In Situ, Airborne Instrumentation: Addressing and Solving Measurement Problems in Ice Clouds

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IN SITU, AIRBORNE INSTRUMENTATION

Addressing and Solving Measurement Problems in Ice Clouds

BY D. BAUMGARDNER, L. AVALLONE, A. BANSEMER, S. BORRMANN, P. BROWN, U. BUNDKE, P. Y. CHUANG, D. CZICZO, P. FIELD, M. GALLAGHER, J.-F. GAYET, A. HEYMSFIELD, A. KOROLEV, M. KRÄMER, G. MCFARQUHAR, S. MERTES, O. MÖHLER, S. LANCE, P. LAWSON, M. D. PETTERS, K. PRATT, G. ROBERTS, D. ROGERS, O. STETZER, J. STITH, W. STRAPP, C. TWOHY, AND M. WENDISCH

WORKSHOP ON IN SITU AIRBORNE INSTRUMENTATION: ADDRESSING AND SOLVING MEASUREMENT PROBLEMS IN ICE CLOUDS

WHAT: A meeting of 31 international experts on in situ measurements from aircraft was held to identify unresolved questions concerning ice formation and evolution in ice clouds, assess the current state of instrumentation that can address these problems, introduce emerging technology that may overcome current measurement issues, and recommend future courses of action to improve our understanding of ice cloud microphysical processes and their impact on the environment.

WHEN: 25–27 June 2010

WHERE: Seaside, Oregon

Despite the progress that has been made in the last 20 years toward understanding the formation and evolution of ice in clouds and its impact on weather and climate, serious gaps remain, many of which are associated with measurement uncertainties and limitations. Unraveling the complex relations between aerosols and cloud particles is hindered by the lack of adequate instrumentation for identifying the primary modes of ice initiation, discriminating liquid water from ice, identifying crystal shapes segregated by size, determining the chemistry of cloud hydrometeors, and measuring the optical properties of single cloud particles and ensembles of cloud particles, to name just some of the problems facing the atmospheric science community. With these issues in mind, a workshop was held with the following five objectives: 1) identify the critical, unresolved scientific questions related to the formation and evolution of ice in clouds; 2) summarize the uncertainties and limitations of in situ sensors currently deployed on aircraft, related to measurements of ice cloud properties; 3) identify and review emerging technologies that can decrease measurement uncertainties; 4) recommend methods for standardizing calibration and quality control; and 5) discuss and evaluate standardization of data processing methodologies.

The meeting had three major themes: 1) scientific issues related to ice formation and evolution, 2) measurement challenges, and 3) emerging technologies. There were 20 keynote presentations that were given by different groups of participants (full presentations can be downloaded at www.uni-leipzig.de/~meteo/en/forschung/airborne_workshop.php).

The four presentations that identified the scientific issues were focused on cirrus formation, contrails and contrail-induced cirrus, mixed-phase clouds, weather modification, and aviation meteorology related to airframe icing and aircraft performance problems associated with the encountering of high ice concentrations. Eleven presentations were made covering measurement challenges, in particular those associated with the following: measuring the composition and concentration of all the modes of ice nuclei (IN); measuring the morphology, mass, surface, and optical properties of individual ice crystals over all sizes; and measuring temperature, humidity, and winds in clouds accurately. Additional measurement issues included operational limitations and sensing uncertainties, airflow distortion and ice crystal shattering, paucity of calibration and data processing standards, and large observed discrepancies when comparing measurements from similar instruments. The four presentations concerned with emerging technology introduced new instruments and measurement approaches that have appeared in the last 5 years, which include improvements in holography, faster electronics, and depolarization measurements that can separate water from ice on an individual particle basis. This session also discussed cloud chambers, wind tunnels, and towed vehicles as alternative approaches for addressing the scientific issues, testing new instruments before putting them on aircraft, and providing a well-controlled environment for instrument calibrations and intercomparisons.

Science issues: Ice formation and evolution in clouds. A large percentage of naturally occurring clouds, as well as those produced from aircraft emissions, are formed from ice particles, and their subsequent impact on weather and climate is directly related to the microphysical properties of these crystals. The forecast of precipitation (i.e., the onset, duration, and intensity) is highly uncertain when clouds are composed of liquid and ice, primarily resulting from how poorly ice processes are simulated in the forecast models. Likewise, simulations of climate forcing by clouds are of questionable validity when ice processes are involved because of the overly simplified parameterizations that are used to represent the formation, sedimentation, and evolution of ice crystals. In defense of the models, the representation of ice processes has had to rely upon a very limited set of in situ observations from which basic theories have been derived that can explain how ice crystals nucleate and evolve.

The key questions, yet to be satisfactorily resolved, are as follows:

1) What are the respective roles of homogeneous and heterogeneous nucleation under different ambient conditions?
2) What is the relationship between IN and ice crystal concentration?
3) When do secondary ice formation processes become important, what are the mechanisms for secondary ice formation, and on what do these processes depend?
4) What are the freezing mechanisms below 205 K?
5) What are the optical properties of ice crystals as a function of habit?
6) What are the sedimentation velocities of ice crystals as a function of habit?
7) What are the spatial scales of cirrus cloud inhomogeneities?
8) What is the value of the accommodation coefficient for ice and does it vary with temperature and humidity?

AFFILIATIONS: Baumgardner—Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de Mexico, Mexico City, Mexico; Avallone—University of Colorado, Boulder, Colorado; Bansemer, Heymsfield, Rogers, and Stith—National Center for Atmospheric Research, Boulder, Colorado; Borrmann—University of Mainz, Mainz, Germany; Brown and Field—Met Office, Exeter, United Kingdom; Bundke—University of Frankfurt, Frankfurt, Germany; Chuang—University of California, Santa Cruz, Santa Cruz, California; Cziczo—Massachusetts Institute of Technology, Cambridge, Massachusetts; Gallagher—University of Manchester, Manchester, United Kingdom; Gayet—Laboratoire de Météorologie Physique, UMR6016 CNRS/Université Blaise Pascal, Clermont-Ferrand, France; Korolev and Strapp—Cloud Physics and Severe Weather Research Section, Environment Canada, Canada; Krämer—Institut für Energie- und Klimaforschung Stratosphäre (IEK-7), Forschungszentrum Jülich, Julich, Germany; McFarquhar—University of Illinois at Urbana–Champaign, Urbana, Illinois; Mertes—Leibniz-Institute for Tropospheric Research, Leipzig, Germany; Möhler—Karlsruhe Institute, Karlsruhe, Germany; Lance—Cooperative Institute for Research in Environmental Sciences, Climate Diagnostics Center, University of Colorado, and National Oceanic and Atmospheric Administration/ESRL/Chemical Sciences Division, Boulder, Colorado; Lawson—SPEC, Inc., Boulder, Colorado; Petters—North Carolina State University, Raleigh, North Carolina; Pratt—Purdue University, West Lafayette, Indiana; Roberts—Scripps Oceanographic Institute, La Jolla, California; Stetzer—Institute for Atmospheric and Climate Science, ETH, Zurich, Switzerland; Twohy—Oregon State University, Corvallis, Oregon; Wendisch—Leipziger Institut für Meteorologie (LIM), Universität Leipzig, Leipzig, Germany
CORRESPONDING AUTHOR: Darrel Baumgardner, Centro de Ciencias de la Atmósfera, Univeridad Nacional Autonoma de México, Mexico City, Mexico 045120
E-mail: darrel.baumgardner@gmail.com

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In addition to the questions related to the specific properties of IN and crystals, there are more general questions related to the characteristics of mixed phase clouds, for example:

1) What is the definition of mixed-phase cloud—that is, what is the minimum ratio of supercooled liquid to ice water mass required to define a cloud as being mixed phase?
2) What are the spatial scales of mixing between liquid and ice and how do they vary with height, meteorological conditions, etc.?
3) For mixed-phase clouds, how are the liquid and ice partitioned with respect to particle sizes (e.g., are all small particles liquid and all large particles ice?)
4) How can small ice particles be distinguished from supercooled droplets and how do frozen water drops evolve in shape according to conditions?
5) What is the relative humidity in mixed-phase clouds and how does it depend on distance scale?
6) What environmental factors determine the glaciation rate of mixed-phase clouds?

Addressing and answering these questions requires accurate measurements of IN (all modes), liquid water content (LWC), and ice water content (IWC), aerosol composition, droplet size distributions, and ice crystal properties (size distribution, density, morphology, optical). In addition, accurate temperature and humidity measurements, in and out of cloud, are essential. These questions remain open mostly as a result of the limitations of the available instrumentation. New measurement approaches, discussed below, offer the possibility that some of these limitations can be overcome, or at least partially circumvented, such that improvements can be made in our understanding of fundamental ice microphysical processes.

Measurement challenges: Limitations and uncertainties. An accurate measurement of fundamental parameters, such as temperature and humidity (water vapor concentration), in clouds continues to be elusive. Nearly all available techniques are limited either by the effects of cloud particle impact (the wetting of sensors and inlets and cooling by evaporation) or by the scattering of light by cloud particles within an optical path (Baumgardner et al. 2011; Wendisch and Brenguier 2012).

One of the principal challenges in understanding how ice forms in cirrus and mixed-phase clouds is to reconcile the concentration of ice crystals measured in clouds with the concentration of available IN. Rarely have cases been found where these two concentrations are in reasonable agreement. In most instances the ice crystal concentrations exceed that of the IN by a wide margin. In mixed-phase clouds these discrepancies can sometimes be explained by secondary ice formation processes, such as ice multiplication, but limitations in the measurement systems also contribute to the differences. Ice crystals can be overestimated because of ice crystal shattering on the inlets and arms of optical spectrometers (Korolev et al. 2011); however, the instruments that measure IN may miss a substantial fraction of the IN population if they are unable to detect all of the possible activation modes. There are at least seven possible modes of ice crystal formation: 1) homogeneous nucleation, 2) deposition nucleation, 3) immersion/condensation freezing, 4) contact freezing, 5) contact freezing “inside out,” 6) evaporation freezing, and 7) electrofreezing (DeMott et al. 2011). To date, no measurement appr oach has been shown to detect IN for all these nucleation modes. Although modes 1–3 are generally accepted as the dominant pathways to nucleation, it is difficult to accurately assess the relative importance of the other modes. There has been, however, significant progress in the development of IN instrumentation and observations (DeMott et al. 2011).

Measurements of the morphology, that is, the detailed shape and roughness, and the density of individual ice crystals over the more than four orders of magnitude in size (from 1 to > 1,000 μm) found in clouds, are essential for evaluating their sedimentation velocities, water content, and optical properties. Cloud lifetimes are sensitive to the sedimentation velocity of the ice crystals, as are the rates of aggregation and riming that depend on the relative fall velocities of ice crystals and supercooled water droplets. The sedimentation velocity can be measured in cloud chambers but has yet to be directly measured from airborne platforms in natural clouds. Given detailed images of the ice crystal structure, and some assumptions about the density and internal structure of the crystals, the fall velocities can be calculated with aerodynamic models. The resolution of optical array probes (OAPs) is not fine enough to provide the necessary detail required for modeling the aerodynamic behavior of particles smaller than about 100 μm; however, instruments like the video ice particle spectrometer (VIPS) that photograph the actual ice crystal captured on a moving tape can provide such detail (Heymsfield and McFarquhar 1996; Schmitt and Heymsfield 2009).

Understanding the radiation budget of Earth and its atmosphere system, and hence its climate, must include an understanding of the optical properties of cloud particles. In particular, the scattering, absorption, and extinction coefficients; the scattering phase function; the single scattering albedo; and the asymmetry factor (which can also be derived from the phase function) are all necessary parameters. As with the calculation of sedimentation velocities from images of ice crystals, the optical properties can also be estimated theoretically with detailed images and some assumptions about the internal structure. Most instruments do not directly measure the optical properties on an individual crystal basis; however, for ensembles of ice crystals, the polar nephelometer (Gayet 1997) measures the phase function, the cloud extinction probe (CEP) measures the extinction coefficient (Korolev 2008), and the cloud integrating nephelometer (CIN) derives an estimate of the extinction coefficient and asymmetry factor (Gerber et al. 2000).

The measurement of the size distribution of ice crystals is complicated by a number of factors, not the least of which is the lack of a universally accepted definition of size when referring to aspherical particles. One of the discussion topics of the workshop was the need for standardized analysis algorithms, including the way in which particle sizes are defined. An effort is currently underway to establish such standardization; however, at present, size is defined by the optical scattering cross section, when ice crystals are measured with single particle optical spectrometers like the forward scattering spectrometer probe (FSSP), cloud droplet probe (CDP), and the cloud and aerosol spectrometer (CAS). When measurements are made with OAPs, the characteristic size can be maximum dimension, projected length, area-equivalent diameter, or other equally descriptive dimensions. Because the optical scattering cross section is sensitive to the orientation of the particle, as well as to the degree of asphericity, a large degree of undersizing, sometimes more than a factor of 2, cannot be avoided when size distributions are reported from instruments like the FSSP.

In addition, number concentrations of particles smaller than at least 50 μm derived from OAPs are uncertain by factors of 2 or 3 because of the operating principles, which limit the determination of sample volume using this imaging technique. Holographic techniques like the Holographic Detector for Clouds (HOLODEC) (Fugal and Shaw 2009) offer the promise of the much better definition of sample volume, as well as obtaining images of the detailed structure of ice crystals.

Although advances in high-speed electronics have led to the development of OAPs like the two-dimensional stereo (2D-S) probe (Lawson et al. 2006) that can measure a more representative particle sample at high airspeeds, all OAPs suffer from contamination by fragments of ice crystals that shatter on the extended arms, or even on aircraft surfaces, ahead of the probes, depending on the measurement location. The issue of ice shattering as a source of measurement contamination remains a major concern when interpreting measurements from any particle spectrometers mounted on aircraft. The FSSP, CAS, and all OAPs are also susceptible to this problem, although there has yet to be a definitive study that quantifies the magnitude of the effect as a function of airspeed and ice crystal characteristics (concentration, size, and crystal morphology). The CDP has a design that greatly reduces the influence of ice shattering (Lance et al. 2010), and new tips have been designed for particle probes that also have been clearly shown to greatly reduce the production of ice fragments from shattering (Korolev et al. 2011). Software techniques related to the elimination of closely spaced particles, assumed to result from shattering, have also been proposed, although they are not yet rigorously evaluated.

Determination of glaciation rates and ice fractions in mixed-phase clouds requires the means to identify liquid droplets separately from ice crystals. This can be accomplished using optical array probes when enough pixels are shadowed to determine the particle shape. Determining the phase of cloud particles smaller than about 100 μm, however, is more challenging, and only recently has the introduction of the small ice detector (SID) and cloud particle spectrometer with depolarization (CPSD) provided the possibility to separate liquid from ice particles on an individual particle basis. The SID measures the forward light-scattering pattern (Cotton et al. 2010) from which aspherical particles can be identified. The CPSD measures the amount by which a cloud particle rotates the polarization of incident light. Water droplets cause very little rotation, whereas ice crystals will rotate the incident light proportional to the complexity of their morphology. Even nearly spherical frozen water droplets will depolarize the light more than water droplets.

Emerging technologies: New sensors, measurement platforms, and ground based facilities. In addition to the new sensors that are capable of providing previously unavailable information on ice crystal properties or that avoid the more serious limitations, newly developed airborne platforms offer new approaches for measuring the microphysical properties of mixed phase clouds. For example unmanned airborne vehicles (UAVs) are now being instrumented to do long-range and long-duration measurements in cirrus clouds, and instrumented sondes towed by an aircraft have allowed measurements of radiation fluxes from the aircraft flying above the cloud, while measurements of microphysics are made in the cloud by the towed vehicle (Frey et al. 2009).

Wind tunnels also continue to be used to better understand measurement issues on aircraft, but in new ways. For example, high-speed photography was used in a wind tunnel to look at ice crystal shattering on the inlet of an FSSP and the arms of an OAP (Korolev and Isaac 2005; Korolev et al. 2011). Techniques to calibrate the mass concentrations of simulated ice clouds in tunnels are now being investigated (Strapp et al. 2008), and will be used to provide more direct accuracy estimates of ice mass concentration measurement devices that to date have all had unknown or very indirect accuracy estimates.

Cloud chambers, such as the Aerosols Interaction and Dynamics in the Atmosphere (AIDA) in Karlsruhe, Germany (Möhler et al. 2003), the Ice Cloud Chamber in Manchester, England, and the Cloud Simulation Chamber in Tsukuba, Japan (Tajiri et al. 2008), are excellent facilities for evaluating ice formation and evolution under controlled conditions. Cloud chambers have proven especially useful for comparing many different instruments while generating cloud particles over a narrow range of shapes and sizes. These types of studies have helped the community to identify measurement issues that may be related to fundamental sensing principles, separate from problems introduced by operating an instrument on an aircraft. Specifically, a number of new instruments that are being developed for the High Altitude Long Range (HALO) research aircraft have already been tested in the AIDA chamber prior to their first airborne deployment.

General problems with new instrument development and the role of national laboratories and funding agencies. The development of new measurement capabilities can be lengthy and costly. Only a small number of universities have facilities for supporting such new developments and few private companies will risk designing new instruments without economic incentives. The length of time and significant resources required to design, develop, and test new measurement techniques discourages graduate students from taking on projects like these as thesis topics. Hence, even as the need for better instrumentation is as dire today as it was 30 yr ago, there are a dwindling number of scientists or engineers with the necessary experience to pursue these developments.

A number of new instruments have been developed in university and government laboratories, but because they are not commercially viable only limited measurements are made during short field programs. The value of such datasets is limited if they cannot be extended over broader spatial and temporal scales by making the new instruments more widely available. The Small Business Innovative Research (SBIR) and the Small Business Technology Transfer (STTR) programs funded by the United States have proven to be a boon to new developments from private companies; however, unless research funds are also available for scientists to purchase and implement new instruments in their research, the new technology cannot spread rapidly.

Building instruments to withstand the harsh conditions encountered on airborne platforms in clouds is a challenging task with limited opportunities for

GENERAL CONCLUSIONS AND OUTCOMES OF THE MEETING

1) The processes by which ice forms and evolves in cirrus and mixed phase clouds are poorly understood, primarily because of the complexity of ice particle nucleation and the paucity of measurements that accurately provide the properties of ice crystals. Twenty presentations (available at www.uni-leipzig.de/~meteo/en/forschung/airborne_workshop.php) summarized our current understanding of ice processes in clouds, the measurement systems available for characterizing these processes, the limitations and uncertainties of these systems, and emerging technologies for improving our measurement capabilities.
2) The key unresolved questions concern the relative roles of homogeneous and heterogeneous nucleation, the relationship between ice nuclei (IN) and ice crystal concentration, the mechanisms for secondary ice formation, the optical properties of ice crystals as a function of habit, and the rates of glaciation in mixed-phase clouds.
3) Currently available instruments are limited by problems caused by ice crystal shattering and sample volume uncertainties for cloud particles smaller than 50 μm. Although consistent and reliable measurements of ice crystal size distributions can be obtained for particles larger than 400 μm, given sufficiently long integration times, large uncertainties still remain at smaller sizes.
4) New instruments are becoming available to differentiate liquid droplets from ice crystals at sizes less than 50 μm by detecting their shapes from forward light scattering and depolarization signals.
5) More incentives are needed to attract young researchers to the observational sciences.

testing prototype instruments. Field programs that specifically target instrument developments have been conducted on a limited basis, but with great success. For example, the Instrument Development and Education in Airborne Science (IDEAS) program, funded by the National Science Foundation (NSF), has provided airborne platforms to test new instruments, and the European Facility for Airborne Research (EUFAR) has encouraged new instrument development through working groups and coordinating groups focused on similar measurement goals.

Workshops such as the one described in this summary serve to focus the scientific community's attention on the most pressing measurement needs, bringing young scientists together with older, experienced researchers to share ideas and work together to resolve long standing problems with innovative new ideas.

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