AIRBORNE INSTRUMENTATION NEEDS FOR CLIMATE AND ATMOSPHERIC RESEARCH

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Observational data are of fundamental importance for advances in climate and atmospheric research. For the study of clouds and aerosols, however, ground- and space-based observations are not enough and need to be supplemented by in situ and remote sensing observations from instrumented aircraft. However, compared to ground and satellite instruments, far less effort has been spent creating an orderly and logical process for aircraft instrumentation development, which, as a result, has proceeded in fits and starts punctuated by long periods of inactivity and low funding. This has held back progress in cloud and aerosol science. In order to expedite progress in cloud and aerosol research, greater efforts must be made to improve our understanding of the operating characteristics of current aircraft instrumentation and the caveats and uncertainties in data acquired by such probes. Greater efforts are also needed to develop new and improved observing methodologies for the acquisition of airborne data.

With these overarching goals, the Atmospheric Radiation Measurement (ARM) Aerial Facilities (AAF) program [information about AAF is available online at www.arm.gov/sites/aaf; note: the AAF was named the ARM Aerial Vehicle Program (AVP) at the time of the workshop] and the Department of Atmospheric Sciences, University of Illinois cosponsored a 3-day workshop in 2008 called Advances in Airborne Instrumentation for Measuring Aerosol, Cloud, Radiation, and Atmospheric State Parameters. The workshop attracted graduate students, postdoctoral, and senior researchers from Europe, the United States, Canada, and Israel. Among the participants were representatives or individuals receiving funding from several major U.S. agencies, including the National Science Foundation (NSF), the Department of Energy (DOE), National Aeronautics and Space Administration (NASA), and National Oceanic and Atmospheric Administration (NOAA). The goals of the workshop were to 1) identify state-of-the-art measurement techniques for aerosol, cloud, radiation, and atmospheric state parameters; 2) determine emerging instruments and developing technologies that, with a modest infusion of support, could be made flight ready within approximately 1 yr; 3) identify gaps in

ATMOSPHERIC RADIATION MEASUREMENT (ARM) AERIAL FACILITIES (AAF) WORKSHOP ON ADVANCES IN AIRBORNE INSTRUMENTATION FOR MEASURING AEROSOLS, CLOUDS, RADIATION, AND ATMOSPHERIC STATE PARAMETERS

WHAT: Graduate students, postdoctoral fellows, and senior researchers working in the atmospheric sciences at U.S. and foreign universities and government laboratories met to discuss state-of-the-art techniques and necessary advances to realize effective airborne measurements of atmospheric parameters for climate and weather research.
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existing airborne instrumentation that are either slowing down or preventing research progress; and 4) promote dialog between scientists and instrument developers on identifying measurement needs.

WORKSHOP. About 65 people attended the workshop, which is a surprisingly large number for such a focused topic; the large turnout is indicative of the considerable interest and unmet needs in this subject area. There were 45 oral presentations and nine posters on instrumentation for measuring aerosol properties, cloud microphysics, radiation fluxes, and state parameters using both in situ and remote sensing techniques. There was a special session on instruments for Unmanned Aerial Systems (UAS). Each session devoted significant discussion time to developing recommendations for instrument priorities in each research area. Graduate students from a course entitled "Clouds and climate" at the University of Illinois acted as scribes for each session, giving them the opportunity to both hear about state-of-the-art instruments and interact with leading scientists in this field. One evening, several participants gathered at the Champaign Willard Airport to review the capabilities of NOAA's Cessna 206 aircraft, which is one example of an instrumented aircraft that is currently available for field campaigns.

The participants emphasized the strong need for calibration standards in order to increase confidence in size- and shape-dependent particle concentrations derived for aerosols and liquid and ice hydrometeors. A potential method for meeting this need would be the creation of a calibration facility, preferably at a national laboratory for the sake of permanence, and through the identification of specific methods by which the calibrations would be applied. One of the main sources of errors in the derivation of aerosol and cloud particle concentrations is the uncertainties in the sample volume. Therefore, the participants recommended that more effort be directed toward the development of multiparticle instruments sampling in a transverse direction; this would lead to a better-defined sample volume and would begin to bridge the many-order-of-magnitude gulf in spatial averaging between remote sensing and in situ observations.

The participants identified other key areas where there are large uncertainties in aerosol and cloud microphysical observations, or where there was a pressing need for better observations. First, there are enormous uncertainties in estimates of the concentrations of small ice crystals (those with maximum dimensions less than ~200 μm) with major impacts both on climate modeling and remote sensing algorithms. This is mainly due to a lack of understanding of the degree to which the shattering of large ice crystals on the tips of probes produces small ice crystals. The splashing of cloud drops on aerosol inlets can also create artifacts in aerosol measurements within clouds. A second identified need was for much higher temporal resolution observations, leading in turn to higher spatial resolution. An aircraft traveling at 100 m s^{-1} and sampling at 1 Hz or less, as many cloud and aerosol instruments do, will average measurements over 100 m or more. This is grossly inadequate for studying the range of scales from the microscale through the large-eddy scale up to the cloud-resolving-model scale, and for studying cloud boundaries (often only tens of meters thick) where intense turbulent entrainment and aerosol–cloud interactions take place. Other needs identified for aerosol and cloud science included better measurements of 1) the concentrations and compositions of ice nuclei; 2) the scattering phase functions of aerosols and clouds; 3) aerosol radiative properties over a wider range of wavelengths, as well as their dependence on relative humidity; 4) aerosol properties near cloud edges; and 5) extinction and ice water contents in ice and mixed-phase clouds.

The location of instruments on the aircraft also needs greater attention, especially because some instruments need to be grouped closely together to examine the finescale structure of cloud and aerosol fields and to determine how aerosols and clouds interact at the microscale. The need for developing modular instruments, as well as smaller instruments that can be easily flown on a wider range of aircraft, was also emphasized. Shorter-term needs included better documentation, the retrieval of the specific sizes of

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cloud particles that are partially imaged by probes, accounting for probe response times, redesign of probe inlets to mitigate shattering and bouncing, the use of nonspherical pollen as difficult test particles in laboratory wind tunnels, and the development of simple portable calibration tools for use in the field. Longer-term needs included the development of nonintrusive measurement techniques and the adaptation of probes for use in slower-moving platforms like balloons, helicopters, and small UASs.

Current sensors limit us to a one-dimensional or at best a two-dimensional view, and it is impossible to simply extrapolate these measurements to three dimensions. Thus, an important scientific priority for proper comparison to models is to measure the 3D distribution of clouds and aerosols as well as their dependence on large-scale through microscale parameters. Especially needed are 3D distributions of latent heat and precipitation.

Other notable measurement priorities include long- and shortwave radiative flux divergence profiles, updraft velocities, instantaneous measurements of liquid water path, profiles of cloud and aerosol light extinction, a cloud lidar working close to the airplane in tandem with in situ observations, spectral radiance especially in the far infrared, surface properties such as albedo, and profiles of water vapor.

A special session was dedicated to UAS as an exciting new technology. In order to make effective use of these platforms in the future, it was emphasized that instruments should be small and lightweight with low power consumption to allow for their installation on some of the smaller UAS platforms. Access to airspace was identified as one of the key limitations with the use of such platforms for science experiments, along with a lack of standardized control systems. Further demonstration projects are needed to prove that UAS platforms can satisfy flight safety and national security requirements while studying important science questions in controlled airspace.

OUTCOME. At the conclusion of the workshop, a steering committee convened to review the discussions and to develop specific recommendations on instrument development needs. Based on the workshop discussions, the highest priority identified was the need to calibrate and characterize instruments in flight tests, environmental chambers such as wind tunnels, and cloud chambers. For this purpose, a dedicated instrument calibration facility is highly recommended. Further, there is an urgent need to support test flights for newly developed instruments before their inclusion in field campaigns.

Other specific needs included the maturation and hardening of instruments making the following measurements: 1) those that quantify and reduce uncertainty of the measurements of small ice crystals (i.e., those caused by shattering artifacts) or those that measure statistically significant populations of small ice crystals; 2) those measuring spectral aerosol absorption and extinction (at ambient conditions or as a function of relative humidity); 3) those measuring cloud extinction at path lengths of many meters; 4) those measuring short- and/or longwave net radiative flux with fast, aircraft-adapted radiometers; and 5) those measuring far infrared (15–25 μm) at high-to-moderate spectral resolution (0.5–3 cm^{-1}). In almost all cases, there is a need for much faster time-response measurements of cloud, aerosol, radiation, and state parameters in order to understand the full range of scales. In addition, the comparison and evaluation of alternative numerical techniques for deriving geophysical parameters from the primary observations was identified as a community need, with the objective of quantifying and reducing the uncertainty of the derived products. All code should be open software to encourage this evaluation of data processing techniques.

AWARDING PROGRESS

As a result of the workshop goal of identifying emerging instruments and technologies that could be made flight ready within approximately 1 yr, the AAF program issued a call for proposals for the maturation and hardening of instruments and selected five different proposals that addressed some of the measurement gaps identified in the workshop. These proposals included the following:

- the modification of a laboratory nephelometer to an airborne version for measuring the scattering phase function of ice crystals and aerosol particles without the use of inlet tubes;
- aircraft integration and flight testing of an airborne sky-scanning, sun-tracking spectrometer for retrieving information on clouds, aerosols, and trace gases;
- further development of a holographic detector for measuring cloud particles;
- laboratory and theoretical calibrations of an airborne probe that measures bulk extinction in ice and mixed-phase clouds; and
- maturation and hardening of a stabilized radiometer platform that allows measurements of solar and infrared irradiance without effects from the pitch and roll of the aircraft.

CONCLUSIONS. In summary, the workshop emphasized the need not only for the development and maturation of airborne instruments, but also for understanding the nature of existing measurements and the development of calibration standards. It is crucially important that reliable, permanent facilities for testing instruments in both the laboratory and on dedicated aircraft flights be made available.

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