar (HCR; Fig. 1e) for the NSF/NCAR GV was originally designed to contain both W- and Ka-band radars. Financial constraints prevented the completion of the Ka-band channel, so it is currently limited to the W-band. While up/down-profiling W- and Ka-band radars are available on the UWKA and NSF/NCAR C-130, the POC recommends adding a matched-beam Ka-band radar to the HCR. This will allow the HCR to see further into precipitation regions and in liquid water clouds than is possible with the W-band component, and will also allow dual-frequency measurements. Another instrument in this category is an airborne Raman lidar, to profile water vapor and possibly temperature. The Multi-function Airborne Raman Lidar (MARLi) has been developed for nadir measurements aboard the NSF/NCAR C-130 and UWKA. It would be useful to extend this capability to the NSF/NCAR GV and to build a zenith-plus-nadir-profiling version. Aside from active remote sensing, airborne passive microwave sensing has untapped potential, providing vertically integrated water vapor and cloud liquid water path data, thereby synergistically extending or constraining cloud measurements from other in situ and remote sensing probes. Its technology has evolved to a point of potential breakthrough in scientific applications, but retrieval algorithms can only be improved through flights in a diversity of cloud conditions, including convective clouds.

Two airborne capabilities can be enhanced by collecting measurements over relatively large volumes of air: one regards turbulence, the other cloud particles. Turbulent kinetic energy is estimated using high-frequency 3D velocity measurements from a gust probe. This requires some time integration. A promising new technology is a laser-based instantaneous turbulent air motion measurement system. This has been developed and tested [e.g., by the National Aeronautics and Space Administration (NASA)] and is currently under development at NCAR. Current airborne in situ cloud physics probes sample small volumes of air, such that the along-track distribution of the largest hydrometeors, which are present at low concentrations but typically dominate the radar...
signal, is not adequately sampled. This underlines the need for probes with a larger sampling volume in order to detect widely spaced large particles. Also desired is further improvement of the 3D imaging capability of the spatial arrangement of hydrometeors, such as the Holographic Detector for Clouds (HOLODEC; Fig. 1d).

Finally, airborne electric field and field change meters allow detailed mapping of electric fields and lightning activity near and within thunderstorms. Such measurements can constrain estimates of charge distributions and charge movement by lightning in and around these storms. This technology exists but currently is not available on the three aircraft in the LAOF pool.

**Profiling systems.** Pilot studies have demonstrated the value of integrated networks of remote sensing instruments for collecting continuous temperature and humidity profiles in the lower troposphere. This includes passive sensors in the microwave and infrared regions, and active sensors, especially differential absorption lidars (DIALs) and Raman lidars. The development of the compact water vapor DIALs at NCAR/EOL (Fig. 1f) addresses this need, and further should be coupled with DIALs or other instruments that provide reliable temperature profiles. The community needs access to a sufficient number of temperature and humidity profiling systems to enable the deployment of a network.

**Scanning radars and lidars.** Mobile X-band systems should be complemented by more powerful, scanning mobile radars at a less attenuating frequency, yet a comparably narrow beamwidth. Phased-array and digital beamforming (“imaging”) techniques can be used to obtain full volume scans in $O(10)$ s, one to two orders more rapidly than traditional antenna scanning techniques, but such radars still lack sensitivity and are expensive. Also desired, in the LAOF pool, is a scanning polarimetric Doppler radar with proper stabilization for shipborne operations, such as the Colorado State University Sea-going Polarimetric (SEA-POL) radar. Scanning Doppler lidars (Fig. 1g) have been developed and used in boundary layer studies (e.g., in the Perdigão field campaign; Fernando et al. 2017; Vasiljević et al. 2017). Currently, the range of commercial units is typically limited to the

---

**Fig. 1.** Collage of platforms and instruments mentioned in this essay. (a) Conceptual design of the APAR panels on the NSF/NCAR C-130. (b) Schematic network of towers and lower-tropospheric profiling systems in the 2017 Perdigão field campaign (Fernando et al. 2017). (c) The U.S. Air Force A-10 aircraft under consideration by NSF for modification for storm research. (d) The HOLODEC-2 mounted on the NSF/NCAR C-130. (e) The HCR on the NSF/NCAR GV. (f) The NCAR/Montana State University water vapor DIAL. (g) The University of Oklahoma Collaborative Lower Atmosphere Mobile Profiling System (CLAMPS) trailer with Doppler lidar, Atmospheric Emitted Radiance Interferometer (AERI), and microwave radiometer. (h) An eMote (Bolt et al. 2018).
boundary layer, but developing the capability to use these systems as profiling units or in synchronized dual- or triple-Doppler scans will provide flexibility in designing measurement strategies that can resolve the spatial and temporal variabilities of boundary layer processes.

**Surface networks.** One item in this category is the need for a lightning mapping array (LMA) with at least ~10 stations that can be temporarily deployed at fixed locations as part of NSF-funded field campaigns, or even a set of LMA stations mounted on a fleet of vehicles that can be driven in formation under evolving thunderstorms. The technology for this instrumentation is well established, but an LMA currently is not available through the LAOF pool.

**Major new facilities.** New facilities are classified as major if their development is expensive, technologically challenging, or subject to difficult logistical or regulatory constraints.

**Airborne measurements.** We discuss four capabilities in this category: volume-covering weather radars, Doppler lidars, an aircraft capable of penetrating thunderstorms, and drone technology. First, a novel C-band, polarimetric, Doppler Airborne Phased-Array Weather Radar (APAR) is currently under development by NCAR for deployment on the NSF/NCAR C-130 (Fig. 1a). The hardware is intrinsically expensive and the technological and data processing challenges are major. This instrument will not only fill a gap in airborne scanning observations of precipitating systems created by the retirement of the Electra Doppler Radar (ELDORA) in 2012 but also provide far better temporal resolution of volume samples. It will be especially valuable in places where ground or ship-based radars cannot be deployed, or where the rapid-scan capability is important (e.g., in deep convection). The use of C-band radars reduces attenuation over that of X-band radars such as ELDORA or the NOAA P-3 fore–aft tail Doppler radars. APAR’s polarization diversity discrimination will help in the identification of the hydrometeor type and understanding microphysical properties. Its development is ambitious and should be encouraged.

The development of airborne Doppler lidars in a number of different contexts will benefit a broad range of atmospheric problems. The NASA has recently demonstrated the feasibility of using a powerful, eye-safe Doppler aerosol lidar (DAWN) to obtain profiles of horizontal wind from flight levels as high as 10–12 km MSL, with adequate returns in areas of relatively low aerosol backscatter levels. An airborne Doppler lidar can provide wind profiles in optically clear air on a much finer horizontal scale than is practical with dropsondes. The combination of a nadir- and a slant-forward-pointing Doppler lidar would allow 2D wind synthesis, and, in combination with a Raman lidar, vertical moisture and heat fluxes could be estimated.

A storm-penetrating manned aircraft that can withstand severe turbulence, hail, and lightning strikes, and can carry a rich array of sensors, is greatly desired by investigators studying continental convection, including severe storms. Such an aircraft will allow the measurement of turbulence, 3D wind, trace gases, aerosol, the 3D electric field, and thermodynamical and cloud physical variables along its flight path. A gap was created with the retirement of the South Dakota School of Mines and Technology T-28 aircraft in 2005. A manned aircraft remains the only reliable way of making such measurements. An A-10 aircraft (Fig. 1c) built for military purposes currently is being evaluated by NSF as one option toward enabling in situ measurements in deep convection. The need for extensive aircraft modifications without existing supplemental type certificates, and the absence of any A-10 aircraft that have been converted for civilian use, may make this an expensive and high-risk project, but the stakes are high for those studying severe convection.

Finally, portable unmanned aerial systems (UASs, or drones), as they become cheaper and their instruments and data systems are being miniaturized, are becoming an increasingly important tool for all sorts of tasks, in particular for formation flights in vertically or 2D stacked arrays. There was widespread agreement among the C-RITE workshop participants that the portion of airborne atmospheric research conducted by drones will continue to increase. A key constraint in the United States and elsewhere remains stringent air traffic regulatory limitations on the use of such platforms. Regulatory limitations are expected to gradually relax through advances in GPS and communication technology that make UAS operation in public airspace safer, but flight ceiling regulations likely will continue to restrict the use of drones for the study of deep convection. The study of deep convection is restrained also by flight challenges inherent to small platforms, including turbulence and airframe icing in supercooled liquid cloud. Other limitations include less-than-generous range, duration, and payload, but they are related to the rather small size of the drones that are currently most commonly
used by the atmospheric science community. Mechanical miniaturization and more sophisticated autonomous guidance systems are being developed to overcome some challenges.

**Surface networks.** Access to a vastly expanded, readily deployable array of towers, at least 30 m high, instrumented with various well-calibrated and cross-validated sensors (including eddy-covariance systems for measuring heat and momentum fluxes) is desired, in order to adequately sample inhomogeneous boundary layers. Even though the technology of the towers and the associated instrumentation are well established, this item is included in the “major new facilities” category, as the inclusion of such an array (with 50+ units) in the LAOF pool is likely to be expensive and labor intensive. Availability of the tower network plus basic sensors through the LAOF pool would allow the community to add complementary, more specialized sensors on these towers (e.g., trace gas chemistry), depending on the research objectives at hand. This is a long-standing need in the field, and currently it can only be mitigated through broad, international collaborations, as in Perdigão (Fig. 1b). Such projects are difficult to get funded, and result in nonuniform networks (different sensor types, different data processing routines, etc.) and thus datasets that lack consistency.

**Desired, currently nonexisting capabilities.** Sometimes there is no obvious way, given current technology, to make the measurements that are needed to advance the science of the atmosphere. Several examples were mentioned at the C-RITE workshop; two of them are mentioned here, because they may significantly improve the understanding and prediction of high-impact weather. The hope is that this will continue to stimulate the development of the technology.

First, there currently is no way to map the 3D thermodynamical fields (temperature, pressure, and humidity) inside a thunderstorm to the spatial resolution obtainable for wind and reflectivity measurements with a Doppler radar network. This applies to any precipitating system, but is most pertinent for severe storms. Lidars are blocked by cloud, and passive microwave and interferometer systems are compromised by hydrometeors. Thermodynamical retrievals (using radar-derived kinematic data) are overly constrained by unknown boundary conditions and questionable assumptions. Upsondes, dropsondes, and storm-penetrating aircraft do not fully solve this problem either, as they only make 1D (in situ) measurements. One possible solution that is being explored is to drop swarms of small, biodegradable probes such as environmental motes, or eMotes (Bolt et al. 2018) (Fig. 1h), into a storm from an overflying aircraft or balloon. These probes would radio back their location and basic thermodynamical data, much as happens with radiosondes. The individual probes will have to be considerably lighter than dropsondes to obtain permission for release over land. Development so far is probably best characterized as being in its infancy, and is subject to some formidable technical and perhaps regulatory challenges.

The second challenge regards the estimation of air–sea exchanges under very strong winds. The behavior of tropical cyclones depends on the magnitude of the fluxes of heat, moisture, momentum, and possibly also cloud-active aerosol from the sea surface. This dependence is poorly constrained since measuring these fluxes at a flight level below 100 m MSL becomes increasingly difficult with increasing wind speeds, owing to the sea state, the hostile environment, and the rarity of extreme conditions. The ability to measure surface fluxes below strong tropical cyclones (e.g., with a swarm of drones, an array of deployable floating buoys, or a controlled towed vehicle tethered below an aircraft) would have a high scientific payoff in the understanding and predictability of tropical cyclones. Some progress has been made in this area through funding by federal agencies other than NSF.

**CONCLUSIONS.** Progress in our understanding of atmospheric processes in turbulent and convective environments has been slowed recently by the challenges in obtaining the necessary observations, largely owing to the limited availability and capacity of current airborne and ground-based platforms and sensors. A common thread among all recommendations stated herein is the need for more highly resolved sampling, both in space and in time. Airborne and ground-based remote sensors, including rapidly scanning millimeter- and centimeter-wave radars, Doppler lidars, and lidars measuring humidity and temperature, need to become more broadly available to the NSF-supported community, as this will spur much scientific progress. Improvements in situ sensing are expected to advance science as well, in particular through access to a manned storm-penetrating aircraft, more flexible deployment of drones, swarms of miniature floating environmental sensors, and airborne turbulence/microphysics probes that capture a larger spatial domain around the sensors.

One question we have not considered in these recommendations is whether a particular facility or instrument should be handled by the LAOF pool or

---

**DECEMBER 2018**

**AMERICAN METEOROLOGICAL SOCIETY**

**BATS** | 2469
by university investigators and private companies. In general, instruments need a sufficient technological readiness level, demonstrated reliability, and broad community demand to become part of the LAOF pool. For instance, the Wyoming Cloud Radar (WCR) and the DOWs initially were not part of the LAOF pool, but as they became technologically mature and had demonstrable community interest, they became LAOF resources available upon request. On the other hand, instruments that have become highly proven, widely used, and inexpensive, such as radiosondes, may be removed from the LAOF pool, except within the context of a bundled set of instruments that are used together for a particular purpose. Decisions of this nature need to be worked out with the knowledge and input of the entire community.

ACKNOWLEDGMENTS. This paper and the C-RITE workshop were both supported by the Division of Atmospheric and Geospace Sciences (AGS) of the National Science Foundation (NSF). Patrick Harr provided the initial guidance for this workshop and served as NSF liaison. NCAR is acknowledged for cosponsoring the C-RITE workshop, which was organized and hosted by the NCAR Earth Observing Laboratory (EOL). Patti Kidd and Amy Honchar of NCAR/EOL are acknowledged for workshop logistics support. Gunilla Svensson, Wayne Angevine, Julie Lundquist, Matt Parker, Larissa Back, Jim Doyle, Pavlos Kollias, Robert Sharman, Larry Carey, Sue van den Heever, Eric Bruning, and Ken Pickering are acknowledged for moderating plenary sessions and/or for presenting science overviews. Special thanks to Fred Carr for his summary of atmospheric research observational needs, based on a broad survey conducted at the 2017 AMS Annual Meeting. NCAR is sponsored by the National Science Foundation.

REFERENCES


