Report of EUFAR Expert Groups on liquid- and ice-phase microphysics measurements.

CIRA, Capua, Italy. 16-20 September 2002

by Philip R.A. Brown

Met Office, Farnborough, UK.

1. Aims

The aims of the workshop were to:

- Describe the main current scientific issues driving the requirement to make microphysical measurements on board research aircraft

- Describe the current "state-of-the-art" in airborne instrumentation to meet these needs

- Consider and make recommendations for "best practices" in the installation, calibration, maintenance and data processing for these instruments

- Give an understanding of the standards of accuracy that can be achieved using particular instruments or combinations.

The planned areas of discussion were:

a) Scientific requirements for liquid- and ice-phase microphysics measurements

- are these currently well-defined and understood?
- are these requirements capable of being met by currently-available or newly-introduced instruments?
- if not, then can we identify what future instrument developments might be required.
- liquid water measurements in mixed-phase clouds - what is needed to quantify contamination of existing LWC measurements by different probes?

b) Calibration

- what calibration standards are in use?
- what is their traceability?
- how often are calibrations performed?
- is there an optimum interval for doing them?
- are there any simple tests which can be conducted in the field to determine correct behaviour of probes?
- quick field-calibration checks (i.e., calibration checks without removing the FSSP etc. from the aircraft)

c) Intercomparisons

Most aircraft operators have some degree of redundancy for LWC measurements so:
- how often are these systematically compared and how repeatable are the results?
- is there any value to doing such intercomparisons on a more regular/systematic basis?
- if so, how can this be facilitated?
- is there a role for regular instrument intercomparisons in controlled conditions in a wind tunnel?

d) Post-flight data processing

- what processing is applied to each instrument's data stream?
- are the algorithms used clearly identified and documented?
- what testing has been applied to the data processing software?
- how to identify and remove ice particles from large drop data before computing size distributions and LWC (i.e., how to process mixed-phase particle size data)?

e) Standardization

The comparability of data between different aircraft operators has always been something of an unresolved issue, so can we do anything towards the standardization

- of laboratory calibration procedures?
- of data processing algorithms?
- of sets of real or idealized data for testing purposes?
- of data presentation (time and/or spatial averaging intervals, output formats etc.)?

2. Current Issues for Airborne Microphysical Measurements

a) Aircraft Icing Studies

George Isaac (Meteorological Service of Canada, MSC) identified measurement issues arising from the need to study conditions relevant to aircraft icing. He presented a summary of data from a number of Canadian measurement campaigns, showing the fractional occurrence of liquid-, ice- and mixed-phase clouds and differences between maritime and continental airmasses. Supercooled large drops (SLD) are a particular problem since they can lead to water freezing on the aircraft structure behind any thermal ice protection systems. Such systems may also be affected by ice cloud, as the ice particles melt on the de-iced part of the structure with the meltwater running aft and re-freezing on the non-deiced parts. This phenomenon was subsequently illustrated in a video presented by Dean Miller.

Discrimination between ice and liquid cloud particles therefore remains a high priority, both for total and size-resolved condensate mass. Particle sizing in the diameter range 50-150 microns is also an important issue. This range can be poorly described by 2-D Optical Array Probes (OAP) even when the most detailed correction techniques are applied to individually characterised probes. Measurement of the mean volume diameter (MVD) of an atmospheric particle size spectrum suffers from inaccuracies that arise from the need to use several different instruments to cover the entire size spectrum.

The required accuracy of cloud microphysical measurements for aircraft icing studies derives from the needs of aircraft certification in the regulatory framework. There is a strong desire to provide full traceability of probe calibrations to absolute standards wherever possible. This will be assisted by the provision of more dedicated facilities for probe calibrations and greater use of and interaction with icing wind tunnels (IWT). Such facilities can provide well-characterised liquid clouds, through the use of icing-cylinder calibration techniques. However, standards for the measurement of ice clouds are still lacking since the type of ice particles that can be generated in wind tunnels (frozen drops or shaved ice fragments) are unrepresentative of those found in natural clouds.

On the data processing side, examples were shown of the variation of bulk microphysical quantities such as mean ice and liquid water contents with the data averaging period. When assembling databases of cloud measurements it is crucial that this and other pertinent aspects of the data processing be included as part of any metadata in the database.

b) Cloud and precipitation microphysics research

Some of the issues relating to the needs of basic studies in this area were raised by Jean-Louis Brenguier (Meteo France). Understanding the links between aerosol, cloud and precipitation requires measurements across a very wide size range from the aerosol nucleation mode (2-100nm), through transformations in the accumulation (0.05-1 μm) and coarse (1-20 μm) modes, CCN activation (0.1-1 μm), cloud droplet growth (1-50 μm) and precipitation formation and growth (50 μm to several cm). Studies of cloud droplet nucleation and growth in pseudoadiabatic conditions have in the past been limited by the artificial size spectral broadening generating by droplet probes such as the FSSP. This remains an important area of study with ongoing investigations of the impacts of soluble gas uptake and organic compounds on droplet growth.

The study of rain initiation in warm clouds via collision/coalescence processes requires measurements of drops that may have formed on a small number (maybe only a few per cubic metre) of giant CCN. The sample volume of OAP devices is inadequate to obtain a statistically significant sample of these drops during a typical penetration of a growing cumulus cloud lasting only a few tens of seconds.

In the study of ice phase microphysical processes, counting the number of ice crystals in the cloud at different stages of its evolution remains a central problem. A number of new devices have been introduced recently (the SPEC Cloud Particle Imager - CPI - and the Univ.of Hertfordshire Small Ice Detector - SID) to address this problem. However, both of these rely on particle asphericity to distinguish ice particles. It has not been proven that this is a sufficient condition in the early stages of ice phase development in clouds.

Many global-scale numerical models used for both numerical weather prediction and climate studies now have some sort of explicit representation of the ice phase for cloud and precipitation. Validation of the ice and liquid condensate distributions generated by these models remains, therefore, another important task. This applies to measurements averaged on the grid scale of the models (typically 10s to 100s of km in the horizontal and 100s of m to ~1km in the vertical) and also to those on the sub-grid scale.

The surface properties of ice particles may play an important role in chemical processes occurring within clouds. There is a need to be able to relate these properties to characteristics that can be measured by in-situ sampling, e.g. the measurements of size, cross-sectional area and edge roughness that are available from imaging probes such as the OAP or CPI.

3. Measurement methods

a) Basic techniques

Darrel Baumgardner (UNAM, Mexico City) gave a review of current and near-future measurement methods and instrumentation.

Impactor/replicator devices such as the Video Ice Particle Sampler (VIPS) or DRI (Desert Research Institute) Cloudscope remain robust and useful instruments for some purposes. They have obvious drawbacks with size-dependent collection efficiency and the shattering of large and/or fragile particles.

Hot-wire probes are used for the bulk measurement of liquid (JW, King, Nevzorov) and ice (Nevzorov) water contents. They suffer from collection efficiency uncertainties for particles smaller than about 5μm and for the LWC sensors, a roll-off in response for droplets larger than about 40μm due to incomplete evaporation and splashing. The maximum LWC that can be measured is limited by the power supply available to the wire and has not been adequate to measure high LWC in tropical convective systems. They also require an accurate knowledge of the local true airspeed (TAS) at the sensor position.

The Counterflow Virtual Impactor (CVI) is a device for sampling particles larger than some specified size after exclusion of the ambient air. Measurements of water vapour thus provide a measure of the LWC or IWC of the accepted particle size range and by an assumption of one aerosol residue to one original cloud particle, the counting of residue particles can provide a measurement of total particle concentration. This device remains a key to understanding those chemical components of the aerosol that are incorporated into cloud particles.

The Rosemount Icing Detector (RICE) is an electrically-excited vibrating rod that projects laterally into the cloudy airstream. Supercooled liquid accretes on the rod, changing its vibration frequency, this appearing as a change in the voltage output of the instrument. Whilst there are concerns about its collection efficiency for droplets smaller than 10μm and the ability of accreted ice to be cleared at temperatures colder than -20C, this device is considered to be a good detector of the presence of supercooled liquid water (Cober *et al.* 2001).

The Forward Scattering Spectrometer Probe (FSSP) in versions manufactured by Particle Measuring Systems Inc. (PMS, now Particle Metrics Inc.) and modified by various user groups is an example of single particle measurement by means of light-scattering techniques. It is a very common method of measurement of the droplet size spectrum in liquid clouds. It has been the subject of numerous studies to identify the causes of uncertainty in its depth of field and beamwidth. Loss of counts due to instrument dead-time has been greatly reduced by the development of faster electronics as used in the so-called Fast FSSP variants (Brenguier et al., 1998) or commercially available electronics upgrade packages.

The OAP in various forms is an example of single particle measurements using shadowing of a photodiode array. This is in common usage for the measurement of particles larger than about 100μm. It has limitations due to the limited pixel resolution for smaller particles, uncertainties in depth of field and the impact of photodetector response time on particle detection and sizing. Derivation of IWC by integration requires the use of largely empirical factors relating various linear or shadow area measurements to individual particle mass.

The SPEC (Stratton Park Engineering Company, Inc.) Cloud Particle Imager (CPI) is a relatively new device providing much higher resolution digital images of cloud particles. It uses a crossed-laser particle detection system to trigger an imaging event. Derivation of ice particle mass follows the same approach as for the OAP, albeit with higher quality images. Estimation of the sample volume has so far relied on scaling measured size spectra against OAP measurements although other techniques are being developed by the manufacturers.

The Particle Volume Meter, PVM-100 (Gerber Scientific Inc.), is an example of measurement of bulk microphysical quantities using light scattering from an ensemble of particles. The probe has two different detectors which are masked by filters of different transmissions to produce signals which are functions of LWC and total cross-sectional area. The former divided by the latter is proportional to the droplet effective radius. Chief uncertainties in the probe output are its sample volume, which can be a function of the droplet number concentration and size, and a roll-off in response when a significant fraction of the LWC is in droplets larger than about 30μm. Its chief advantage is its very high frequency response, up to 1000 Hz, making it a good instrument for the study of fine-scale entrainment processes.

Biagio Esposito (CIRA) then described the principle of the Phase-Doppler Particle Analyzer (PDPA) (Bachalo and Houser 1984). Two crossed laser beams define the sample volume. Interference between the two beams creates a fringe pattern within this volume. As a particle passes through the sample volume, it scatters light and projects the fringe pattern. The receiving optics and photodetector are located off-axis. The detector produces a Doppler signal with a frequency proportional to the particle velocity. The phase shift between signals from two different detectors is proportional to the size of the spherical particles. The device has been extensively used in wind-tunnel and other laboratory environments and is now available in an airborne version, one of which will be carried on the FAAM BAe146 aircraft in the UK.

The PDPA has the advantage that its particle size measurement is only a function of the laser wavelength and optical configuration and are independent of beam intensity. The response of the probes to non-spherical droplets and ice crystals in natural clouds has not been established. Comparisons of wind-tunnel LWC measurements from PDPA and icing cylinders have been performed. Examples of preliminary comparisons of PDPA and FSSP measurements in clouds at the Jungfraujoch obtained from Martin Gallagher (UMIST, UK) were shown. Whilst there is good agreement in the case of monomodal spectra, the larger size mode of bimodal spectra appears to be undersized by the FSSP, when compared to the PDPA.

Paul Field (Met Office) described the Small Ice Detector (SID) developed at University of Hertfordshire (UK). This has 6 detectors disposed around a laser beam at a scattering angle of approximately 30 degrees. One detector is stopped down to provide an optically-limited sample volume. Spherical particles in the centre of the sample volume scatter light equally onto the other 5 detectors whereas aspherical particles (assumed to be ice) generate varying signals. High asphericity values can be associated with large droplets on the edge of the sample volume so it is not currently possible to use a simple threshold value of asphericity to classify single particle events as spherical (water) or non-spherical (ice).

b) Current and future developments

Devices are now available that incorporate combinations of the basic functionalities described above. For example, the Cloud, Aerosol and Precipitation Spectrometer (CAPS), developed by Droplet Measurement Technologies (DMT), is a new probe that combines the features of the fast FSSP, OAP, and hot-wire LWC sensor into a single package, along with an airspeed sensor at the point of measurement. The single particle scattering section measures backward as well as forward scattered light. This feature may be used to discriminate between spherical and aspherical particles. The DMT Integrated System for Icing Studies (ISIS) combines in one package the functions of FSSP, OAP, liquid and total water hot-wire probes and RICE, in addition to pressure, temperature and airspeed sensors. Another combination instrument under development in collaboration between Cynthia Twohy (Oregon State University) and DMT will include CVI and FSSP functions in a standard PMS canister. This will enable CVI measurements to be made on a wider range of aircraft and with a reduced need for user intervention.

DMT are developing a re-packaged version of the FSSP functionality, with a smaller external sensor head incorporating laser and detector and an internally mounted electronics package. The reduced external profile may enable droplet spectrum measurements to be made at a wider range of locations on an aircraft, and enable the validation of CFD calculations of flow-induced measurement distortions.

The Cloud Integrating Nephelometer, CIN (Gerber Scientific Inc.), is a relatively new instrument that approximates the asymmetry parameter, volume cattering coefficient and backscatter ratio in clouds. This instrument measures the light scattering from an ensemble of particles with four detectors placed at forward and back angles. One set of forward and backscatter detectors have cosine masks to approximate the cosine function needed to approximate the asymmetry factor. This instrument has been flown on at least two research aircraft but is still under evaluation.

Thierry Perrin (Meteo France) described a new droplet size spectrometer under development by Meteo-France. The X-probe uses 2 laser beams intersecting at an angle of 60 degrees for better definition of sample volume. Each beam has a forward scattering detector (7.5-15 deg. collection). There is an additional detector (22.5-37.5 deg. collection angle) receiving light scattered from both beams. The use of two different scattering angles enables the probe to cover the size range 0.1 to 50μm diameter in 1023 bins.

SPEC are developing an advanced version of the OAP, referred to as the 2D-S. This has two separate laser beam and photodetector systems with intersecting beam paths to provide an unambiguous sample volume for sub-100μm particles. High-speed detectors will alleviate some problems of particle undersizing that occur with standard 2D-C probes.

4. Operational, calibration and software issues

Alexei Korolev (MSC) discussed the impact of ice particles on hot-wire LWC sensors. Mechanisms for the spurious signal includes ice particles partially melting on or fragments sticking to the hot wire. In wind-tunnel tests, King and Nevzorov LWC sensors show a residual response when the spray is frozen. Similar results are seen in flight data when RICE indicates an absence of supercooled water (no change in output voltage). In flight tests at 100 ms^{-1}, the LWC response is around 10% of the measured IWC, with higher values indicated at higher airspeeds. Other factors influencing the residual signal are the shape and roughness of the sensor wire and the air temperature. If the fraction, β, of the IWC measured by the LWC sensor in fully ice cloud is known, true values of IWC and LWC measured by a Nevzorov probe may be determined. β is required to be known for each individual probe/installation.

The frequency response and high-LWC saturation of hot-wire probes were discussed. Tests indicate that the true response of constant temperature devices such as King and Nevzorov LWC is better than 1Hz. These probes saturate at around 2 g m^{-3}, dependent on the thickness of the enamel coating of the hot wire. The latter determines the maximum rate of heat transfer available to evaporate water. . Science Engineering Associates has developed a version of the Johnson-Williams hot-wire LWC for the Meteorological Service of Canada that will operate at constant temperature (rather than constant current) and be capable of measuring up to 5 g m^{-3}. Both cylindrical LWC sensors and half-cylinder TWC sensors are available.

George Isaac (MSC) and Dean Miller (NASA) showed examples of high-speed video imagery from icing wind tunnel experiments. These showed the effects of re-freezing of liquid water running back from a heated wing leading edge, ice particles fragmenting and rebounding from an unheated wing, and particles bouncing or splashing from a deiced wing in a mixed phase supercooled cloud (water spray plus shaved ice).

Jean-Louis Brenguier (Meteo France) described some general properties of particle-counting devices such as the FSSP and how to use measurements of activity and total strobes to improve measurements of concentration and describe cloud inhomogeneity (Brenguier and Amodei, 1989; Brenguier, 1989; Brenguier et al., 1993, 1994). He also described a method of using the sizing ambiguity cause by resonances in the Mie scattering curve to improve size calibation (Brenguier et al. , 1998) in the FastFSSP. With 255 size channels available, particles with diameters in the region where the resonance peaks occur (2-20μm) are counted preferentially into certain size bins. If the collection angle of the receiving optics is accurately determined, the expected bins which will exhibit mode counts may be determined from theory, providing a potential absolute size calibration for the probe. Finally he discussed measurements at the cm scale using inter-arrival time data provided by the Fast-FSSP for each detected particle (Brenguier, 1993; Brenguier and Chaumat, 2001, Chaumat and Brenguier, 2001), and how small scale fluctuations of droplet concentration can be derived by optimal estimation (Pawlowska et al., 1997).

Frederic Burnet (Meteo France) described some comparisons of Fast and standard FSSPs (Burnet and Brenguier, 1999). Uncertainties due to the size calibration, the pulse duration selection and variations of the sample cross-section (depth-of-field × beamwidth) were shown. The effect of droplet coincidence on measurements was also discussed. Correction of droplet concentration is possible by using appropriate procedures, but the broadening of the spectra toward larger sizes can not be corrected except by a statistical procedure described by (Cooper 1988). This leads to a significant overestimation of the derived LWC at high droplet concentration.

Walter Strapp pointed out the the effect of FSSP coincidence-oversizing is particularily acute in wind tunnels, where droplet concentrations are typically higher than in natural clouds. Strapp showed data from some NASA IRT testing that suggested that the PDPA did not suffer from such coincidence oversizing problems.

Paul Field (Met Office) showed measurements of particle inter-arrival times from a FastFSSP in ice and mixed-phase clouds. Measurements in ice show a bimodal distribution. Statistical analyses of the data have been conducted to determine whether this results from a real clustering of ice particles in the atmosphere or is the result of the breakup of large ice particles on the probe structure ahead of the sample volume.

Dagmar Nagel (GKSS) described work on the development of laboratory calibration devices for PMS probes. A monodisperse droplet generator is being developed that can be used with an optical spectrometer to determine the accuracy of sizing droplets anywhere within the probe sample volume. Since the droplet velocity through the beam is only 2 ms^{-1} this cannot reproduce the effects of detector response time at typical aircraft speeds. For this purpose a spinning disk carrying a small fibre has been developed. Creation of a removal panel in the side of the FSSP sample tube enables this test device to be used with the probe mounted on the aircraft in the field. This can be used to calibrate changes in the depth of field and particle sizing that are dependent on particle velocity and also to identify optical alignment errors.

Alexei Korolev (MSC) reviewed the response of 2D OAPs to drizzle drops. He illustrated the effects of diffraction and detector response time on the images that are produced of spherical drops. It is possible to derive correction matrices to derive a true particle size spectrum from a measured one. However, since the characteristics of individual probes (or even individual elements of the photodetector array) may vary significantly, each probe requires a detailed laboratory characterization before such correction techniques may be implemented.

Alexei Korolev also reviewed the derivation of particle size and mass from OAP imagery. OAP IWC derived using power law representations in the form $M = a D^b$ was shown to compare well with bulk values obtained from a Nevzorov probe when the exponent b = 1.9 was used. However, it was found that the prefactor, a, commonly varied between flights or cloud regions within the range $4 \pm 1 \times 10^{-11}$ giving IWC values about half of those calculated by the method of (Brown and Francis 1995). He showed examples of 2D-C size spectra where use of the technique of (Heymsfield and Parrish 1978) to reconstruct incomplete droplet images apparently gave good results when applied to irregular ice crystal images. It was emphasised that such usage requires careful validation against (for example) coincident radar reflectivity measurements. David Rogers (NCAR) showed data from the recent CRYSTAL-FACE campaign demonstrating good agreement in IWC measurements from a 2D-C and a CVI probe.

David Rogers (NCAR) showed examples of spurious signals generated in clear air in an OAP-260X (1d OAP) by electromagnetic interference. The spurious data were not corroborated by measurements from any other probe and were removed after careful attention to cable shielding within the probe. Dagmar Nagel (GKSS) described a similar impact on a 2D-C probe where image quality and spurious data were reduced after attention to crosstalk between signal and power cables.

5. Review of progress in aircraft microphysical measurements

It is appropriate to review areas where significant progress has been made since the 1988 aircraft instrumentation workshop held at NCAR (Cooper and Baumgardner 1989). Noting particularly the section on needs and opportunities for new instruments:

- Airborne versions of continuous-flow ice nucleus counters are now in use (Rogers *et al.* 2001).
- Two new instruments capable of counting ice crystals at much smaller sizes than detectable in OAP images are now in use, SID (Hirst *et al.* 2001) and CPI (Lawson *et al.* 1998) although both of these rely on non-sphericity to define ice particle counting events or images.
- Independent measurements of the bulk IWC have been developed using either hot-wire probes such as the Nevzorov (Korolev *et al.* 1998b) or evaporative techniques (Brown and Francis 1995; Noone *et al.* 1993; Strom and Heintzenberg 1994; Twohy *et al.* 1997).
- Instruments have been developed and used to measure directly important optical characteristics of the particle size spectrum such as extinction, scattering phase function (the PI-nephelometer, (Gayet *et al.* 1994) and asymmetry parameter (the Cloud Integrating Nephelometer, Gerber *et al.* 2000).
- Theoretical and laboratory studies have led to the development of more advanced correction algorithms for 2D OAPs. These are applicable after laboratory characterisation of individual probes (Baumgardner and Korolev 1997; Jensen and Granek 2002; Korolev *et al.* 1998a; Strapp *et al.* 2001).
- There have similarly been further advances in the understanding of the limitations and measurement accuracy of the FSSP and the operational methods required to achieve optimum data quality (Brenguier *et al.* 1993; Brenguier *et al.* 1994; Lock and Hovenac 1989a; Lock and Hovenac 1989b).
- The Low-Turbulence Inlet has been developed to improve the sampling of large aerosol particles.
- The FastFSSP has observed significantly narrower droplet spectra in near-adiabatic cloud cores than those obtained by standard FSSPs (Brenguier *et al.* 1998).
- Intercomparisons have helped to establish the accuracy obtainable from a range of probes, e.g. (Burnet and Brenguier 1999; Gayet *et al.* 1993; Wendisch 1998)

Areas where current measurement capabilities remain deficient include:

- Ice/liquid mass partitioning in mixed phase cloud. Individual Nevzorov probes require characterisation of the sensitivity of their LWC sensors to ice. The Nevzorov TWC has a relatively small sample cross-section for the collection of particles larger than ~1mm.
- Lack of standards for calibration of IWC measurements in wind tunnels and their inability to generate ice particles with characteristics representative of those found in the atmosphere.
- Underestimation of the total hydrometeor mass due to the large particle roll-off of hot-wire probes and the low sample volume of OAPs for particles approaching the detector array width.
- Size distribution of ice water mass depends on use of size-mass relationships applied to measured particle images (OAP or CPI). Validity of the choice of relationship must be checked against bulk IWC measurement or other bulk parameter such as radar reflectivity.
- Estimation of droplet MVD for aircraft icing studies is still insufficiently accurate due to measurement uncertainties in the 50-100 μm size range.
- King and Nevzorov sensors are easily damaged by impact with large, dense ice particles (graupel or small hail).

- Whilst particle size measurements may be calibrated by means of glass beads, fibres etc., there is a lack of a calibration standard for particle concentration. Such measurements still depend on careful measurement of the instrument sample volume (shown to be variable in a dynamic environment rather than the static laboratory measurements normally performed) and an understanding of uncertainties generated by coincidence etc.
- Characterisation of the sample volume of the CPI (although significant work is underway to address this issue).
- Airborne IN counters may fail to reproduce modes of activation which operate in natural clouds.
- Improvements are still required in the measurement of in-cloud temperature, humidity and wind velocity to support microphysical process studies.

6. Recommendations

Discussions following the presentation periods resulted in the following list of recommendations.

For instrumentation operators and developers:

a) The protection of optoelectronic probes against electromagnetic interference requires checking at all altitudes.
b) Sample disturbance due to the airflow around a probe remains a significant issue. Developers of new probes are encouraged as far as possible to adopt non-intrusive designs for new devices, for example avoidance of the use of sample intake tubes.
c) The use of wind tunnel facilities with high-speed imaging capabilities is encouraged as a means of examining sample disturbance and the behaviour of ice particles interacting with existing measurement devices, in particular the FSSP.
d) The PDPA probe may offer distinct advantages over conventional droplet measurement devices such as the FSSP, particularly in high concentration cases such as commonly observed in wind tunnels. Comparisons with conventional instruments should be undertaken in wind tunnels and on airborne platforms. This is of particular importance to the aircraft icing community, which has characterized the natural environment using aircraft with conventional instrumentation, and produces ice shapes for performance degradation estimation in wind tunnels that are calibrated with different suites of instruments (e.g. PDPA).
e) A more accurate characterization of the droplet spectrum in the 50-100 μm size range is still required for proper MVD estimation, and further instrumentation development to this end is encouraged,
f) The Rosemount Icing Detector is considered to be the most reliable detector of supercooled liquid water in clouds and its wider usage is encouraged.
g) Independent testing of new instruments outside the manufacturer's facility is highly desirable to maximize confidence in the data. It is necessary to maintain a two-way dialogue between manufacturers and users in the development and testing of new instruments.
h) There needs to be clear definition and documentation of the calibration procedures applied to airborne probes. The development of such procedures should aim to provide a recognizable quality standard for users of data outside the research community and for instrument manufacturers and developers. There is a need to establish that calibration methods are fully traceable, particularly for data users in the aircraft icing community.
i) The design and operation of a probe should provide sufficient housekeeping data to continuously monitor all aspects of the probe performance.
j) The use of modified electronics for FSSP probes, able to classify particle counts into ~255 size bins, is encouraged. This enables the adoption of near real-time methods of checking the size calibration of the probe.
k) Where it is possible to do so, a new instrument and its installation should be designed to minimize interference with the sample air. Installation design should make use of airflow calculations to assess the impact of aircraft flow fields on particle distributions. Instrument design should minimize the amount of structure upstream of the sample volume.

For data users:

l) There should be continued dialogue with the aircraft instrument operators for the communication of new measurement requirements and the development of specifications of measurement accuracy.
m) Any databases of aircraft microphysical data or publications based on such data should report all relevant details of post-flight data processing that are applied. This will include, for example, algorithms used to determine particle size from imaging probes, size-mass and size-fallspeed relationships, correction procedures applied to correct known systematic biases, the averaging period used, and the way any cloud-free periods are treated.

For funding agencies:

n) The provision of funding to provide flying time dedicated to the testing and intercomparison of new or modified instruments is very beneficial (for example, the NCAR IDEAS programme). Such funding could also provide coordinated access of groups of instruments to wind tunnels for testing and intercomparison purposes.
o) There should be ongoing funding available for workshops focussed on specific instrumentation issues.
p) Consideration should be given to the establishment of a small number of centres of excellence in the calibration of airborne microphysics probes. Such centres would require the provision of long-term funding in order to maintain a core of experienced staff.
q) There is a need to continue the development of calibration standards for airborne probes that can be transferred between the laboratory and a probe mounted on an aircraft in the field. The GKSS spinning fibre device is a good example of such equipment.
r) There is a need for laboratory studies of the freezing of water droplets or deliquesced aerosol particles and their subsequent growth. This will help to establish whether asphericity alone is a sufficient criterion by which to classify a particle as an ice crystal.
s) There should be a more rapid dissemination of news and information concerning instrumentation developments, calibration issues etc. Whilst the EUFAR website is a good vehicle for carrying the information, a mailing list should be established to alert interested parties of the availability of new information. The website should provide links to other with interests in aircraft instrumentation (such as the US HIAPER programme).

Attendees

The full list of attendees for microphysics component of the workshop was:

Table 1

Philip	Brown	Met Office, UK	phil.brown@metoffice.com
Paul	Field	Met Office, UK	paul.field@metoffice.com
Biagio	Esposito	CIRA, Experimental Aerodynamics Laboratories	b.esposito@cira.it
Martin	Gallagher	UMIST, UK	martin.gallagher@umist.ac.uk
Dagmar	Nagel	GKSS Forschungszentrum, Germany	dagmar.nagel@gkss.de
Uwe	Maixner	GKSS Forschungszentrum, Germany	uwe.maixner@gkss.de
Jean-Louis	Brenguier	CNRM, Meteo-France	jean-louis.brenguier@meteo.fr
Thierry	Perrin	CNRM, Meteo-France	thierry.perrin@meteo.fr
Frederic	Burnet	CNRM, Meteo-France	burnet@cnrm.meteo.fr
Walter	Strapp	Meteorological Service of Canada	walter.strapp@ec.gc.ca
George	Isaac	Meteorological Service of Canada	george.isaac@ec.gc.ca
Alexei	Korolev	Meteorological Service of Canada	alexei.korolev@ec.gc.ca
Jeff	Stith	NCAR / RAF	stith@ucar.edu
David	Rogers	NCAR / RAF	dcrogers@ucar.edu
Darrel	Baumgardner	UNAM, Mexico City	darrel@servidor.unam.mx
Christophe	Duroure	LAMP, Clermont-Ferrand, France	C.Duroure@opgc.univ-bpclermont.fr
Oscar	Serrano Vargas	INTA, Spain	serranovo@inta.es
Mario	Massucci	British Antarctic Survey	m.massucci@bas.ac.uk
Tom	Lachlan-Cope	British Antarctic Survey	tlc@bas.ac.uk
Dean	Miller	NASA Glenn Research Center	Dean.R.Miller@grc.nasa.gov

REFERENCES

Bachalo, W. D. and M. J. Houser, 1984: Phase Doppler Spray Analyzer for Simultaneous Measurements of Drop Size and Velocity Distributions. Optical Engineering, **23**, 583-590.

Baumgardner, D. and A. Korolev, 1997: Airspeed corrections for optical array probe sample volumes. Journal of Atmospheric and Oceanic Technology, **14**, 1224-1229.

Brenguier, J. L., and L. Amodei, 1989: Coincidence and dead-time corrections for the particle counters. Part I: A general mathematical formalism, *J. Atmos. Oceanic. Technol*., 6, 575-584.

Brenguier, J. L., 1989: Coincidence and dead-time corrections for the particle counters. Part II: High concentration measurements with an FSSP, *J. Atmos. Oceanic. Technol.*, 6, 585-598.

Brenguier, J. L., A. R. Rodi, G. Gordon, and P. Wechsler, 1993: Real-Time Detection of Performance Degradation of the Forward- Scattering Spectrometer Probe. Journal of Atmospheric and Oceanic Technology, **10**, 27-33.

Brenguier, J. L., 1993: Observations of cloud microstructure at the centimeter scale. *J. Appl. Meteor.*, 32, 783-793.

Brenguier, J. L., D. Baumgardner, and B. Baker, 1994: A Review and Discussion of Processing Algorithms for Fssp Concentration Measurements. Journal of Atmospheric and Oceanic Technology, **11**, 1409-1414.

Brenguier, J. L., T. Bourrianne, A. D. Coelho, J. Isbert, R. Peytavi, D. Trevarin, and P. Weschler, 1998: Improvements of droplet size distribution measurements with the Fast-FSSP (Forward Scattering Spectrometer Probe). Journal of Atmospheric and Oceanic Technology, **15**, 1077-1090.

Brenguier, J. L., and L. Chaumat, 2001: Droplet spectra broadening in cumulus clouds. Part I: Broadening in adiabatic cores. *J. Atmos. Sci. .* 58, 628-641.

Brown, P. R. A. and P. N. Francis, 1995: Improved Measurements of the Ice Water-Content in Cirrus Using A Total-Water Probe. Journal of Atmospheric and Oceanic Technology, **12**, 410-414.

Burnet, F. and J. L. Brenguier, 1999: Validation of droplet spectra and liquid water content measurements. Physics and Chemistry of the Earth Part B-Hydrology Oceans and Atmosphere, **24**, 249-254.

Chaumat , L., and J. L. Brenguier, 2001: Droplet spectra broadening in cumulus clouds. Part II: Micro-scale droplet concentration heterogeneities. *J. Atmos. Sci. .* 58, 642-654.

Cober, S. G., G. A. Isaac, and A. V. Korolev, 2001: Assessing the Rosemount Icing Detector with in situ measurements. Journal of Atmospheric and Oceanic Technology, **18**, 515-528.

Cooper, W. A., 1988: Effects of Coincidence on Measurements with a Forward Scattering Spectrometer Probe. Journal of Atmospheric and Oceanic Technology, **5, #6,** 823-832.

Cooper, W. A. and D. Baumgardner, 1989: Meeting Review: Workshop on Airborne Instrumentation 19-21 October 1988. NCAR Technical Note NCAR/TN-330,

Gayet, J. F., P. R. A. Brown, and F. Albers, 1993: A Comparison of In-Cloud Measurements Obtained with 6 Pms 2D-C Probes. Journal of Atmospheric and Oceanic Technology, **10**, 180-194.

Gayet, J. F., O. Crepel, J. F. Fournol, and S. Oschepkov, 1994: A new airborne polar nephelometer for the measurements of optical and microphysical cloud properties. Part I. Theoretical design. Part II. Preliminary tests. Annales Geophysicae, **15**, 451-470.

Gerber, H., Y. Takano, T. J. Garrett, and P. V. Hobbs, 2000: Nephelometer measurements of the asymmetry parameter, volume extinction coefficient, and backscatter ratio in Arctic clouds. Journal of the Atmospheric Sciences, **57**, 3021-3034.

Heymsfield, A. J. and J. L. Parrish, 1978: A computational technique for increasing the effective sampling volume of the PMS two-dimensional particle size spectrometer. Journal of Applied Meteorology, **17**, 1566-1572.

Hirst, E., P. H. Kaye, R. S. Greenaway, P. Field, and D. W. Johnson, 2001: Discrimination of micrometre-sized ice and super-cooled droplets in mixed-phase cloud. Atmospheric Environment, **35**, 33-47.

Jensen, J. B. and H. Granek, 2002: Optoelectronic simulation of the PMS 260X optical array probe and application to drizzle in a marine stratocumulus. Journal of Atmospheric and Oceanic Technology, **19**, 568-585.

Korolev, A. V., J. W. Strapp, and G. A. Isaac, 1998a: Evaluation of the accuracy of PMS Optical Array Probes. Journal of Atmospheric and Oceanic Technology, **15**, 708-720.

Korolev, A. V., J. W. Strapp, G. A. Isaac, and A. N. Nevzorov, 1998b: The Nevzorov airborne hot-wire LWC-TWC probe: Principle of operation and performance characteristics. Journal of Atmospheric and Oceanic Technology, **15**, 1495-1510.

Lawson, R. P., A. V. Korolev, S. G. Cober, T. Huang, J. W. Strapp, and G. A. Isaac, 1998: Improved measurements of the drop size distribution of a freezing drizzle event. Atmospheric Research, **48**, 181-191.

Lock, J. A. and E. A. Hovenac, 1989a: A Correction Algorithm for Particle-Size Distribution Measurements Made with the Forward-Scattering Spectrometer Probe. Review of Scientific Instruments, **60**, 1154-1160.

Lock, J. A. and E. A. Hovenac, 1989b: An Improved Correction Algorithm for Number Density-Measurements Made with the Forward-Scattering-Spectrometer- Probe. Review of Scientific Instruments, **60**, 1143-1153.

Noone, K. B., K. J. Noone, J. Heintzenberg, J. Strom, and J. A. Ogren, 1993: In-Situ Observations of Cirrus Cloud Microphysical Properties Using the Counterflow Virtual Impactor. Journal of Atmospheric and Oceanic Technology, **10**, 294-303.

Pawlowska, H., J. L. Brenguier and G. Salut, 1997: Optimal non-linear estimation for cloud particle measurements. *J. Atmos. Oceanic Technol.*., 14, 88-104.

Rogers, D. C., P. J. Demott, S. M. Kreidenweis, and Y. L. Chen, 2001: A continuous-flow diffusion chamber for airborne measurements of ice nuclei. Journal of Atmospheric and Oceanic Technology, **18**, 725-741.

Strapp, J. W., F. Albers, A. Reuter, A. V. Korolev, U. Maixner, E. Rashke, and Z. Vukovic, 2001: Laboratory measurements of the response of a PMS OAP-2DC. Journal of Atmospheric and Oceanic Technology, **18**, 1150-1170.

Strom, J. and J. Heintzenberg, 1994: Water vapor, condensed water, and crystal concentration in orographically influenced cirrus clouds. Journal of the Atmospheric Sciences, **51**, 2368-2383.

Twohy, C. H., A. J. Schanot, and W. A. Cooper, 1997: Measurement of condensed water content in liquid and ice clouds using an airborne counterflow virtual impactor. Journal of Atmospheric and Oceanic Technology, **14**, 197-202.

Wendisch, M., 1998: A quantitative comparison of ground-based FSSP and PVM measurements. Journal of Atmospheric and Oceanic Technology, **15**, 887-900.