Requirements for *In Situ* and Remote Sensing Capabilities in Convective and Turbulent Environments (C-RITE) Community Workshop*

May 22-24, 2017
Boulder, Colorado

FINAL REPORT

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**Sponsored by the National Science Foundation, Atmospheric and Geospace Sciences, and the National Center for Atmospheric Research Earth Observing Laboratory*

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1. Executive Summary

The Community Workshop on Developing Requirements for *In Situ* and Remote Sensing Capabilities in Convective and Turbulent Environments (C-RITE) was carried out to assist the National Science Foundation (NSF) in defining next generation technologies and observing capabilities best suited for studying convection and turbulence in the atmosphere. With the help of over one hundred investigators from the scientific community, the Workshop developed a series of recommendations to NSF on this topic. These recommendations address facilities and capabilities ranging from existing ones that need to be retained and/or incrementally be improved, to urgently needed new facilities, to desired capabilities for which no solutions are as of yet on the horizon.

2. Introduction

The ability of the research community to obtain *in situ* and remotely-sensed observations in turbulent and convective environments has stagnated within the past decade or so, owing to reduced availability and capacity of airborne and ground-based platforms and sensors, and lack of resources for innovation. Such observations are needed for scientific advancement in understanding and prediction of turbulent and convective processes and their impacts across environments. Specifically, they are required to study the dynamics, thermodynamics, microphysical, chemical, and electrical and aerosol characteristics in environments, ranging from turbulent boundary layers, shallow to deep convection, organized mesoscale convective and supercell convective systems, tropical cyclones, and to better understand exchanges of heat and momentum between the atmosphere and the underlying surface.

The Community Workshop on Developing Requirements for *In Situ* and Remote Sensing Capabilities in Convective and Turbulent Environments (C-RITE) was held on May 22-24, 2017 at NCAR (see details in Section 3), to assist NSF in defining next generation technologies and observing capabilities needed for atmospheric observations of phenomena related to dry and moist convection, which intrinsically involve turbulence and cloud processes. There are many observational challenges including safety, intermittency of occurrence, remoteness of locations, instrument performance challenges due to turbulence or attenuation, and difficulty in obtaining sufficient temporal and spatial coverage.

The main objectives of C-RITE, summarized in this report, were to:

- Identify science requirements for future observing capabilities that are informed by the need for broader advancement in understanding processes, interactions among processes, and simulations for understanding;
- Match science requirements with the inventory of existing atmospheric observing facilities currently available for *in situ* and remote sensing in turbulent and convective environments;
- Identify gaps in the current facility inventory;
- Identify a facility suite that will meet the requirements for future observing capabilities.

In order to make the enormous breadth of this topic more tractable and focused, the Program Organizing Committee (POC; see Section 6, Acknowledgments) decided to organize the Workshop around the following four major topics:

- Boundary layer flow and turbulence (including topography and land use)
- Dynamics and thermodynamics of convection (deep and shallow, continental and maritime)
- Free-tropospheric flows and turbulence (including mountain winds)
- Physical processes in convection (aerosols, cloud physics, chemistry, radiation and lightning)

Under each major topic were three sub-topics to encourage focused discussion in key disciplinary research areas. For each sub-topic, information was gathered during the Workshop from a combination of invited plenary talks and breakout discussions. The discussions have been summarized in Section 5, for each of the four major topics. This was the basis for the POC to build a series of recommendations (Section 4). Also provided in the Appendix are the instrument priority table (Section 7.4) and the science traceability matrix (Section 7.3). The instrument priority table begins with instruments (existing or planned) and links these to the various science topics. This bi-directional mapping is useful for identifying consistency between scientific needs and available/experimental facilities. In principle, this can identify critical missing instruments, platforms, or deployment strategies (gaps), and instruments that have greater and lesser use for multiple science goals. Each row in the science traceability matrix flows (left to right) from the major science goal, to required measurements, required instruments (denoted as available or otherwise), and observation challenges (technical or logistical).

The primary goal of this report is to summarize the Workshop and highlight the identification of gaps in our observational capability that represent obstacles to advancing science. Of equal importance is identifying 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 the Workshop is to reaffirm the utility of current observational facilities for addressing key science goals.

3. C-RITE Workshop Organization

The C-RITE Workshop took place at NCAR on May 22-24, 2017. The Workshop extended over two and a half days and included a series of formal presentations to introduce science topics, breakout sessions to discuss and develop observational needs, summary plenary gatherings and a plenary synthesis session on the last day. An informal poster session extended for the duration of the Workshop with posters on various subjects germane to the topics covered by the Workshop. The detailed agenda of the Workshop is provided in Appendix 7.1.

There were a total of 145 participants in the C-RITE Workshop, including 113 on-site and 32 remote participants (Appendix 7.2). The C-RITE Workshop supported travel for 20 early career scientists, graduate students and post-docs. The Workshop was international in scope and included representation from 27 universities from the US and abroad, three US federal agencies, two representatives from the US private sector and five non-US companies/agencies.

The Co-Conveners of the C-RITE Workshop, NCAR/EOL Director Vanda Grubišić and NCAR/MMM Director Chris Davis, provided an overall direction for the organization of the Workshop. To that end, they formed two Workshop support teams, including a Program Organizing Committee (POC) and a Local Organizing Committee (LOC). The members of the POC and LOC are listed in Appendix 7.2.

The collective expertise of the POC encapsulates a diverse set of disciplines represented at the Workshop. The POC as a group identified science topics (e.g., continental convective systems, tropical convective systems, storm chemistry, storm electrification, planetary boundary layer, and atmospheric composition) and the key science requirements for each topic. Each member of the POC took the lead in one or more science topic areas, including leading the Workshop sessions on their topical areas and identifying other presenters, breakout session leads and rapporteurs for the main topics and sub-topics. Prior to the Workshop, the POC was also responsible for compiling the inventory of existing facilities and instrumentation (available as auxiliary information on the EOL C-RITE Workshop website, https://www.eol.ucar.edu/c-rite), and making decisions on travel support for the early career scientists, post-docs and graduate students. During the Workshop, they led plenary sessions to discuss and supplement the initial instrumentation inventory and match the existing instrumentation to science needs, leading to the identification of gaps. Finally, the POC members authored this Workshop report, and facilitated creation of the science traceability matrices and the instrument priority table, provided in Appendices 7.3 and 7.4 of this report.

The LOC, led by Jim Moore (NCAR/EOL), was responsible for all local arrangements for the Workshop. This included the venue, website, collaborative online environment support and related on-site arrangements. The LOC was also responsible for travel arrangements for the supported Workshop participants. Staff from both EOL and the UCAR Cooperative Programs for the Advancement of Earth Systems Science (CPAESS) Office were involved in these efforts.

4. 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 developments are discussed that are significant but do not rise to the level of major enhancements. Third, important facilities requiring extensive development and/or major funding are indicated. Fourth, there are highly desired measurements that we do not yet know how to make. The instruments and capability recommendations appear in a bulleted list in each of these four categories. These lists are designed to be comprehensive for the study of turbulence and convection, except for the fourth category, which merely illustrates items on what could be a long wish list. Nevertheless, *the list of recommendations should not be perceived as exhaustive, nor rank-ordered*.

A common thread amongst all topics related to convection and turbulence is *the need for higher temporal and higher spatial resolution* sampling than is currently available. As computational power has grown steadily, numerical simulations have outpaced observational systems in their ability to capture fine details, e.g. cold pool development in supercell storms, wave breaking into turbulence, or the effect of fine-scale turbulence on precipitation growth. Instruments are being developed to address this need, e.g. phased array radar and fine-resolution 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 Lower Atmosphere Observing Facilities (LAOF) pool, and thus can be requested as part of an observationally focused NSF proposal.

4.1 Existing facilities

Many facilities currently exist that are important to retain and support. We present here only those that rise to a level of major significance.

- Three aircraft platforms currently exist in the NSF atmospheric science arsenal: the NSF/NCAR Gulfstream V (GV), 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 array, are central to the NSF atmospheric science program. The NSF/NCAR GV is in high demand for a wide variety of projects, the NSF/NCAR C-130 is uniquely capable of carrying heavy loads, and the UWKA provides a less expensive and more agile platform.
- The current inventory of airborne instrumentation available on the NSF/NCAR and Wyoming aircraft, particularly the radars and lidars and *in situ* cloud physics, trace gas, aerosol, radiation, and turbulence probes are indispensable.
- Dropsondes continue to be irreplaceable for obtaining finely resolved vertical profiles over broad reaches of the oceans and in some cases over land. Though expensive, they provide the only way to obtain mesoscale arrays or grids of comprehensive kinematic and thermodynamic profile information over the ocean.
- Radiosondes are similarly important over land or for making long sounding time series from ships over the ocean. Current technology for launching soundings is inexpensive, compact and highly mobile. The ability for a radiosonde to also collect good data on the way down (following separation from the balloon) is desirable. Consistency in radiosonde launch procedures, data processing, and quality assurance, as well as intercomparisons of sondes from diverse vendors against a reference sonde, are critical for obtaining high-quality data sets that can advance the science. This task is a role NCAR/EOL is in a strong position to assume, even though NCAR/EOL no longer provides radiosondes as a stand-alone facility in the LAOF pool.
- Surface-based continuously-operating tropospheric profiling systems, including wind profilers, cm-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, except for wind profilers, these systems currently are not part of the LAOF pool.

- The highly mobile and versatile Doppler On Wheels (DOW) radars, including the Rapid Scan DOW, are central to the study of convection and turbulence. These radars can be combined with non-LAOF mobile radars to obtain a more complete three-dimensional (3D) structure of storm motions and precipitation characteristics. The S-band Dual Polarization Doppler Radar (S-PolKa) should be retained in the LAOF pool, not just for international deployments, but also for domestic use, as it has capabilities that the WSR-88D network does not have, including dual-frequency and controllable scan strategy (e.g., RHI and vertical pointing).
- Mesoscale networks of ground-based observations, in the US typically coordinated at the state level (e.g. in Oklahoma), play an essential role in the study of both the boundary layer and deep convection. Aside from the usual surface meteorological parameters, chemistry, aerosol, and turbulence measurements can also be made, especially when towers for near-surface profiles are included. Some networks also include lower-tropospheric wind and thermodynamic profiling capabilities.

4.2 Minor enhancements or additions

This list is not necessarily exhaustive but includes those facilities that were prominent in the discussions at the C-RITE Workshop and by the POC:

- NCAR's HIAPER Cloud Radar (HCR) for the NSF/NCAR GV was originally designed to contain both W-band and Ka-band radars. Financial constraints prevented the completion of the Ka-band channel, so it is currently limited to W-band. The committee recommends adding a matched-beam Ka-band radar. This would allow the radar to see further into rainfall regions than is possible with the W-band component, and allow dual-frequency measurements.
- Pilot studies have demonstrated the value of integrated networks of passive (microwave and infrared) and active (e.g. DIAL or Raman lidars) remote sensing instruments for collecting continuous temperature and humidity profiles in the lower troposphere. The development of the Water Vapor DIAL at NCAR/EOL addresses this need, and further should be coupled with 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 of those.
- Mobile X-band systems should be complemented by more powerful, scanning radars at a less attenuating frequency, yet a comparable narrow beam width. Also desired, in the LAOF pool, is a scanning polarimetric Doppler radar with proper stabilization, needed for ship-borne operations.
- An airborne Raman water vapor plus temperature lidar, the Multi-function Airborne Raman Lidar (MARLi), has been developed for nadir measurements on 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.
- A laser-based turbulent air motion measurement system would provide 3D turbulence velocities near the aircraft. This capability has been developed and tested, e.g. by 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 hydrometers, 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, or with a 3D particle mapping capability, in order to detect widely spaced large particles.
- Electric field and field change meters on aircraft would allow routine measurement and mapping of electric fields and lightning activity near thunderstorms. These measurements would help constrain charge distributions and charge movement by lightning in and around these storms. A surface-based portable lightning mapping array (LMA) would allow rapid deployment of this technology near thunderstorms. The technology for this instrumentation is well established, but an LMA currently is not available through the LAOF pool.
- Ground-based scanning Doppler lidars have been developed and used in boundary layer studies. Currently the range of commercial units is typically limited to the boundary layer, but the skill of using

these systems as profiling units or in synchronized dual or triple Doppler scans provides a lot of flexibility in designing measurement strategies that can resolve the spatial and temporal variability of boundary layer processes.

4.3 Major new facilities

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

- A first-ever C-band, polarimetric, Doppler Airborne Phased Array Radar (APAR) is currently under development by NCAR for deployment on the NSF/NCAR C-130. However, the hardware is intrinsically expensive and the technological and data processing challenges are major. This instrument would not only fill a gap in airborne scanning observations of precipitating systems created by the retirement of the Electra Doppler Radar (ELDORA), but also provide new capabilities. It would 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. Use of C-band reduces attenuation over that of X-band radars such as ELDORA or the NOAA P-3 tail radars and the polarization diversity feature would help in the identification of hydrometeor type and understanding microphysical properties. Its development is ambitious, and should be encouraged.
- The instrumentation of a storm-penetrating manned aircraft that can withstand severe turbulence, hail, and lightning strikes is greatly desired by investigators studying continental convection, including severe storms. Such an aircraft would allow measurement of turbulence, 3D wind, trace gases, aerosol, the electric field, and thermodynamic and cloud physical variables along its flight path. A manned aircraft is currently the only reliable way of making such measurements. A US Air Force A-10 aircraft is currently being evaluated by NSF for this role. The need for extensive aircraft modifications without Supplemental Type Certificates, and the lack of other A-10s for civilian use, make this an expensive and high-risk project, but the stakes are high for those studying severe convection.
- Access to a vastly expanded, readily deployable array of towers, at least 30 m high, instrumented with various 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 understood, this item is included here, under major new facilities, as the inclusion of such 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 deploy more specialized sensors, e.g. trace gas chemistry, depending on the research objectives at hand. This is a long-standing need in the field, and currently can only be mitigated through broad, international collaborations, which are difficult to get funded, and result in non-uniform networks (different sensor types, different data processing routines, etc.) and inconsistent data sets.
- Though perhaps not as expensive as the above projects, the development of airborne Doppler lidars in a number of different contexts would benefit a broad range of atmospheric problems. NASA has recently demonstrated the feasibility of using a powerful, eye-safe airborne Doppler Aerosol Wind Lidar (DAWN) to obtain profiles of horizontal wind from altitudes of 10-12 km, even in areas of relatively low aerosol backscatter levels. An airborne Doppler lidar would 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 forward pointing Doppler lidar would allow two-dimensional (2D) wind synthesis, and in combination with a Raman lidar, vertical moisture and heat fluxes could be measured.
- Portable Unmanned Aerial Systems (UASs, or drones) are becoming an increasingly important tool for all sorts of tasks, in particular for formation flights in vertically or 2D stacked arrays, as drones become cheaper and instruments and their data systems are being miniaturized. A key constraint in the US and elsewhere remains stringent regulatory limitations for the use of such platforms. Regulatory limitations are expected to gradually relax through GPS and communication technology, but flight ceiling regulations likely will remain restrictive 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 clouds. Other limitations relate to range, duration, and payload. Mechanical miniaturization and more sophisticated autonomous guidance systems can be developed to overcome some challenges.

4.4 Desired, currently non-existing capabilities

Sometimes there is no obvious way, given current technology, to make the measurements that are needed to advance the science of the atmosphere. Two such cases are listed here with the hope that this will stimulate the development of the technology needed to solve these problems.

- Currently there is no way to map the 3D thermodynamic fields inside a thunderstorm (or any precipitating system) to the spatial resolution obtainable in wind and reflectivity measurements with multiple Doppler radar. Lidars are blocked by cloud, and passive microwave and interferometer systems are compromised by hydrometeors. Upsondes, dropsondes, and storm-penetrating aircraft would not solve this problem, as they only make one-dimensional (1D) measurements. One possible solution that is being explored is to drop swarms of small, biodegradable probes into a storm from an overflying aircraft or balloon. These probes would radio back their location and basic thermodynamic 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 behavior of tropical cyclones is hypothesized to depend strongly on the magnitude of heat, moisture, and momentum fluxes from the sea surface. Measuring these fluxes at a flight level below 100 m MSL becomes increasingly difficult with increasing wind speeds, due 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.

4.5 Disclaimers

The list of instruments/capabilities listed above is neither prioritized nor exhaustive. The recommendations are intended to provide NSF with the most significant information, which by itself probably is 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 the NSF will judge such projects based on their merits irrespective of whether they have appeared in this report.

One aspect of the instrumentation inventory we have not considered is the decision as to whether a particular facility or instrument should be handled by the LAOF pool or by university investigators and private companies. In general instruments need a sufficient technological readiness level, demonstrated reliability and community value 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. 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 in the context of a bundled set of instruments, which 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.

5. Science Discussion Summaries

This section contains summaries of the key frontiers and related observational capability needs for each of the four major topics addressed at the Workshop. Each of the four topics (or sessions) was further divided into three sub-topics (see Workshop Agenda, Appendix 7.1). The summaries below are based on the more extensive summaries produced for each sub-topic. The detailed sub-topic summaries are available online at the C-RITE Workshop website, https://www.eol.ucar.edu/c-rite.

5.1 Boundary layer flow and turbulence

The presentations and discussions of stable boundary layers (SBL), convective boundary layers (CBL), and influences of topography and land use all have some common themes. The highly idealized cases of Atmospheric Boundary Layers (ABLs) over homogeneous terrain that underpin current parameterizations used in most weather and climate models are rarely found in nature. While some progress has been made, important interactions of the ABL with the flow aloft and also with near-surface processes are still poorly understood primarily because observations from previous studies had limited spatial coverage or lacked information about important parameters. Many applications, of great societal relevance, require improving our understanding of realistic ABL flow and turbulence phenomena. Observational capabilities that capture the spatial and temporal variability, and multi-scale interactions of ABL flow and turbulence processes, are critical for meeting these needs. Data sets from these observations can also facilitate the development of better parameterization schemes and ultimately lead to improved predictions from weather and climate models. Data quality and management were also identified as being very important for successful observational campaigns.

In terms of key scientific frontiers and observational needs, the group identified three broad topic areas, and various needs related to each topic:

1. Observations that document the structure of the entire ABL and its interactions with the free troposphere:
    - Understanding basic characteristics of turbulence structure in SBLs and its representation in models
    - Interactions between kinetic and thermal energy in SBLs
    - Role of large coherent eddies and wave flow in SBLs
    - Transition from clear to cloudy CBLs (the topic of moist BL convection is addressed in section 5.2)
    - Processes at top of boundary layer (entrainment, shear instability, waves, subsidence)
    - Aerosol concentrations and composition to investigate possible aerosol effects on entrainment and cloud processes
    - General definition of the ABL in complex terrain and urban areas
    - Is the concept of the mixing height still relevant? Model validation really requires continuous vertical profiles of turbulence parameters.
2. Observations that document the structure of the entire ABL and its interactions with the land or ocean surface
    - Structure of the SBL over plant and urban canopies
    - Radiative flux divergence near the surface
    - Surface energy balance and its relationship to CBL evolution
    - Turbulence, biology, and chemistry interactions in and above canopies
    - Structure, dynamics and turbulence properties in the canopy (vegetation/urban) layer, roughness sub-layer and mountain ABLs
    - Sea-air fluxes and MBL structure under high wind speeds and choppy waters

- Do the idealized concepts of urban dome circulation vs. urban plume apply and what are the conditions under which they form? Details about flow and turbulence characteristics are needed to investigate impacts on air quality and convection.

3. High-resolution observations of ABL spatial and temporal variability
   - Heterogeneity of thermal and frictional properties
   - Step changes versus patchy variability in surface properties
   - Improved physics of the morning and afternoon transitions
   - Role of advection and mesoscale processes
   - ABL turbulence and depth characteristics in convergence zones (thermally or topographically-driven)
   - Dynamic feedbacks between boundary layers and convection and influence on precipitation (type, intensity)
   - Impacts of natural and anthropogenic changes of the land-surface characteristics and potential related emissions of trace gases and aerosols caused by wildfires, oil and gas exploration, renewable energy, natural disasters, seasonal changes in vegetation
   - New theoretical approaches for dealing with heterogeneity such as stochastic approaches and probability density functions

The C-RITE participants felt very strongly that integrated measurements of traditional meteorological parameters and chemical species concentrations throughout the ABL can lead to new insights about ABL dynamics and atmospheric chemistry. Good coordination between the meteorology and chemistry community in designing measurement campaigns can leverage resources and most importantly also advance our scientific understanding.

While the discussions in the breakout sessions also highlighted the need for airborne instrumentation, particularly for lidars and radars, the summary of the instrumentation needs below focuses primarily on ground-based platforms. Given the cross-cutting nature of some of the topics, and given that the needs for airborne platforms are well described in Sections 5.2-5.4, it was decided not to duplicate the list here in Section 5.1.

Detailed information about the specific instrumentation needs can be found in the traceability matrix (Appendix 7.3) and instrumentation priority table (Appendix 7.4). The six most critical facilities and their current status are:

1. A well designed and integrated **network of towers** with eddy covariance sensors, state variables, nano-barometers (greater than 10 Hz time resolution), 4-component radiometers (measuring each the incoming and outgoing shortwave and longwave radiation, respectively), and atmospheric composition (including aerosols) at multiple levels. Consistency is absolutely critical, in sensor design and accuracy, in data acquisition, transmission, storage, and management, and also in the scientific processing of the data. Having such capabilities in the LAOF pool is extremely valuable. It would be ideal if the network could be expanded to 50+ towers to allow detailed measurements of the turbulence structure in the lowest 100 m. In addition to atmospheric observations, the tower network should be supported by soil temperature and moisture profiles, soil heat flux measurements, and measurements of plant characteristics (such as leaf area index, stomata, conductance, etc.).
2. A reliable and quality-assured, high-frequency **radiosonde network**. Sampling during both up and down transects is a simple way of doubling the observation frequency. The current radiosonde calibration and QC capability in the LAOF remains valuable and critical, especially given the diversity of PI-provided radiosonde systems.
3. **A network of kinematic BL profilers,** including scanning Doppler wind lidars (with option of dual and triple Doppler lidar scans) as well as clear-air radar wind profilers. A well designed and integrated network of these profiling instruments will allow capturing the entire ABL structure, interactions between the ABL and larger scale flow, and can provide more detailed information about the spatial variability in urban areas or

complex terrain. While several groups have components of such a network, there is no easy mechanism for the NSF community to get access to an integrated profiler network.

4. **A network of thermodynamic/humidity profilers**. Both passive (microwave and infrared) and active (e.g. DIAL or Raman lidars) remote sensors can provide continuous T, q profiles. As with the kinematic profilers, such a network is critical for advancing the science. While several groups have components of such a network, a well-designed community network does not exist.
5. **Unmanned Aerial Systems** (UASs) provide novel opportunities for sampling the ABL and have the potential to provide unique data sets that can advance the discussed scientific frontiers. As an example, UAS observations can more easily document the spatial variability of surface and atmospheric properties. However, for successful UASs applications it is critical that new and well-tested sensor packages are developed that provide reliable observations of thermodynamic, dynamic, chemical and turbulence parameters. Much progress has been made by individual groups but access to reliable platforms and sensor packages by the larger community is currently difficult and the regulatory environment remains uncertain.
6. Instrumentation for observing **sea-air fluxes in high wind speeds**, e.g., in tropical cyclones. This remains an unresolved challenge (Section 4.4).

5.2 Dynamics and thermodynamics of convection

Understanding and representing convection, in its various forms, is central for developing convective parameterizations in weather and climate models, as well as improving forecasts and nowcasts of high-impact convective events. The focus here is on process studies of convection, from shallow to deep convection, over land and over oceans. While the basic dynamics of various idealized convective systems (e.g., shallow convective cells organized in linear or cellular patterns, ordinary thunderstorms, multi-cellular clusters, supercells, squall lines, mesoscale convective systems, hurricane rainbands, etc.) are reasonably well understood, convection in less archetypal forms needs to be understood better. A good deal of convection does not fit common idealizations.

The two-way interaction of convection with its environment is rather poorly understood, for all forms of convection. This interaction includes the heat, moisture, and momentum added to the environment by convection. It also includes the form of convection, especially organized convection, that arises for spatially variable environmental conditions. Mesoscale budget measurements plus direct observation of convective characteristics are the keys for improving our understanding of these processes.

An emerging theme about convection that warrants particular attention involves transitions. These include the transition from shallow to deep moist convection, changing mesoscale patterns of shallow convection, non-aggregated to aggregated deep convection, and convective dissipation. Transitions are also an important manifestation of the diurnal cycle, which necessitates our inclusion of BL processes and cloud-radiative interactions. A challenge for observing transitions is the need for continuous sampling over a period longer than typical research flight durations or over an area larger than the available surface-based instrumentation network.

There are notable gaps in instrumentation to observe convection, but gaps arise for different reasons. Certain platforms and instrumentation are expensive (long-endurance, high-altitude drones, ships), face regulatory obstacles (drones, dropsondes over land), and their deployment may be technically difficult (e.g., thermodynamic measurements in deep convection). Many of the tools needed already exist, and will continue to be indispensable for observing convection, but targeting is difficult, especially for rare events like tornadoes, and deployment is sometimes hampered by logistical or safety concerns. Other instruments are in development (see C-RITE instrumentation inventory in the Appendix) or mostly conceptual (such as the swarms of small, biodegradable probes, discussed in Section 4.4).

The following is a list of high priority instrumentation needed to resolve basic questions of convection. Gaps or shortcomings associated with each are noted:

1. **Dropsonde** technology is proven and remains a bedrock instrument for studying the environment of all types of convection, but dropping sondes is highly restricted over land. Therefore **radiosondes** are key for the study of deep convection over land, and they are often released in rapid sequence and close proximity. Dropsondes are currently the only reliable tool to obtain grids of soundings over the ocean.

2. FAST (Fore/aft scanning technique) **scanning airborne Doppler radar** facilitates dual Doppler synthesis of 3D wind fields at high resolution. C-band is preferable to minimize attenuation and polarization diversity helps identify precipitation type. The NCAR APAR instrument is a promising development for use on the NSF/NCAR C-130, although it may be years before it can be used to study deep convection. The absence in the LAOF pool of an airborne scanning Doppler radar implies that the NSF community currently is unable to examine the 3D (or even merely the horizontal) structure of precipitating systems using aircraft.
3. **Ground- or ship-based Doppler radar** can be used in single or multiple Doppler mode with the aid of other radars. NSF's highly capable S-Polka radar and the highly mobile Doppler On Wheels radars are essential facilities for convective work over land. There are no shipborne scan-stabilized radars available to the NSF community and ship time is scarce and expensive.
4. **Airborne broadband radiative flux instruments** (visible and infrared) are readily available and remain important for measuring cloud-radiation interactions.
5. ***In situ* airborne high-frequency temperature/humidity/wind/pressure instruments** exist, including radiometric in situ temperature measurement unaffected by exposure to cloud water. However, there are significant restrictions on the penetration of strong convection with existing aircraft.
6. **W- and K-band airborne and ground/ship-based Doppler radar profilers** are important tools for characterizing hydrometer characteristics and cloud vertical velocities. The NSF LAOF pool includes a W-band radar for all three aircraft (WCR for UWKA and NSF/NCAR C-130, HCR for the NSF/NCAR GV). Addition of a beam-matched Ka-band capability to the HCR should be high priority. These radars are very useful for vertical structure, whereas APAR will be most useful for horizontal (and 3D) structure.
7. **Airborne and surface-based cloud and precipitation particle sizing and imaging instrumentation** is important in the study of deep convection since cloud and precipitation properties are important to storm dynamics and storm hazards.
8. **Airborne profiling lidars for wind, temperature, and humidity** can supplement dropsondes under certain circumstances. This technology is experiencing rapid development, and some airborne lidars already exist: for instance, the NASA DAWN Doppler lidar uses scattering from atmospheric aerosol particles. It is meant for boundary layer observations, but recent tests over the Gulf of Mexico and Caribbean show that mid-tropospheric signals in maritime conditions are sometimes usable as well. The MARLi Raman lidar is able to profile water vapor and temperature below the NSF/NCAR C-130 and the UWKA at a resolution of ~1000 (100) m in the horizontal (vertical). Ground-based profiling lidars are becoming available to the community: NCAR operates compact water vapor DIALs (differential absorption lidars) on the ground, and is planning to add temperature profiling capability. Temperature and humidity lidars have a higher resolution than passive microwave instruments, but are confined to optically-clear regions.
9. **Ground, buoy, or ship-based surface flux measurements** supply the lower boundary conditions for convection and are more accurate than fluxes derived from soundings using bulk techniques.
10. **Mobile surface stations** ("mobile mesonets", "sticknets") have been the primary way by which surface thermodynamic and wind observations have been obtained in severe continental storms.

NSF maintains several platforms that currently deliver or are capable of delivering most of the instrumentation listed above. These include ships, the NSF/NCAR GV, the NSF/NCAR C-130, and the UWKA. However, none of the airborne platforms can penetrate strong convection, especially continental convection, and strong tropical convection within developing or mature tropical cyclones. Thus, **a convection-penetrating aircraft is highly desired**. Microphysical and *in situ* thermodynamic observations would be especially useful; with respect to the former, we have almost no ability to validate polarimetric radar-based hydrometeor retrievals or model microphysics schemes without *in situ* microphysical observations, and we presently have no platform that can obtain these. Usefulness for maritime convection depends on aircraft and radar range capabilities. Usefulness for continental convection depends on ability to penetrate regions with hail and active lightning.

5.3 Free tropospheric flows and turbulence

While the flow above the ABL and away from penetrating convection generally is laminar, turbulence occurs occasionally and poorly predictably, over a range of scales and intensities. The horizontal and vertical extent, persistence, and power spectrum of free-tropospheric turbulence is poorly understood. Recent fine-scale radar and lidar observations and simulations have shown narrow ribbons or sheet-like regions of breaking billows or waves generated by shear flows in otherwise mostly laminar flow. Shear instabilities often are released near jet streaks, fronts, and terrain-driven flows, including downslope wind storms. Vertically propagating gravity waves may break, e.g. near a critical level. Turbulence can occur both in clear air and in clouds, and clouds may be coincidental or the source of turbulent kinetic energy (TKE).

The important scales of in-cloud turbulence range from millimeters to hundreds of meters. On the scale of typical distances between hydrometeors, turbulence may affect microphysical processes such as droplet collision/coalescence and rain growth, accretional growth in mixed-phase clouds, and snow aggregation. On larger scales, turbulent drafts may affect supersaturation and thus droplet and ice initiation, and may produce variable concentrations of liquid water and hydrometeors. Both in clear air and in cloud, pockets of turbulent flow obstruct the stratified flow in their vicinity much as mountains do, and can be responsible for waves and turbulent flow phenomena similar to those forced by mountains.

Irrespective of whether turbulence occurs in cloud or in clear air and over mountains or not, some key scientific questions remain largely unanswered, and turbulence of hazard to aviation remains poorly predicted. Remotely sensed observations depicting the spatial structure of turbulent flows at a resolution of O (10 m) or better are needed. These, in combination with more comprehensive *in situ* measurements (that capture not only the flow, but also state variables and cloud microphysics), numerical simulations, and theoretical studies, will transform understanding of how turbulent flows are generated and how they evolve. Some examples of applications of this understanding are the influence of microscale turbulence on the interaction of hydrometeors as they collide and coalesce/aggregate or rebound, important for understanding precipitation formation, and cloud electrification through charge exchange in rebounding collisions.

Workshop participants proposed a number of priority observing platforms and instruments to obtain both remote and *in situ* observations:

1. In the area of **remote sensing**, the most highly-desired instrument characteristics are higher sensitivity, finer resolution, and, for scanning systems, faster volume sampling.
   - In areas of sufficient scatterers (cloud, precipitation, or chaff), profiling and scanning Doppler radars are needed. Shorter wavelengths with narrower beam widths are preferred, to maximize sensitivity and resolution. The technology exists to build ultra-high-resolution, sensitive Doppler radars collecting RHI scans in rapid sequence.
   - In clear air, Doppler lidars and passive optical spectrometers are useful, although current lidars lack sensitivity to detect backscatter in the relatively clean upper troposphere.
   - The Doppler spectrum of wind profiler and shorter-wavelength profiling radars offers a useful surrogate for TKE in precipitation (and also in clear air for wind profilers), but this surrogate does not depict the fine-scale structure of turbulent flows.
   - Airborne profiling radars can obtain higher-resolution data in proximity of the aircraft, and relate the Doppler radar data to *in situ* measurements.
2. Transformational ***in situ*** **observations** can be obtained using high-rate sensors on aircraft, manned and unmanned, and new balloon-borne instrument packages as well as state-of-the-art dropsondes.
   - An airborne 3D laser-based turbulent airflow sensor, currently in development at NCAR, promises to yield high-resolution turbulent flow measurements at scales broader than captured by the commonly used eddy dissipation rate sensors.
   - To study how turbulence affects droplet growth and other cloud microphysical processes, probes are needed that describe the spatial arrangement and movement of hydrometeors, as well as microphysical

probes that can sample larger volumes faster to detect and depict particles ranging in size from micrometer to cm-scale.

- A swarm of small instrumented UASs could be deployed in a formation to sample transects or volumes of the atmosphere. This technology is still in its infancy, and there is a long path to resolving air traffic control coordination issues for unmanned aircraft sampling in the free troposphere.
- Balloon-borne *in situ* studies of either cloud or clear-air turbulence also will require more sensitive and higher frequency thermodynamic and wind observations than are currently available from standard radiosondes. Such measurements have been made in the boundary layer, using tethered systems. They are desired in the free troposphere as well, e.g. using long-duration driftsondes (see #4 below).

3. **A network of all-weather flux towers**, at least 30 m tall, as called for in Session I (Boundary layer flow and turbulence), will allow much progress in understanding turbulent phenomena in complex terrain. A large collection of mobile, or at least easily deployable, units is desirable so studies can be conducted in different geographic settings using the same suite of instruments.
4. A novel capability for balloon-borne observations involves commercially available "**driftsondes**", i.e. large balloons that drift with some control in the upper troposphere/lower stratosphere. Along the way, they may deploy a series of dropsondes and obtain *in situ* observations, over an extended period of time. A new concept, currently under development, is to deploy a long tether from a driftsonde, or a controlled tow vehicle from an aircraft, with instrumentation attached at regular intervals, yielding a vertical profile of thermodynamic, wind and TKE observations along the balloon or aircraft track.
5. **An autonomous turbulence probe on commercial aircraft, in a partnership with the aviation industry**. This could dramatically improve the monitoring, nowcasting, and prediction of free-tropospheric turbulence. Different observing schemes may be better for clear-air turbulence than for orographic and in-cloud turbulence. The turbulence probe may be combined with other atmospheric sensors. Limited campaigns of this type have been conducted successfully. With advances in instrumentation and autonomous controls, and even active control from the ground, better coverage with more comprehensive as well as more sensitive and accurate observing systems on the operational transportation aircraft fleet is possible.

Advances in understanding and nowcasting/predicting free tropospheric turbulence are possible, driven by new observing technologies and new numerical simulation capabilities. Such advances will be most welcome to the aviation industry, as hazardous turbulence remains poorly observable and predictable.

5.4 Physical processes in convection

There is no natural separation into discrete categories of the physical processes impacting convection. Advances in our understanding of cloud electricity and lightning rely on better observations of aerosol and cloud microphysics as well as cloud structure and dynamics. Advances in our understanding of chemistry, such as upper tropospheric ozone production, rely on better observations of lightning flash rate, storm extent, and other storm characteristics. Advances in cloud physics rely on proxy measurements such as level of maximum detrainment from chemical tracers to constrain the updraft and entrainment characteristics. These are just a few examples of how the three subcategories of physical processes discussed in this section are interconnected.

Because these processes are all intertwined, observational platforms that advance the science in one area will benefit the science in all the areas. **A common thread is a need for high temporal (less than 1 minute) and high spatial (10 m) sampling** to capture the convective scale processes. Key observational needs benefiting our understanding of physical processes in convection are as follows:

1. A **storm-penetrating aircraft** is needed to make high spatial and high temporal resolution airborne measurements of vertical velocity, full hydrometeor size distributions (as noted in Section 5.2), hail/graupel characteristics, electrical charges on these hydrometeors, aerosol concentrations and characteristics, and a wide range of trace gases. A storm penetrating aircraft will significantly advance our knowledge by obtaining these measurements in storm cores of strong convection. Such measurements will also provide calibration information for remote sensing platforms (e.g., ground-based dual-polarization radars and satellite-based retrievals). Concurrently, storm inflow and outflow regions need to be sampled by the same aircraft, using

inlets suitable for removing cloud particles from the inlet lines of the instrument, allowing the budget of moisture, aerosols, or trace gases to be closed.

2. The **3D spatial and temporal distributions of aerosol concentrations, cloud water and ice, and trace gases** are also desired to understand the role of heterogeneities of these distributions. Aerosol concentrations can be collected with aircraft and aerosol lidar. High resolution cloud physics measurements can be made with rapid scan radars, such as phased array radars. Both mm-wave and cm-wave radars are useful, to distinguish cloud and precipitation echoes. Trace gas concentrations are measured primarily by *in situ* methods, but remote sensing techniques also exist (e.g., ozone and NO_2 lidars).
3. To better understand the physics of the lightning process, **lightning observing platforms** need expanded "visibility" to all components and locations of the flash, by including other frequencies and newer techniques (e.g., VHF broadband interferometer array, E-field change (Marx) meter array). A portable lightning mapping array is required to collect data on lightning characteristics from a wider range of storms and thermodynamic environments

As the physical and chemical processes are intertwined, the processes in convection in general overlaps strongly with the other topics discussed in the CRITE Workshop. Thus, many of the measurement capabilities needed to better understand the physical processes are also required for Boundary Layer Flow and Turbulence (Section 5.1) and Dynamics and Thermodynamics of Convection (Section 5.2). Advances in observations and scientific understanding of these fields will advance the understanding of physical processes in convection. Conversely, advances in physical processes aid the science and observations of boundary layers and convection. We emphasize that good coordination between the severe storm and air chemistry communities in designing measurement campaigns can leverage resources and advance our scientific understanding.

6. Acknowledgments

A large number of individuals and organizations have been involved in the realization of the C-RITE Workshop. Their individual efforts and contributions are acknowledged here.

Co-Conveners: Vanda Grubišić (NCAR/EOL), Chris Davis (NCAR/MMM)

Program Organizing Committee (POC) Members: Mary Barth (NCAR/ACOM), Gretchen Mullendore (University of North Dakota), Petra Klein (University of Oklahoma), Andy Detwiler (South Dakota School of Mines & Technology), Bart Geerts (University of Wyoming), Wen-Chau Lee (NCAR/EOL), Paul Markowski (Pennsylvania State University), David Raymond (New Mexico Tech)

Local Organizing Committee (LOC) Members: EOL Staff: Patti Kidd, Amy Honchar, Jim Moore; CPAESS Staff: Melanie Russ, Gete Bond, Megan Jennings

Plenary Leaders, Science Topic Overview Presentations, Plenary Synthesis: Petra Klein, Gunilla Svensson, Wayne Angevine, Julie Lundquist, David Raymond, Matt Parker, Larissa Back, Paquita Zuidema, Bart Geerts, James Doyle, Pavlos Kollias, Robert Sharman, Mary Barth, Larry Carey, Sue van den Heever, Ken Pickering

Breakout Session Leaders: Jielun Sun, Jordi Vila, Petra Klein, Steve Nesbitt, David Raymond, Tammy Weckwerth, Vanda Grubišić, Bart Geerts, Stan Trier, Andy Detwiler, David Turner, Gretchen Mullendore

Breakout Session Rapporteurs: Tim Wagner, Andrey Grachev, Dan Li, May Wong, Adel Igel, Stipo Sentić, Rochell Worsnop, Rosimar Rios Berrios, Dave Bodine, Mikael Witte, Minghui Diao, Justin Whitaker

Special thanks are extended to Fred Carr, for his summary of observing needs from the 2017 AMS Annual Meeting; Eric Bruning, for contributing to the cloud electricity and lightning summary document; James Hurrell, the NCAR Director and Vanda Grubišic, the EOL Director for co-sponsorship and facility support; and the National Science Foundation for supporting the C-RITE Workshop.

7. Appendix

7.1 Workshop Agenda

7.2 Workshop Participants

7.3 Science Traceability Matrices

7.4 Instrument Priority Table

7.5 Instrument Inventory (https://www.eol.ucar.edu/c-rite)

7.6 Summary Documents for all 12 sub-topics (https://www.eol.ucar.edu/c-rite)

1) Boundary Layer Flow and Turbulence
   a) Stable Boundary Layers
   b) Convective Boundary Layers and Entrainment Processes
   c) Effects of Topography and Land Use
2) Dynamics and Thermodynamics of Convection
   a) Continental Convection
   b) Maritime Convection
   c) Shallow Convection
3) Free Troposphere Flows and Turbulence
   a) Mountain Winds And Turbulence
   b) Turbulence in Clouds
   c) Clear-Air Turbulence
4) Physical Processes in Convection
   a) Cloud Electricity and Lightning
   b) Aerosols, Cloud Physics and Radiation
   c) Chemistry

7.1 Workshop Agenda

The C-RITE Workshop was held at the UCAR Center Green Campus (22-23 May 2017) and at the NCAR Foothills Campus FL2 (24 May 2017), in Boulder Colorado.

Day 1: Monday, 22 May 2017

- 7:30-8:00: Registration Continental Breakfast, Set-up of posters
- 8:00-8:10: Welcome from NSF (Pat Harr)
- 8:10-8:25: Workshop Goals and Expectations (Vanda Grubišić)
- 8:25-8:30: Logistics (Jim Moore)
- Session I: Boundary Layer Flow and Turbulence (All plenary sessions in CG Auditorium)
  - 8:30-8:40: Plenary - Goals and expectations of Boundary Layer Flow and Turbulence (Petra Klein)
  - 8:40-9:40: Overview Presentations (three 20 min presentations)
    - Stable Boundary Layers (Gunilla Svensson)
    - Convective Boundary Layers and Entrainment Processes (Wayne Angevine)
    - Influence of Topography and Land Use (Julie Lundquist)
  - 9:40-10:00: Discussion
  - 10:00-10:15: Break (move to breakout rooms) set up posters (new and emerging technologies), posters will remain for 2 days
- 10:15-11:30: Session I Breakout Groups
  - Stable Boundary Layers (Jeilun Sun) (CG1 room 3131)
  - Convective Boundary Layers and Entrainment Processes (Jordi Vila) (CG1 Auditorium)
  - Influence of Topography and Land Use (Petra Klein) (CG1 S. Auditorium)
  - 11:30-12:15: Plenary - Summary from each breakout session and brief discussion/clarifications
  - 12:15-13:30: Lunch (on your own, NCAR Center Green Cafeteria)
- Session II: Dynamics and Thermodynamics of Convection (All plenary sessions in CG Auditorium)
  - 1:30-1:40: Plenary - Goals and expectations of Dynamics and Thermodynamics of Convection (David Raymond)
  - 13:40-14:40: Overview Presentations (three 20 min presentations)
    - Continental Convection (Matt Parker)
    - Maritime Convection (Larissa Back)
    - Shallow Convection (Paquita Zuidema)
  - 14:40-15:00: Discussions
  - 15:15-15:30: Break (move to breakout rooms)
- 15:30-16:45: Session II Breakout Groups
  - Continental Convection (Steve Nesbitt) (CG1 Center Auditorium)
  - Maritime Convection (David Raymond) (CG1 room 3131)
  - Shallow Convection (Tammy Weckwerth) (CG1 South Auditorium)
  - 16:45-17:30: Plenary - Summary from each breakout session and brief discussion/clarifications
- 17:45-20:00: Reception and Special Presentation (CG1 Auditorium)
  Summary of AMS work on observations from AMS Annual Meeting (Fred Carr)

Day 2: Tuesday, 23 May 2017

- 7:50-8:20: Continental Breakfast
- 8:20-8:30: Logistics (Jim Moore)
- Session III: Free Troposphere Flows and Turbulence (All plenary sessions in CG Auditorium)
  - 8:30-8:40: Plenary - Goals and expectations of Free Troposphere Flows and Turbulence (Bart Geerts)
  - 8:40-9:40: Overview Presentations (three 20 min presentations)
    - Mountain Winds and Turbulence (Jim Doyle)
    - Turbulence in Clouds (Pavlos Kollias)
    - Clear-air Turbulence (Robert Sharman)
  - 9:40-10:00: Discussions

- 10:00-10:15: Break (move to breakout rooms)
- 10:15-11:30: Session III Breakout Groups
  - Mountain Winds and Turbulence (Vanda Grubišić) (CG1 South Auditorium)
  - Turbulence in Clouds (Bart Geerts) (CG1 Center Auditorium)
  - Clear-air Turbulence (Stan Trier) (CG1 room 3150)
  - 11:30-12:15: Plenary - Summary from each breakout session and brief discussion/clarifications
  - 12:15-13:30: Lunch (on your own, NCAR Center Green Cafeteria)
- Session IV: Physical Processes in Convection (All plenary sessions in CG Auditorium)
  - 13:30-13:40: Plenary - Goals and expectations of Physical Processes in Convection (Mary Barth)
  - 13:40-14:40: Overview Presentations (three 20 min presentations)
    - Cloud Electricity and Lightning (Larry Carey)
    - Aerosols, Cloud Physics and Radiation (Sue van den Heever)
    - Chemistry (Ken Pickering)
  - 14:40-15:00: Discussion
  - 15:15-15:30: Break (move to breakout rooms)
- 15:30-16:45: Session IV Breakout Groups
  - Cloud Electricity and Lightning (Andy Detwiler) (CG1 South Auditorium)
  - Aerosols, Cloud Physics and Radiation (David Turner) (CG1 Center Auditorium)
  - Chemistry (Gretchen Mullendore) (CG1 room 3150)
  - 16:45-17:30: Plenary - Summary from each breakout session and brief discussion/clarifications
  - 1730: Take down all posters
  - Time for Breakout rapporteurs to meet to produce summary information for synthesis session

Day 3: Wednesday, 24 May 2017
- 7:50-8:20: Continental Breakfast
- 8:20-8:30: Logistics (Jim Moore)
- Session V: Plenary Synthesis (NCAR Foothills Campus, FL2-room 1022)
  - 8:30-8:45: Summary of Boundary Layer Flow and Turbulence (Petra Klein)
  - 8:45-9:00: Summary of Dynamics and Thermodynamics of Convection (Dave Raymond)
  - 9:00-9:15: Summary of Free Troposphere Flows and Turbulence (Bart Geerts)
  - 9:15-9:30: Summary of Physical Processes in Convection (Mary Barth)
  - 9:30-9:50: Discussion
  - 9:50-10:20: Break
- 10:20-11:40: Synthesis of Priorities and Recommendations (Vanda Grubišić)
- 11:40-12:00: Wrap Up (Pat Harr)

7.2 Workshop Participants

Local participants: Fiaz Ahmed; Nicholas Anderson; Wayne Angevine; Brian Argrow; Linnea Avallone; Duncan Axisa; Larissa Back; Robert Banta; Mary Barth; Michael Bell; Laura Bianco; David Bodine; Tim Bonin; Paloma Borque; Stacy Brodzik; Eric Bruning; Michael Buban; Larry Carey; Fred Carr; Joseph Cione; Scott Collis; Andy Detwiler; Minghui Diao; James Doyle; Harald Edens; Chris Fairall; Graham Feingold; Stephen Frasier; Jeff French; Eric Frew; Guoqing Ge; Bart Geerts; Franziska Glassmeier; Alan Goldstein; Andrey Grachev; Vanda Grubišić; Samuel Haimov; Patrick Harr; Andrew Heymsfield; Terry Hock; Laura Hutchinson; Adele Igel; Alexander Jacques; Jorgen Jensen; Alicia Klees; Petra Klein; Kevin Knupp; Pavlos Kollias; Karen Kosiba; Andrew Kren; Alexander Krull; Wen-Chau Lee; Don Lenschow; Dan Li; Eric Loew; Julie Lundquist; Lou Lussier; Don MacGorman; Paul Markowski; Shane Mayor; Katherine McCaffrey; Lynn McMurdie; Shree Mishra; Jim Moore; Hugh Morrison; Gretchen Mullendore; Steve Nesbitt; Larry Oolman; Vladimir Ostashev; Matthew Parker; Ola Persson; Ken Pickering; David Plummer; Jim Ranson; David Raymond; Rosimar Rios-Berrios; Andrew Roberts; Glen Romine; Steven Rutledge; Thomas W. Schlatter; Seda Senay; Stipo Sentić; Robert Sharman; Paul Shepson; Paul Smith; Jeff Snider; Scott Spuler; Daniel Stechman; Jeff Stith; Greg Stossmeister; Jenny Sun; Jielun Sun; Gunilla Svensson; Michael Tjernström; Stan Trier; David Turner; Kristie Twining; Sue Van den Heever; Jorge Vila Guerau De Arellano; Jothiram Vivekanandan; Holger Vömel; Tim Wagner; Jingyu Wang; Zhien Wang; Tammy Weckwerth; Morris Weisman; Justin Whitaker; William Winn; Mikael Witte; Cory Wolff; May Wong; Rochelle Worsnop; Joshua Wurman; Paquita Zuidema

Remote participants: Teresa Campos; Brian Carroll; Leila Carvalho; Chandra V. Chandrasekar; Aditya Choukulkar; John Cortinas; Stephan De Wekker; Wiebke Deierling; David Delene; Belay Demoz; Ankur Desai; Jim Dye; Javier Fochesatto; Stephen Frasier; Samuel Hall; Cameron Homeyer; John Horel; Heidi Huntrieser; Matthew Igel; Alicia Klees; Kristen Rasmussen; Yvette Richardson; Alfred Rodi; Perry Samson; Russ Schumacher; Megan Schwartz; Matthias Steiner; Jeff Stith; Sarah Stough; Robert Wood; Paul Wooldridge; Zhifeng Yang

7.3 Science Traceability Matrices

One of the major outcomes from the C-RITE Workshop was to develop a set of Science Traceability Matrices (STM)s for each of the 12 science sub-topics. There are five columns in each STM: the Science Frontier, Key Measurement Requirement (e.g. physical parameter), Instrumentation Requirements, Challenges (technological, cost, resolution, coverage), and other comments to help explain the concept described.

Boundary Layer Flows and Turbulence

Stable Boundary Layers				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. Structure of the entire stable boundary layer (SBL) and the free flow Kinetic and thermal energy conservation, e.g., how momentum is extracted from the atmosphere, interactions between kinetic and thermal energy in controlling turbulence intensity and intermittency, and coupling with the background large-scale flow.	Vertical profiles of temperature, wind vector (u,v,w), water vapor, pressure, through the SBL, residual layer and into the free troposphere as well as all surface energy budget terms. Large-scale advection of the flow properties.	Mean and turbulence quantities, including fluxes with standard *in situ* instrumentation (towers with sonics, soundings, tethered instruments, radiation sensors etc.) combined with remote sensing profilers (Doppler lidar, sodar, radiometers etc.) Soil temperature sensor and soil water sensor or soil heat flux plate for ground heat flux.	High vertical resolution O(1 m), specially near the surface. High temporal resolution O(1 min), challenge for remote sensing. Observations of advection tendencies are difficult, reanalysis cannot be used for the SBL although models are useful.	Need measurements to provide all components in kinetic, thermal, and momentum budget across a wide range of temporal scales, i.e., across frequencies from synoptic scale to turbulence. Adequate spatial and temporal coverage of observations is critical to understand physical processes. Latest aerosol scanning Doppler lidars may provide detailed instant 3-D volume rendering of the flow.
2. Flux divergence near the surface	Same as above	Same as above	Higher vertical resolution Standard eddy correlation techniques are not sufficient, undersampling of small eddies	Theoretical challenges on what is observed: roughness elements and fetch present issues. Virtual tower using multiple lidars could be explored.
3. Horizontal and vertical heterogeneity are particularly important for SBL.	Same as above, plus: Soil temperature, water, conductance, type (clay etc.) to address thermal characteristics of soil thermal contribution to the atmosphere Characteristics of the roughness sublayer, including plant/building characteristics such as plant types, building heights and gaps etc.	Same as above, but with high spatial coverage Soil and vegetation characteristics	Same as above Spatial coverage with relevant horizontal resolution. O(~100) towers with *in situ* turbulent and mean variable measurements e.g., CentNet. Low flying UAS, scanning remote sensing etc.	Same as above. One broad, collaborative field campaign will serve the needs better than many small focused campaigns. Such campaign can be highly interdisciplinary, may need to team up with ecologists, hydrologists, and soil scientists.
4. Atmosphere-surface (land and water, snow and ice) interaction.	Same as above	Same as above	Mini towers, Doppler lidar for point measurements to resolve turbulent fluxes, water wave measurements and temperature profiles in water for air-water interactions	We lack understand on the vertical transition from molecular diffusion near the surface to turbulent mixing above. The traditional approach of conductance no sufficient. Extremely high spatial characterization and vertical resolution to capture the transition of molecular diffusion to turbulent mixing. Measurements below the surface may be needed too.

Convective Boundary Layers				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. Clouds	Cloud base Cloud top Cloud optical depth Liquid water content Turbulence profiles Cloud field properties	Ceilometers Raman Lidar Radar Aircraft platforms Doppler lidar All-sky camera Radiometric profilers	Continuous column vs. instantaneous line	Testbed strategy Remote sensing for cloud spatial distribution
2. Surface Energy Budget	Sensible heat flux, evaporation, ground heat flux, shortwave and longwave incoming and outgoing, soil moisture	Eddy covariances Scintillometer Soil moisture profiles		In combination with remote sensing
3. Processes at the BL top (entrainment, shear, waves, clouds)	State variables interface Boundary layer growth Turbulence profiles	Radiosondes UAS Aircraft platforms Lidar Tethered observations		
4. Large-scale Forcing of the BL (Subsidence, advection)	Subsidence is unmeasurable Spatial distribution of mean variables on large scale	Radiosondes Aircraft? Dropsondes? Radar wind profiler Radiometric profilers	Indirect (budget) methods necessary	Can often best be provided by operational models. Telescoping strategy: central site with detailed observations surrounded by smaller sites at larger spatial scales
5. Spatial and Temporal BL transitions	State variables: surface and upper vertical profiles (mean and fluxes)	Tall tower (network) Doppler lidar High-frequency radio-soundings		
6. Sub-grid heterogeneity	Spatial distribution of mean and flux variables Plant and canopy properties (subannual variability)	Multiple eddy covariance array network Scintillometer (microwave) Active and passive optical fiber IR camera	Need direct survey of plant properties, which are labor intensive	

Convective Boundary Layers				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
7. Physics-chemistry-vegetation interaction	In and above canopy: mean and fluxes Plant physiology Soil exchange	Fast and precise frequency atmospheric compounds EC isotopes	Need to deploy and integrate comprehensive measurements of dynamics and chemistry	Synergy with remote sensing
8. Aerosol interaction: Land/clouds/chemistry	Optical characteristics Aerosol composition Atmospheric composition	Lidar Size and concentration of aerosols	Raman lidar-based trace gas measurement is a new development	

Influence of Topography and Land Use				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. High spatial and temporal variability of flow, turbulence, and thermodynamics in complex terrain and heterogeneous BLs in urban areas, vegetative canopies, coastal regions, at geo-engineered sites, and areas affected by wildfires.	Profiles of wind speed, wind direction, turbulence parameters, temperature, and humidity at O(10m) horizontal and vertical resolution and sub-minute temporal resolution Radiation, heat, momentum, and moisture fluxes Some applications require long-term continuous measurements Measurements of trace gases Measurements that allow to distinguish hydrocarbons from vegetation and from anthropogenic sources Minimum set of chemistry observations: O_3, NO_x ratios, CO_2, PM1, PM2.5, PM10, and hydrocarbons like propane and isoprene	Scanning lidar Radar wind profilers Radiometers Integrated networks of towers (CentNet!) for eddy covariance fluxes Networks of UAV/UAS/RPAS to assess role of spatial heterogeneity (direct *in situ* measurements safely and slowly and continuously), coupled with basic chemistry Large aperture optical and microwave scintillometers for sensible and latent heat estimates over large areas. Scanning radars (Ka-band and X-band) can get turbulence intensities and maybe TKE at 10-m resolution	Coordinated scans from multiple costly Doppler lidar or radar, resolution is ~ 50m typically but ~ 10m resolution is needed, range of affordable commercial systems is still limited. Lidars cannot see through clouds, do not work in rain, and require aerosols. Radar wind profiles: network is crucial for larger-scale flow, useful to see up to 3-4 km; limited by lowest range gate (rely on sodar or profiling lidar below first range gate) Ozone lidars and aerosol lidars Radiometers (passive and IR) need finer vertical resolution in T, RH, water vapor UAS/UAV/RPAS flux measurements Challenges with SODAR and RASS due to noise issues in urban areas	High variability requires dense network of well calibrated and coordinated measurements.. Ground-based vs airborne: some towers are hard to site, remote sensing is easier as long as power is available. Long-term continuous measurements are valuable, but difficult to get from airborne measurements. Some prospects with instrumenting commercial aircraft. There is no Doppler lidar (network) in the LAOF pool. LAOF can and has leased a Doppler lidar (Windcube 200S in 2013). UAV/UAS/RPAS: technology is such that some turbulence parameters can be measured but uncertainties remain and not all components of the TKE budget can be easily measured. Detailed chemistry measurements can also give insight into dynamics. Need a list of chemistry measurements "blessed" by both chemists and dynamicists. Many new instrument developments but not all are easily accessible by science community and integration of different platforms into dense network remains a challenge.
2. How to integrate surface and boundary layer processes (including vegetation, chemistry, aerosols) at subgridscale, gridscale (e.g., urban canopy parametrizations), and climate-scale models?	Same as above, plus: Fluxes regulated by biological organisms require measurements of vegetation type, leaf gas exchange, soil properties, surface reflectivity, and microbial properties (need human observers)		Some applications require long-term continuous measurements	Datasets must provide information that facilitates the evaluation and improvement of stochastic sub-grid scale parameterizations. Better communication of requirements between modeling and observations communities.

Influence of Topography and Land Use				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
3. How does topography/land use interact with larger-scale atmospheric processes mediated by the ABL (convection, microphysics, precipitation type)	Same as above, plus: Detailed measurements of aerosol properties, microphysics parameters, hydrometeor types			See sub-topic “orographic flow and turbulence”

Continental Convection				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. How complexities of real world storms coincide with and differ from conceptual models a) non-classical environments b) impacts of mesoscale variability (spatial scales and domains) c) properties of real turbulent updraft cores Improving predictability on the mesoscale	Mapping of lower troposphere outside the storm: q, T, wind profile, instantaneous vertical columns, aerosols Within storms: thermodynamic properties, microphysical properties, updraft core characteristics Fuller depiction of cloud water	Dual/multi-Doppler velocity retrievals Dual-pol radar measurements of precipitation Large fleets of UAVs, mini-drifters Storm penetrating aircraft (A-10?) Profiling instruments: *in situ* (sondes, mini-drifters, etc.), remote sensors (lidars, radiometers, etc.)	Miniaturization of sensors/payloads (and accuracy of miniaturized sensors) Operability in precipitation Cost (flight hours, scalability of surface-based sensors) Viability of aircraft in severe storms Support for integration of diverse datasets	The time has come to move away from a single sounding representing the environment. For all continental projects, we still need the “backbone” of surface-based mobile radars, soundings, and mesonets. FAA restrictions on UAVs and dropsondes remain challenging
2. Lower tropospheric processes that produce (or fail to produce) tornadoes and intense mesovortices	Thermodynamic variables above the ground within storms	Shorter updates with phased array radars Independent observations of thermodynamics and kinematics *In situ* observations of thermodynamics via airborne drifters, drones, UAVs Storm penetrating aircraft Microwave profiling radiometer with radar measurements	Durability/operability in high winds, hail cores, low visibility	Techniques need to work in precipitation; instruments need to be durable. FAA restrictions on UAVs remain challenging (limited airspaces, visual contact required at all times in flight), UAVs might not be well-suited to observe some key areas in severe storms owing to low visibility, extreme turbulence, large hail, strong downdrafts, and airframe icing.
3. Impacts of aerosols on storms, processes in the mixed-phase region, and subsequent impacts	Aerosol contents/concentration, *in situ* measurements of precipitation particles	Storm penetrating aircraft (A-10?)		*In situ* measurements to supplement dual-pol radar and surface disdrometers

Maritime convection				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. Mesoscale budgets of mass, entropy, moisture, momentum	Mesoscale vertical mass flux profiles. Vertically integrated moisture convergence. Vertically integrated moist entropy convergence. Vertical transport of horizontal momentum.	Dropsondes Passive microwave profilers for temperature and humidity. Airborne profiling lidars: Raman (T, q), DIAL (q), and Doppler lidar (wind). Airborne radar wind and vertical velocity in 3D or in transect along flight track.	These measurements need to be made from near or above cloud top – NSF/NCAR GV or Global Hawk. The dropsonde is the definitive tool, but they lack time/horizontal resolution The passive profiling systems have coarse vertical resolution, compromising budget estimates.	NASA facilities are shown in red. NSF has only a temperature profiler and a W-band profiling radar. NASA's DAWN aerosol Doppler lidar performed well from high altitude in a recent field program, sometimes getting data at middle levels as well as in the boundary layer.
2. Mesoscale radiation budget	Visible and IR fluxes at surface. Visible and IR fluxes above cloud tops.	NCAR has adequate radiation instruments available for aircraft deployment.	To get both top and bottom of atmosphere measurements simultaneously requires two aircraft.	Radiative transfer calculations may reduce the need for bottom of atmosphere measurements if remote sensing can characterize clouds.
3. Comparison of actual convection with cloud resolving models	Wind fields in and around convective cells. Temperature and humidity fields in and near convective cells. Distribution of precipitation. Radiative effects of associated clouds.	Dropsondes. Passive microwave profilers for temperature and humidity. Airborne profiling lidars: Raman (T, q), DIAL (q), and Doppler lidar (wind). Airborne radar wind and vertical velocity in 3D or in transect along flight track. *In situ* aircraft observations of wind (gust probe), temperature (radiative measurements in-cloud), humidity, visible and infrared radiation, and precipitation.	Expensive, due to the need for multiple aircraft. The C-band airborne radar does not yet exist. With existing aircraft there are limitations on penetrating strong convection.	Dual Doppler from ships is another possibility, but this is also an expensive proposition.

Shallow Convection				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. Interactions between shallow convection and turbulent scale and feed back to environment	High resolution water vapor, temperature and 3D winds Surface fluxes at ~1 km or less TKE Vertical wind profiles	Laser/microwave scintillometer Water vapor DIAL & Raman lidar AERI Sonic anemometer Doppler radar and wind lidar vertical wind profiles Aircraft ACTOS-type platform (allows for *in situ* intercomparisons)	Precision 5% in moisture 0.3K in temperature better at high altitude/ice-saturated environments Vertical resolution 25m (or better for certain applications)	Specifying precision High resolution airborne temperature and water vapor remote sensing capabilities need to be developed. Airborne precipitation radar with Doppler and polarimetric capability needs to be developed.
2. Physical mechanisms control the shape and structure of shallow convection (open-, closed-, rolls) and transition among them?	Wind shear Buoyancy Mass fluxes Spatial distribution Cloud macrophysics	Scanning radars at different frequencies High-resolution satellite imagery Wind lidar Wind profiler Aircraft	Spatial resolution of 20m up to domain of 10s of km (land)	
3. Mesoscale organization from shallow-to-deep convection transition (over both ocean and land)?	Wind shear Buoyancy Mass fluxes Spatial distribution Cloud macrophysics	Scanning radars at different frequencies (ground-based, shipborne, and airborne) High-resolution satellite imagery Wind lidar Wind profiler	High spatial and temporal sampling of a large area	Long-endurance aircraft needed for open-ocean measurements

Shallow Convection				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
4. Maritime high-latitude cloudy boundary layer structure and interactions with sea ice/open water/land boundaries	Wind shear Buoyancy Mass fluxes Spatial distribution Cloud macrophysics Water vapor	Scanning radars at different frequencies High-resolution satellite imagery Wind lidar Wind profiler	Airborne remote sensing and *in situ* measurement of wind, temperature, water vapor, microphysics (e.g., NSF/NCAR C-130 with APAR)	Long-endurance aircraft needed for open-ocean measurements
5. Relationship between shallow convection, microphysics, and aerosol?	Full *in situ* microphysical measurements for both liquid and ice Aerosol spectrum LWP	Multiple wavelengths and/or polarimetric Radars (to distinguish MP) *In situ* microphysical measurement	Adequate sampling volume >1Hz sampling	

Orographic Flows and Turbulence				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. Coupling of waves and BL flows: i) impact of upwind PBL flow and turbulence on launching of lee waves, ii) interaction of gravity waves and downwind PBL iii) impact of PBL (heating, turbulence) on atmospheric rotors	Air motion, deep, tropospheric wind profiles Surface fluxes Upstream environmental conditions (profiles of u, v, T, q, p)	Ground-based: Doppler Lidar, wind profilers (re-establish tropospheric wind profiler networks), soundings (up-sondes and dropsondes) DIAL profilers (T, q) Scanning aerosol backscatter lidars to map aerosol layers (proxy for isentropes) Airborne: *in situ* and remote sensors (lidars, cloud radars), turbulence	High-resolution may be needed for lidar, network of profilers is expensive Representativeness of a single upstream sounding… Address uncertainties in representativeness - multiple upstream profiles and downstream Doppler lidars Consider 24/7 continuous measurements of profiles up/downstream for robust model evaluation	Model resolution is outpacing spatial resolution of observations
2. Characterization of low-level turbulence in downslope windstorms, rotors and low-level wave breaking : origin of turbulence, impact of moisture	Turbulence (TKE, eddy dissipation rate, momentum fluxes,..) Thermodynamics Downslope flow characteristics prior to flow separation Pressure perturbations for turbulence and lee wave characterization	Airborne *in situ* measurements and remote sensors (cloud radar with high spatial resolution) Ground-based remote sensors: wind profilers (449 and 915 MHz), Doppler lidars (or dual Doppler), turbulence towers	Challenging environment to make direct measurements Challenging to make direct measurements in clouds Technical and financial challenges for direct measurements of turbulent flows and rotors (particularly A10 aircraft) Cloud radars need scatters, and there are clear air limitations	Safety of operations for obtaining *in situ* airborne measurements: too turbulent to observe *in situ*? Recommended instrument developments: - Airborne Doppler lidar - Phased array mm-wave radars for high- resolution rapid-scan - Airborne laser air-motion system (4 or even 12 beam system) for turbulence measurements
3. Internal hydraulic jumps vs. low-level wave breaking: Characteristics of turbulence and vortex breakdown	Airborne measurements of turbulence, air motion, pressure, temperature, etc.	High-frequency probes, High-spatial resolution remote sensors	Intermittency of phenomena, most interesting events and regions may be too difficult to fly through	Safety of operations for obtaining *in situ* measurements by aircraft
4. Upper-level wave breaking: What are fine scale (spectral) characteristics of wave breaking?		*In situ* airborne measurements, dropsondes, Rayleigh lidar		Hard to target: highly intermittent in space and time

Orographic Flows and Turbulence				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
5. Vertical energy fluxes due to mountain waves Gravity Wave Drag (GWD) parameterizations	Need accurate pressure perturbations (via differential GPS) Long aircraft legs for u', v', w' statistics	*In situ* airborne measurements, dropsondes (high density, acceleration measurement to give an indication of turbulence), satellite based remote sensing	New dropsonde technology needed for turbulence measurements	Need long aircraft legs Need to distinguish wave spectra from turbulence spectra
6. Steep terrain and representation of steep slopes			Observational challenges in regions of steep slopes; model challenges	
7. Orographic precipitation	Kinematics (air motion), thermodynamics (temperature, pressure, etc.), microphysical parameters Measure the large scale environment including upstream conditions PBL and turbulence measurements Embedded convection: CI mechanisms	<u>Ground based</u>: - Network of precip gauges and disdrometers across terrain - Network of Dual Pol radars (dense enough to obtain good low-level coverage), X-band is adequate given network density <u>Airborne</u>: profiling radars, *in situ* particle imaging and sizing probes	Coincident remote sensing and ground based data are needed Multiple Doppler and Dual-Pol radars are needed Convective initiation is poorly understood for orographic precipitation Need to improve remote sensing of orographic precipitation (remote regions need better sampling) - need airborne capability	Challenge is that accurate measurements are needed at multiple elevations in the mountains

Turbulence in Clouds				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. <u>Warm boundary layer clouds</u> 3D turbulence Vertical transport Condensational growth and turbulence Collisions, coalescence and turbulence Decouple BL clouds	3D laser-based wind measurements in 3D space at small scales (25 m) Profiles of cloud fraction, cloud size distribution, aspect ratio Liquid water content EDR statistics from large data set using remote sensing In-cloud fluxes Time evolution of turbulent structure in clouds	High spatial resolution wind/turbulence and WV measurements (cm to 10's m) HOLODEC-like sensor (particle distribution within O(0.1 m)) Doppler cloud radars and lidars DIAL, Raman lidar Use chaff/tracers to study dynamics outside of clouds Fleets of RPAS to study/follow clouds Track clouds using radar/lidar, sector and along wind RHI's	Intermittent nature of turbulence limits our ability to measure EDR at very small scales High resolution WV measurements (laser absorption) - the GV may have such capability Challenging to make covariance measurements in clouds (i.e., w and q) Lack access to high-resolution, sensitive ground-based profiling Doppler radars	Progress in data processing of *in situ* data at high sampling rates Slower moving platforms can overcome some of the sampling, covariance measurement needs synergy of systems: coincident measurements of *in situ* and remotely sensed data are essential.
2. <u>Mixed-phase clouds</u> Cloud-forced turbulent mixed-layer Formation and evolution (persistence) of decoupled (elevated) supercooled liquid layers Sources of IN/CCN and moisture in decoupled cloud layers - role of turbulence in entraining moisture/aerosols Role of in-cloud turbulence-generating processes in **ice nucleation**	<u>In stratiform clouds</u>: amplitude and frequency of gravity waves, cloud-top generating cells, K-H billows <u>In convective clouds</u>: size, intensity, and life cycle of convective updrafts High-resolution measurements of vertical velocity, TKE, water vapor pressure (supersaturation), and temperature (buoyancy) IN and specific humidity (q) measurements above/within/below cloud boundaries Ice/liquid partitioning (particle-basis), and IWC/LWC	Ice microphysics High spatial resolution wind/turbulence and q measurements (cm to 10's m) Coincident microphysical and dynamical measurements Ground-based or airborne profiling cloud Doppler radar Multi-wavelength radar to improve microphysical retrievals High-rate *in situ* aircraft observations of 3D wind, turbulence, temperature, vapor pressure, and cloud microphysics (LWC, IWC, droplet spectra, particle imagers …)	Ice particle shattering (partially solved problem) Supersaturation relative to ice is difficult to estimate at low T Need coincident radar / lidar / *in situ* measurements of ice particles, in order to train retrieval algorithms	Techniques for observing in-cloud features from profiling Doppler cloud radars are mature, but need to obtain Higher spatial/temporal resolution is desired. Aircraft studies of KH billows, cloud top generating cells, shallow-medium convection, and deep-convective anvils, are possible (no safety hazard). Need to improve remote sensing capabilities of humidity and ice microphysics.

Turbulence in Clouds				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
3. Small-scale, interfacial **entrainment and mixing**	Structure, depth, and intensity of cloud-scale and small scale eddies near cloud boundaries Vertical and lateral mass fluxes, water content and thermodynamic properties across the clear/cloudy interface Cloud microphysics (esp. drop size distributions)	Airborne Doppler cloud radar Vertically profiling Doppler cloud and precipitation radars (W, Ka, X and S band) Measurement of cloud water and ice particle types and concentrations plus hydrometeors	The vertical resolution needed (2-5 m) exceed the one obtained by current-generation profiling and scanning cloud radars Airborne radars cannot provide enough time resolution. Need studies of cloud lifetime (echo tracking) Need coordination between airborne and ground-based facilities	Entrainment is a very important parameter, but we continue to struggle on how to measure it and how to make observations suitable for model validation Need balloon- or helicopter- based towed platform (e.g., ACTOS) to sample the cloudy-clear air interface. Need to go beyond a soda-straw view of clouds, add Lagrangian approach either using scanning cloud radars or helicopter/aircraft observations
4. Impact of in-cloud turbulence to cloud macroscopic structure (formation, maintenance, dissipation) and precipitation processes (collision, coalescence)	Cloud-scale measurements of vertical air motion, eddy dissipation rate Cloud liquid water content, precipitation rate, particle size In cloudy-topped boundary layers, sub-cloud layer turbulence measurements are needed.	Profiling Doppler cloud radar, Doppler lidar, ceilometer microwave radiometer Aircraft observations of cloud microphysics and dynamics Radiosondes	In warm clouds, remote sensing can provide high quality turbulence and microphysics. In mixed-phase clouds, ice complicates the interpretation of remotely sensed data High frequency thermodynamic measurements are desirable Aircraft observations in high SLW conditions are challenging	Forward modeling of radar and lidar observations can facilitate the comparison of model output and observations The cloud-scale studies of turbulence need to be put in the context of larger-scale variability
5. Air-sea exchange in strong winds (esp. hurricanes)	Estimation of fluxes of heat, momentum, vapor, droplets, and aerosols across air-sea interface	*In situ* probes, lidar on tethered airborne sondes (controlled towed vehicle or CTV), UAS, ship, moorings	High turbulence, corrosive environment, unsafe seas	Models are least constrained in this environment, yet high-impact weather
6. Role of the land surface on cloud processes, esp. in complex terrain	*In situ* cloud physics and aerosol measurements between the surface and lowest permissible flight level (~1 km AGL)	Multi-frequency scanning or profiling radars, cloud probes on UAS, tethersondes	UAS operation constrained by legal framework, challenging flight under strong BL turbulence and strong vertical drafts	Surface aerosol sources and blowing snow in winter storms unknown

Clear-Air Turbulence				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. What does CAT (or in-cloud turbulence) look like?	Visualization of the turbulence itself	Doppler lidar (clear-air), mm-wave radar (in cloud), RASS, Doppler spectrum	We do not measure the 3D spatial extent and evolution of regions of turbulence	
2. What are the direct sources of CAT, their frequency of occurrence, and damping mechanisms? - KH instability? - gravity wave breaking? - shallow convection? - Rossby wave amplification/ breaking? - others?	Ambient conditions need to be sampled to understand degeneration into turbulence (vertical shear, Ri, inertial stability, dry and moist static stability …)	Radiosondes, driftsonde (fiber optic curtain, 2-km depth) to measures temperature and moisture (e.g., Strateole2 campaign), drones		
3. What is the primary mechanism of gravity wave induced CAT? -Wave breaking? -Ri reductions?	Vertical motion Horizontal divergence	*In situ* observations from research aircraft	expensive difficulty in spatial coverage	
4. How does gravity wave energy cascade to aircraft-influencing scales (~10 m – 1 km)?	Vertical velocity, horizontal wind and temperature spectra	Long flight legs with specially outfitted commercial aircraft (MOZIAC, IAGOS)		
5. What process contribute to shape of mesoscale energy spectrum? What is the degree of isotropy?	Static stability	Multiple aircraft, sequenced UAVs Forward-looking lidar combined with *in situ* vertical motion sensors	expensive	Important for forward-looking sensors on aircraft
6. What is the role of remote deep convection on CAT? What determines horizontal extent of turbulence associated with upper-level cirrus? Latent heat release, radiative heating, or both?	Environmental and mesoscale horizontal flow perturbations Potential temperature and moist static stability	Field experiment with frequent radiosonde launches Constant-pressure balloons? Nano-driftsondes? (Some brands can be dropped from a high altitude.) May be well suited for clear air	expensive	Problems for turbulence forecasting because accurate prediction of convection in models is nondeterministic
7. How common are coherent roll-like structures in the UTLS and how are they generated?	Horizontal vorticity	Upward-pointing lidar		Could identify regions where turbulence is likely and set up there.

Clear-Air Turbulence				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
8. What is the connection between unbalanced flow and CAT? -inertial instability -spontaneous gravity wave emission	Mesoscale horizontal wind fields (a few to 100s of km)		Cloud-tracked winds from satellite GPS-RO for soundings research aircraft with long flight legs to measure vertical velocity	
9. What is the role of the tropopause and tropopause folds? How important is the detailed vertical structure of these environmental features?	Vertical shear and static stability	Nano-driftsonde curtains Radiosondes		

Physical Processes in Convection

Aerosols, Cloud Physics and Radiation				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. Assess the feedbacks between vertical motion and aerosol and microphysical processes as a function of storm morphology, lifetime and environment	Updraft / downdraft vertical velocity Base state variables within the updrafts / downdrafts Liquid water and ice mixing ratios and number concentrations Supersaturation Microphysical Processes Aerosol size distributions	Co-located measurements (e.g., radar, vertical motions, thermodynamics on storm penetrating aircraft) Global High temporal frequency (mins) Storm lifetime Convective storm types Range of environments W: 1-2 m/s (both *in si*tu and via remote sensing with multiple radar approaches) Condensate mixing ratios using suite of *in situ* probes to cover entire particle size distribution: 0.01 g/kg Number concentration (using suite of *in situ* sensors): varies by species SS: 0.1 to 0.2%	While costs of global platforms are coming down this remains a high-cost exercise Processes cannot be directly observed	Multi-frequency, dual-Doppler radars on space-borne swarms of Cubesats

Aerosols, Cloud Physics and Radiation				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
2. Evaluate the role of hydrometeor size distributions in microphysical processes and cloud-radiative forcing	Liquid and ice hydrometeor number concentrations Liquid and ice mixing ratios Liquid and ice hydrometeor sizes	Number, mixing ratio and size requirements all species dependent (*in situ*) Remote sensing particle size profiles (ice and water): multi-wavelength radar, radar/lidar Over storm lifetime Wide range of convective storm types Wide range of environments Vertical covariance of particle size distributions	Challenging with rapidly moving platforms	Tethered balloons UAVs / drones Storm penetrating aircraft
3. Determine how the characteristics of graupel and hail vary as a function of storm morphology, lifetime and environment	Surface number concentrations and size of hail and graupel In storm number concentration, mixing ratio and size Hail and graupel density and fall speed Role of formation processes	Size: 1-2 mm Mixing ratio: 0.5 g/kg Over storm lifetimes Wide range of convective storm types Wide range of environments	Characteristics cannot be directly observed	Additional field campaigns focused on graupel and hail Storm penetrating aircraft
4. Analyze the impacts of vertical and horizontal aerosol distribution on cloud microphysical and radiative processes	Profiles of cloud nucleating and ice forming AP number concentrations, mass and size Profiles of cloud nucleating and ice forming AP composition	Number: tens per cc Size: mode dependent Near-storm environments Over storm lifetime	Restrictions for in-cloud measurements by remote sensors	Tethered balloons UAVs / drones Storm penetrating aircraft

Cloud Electricity and Lightning				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. Assess the role of varying microphysical properties and processes in electrifying storms and any resulting lightning properties as a function of clouds morphology and lifecycle (and vice versa)	Hydrometeor (cloud and precipitation phase, type, size, charge, concentration, shape, density, growth state, fall mode) Cloud water content Airborne *in situ* e-field and particle charge Surface electric field mill Flash rate, type, extent, polarity, energy, radiance	Storm penetrating aircraft, balloon for *in situ* particle charge, e-field, microphysics Community deployable lightning mapper using variety of techniques and frequencies (e.g., LMA, interferometer, e-field change meter, electric field) Mobile (truck, airborne, drone) multi-frequency (Ka, Ku, X, C) dual-polarization to complement WSR-88D Could be other aircraft (GV) if non-lightning producing Surface profilers, disdrometers, satellite	Microphysical measurements ≤ 1 min and 100's meters sampling preferred Technical limitations in phased array radars for dual-pol measurements? Particle charge measurement difficult yet badly needed Difficulty of measuring low water content (e.g., in weak convective, winter, stratiform anvil) Develop small electric field mill device for small, non-traditional *in situ* vehicles (e.g., UAV, drone)	Require *in situ* observations to validate remote sensing (e.g., dual-pol models and retrievals (e.g., hydrometeor ID)) Instrument performance for lightning mapping and other electrical or lightning instruments Stratiform MCS, anvil, winter storm Continued investment in lightning test site such as Langmuir Lab (e.g., available restricted airspace, infrastructure) Mobile (truck, airborne, drone) multi-frequency (Ka, Ku, X, C,S) for spatial scale
2. Assess the role of *kinematic properties and processes* in establishing charge structure and polarity and resulting lightning properties as a function of storm morphology and lifecycle (and vice versa)	3-D wind at high temporal and spatial resolution of advective and turbulent flows	≤ 1 min and 10-100 meters sampling preferred. Mobile-truck based fleet/network IOP vs. aircraft Phased array (or imaging radar?) to supplement mechanical scanning Inexpensive X-band scanning radar network for long term studies Profilers, satellite	Spatial scale of 10 m currently only available in 2-D slices. How to accomplish this in 3D? Multiple radar networks for coverage. Dual-polarization limitations in phased array, imaging radar? Techniques for improving spatial scale (e.g., pulse compression)	Temporal scale limited by mechanical scanning. Require rapid scan technology (frequency hopping, phase array, or imaging radar) to obtain < 1 min (e.g., DOW dual-frequency, dual pol). Adding frequency is scalable for accuracy.

Cloud Electricity and Lightning				
Key measurement requirements (e.g., physical parameter)	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**	
3. Determine the impact of the *environment* on storm kinematics, microphysics and the resulting charge structure and lightning properties (and vice versa)	State parameters, wind, moisture, aerosol (CCN, IN)	Mobile mesonet network for IOP Mesonet for long-term studies (paradigm of fixed cheap for good enough?) Aircraft, multiple UAS/drone network Balloon sonde, tethersonde Dropsonde, drones Profilers, limited satellite	Near storm environment vs. updraft inflow proximity Cost of expendables (sondes) Access for UAV, drones Satellite limitations at low-levels and around storms where it matters most	
4. Investigate the meteorological context (microphysical, kinematic, environmental) of the initiation and propagation of lightning and energetic and upper atmospheric discharges	Flash rate, type, extent, polarity, energy, radiance Charge structure (polarity, amount)	Continued support fixed LMA's for long-term Develop and expand mobile LMA's for IOP Other frequencies and techniques for mapping and charge retrieval (e.g., VHF broadband interferometer array, E-field change meter array) GLM Storm penetrating aircraft and/or balloon (UAV, drone?) e-field and particle charge measurements	Rapid analysis of LMA to guide aircraft to specific altitude where lightning might be getting ready to happen Expand frequencies and techniques of lightning mapping to see all components and locations in a flash Mobile/fixed LMA and other lightning mappers needed for sub-storm scale studies GLM useful for storm-scale summary over region for long period Access to drones	

Chemistry				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
1. Better understand characteristics of convective transport using chemical and aerosol tracers	Mixing ratios of chemical species with lifetimes much longer than that of convective cell: CO, O_3, C_2H_6, C_3H_8, CH_3I, NMHCs, Black carbon, DMS 3D volumes of tracer concentrations (wish list) trace gas and aerosol concentrations in PBL Mapping of O_3 with airborne lidar; *in situ* observations on flight legs at multiple levels *In situ* measurements of total bromine, CH_2Br_2, $CHBr_3$, etc. from PBL to stratosphere Water vapor For PBL venting: *in situ* aircraft trace gas observations below, within and above clouds; vertical velocities; vertical fluxes of trace gases; tracers, gases indicative of cloud processing	Instruments exist; need *in situ* observations at numerous levels in cloud, cloud outflow and cloud inflow Traditional aircraft Some tracers available from small UAS Air grab samples (single or tube for time series) Balloons Aerosol composition Lidar for H_2O, ozone, NO2, aerosols Scanning cloud radar	Can hydrocarbon measurements be done more frequently? Source attribution – long and short range, including residual layer sources Need mesoscale variability of trace gases and CO_2, water vapor Gas and oil field sources possibly valuable for source attribution	Possible use of tracer releases of SF_6, perfluorocarbons, isotopes (water, carbon, sulfur, etc.) 2D possibly from long path absorption instruments in a network setup (FTIR, DOAS) Surface flux measurements needed for constraining chemical budget
2. Investigate relationship between NO_x production and lightning characteristics (e.g., flash length, flash rate)	NO and NO_2 measurements in storm core; lightning flash rates and lengths	Storm penetrating aircraft; overflights by high altitude aircraft with UV/Vis spectrometer (250m horiz. res.); satellite UV/Vis spectrometer; LMA		
3. How much O_3 titration occurs in storms due to lightning NO and how much O_3 is produced downwind?	NO, O_3 and photolysis rate measurements in storm core and anvil O_3, precursors (NO_x, HO_x), other NO_y species measurements at multiple downwind transport times	Storm penetrating aircraft Suite of tracers for source attribution	How well can j values be measured in cloud? Fine in anvil Locating correct sampling regions	Is there 100% darkness in storm core? Light is isotropic

Chemistry				
Science Frontier	**Key measurement requirements (e.g., physical parameter)**	**Instrument requirements**	**Challenges (technological, cost, resolution, coverage)**	**Other comments**
4. Investigate trace gas loss in convection due to wet scavenging, including retention in ice phase hydrometeors	Observations of HNO_3, HCHO, H_2O_2, CH_3OOH, SO_2, etc. in storm core and anvil	Storm penetrating aircraft; collection of cloud ice and graupel for subsequent analysis Counterflow Virtual Impactor (CVI)	Proper inlets needed for in-cloud aerosol and trace gas measurements	
5. Investigate magnitude and rate of new particle formation in convective outflow	*In situ* aerosol number, mass, size distribution, speciation observations in outflow; lidar observations possible in moist air between shallow Cu	Airborne lidar *In situ* sampling	Proper inlets needed for in-cloud aerosol and trace gas measurements	Missing early aerosol growth stages because they are too small to observe: need < 4 nanometer-size *in situ* particle measurement
6. Investigate composition of fire plumes (e.g., pyro-convection, biomass burning)	Experiments such as WE-CAN, FIREX, FIRE-Chem		Limited to remote sensing for extreme events	Biomass burning observing network limited in developing countries; foreign collaboration needed

7.4 Instrument Priority Table

Instrument color coding:

Black Established instrument: can be deployed as is, QC & processing software in place (LAOF *or* user-provided)
Green Experimental instrument: can be deployed, but improvements are needed (accuracy, resolution, scanning capabilities, # of systems, ability to integrate on platform, QC/QA …)
Red Currently exists but not easily accessible to the NSF research community (non-LAOF, and not readily included in the budget of an NSF proposal)
Magenta Does not exist yet as an observing system (e.g., conceptual design, in development, etc.)

Priority checkmark greyscale:

X essential
o useful/desirable

Manned Aircraft- or Helicopter-based

	instrument type	**boundary layer flow & turbulence**			**(thermo)dynamics of convection**			**turbulence in the free troposphere**			**physical processes in convection**		
		SBL	CBL	PBL & terrain	conti-nental	marine	shallow	oro-graphic	in-cloud	CAT	light-ning	aerosol cloud	chem-istry
Non-storm penetrating aircraft: *in situ*	Cloud imaging and size spectra				o	o	o		X		X	X	X
	Liquid/ice phase discrimination				o	o	o				X		
	3D spatial arrangement of cloud particles (e.g., HOLODEC)								X		o	X	o
	Large-sampling volume particle size distribution probe				X	X	X				X	X	X
	High-frequency 3D winds	X	X	X				X	X	X	X	X	X
	High-frequency thermodynamics (T, q_v, p)	X	X	X	X	X	X				X	X	X
	Turbulence sensor designed for commercial aviation fleet							X	o	X			
	State variables and turbulent fluxes	o	o	o	X	X	X	X	X	X	o	o	o
	Continuous (1 Hz) grab samples (canisters or tubes)												X
	Water chemistry (e.g., CVI), cloud water collector											X	X
	Inlets for in-cloud sampling											X	X
	Radiation (broadband irradiance, spectrally resolved irradiance, actinic flux)											X	X
	Supersaturation (0.1 to 0.2%)										X	X	X

Manned Aircraft- or Helicopter-based

	instrument type	boundary layer flow & turbulence			(thermo)dynamics of convection			turbulence in the free troposphere			physical processes in convection		
		SBL	CBL	PBL & terrain	conti-nental	marine	shallow	oro-graphic	in-cloud	CAT	light-ning	aerosol cloud	chem-istry
Storm penetrating aircraft: *in situ*	*In situ* 3D winds/turbulence				X	X	X				X	X	X
	In situ thermodynamics (T, q_v, p)				X	X	X				X	X	X
	In situ trace gases											X	X
	In situ electric field, hydrometeor charge				o						X	X	X
	Cloud & precipitation probes (concentration, size distribution, particle imaging)				X	X	X				X	X	X
	Physical and chemical properties of aerosols										X	X	X
	Hemispheric radiation (LW, SW)											X	X
	Inlets for in-cloud sampling											X	X
	Water vapor, LWP (radiometric)				X	X	X		X		o		o

	instrument type	boundary layer flow & turbulence			(thermo)dynamics of convection			turbulence in the free troposphere			physical processes in convection		
		SBL	CBL	PBL & terrain	conti-nental	marine	shallow	oro-graphic	in-cloud	CAT	light-ning	aerosol cloud	chem-istry
Aircraft remote sensing	Profiling or scanning Doppler radar (W, Ka, X)				X	X	X	X	X		X	X	X
	Rapid-scan radars (phased-array)				X	X	X	X	X		X	X	X
	Aerosol backscatter lidar	o	o	o	X	X	X	X		X		X	
	Doppler lidar	o	o	o	X	X	X	X		X			
	Water vapor, temperature (Raman, DIAL)	o	o	o	X	X	X	X	X	o	X	X	X
	Water vapor, T, LWP (radiometric)				X	X	X		X				
	3D turbulence *near* aircraft (e.g., laser air motion system)							o	X	o	X	X	X
	Ozone lidar, NO_2 lidar	o	o	o							X	X	X
	UV/ Visible spectrometer for trace gas column amounts												X

Unmanned aircraft

	Instrument Type	boundary layer flow & turbulence			(thermo)dynamics of convection			turbulence in the free troposphere			physical processes in convection		
		SBL	CBL	PBL & terrain	conti-nental	marine	shallow	oro-graphic	in-cloud	CAT	light-ning	aerosol cloud	chem-istry
Portable UAS (cloud-penetrating but not storm penetrating)	*In situ* meteorology (u,v,w,p,T,q_v)	X	X	X	X	X	X	X	o	X	X	X	X
	Cloud microphysics (particle sizing, imaging)							X	X		X	X	X
	High-frequency 3D winds, plus T, q fluxes	X	X	X				X	X	o			
	Active/passive remote sensing	o	o	o				X	X				
	Concentrations of CO_2, O_3, and other trace gases (high frequency open path measurements, grab samples)	X	X	X							X		X
	Aerosol (e.g., black carbon)												X
	Electric field, charge measurements										X		

Balloon-borne

	Instrument Type	boundary layer flow & turbulence			(thermo)dynamics of convection			turbulence in the free troposphere			physical processes in convection		
		SBL	CBL	BL & terrai	conti-nental	marine	shallow	oro-graphic	in-cloud	CAT	light-ning	erosol cloud	chem-istry
Balloon systems	Radiosondes, dropsondes	X	X	X	X	X	X	X	X	X	X	X	X
	Sondes with enhanced capabilities (LWC, electric field, cloud size distribution, snow crystal imaging …)				X	X			X		X		
	Nano drift sondes				X	X		X	o	X			
	Long-duration drifting balloons (e.g., Stratéole)								X	o			
	Tethered balloons (u,v,w, TKE, p,T,q)	X	X	X				o	o				
	Ozone profiles		X	X									X
	Continuous (1 Hz) grab samples (canisters or tubes)												X

Ground-based

	instrument type	boundary layer flow & turbulence			(thermo)dynamics of convection			turbulence in the free troposphere			physical processes in convection		
		SBL	CBL	PBL & terrain	conti-nental	marine	shallow	oro-graphic	in-cloud	CAT	light-ning	aerosol cloud	chem-istry
Ground-based *in situ*	Flux towers (single tower, or small network)	X	X	X	X		X	X	X				
	Large instrumented tower network (>50 units) with observations of atmospheric composition (including aerosols and 4-component radiometers) at multiple levels (e.g., CentNet)	X	X	X	o		o					o	o
	Precipitation (gauges, parsivel or video-disdrometer, …)				X	X	X		X		X	X	X
	Soil temperature and moisture profiles and soil heat flux	X	X	X									
	Plant characteristics (leaf area index, stomata, conductance)	X	X	X									
	Nanobarometer (>10 Hz)	X	X	X									
	Mobile mesonet network measuring u,v,w,T,q,CCN,IN, trace gases, long path absorption				X		X				X	X	X
Ground-based remote sensing	Radar wind profiler network	X	X	X	X	X	X	X	X	X			
	Rapid-scan, mobile, multi-frequency Doppler/dual-pol radars				X	X	X	o	X	o	X	X	X
	Profiling Doppler cloud radar network	X	X	X			X		X				
	Differential Absorption Lidar (DIAL) network	X	X	X	X	X	X	X	X				
	Backscatter aerosol lidar				X	X	X	X	X	o			
	Scanning/profiling Doppler wind lidar (dual and triple Doppler lidar synthesis)	X	X	X	X	X	X	X		X			
	Water vapor, temperature profiling lidar (Raman, DIAL)				X	X	X	o	o	o	X	X	X
	Ozone, NO_2 profiling lidar	X	X	X								X	X
	Water vapor, T, LWP (radiometric or AERI) network	X	X	X	X	X	X		X				
	Ceilometer network	X	X	X									
	Infrared all-sky cameras	X	X	X									
	Scintillometers	X	X	X									
	Portable Lightning Mapping Array				X	X					X		X