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Content

1. Introduction

1.1 Background and Motivation

The National Science Foundation (NSF) Division of Atmospheric and Geospace Sciences (AGS) plays a vital role in advancing fundamental research in atmospheric sciences by supporting state-of-the-art instruments and facilities. In 2021/2022, several changes related to facility support were implemented by NSF including the creation of an expanded **Facilities for Atmospheric Research and Education (FARE)** program and the introduction of the **Facility and Instrumentation Request Process (FIRP)** solicitation. NSF updated the FIRP solicitation and the review process in 2023.

The 2023 FARE Users' Workshop, which was funded by NSF, was motivated by several factors. For one, the last community workshop that focused on atmospheric measurements took place six years earlier (the 2017 Community Workshop on Developing Requirements for In Situ and Remote Sensing Capabilities in Convective and Turbulent Environments), making it desirable to organize a follow-up event to examine and evaluate the developments that have occurred since then. Second, there had been no coordinated effort to showcase the capabilities of the Community Instruments and Facilities (CIF) that became available to the community in 2021. Third, NSF is highly interested in broadening facility use, particularly by early career scientists and by those from underrepresented backgrounds across diverse institutions, regions, and demographics. In addition, the timing of this workshop was opportune, given the recent changes to the FIRP solicitation.

1.2 Summary of FARE Resources

The FARE Program comprises two key components: the **Lower Atmosphere Observing Facilities (LAOF)** and the **Community Instruments and Facilities (CIF)**. Both portfolios play a critical role in facilitating geosciences research by providing specialized facilities, advanced instrumentation, laboratories, and field support services necessary for the successful execution of scientific fieldwork focused on a wide spectrum of geophysical phenomena. These valuable resources are made accessible through a consortium of 12 US institutions (see Table 1). FARE assets include research aircraft, fixed and mobile radars, lidars and profiling systems, a suite of remote and in-situ airborne sensors, laboratories, and chambers.

Table 1: *FARE Providers and Assets*

Lower Atmosphere Observing Systems (LAOF)	
National Center for Atmospheric Research	NSF C-130, NSF GV, ISS, ISFS, HCR, HSRL, AVAPS dropsonde, S-Pol, MPD
University of Wyoming	UWKA, WCR, WCL
Community Instruments and Facilities (CIF)	
Clemson University	Clemson Soot Photometer
Colorado State University	Sea-Going and Land Deployable Polarimetric Radar (SEA-POL)
Michigan Technological University	PI Cloud Chamber
North Carolina State University	NC State IC Nucleation Cold Stage
SUNY at Stony Brooks	Millimeter-Wavelength Radar Facility for Cloud and Precipitation Research
University of Alabama - Huntsille	Mobile Atmospheric Profiling Network (MAPNet)
University of Illinois - Urbana-Champaign	Flexible Array of Radars and Mesonets (FARM)
University of Oklahoma	Rapid X-band Polarimetric Radar (RaXPol)
University of Utah	Storm Peak Laboratory (SPL)
University of Wisconsin	SSEC Portable Atmospheric Research Center (SPARC)

1.3 FARE Users' Workshop Summary

The FARE User's Workshop, jointly organized by NCAR's Earth Observing Laboratory and the University of Wyoming, was held in Boulder, CO from 18-22 September 2023. The event attracted 182 participants from 50 distinct institutions, including several non-R1 universities, both in-person and virtually.

The workshop was structured into two distinct segments: **FARE Process** and **FARE Future**. The primary objective of **FARE Process** was to enhance community awareness of and acquaint attendees with the expanded FARE Program and associated FIRP Solicitation. This aimed to encourage and support especially new users in the preparation and submission of NSF proposals that incorporate one or more of the available FARE assets for research and education. Attendees had a chance to interact with facility providers through an *Instrument Circuit* (theme-based, provider-attended poster session) as well as an on-site display of several of the mobile CIF assets, enhancing the overall experience.

In contrast, the primary focus of **FARE Future** was to provide a platform for the community to engage in ongoing discussions related to science drivers, emerging technologies, and community needs within the context of observational atmospheric research. The ultimate aim was to foster the formation and strengthening of robust partnerships and sustained innovative collaboration across the community.

A transitory day was added to the program to allow workshop participants to visit the NSF aircraft at the NSF NCAR Research Aviation Facility including several airborne instruments and the Design and Fabrication workshop at the NSF NCAR Foothills Campus. Also included was a Data FAIR (Findability, Accessibility, Interoperability and Reuse of digital assets) to familiarize future users with all aspects of EOL data management and field support tools.

The workshop's format included a diverse range of activities such as presentations, user stories, breakout sessions, poster sessions, an exhibit of several of the FARE assets, a data FAIR, and other valuable opportunities for networking.

1.4 Disclaimer

This report was composed based on extensive written and oral input collected during the workshop. The questions that arose and recommendations that resulted in the various workshop sessions were shaped by the scientific interests of individual workshop participants and may not represent a comprehensive scoping study. The list of recommendations listed in this report is neither ranked nor exhaustive. The report is intended to provide NSF and the community it supports with current priorities. By itself, the report is inadequate to justify decisions. There are undoubtedly worthy recommendations and priorities that have escaped the attention of the workshop participants and the Steering Committee. We hope that the NSF will judge such initiatives based on their merits irrespective of whether they have appeared in this report.

2. FARE Resource Accessibility

The NSF Atmospheric and Geospace Sciences (AGS) section is actively seeking ways to improve and widen access to facilities and educational opportunities beyond its traditional user base including non-R1 universities and Minority Serving Institutions (MSIs). This section summarizes the opportunities, challenges, needs, and recommendations expressed by workshop participants to request facilities through the FIRP Process, broken down by Track 1 (Educational Projects) and Tracks 2 and 3 (Research Projects).

2.1 FARE Process - Track 1 - Educational Projects

BACKGROUND

NSF defines Track 1 proposals as *requests for limited field or laboratory activities that target education and outreach.* Under special circumstances, Track 1 proposals allow use of the LAOF aircraft either as a stand-alone project or as a supplement to a Track 3 proposal.

OPPORTUNITIES

Track 1 proposals serve as an accessible entry point, offering excellent opportunities to introduce university students to core facets of the observational research process, including development of science questions; design of simple field studies; introduction to instrument theory, measurement techniques, and instrument performance; data collection and analysis; and synthesis of scientific information. Projects that focus on local atmospheric phenomena that can cause hazardous conditions (e.g., air quality, lake effect snow, severe weather) are helpful in creating interest and introducing students to observations. The most common examples of Track 1 applications include integrating field-based research into course curricula at a university and facilitating experiential learning in a laboratory setting. Additional opportunities include working with a FARE provider in instrument calibration and testing activities, supplementing Research Experiences for Undergraduates (REU) programs, and augmenting instrument-focused courses.

CHALLENGES

The workshop highlighted limited awareness of the FARE program and available resources beyond a core user group, which is mostly R1-based. The complexities of initiating a Track 1 proposal were primarily centered around investigator experience or lack thereof, student engagement, time constraints, funding limitations, and overall workload. Major concerns include instructors' unfamiliarity with instrumentation and measurement techniques, error management, and data analysis, which will ultimately impact the success of an E&O project. Time constraints, alignment of funding decisions with class schedules, and the challenge of integrating instrumentation into course-linked projects pose additional burdens, particularly for instructors with heavy teaching loads. Engaging a critical mass of students in hands-on activities during the semester proves difficult due to the students' class commitments. Challenges include attracting the right students, bringing them up to speed on instrumentation, providing extensive student guidance that ensures widespread and measurable benefits, integrating with diverse schedules, and enabling remote participation. Instructors also face logistical challenges, including universities' unfamiliarity with field observations, requirements for off-campus safety plans, and logistical arrangements. Many of these challenges can seem overwhelming and addressing these issues is crucial for the success of the Track 1 projects.

NEEDS AND RECOMMENDATIONS

- *Collaborative community awareness initiatives*: Encourage collaboration between NSF representatives and FARE asset providers to raise awareness of Track 1 opportunities through various channels such as publications, websites, town halls, and open houses.
- *Establishment of Mentor/Mentee relationships*: Advocate for the establishment of mentor/mentee relationships between facility provider and instructors to assist in navigating the proposal process. This relationship can help overcome initial hurdles and provide valuable guidance in defining educational initiatives and learning outcomes.
- *Utilization of facility providers as a resource*: Recognize facility providers as invaluable resources for designing and implementing executable project ideas. Their contributions can extend to serving as subject matter experts, guest lecturers, and organizers of training sessions for instructors.
- *Creation of repository for shared resources*: Establish a repository for shared resources that offers access to previous Track 1 project examples, templates and lessons. Encourage open access to training materials developed as part of educational projects, which is deemed invaluable in aiding the development of syllabi and course materials.
- *Provision of checklists and templates*: Provide checklists for funding application and post-approval project execution, preventing redundancy and ensuring essential details are addressed. Accessible templates, such as safety and communication plans, can also facilitate project implementation.
- *Integration with Track 3 Field Campaigns*: Track 3 PIs should encourage faculty from nearby universities (esp. MSIs) to submit a Track 1 proposal as soon as a Track 3 field campaign is greenlighted to provide local students with insights into observational research alongside experts in the field at a low cost. The separate deadlines of Track 1 and Track 3 proposals allow such piggybacking.
- *Lowering the bar for airborne measurements*: Reintroduce programs like the Airborne Research Instrumentation Testing Opportunities (ARISTO) to provide regular opportunities for in-person and virtual student engagement in airborne observations.

2.2 FARE Process - Tracks 2&3 - Research Projects

BACKGROUND

Track 2 (single facility requests) and Track 3 (field campaigns) proposals support observational research through the deployment of one or more FARE assets, both domestically and internationally.

OPPORTUNITIES

Workshop participants agreed that the FARE Program offers an extensive array of instrumentation to the NSF-funded community to address a wide range of science questions. Moreover, NSF routinely funds field support services such as data and project management, primarily provided by NSF NCAR. Both Track 2 proposals and large, multi-investigator Track 3 campaigns provide opportunities for less experienced or early-career users to enter the field of observations. Once a project is greenlighted, facility teams will provide the necessary tools and experience to enable even novice investigators to plan and execute a successful field campaign.

CHALLENGES

Many of the challenges raised for Track 1 proposals also apply to Track 2 and 3 proposals. The lack of awareness of the FARE program among certain sections of the academic community was highlighted, resulting in most FIRP proposals originating from repeat PIs, most of whom are at well-established atmospheric sciences departments. While the FIRP solicitation outlines proposal tracks and steps to be taken, workshop participants found it difficult to find detailed FARE information in one centralized location. Researchers new to the FARE program face challenges in navigating the proposal and facility request process, describing it as both intimidating and overwhelming.

Developing a robust Track 3 science proposal, particularly those involving aircraft, is a time-intensive process that demands in-depth knowledge crucial for campaign success. Many researchers perceive Track 3 proposals as high risk with low reward, given the historically low success rate of such proposals. The initiation and leadership of Track 3 campaigns are considered daunting for early career scientists and first-time users due to limited experience and lack of professional connections. A common assumption is that tenured professors are best equipped to lead a Track 3 campaign, especially “complex” field campaigns. Moreover, early career scientists and members from non-R1 universities struggle to allocate time for crafting well-written proposals due to teaching commitments, expertise gaps, limited peer support, lack of funds to attend planning meetings, and insufficient administrative support, especially within small departments.

The volume of logistics involved in preparation of a field campaign can be significant. PIs usually don't have experience with experimental design planning, data management, or project management. Workshop participants learned about services provided by facility providers and especially NSF NCAR in all stages of campaign planning and execution, and in data management. Nevertheless, they expressed uncertainty about the clear demarcation of roles and responsibilities between facility providers and PI teams.

Student participation in field campaigns is crucial, but managing and mentoring students requires significant time and careful attention. Recruiting qualified and interested graduate students and training them to operate and troubleshoot instruments is an extensive and time-consuming process. The misalignment of proposal funding timelines with student recruitment and graduation timelines, particularly undergraduate and MS students, poses a significant challenge, especially if funding that supports student involvement is delayed. Advisors must navigate the task of keeping students engaged productively in the interim, however non-R1 institutions find it difficult to accommodate longer funding lead times.

As mentioned in the FIRP solicitation, FARE facilities can be requested as part of NSF cross-directorate solicitations such as NSF CAREER (Faculty Early Career Development Program), EAGER (Early-concept Grants for Exploratory Research), and RAPID (Rapid Response Research). Workshop participants were confused whether the FIRP deadlines also apply to cross-directorate solicitations, and whether all GEO directorate solicitations (such as GEO-EMBRACE) qualified for facility use covered directly by FARE. Multi-agency campaigns add yet another layer of complexity due to differences in funding timelines and decision making, requiring help from NSF to successfully navigate agency interactions.

NEEDS AND RECOMMENDATIONS

Workshop participants recommended a series of strategies for the following four goals:

Goal 1: *Enhancing FARE Program visibility*:

- FARE Users' Workshops: Host FARE Users' Workshops every 4-5 years to facilitate collaboration and knowledge sharing among participants.
- Town Halls and Mini-Workshops: Conduct town halls at professional meetings (AGU, AMS), and organize regular regional FARE workshops across the US to engage with the broader scientific community.
- Open Houses: Arrange regular Open Houses to showcase instrumentation, particularly as part of field campaigns, providing opportunities for hands-on experience and interaction with researchers.
- Seminars and lectures: Schedule seminars and lectures by facility providers, with a focus on engaging non-R1 universities to broaden access to FARE resources and expertise.

- Integration into NSF NCAR/UCAR programs: Integrate FARE information into NSF NCAR/UCAR programs targeting early career scientists, such as the Advanced Study Program, ensuring that relevant information is readily accessible to this demographic.

Goal 2: *Enhancing communications and accessibility*:

- Comprehensive NSF FARE Program guidance: Complement the NSF FARE page with a comprehensive FAQ section, and build NSF NCAR-hosted pages that elaborate on FARE details including a FARE Tutorial, best practice guidelines, and checklists covering facility information, contacts, timelines, and asset availability.
- Regular Virtual NSF Meetings: Offer regular virtual NSF FARE Program meetings to facilitate communications and alleviate a perceived intimidation factor. Provide a roster of Subject Matter Experts (e.g., flight operations, data management) to existing NSF Points of Contact to offer specialized guidance and support.

Goal 3: *Facilitating proposal development and campaign implementation*:

- Clarification of roles and responsibilities: Provide clear descriptions of the roles and responsibilities of facility providers, along with a detailed overview of the field campaign services provided by NSF NCAR. Such information would reassure PIs that assistance is available throughout the campaign planning and implementation process.
- Checklists: Offer access to checklists and timelines to aid PIs in assessing their progress and ensuring that crucial aspects are not overlooked during campaign planning and execution.
- Peer mentoring and Co-PI opportunities: Recognize the importance and need for formalized peer mentoring and Co-PI opportunities to address the lack of essential knowledge crucial for campaign success. Proposed solutions included creating networking opportunities, both in person (side meetings at conferences) and virtually (e.g., forums, slack channels) to enable researchers to cultivate ideas and find complementary expertise to build more comprehensive field campaigns. Additionally, encourage field campaign PIs to appoint early career scientists into deputy leadership positions to shadow and assist with roles such as the chief scientist, IOP director, or aircraft coordinator. Substantive participation in a single campaign often is enough to launch careers in field observations.

Goal 4: *Broadening participation*:

- Encouragement for MSI and Early Career Scientists: Promote the involvement of MSI or early career scientists as co-PIs as part of the proposal requirement, with an emphasis on mentorship components. To support these initiatives, NSF could provide small amounts of funding through a simple application process, to incentivize early-career scientists to participate in a campaign. Alternatively, NSF could collaborate with and fund professional societies to develop established mentorship programs.

- Addressing concerns and obstacles: Acknowledge concerns about competition in the proposal development process, such as the risk for sharing confidential ideas during the preparation stage, and the potential budget burden of inviting more early- and mid-career researchers as well MSI participants to the project. Explore strategies to mitigate these concerns while promoting inclusivity and collaboration.
- Facilitation of Collaboration: Create and maintain a bulletin board to facilitate collaboration among PIs from R1 universities and researchers from MSIs in developing proposals for field campaigns.
- Importance of Co-PIs: Through the proposal process, emphasize the importance of scientists unfamiliar with campaigns joining as Co-PIs to gain familiarity with the process and acquire valuable experience. Encourage senior PIs to actively involve early-career scientists in leadership positions during campaigns to provide them with substantive participation opportunities.

3 Cross-cutting Themes

A few themes were evident throughout most, if not all, breakout sessions during the workshop. The recommendations from those breakouts have been synthesized in chapters 4-6. In this section, we aim to highlight some of the cross-cutting themes for clarity and emphasis.

3.1 Workforce development and sharing instrument knowledge

Workshop participants repeatedly highlighted the pressing need for structured educational programs aimed at equipping the next generation of professionals with the necessary skills to deploy, calibrate, and interpret experimental observations. Discussions during the workshop identified *a critical lack of expertise* in many of the instruments within the FARE pool. This deficiency reflects a history of sparse teaching of atmospheric technology courses and insufficient training of the next generation of experimental atmospheric scientists. This impedes scientific advancement that could otherwise be achieved using these often unique and powerful observation systems.

The nationwide lack of training in atmospheric observational technology, particularly in specialized areas such as cloud physics or flux measurements, has direct repercussions for the FARE program. Over time, this lack of expertise hampers progress in atmospheric sciences, including the development and implementation of new observational systems. It even hampers progress in numerical modeling, as it remains inadequately constrained by observations.

While the FARE facility providers are responsible for the delivery of quality datasets and value-added products, and while facility providers can and should provide expert insights on the merits and limitations of the measurements, effective use of FARE resources requires *more* *faculty training opportunities* on the capabilities and potential of these observational systems. In order to grow the participation from underserved university communities, it is important to focus the training on faculty from MSIs, as well as non-R1 universities. The training of faculty and early-career scientists is a prerequisite for continued student training in atmospheric technology. An excellent, comprehensive resource particularly geared towards undergraduate students, is the 2017 UCAR COMET course Foundations of Meteorological Instrumentation and Measurements, developed in partnership with Millersville University and NSF NCAR. While more in-depth training modules are available for certain systems like radars, others such as passive microwave radiometry and infrared spectroscopy lack equivalent depth.

Other specific suggestions include (a) the creation of community groups focused on specific instrument groups, e.g., microwave radiometers. Such groups can create and maintain repositories of basic information, software, troubleshooting FAQs, and assistance with data interpretation; (b) more comprehensive training of early-career scientists during Track 3 deployments (field campaigns), e.g., by rotating graduate students around different platforms and organizing instrument-focused lectures during the campaign; and (c) the encouragement of Track 1 Educational Campaign proposals that detail plans for teacher training (rather than just facility "show and tell") and data use in the course curriculum.

3.2 Interactions between modelers and experimentalists

Advancements in computing have allowed for increasingly detailed modeling that is used for advancing understanding of atmospheric processes. This knowledge is often transferred into Numerical Weather Prediction and climate models via improved parameterizations. This makes validation and improvement of so-called process models (e.g., LES, bin-resolved microphysics, turbulence anisotropy, spectrally resolved radiation) as important as ever. To validate these models effectively, experimental observations are needed beyond the operational observations. These observations should be strategically conducted in terms of when, where, and how they are made. One way to guide answers is to couple rapidly advancing high-resolution models with instrument simulators (such as wavelength-specific radar reflectivity) to determine optimal observing strategies for a given target. Such a strategy could also link observable properties to other unobservable properties to facilitate advances in process understanding and model development. Coupling of measurements with models via data assimilation or data denial is also facilitated by such a framework, which is usually difficult in practice due to limited measurements. Of course, besides improved scientific understanding of processes, a primary motivation for measurements is improved weather and climate prediction, and that occurs through both data assimilation and improved physics parameterizations relying on ground "truth."

Field campaigns are often justified in terms of the need to improve weather or climate models. Some of the main obstacles in linking field campaign observations with model simulations include but are not limited to the differences in their spatial resolution, differences in parameters measured vs simulated (solved in part with instrument simulators), uncertainties in instrument accuracy and in measurement representativeness, and the relative lack of measurements in the time-space domain. Close collaboration with modelers is recommended in all three stages of experimental research: before, during, and after the field campaign.

In the first stage, model simulations are used increasingly in the proposal stage in part to justify field campaigns. For instance, SOCRATES (McFarquhar et al. 2021) was largely motivated by the discrepancy between modeled and satellite-observed cloud albedo over the Southern Ocean, calling for a process-focused airborne campaign. Simulations are being used also to refine the experimental design plan of field campaigns, e.g., locating an instrument or network in a region where model uncertainty is the largest, or where the model is most sensitive to a parameter that is not measured operationally. Synthetic observations extracted from large eddy simulations (LES) can be used to optimize flight tracks.

In the second stage, i.e., during field campaigns, real-time high-resolution models (including in-line instrument simulators) may be run for daily decision making, i.e., to aid effective targeting of desired meteorological conditions, a method heavily used in the Plains Elevated Convection at Night (PECAN) field campaign (Geerts et al. 2017). These simulations can be archived (e.g., on the NSF NCAR EOL Data Archive) for in-depth post-campaign analysis.

In the final phase, the campaign-based research period, which typically lasts many years, modelers and observationalists can collaborate to build a 4D dynamically consistent gridded dataset by assimilating experimental data into a high-resolution model. This requires participation of instrument experts, as the assimilation needs an accurate description of the error characteristics of all measurements. This gridded dataset can then be used to test and improve various parameterizations in coarser resolution models. It can be used also for Observing System Simulation Experiment (OSSE) studies, to examine the impact of instrument spacing, type, and integration on forecast skill.

The workshop identified the following non-exhaustive list of emerging technologies that may substantially improve model performance, if suitably deployed: mobile phased-array and conventional weather radars at X- to S-band; profiling Doppler lidars; differential absorption lidars, Raman lidars, and infrared spectrometers to monitor lower-tropospheric humidity and temperature profiles; networks of low-cost aerosol and trace gas sensors; instrumented drones; and airborne remote sensors including phased array and dual-pol radars, lidars, and multi-angle multi-spectral polarimeters for aerosol and cloud microphysics.

4 Science drivers for FARE

4.1 Aerosols, clouds, and precipitation

During the breakout session on aerosol, clouds, and precipitation, several key questions were posed, and recommendations made. One question pertains to the controls of secondary ice production (SIP) in mixed-phase clouds, which is essential to improve model parameterization of SIP. Progress requires collocated measurements of temperature, turbulence, and small-particle imaging. Airborne measurements may be complemented by experiments in a well-controlled cloud chamber.

There is much interest in the dynamics, microphysics, and radiative properties of thin ice clouds as well, especially convectively generated cirrus clouds. How do cirrus microphysical and radiative properties vary with cloud lifetime? What mechanisms act to sustain convective anvils? Progress with this and related cloud physics questions requires more resolved radar/lidar sensing and collocated in-situ measurements.

Finally, many questions about aerosol-cloud-precipitation interactions remain. What is the best observational strategy to separate aerosol and meteorological effects on cloud and precipitation properties? This requires measurements of cloud-active aerosol before, in, and outside clouds at multiple levels. The best platforms may be fixed aerial platforms (in a storm-relative sense), e.g., UASs with cloud and aerosol probes (discussed in Section 6.3), and mountain sites (for a long-term statistical viewpoint). How do cloud-active aerosols affect deep convection and hail? This question adds the extra challenge of (un)crewed aircraft penetration into thunderstorms. Lacking this capability, multi-aircraft coordination is needed to both sample the low-level inflow region and to remotely sense from above the cloud anvil.

4.2 Deep convection and tropical cyclones

High-impact events such as severe convection and tropical cyclones are rare, hence staging a field campaign is challenging. Two approaches are feasible: severe weather events that can be forecasted well in advance with high confidence (such as some hurricanes) should be observable through adaptive and rapidly deployable platforms. The observational platforms from multiple agencies (NOAA, NSF, NASA, DOE, and universities) can be pooled together to deploy and observe severe weather rapidly. For less predictable, transient events (such as tornadoes), a suite of instruments can be deployed in a fixed configuration during the entire peak season to measure such events' environmental conditions and cloud properties. The latter approach may still involve mobile airborne or ground-based platforms but is difficult to justify intensive field campaigns lasting an entire season.

Technological advances are required to measure the 3-dimensional vector winds regularly and affordably at fine-scale resolution (<100m), as well as temperature and humidity, both inside and outside clouds. Few detailed comprehensive observational analyses of intense deep convection exist, for lack of field campaigns and difficult targeting. More measurements within convective updrafts and downdrafts for all convective cloud morphologies, life cycle stages, and environments are needed to characterize dynamics and microphysics variability and controls properly.

The workshop recognized the value of large, multi-agency field campaigns with comprehensive measurements. Streamlining cross-agency procedures to allow for collaborative deployment of platforms, scanning/sampling strategies during field campaigns, and coordinated data processing/analysis post-field campaigns would be ideal. Absent that, a process is needed that better allows for large but very focused multi-agency field campaigns to be funded that truly have a chance to make substantial advances in one topic. The multi-agency effort to study the development of extremely deep convection near an isolated terrain ridge in Argentina (Nesbitt et al. 2021; Varble et al. 2021) is a success story.

The workshop further recommended better integration of operational, field campaign, and modeling efforts in all stages, and continued proposal writing for campaign-based science well after the campaign.

4.3 Atmospheric thermodynamics and radiation

The key question discussed in this breakout focused on what drives the spatial, vertical, and temporal variability of boundary layer water vapor and temperature, and how is this linked to the underlying land surface? A large deployable network of surface flux/energy balance and boundary layer profiling systems is recommended, as well as sufficiently long field campaigns to sample a broad variety of environmental and land surface conditions and to facilitate attribution. Given the limited resources of the FARE program, multi-agency campaigns may be appropriate, involving, for instance, the DOE ARM program or the NSF NEON program.

Results from a robust campaign can be as transformative as the 1968 campaign over a Kansas wheat field, which yielded the similarity functions used in Monin-Obukhov Similarity Theory (MOST) used in most PBL schemes to this day. Novel machine learning techniques (rather than simple regressions) then can be used to extrapolate experimental results to other land surfaces and to improve the parameterization of the surface layer. Close collaboration with modelers is recommended as dense networks over heterogeneous surfaces are needed to improve MOST and to quantify observational impact through OSSEs. The retrieval of thermodynamic profiles in the boundary layer from passive remote sensors is complex and accurate flux estimation requires extensive data experience. Broader training of students and early career scientists on these techniques is deemed essential.

4.4 Boundary layer processes and air quality

Two key recommendations emerged from this breakout session. First, to answer critical questions about boundary layer processes including air quality, the gap between surface and airborne observations should be narrowed. This is best done by combining dense networks of surface stations and lower tropospheric profiling systems with instrumented UASs (discussed in Section 6.3) and possibly with larger airborne assets (e.g., Hallar et al., 2021). Second, boundary-layer focused field campaigns, more than other campaigns, benefit from close collaboration between experimentalists and modelers at all stages of the project (see Section 3.1). However, boundary layer profilers should be complemented with observations of surface properties, and in particular turbulent and radiative fluxes, so that the surface-atmospheric interactions can be understood. This is because the advent of computationally intensive LES now enables critical testing of BL parameterizations with targeted experimental data.

4.5 Trace gases, biogeochemical cycles, and climate

Interest in atmospheric chemistry has grown in recent years, in large part because of growing air quality impacts and their linkages to climate change. Carbon cycle studies are also gaining in attention in response to pressing needs to better understand carbon-climate feedback and develop methodologies for greenhouse gas emission monitoring and verification. Experimental measurements include carbon dioxide, methane, ammonia, sulfur compounds such as DMS, biogenics, wildfire emissions, other greenhouse gases and related tracers, and gas-aerosol interactions. This breakout resulted in several recommendations.

The FARE atmospheric chemistry instrument suite is relatively small and aging. Trace gas instrumentation has improved radically in accuracy and sampling rate, but some instruments are too expensive for single PIs, hence the interest in FARE-based access. On the other hand, FARE support is redundant for low-cost trace gas probes that are widely available in the academic community.

Emission quantification for relatively large/dispersed sources requires access to an aircraft with high-accuracy, high-rate instruments. Therefore, atmospheric chemists seeking FARE support gravitate towards the aircraft fleet. The transition of PI-provided instruments from the lab to an aircraft remains challenging, requiring engineering and technical support.

Finally, it was mentioned that atmospheric chemistry field campaigns benefit from effective collaboration with and within NSF NCAR, in particular the Atmospheric Chemistry Observations and Modeling (ACOM) lab and the Earth Observing Lab (EOL).

5 Instruments

5.1 Radars

BACKGROUND

The workshop discussed wind profilers, cm-wavelength weather radars, mm-wave cloud radars, active and bi/multi-static (passive) radar networks, mechanically-scanning and phased-array systems, and differential absorption radars to extract water vapor profiles. The FARE pool includes both ground-based deployable/mobile and airborne radars. Most radars employ dual-polarization to enhance data quality and characterize hydrometeors.

OPPORTUNITIES

Radars and radar networks continue to improve in terms of spatio-temporal resolution, sensitivity, and processing techniques. They remain an essential part of the FARE pool. The prospect of better airborne scanning cm-wave radar capability is much anticipated. There is much excitement about research that will be enabled by the Airborne Phased-Array Radar (APAR) under development at NSF NCAR (Vivekanandan and Loew 2018) and Horus, a fully digital Polarimetric Phased Array Radar, at the University of Oklahoma (Palmer et al. 2023), especially in the severe weather community. A promising new development is smart radar signal processing, whereby machine/deep learning algorithms are used to optimize information extraction from radar returns, including hydrometeor identification, precipitation rate, hail size, and multi-Doppler synthesis.

CHALLENGES

The potential of constructing full-size phased-array radars (PAR) using scalable architecture in a modular approach may soon be realizable. PARs are currently expensive, but modularity and scalability offer flexibility in realizing full-size PARs of desired technical specifications at a reduced cost. The PAR technology's most difficult challenge is the addition of radar polarimetry but advanced architectures, such as fully digital designs, hold promise for routine and robust calibration.

RECOMMENDATIONS

- *Invest in cm-wavelength PAR architecture development:* Further invest in the development of cm-wavelength PAR architectures, including fully digital designs, to explore adding polarimetry and the ability to emulate various PAR architectures effectively (Fulton et al. 2016).
- *Preserve access to mobile radars:* Maintain community access to fully mobile, flexible weather radars operating at X- to S-band frequency as a priority, given the significant

utilization in numerous Track 1 and Track 3 FARE proposals.

- *Provide access to multi-wavelength radars:* Expand the FARE program to include beam-matched, multi-wavelength radars, which are useful for characterizing mixed-phase clouds and ice habits, density, shape, and size.
- *Explore integration of G-band radars:* Investigate the integration of G-band (183 GHz) radars alongside X-, Ka-, and W-band radars, lidars and passive microwave radiometers to enhance observational capabilities further.
- *Invest in Wind Profilers with Passive Multistatic Radars:* Foster research and development of modular wind profilers with passive multistatic radars, offering a cost-effective solution for establishing a network of 3D wind profiles.
- *Foster development of Differential Absorption Radar (DAR) Technique:* Encourage continued development of DAR technique, leveraging multiple radar frequencies near a water vapor absorption line (e.g., 183 or 325 GHz) to profile water vapor (e.g., Lamer et al. 2021) and characterize cirrus clouds effectively.
- *Encourage open-source software development:* Promote collaboration between the research community and open-source software developers like LROSE (http://lrose.net/) and Py-ART (https://arm-doe.github.io/pyart/, Helmus and Collis 2016) to enhance existing software and introduce new analysis tools.
- *Facilitate data access and processing:* Ensure open and easy access to large datasets, particularly from previous field campaigns, to accelerate smart radar signal processing, needed for high-quality machine learning.

5.2 Lidar systems

BACKGROUND

The workshop discussed ground-based (fixed/mobile) and airborne Doppler (wind) lidars, backscatter polarization lidars, Raman lidars, and differential absorption lidars.

OPPORTUNITIES

While quantitative wind lidar is widely used commercially and in research, lidar for temperature and water vapor retrieval is currently underutilized (primarily due to lack of instruments with these capabilities). Even for scanning wind lidars, no standardized multiple-Doppler lidar systems are consistently implemented or used, making it challenging to take advantage of the possibilities for fully coordinated mobile measurement systems. Quantitative lidars have a reputation for requiring skilled operators and extensive QA/QC and data processing. As such their use remains rather labor-intensive. Public investment in software to enable visualization, analysis, and coupling of observations with modeling tools (for virtual systems, OSSEs, data assimilation, and experiment design) can enable broader use, which will result in deeper insights into boundary layer dynamics and thermodynamics. A dense demonstration network of quantitative systems, coupled with LES modeling, can have a transformative impact and result in broader operational use of lidar.

CHALLENGES

Significant roadblocks include the challenges in coupling measurements and models, the lack of widely used or standardized tools for using lidar data, the challenges of commercialization and the expert level required for less mature products, lack of workforce training, misunderstanding by users of information content (which is complicated by marketing by private companies being sometimes less precise than required), and, for the development of new systems, the long timeline for development compared to typical grant lifetimes.

RECOMMENDATIONS

- *Develop a demonstration network of lidars:* Establish a demonstration network comprising both mobile and fixed quantitative lidars, drawing inspiration from the Danish Technical University's WindScanner system https://wind.dtu.dk/facilities/windscanner (Vasiljević et al. 2016). This network would enhance research capabilities and provide valuable insights into atmospheric dynamics and wind patterns.
- *Invest in data visualization and analysis tools:* Foster and advocate for public investment in widely usable or sharable tools for visualizing and analyzing lidar data. This initiative could take cues from successful examples in the radar community (https://github.com/NCAR/CfRadial), or expand existing platforms like the Lidar-Radar Open Software Environment (LROSE, http://lrose.net/), with a focus on enhancing usability within the wind lidar community.
- *Invest strategically in virtual lidars and simulation tools:* Allocate strategic investments towards the development of virtual lidars and simulation tools to enable Observing System Simulation Experiments (OSSEs) and data assimilation techniques. Leveraging insights from recent simulation studies (Robey and Lundquist 2022; Ye et al. 2022; and Letizia et al. 2021) as well as novel methodologies (e.g., Adam et al. 2016; Pu et al. 2017; Tan et al. 2022) would enhance predictive capabilities and improve understanding of atmospheric processes.

5.3 Passive remote sensing

BACKGROUND

The breakout discussion focused primarily on passive remote sensing systems for thermodynamic profiling. There are two primary classes of instruments in this category: (1) multi-channel microwave radiometers (MWR) that observe the atmosphere in the 20 to 30 GHz region (K-band) and 50 to 60 GHz region (V-band) although there is movement for more systems operating from 170 to 183 GHz (G-band); and (2) infrared spectrometers (IRS) that observe the atmosphere in the thermal infrared between 7 to 18 µm. The workshop briefly discussed passive observations that might be useful for characterizing the macro- or microphysical properties of clouds or aerosols, and surface properties.

OPPORTUNITIES

While there have been multiple commercial vendors for MWR and IRS systems, these instruments continue to be mainly used in very limited ways during field campaigns (with the exception of the MWR network as part of the New York State Mesonet and the few DOE Atmospheric Radiation Measurement sites). There is a strong need to improve the affordability of these systems, and to reduce their weight and power requirements, so that they can be more easily deployed in long-term networks and in new environments (e.g., marine locations on buoys, on crewed and uncrewed aircraft). Continued development of common open-source retrieval methods are needed, especially to provide a way to create a homogenized dataset from a range of different instruments with a full error and information content characterization. Observations from these passive remote sensors have been used for a wide range of studies, ranging from process-level research, NWP model evaluation, data assimilation, and more.

CHALLENGES

Currently, there isn't a well-organized passive remote sensing community within the US. An (inter)national user community can share knowledge on calibration, quality control, retrievals, and analysis with new researchers and groups. Some MWR systems are available in the FARE pool, for instance from MAPNet, but most users do not critically question the products from these passive ground-based systems, for lack of open-source software and understanding. For instance, retrieved profiles from passive remote sensors should not be taken to have the same characteristics as radiosondes; this is why error characterization and information content profiles are critical so that the data are properly interpreted. Most universities do not have courses on passive remote sensing, which hinders the creation of early career professionals that are pre-trained to understand how radiometric observations are converted to thermodynamic profiles, and to use retrieved products more effectively. Thus, there are limited ways to develop experience in operating, using, and interpreting data from MWR and IRS systems. Furthermore, MWR instruments need periodic manual calibration, and it can be difficult to determine when these systems need to be calibrated and if the calibration procedure was successful. The European Union has, over the last decade, developed an international group that has worked to establish calibration procedures and standards, quality control, and more for their MWR community; we need either a similar effort within the US or to join the EUMETNET effort.

RECOMMENDATIONS

- *Foster a US-based user community:* Establish a user community within the U.S. to facilitate knowledge sharing on operating, calibrating, QA/QC, and interpreting data from MWR and IRS systems. Encourage the development of in-depth educational modules for university programs.
- *Invest strategically in observing systems:* Acquire additional MWR and IRS systems to expand the NSF instrument pool. These systems can support field campaigns including regional network configurations and contribute to educational initiatives.
- *Invest in instrument development:* Encourage investment in instrument development aimed at reducing the size and power requirements of these instruments. This would facilitate their deployment in marine environments and on aircraft, broadening their applicability and utility in diverse research settings.

5.4 In situ (trace) gas instruments

BACKGROUND

The current needs identified within the field of in situ gas instrumentation can be grouped into three main themes: 1) improving access to state of the art instrumentation to provide improved measurement quality and coverage, 2) development of low-cost instrumentation for network deployment, and 3) aging infrastructure and lack of innovation for crucial measurements.

OPPORTUNITIES and CHALLENGES

Two instrument classes that have recently shown promise and have experienced rapid growth in the field of in situ gas measurement are chemical ionization mass spectrometry (CIMS) and optical measurements (e.g. near- and mid-infrared, laser induced fluorescence (LIF), and open path). CIMS instrumentation provides flexibility to target species, high (> 1Hz) measurement frequency, and simultaneous observation of 100s of compounds. Recent developments in the underlying technology and methodology have yielded higher molecular specificity and instrument stability, particularly for airborne deployment. The accessibility of this technique, however, is limited by the high cost, large size, and lack of access to the expertise needed for the development of field deployable instrumentation. Investments in CIMS instrumentation will provide access to these instruments which are currently concentrated in a few R1 universities. Optical techniques, in comparison, are often more affordable and compact making this technique ideal for field deployment. Recently there have been significant advances in optical methods such as the development of NO, NO_2, NO_y LIF (Rollins et al. 2020) and high-quality measurements of CO_2, CH_4, and CO becoming more routine. Relative to CIMS methods, optical techniques observe a small number of species, however calibration is less challenging and instrumentation cost is relatively reduced. Modern instrumentation has the advantage of providing additional observations such as the measurement of isotopologues for source attribution and further potential for miniaturization. Investment in high-risk, high-reward optical instrumentation will help extend their application to additional desirable gases and platforms.

Contrasting these specialized, high-cost instruments is a desire for lower cost, network-deployable instrumentation and sensors. There is an increasing need for network observations in regions with large source variability, e.g. urban air quality, energy production, waste facilities, indoor air quality, environmental justice applications. The high cost of research grade instrumentation limits the deployability of multiple sensors in networks as well as the ability of non-R1 universities and underserved communities to access air quality instrumentation and observations. Investments into the development of local sensors, data analysis, archiving and accessibility are necessary to remove the barriers for access. In addition to targeting the development of new sensors, support for existing underutilized, aging instrumentation can be leveraged to improve accessibility.

RECOMMENDATIONS

- *Address measurement infrastructure needs:* Recognize the increasing need to support measurement infrastructure that is at risk or currently limited in its growth. Two examples include the need for hydrogen oxide radicals (HOx) and volatile organic carbon (VOC) canister/flask measurements. These valuable measurements are vital but currently reliant on a small, predominantly academic community nearing retirement.
- *Innovate instrumentation:* Ensure the longevity and accessibility of crucial measurements by innovating the next generation of instrumentation. Leverage the expertise of existing experts to develop advanced tools that meet evolving scientific needs.
- *Renew support for research and development:* Advocate for renewed support for research and development aimed at training the next generation of instrument operators, especially in at-risk programs such as HOx and VOC measurements. This support is essential for sustaining and advancing measurement capabilities in critical areas of research.

5.5 In situ aerosol, cloud, and precipitation probes

BACKGROUND

The workshop discussed probes that image and size liquid and frozen hydrometeors, bulk water probes, and probes that size aerosol particles and measure their chemical composition and nucleating properties.

OPPORTUNITIES

In situ particle probes, mainly used on aircraft, continue to improve in terms of image resolution and processing techniques. They remain an essential part of the FARE pool. Furthermore, aerosol mass spectrometers have dramatically improved in the last decade and are now readily available commercially.

CHALLENGES

The main limitations of current in situ samplers is the small sample volume (which limits the resolution for the larger particles and effective model validation), the large variation in particle sizes and concentrations, hydrometeor phase discrimination uncertainty, and the ability to sample the more extreme environments.

RECOMMENDATIONS

- *Enhance particle holography:* Pursue advancements in particle holography to gain new insights into mixed-phase cloud processes such as secondary ice production and ice nucleation. Efforts should focus on improving small particle phase discrimination and developing open-source data processing software to facilitate broader use.
- *Refine cloud phase characterization:* Enhance cloud phase characterization by refining measurement of scattering properties, including polar scattering.
- *Collaborate on open-source software:* Foster collaboration within the community to develop open-source software for computing hydrometeor size distributions and generating value-added products based on a variety of in situ probes.
- *Foster partnerships with other agencies:* Facilitate collaboration between the NSF community and other agencies, in particular with DOE ARM for the long-term deployment of aerosol mass spectrometers, levering respective expertise and resources.
- *Enable technology testing:* Address challenges in flight-testing new technologies, developed through SBIR or other grants. Consider the creation of a FARE track specifically for testing experimental instrument suites.
- *Explore UAS application and collaborate on engineering:* Explore the feasibility of deploying aerosol and cloud probes on UASs to enhance sampling in undersampled environments such as orographic clouds close to terrain. Foster collaboration between

the NSF community and DOE ARM to support extensive engineering development of the ArcticShark for aerosols sampling, maximizing shared resources and expertise.

6 Networks and Platforms

6.1 Instrument Networks

BACKGROUND

This includes any network of synergetic atmospheric sensors, including surface energy balance / flux networks, lower tropospheric profiling networks, X-band radar networks, air quality arrays, rapidly deployable arrays, etc.

OPPORTUNITIES

The FARE program contains several instrument arrays or platforms that can be deployed as a network. There is strong scientific interest in certain networks, e.g., to estimate surface heat flux heterogeneity and turbulence anisotropy, or to obtain the full flow field Doppler radar/lidar arrays.

CHALLENGES

The main practical concern in many field campaigns is the availability of robust power and real-time communications. Reliability and usefulness of network data are critically dependent on these. Another concern is that the various systems used in a field campaign (e.g., radiosondes from different vendors) often are somewhat different, which makes data processing more difficult and hampers atmospheric signal isolation. Finally, the science community may question data quality from commercial vendors (e.g., Purple Air AQ sensors, Weatherflow radars) when sensor costs often are minimized by excessive miniaturization, reduced sensitivity, low power, poor QC, and poor maintenance.

RECOMMENDATIONS

- *Incentivize collaboration:* Encourage the research community to work more effectively with instrument vendors and communication providers, fostering mutually beneficial partnerships during the consideration and testing phases of new operational networks. Guidance from the AMS Nationwide Network of Networks (NNoN) committee could provide guidance and facilitate this process.
- *Support ad hoc platforms of opportunity usage:* Deploy instrument arrays on ad hoc platforms of opportunity when the FARE program cannot provide a suitable platform.

Examples include mountain top stations in ski resorts, survey or patrol aircraft, and resupply or ferry ships.

- *Develop synergies and partnerships:* Foster synergies and partnerships to address discrepancies in measurement procedures, Q/A processes, data formats, and analysis tools among different networks measuring similar atmospheric variables. Specifically for FARE, leverage NSF NCAR's expertise in ground-based arrays (ISS, ISFS) to lead QA/QC efforts and facilitate data archival and distribution.

6.2 Crewed Aircraft

BACKGROUND

The FARE program supports a fleet of three aircraft: the NSF/NCAR C-130 and G-V, and the University of Wyoming King Air (UWKA). The latter is a new, upgraded facility that became available for FARE requests in 2023.

OPPORTUNITIES

Crewed aircraft remain a key component of the FARE pool, as they are essential to make in situ and remote measurements from the boundary layer to the lower stratosphere, especially in remote environments where few data otherwise are available for model validation.

CHALLENGES

Many commercially available airborne instruments, while providing important datasets, do not provide all the information needed by many studies (e.g., either in variables measured, resolution, etc.). A roadblock in airborne science is the lengthy process of bringing new technology from the idea phase through all the steps of design, assembly, installation, flight testing, QA/QC and software development to reliable use in a field campaign. The ARISTO program (Chapter 2) was intended to provide aircraft access, engineering and technical support, and flight time for testing new instrumentation, but community awareness was limited, and it became difficult to justify the use of the NSF aircraft. Some atmospheric sensors could be developed/tested on non-NSF aircraft (other agencies or commercial services) but that is programmatically difficult or cost prohibitive. On the aircraft use side, proposing a field campaign with any of the aircraft is a complex collaborative process making it difficult for early career scientists to become involved. The workshop also noted the lack of storm-penetrating aircraft in the FARE fleet, essential to better understand cloud microphysics in thunderstorms, and pointed to the limitations of UASs in severe weather.

RECOMMENDATIONS

- *Integrate instrument development:* Establish a linkage between NSF-funded instrument development, such as through an MRI award, and aircraft access, facility engineering, technical support, and flight time.
- *Simplify the certification process:* Streamline the increasingly complex instrument certification process and explore the possibility of designating the NSF aircraft fleet as "public use" akin to NASA's research aircraft, with flexibility for "experimental" designation as needed based on payload requirements.
- *Implement a rapid deployment track:* Introduce a new track for out-of-cycle, rapid deployment to leverage underutilized FARE aircraft, increasing overall aircraft usage and flight time. Regular flight time is critical for maintaining aircraft performance, pilot proficiency, and instrument testing.
- *Promote early career scientist engagement:* Consider establishing a FARE Track that mandates participation of NSF CAREER scientists or explore alternative initiatives to foster early career scientist participation, particularly in aircraft campaigns.
- *Enhance data connectivity:* Recognize the importance of investing in improved data bandwidth and remote access to airborne instruments, despite associated costs, as it enables larger instrument payloads and facilitates informed in-flight decision-making.
- *Revive testing programs:* Reinstitute the ARISTO program or an equivalent test program initiative for airborne instrumentation, ensuring robust evaluation and validation of instruments for research purposes.
- *Maximize resource sharing:* Explore opportunities for sharing airborne resources at the agency level to optimize aircraft utilization and maximize the efficiency of research efforts.

6.3 Uncrewed Aircraft

BACKGROUND

The workshop discussed fully-guided to fully-autonomous fixed-wing and rotary-wing uncrewed aerial systems (UASs) with various payload sizes, endurances, and altitude capabilities. It did not address tethered balloons, nor other aerostats such as super-pressure balloons.

OPPORTUNITIES

UASs are an underutilized and rapidly developing technology for atmospheric research. Despite the continued advancement of these systems, some are relatively mature from a scientific perspective, supported by decades of development. Instrumentation ranges from sensors measuring basic thermodynamic and kinematic properties, to sensors designed to measure aerosol and air quality properties, cloud microphysics, turbulence and turbulent fluxes, and surface properties. Current efforts to advance AI-based target detection is aiming to optimize sampling regions of scientific interest. For example, UAS equipped with cloud microphysical sensors could be programmed to seek out and enhance sampling in temperature / supercooled droplet regimes deemed optimal for secondary ice production, a process that remains poorly understood and difficult to measure. Sensor miniaturization and platform advancement to support innovative flight capabilities (e.g., swarm flights, ground-based or airborne collision avoidance systems) are supported through a combination of work conducted at universities, commercial entities, and national laboratories.

CHALLENGES

Consistent deployment of UAS is hampered by a variety of different challenges. Building a significant safety record to facilitate more complex flight operations within the regulated airspace takes time and collaboration with aviation authorities (FAA in the United States). As such, airspace regulations and the somewhat complex permitting process is currently a roadblock for widespread pursuit of the types of flights required to support advancement of key atmospheric science disciplines. For example, cloud microphysical research could benefit significantly from the deployment of cloud probes on small, slow-moving UASs. Similarly, flight over extended horizontal distances can support collection of measurements in otherwise difficult to sample environments. However, both in-cloud and extended-range flight require beyond visual line of sight approvals, which for the time being are challenging to obtain.

Another challenge for consistent deployment of UAS is the current dependence on campaign-based funding, which is not conducive to advancing technology and innovative sampling. Such short-term funding solutions make it difficult to maintain personnel and institutional knowledge in a field that requires significant training, slowing progress on capability development and reducing the ability to deploy experienced crews for more complex flight conditions. From a sampling perspective, while payload and instrument capabilities continue to be expanded, UASs for atmospheric research are generally relatively small and not designed for expensive/heavy/power-intensive sensors such as radars. Continued innovation in the sensor space is required to advance the capabilities of these systems.

Finally, UAS flight in extreme conditions (such as in strong winds, near steep terrain, in supercells, and in airframe icing conditions) is challenging. At the same time, numerous examples exist of UAS being deployed in areas that are far too hazardous for larger crewed research aircraft. This includes flight in the surface layer of hurricanes, near supercell storms, near wildfires, at extremely low altitudes over remote locations (Arctic, remote ocean) and near volcanoes. Sunsetting the visual line-of-sight flight requirement would enhance sampling in such extreme environments and reduce risk for operating crews. The NSF FARE program currently does not support a UAS-focused facility, making high-quality UASs for atmospheric research relatively inaccessible. Several university programs have demonstrated significant operational capabilities and could be leveraged as partners to facilitate use of UAS by the NSF-supported atmospheric science community.

RECOMMENDATIONS

- *Strengthen collaboration:* The NSF-funded UAS community should collaborate with other agencies, organizations, and UAS advocates to facilitate easier and broader access to airspace currently restricted to UASs.
- *Invest in technology:* Emphasize sustained investment in sensor development and platform robustness, both for research institutions and commercial providers.
- *Foster partnerships:* NSF should actively promote and support development of partnerships to facilitate regular integration of instrumented UASs into the FARE pool, especially focusing on Track 3 and Track 1 deployments.

6.4 Laboratory Systems

BACKGROUND

Many community facilities exist, although their access could be improved through identification of new partnerships and provide support of existing facilities under the CIF program. The workshop identified three facility types to address specific needs in the community: cloud chambers, environmental smog chambers, and a wind tunnel facility. While this is not a comprehensive list of potential laboratory systems, our recommendations are illustrative of the type of facilities that are being requested throughout the community.

OPPORTUNITIES

The workshop identified several existing facility types that, if they were more accessible and better funded, would better meet the needs of the cloud physics, aerosol, trace gas, and turbulence communities. Objectives include better calibration and characterization of existing instrumentation and testing of new instruments, as well as laboratory analysis of environmental samples.

CHALLENGES

Existing cloud and smog chambers are generally limited or not made widely available to the academic research community. The NSF FARE program supports the PI Cloud Chamber at Michigan Technological University. There is no comparably accessible smog chamber facility. Such a facility would provide a platform to study the formation and growth of secondary aerosols, aerosol coatings, radiative properties, and oxidation mechanisms of gas phase species. Several wind tunnel facilities exist in support of wind energy and aviation interests, but these are not readily available to the atmospheric research community. Such a facility would provide a platform to develop and test aircraft installations such as next generation inlets and sampling platforms and for conducting experiments to test the results of computation fluid dynamic (CFD) simulations. This work would lead to necessary improvements in airborne sampling of cloud condensation nuclei (CCN), cloud droplets, and thermodynamic instrumentation.

RECOMMENDATIONS

- *Invest in cloud chamber development:* Invest in the development of a sufficiently large cloud chamber capable of supporting research on various topics including warm rain processes, ice nucleation, secondary ice formation and ice riming. This controlled-environment facility would enhance model parameterization and could also serve to examine aerosol-cloud interactions.
- *Invest in wind tunnel expansion:* Develop a large-scale wind tunnel to facilitate testing of turbulence parameterizations and airborne instruments, enabling more comprehensive research in this area.
- *Promote laboratory access:* The FARE instrument suite has not evolved much recently. Transformational research often is enabled by a novel instrument. New and diverse instrumentation development often starts in the lab. Many of the instrument needs are being highlighted elsewhere in this report, and access to state of the art laboratory facilities complement these needs.
- *Address calibration standards:* Recognize the need for calibration standards for aerosol instrumentation. Utilize facilities to establish standardization in calibration techniques, addressing various parameters such as size, shape, composition, optical properties, and number concentration. Additionally, consider development of remote sensing instrumentation for chambers and improved submillimeter disdrometers to study warm rain processes as complementary to the laboratory systems.

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