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BIOLOGICAL AND ENVIRONMENTAL RESEARCH

Climate and Environmental Sciences Division

AERIAL OBSERVATION NEEDS WORKSHOP
MAY 13–14, 2015

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ORGANIZERS

Shaima Nasiri, Atmospheric System Research
David Lesmes, Subsurface Biogeochemical Research
Rick Petty, Atmospheric Radiation Measurement Climate Research Facility

CO-CHAIRS

Beat Schmid, Pacific Northwest National Laboratory
Shawn Serbin, Brookhaven National Laboratory
Andrew Vogelmann, Brookhaven National Laboratory

WRITING TEAM

Gijs de Boer, University of Colorado/Cooperative Institute for Research in Environmental Sciences
Baptiste Dafflon, Lawrence Berkeley National Laboratory
Alex Guenther, Pacific Northwest National Laboratory
David Moore, University of Arizona
Beat Schmid, Pacific Northwest National Laboratory
Shawn Serbin, Brookhaven National Laboratory
Andrew Vogelmann, Brookhaven National Laboratory

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Executive Summary

The mission of the Climate and Environmental Sciences Division (CESD) of the Office of Biological and Environmental Research (BER) within the U.S. Department of Energy's (DOE) Office of Science is "to advance a robust, predictive understanding of Earth's climate and environmental systems and to inform the development of sustainable solutions to the nation's energy and environmental challenges." Accomplishing this mission requires aerial observations of the atmospheric and terrestrial components of the climate system. CESD is assessing its current and future aerial observation needs to develop a strategy and roadmap of capability requirements for the next decade. To facilitate this process, a workshop was convened that consisted of invited experts in the atmospheric and terrestrial sciences, airborne observations, and modeling. This workshop report summarizes the community input prior to and during the workshop on research challenges and opportunities, as well as specific science questions and observational needs that require aerial observations to address.

Manned and unmanned aerial systems (UASs) are essential to study atmospheric and terrestrial processes and to bridge scales from single points to space-borne observations in order to better represent and model the properties and processes that drive spatial and temporal variability in Earth's climate system and terrestrial biosphere. Moreover, these platforms provide the capabilities for targeted, on-demand data collection and the observation of difficult-to-reach environments; they are essential for providing in situ validation of atmospheric remote-sensing retrievals. As numerous UAS platforms and UAS-compatible sensors are currently available and many more are in development, there is growing interest in using UAS platforms of various size, complexity, and payload capabilities to make cost-effective, targeted observations. Although such advancements enable the use of UAS to address an increasing number of scientific topics, piloted research aircraft will continue to provide a vital function as current regulations limit the use of UAS technology in the United States and abroad. The greater payload capacity of piloted aircraft is also necessary for multi-sensor instrument packages, cutting-edge instruments (such as those requiring an onboard operator), or those that cannot be miniaturized. Multi-sensor payloads are needed to make the simultaneous measurements necessary for understanding covariability and interaction between climate system components, both of which represent a pressing need of the atmospheric and terrestrial science communities.

Improved, new, or multi-sensor integration measurement capabilities are critically important to address evolving research challenges within the atmospheric and environmental science communities. Observations of atmospheric systems are essential to improve fundamental process-level understanding of the interactions among aerosols, clouds, precipitation, radiation, dynamics, and thermodynamics that are important to climate. Improved understanding of the impact of aerosols on climate requires frequent in situ vertical profile measurements from an aerial platform to characterize the spatially inhomogeneous aerosol, physical, chemical, and optical properties and their trace gas precursors. Employing UAS to make these profile measurements is desirable, but requires miniaturization of instruments to measure aerosol size distribution and composition, the concentrations of ice and cloud nucleating particles, and aerosol trace-gas precursors. Further, instrument development is needed for improved measurements of aerosol absorption and to fill current key gaps in airborne observations of ice nucleating properties of aerosol, covering all relevant aerosol sizes, and all relevant freezing processes.

To improve model representations of ice cloud processes, concurrent advancements are needed to reduce considerably the uncertainties in airborne measurements of total ice mass and ice particle size distributions. To understand the persistence of mixed-phase clouds in the Arctic, airborne instrumentation must be developed that can separately measure the masses of ice and liquid water within a volume. Numerous advancements are being made in methods that can remotely sense cloud microphysics properties, such as water content and average particle size. These advancements can provide the statistical database needed for improving model representations of clouds that are critical to improving climate projections. However, these remote-sensing methods require validation, which can only be achieved by frequent, collocated airborne cloud property measurements. Further, airborne platforms and/or instrumentation are needed that can provide high-spatial resolution measurements of detailed cloud properties (e.g., particle size distribution) and in-cloud atmospheric state (i.e., temperature and water vapor concentration) that cannot be remotely sensed and are necessary to understand and parameterize processes that governing cloud life cycle, such as the mixing of dry air into the cloud.

Observations of terrestrial environments are essential to understanding the patterns of carbon storage, biodiversity and species distributions, water distribution and quality, and other key characteristics as well as their dynamics through time. Such measurements are critical for gaining a predictive understanding of how watersheds respond to drought, floods, land-use change, contaminant releases, and climate-induced and other disturbances. Measurements are also critical to understanding ecosystem feedbacks to climate. To properly characterize terrestrial processes that operate on decadal, annual, and seasonal to diurnal timescales, the workshop identified a number of critical measurement and observational priorities that included active lidar and Synthetic Aperture Radar systems, imaging spectroscopy, thermal infrared, vegetation solar-induced fluorescence (SIF), and geophysical techniques and high-resolution digital imagery. In addition to the importance of critical sensor technologies, multi-sensor integration onto single platforms, paired platforms, or platforms in near succession are also necessary to fully capture complex surface/subsurface processes, interactions, and couplings. For example, the combination of lidar and spectral observations are optimal for capturing species composition and structure, and thermal and spectral observations are optimal for estimating water distribution and use.

Measurement frequency limits which processes can be observed. Campaigns at annual or decadal timescales are sufficient to quantify long-term changes in soil, landscape, and vegetation characteristics, whereas campaigns at higher temporal frequencies (2-3 days) are required through specific periods to quantify physiological activity of vegetation or to capture hot moments in surface or subsurface processes. For frequent or rapid targeted measurements, several instrument technologies would need to be miniaturized for UAS deployment (e.g., imaging spectroscopy, lidar, SIF). Finally, observing networks such as AmeriFlux, Forest Inventory and Analysis program, Next-Generation Ecosystem Experiments, and the large subsurface biogeochemistry science focus areas deployed in important U.S. river basins present an important opportunity to link surface observations of states and fluxes to airborne observations. This enables scaling and mapping changes across landscapes and through time to answer core science questions related to soil-vegetation and land-atmosphere interactions. Therefore, there is an obvious need for airborne monitoring systems with a sufficient portfolio of manned and unmanned assets designed to capture the terrestrial ecosystem and watershed properties needed to inform modeling activities at the appropriate spatial and temporal scales.

Many of the proposed measurements would involve instrument development of some form—from refining an existing technique to developing a new technique. This may also include new hardware/software to enable efficient multi-sensor synergism within and across disciplines (e.g., atmospheric properties coupled with land observations). Discussions noted that instrument development and testing could be supported by Small Business Innovation Research and Small Business Technology Transfer Programs, but that targeted instrument maturation funding is also desirable. Further, there is a need to create opportunities to facilitate airborne testing of new aerial methods or instruments. Finally, clarification and easing of the regulatory environment for UAS platforms is needed to make the best use of this technology.

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1. Introduction

1.1 Background

The central mission of U.S. Department of Energy's (DOE) Climate and Environmental Sciences Division (CESD) is to "advance a robust predictive understanding of Earth's climate and environmental systems and to inform the development of sustainable solutions to the Nation's energy and environmental challenges" (U.S. DOE 2012). CESD supports fundamental research to understand and predict the interactions between the Earth's climate and environmental processes and energy production with a focus on the potential impacts and associated feedbacks of increased anthropogenic emissions on Earth's climate system. Specifically, the CESD Atmospheric System Research (ASR) and Environmental System Science (ESS) programs seek to advance the predictive understanding of the atmospheric, terrestrial, and subsurface ecosystem components of the climate system using a combination of state-of-the-art mathematical process-based models and measurements. Both the ASR and ESS programs require aerial observations to meet their research objectives.

The ultimate goal of ASR is to reduce the uncertainty in global and regional climate simulations and projections through quantification of the interactions among aerosols, clouds, precipitation, radiation, dynamics, and thermodynamics that improves fundamental process-level understanding (U.S. DOE 2010). This goal is pursued in partnership with the Atmospheric Radiation Measurement (ARM) Climate Research Facility, which is a DOE scientific user facility that provides the climate research community with data from strategically located ground-based in situ and remote-sensing observatories (U.S. DOE 2014). The measurements are designed to improve understanding of processes that comprise the cloud and aerosol life cycles and the interactions among them and their coupling with the Earth's surface, all of which are essential to improve the accuracy of climate models. The ARM Aerial Facility (AAF) supports this mission by providing airborne in situ cloud, aerosol, and trace gas observations as well as measurements of atmospheric state and atmospheric radiation that complement the ground-based observations, which are essential to improve process-level understanding.


Atmospheric processes from bedrock to the top of the atmosphere need further study with support from aerial observations.

The goal of the ESS activity, which includes the Terrestrial Ecosystem Science (TES) and Subsurface Biogeochemical Research (SBR) programs, is to advance a robust predictive understanding of terrestrial ecosystems, extending from bedrock to the atmospheric boundary layer and from molecular to global scales in support of DOE's energy and environmental missions. Using an iterative approach to model-driven experimentation and observation, interdisciplinary teams of scientists work to unravel the coupled physical, chemical, and biological processes that control the structure and functioning of terrestrial ecosystems across vast spatial and temporal scales. State-of-science understanding is captured in conceptual theories and models that can be translated into a hierarchy of computational components and used to predict the system response to perturbations caused, for example, by changes in climate, land-use/cover, or contaminant loading. The predictive skill of these models is improved through this iterative cycle of experimentation and observation by targeting key system components and processes that are suspected to dominate uncertainty. The strategy of executing this mission has focused on understanding ecosystem processes from a few highly instrumented research sites using biogeochemical, biogeophysical, or eddy covariance (EC) methods. These have been explored at single points or alternatively from very large scales using inversion analyses, satellite remote sensing or land-surface modeling (LSM) approaches, or some combination of these. This strategy includes a challenging conceptual and technological leap in scale from a few hundred meters to broad regions and the globe.

1.2 CESD Aerial Observation Needs Workshop

CESD is evaluating its current and future aerial observation needs to develop a strategy and roadmap of capability requirements for the next decade that involves choices of platforms and technologies. Recognizing that the above mentioned CESD programs all require aerial observations to address their scientific needs, a joint CESD workshop was convened to bring together experts in the scientific community to identify and discuss research challenges, specific observational needs, scientific questions, and opportunities. The workshop was held May 13-14, 2015, in Gaithersburg, Maryland. It brought together 31 key experts in the atmospheric and terrestrial sciences, airborne observations, and modeling, from both the university and national laboratory communities. The workshop agenda is in Appendix A and the list of attendees in Appendix B.

Over 50 responses were received from attendees and external contributors. A list of respondents is given in Appendix C. Workshop chairs synthesized the responses. Following the overview presentations of the aforementioned CESD programs, the chairs presented high-level summaries of the synthesized responses during the first session of the workshop. Themes from the responses also served as starting points for discussion in the breakout sessions. The research directions discussed in the first set of breakout sessions were prioritized in a second set of breakout sessions where the timescale needed to address each topic was also estimated. Input obtained through this process forms the basis of this workshop report.

Prior to the workshop, the organizers solicited written input from the attendees and the broad science community, using mailing lists maintained by the aforementioned programs, in response to two guiding questions:

1. What key science questions or objectives relevant to the DOE Climate and Environmental Sciences Division require aerial observations to be answered or properly constrained?

   What observations or observational strategies have been missing? Please consider near-term (<5 years) and long-term (5-10 years) goals (the latter may require capability developments). Also consider locations that are CESD priorities and making use of current and planned CESD investments.

2. For the science questions identified, what key measurements or observations are required?

   (a) Please consider the needed measurement frequency, resolution, accuracy, and any coincident observation requirements needed to address the questions including ground observation networks. (b) Also identify needs and gaps in current CESD aerial observation capabilities with respect to the scientific questions and measurements that need to be addressed (i.e., what would be a "dream" capability?). Needs may include, as appropriate, critical support of the observations needed for optimal use.

In the report that follows, it is acknowledged that the atmospheric and terrestrial components are written from slightly different perspectives. This difference follows naturally from where the fields currently are and is a reflection to some extent of the differing levels of prior support for aerial operations between the two science communities. For example, AAF campaigns have largely focused on atmospheric processes (Schmid et al. 2014) and have resulted in continued refinement of in situ atmospheric measurement technologies and sampling strategies. As such, workshop discussions focused on what detailed improvements are needed to advance these measurements to meet new observational challenges. Terrestrial needs are currently less limited by instrument capabilities, except for potential miniaturization of these technologies for UAS platforms, but more so on field deployments and the need for more multi-sensor integration onto a single platform. While atmospheric and terrestrial disciplines can both benefit from more frequent/expansive deployment of existing instrumentation, terrestrial workshop discussions tended to focus more on needs for flying currently available instruments more often, at targeted sites, or across more biomes than is currently done. As such, discussions tended to focus more on scoping out what the deployment needs are and why it is important.

2. Existing Resources and Research Challenges

Aerial needs were discussed within the context of specific research challenges and opportunities where knowledge gaps and needs can be met with new aerial platforms and airborne measurements. Opportunities particularly focused on those that leverage existing DOE resources.

2.1. Atmospheric Systems

Airborne observations by the AAF are an integral component of the ARM observational strategy to improve understanding of climate-relevant atmospheric processes and their model representations. The ARM Facility has developed extensive ground-based observation capabilities that make long-term atmospheric measurements at fixed sites across a variety of meteorological regimes where climate models need improvement, from the tropics to the poles. Fixed sites include the Southern Great Plains (SGP) site in Oklahoma, the North Slope of Alaska (NSA) site at Barrow, and the Eastern North Atlantic (ENA) site on Graciosa Island in the Azores west of Portugal (Mather and Voyles 2013). Additional observatories and a group of mobile facilities also have been established over the last decade, including an extended mobile facility deployment to Oliktok Point, Alaska. Airborne observations by the AAF are an essential extension to the ARM surface site measurement strategy by providing information that cannot be obtained by ground-based instrumentation, and the AAF also participates in intensive observational campaigns in targeted regions of interest to climate process understanding (U.S. DOE 2014; Schmid et al. 2014). Specifically, the AAF enhances ground-based ARM measurements by providing:

1. vertical and horizontal context for ground-based measurements;
2. evaluation of remote-sensing measurements made from the surface (or space);
3. information for process studies that are not available from remote-sensing methods; and
4. data for development of model parameterizations through improved process-level understanding.

To support these activities, AAF currently uses two dedicated platforms, a Cessna 206 and a Gulfstream-1 (G-1) aircraft and has also leased aircraft as needed (Schmid et al. 2014). AAF has also employed the use of remotely piloted unmanned aerial systems (UAS), which are becoming of increasing interest within the environmental sciences communities. The AAF has acquired a wide range of state-of-the-art airborne instrumentation for the measurement of aerosol, cloud microphysical, radiative, and atmospheric state properties (see Table 2 in Schmid et al. 2014). In support of these activities, the AAF has also deployed guest instruments as needed and has supported technical maturation of a number of instruments (see Schmid et al. 2014 and McFarquhar et al. 2011). These investments have facilitated scientific discovery across the spectrum of atmospheric science disciplines. However, there are cases where these aerial investments have not been enough to address needs identified by the research community or the new knowledge gained makes clear which processes still require more detailed observations to enable further improvements.

Aerosols affect climate through their scattering and absorption of solar radiation and through their impact on cloud evolution when they act as cloud particle nuclei. Quantifying the influence of aerosol on climate is a continuing challenge because it requires understanding a wide range of processes, as depicted in Figure 1, that control aerosol amount and their microphysical, chemical, and optical properties. In particular, due to their relatively short lifetime, aerosols and their trace gas precursors are inhomogeneous in the vertical and horizontal dimensions, which present a challenge to properly observe them. Aerial observations are needed because ground-based in situ measurements can provide information at the surface, but this is hardly sufficient given the large degree of vertical and horizontal inhomogeneity. Uncertainty in the scattering and absorption of radiation by aerosols in cloud-free air contributes substantially to the total uncertainty associated with aerosol radiative forcing of climate change over the industrial period. Prototype ground-based remote-sensing techniques (i.e., multi-wavelength, high-spectral resolution lidars) are promising in that they could provide information on aerosol scattering, absorption, size, and shape along the vertical dimension; however, these techniques only work in clear-sky or below cloud-base and, furthermore, are in need of validation. The influences of aerosol on clouds and precipitation remain the most uncertain components in climate change forcing over the industrial period (IPCC 2013). However, with perhaps the exception of mountaintop locations, the observations needed for improved process-level understanding of these influences cannot be measured at the surface. These scientific needs demand aerial platforms and instrumentation capable of making in situ measurements of a range of aerosol properties and their trace gas precursors, preferably at high frequency, in multiple climate regimes.

The ARM Climate Research Facility operates a Cessna 206 and Gulfstream-1 through the AAF for routine aerial observations or episodic field studies depending on the scientific request.

Proper simulation of clouds and their impact on the Earth's energy budget and precipitation continues to challenge numerical models of all scales. Cloud feedback—the coupled response of cloudiness to surface air temperature change that amplifies or diminishes the initial temperature change—represents

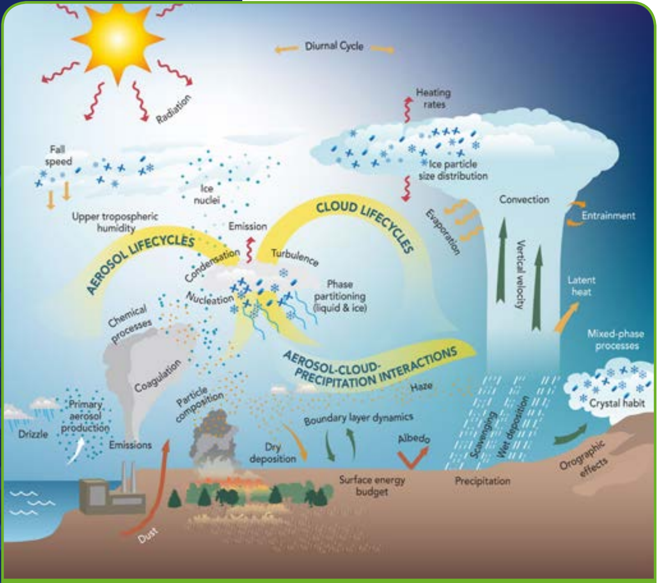

Figure 1. A multitude of dynamic processes comprise the atmospheric system.

the largest uncertainty amongst all climate feedbacks in the general circulations models (GCMs) used to project climate (IPCC 2013). Resolving this uncertainty requires improved process-level understanding and model representations of how cloud microphysical properties interact with the environment. To address this need, algorithms are being developed that use new ARM investments in remote-sensing capabilities such as multi-wavelength, polarimetric, Doppler radars, and Doppler lidars to retrieve bulk microphysical properties (e.g., cloud particle concentration, mass mixing ratio, water-ice phase partitioning). However, only aerial platforms can provide measurements of the bulk properties needed for validation of these retrievals. Further, the detailed interaction of cloud microphysical properties (e.g., how cloud particle size distribution is affected by aerosol) requires aerial observations since such properties cannot be retrieved or the presence of cloud blocks the retrieval (e.g., in-cloud temperature and water vapor mixing ratio).

2.2. Environmental System Science: Subsurface, Vegetation, and Land-Atmosphere

Airborne observing platforms present an opportunity to overcome a number of limitations of current observing systems needed to address key scientific questions at the core of the DOE ESS mission. Targeted, repeatable campaigns at the intermediate scale provided by airborne observation platforms are lacking. These types of campaigns are required to bridge scales from points to coarse grid scales and in order to capture the characteristics of sub-grid heterogeneity that is needed for scaling and adequate process representation and robust model benchmarking and to facilitate model improvements.

Terrestrial ecosystems and watersheds are complex systems where structure, functions, and feedbacks to the climate system are mediated through a variety of processes including changes in energy balance, hydrological flow and biogeochemical cycling operating on different timescales. The first order effect is the nature and structure of vegetation, topography, and subsurface; this influences the energy balance through surface roughness, reflectivity and hydrological function. Biogeochemical cycles are also dictated by changes in surface properties, landscape geomorphology, and land-cover type. Vegetation composition, and therefore its structure and function, changes through successional dynamics that operate on decadal timescales, but they can also change quickly in specific areas or regions due to natural disturbances (e.g., devastating storms). In addition, abrupt and potentially long-term changes to vegetation type and cover can occur due to land-use changes. Some biogeochemical processes show strong interannual patterns; net primary productivity (the annual sequestration of carbon into vegetation) varies inter-annually (and on longer timescales). In part these inter-annual variations are understood through processes that vary seasonally (photosynthesis, respiration) because of phenological changes within the ecosystem.

While many ecological processes might be effectively studied at daily to inter-annual timescales, earth system models (ESMs) must resolve the diurnal changes in energy balance between the terrestrial biosphere and the atmosphere so very short timescales are of interest as well. Current watershed models are unable to mechanistically predict watershed hydrological-biogeochemical dynamics, including responses to both press and pulse disturbances that influence the distribution of water, nutrients, and metals within river basins. Moreover, the spatial heterogeneity of terrestrial systems play a key role in driving patterns and process, as well as flows of mass and energy into and out of vegetation, soil, and deeper subsurface. Thus, because LSMs reflect a mathematical integration of ecosystem function relevant at regional to global scales, observations at many of these scales are required to effectively parameterize them.

Addressing the scale mismatch, both temporal and spatial, between ground and remote-sensing instrumentation and watershed scale models or ESMs requires multi-scale observations and algorithms to efficiently aggregate information, with explicit accounting of uncertainties, to inform model parameterizations and representations (see Figure 2). Simply observing at larger scales is insufficient because vegetative cover and function do not scale linearly. The heterogeneity of aboveground vegetation and subsurface structure requires consideration of appropriate scale of observation and ability to represent sub-grid heterogeneity across scales, particularly in the context of modeling activities. Moreover, some important events are transient, temporal, or spatial "hot spots and hot moments" such as the impacts of snowmelt, floods, or patchy wildfire. These events require platforms and observations that can be deployed in a "just in time" fashion.

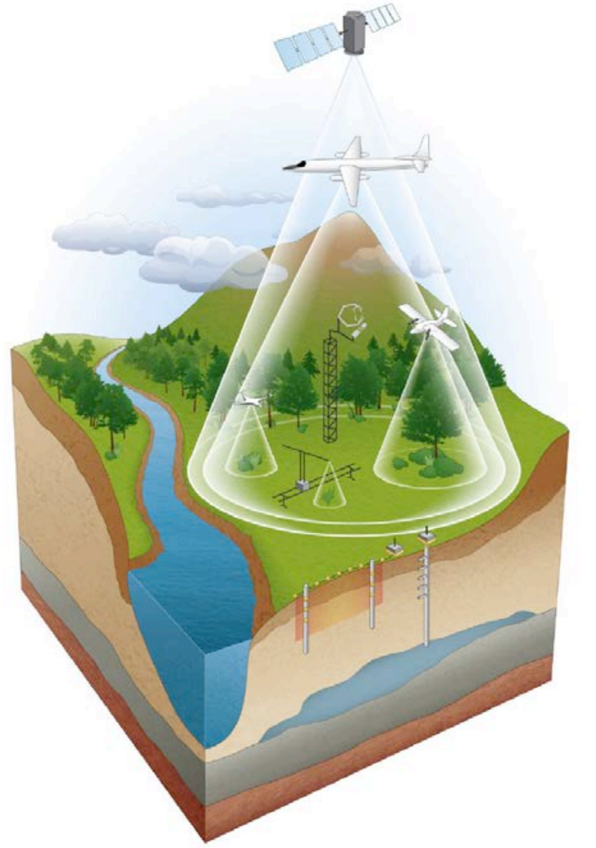

Figure 2. Understanding the state, dynamics, and evolution of terrestrial ecosystems and the coupling of the biosphere with the atmosphere requires key measurements across spatial and temporal scales together with remote sensing observations from manned and unmanned airborne platforms. This multi-scale, multi-instrumentation airborne remote sensing approach is required to capture and scale the key states and processes that drive the cycling of carbon from the land to the atmosphere, as well as the fluxes of water and energy from points to next-generation ESM grid scales. These airborne platforms can include off-the-shelf low to high-altitude and long-range UASs together with manned aircraft platforms that are capable of larger payloads and multi-sensor integration. Leveraging these airborne platforms together with measurement campaigns, such as NGEE-Arctic and NGEE-Tropics, and core sites, such as the AmeriFlux EC network and subsurface biogeochemistry SFA projects, provides an important opportunity to improve characterization and representation of surface/subsurface and terrestrial ecosystems, atmosphere, and the interaction of the land-surface with the atmosphere in state-of-the-art models.


Thawing permafrost needs "just in time" observations deployable with minimal notice.

Airborne observations can help address the core issues of the scale of phenomenon (both temporal and spatial), landscape heterogeneity, spatial resolution and instrument sensitivity, and the need for coupled measurements to adequately characterize some processes. Current observation networks include satellite observations, land-cover maps and distributed sites where carbon and water exchange is quantified. Satellite-derived spectral vegetation indices (SVIs) are commonly used to estimate vegetation dynamics and stocks from the retrieved reflectance of leaves and plant canopies at daily to monthly timescales and from tens of meters to 1 km nominal spatial resolutions. At the other end of the scale spectrum, the AmeriFlux network (**http://ameriflux.lbl.gov/**) collects near continuous observations of surface energy, water and carbon fluxes at point locations using the EC technique. These measurements are typically compiled to estimate the net ecosystem exchange of carbon and evaporative fluxes between vegetation and the atmosphere often at daily, hourly, or 30-minute intervals, at a single point that is representative of a landscape from tens to several hundred meters depending on the height of the EC tower deployment. A small number of EC sites, clustered in the temperate zone, have records of a decade with one or two running for two decades or more while others have detailed inventories of stand structure and repeat measurements of vegetation stocks (e.g., leaf area or tree biomass estimates). In addition, the U.S. Forest Inventory and Analysis program regularly assesses forest structure and carbon stocks. Leveraging these surface observations together with targeted airborne instrument packages and additionally relevant ground-based measurements presents an important opportunity for examining short-to-long-term processes, such as vegetation growth, scaling of function to the larger landscape, as well as examining soil-vegetation-atmosphere interactions in greater detail. The current configuration of our terrestrial observation networks provides global estimates of stocks inferred from SVIs and sparse-but-detailed estimates of vegetation physiological function, with obvious disparities in both temporal and spatial scale between them that could be bridged with airborne measurements.

To date, terrestrial ecosystem research has focused on a generally narrow range of bioclimatic zones. New capabilities are required to provide observations in climatically sensitive, but remote, regions in high northern latitudes and the tropics (Schimel et al 2015). DOE's investment in the ongoing Next-Generation Ecosystem Experiments in the Arctic and Tropics (NGEE-Arctic, **http://ngee-arctic.ornl.gov/**, and NGEE-Tropics, **http://esd1.lbl.gov/research/projects/ngee_tropics/**) are designed to provide a broad range of observations, models, and uncertainty estimates across a range of scales, but still face issues similar to the AmeriFlux network described above. A major goal of the NGEE projects is to provide observations that represent spatial variation in the characteristics of each biome to evaluate and improve the next-generation, modeling framework at a higher-resolution grid scale (15-25 km). Three large, team-based subsurface biogeochemical science focus areas (SFAs) have developed well-instrumented watershed field study sites to quantify the influence of disturbances on hydrological and biogeochemical cycling within watersheds and river basins, including water resources, water quality, and nutrient cycling. Within each SFA, long-term, team-research projects have been built around established field research sites in eastern and western river basins. The sites include a mountainous headwater catchment in the semi-arid Upper Colorado River Basin, a 75 km flood-plain reach of the Columbia River in the sparsely vegetated Columbia Plateau Region, and the spring-derived East Fork Poplar Creek that flows into the Clinch River in humid Oak Ridge, Tennessee. These significant NGEE and SFA field studies would benefit greatly from a suite of aerial observations.

New scaling methods and remote observational platforms are needed to support the scaling and model development activities within many DOE-funded projects. The frequency of cloud cover in tropical systems limits the utility of satellite resources and the remote nature of many important study areas makes airborne remote sensing an attractive and economical approach. Coupling of active and passive sensor technologies would provide an opportunity to link surface and subsurface observations and develop scaling algorithms to provide spatially and temporally rich data sets needed for model development, parameterization, and benchmarking of model predictions at the relevant scales.

More field studies with aerial observations are needed to quantify the influence of disturbances on hydrological and biogeochemical cycling within watersheds and river basins.

Similar to atmospheric research activities, the development of UAS for terrestrial ecosystem science presents an opportunity for routine and targeted sampling campaigns that can provide information on vegetation and subsurface dynamics at temporal scales not currently possible with piloted and satellite platforms. While UAS platforms generally do not have the range or payload of other platforms, their ability to rapidly cover specific locations, on demand, at variable altitudes and repeatedly with an increasingly wide range of instrumentation provides a new and key component in the monitoring of terrestrial systems for addressing model needs. UAS platforms are particularly well suited for observations and measurements requiring high resolution (spatial and temporal), such as quantifying vegetation-stand dynamics and fine-scale structure, or monitoring water, heat, and gas exchanges in the soil-vegetation-atmosphere system. Repeated measurements from UAS are needed to quantify vegetation, surface, and subsurface changes during shoulder seasons (bud break, spring thaws, senescence) or immediately following extreme event or ecological disturbance (fire, insect outbreak, storm, flooding). Continued development and miniaturization of instrumentation for terrestrial observations will enhance the scope and impact of UAS platforms.

Finally, a major challenge in the passive observation of terrestrial ecosystems for measuring and monitoring structure and functioning is the impact of the atmosphere on surface retrievals. While active systems, such as lidar and radar, do not require atmospheric corrections, passive systems, such as spectrometers and thermal infrared (TIR) instrumentation, are impacted by variations in atmospheric water vapor, aerosol, and trace gas concentrations that require careful consideration. For example, the conversion of surface radiance to at-surface reflectance needed for many mapping and scaling activities requires detailed knowledge of atmospheric composition. Often this information is inferred from coarse-scale observation networks or estimated from other sources; however, an opportunity exists within CESD to coordinate collection activities such that critical atmospheric measurements are made at suitable scales for improved retrieval of vegetation properties. In addition, simultaneous collection of both surface and atmospheric properties could yield important insight into the drivers and evolution of aerosols and atmospheric states, which are tied to surface properties, as well as help attribute trace gas fluxes in the atmosphere to the dynamics of surface vegetation.

3.0 Aerial Infrastructure Needs to Address Overarching Science Questions

The following section identifies science questions for which CESD programs need aerial measurements to address as well as the platforms and instrumentation required to do so. CESD primarily has used piloted aircraft to address many of its aerial measurement needs, although there has been growing interest in the use of UAS. The UAS spectrum includes kites, tethered balloons, rotorcraft (e.g., quad-copters or hexa-copters), and small and mid-sized fixed-wing unmanned aircraft. The platforms differ in payload capacity, cost, complexity, and operational footprint and offer various performance benefits relative to one another. For example, kites, unlike tethered balloons, perform better the higher the wind speed. Numerous UAS-compatible sensors—measuring radiation, atmospheric state, gases, and aerosol properties—are currently available, and many more are in development.

Current regulations make flying UAS in the U.S. National Air Space (NAS) quite difficult, requiring special approvals from the Federal Aviation Administration (FAA) that are tied to a specific platform and duration, a small geographical area, and very low flight altitudes. The FAA has been tasked by Congress to study the inclusion of UAS into the NAS. CESD is in a unique situation in that it controls special-use airspaces (managed by the ARM Facility) over and to the north of the Oliktok Point site, which provides opportunities to undertake UAS-based research in the Arctic (Mather and Voyles 2013). Thus, while such advancements enable the use of UAS to address an increasing number of scientific topics, piloted research aircraft will continue to provide a vital function. In addition to the current airspace limitations, the payload capacity (volume, weight, and electrical power) of UAS is orders of magnitudes smaller than those of piloted aircraft and many of the currently required instruments cannot be miniaturized in the foreseeable future for use on UAS. Furthermore, new and cutting edge instruments often require considerable hands-on interaction from an onboard operator before they can be deployed in an autonomous fashion, which is a needed step prior to their miniaturization, where possible.


CESD currently controls special-use airspace near Oliktok Point where UAS, like this DataHawk, can be flown for atmospheric observations.

The science drivers dictate the scope of needed measurements and the observation strategy. Generally speaking, in the sections that follow, there are two main observational perspectives that differ in their primary scientific goal. The first is the more traditional field campaign in which intensive observations are made of a broad range of variables over a limited duration to characterize a set of processes or states in a specific region. The second involves routine observations of a limited number of variables to closely monitor or acquire statistics of a specific part of a system or region.

Intensive observational platforms make a wide variety of complementary measurements (e.g., cloud, aerosol, trace gases, atmospheric and radiative state, vegetation structure, vegetation dynamics and growth, soil water content) needed to provide a holistic understanding into critical processes. Such observations are important for integrated characterizations of terrestrial ecosystems or improved atmospheric process-level understanding needed to improve climate model representations. The operation of intensive platforms and their personnel are financially demanding which necessitates limiting their deployment periods. However, the knowledge gained may include identifying those properties that require higher frequency aerial observations, which might be met with a smaller platform with a more minimal, targeted payload. Although the collection of measurements could be obtained by multiple platforms during intensive measurement campaigns (e.g., multiple UAS), there is benefit to having measurements made on a single, very large platform (e.g., a C130 or DC-8) to assure collocation of the properties and enable study of their covariations.

Routine/frequent observations can provide long time series that characterize the statistical variation of terrestrial and atmospheric properties under a variety of environmental conditions (e.g., seasonal variation at multiple locations) to an extent that is not feasible with traditional intensive observational campaigns (e.g., Andrews et al. 2011). Quantification of these statistical relationships is needed to test model parameterizations under a range of conditions, validate remote-sensing algorithms, and disentangle the effects of covarying properties, such as distinguishing aerosol versus thermodynamic effects on cloud properties or the intra-annual seasonality of vegetation properties regulating carbon dioxide, water, and energy exchanges. To be financially practical, platforms suitable for routine sampling must have minimized operational requirements, such as small manned or remotely piloted aircraft, tethered balloons, or kites. The payloads must also be minimal and easy to use, which may necessitate designing them to target a limited set of questions versus being more comprehensive. Developmental work might be required for a sensor to be suitable for turnkey operation or to be miniaturized for payload-limited platforms.

Beyond these two main scenarios, there is also a need for platforms with extended duration to observe the long-term evolution of a system, not just capture snapshots. Examples of where this capability is needed include cloud evolution from initial formation to dissipation, aerosol evolution from Lagrangian sampling or long transects (e.g., trans-Pacific), the diurnal cycle of vegetation function at a site, or the evolution and progression of a disturbance such as fire or insect activity. The duration depends on the phenomena of interest, which could range from 12 hours to several days. These platforms may be based on long-duration kites, tethered balloon, high-altitude balloons, or other as-of-yet undeveloped technology. Future platforms are of particular interest that would be able to observe remote locations where surface-based measurements are sparse, such as high-latitude areas or pristine conditions over open ocean far from coastal influences.

3.1. Atmospheric Measurements

Atmospheric measurement needs are presented by their primary topic area: aerosol and trace gases, cloud microphysics, and atmospheric state.

3.1.1. Aerosol and Trace Gases

Given that aerosols and their trace gas precursors are so inhomogeneous in the vertical and horizontal dimensions due to their short lifetimes, frequent spatially-resolved measurements are needed to characterize their properties. The greatest scientific value would be added by filling this information gap with frequent (2-3 times per week) vertical profiles using aerial platforms in different locations and aerosol regimes. Obtaining profiles of aerosol physical properties has a somewhat higher priority than profiles of those properties needed to characterize physicochemical aerosol-cloud interactions, such as hygroscopicity and concentrations of condensation nuclei (CCN) and ice nuclei (IN). Experts at the workshop listed the following measurements in general priority order:

- number concentration
- size distribution (Ångström exponent at a minimum)
- absorption
- composition
- hygroscopicity

- concentration of CCN
- IN
- precursor gases
- oxidants.

While scientific advancements could be made by individual measurements of these properties, there are synergistic advantages of having multiple measurements on the same platform. It will, however, be challenging to make some of these measurements concurrently on a frequent basis.

Aerosol size distributions are needed for diameters from 5 nm to 10 µm. The lower limit of about 5 nm is needed for aerosol-cloud interactions studies, as these particles can quickly grow into CCN active sizes, and the upper limit of 10 µm is needed for ice nucleation studies and (e.g., Kassianov et al. 2012) aerosol radiative forcing. Currently, no single instrument measures over this entire size range. Therefore, measurements from multiple instruments need to be merged and some of the required instrumentation has not yet been miniaturized. New techniques for size distribution measurements are desired that are not biased due to shape and Mie theory limitations (i.e., shadowing and imaging techniques not relying on angular light scattering). While 5 nm is easily achievable with existing technology, to truly understand the aerosol life cycle, measurements would need to go down to as small as 1.5 nm diameter.

Aerosol absorption measurements, which are needed to quantify aerosol impacts on the atmospheric heating profile, are challenging even for ground-based instruments. Filter-based methods have biases, low temporal resolution, and sensitivity while photoacoustic techniques have low sensitivity. Photothermal techniques are more sensitive and hold promise but require more characterization before they lead to commercially available instrumentation. The aircraft environment is particularly difficult for the existing measurement approaches as they need to be immune to vibration, pressure changes, acoustic noise, and require high temporal resolution and sensitivity. Slow-flying platforms (e.g., balloons) will help with the latter two issues; however, developmental work is needed to make instruments smaller. An important need is to extend spectral measurements into the ultraviolet (UV) to attain attribution of absorption to aerosol type (i.e., brown carbon, black carbon, dust, etc.). Finally, in situ aerosol absorption measurements are currently reliable only for dried aerosol. An important, major challenge is the ability to measure aerosol absorption at ambient conditions, i.e., in the state where they impact the radiation field.

Existing aircraft cloud and aerosol probe technology needs development work to miniaturize instrumentation for smaller platforms, like balloons and UAS.

Aerosol composition measurements, needed to understand the aerosol life cycle and its interaction with clouds and precipitation, would require lighter, smaller instrumentation with sampling biases that are understood and can be corrected. If frequent vertical profiles of composition cannot be achieved, at least understanding when ground-based measurements are representative of properties aloft would be a helpful first step. For example, simple aerosol measurements (i.e., aerosol number from a small unmanned aerial vehicle or balloon) would be valuable to characterize the boundary-layer structure and determine whether the atmosphere is well-mixed or decoupled.

Aerosol hygroscopicity affects CCN, optical properties, and size distribution. Its measurement is necessary to identify aerosol components in external mixtures that have different hygroscopic growth behaviors, to transform dry mass in climate models to ambient column extinction, and to relate aircraft-based dried measurements to ambient conditions. While significant drying of the aerosol sample stream is inevitable in aircraft-based measurements (ram heating occurs as the sample stream is decelerated from aircraft speed to sampling speed inside the instrument), the current paradigm of using ground-based dried measurements must be challenged. Measuring frequent vertical profiles of aerosol hygroscopicity would address this issue, which requires development of miniaturized aircraft instruments.

In addition to characterizing these physical and chemical aerosol properties, understanding which aerosols are controlling cloud processes is paramount for climate prediction. Measurements of CCN at the surface are not representative of the aerosol entrained into clouds from above, nor of the concentrations within cloud when the atmosphere is decoupled. Widespread new particle formation events may occur aloft that contribute to CCN concentrations, but little is known of the frequency and extent of these events. Thus, regular vertical profiles with a miniaturized CCN counter are necessary. AAF has flown a prototype of such an instrument; however, there is not currently a commercially available version. As GCMs do not properly capture CCN profiles, such measurements are valuable with or without the presence of clouds.

Ice nuclei are low in concentration but strongly affect cloud formation and precipitation; however, better understanding is needed of IN amount, its relationship with the rest of the aerosol population, and the impacts of IN. As for CCN, IN concentrations need to be measured aloft since ground-based measurements would be of limited value. To accomplish this, instrument development is critically needed. Aircraft instruments must be developed that are smaller, lighter, commercially available, cover all relevant sizes of IN, and measure all relevant freezing processes. Microfluidic devices hold promise here. The size-cuts of the Counter-flow Virtual Impactor (CVI) inlet need to be carefully assessed after each installation and, ideally the size-cuts would be adjustable. A major accomplishment would be the development of an aircraft CVI inlet that allows separation of cloud droplets and ice crystals when flying in mixed-phase clouds to allow separation of CCN and IN in the sample stream needed to improve understanding of mixed-phase cloud physics. Since IN concentrations are very low, the use of aerosol concentrators should be explored.

Pollen and agricultural dust are an emerging area of interest, especially as possible source for IN and CCN. Commercial ground-based instruments are available that can detect and size such aerosols, including the Wideband Integrated Bioaerosol Sensor (WIBS) and Ultraviolet Aerodynamic Particle Sizer (UV-APS). However, such instruments need to be characterized and potentially modified for aircraft operation. Most of these aerosols are in the super-micron size range and cannot be sampled by mass-spectrometers (to determine composition) nor by the IN instruments that can currently be flown (to determine their ability to serve as IN). Thus, instrument improvement is needed here.

A high priority for all aerosol studies (and particularly those dealing with super-micron aerosols) is to characterize and improve aerosol inlets and sampling lines to ensure that the transmission efficiency as a function of particle size is acceptable and quantified. Further, processes associated with wet removal of aerosols remain key sources of uncertainty in global aerosol-climate models. The ability to measure in-cloud trace gases and non-activated, or interstitial, aerosol within clouds is required for wet scavenging studies, where the latter requires improvements/modifications of the current aircraft inlets.

However, some of the most-sophisticated analyses available to study aerosols can only be brought to bear in laboratory settings, such as CESD's Environmental Molecular Science Laboratory (EMSL). Thus aerosol samples need to be collected in the air for subsequent lab analysis. Improving collection efficiency and time-resolution of such aerosol samples is highly desirable for IN grids and instruments such as the Time Resolved Aerosol Collector (TRAC) and the Particle in Liquid Sampler (PILS).

Airborne aerosol samples need to be collected for sophisticated analysis at laboratories, like CESD's Environmental Molecular Science Laboratory.

Process understanding from precursor gases to aerosols, particularly total aerosol concentration, is needed for predictive climate modeling. Very high temporal resolution measurements, ~10–20 Hz, are needed to capture small-scale heterogeneities and fluxes of precursor gases and aerosols. Such measurements are needed in the vertical profile, but also in Lagrangian studies to study temporal evolution. Miniaturized instruments to measure biogenic volatile organic compounds (BVOCs) are needed, and so is better detection for currently undetectable compounds, such as extremely low volatility organic compounds (ELVOCs) that are important precursors for secondary organic aerosol (SOA). For improved performance of mass spectrometers, there was a desire to address the catastrophic failures that can occur in their turbo-pumps during spin-down/up, which requires manufacturer involvement. A miniaturized aerosol chemical ionization mass spectrometry (CIMS) instrument and/or mid-infrared spectroscopy approaches may lead to much smaller instrumentation than current mass spectrometers, which would increase the number of instruments in a payload (e.g., G-1) or enable their deployment on unmanned aerial vehicle or light aircraft. Whole-air sampling with off-line analysis can characterize a wide range of trace gases; however, this analysis can only be done at low-temporal resolution and could be improved by the development of techniques requiring smaller sample volumes. Development and testing of miniature analyzers for ozone, the hydroxyl radical (OH) and other trace gases relevant to climate science applications is required. To better understand aerosol reactions, the ability to make on-line measurements of viscosity was desired.

In summary, the prioritization of the aerosol topics are provided in Table 1 along with an estimation of the timeframe needed to achieve a given task. Workshop participants ranked the importance of each topic 1–3 (one is highest) and estimated the time needed to achieve each task:

- S for short term, 0–2 years;
- M for medium term, or 2–5 years; and
- L for long term, or 5–10 years.

Coloring aides visualizing the importance ranking and time period needed:

- dark green, high importance or achievable in the short term;
- yellow, secondary importance or medium term; and
- red, lowest importance or long term.

Rankings or periods that fall in between green and yellow are light green, and those falling in between yellow and red are orange. Acronyms not previously defined are provided in the footnote.

Table 1. Prioritization of Aerosol Topics.

Topic	Importance (1–3)	Achievable Under What Time (S, M, L)
Frequent vertical profiles of aerosol number and size, preferably down to sizes of a few nm	1	S
Aerosol inlet (i.e., isokinetic and CVI)/ sampling lines characterization (i.e., transmission efficiency, size cut-offs) and improvement; need ability to measure interstitial aerosol without artifacts	1	S–M (required for every platform)
Capability to sample/analyze super-micron aerosols with aerosol mass spectrometers	1	S–M
Frequent vertical profiles of aerosol absorption, techniques other than filter based needed at ambient RH, include UV wavelengths	1	S (filter-based) M–L (new-techniques)

Development of IN aircraft instruments that are smaller, lighter, commercially available, cover all relevant sizes, including super-micron, and measure all relevant freezing processes; include collection of IN for post-analyses	1	M–L
Miniaturization and validation of numerous online-instruments to measure: CCN, gases, aerosol size distribution, composition (e.g., with micro fluidic techniques, electro chemical sensors)	1	M–L
High-frequency measurements (10-20 Hz) of gases, and aerosols for fluxes	1–2	M
Frequent vertical profiles of aerosol composition	1–2	M–L
Lagrangian studies of aerosol evolution, such as balloon chase	2	S (with manned aircraft)
Implementation of aerosol concentrators	2	S (for manned platforms due to high flow requirements)
Measurement of biological particles	2	S–M
Frequent vertical profiles of aerosol precursors and oxidants	2	S–M (manned)
		M–L (UAS)
Frequent vertical profiles of aerosol hygroscopicity (i.e., scattering, absorption, size distribution)	2	S (scattering hygroscopicity on manned)
		M–L (scattering hygroscopicity on UAS)
		M–L (hygroscopicity of absorption and size distribution on manned)
Better detection of currently undetectable compounds, including ELVOCs, potential for spectroscopy approaches (mid-infrared) that are smaller than mass specs	2	S (FT-IR[a], HR-PTR-MS[b])
		S–M (CIMS/FIGAERO[c])
		L (spectroscopy for UAS)
Improving collection and time-resolution of aerosol samples for off-line analyses (e.g., TRAC, PILS-sampler, IN grids)	2	M
Miniaturized instruments to measure OH (with techniques such as CIMS, LIF[d])	3	S–M
Miniaturized instruments to measure BVOCs	3	S–M
Address catastrophic failures of mass spectrometer turbo-pumps during spin-down/up—needs manufacturer improvement	3	M

[a] FT-IR: Fourier Transform InfraRed (spectrometer)

[b] HR-PTR-MS: High Resolution – Proton Transfer Reaction – Mass Spectrometry

[c] FIGAERO: Filter Inlet for Gas and Aerosols

[d] LIF: Laser Induced Fluorescence

3.1.2. Cloud Microphysics

Improving cloud processes in models requires information on the cloud microphysical properties, such as particle size distribution, and the coincident cloud dynamical properties, such as turbulence. Only aerial measurements can provide detailed cloud microphysical information (e.g., size distributions) or bulk properties needed to validate remote-sensing retrievals. With only a couple of exceptions, the priorities of the topics discussed ranked generally high with no preference with cloud type (liquid water, ice, and mixed-phase). Thus, the aerial needs are discussed usually by type with the highest ranked given first for each type.

Mixed-phase clouds provide a particular challenge for models of all scales due to the inherent phase instability associated with having ice and liquid in close proximity (Morrison et al. 2011). In addition to the desired improvements on size distributions and bulk properties discussed in subsequent paragraphs, capabilities are needed that provide information on mass-based ice/water phase partitioning within a given volume. Such measurements would help to inform on mechanisms for sustaining the relative partitioning of phase within clouds. In the saturated environment expected in mixed-phase clouds, small ice crystals grow very rapidly, with simulations suggesting that ice particle diameter can quickly exceed 100 µm (Avramov et al. 2011; Fridlind et al. 2012). Thus, size-resolved measurements would need to be able to observe ice crystal sizes larger than this value. Better understanding of the influences of aerosols and radiation on mixed-phase microphysical quantities would benefit from sustained, high-spatial resolution observing within the region near cloud top. It is important to note that deploying instrumentation in mixed-phased clouds will require overcoming issues of instrument and platform icing.

Total ice mass is a quantity with high uncertainty in observations, process models, and climate models (e.g., Eidhammer et al. 2014; Waliser et al. 2009). Current estimates are that ice mass mixing ratio cannot be measured to better than a factor of two. While both bulk and single-crystal mass are of interest, it will be more scientifically valuable to first focus on improving quantification of bulk properties. Routine aerial observations over ARM sites can provide the in situ statistical characterization of ice mass necessary to validate ground-based retrievals, such as those being developed using new, multi-frequency Doppler radars. Doing so requires co-location of in situ and radar measurements, which could be addressed with an aerial platform that remains local (e.g., tethered balloon). Another potential solution may be to greatly improve co-location by mounting a cloud radar (operating at the same frequency of surface-based sensors) on a research aircraft to provide simultaneous near field measurements just above and below the plane. A similar approach also could be applied to in situ measurements and a forward-pointing lidar, and the combination of the two would allow for evaluation of multi-wavelength retrieval algorithms. In addition, measuring ice water content in combination with particle area would provide needed information on ice particle mass and would also enable evaluating and improving the area-mass relationships commonly assumed in image probe processing and in modeling.

Entrainment mixing is a process critical to cloud life cycle (e.g., Sanderson et al. 2008). Advancement of its understanding requires instruments that can provide high-spatial resolution (sub-meter) information on the co-variability of cloud microphysical parameters and turbulence. Such high-resolution measurements could be made using very fast-response instruments from a moving platform (aircraft). More ideally, such measurements would be made in a near-Lagrangian setting, such as that provided from a blimp, helicopter, or small UAS. In general, measurement of cloud microphysics using volumetric imaging methods has advantages over particle-counting methods, since the extended averaging required by the latter to ensure adequate count statistics reduces the needed high-frequency information. Improvements are needed in droplet size distributions by particle-counting methods under polluted conditions to understanding the impact of aerosol on cloud in a changing climate. Substantial differences have been found between size distributions measured simultaneously by different sensors when droplet concentrations are high (> 1,000 cm-3). Such differences need to be resolved and the uncertainties of the size-resolved measurements better characterized as a general practice.

Tethered balloons provide a potential alternative to aircraft platforms for in situ observations collocated with existing radar instrumentation.

Models also tend to do a poor job representing ice crystal growth processes, including nucleation, initial growth, and multiplication factors (e.g., Zhang et al. 2013). Model improvements are being held back by the need for improved measurement of the ice crystal size distribution and quantification of its uncertainty. One issue has been that measurement of small ice crystals (<50 µm) can be contaminated by residuals of ice crystals shattered after impact with the cloud probes. This affects the measured total ice particle number concentration, a quantity fundamental to cloud modeling. Shattering has been reduced recently through the installation of knife-edge tips on cloud-sizing probes, but work is needed to further quantify these effects. Any shattering impacts measurements in the size range needed to study ice nucleation and initial growth, so methods are needed for making measurements from a slow-moving or nearly stationary platform (e.g., tethered balloon, blimp) to further minimize shattering or avoid it altogether. To further assist ice physics and modeling studies, quantified uncertainties of ice size-resolved number distribution measurements are needed. In addition to shattering effects, ice size distribution measurements are also affected by multiple un-quantified instrumental factors, such as an unknown depth of field of the probes. Currently no definitive uncertainty estimate is available, but an accuracy of around 10% per bin is desired. In addition, a common framework for processing data from aircraft optical imaging probes is sorely needed, since the same data set processed by different groups can result in an order of magnitude differences. There is ongoing work within the community to improve ice size distribution measurements, and CESD will be able to look to the report for details on best practices once it is released. Given the uncertainties in ice size distributions, inclusion of long-path extinction measurements could provide a valuable overall constraint. In addition to these size distribution measurements, improving the computation of ice scattering phase functions requires finer resolution in situ imagery of surface roughness and nephelometer measurements of the scattering phase function for varying conditions.

Hydrometeor number concentration and mass mixing ratio are directly used in the two-moment microphysics schemes commonly used within the modeling community (e.g., Gettelman and Morrison 2015; Morrison and Gettelman 2008). Routine measurements of these two parameters at ARM surface sites would likely provide substantial value to modeling and related retrieval development of these parameters. The utility of such measurements would be greatly enhanced by coincident airborne measurement to study covariations, such as of atmospheric state (e.g., vertical velocity, water vapor mixing ratio, and temperature) and/or aerosol properties (e.g., aerosol number concentration, size distribution, composition, and CCN/IN number concentrations). For example, routine coincident aerosol and mixed-phase water and ice-mixing ratio measurements would elucidate the relationship between aerosol loading, type, and phase partitioning. Payload restrictions of UAS capable of routine measurements may preclude a comprehensive measurement package, and thereby, necessitate careful selection and planning of the measurements to be made simultaneously. In general, cloud properties change more quickly than aerosol properties, so a possible strategy would be to intersperse an aerosol platform deployment within more frequent cloud platform deployments. In addition, multiple UAS platforms deployed in formation could provide the correct balance of sensors necessary to capture the variability within the atmosphere. Co-locating such sampling at the ARM surface sites allows for integration of complementary, surface-based measurements and also aids in development of retrieval products.

Finally, evaluation of the evolution of physical process within a model grid cell requires ample statistics of the resultant state. For example, flights designed to study aerosol-cloud interactions would benefit from airborne passive measurements that could be used to obtain cloud and aerosol field statistics, such as aerosol optical depth and liquid water path. Retrievals of liquid water path and effective radius in inhomogeneous or broken cloud fields would require a spectroradiometer that can take high-frequency (>1 Hz) radiance measurements at visible and near-infrared wavelengths (0.4 to 1.6 μm). Obtaining an even larger scale view of the cloud and aerosol field statistics might be possible by working with other agency platforms, such as National Aeronautics and Space Administration (NASA) satellite and aircraft. However, there may be issues with resolution relative to the scale of the campaign, particularly when smaller (i.e., UAS, tethered balloon) platforms are considered. In theory, high-altitude manned or unmanned aircraft could provide higher resolution insight into a specific region.

In summary, the prioritization of the cloud topics are provided in Table 2 along with an estimation of the timeframe needed to achieve a given task. Provided is the importance of each topic and the estimated time needed to achieve it. See the paragraph before Table 1 for further instructions on how to read the table.

Table 2. Prioritization of Cloud Topics.

Topic	Importance (1–3)	Achievable Under What Time (S, M, L)
Instrument capable of providing the ice/water phase partitioning by mass within a given volume (bulk only, not size distribution)	1	S–M
Reduce uncertainty of total ice mass measurements	1	M
Collocated/correlated measurements of in situ cloud microphysics and radar remote sensing	1	M
High-spatial resolution microphysics measurements needed for cloud entrainment studies	1	M
Accurate ice particle size distribution measurements including uncertainties	1	M–L
Routine droplet number concentration and mass	1–2	S
Accurate drop size distributions measurements including uncertainties	1–2	S
Collocated/correlated measurements of in situ cloud microphysics and passive spectral remote-sensing	1–2	S
Collocated/correlated measurements of in situ cloud microphysics and scanning lidar for retrieval development	1–2	M
Single particle ice mass	2	L
Ice crystal roughness for radiative transfer	3	S

3.1.3. Atmospheric State

Studies of cloud and aerosol physics require accurate specification of the atmospheric state. This includes spatial information about water vapor mixing ratio, temperature, pressure, winds (horizontal and vertical), and their turbulent structure. Such parameters, for example, are often needed as inputs in model parameterizations. While surface-based instrumentation can provide measurements of many of these parameters to varying degrees, the level of accuracy and/or high-spatial resolution needed for an application often necessitates aerial observations.

A high priority need is the profiling of temperature and water vapor over ARM facilities at frequencies greater than currently available from radiosondes, particularly of the boundary layer. Such measurements are needed to determine the inversion strength and resolve the coupling of boundary layer dynamics with cloud. This is particularly important to observe when the boundary layer is evolving rapidly, such as at maritime locations during transitions between coupled and decoupled states or at continental locations during the warm season when surface heating is driving boundary layer growth. ARM surface-based profiling capabilities partially address this need, but the remote sensors capable of providing highly resolved vertical profiles cannot penetrate cloud base. A minimum airborne profiling frequency of 3 hours is preferable and 1 hour or better would be ideal. Further, a limited network of such measurements could meet a secondary need of distinguishing at a given location the effects of local versus large-scale advective contributions to the water and temperature budgets. Even higher frequency measurements are needed of cloud top temperature to determine the cloud cooling rate and subsequent turbulence generation in stratiform clouds, such as in the Arctic or maritime stratus. In this case, continuous temperature profiling through the cloud layer are needed for precise determination of cloud top temperature and its temporal variations, which could be obtained with a tethered balloon system or kite that suspends a fiber optical line of temperature sensors.

Regular radiosonde launches over ARM sites do not provide enough frequency of measurement of water vapor and temperature, particularly in the boundary layer.

Understanding and simulation of cloud processes require precise and accurate airborne measurements of water vapor mixing ratio and temperature at high-spatial resolution. Of particular importance is using these two measurements to compute supersaturation, which cannot be measured directly and is fundamental to cloud droplet growth. Cloud physics studies require accuracy in supersaturation with respect to ice to be within a few percent for cold clouds, whereas warm clouds need accuracy of 0.1% in supersaturation with respect to liquid. However, regularly attaining such accuracies has been challenging. Radiosondes cannot provide horizontally resolved measurements in the vicinity of cloud needed for process studies and their accuracy is not always reliable, especially for the low water vapor amounts in the upper troposphere. To fill this need, airborne in-cloud temperature measurements must be precise and accurate because very small uncertainties in temperature can have large impacts near saturation. Achieving such accuracies from a moving platform can be difficult because temperature measurements can be affected by condensate; thus, counterflow measurement techniques must be employed to avoid this effect. For supersaturation calculations, water vapor measurements must be made in sync with the temperature measurements. Capturing water vapor gradients in and around cloud requires aircraft measurements that are fast-response and are also unaffected by cloud condensate.

The needed response time depends on the aircraft speed and the spatial resolution needed for an application. A resolution of 100 m is sufficient to characterize the horizontal variability for many applications (e.g., 1 Hz moving at 100 m/s) and centimeter scale is needed for entrainment studies (e.g., 100 Hz moving slower at 10 m/s). Optical measurement techniques (e.g., diode laser hygrometer) can provide fast-response water vapor measurements. However, their performance has not yet been assessed at cold temperatures and low moisture amounts, such as those in the upper troposphere where attaining accurate supersaturations is particularly challenging since water vapor concentrations are only a few parts per million. Such conditions can be found at G-1 attainable altitudes in high latitude atmospheres. While such fast-response water vapor measurements are available on larger manned platforms, continued development efforts are required to bring this capability to smaller UAS platforms to facilitate more frequent sampling of cloud systems. In addition to the fast-response water vapor and temperature measurements, understanding and evaluating the different entrainment models also require commensurately high-resolution turbulence and microphysics measurements. This is a high priority because, if achieved, it would make a mark in the field.

Another need for fast water vapor, temperature, and turbulence measurements is determining the spatial variability of turbulent fluxes (sensible and latent heating) across a region, which is critical to understanding the surface-atmosphere interactions (land, ocean cryosphere). Eddy correlation measurements are made around ARM sites, but are limited because they are discrete observations of fluxes that can vary rapidly with distance and, further, measurements are not made over some surface types (e.g., over ice). Survey flights are needed to characterize the fluxes through the year and frequent flights are needed during transition seasons when the energy fluxes are changing rapidly, such as melt/freeze periods in the Arctic or the May greening period at the SGP. This need can be addressed by airborne measurements of surface turbulent fluxes (at 10-20 Hz) that must be made close to the surface (10 m). Safety reasons prevent piloted aircraft from flying so close to the surface, but UAS would be capable of performing this need after developmental efforts. While accurate vertical velocity and horizontal wind measurements can be made from larger aircraft, UAS-deployable inertial measurement units must be improved

Frequent flights are needed during the transition seasons, like the greening period of the SGP site, to characterize surface fluxes.

to provide these measurements with sufficient accuracy to deduce fluxes. Such flux measurements should be made in an integrated fashion to link with detailed information on other surface characteristics (e.g., land-use, plant canopy, soil moisture and temperature). Such UAS-based characterizations would greatly benefit from the capability to operate beyond visible line of sight and, even further, beyond radio line of sight via satellite link. Operations beyond visible line of sight in the Arctic would also require de-icing mechanisms to prevent loss of aircraft control should icing conditions be encountered en route.

In summary, the prioritization of the atmospheric state topics are provided in Table 3 along with an estimation of the timeframe needed to achieve a given task. Provided is the importance of each topic and the estimated time needed to achieve it. See the paragraph before Table 1 for further instructions on how to read the table.

Table 3. Prioritization of Atmospheric State Topics.

Topic	Importance (1–3)	Achievable Under What Time (S, M, L)
Hourly (or near-hourly) profiles of water vapor mixing ratio and temperature	1	S–M
High spatial resolution temperature, water vapor measurements, and turbulence needed for cloud entrainment studies	1	M
High frequency measurements (10-20 Hz) of thermodynamics for fluxes	1–2	M
Coincident water vapor, temperature, 3D velocity for sensible and latent heating profiles	2	M
Measurement system for budget of local vs. advection of total mixing ratio and temperature	2	M

3.2. Environmental System Science Measurements

Observations of terrestrial ecosystems are essential to our understanding of the patterns of carbon storage, biodiversity and species distributions, water status, and other key landscape and soil characteristics as well as their dynamics through time. To benchmark and improve the representation of terrestrial ecosystem processes in ESMs, we must evaluate the current state of ecosystems from bedrock to the atmosphere and evaluate changes to ecosystem processes in response to natural or imposed environmental changes. These requirements suggest two broad aerial observation strategies needed to achieve a better process understand of terrestrial ecosystems (see Figure 2 in Section 2.2). The first strategy would include campaigns designed to provide detailed characterization of the state of the system, such as vegetation structure, biomass, and soil characteristics using a comprehensive suite of instrumentation. The second would develop targeted, repeat observations with more mobile and rapidly deployable platforms using a smaller set of instrumentation designed to characterize changes (i.e., dynamics) brought about by specific ecosystem processes or natural disturbances, as well as changes due to anthropogenic inputs, and their environmental responses. The processes themselves can be separated into terrestrial ecosystem processes that act on daily to centennial timescales and land-atmosphere exchange processes that operate as instantaneous responses to the environment.

3.2.1. Terrestrial Ecosystem/Watershed States

Detailed characterization of the state of terrestrial ecosystems, including vegetation and surface/subsurface properties, is needed because of their strong control on the critical processes and dynamics within a given ecosystem over the investigated timescale. The soil, landscape and vegetation structure and characteristics in terrestrial ecosystems strongly influence climate feedbacks and water quality/availability through ecosystem carbon, water, and energy exchange. While some of these states can be relatively well quantified today, such as the topography, others face more critical issues for being quantified directly and even indirectly, such as soil biomass distribution, soil organic matter content, and soil hydraulic parameters.

Variation in the compositional status of vegetation plays an important role in the functioning of terrestrial ecosystems and nutrient cycling. Importantly, plant species composition, land-cover type, and functional or biological diversity can be distinguished using spectral signatures measured by ground or airborne spectroscopic or "hyperspectral" surveys (Asner et al. 2014; Singh et al. 2015). The spectroscopic signature of soil can also be used to infer properties that influence the soil spectral signature such as chemical composition, subsurface geochemistry, and water content. Airborne campaigns utilizing imaging spectroscopy instrumentation can provide detailed information on the plant functional diversity of ecosystems, water status, nutrient cycling, and plant-soil coupling (see Figure 3). In addition, active sensors such as lidar and radar systems provide retrievals of vegetation and shallow subsurface structure and moisture. Lidar systems can provide detailed characterization of the three-dimensional (3D) structure of aboveground vegetation and canopy organization as well as high-resolution digital surface models (DSM) as depicted in Figure 4. For example, utilizing lidar together with surface observation networks (e.g., AmeriFlux, U.S. Forest Inventory and Analysis, and NGEE) enables the upscaling and extrapolation of information on vegetation structure to inform radiative transfer within canopies as well as characterizing vegetation carbon stocks, successional dynamics, and disturbances at a much higher spatial and temporal resolution than in situ observations alone. All-weather systems, such as Synthetic Aperture Radar (SAR) operating at long wavelengths (between 20-80 cm) and multiple polarizations, can volumetrically characterize vegetation structure and standing biomass, as well as capture key properties, structure, and moisture of the soil column at various shallow depths depending on wavelength or combination of wavelengths (Mulder et al. 2011). Importantly, combining airborne spectroscopy, lidar altimetry, and/or Synthetic Aperture Radar (SAR) data can improve quantification of structural and functional characteristics of ecosystems based on co-located spectral reflectance, 3D point clouds and SAR backscatter retrievals (Swatantran et al. 2011; Cook et al. 2013).

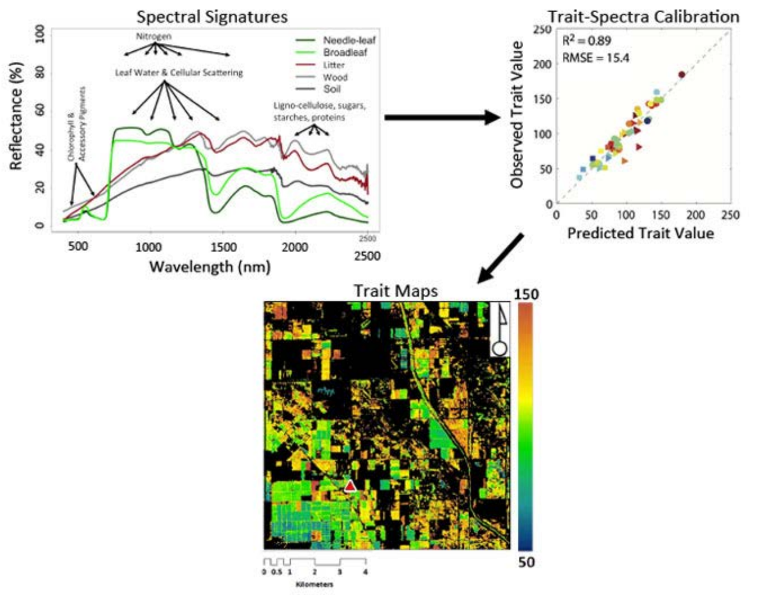

Figure 3. Spectroscopy and imaging spectroscopy instrumentation provide a critically important means of scaling and measurement of surface and vegetation properties, including plant traits that drive the fluxes of carbon, water, and energy from vegetation to the atmosphere and that are important inputs in models of vegetation growth and physiology. Leveraging these high- spectral resolution sensors mounted on UAS and manned aircraft enables the characterization of the state and dynamics of surface properties at the spatial and temporal scales needed to inform modeling activities. Miniaturization of full-range (i.e., 350-2500 nm) imaging spectroscopy instrumentation for use on off-the-shelf UAS platforms would provide a transformation change in the ability to monitor terrestrial ecosystem dynamics, including the tracking of key phonological changes or short-term “hot spot” events.

Detailed characterization of vegetation canopies, structure, and biomass are useful for process model initialization, parameterization, and benchmarking of carbon storage and turnover rates, as well as modeling carbon, water, and energy exchanges. Importantly, the biophysical properties related to carbon uptake and vegetation dynamics are critical for properly simulating photosynthesis, phenology, water cycling, and surface energy balance, but are often poorly constrained, represented or understood in terrestrial biosphere models. For example, LSM-representations of the radiative transfer within canopies lag behind many other representations in models, and, as a consequence, the ability to properly simulate the seasonal carbon uptake and storage of vegetation is limited. Lidar observations, particularly full waveform retrievals (Figure 4), together with detailed high-spectral resolution observations of canopies (at the leaf-to-landscape scales) could be used to improve the modeling of light penetration and utilization, thus improving our ability to represent and model energy, water, and carbon fluxes as well as long-term sequestration of carbon in biomass. In addition, the characterization of canopy structure along environmental gradients, disturbance regimes, and management practices can be used to inform the modeling of plant succession and recovery from disturbance. Further, DSMs from lidar observations provide a highly detailed characterization of surface structure useful for hydrologic modeling and identification and delineation of soil and landscape units with specific characteristics, especially when combined with optical measurements. Belowground soil properties estimation strongly relies on indirect estimation. While radar systems can also provide information on soil characteristics—and primarily moisture content in the upper soil layers—estimation of many soil properties deeper in the subsurface require the use of empirical or mechanistic link between subsurface and surface properties, or remote sensing observation, or the use of classical airborne geophysical approaches.

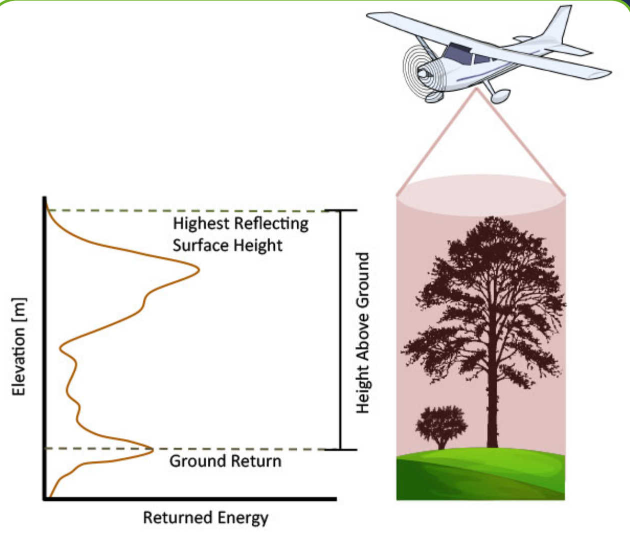

Figure 4. This figure illustrates the retrieval of vegetation canopy 3D structure and generation of high-resolution DSMs from an airborne waveform lidar instrument.

The properties of soil that are of major importance for ecosystem and watershed modeling include those controlling water and heat fluxes in the soil which drive the partitioning of soil moisture between infiltration, evaporation and water uptake from plants. The estimation of hydraulic parameters such as water retention functions and hydraulic conductivity cannot be made directly from remote-sensing data but are generally made using a non-mechanistic or a mechanistic parameter estimation approach involving remote-sensing observations. The non-mechanistic approaches exploit the correlation between hydraulic parameters measured at local or laboratory scales and soil texture, topographic attributes, and vegetation characteristics to define pedotransfer functions (Mohanty 2013). These approaches are used to estimate hydraulic parameters at larger scale using remotely sensed estimates of soil texture, topographic attributes, and vegetation characteristics. The mechanistic approach consists of iteratively solving for the distribution of soil hydraulic parameters using a parameter estimation approach that minimizes the error between prediction and measurements of various properties including ground-based and/or above-ground measurements of soil moisture and temperature data (Vereecken et al. 2008; Steenpass et al. 2010; Mohanty 2013). Thus, all measurements informing on water and heat fluxes at the surface and in the subsurface are of interest, including TIR, imaging spectroscopy, lidar, radar and electromagnetic induction (Robinson et al. 2008). Estimation of the soil characteristics controlling water and heat fluxes not only enables predictive simulation of water and heat fluxes using meteorological data but also advanced estimation of evaporation and water uptake from plants.

Prediction of watershed structure and function requires bedrock-through-canopy characterization and monitoring. Characterization of subsurface characteristics deeper than tens of centimeters rely on the use of classical airborne and ground-based geophysical approaches, including electromagnetic, magnetic, gamma-ray spectroscopy, gravimetric, ground-penetrating-radar and cosmic-ray neutron. Most of these approaches are commonly used in mineral and oil exploration, but have gained increasing interest to investigate soil and rock properties at shallower depths relevant for hydrological and terrestrial ecosystem modeling efforts (Robinson et al. 2008). Airborne electromagnetic induction imaging (e.g., Minsley et al. 2012) provides the 3D distribution of soil electrical conductivity, which provides data and information on the distribution of salinity, water, frozen and unfrozen ground, extent of aquifers, depth-to-bedrock, and geological structures. Magnetic survey defines the local variations in strength and direction in the Earth's magnetic field that depends on the spatial distribution and relative abundance of magnetic mineral and provides data and information on soil magnetic properties, geological structure, and faults. Gamma-ray spectrometry measures terrestrial gamma radiation and thus provides data and information on the natural and artificial presence of elements such as uranium, thorium, and potassium in soil and rocks. Gravimetric methods investigate gravity anomalies produced by density variations in space or time and can provide data and information on the volume of large sedimentary basin, aquifer, and salt domes. Finally, ground-penetrating radar is successfully used to investigate depth of a sharp boundary such as glacier thickness, while signal depth penetration in non-frozen environment is generally very limited. Future promising development of radar-based method for water content estimation in the top meter of soil will possibly come from the development of radar in the UHF and VHF bands (e.g., Ochsner et al. 2013). One additional potential approach may be the use of the cosmic-ray neutron method (Zreda et al. 2008) on an airborne platform to improve mapping of soil water content distribution. Continuing the development of these sensors on aircraft and potentially UAS platforms could yield critically needed higher spatiotemporal resolution retrievals that could be used to inform next-generation models.

In summary, the prioritization of the terrestrial state topics are provided in Table 4 along with an estimation of the timeframe needed to achieve a given task. Provided is the importance of each topic and the estimated time needed to achieve it. See the paragraph before Table 1 for further instructions on how to read the table.

Table 4. Prioritization of Terrestrial Topics.

Topic	Importance (1–3)	Achievable Under What Time (S, M, L)
Aerosol and Gases		
Surface carbon, water, and energy fluxes from vegetation	1	M-L
Carbon dioxide and methane soil emission, not only from vegetation	1	M-L
BVOC emissions from vegetation	2	M-L
Above-ground		
Vegetation 3D structure and vertical heterogeneity	1	S
Vegetation growth and mortality	1	S-M
Canopy disturbance, removal, and succession	1	M-L
Canopy foliar biochemistry	1	S-M
Canopy physiology and functioning	1	M-L
Vegetation transpiration/ evapotranspiration	1	S-M
Vegetation SIF	1	M-L
Terrain		
Digital terrain model/microtopography/ snow thickness/soil settlement, subsidence, or deformation/bathymetry	1	S-M
Surface water distribution/drainage pattern/bathymetry	1	M

Land cover (and classification)	2	S
Land-surface (skin) temperature	1	S
Soil surface properties including salinity, chemistry, soil mineralogy, and water/ mineral/organic fraction	2	M-L
Soil and Subsurface Characteristics		
Surficial soil moisture	1	S
Soil moisture (more than a few cm)	1	M-L
Soil hydraulic and thermal parameters	1	M-L
Soil composition (e.g., organic, mineral, clay content) and root biomass distribution	1	M-L
Soil salinity	2	M
Seasonal freeze/thaw state and thickness	2	M-L
Subsurface structure (geological layers, aquifer thickness, glacier volume)	1	M

3.2.2 Surface and Subsurface Processes

The relative abundance of vegetative species in terrestrial ecological systems changes through time progressively with ecological succession and through disturbances such as drought, wildfires, flooding, landslides, insect outbreaks, and anthropogenic land-use changes. Land form, water quality and abundance, and solute transport can also change rapidly through such disturbances or more slowly as the result of geomorphological processes, such as erosion. At shorter timescales, many soil and vegetation properties, as well as surface water and snow distribution, are directly influenced by meteorological forcing and soil-vegetation-atmosphere exchanges, and thus imaging the variation and change in terrestrial ecosystems over time is crucial to investigate dynamics and coupling between the various compartments.

Characterizing the biogeochemical cycling, canopy chemistry and physiological functioning of vegetation through time is critical to our understanding the terrestrial carbon cycle, phenological timing of the growing season, and aboveground soil coupling. The ability to monitor the functional status and biochemistry of vegetation with remotely sensed data is based on the principle that plant physiological properties, fundamentally tied to the biochemical composition, structure and distribution of foliage within plant canopies, are reflected in the optical characteristics of the canopy that can be observed using remote-sensing instruments (Curran 1989; Kokaly et al. 2009; Serbin et al. 2014). Terrestrial biosphere models (including vegetation and LSMs) require information on vegetation properties and plant traits related to ecosystem functioning in order to parameterize key submodels and representations. Spectroscopic and imaging spectroscopy instrumentation provides the capability to scale and capture the variability in canopy biochemistry and function across ecosystems, gradients, and through time (Figure 3; Martin et al. 2008; Singh et al. 2015). In particular, imaging spectroscopy data enable the remote retrieval of key properties needed for modeling vegetation nutrient cycling, water status, stress and health, as well as physiological functioning.

Imaging spectroscopy data also provide the capacity to remotely estimate photosynthetic capacity of vegetation (e.g., Serbin et al. 2015), which is a critical need for models (Schaefer et al 2012; Rogers 2014). The capacity to provide detailed, spatially and temporally rich trait maps from airborne imaging spectroscopy data (Figure 3) for modeling activities yields a great potential to aid in the ongoing development of trait-based modeling approaches that are part of NGEE-Arctic and NGEE-Tropics activities (respectively, Wullschleger et al. 2015 and Chambers et al. 2014). Furthermore, the strong coupling between vegetative properties and soil processes allows for the indirect estimation of key soil properties and function using airborne imaging spectroscopy observations coupled with ground-based measurements through the use of "optical surrogacy" approaches (Madritch et al. 2014). Finally, imaging spectroscopy data together with measurements of vegetation structure (e.g., from lidar) are needed to inform development of radiative transfer modeling (RTM) schemes for use with LSMs that not only capture surface heterogeneity but can be efficiently parameterized across a range of biomes, canopy structures, and land-use histories to better model surface albedo and capture process and feedbacks.

Together with spectroscopic approaches, TIR observations collected from aerial platforms could provide critical information on vegetation status, function, drought response, and evapotranspiration from the land surface to the atmosphere (Anderson et al. 2008). TIR instruments measure the radiant energy emitted in long infrared wavelengths (8-12 µm) that is a function of the temperature of the emitter, such as vegetation and soil. As such, TIR data from an airborne platform can yield timely and critical information on ecosystem properties through time and in response to environmental changes or disturbance, as well as coupling between vegetation and subsurface dynamics. For example, monitoring surficial water content, vegetation water status, and evapotranspiration can be used to infer rooting properties and sub-surface hydrological parameters—all of them important to understand and predict ecosystem/watershed response to disturbances. TIR observations can also potentially be used to constrain estimation of fractions of water, mineral and organic fraction in soil because these control thermal parameters that influence the surface temperature distribution. As such, collection of high-frequency TIR data from airborne platforms (aircraft or UAS) provides the ability to capture and monitor vegetative function and water cycling at scales relevant for model evaluation, process development, and benchmarking. Studying the footprint of EC towers with TIR instrumentation on airborne platforms is needed to inform our understanding of heat versus water vapor transport in the boundary layer (Bertoldi et al. 2013). Using aerial observations of TIR would serve to fill a critical gap in our ability to capture and scale properties and processes that drive variation in vegetative water use and soil water capacity. Together with surface observations and satellite retrievals, airborne TIR from piloted and UAS platforms would help to capture surface heterogeneity and deconvolve surface (e.g., soil) from vegetative temperatures and thus aid in the modeling of surface energy balance.

Monitoring surface elevation dynamics is another crucial issue to improve understanding and modeling of terrestrial ecosystem/watershed functioning. Lidar observations of canopy structure through time provide the capacity to characterize vegetation dynamics, succession, and mortality. Lidar and optical observation of ground elevation, snow layer thickness, surface inundation distribution, and variations in water level are crucial to manage water resources and parameterize hydrological models. Finally lidar has a strong potential to evaluate ground surface changes due to erosion or depositional processes, and in particular where such processes are relatively rapid, such as for example coastal erosion, ground deformation due to volcanic activity or rupture process, or river channel dynamics. Depending on the scale of observation, various radar systems can be used to quantify above processes.

Monitoring changes over time in soil properties is still very challenging. Soil moisture, for example, is of critical interest to understand water re-distribution, energy and water exchange, biogeochemical processes, and to constrain the estimation of soil hydraulic parameters. Information on moisture content in the top 5 cm of soil can be obtained from the L-band from a passive radiometer and/or coupled with SAR (active), while a microwave sensor with different wavelength (e.g., P-band, UHF, VHF) may penetrate slightly deeper (Mulder et al. 2011; Robinson et al. 2008). Soil moisture estimation can also be constrained by TIR observation and/or radiation measurements. Second, indirect estimation approaches are also often used to investigate soil moisture distribution while considering the soil-vegetation-atmosphere system. This is, for example, the case of the Soil Energy Balance (SEBAL) approach (Bastiaanssen et al. 2005) that produces spatio-temporal prediction of evapotranspiration that can be linked with soil water distribution. A variety of platforms providing radiance can be converted first into land-surface characteristics such as surface albedo, leaf area index, vegetation index, and surface temperature, and then used as input in such energy balance modeling. Finally, monitoring changes deeper than the top tens of centimeters relies primarily on the use of the previously discussed classical geophysical approaches from aircraft and potentially UAS platforms. This presents a promising means to inform the modeling of temporal variations in subsurface properties such as soil salinity and water distribution. UAS systems could also build on techniques already deployed on satellite platforms, for example the Soil Moisture Active Passive (SMAP) mission or the Gravity Recovery and Climate Experiment (GRACE) satellite.

In addition to sensing technologies and combined sensor packages, there is a critical need for aerial observations at key phenological stages in order to capture the functional phenology of the vegetation and subsurface. For example, imaging spectroscopy and TIR observations at the key shoulder seasons are needed to explore the timing and controls on ecosystem function in order to inform model development activities. Moreover, regular lidar observations of key locations can provide important information on vegetation structural changes, dynamics, and succession, as well as for benchmarking model outputs.

In summary, the prioritization of the terrestrial surface and subsurface process topics are provided in Table 4 in Section 3.2.1., along with an estimation of the timeframe needed to achieve a given task. These developments are highly relevant for several DOE-funded projects, including NGEE, AmeriFlux, and the SFAs.

3.2.3 Land-Atmosphere Exchange

The land-atmosphere interface is a central component of the Earth's climate system, regulating complex interactions and processes including biogeochemical cycling, mass and energy exchanges, and storage with significant feedbacks and lags on climate. Changes in land cover driven by climate, disturbance, or anthropogenic land-use can dramatically modify the functioning and feedback of this interface resulting in significant modifications in mass, energy, and momentum fluxes. These changes can have major implications for climate, atmospheric composition, ecosystem functioning, carbon storage or release, and the subsequent change to radiative forcings. Furthermore, feedback couplings such as BVOCs emitted from land ecosystems due to natural development or stress result in the formation of aerosols, which, in turn, modify climate. Therefore, adequate characterization and modeling of the interaction of surface energy and carbon fluxes, moisture, and vegetation health and status with the atmosphere is critical for informing and benchmarking models.

Eddy covariance (EC) tower sites provide our best understanding of the landscape-scale exchanges of mass and energy from the land surface to the atmosphere and the responses of surface-atmosphere coupling to changes in light, water, temperature, nutrients, disturbance and other factors. As such, EC towers are widely used to quantify the net ecosystem exchange of ecosystems as well as other trace gas fluxes that influence atmospheric composition and radiation scattering. While networks of EC tower sites have greatly increased our observations of trace gas fluxes, there remains a critical need for airborne observations to characterize and quantify the immense variability in vegetation composition and properties that govern photosynthesis, carbon uptake, energy and water fluxes, as well as BVOCs, aerosols, organic and nitrogen compounds, and oxidants emissions to constrain our understanding of land-atmosphere coupling in relation to various environmental conditions and external drivers of change. This information is critical for regional atmospheric, hydrological, and ecological studies, as well as for improving model representations of land-atmosphere dynamics. Airborne capabilities also provide a means of investigating gradients of disturbance, land-cover change, and stress and also provide the ability to target events involving rapid change such as insect outbreaks, floods, or drought related to local or global teleconnections.

The fluxes of carbon into vegetation through photosynthesis and release through respiration represent a significant component of the global carbon cycle. The gross photosynthetic uptake or gross primary productivity (GPP) of vegetation can be inferred from EC towers and has been the focus of upscaling and mapping using various satellite observations and approaches, including correlations with SVIs or quasi-mechanistic light-use efficiency modeling approaches. Airborne spectral and/or TIR observations over AmeriFlux or other EC sites (e.g., NGEE) would allow for improved upscaling, particularly if UAS platforms enabled high-temporal frequency observations that would improve the ability of remotely sensed methods to capture short-term (daily to weekly) changes in surface-atmosphere exchanges. Moreover, high-spectral resolution remote sensing has shown promise to provide estimates of key parameters that drive photosynthetic fluxes of vegetation (e.g., Serbin et al. 2015). High frequency airborne collections of imaging spectroscopy data over EC sites could thus yield important improvements in our ability to map and model vegetation function. In addition, an emerging approach to remote sensing of GPP is based on the relationship between vegetation photosynthesis, radiation utilization, and the emission of energy from vegetation through fluorescence (under stress and high light conditions). Using very narrow-band remote-sensing instruments to capture the solar-induced fluorescence (SIF) signal from vegetation, it may also be possible to provide key mechanisms that allow for the indirect monitoring of the photosynthetic activity of vegetation. However, to date the use of SIF has been limited to coarse-scale satellite retrievals, and the link between fluorescence and photosynthesis at the canopy is complex. Nevertheless, laboratory and small-scale studies have shown clear relationships between GPP and SIF, and airborne platforms could serve as an important means to scale and map GPP of canopies over broad areas and through time. Importantly, SIF from airborne platforms could be collected at temporal frequency, enabling the better characterization of photosynthesis both spatially and temporally at key sites, such as at EC tower locations and across NGEE campaigns.


Tall tower networks provide the best understanding of the landscape-scale exchanges of mass and energy from the land surface to the atmosphere, which could be significantly enhanced with frequent airborne collections of imaging spectroscopy data, yielding important improvements in the ability to map and model vegetation function.

Aerosol and BVOC fluxes are especially challenging due to the large variety of chemical species; however, coupling of airborne flux measurements with observations of surface and vegetation composition and functioning could improve the understanding of BVOC and aerosol formation. The rapid development of airborne flux measurement techniques has enabled quantification of land atmosphere fluxes at relatively high (< 2 km) spatial resolution. Flux measurement systems for carbon dioxide, water, and energy are relatively compact, inexpensive, and robust. They are easily deployed on light aircraft and could potentially be operated on larger UAS platforms. While airborne flux measurements of aerosol, ozone, mono-nitrogen oxides, and BVOC are more challenging, aircraft systems have been demonstrated for all of these constituents. Combined observations of atmospheric trace gas fluxes from the land surface together with simultaneous observations of the spectral and thermal properties of vegetation and soil surface could aid in the attribution of surface fluxes and underlying controls. If detailed characterization of surface topographic and vegetation structure through the use of active lidar and radar systems were added, a much better picture of ecosystem dynamics across environmental gradients and through time could be achieved. Similarly the development of multi-frequency lidar may lead to improvement in measuring the distribution of gas concentrations such as carbon dioxide, methane and water vapor.

In summary, the prioritization of the land-atmosphere exchange topics are provided in Table 4 in Section 3.2.1, along with an estimation of the timeframe needed to achieve a given task.

3.2.4 Multi-Sensor Integration and Sensor Calibration Requirements

In addition to the individual active and passive instruments needed to capture ecosystem states, dynamics, and fluxes, the airborne systems should also allow for the integration of multiple instrument types on the same platform or multiple platform types used together in time or temporally staggered. This would address questions requiring multiple remotely sensed measurements to capture an important process. For example, the combination of TIR and imaging spectroscopy observations provides the capability to quantify vegetation composition, function, biochemistry, and evapotranspiration at spatial and temporal scales needed for model evaluation or coupling with EC towers. Combining imaging spectroscopy with lidar provides the ability to efficiently scale surface measurements to the canopy and to the larger landscape while providing the connection between vegetation structure and functioning (Higgins et al. 2014). In addition, the understanding of some processes, such as capturing carbon uptake, growth, and mortality, could be improved significantly by leveraging several sensor types flown simultaneously together with staggered collections of other measurements. For example, airborne SIF and TIR collected together at high temporal frequency would allow for the characterization of the diurnal GPP and evapotranspiration signal while imaging spectroscopy flown at multiple phenological periods would enable a better understanding of the seasonality of plant function.

Adding microwave campaigns would provide the soil water constraint on carbon uptake, and finally lidar flown at interannual periods providing information on carbon stocks by capturing plant growth, mortality, and recruitment. Similarly, finding connections between lidar, digital imagery, imaging spectroscopy, and geophysical data is crucial to scale subsurface characteristics to larger spatial scales as shown in Figure 5 (Wainwright et al. 2015). In addition to coupling terrestrial sensing technologies, combining surface with atmospheric measurements is needed to address the challenges with the removal of atmospheric "contamination" from surface observations (e.g., imaging spectroscopy). Important to all of the measurements, adequate sensor calibration is necessary to separate sensor noise from environmental and variability and to enable interoperability and consistent time-series. Another challenge is to improve existing sensors and develop novel technologies to increase our ability to monitor various surface and subsurface properties, and in particular properties that are not directly in the field of view of the sensor such as the vertical and lateral distribution of soil moisture and biomass content. Finally, miniaturization of some instrumentation would increase the ability to coordinate measurements and capture processes at multiple spatial and temporal scales, critically the scales needed to directly inform model predictive capabilities.

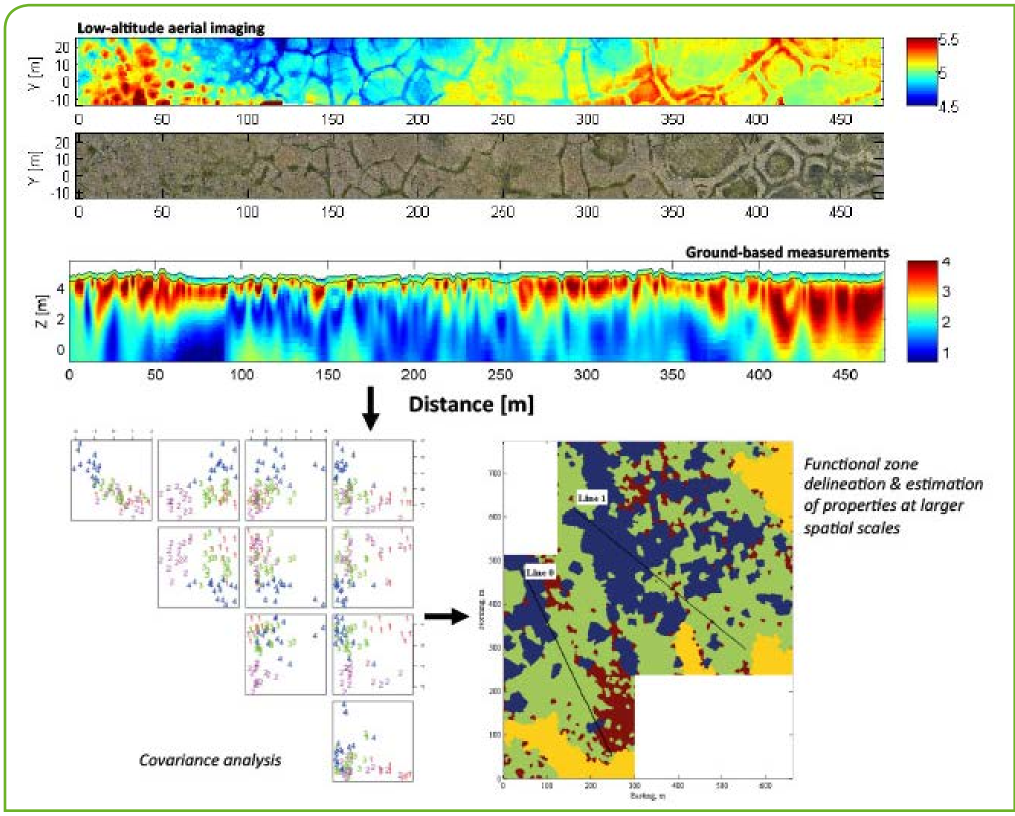

Figure 5. Acquiring remote observations from aerial platforms together with ground-based measurements enables the investigation of covariance of the dynamics, as well as the relationships, between subsurface and surface properties, which provides a key opportunity to upscale results from intensively investigated locations to larger spatial scales (schematic based on study of Wainwright et al. 2015).

4.0 Conclusions

Aerial measurements are essential for CESD to improve predictive understanding of the energy environment-climate system in order to inform sustainable solutions for the production, use, and security of energy. To facilitate CESD planning a forward-looking strategy of aerial measurement capability requirements for the next decade, input from the scientific community was synthesized to identify gaps and needs in existing airborne observational capabilities. This activity produced a comprehensive list of available capabilities that are currently underutilized and unavailable capabilities that could advance research and address the emerging scientific challenges for the atmospheric and terrestrial research communities. These topics were prioritized to evaluate where the most beneficial progress can be made with resource allocations, and estimates were made of the timescales involved with development and implementation of the instrumentation and platforms necessary to make such a measurement.

The atmospheric community that CESD serves and represents has the benefit of access to the mature AAF that includes two dedicated aircraft, over 50 dedicated aircraft instruments, and numerous guest instruments. The ARM Facility is also currently building a UAS capability that will complement the existing piloted-aircraft capability. Within this context, the following atmospheric airborne observational capabilities are among those identified as having the greatest likelihood of high scientific impact.

Given that aerosols are so inhomogeneous, frequent (2-3 times per week) vertical profiles were identified as a highest priority to collect physical and optical aerosol properties using aerial platforms in different locations and aerosol regimes. Frequent vertical profiles of aerosol absorption are required because they are a key aerosol optical property with significant impact on radiative forcing. Here, instrument developments are needed to apply new techniques different from the current, artifact-plagued, filter-based methods, and that also allow measurements at ambient conditions including UV wavelength techniques. A key gap is the complete absence of an aircraft instrument capable of measuring ice-nucleating properties of aerosol that could cover all relevant aerosol sizes and measure all relevant freezing processes. The highest priority mid- and long term goal is the miniaturization and validation of numerous online instruments to measure IN, CCN, gases, aerosol size distribution, and composition for eventual use on UAS.

Improving cloud processes in models requires information on the cloud microphysical properties and the coincident cloud dynamical properties. Hourly, or near-hourly, profiles of water vapor mixing ratio and temperature were identified as a high priority to determine the inversion strength and resolve the coupling of boundary-layer dynamics with clouds. As only aerial measurements can provide detailed observations to validate remote-sensing retrievals of cloud properties, collocated/correlated measurements of in situ cloud microphysics and radar remote sensing were identified as highest priority. Improvements of in situ measurements of ice phase clouds are needed for retrieval evaluation as well as process studies. Uncertainties must be reduced considerably in measurements of total ice mass and ice particle size distributions, and for mixed-phase clouds, airborne instrumentation is needed that is capable of providing the ice/water phase partitioning by mass within a given volume. Improving model representations of cloud entrainment mixing is critically important to cloud life cycle, so high importance is placed on the high-spatial resolution cloud microphysics and atmospheric state measurements needed for entrainment studies.


Only aerial measurements can provide detailed observations of cloud properties.

For research in terrestrial ecosystem and watershed science, a number of critical measurement needs and observational priorities were identified to characterize relevant processes that operate on decadal, annual, and seasonal to diurnal timescales. Processes that cause change slowly (years to decades) control the long-term carbon, water cycling, and energy balance. These processes include ecosystem disturbance (fire, flood, or land-use change), ecological succession, and changes in geomorphology and soil and geological structure. These can be monitored at the annual to decadal scale by mapping subsurface structure (geological layers), macro- and micro-topography, and bathymetry that would inform subsurface water distribution, drainage patterns, soil settlement, subsidence, or deformation. Similarly, the surface annual mapping of vegetation growth and mortality and canopy foliar biochemistry would be useful in characterizing the controls of annual to decadal processes. This results in a need for airborne monitoring systems designed to capture these quantities at the annual timescale.

Ecosystem and subsurface processes that vary on the sub-annual timescale are also important controls of land-surface-atmosphere interactions and cause significant uncertainty in current ESMs. These processes include variations in vegetation phenology and growth (carbon allocation), snow cover, water distribution at the surface and in the subsurface, evapotranspiration, and land-surface exchange of carbon and water. These processes can be quantified by repeated measurements (from seasonal to diurnal) of micro topography, vegetation, 3D structure, vertical heterogeneity, land surface (skin) temperature, vegetation physiological capacity, water content, and gas concentration measurements. This results in a need for airborne monitoring campaigns to quantify surface changes at optimal frequency. Monthly surveys may provide adequate information on the dynamics of leaf area, water use, and physiological activity, but during phenologically important times (spring or fall), surveys occurring at 2-3 day intervals would allow leaf out and senescence to be quantified.

Some key instrumentation and development identified for aerial observing systems for terrestrial ecosystem science include the combination of and miniaturization of:

1. active lidar and radar systems for vegetation structure, terrain, and soil moisture;
2. imaging spectroscopy for characterizing physiology and biochemistry of vegetation and linkage to belowground processes;
3. TIR for studying energy balance;
4. geophysical techniques for subsurface properties imaging; and
5. digital imagery for surface classification, disturbance monitoring, and quality assurance.

The integration of sensor technologies onto single airborne platforms or within single campaigns is important because some inferences rely on combining measurement types. For example, lidar and spectral observations are optimal for species identification, and thermal and spectral observations are optimal for estimating water-use efficiency. Versions of these technologies already exist, but because the systems are not integrated with each other on the same aerial platform, their utility is limited. In addition, some instrumentation was identified as having a need for miniaturization for UAS deployment to fill the role of more frequent observations. Ongoing projects such as AmeriFlux, NGEE-Arctic, and NGEE-Tropics, SFAs, and interdisciplinary projects with significant field components present an important opportunity to leverage detailed surface observations to develop, test, and operationalize critical observing methodologies with aerial platforms and to collaborate to answer critical science questions.

Many of the proposed measurements would involve instrument development of some form, from refining an existing technique to developing a new technique. This may also include new hardware/software to enable efficient multi-sensor synergism within and across disciplines (e.g., atmospheric properties coupled with land observations). Discussions noted that instrument development and testing could be supported by Small Business Innovation Research and Small Business Technology Transfer Programs, but that targeted instrument maturation funding is also desirable. Further, there is a need to create opportunities to facilitate airborne testing of new aerial methods or instruments.

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Appendix A – Workshop Agenda

Climate and Environmental Sciences Division
Aerial Observation Needs—May 13-15, 2015

Wednesday, May 13

11:30	Lunch meeting with workshop leads
1:00 – 1:10	**Welcome: Goals and Expectations for Workshop** *Shaima Nasiri, Office of Biological and Environmental Research, Climate and Environmental Sciences Division*
1:10 – 1:20	**Participant Introductions**
1:20 – 1:30	**Atmospheric Systems Research (ASR) – Overview** *Shaima Nasiri, Office of Biological and Environmental Research, Climate and Environmental Sciences Division*
1:30 – 1:50	**ARM Aerial Facility – Overview** *Beat Schmid, Pacific Northwest National Laboratory (PNNL)*
1:50 – 2:05	**Environmental System Science (ESS) – Overview** *David Lesmes, Office of Biological and Environmental Research, Climate and Environmental Sciences Division*
2:05 – 2:25	**Challenges and Opportunities – Atmospheric Systems: Summary of Atmospheric White Papers** *Andy Vogelmann, Brookhaven National Laboratory (BNL)*
2:30 – 2:50	**Challenges and Opportunities –Terrestrial Systems: Summary of Terrestrial White Papers** *Shawn Serbin, BNL*
2:50 – 3:05	Break
3:05 – 3:15	**Introduction to Breakout Sessions**
3:15 – 5:25	**Breakout #1: Science Drivers** *10 minute mini-break around 4:15* **Session 1A:** Atmospheric Processes – Clouds, Boundary Layer, and Thermodynamics **Session 1B:** Atmospheric Processes – Aerosols and Trace Gases **Session 1C:** Terrestrial Processes
5:25 – 5:40	Break
5:40 – 6:10	**Reports from Breakout #1: Sessions A, B, and C**

Thursday, May 14

8:30 – 9:00	Lightning Talks on Land-Atmosphere Interactions and Cloud-Aerosol Interactions (5 minutes each) *Baptiste Dafflon, Lawrence Berkeley National Laboratory (LBNL)* *Michael Madritch, Appalachian State University* *Sebastien Biraud, LBNL* *Larry Berg, PNNL* *Ann Fridlind, NASA Goddard Institute for Space Studies*
9:00 – 9:20	**Lightning Talks Discussion**
9:20 – 9:25	**Introduction to Breakout #2**
9:25 – 9:35	Break
9:35 – 11:30	**Breakout #2: Land-Atmosphere Interactions and Cloud-Aerosol Interactions**
	Session 2A: Land – Atmosphere Interactions
	Session 2B: Cloud – Aerosol Interactions
11:30 – 11:45	Break
11:45 – 12:15	**Reports from Breakout #2: Sessions A and B**
12:15 – 1:15	Lunch and a group photo
1:15 – 1:20	**Introduction to Breakout #3: Prioritization of Research Directions Using a Phased Approach (0–2 years, 2–5 years, 5–10 years)**
1:20 – 2:20	**Breakout #3: Sessions A, B, and C**
	Session 3A: Atmospheric Processes – Clouds, Boundary Layer, and Thermodynamics
	Session 3B: Atmospheric Processes – Aerosols and Trace Gases
	Session 3C: Terrestrial Processes
2:20 – 2:30	Break
1:20 – 2:20	**Breakout #3: Sessions D and E**
	Session 3D: Land – Atmosphere Interactions
	Session 3E: Cloud – Aerosol Interactions
3:30 – 3:45	Break
3:45 – 4:15	**Reports from Breakout #3: Sessions A, B, C, D, and E**
4:15 – 4:45	**Open Discussion**
4:45 – 5:00	**Concluding Remarks**

Friday, May 15

8:30 – 11:30	**Writing Team Begins Drafting Report**
11:30 – 1:30	Lunch (optional)

Appendix B – Workshop Organizers and Participants

Climate and Environmental Sciences Division Aerial Observation Needs

Organizing Committee

Shaima Nasiri
Atmospheric System Research

David Lesmes
Subsurface Biogeochemical Research

Rick Petty
Atmospheric Radiation Measurement Climate Research Facility

Co-Chairs

Beat Schmid
Pacific Northwest National Laboratory

Shawn Serbin
Brookhaven National Laboratory

Andrew Vogelmann
Brookhaven National Laboratory

Participants

Larry Berg
Pacific Northwest National Laboratory

Sebastien Biraud
Lawrence Berkeley National Laboratory

Pete Colarco
NASA Goddard Space Flight Center

Baptiste Dafflon
Lawrence Berkeley National Laboratory

Gijs de Boer
University of Colorado at Boulder/ Cooperative Institute for Research in Environmental Sciences

Graham Feingold
National Oceanic and Atmospheric Administration

Andrew Fox
National Ecological Observatory Network

Ann Fridlind
NASA Goddard Institute for Space Studies

Alex Guenther
Pacific Northwest National Laboratory

Participants (continued)

Nicki Hickmon
Argonne National Laboratory

Mark Ivey
Sandia National Laboratories

Bill Kustas
U.S. Department of Agriculture

Ruby Leung
Pacific Northwest National Laboratory

Michael Madritch
Appalachian State University

Jim Mather
Pacific Northwest National Laboratory

Allison McComiskey
National Oceanic and Atmospheric Administration

Burke Minsley
U.S. Geological Survey

David Moore
University of Arizona

Douglas Morton
NASA Goddard Space Flight Center

Sally McFarlane
Atmospheric Radiation Measurement Climate Research Facility

Carl Schmitt
National Center for Atmospheric Research

Art Sedlacek
Brookhaven National Laboratory

James Smith
National Center for Atmospheric Research

Ryan Spackman
National Oceanic and Atmospheric Administration

Rune Storvold
Norwegian Research Institute in Tromsø

Ryan Sullivan
Carnegie Mellon University

Appendix C – Written Respondents

Dennis Baldocchi
University of California, Berkeley

Larry Berg
Pacific Northwest National Laboratory

Sebastien Biraud
Lawrence Berkeley National Laboratory

Jessica Cherry
University of Alaska Fairbanks

Patrick Chuang
University of California, Santa Cruz

Baptiste Dafflon
Lawrence Berkeley National Laboratory

Gijs de Boer
University of Colorado at Boulder/
Cooperative Institute for Research in
Environmental Sciences

Ankur Desai
University of Wisconsin–Madison

Paul Dirmeyer
George Mason University

Jerome Fast
Pacific Northwest National Laboratory

Rich Ferrare
NASA Langley Research Center

Josh Fisher
NASA Jet Propulsion Laboratory

Andrew Fox
National Ecological Observatory Network

Ann Fridlind
NASA Goddard Institute for Space Studies

Andrew Gettelman
National Center for Atmospheric Research

Steve Ghan
Pacific Northwest National Laboratory

Alex Guenther
Pacific Northwest National Laboratory

Jerry Harrington
Pennsylvania State University

Andy Heymsfield
National Center for Atmospheric Research

Maoyi Huang
Pacific Northwest National Laboratory

Jim Hudson
Desert Research Institute

Pavlos Kollias
McGill University

Dan Krofcheck
University of New Mexico

Chongai Kuang
Brookhaven National Laboratory

Paul Lawson
Stratton Park Engineering Company

Ernie Lewis
Brookhaven National Laboratory

Zhanqing Li
University of Maryland, College Park

Chuck Long
National Oceanic and Atmospheric
Administration

Ed Luke
Brookhaven National Laboratory

Allison McComiskey
National Oceanic and Atmospheric Administration

Nate McDowell
Los Alamos National Laboratory

Greg McFarquhar
University of Illinois at Urbana–Champaign

Brenden McNeil
West Virginia University

Joe Michalsky
University of Colorado at Boulder/Cooperative Institute for Research in Environmental Sciences

Steve Running
University of Montana

Art Sedlacek
Brookhaven National Laboratory

Carl Schmitt
National Center for Atmospheric Research

Courtney Schumacher
Texas A&M University

Raymond Shaw
Michigan Technological University

John Shilling
Pacific Northwest National Laboratory

Matthew Shupe
University of Colorado at Boulder/Cooperative Institute for Research in Environmental Sciences

James Smith
National Center for Atmospheric Research

Margaret Torn
Lawrence Berkeley National Laboratory

Bastiaan Van Diedenhoven
NASA Goddard Institute for Space Studies

Hailong Wang
Pacific Northwest National Laboratory

Dick Waring
Oregon State University

Peter Wolter
Iowa State University

Rob Wood
University of Washington

Jin Wu
University of Arizona

Stan Wullschleger
Oak Ridge National Laboratory

Chunggang Xu
Los Alamos National Laboratory

Xi Yang
Brown University

Yonghong Yi
University of Montana

Appendix D – Acronyms

AAF	ARM Aerial Facility
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
BER	Office of Biological and Environmental Research
BVOC	biogenic volatile organic compound
CCN	condensation nuclei
CESD	Climate and Environmental Sciences Division
CIMS	chemical ionization mass spectrometry
CVI	Counter-flow Virtual Impactor
DOE	U.S. Department of Energy
DSM	digital surface model
EC	eddy covariance
ELVOC	extremely-low volatility organic compound
ESM	earth system models
ESS	Environmental System Science
FAA	Federal Aviation Administration
G-1	Gulfstream-159
GCM	general circulation model
GPP	gross primary productivity
IN	ice nuclei
LSM	land-surface modeling
NAS	U.S. National Air Space
NGEE	Next-Generation Ecosystem Experiments
NGEE-Arctic	Next-Generation Ecosystem Experiments Arctic
NGEE-Tropics	Next-Generation Ecosystem Experiments Tropics
OH	hydroxyl radical
SAR	Synthetic Aperture Radar
SBR	Subsurface Biogeochemical Research
SFA	science focus area
SIF	solar-induced fluorescence
SOA	secondary organic aerosol
SVI	spectral vegetation indices
TES	Terrestrial Ecosystem Science
TIR	thermal infrared
UAS	unmanned aerial system
UV	ultraviolet

For More Information

Climate and Environmental Sciences Division

http://science.energy.gov/ber/research/cesd