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IN SITU MEASUREMENTS OF CLOUD AND AEROSOL PROPERTIES RELEVANT TO PRECIPITATION AUGMENTATION

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Cloud and precipitation studies in the atmosphere continue to have a very strong empirical component. In-situ observations from aircraft are indispensable for documenting the composition of clouds and thereby providing diagnoses of the processes within them. The importance of such observations is well demonstrated by the progress they helped to make over the last 30-40 years. Advances were quite spectacular over this period both in aircraft capabilities and in the instrumentation carried by them . Cloud physicists became very adept at combining the in-situ observations with data from ground-based remote sensors (radars, lidars, etc.), and to integrate the measurements with numerical models.

In the field of weather modification, the measurements needed are fundamentally the same as in the broader research context, but there are also requirements for more specialized tasks such as the diagnosis of suitable seeding opportunities and the monitoring of seeding effects. These tasks are often undertaken with relatively simple instrumentation in order to limit costs.

The aim of this paper is to provide an overview of the current state of development of aircraft instruments for the observation of cloud and aerosol properties. The principal focus is on the initiation and growth of precipitation and on the air motions that accompany them in clouds, as those are the most important factors in determining precipitation enhancement potential. Priority is given to instruments of proven performance; it is not the purpose of this paper to review the newest developments, nor to discuss instruments of specialized research applications. There will be no discussion of the types of aircraft used; neither will other related uses of aircraft be considered such as flux measurements, the dispersion of cloud seeding materials, photogrammetry, aerosol and cloud chemistry, the radiative properties of clouds, etc. In keeping with the survey nature of the paper, none of the topics are discussed in great detail. Emphasis is on the results obtainable, not on the technical aspects of the developments. The material included in the paper is a somewhat subjective collection.

Air temperature.

The measurement of temperature in cloud-free air is a relatively straightforward problem as long as no excessive demands are placed on the time-response of the measurement. The only problems to resolve, beyond the factors normally encountered in meteorological temperature measurements, are how to correct for aerodynamic heating and how to protect the sensing element from physical damage. In practice these problems become linked since the housing used to protect the sensor influences the correction needed to account for the aerodynamic heating. Based on wind-tunnel experiments and on flight tests, an acceptable solution is to apply a fraction, ***r***, of the theoretical heating effect which is calculated for an adiabatic compression of air at the velocity of the aircraft. The numerical value of ***r***, called the recovery factor, is dependent on the housing design (e.g. Veal et al., 1978). With the instruments most frequently used, the Rosemount and reverse-flow probes, measurements with 0.55C absolute accuracy, 0.0055C relative precision and about 1...10 m spatial resolution (depending on the housing design and airspeed) are possible.

For measurements inside clouds, and especially for considering complex cloud processes, the requirements placed on temperature measurements become much more stringent. The most widely used instruments mentioned above are not fully satisfactory in this regard, though the problems are of importance only when precise calculations of thermodynamic parameters is needed. Two limitations exist: the wetting of the sensor and the slowness of response. Unfortunately, solutions for one of these problems tends to worsen the other.

Sensor wetting can be a serious problem, since the cooling effect of evaporation (in subsaturated air) can amount to several 5C. The reverse flow housing (Rodi and Spyers-Duran, 1972), which is in use on most cloud physics aircraft, directs airflow to the temperature sensor in such a way that cloud elements are separated from it. The Rosemount 102 thermometer also has some, but much less complete separation of cloud elements. Even so, investigations revealed that these thermometers can become wet in clouds with high liquid water contents (Lawson and Cooper, 1990). There appears to be no problem in supercooled clouds, since water then freezes onto the probe housing rather than flowing on its surface and getting blown onto the sensor element by turbulence. There is no full solution to wetting; even recent attempts (Lawson and Rodi, 1992; Haman, 1992) show only partial success. It is therefore, important to be aware of the problem and recognize its symptoms when analyzing temperature data from cloud penetrations.

A non-contact approach to temperature measurements in clouds was suggested by Nelson (1982) and tested by Lawson and Cooper (1990). This device is a short-path radiometric detector of emissions from CO_2 at 4.255 m wavelength. Since this instrument has no parts directly exposed to the airstream, the only possible wetting problem is that of the windows and this can be prevented. The large volume from which the signal is derived provides some immunity from small-scale perturbations. The radiometer is also free of the uncertainties associated with determinations of the recovery coefficients of immersion sensors, and it has a response time which is only limited by electronics, rather than by airflow considerations. The major drawback of this device is its cost. Also, some further tests and calibration will be needed.

Humidity.

The simple assumption that within clouds the humidity is 100% is a reasonable one for dense clouds and for averages over some distance. However, for examinations of fine-scale structure and of phenomena at cloud boundaries, plus the need for accurate measurements in the surroundings of clouds, including the inflow, necessitate humidity measurements of good accuracy and rapid response. The currently available instruments do not fully satisfy these needs.

The chilled-mirror type dew-point instrument, most widely used on research aircraft today, provides reasonably good data in clear air, but it has slow response (order of seconds), and is only accurate to perhaps +15C. It is not reliable within clouds and the solution usually adopted is to accept the assumption of 100% humidity for periods when the aircraft is in cloud, based on an independent indication by droplet probes or other means.

The only alternative to the chilled-mirror instruments that has been tested in recent years is the Lyman-alpha hygrometer, which measures the absorption of light (at the Lyman-alpha wavelength) through a known path-length of the order of centimeter. Instruments of this type have been now installed on several aircraft, and are operational; the major problems still not fully resolved are the stability and calibration of the device. Some of the causes of these problems have been recently identified (Eloranta et al., 1989; Lind and Shaw, 1991) so it may be hoped that remedies will be soon forthcoming. A dual-path version of the device, in which a continuous reference reading is also taken, is now under development.

Relative humidity sensors that use hygroscopic coatings or physical size changes, or capacitance as the measurement principle have not proven to be useful for aircraft applications because of their slow response, unstable calibration and sensitivity to interference by environmental factors.

Water and ice mass measurements.

The mass concentration of condensed water ("liquid water content, LWC" , "ice water content, IWC" and "total water content, TWC") is the most fundamental, but in itself insufficient, parameter that influences precipitation development and the potential for precipitation enhancement. Yet, it is still a difficult parameter to observe with accuracies better than several tens of percent. The major difficulties arise from the need that the instruments respond to a large range of sizes of particles, that they have large sampling rates, that they measure mass concentration over a range of more than two orders of magnitude (from near 0.02 g m^{-3} to above 4 g m^{-3}) and that they have rapid response times. The particle counting and sizing instruments, to be discussed in following sections, can also be used to obtain integral mass concentrations. This is, however, an inherently imprecise approach, because of the third power of size which enters the calculation, and because, for ice particles, there is the additional variable of density. Also, the sampling rates of the spectrometers are at best marginal for sampling the larger particles which contribute much of the total water content.

<u>Cloud droplets.</u>

Strictly speaking LWC should include the mass of all liquid hydrometeors. In practice, LWC is often used to refer to the mass concentration of cloud droplets (< 50 m diameter). This usage is justified to some degree by the fact that cloud droplets usually contribute more to the total mass than drizzle drops or raindrops. Nonetheless, it is important to state clearly what is meant in cases where there is the possibility of ambiguity.

The two most widely used instruments (Johnson-Williams, JW[1], and CSIRO-King[2] probes) obtain a measurement of LWC from the cooling effect of cloud droplets impinging on a heated sensor element that is exposed to the airflow outside the aircraft. A third version is described by Nevzorov (1980) and Korolev et al. (1996b). The Johnson-Williams probe references the sensor element to another element that is cooled by the air but is not exposed to cloud droplets. The main features of the CSIRO-King probe are: the temperature of the sensor is kept constant (at about 1605C), buffer coils protect the sensor from heat loss to the supporting structure, and the power needed to maintain the sensor temperature constant in spite of cooling by the droplets is the measure of the LWC. The cooling due to the air alone is predicted from heat-transfer equations and is set using measurements taken in clear air (free of cloud). The Nevzorov probe uses a reference element that is not exposed to cloud and the active element is compensated (using AC) for the power needed to keep the elements at constant temperature; the additional power needed to react to cooling by cloud droplets is measured by a separate DC signal. All these instruments have detection limits of about 0.02 g m^{-3}, and have decreasing detection efficiencies for droplets above about 30 m diameter for the JW, and above about 60 m for the CSIRO-King and Nevzorov probes. This limitation is due to the increasing probabilities that larger droplets disintegrate on impact, and that some of their mass gets blown off the sensor prior to full evaporation. The CSIRO and Nevzorov probes can provide measurements up to about 10 Hz frequency.

In laboratory wind-tunnel tests, reported by King et al. (1985) and by Biter et al. (1987), the CSIRO probe was shown to be capable of providing better than 10% accuracy for a large range of drop sizes. It is still somewhat of an open question, whether similar accuracies can be achieved in field use of the probe; the comparisons of Baumgardner (1983) and of Gerber et al. (1994) indicate that discrepancies between different instruments are often 20...50%. Promising results are reported for the Nevzorov probe by Korolev at al. (1996b). Overall, these heated-element probes are proving to be quite reliable and simple to use. The main drawbacks are their somewhat uncertain response to larger cloud droplets, drizzle drops and ice crystals. They are also subject to mechanical damage by graupel particles hitting them. The accuracy of these devices appears to be about 10% under good conditions but larger discrepancies are not uncommon and not well understood. More will be said of this later.

A device originally designed to serve as a detector of aircraft icing (Rosemount icing rate detector), has been added to several cloud physics aircraft, and its quantitative use explored in the laboratory by Baumgardner and Rodi (1989). Field results are also quite encouraging (Heymsfield and Miloshevich, 1989), especially for the detection of very low LWC values. This device can operate only at temperatures below 05C, since it measures the mass of the accumulated ice on the probe tip. The instrument becomes inoperable at high LWC (0.5...1 g m^{-3}, depending on temperature and airspeed), because of incomplete freezing of the impacted water mass and because of the large fraction of time spent in de-icing the sensor rod.

1 As of late 1996, the Johnson-Williams probes are no longer available from the manufacturer.

2 There are many versions of this probe in use. Some were manufactured 'in-house' by the users and there are at least two commercial firms marketing such probes.

Optical response, rather than direct collection of cloud droplets, is the basis of two LWC measuring instruments. They operate on similar principles: scattered light from a volume containing a large number of droplets is analyzed with a special optical filter to yield various moments of the droplet size spectrum, among them the third moment, i.e. mass. The Gerber-PVM (particle volume monitor) instrument (Gerber et al., 1994) has been extensively tested both in wind-tunnels and in flight and has shown good stability and accuracy. The instrument of Lawson and Cormack (1995), the 'SPEC-CDS cloud droplet spectrometer', is less well tested but also promises good performance. These optical devices have the advantages of large sample volumes, good response to a larger range of droplet sizes, fast time response, and immunity to airflow and air temperature fluctuations. These instruments are more expensive than the heated-element devices by at least factors of 2 to 5, but this is compensated to a large extent by the reliability of the probes and by the fact that more information than just the LWC is derived from the measurements. These additional capabilities will be discussed in later sections.

Drizzle, rain, ice and total mass.

Adequate sampling of larger drops[3] and crystals requires large sampling volumes because of the usual strong decreases in number concentrations with increasing sizes. Thus, the instruments designed for these measurements are larger, more complex and more expensive than those for cloud droplets.

Because larger drops and crystals have a tendency to break into fragments upon impact at aircraft speeds, a simple scaling up of the cloud droplet instruments is not practical. Yet, the principle of mass measurement via the power needed to evaporate the hydrometeors has been applied in at least two heated-element collector devices for larger drops and crystals. Principally for the measurement of IWC, an instrument based on the principle of the CSIRO probe was built by King and Turvey (1986). The heated element was made much larger (about 1 cm width) and was given a convex cylindrical shape to allow particles to remain in contact with the element long enough to be evaporated and not be blown off the probe. Some field tests showed this approach to be promising, but it has not been given sufficient attention yet. Nevzorov (1980) introduced a similar probe, using a convex depression in the end of a cylinder to hold the impinging drops and crystals and Korolev et al. (1996b) present some promising results for this device though the size-dependence of the collection efficiency is not yet published. In general, due to their larger physical size and possibly low collection efficiencies for small objects, these collector devices may in fact not be sensitive to cloud droplets, so that to obtain the TWC the data from them may have to be combined with that from a probe for cloud droplets. Uncertainties in the overlap in size sensitivity between the two types of probes is in fact a problem for precise evaluation of the TWC.

Another approach to in-situ mass concentration measurements is that of Ruskin (1967), and of Nicholls et al. (1990). In these instruments air is passed through an evaporator, so that all hydrometeors (liquid and solid) are vaporized, and the total water vapor content of the air is determined using a Lyman- absorption

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[3] The definition adopted throughout this paper is: 'droplets' are < 50 µm in diameter, 'drops' are > 50 µm in diameter. Drops may further be classified as 'drizzle drops' and 'raindrops', with 500 µm as the approximate demarcation point.

hygrometer. The devices have a reported sensitivity of 0.005 g kg^{-1} and an accuracy of 0.15 g kg^{-1}. The mass concentration of the condensed phases is obtained by subtracting the saturated vapor content from the measured total. Air is taken into the instrument through a tube of several centimeter is diameter and the instrument is located either inside the fuselage or in some external housing. In one particularly productive version of this principle (Ström and Heintzenberg, 1994), the sample is taken with a counterflow virtual impactor (CVI) which separates droplets or crystals above a threshold size (say 2 µm) from the airstream and thus concentrates them; the result is a higher water to air mass ratio and greater sensitivity. With the addition of a particle counter, the residues of the evaporated droplets or crystals can also be counted and thus their number concentration in the cloud determined (assuming that each droplet or crystal leaves a single non-volatile residue). In general, these evaporator measurements rely on a simple and direct principle and that makes the data reliable and unambiguous. The CVI application is specially attractive. What limitations exist are of a practical nature: the design of the intake and its location are critical factors, the operation of the Lyman- detector is somewhat troublesome, and a relatively large amount of power is required to heat the volume of air passing through the instrument. Also, no information is gained on the phase of the condensate.

Remote sensing.

The methods described so far rely on in-situ (immersion) sensing of hydrometeor mass concentration and are therefore limited to measurements along the flight line. Such data are very usefully supplemented by remote sensing data either from the ground or from the aircraft. Microwave radiometry has been shown to be capable of yielding path-integrated measurements of LWC (e.g. Snider et al., 1980; Snider and Rottner, 1982; Hogg et al., 1983). Two frequencies are used, one of these at a vapor absorption line (near 21 GHz) to estimate the total water vapor content and another that responds to emission by liquid water (near 32 GHz for example). If the vapor content can be estimated independently, based on temperature soundings for example, then the liquid water column can be determined using a single frequency. The measurements yield the liquid water mass per unit area (kg m^{-2}, or mm) between the receiver and infinity, though the outer limit normally means the tops of the clouds or at worst the tropopause. The interpretation of such data depends on the complexity of the cloud examined and on the other sources information available in addition to the radiometric data. For consideration of cloud-scale fluxes of moisture, the vapor measurement has its own value. A complicating factor of some concern is that if the water content is high, such as in the presence of intense precipitation, then an unpredictable amount of attenuation reduces the emission signal. Only in conjunction with radar data can this problem be resolved.

Microwave radiometers have seen only limited use in aircraft so far, in part because the costs of the instrument and of the installation are fairly high. However, there is great potential value in a vertically integrated measure of water content (Hill, 1994; Huggins, 1995; Reinking, 1995; many others). Considering the mobility of the aircraft, plus the in situ data it collects simultaneously, makes aircraft application of microwave radiometers very attractive for work related to precipitation enhancement. Going beyond vertical profiles, the technique proposed by Warner et al. (1985) and tested by Warner and Drake (1988) derives the spatial distribution of the LWC in a vertical plane containing the aircraft flight path. Radiometers are used extensively for the detection of rain from satellites and also from aircraft (Kummerow et al., 1991).

Cloud droplet spectra.

The number and size of cloud droplet (the droplet spectra) are principal factors in the evolution of precipitation via coalescence and also influence the growth of ice crystals by riming. Knowledge of the droplet spectra also aids the interpretation of cloud dynamics and allows inferences to be made regarding the source of air in which the cloud formed. In general, one can view the droplet spectra as the link between the external factors influencing cloud formation and the evolution of its hydrometeor content. It is also a main determinant of the radiative properties of the cloud and of the chemical reactions within it.

The most widely used tool for droplet size measurements is the light-scattering device developed by Particle Measuring Systems, Inc. (PMS) (Knollenberg, 1976, 1981), called the Forward Scattering Spectrometer Probe (FSSP). These devices have been in use now for over 20 years so that the possibilities and limitations of the device are quite well known. There are several FSSP models in use, with differences in the elctro-optical definition of the sample volume and in data processing. When examining data from these probes, these possible differences must be born in mind but the following discussion emphasizes the common capabilities and limitations.

The FSSP is mounted in a pod under the wing of the aircraft so that cloud can freely stream through its sampling aperture. The instrument counts and sizes individual droplets by the light they scatter as they traverse a laser beam. Optical and electronic means are used to define the sample volume. The output of the instrument normally consists of the droplet counts in fifteen size channels. The upper limit of the measurement range is adjustable from 7.5 to 15, 30 or 45 m droplet diameter. The sampling volume is large enough to allow up to 10 Hz sampling rate with adequate statistical accuracy in all clouds except those with very low droplet concentrations; however, satisfactory sampling of the largest droplets of the distribution may require longer averaging times.

The accuracy of the FSSP probe received a great deal of scrutiny over the past decade (Baumgardner et al., 1985; Cooper, 1988; Brenguier and Amodei, 1989; Baumgardner and Spowart, 1990; Kim and Boatman, 1990; Kim et al., 1990; many others). Also, special 'high performance' versions have been built. These studies led to better ways of processing and analyzing the data, to improvements in the hardware configuration, and to an appreciation of the degree of confidence, and also caution, the data deserve. One of the main results from these efforts is the method developed by Brenguier et al. (1993) for monitoring instrument performance by examination of the internal consistency and stability of the data. These methods are very helpful for establishing confidence in the collected data, and provide criteria for the rejecting faulty data. The application of this method requires that the probes be equipped with output lines for ”activity”, ”total strobe” and ”total reset”. Experimental methods of calibration of the FSSP also have been improved. Brenguier (1989) reported on the development of a random pulse generator for use in evaluating coincidence corrections. Hovenac and Hirleman (1991) describe a rotating pinhole device which can be readily attached to the probe and give well-repeatable checks of size calibration. Injection of glass beads of known sizes into the sample volume remains a relatively reliable and simple method of 'first order' size calibration. Calibration of the FSSP is not a trivial task, but the procedures are well-established so that the instrument can be maintained in good working condition with moderate effort. The FSSP can be considered the 'standard' cloud droplet probe for aircraft use at the present, with the limitation that its detection range extends only to 45 m droplet diameter. This leaves a gap between the FSSP data and the roughly 100 m size above which the imaging probes (discussed in the following section) can provide reliable data.

As already mentioned in the section on LWC measurements, the two probes (Gerber's PVM and the SPEC-CDS) in which scattered light from a large volume containing many drops is analyzed yield information not only on the total volume of the scatterers but also on other characteristics of the droplet distribution. In the Gerber-probe the second moment of the size-distribution, i.e. total surface area, is also detected. From the volume and surface data the 'effective radius' of the distribution can also be calculated. The surface data has its own utility and the effective radius is an important parameter for the radiative properties of the cloud. The effective radius obtained from the PVM can providie a check on, or correction of the size spectra obtained from the FSSP. A systematic difference, believed to be due to the velocity-dependence of the FSSP response, was noted by Gerber et al. (1994) and Gerber (1996).

Drop and crystal spectra.

For hydrometeors of drizzle and precipitation sizes (>50 m) the optical array probes of Particle Measuring Systems Inc. (PMS) continue to be the most widely used. Both in the one-dimensional (1D) and in imaging (2D) configuration, these probes utilize laser illumination and linear arrays of photodetectors.

The 1D probe's output is similar to that of the FSSP: numbers of particles in 15 size channels. The resolution (channel width) of this probe can be 12.5 or 25 m; in the higher-resolution form the probe provides a useful bridge between the FSSP and the 2D probes. A statistical correction is needed to take care of instances where particles pass at the edge of the sampling cross-section. Perhaps the most severe limitation of the 1D probes is that little can be done to effectively eliminate artifacts from the data. For these reasons, the 1D probes are not given much emphasis by researchers; their use is favored by the instrument's relative simplicity and low data output rate.

The 2D imaging probes are perhaps the most powerful tools for cloud particle studies; the availability of these probes had a rather significant impact on cloud physics. Various forms of the probes exist. The two most widely used versions have array-element sizes of 25 and 200 m, respectively, and contain 32-element detectors. By rapid sampling of the array, the shadow image of the particle passing through the laser beam is recorded. The basic design of these instruments didn't change much over the years. Most development work addressed shape recognition and artifact rejection methods in the processing software.

The first task that is addressed in the image analysis routines is to eliminate 'artifact' records. Contamination of the data can result from drops or crystals that hit the probe tips and break apart, from water streaming off the probe apertures, from water or ice on the mirrors, from electronic errors, etc. Each of these artifact image types need to be recognized through special algorithms. While there is no fully satisfactory way to accomplish the artifact rejection, procedures that have been designed do take care of the large majority of the problems.

Determination of the phase of the sampled particles (water vs. ice) was found to be best addressed through analyses of the 2D image shapes (quasi-round and smooth vs. irregular or faceted). This discrimination can be successful only for images that are at least 4 to 6 times larger than the individual array elements. Smaller images have to be treated as ambiguous. Attempts to distinguish ice and water particles by the amount of depolarization they produce as they pass through the laser light failed to produce convincing results.

Recognition of ice crystal shapes (crystal habits) is essential for the estimation of crystal surface area and mass, for the estimation of the degree of riming on the crystals and for deducing the crystal's growth history. Accordingly, this question received considerable attention. The problem of reconstructing particle size from partial images (particles at the edge of the sample volume, or larger than the sample volume) was addressed by Cooper (1980). Algorithms for classifying the images have been devised by Rahman et al. (1981), Duroure (1982), Holroyd, (1987) and others. Heymsfield and Baumgardner (1985) report the results of intercomparisons among the various schemes. The success of these classification methods has not been critically tested due to the lack of independent determinations of crystal habits (other than visual inspection of the images) or of total crystal mass.

Beyond the qualitative information on hydrometeor phase and shape, total drop or ice crystal concentration and size distributions are the main data to be derived from the optical array probes. Since the sample volume is defined, to a first approximation, by the aperture width and by the total array width - both physical dimensions - the total number concentration can be reasonably well estimated in a straightforward manner. The accuracy of this estimate is probably controlled by the success of the artifact rejection rather than by the approximations involved. The magnitude of the sample volume can be refined by taking into account the location of the center of mass of partial images and by accounting for the size-dependence of the depth of field of the detector optics. Further improvements in the analysis of the 2D probe data have been derived by Baumgardner and Korolev (1996) and Korolev et al. (1996a). The corrections identified in these papers most seriously affect the smallest particles detected by the probes; that is where discrepancies between data from probes covering different size ranges have been frequently noted. The coexistence of both liquid and solid hydrometeors may present a problem if the concentration of large cloud droplets, or of drizzle drops is so high that the probe electronics become saturated (Rauber and Heggli, 1988).

Evaluations of the performance of the 2D probes were reported by Joe and List (1987) and by Korolev et al. (1991) among others. Based on these studies and on the amount and variety of published papers in which such data are utilized, it is clear that in spite of their limitations the 2D imaging probes have a very high success rate. The 1D array probes are less well known and are generally given less emphasis even though they can provide data in the size gap between the single-particle scattering probes and the imaging probes.

Another approach to recording particle images is laser holography. Holography offers the major advantage of a large and undisturbed sample volume in which several particles might be present at the same time. Because the sample volume is far removed from mechanical parts, disturbance on the airflow is minimal. The method has the inherent disadvantage of intermittent sampling. Successful field uses of a holographic system ware reported by Brown (1989) and Lawson et al. (1996). The resolution achieved appears to be comparable or better than the imaging probes (25 m), and even droplets down to 12 m diameter have been successfully detected and sized.

Detection of ice particles in clouds was shown (Jones et al., 1989) to be possible with a rather simple, light-weight device which records the electric charge generated when ice particles collide with an ice-coated sensor wire. The large sample volume provides for high spatial resolution in the data, but no sizing information is obtained. The detection efficiency of the probe may vary with cloud conditions, influencing the reliability of the measured concentrations. This device may have some limited utility but doesn't seem adequate for general application.

Hydrometeor charge.

Progress toward understanding the generation of electric charges within clouds is substantially aided by recent techniques which allow the size, type and electric charge of hydrometeors to be obtained simultaneously. These instruments represent advances over earlier techniques in which the particle charge was measured in one device, while complementary information on the type of hydrometeors was derived from other instruments.

Two similar instruments have been tested by Cupal et al. (1989) and Weinheimer et al. (1991). Both devices combine an induction ring for charge measurement with a 2D imaging probe. The data are recorded in such a fashion that the charge produced by a particle can be directly related to its shadow image. In combination with other cloud parameters, including electric field strength (using the well established 'field mills'), these new instruments can be expected to become useful contributors to cloud electrification studies.

Probe mounting on aircraft.

In addition to the advances made in the development and use of various sensors for use on aircraft, the problem associated with selecting appropriate mounting locations on the aircraft have also been addressed. This is far from a trivial question, since the disturbance produced by the body of the aircraft can substantially alter, or render useless the measurement being made. The problem is present even for the simplest of sensors, such as static and dynamic pressure, temperature, etc., but long experience with those sensors has led to workable solutions. The situation is more critical for particle detectors.

Analytic studies of the airflow around the complex structures represented by the aircraft and the probe itself were developed by King (1985, 1986), by Drummond and MacPherson (1985) and by Norment (1988), among others. Actual measurements of the pressure field around a probe mount were reported by MacPherson and Baumgardner (1988). These studies show that for probes mounted under the wings of aircraft (one of the better locations possible), variabilities of up to around 20% might be expected in the flux of particles. That value applies for rather large angles of attack; under more closely normal operating conditions the effects are smaller. The studies also explain the frequently observed preferential orientation (distortion) of images recorded with 2D probes.

Aerosol and nucleus measurements.

The aerosol content of the air in which clouds form and with which the cloud may interact through entrainment can greatly influence the evolution of the cloud and the formation of precipitation in it. This linkage to nuclei is, of course, the fundamental basis for most precipitation enhancement attempts. Therefore, knowledge of the natural conditions and the ability to observe induced changes are crucial to research and operational precipitation enhancement work.

The connection with cloud characteristics is most clearly demonstrated for cloud condensation nuclei (CCN). For a given updraft velocity, there is a direct relationship between the CCN spectra (number vs. supersaturation) and the initial cloud droplet spectra (at cloud base). Since updraft velocities in given cloud types vary only within relatively narrow limits, CCN effectively control the initial droplet size distributions. A similar role is predicted to exist for ice nuclei (IN), but this is not clearly evident in observations of clouds. The lack of certainty about IN is due to the facts that secondary processes of ice initiation also exist, that the natural variability of IN appears to be relatively minor and that our ability to measure IN is very limited. Clearly, the validity of the statement about natural variability is conditioned by the uncertainties in measurement capabilities. The situation is also complicated by the existence of several distinct ice nucleation modes, each of which requires a separate measurement.

While not directly linked to cloud formation, it is also very useful to know the total aerosol content of the cloud environment, and as much about the aerosol size distribution and composition as possible. These parameters can serve to characterize the origins of air parcels and help to fill gaps in the CCN and IN measurements.

Total aerosol concentration.

The number concentration of aerosols is readily determined by causing condensation to take place on them at a high supersaturation. Instruments in which the high supersaturation is produced by rapid expansion have been very successful in a wide range of applications. Concentration is determined by optical measurement of the cloud density inside the chamber or by single particle counting. Commercial versions of this type of instrument (CN counters) are available and have proven to be reliable. Air samples are brought to the instrument within an aircraft from an external intake; the design of the intake and of the ducting is not very critical for this measurement alone (since very small aerosols dominate the total count) but usually the intake also serves other instruments and those are likely to dictate the requirements.

Aerosol mass and composition can also be measured by relatively simple techniques if low resolution in space and time (sampling times of the order of tens of minutes) are acceptable. High-resolution measurements on the other hand are very demanding and expensive. Detailed descriptions of the various methods and the analysis techniques can be found in the air chemistry literature (e.g. Finlayson-Pitts and Pitts, 1986).

Cloud condensation nuclei, CCN.

CCN are detected by activation at supersaturations likely to be encountered in clouds (< 2%). The two most frequently used instruments for CCN measurements are the 'traditional' static diffusion chambers and the more complex continuous-flow chambers.

The static diffusion chamber is a batch-processing instrument and measurements are taken at one supersaturation at a time. These limitations result in a sampling frequency of about 30 s per datum and about 3 min for obtaining a complete spectrum. This type of instrument has a lower operating limit of about 0.2% supersaturation. For general airmass characterization these sampling rates are acceptable. Much of the literature on CCN originated from measurements with static diffusion chambers (cf. Twomey, 1977; Götz et al., 1991), and reliability, relatively small size and moderate cost lead to widespread use of these devices. For aircraft use the additional requirement of adequate pressure isolation from the interior of the aircraft cabin has to be addressed. There are approximately 2 to 5 such instruments in current use; the latest version (Wechsler, private communication) uses solid state laser illumination and a photodetector. Progress has also been made in the development of calibration methods for these instruments so that results are probably accurate to within 10 or 20%.

Instruments of greater capabilities (CCN spectrometers) have been developed by Fukuta and Saxena (1979) by Radke et al. (1981) and by Hudson (1989). The common advantage of these continuous-flow devices is that a full CCN spectrum cen be obtained in about 30 s. In the first two of these devices air is drawn through one or more chambers in a steady flow and is subjected to a range of supersaturations; the number of droplets that form is then counted by optical single-particle counters (OPC's). In the instrument of Hudson, the sizes of the emerging droplets are used to infer the supersaturation at which they became activated. This design leads to simpler construction, yields essentially instantaneous spectra and extends the measurements to 0.01% supersaturation. Results from this instrument have been reported by Hudson (1993), Hudson and Li (1995) and Hudson and Svensson (1995).

A common concern for all types of CCN measurements from aircraft is the design of air intakes and ducts that do not significantly bias the aerosol content of the sample air.

Ice nuclei, IN.

Measurements of IN have been made with a large variety of instruments (e.g. Vali, 1985) but none have been proven so far to be fully acceptable. Reasons for this situation were already mentioned.

About the only technique in current use is filter sampling. This method has well-known limitations but is relatively simple and therefore represents a compromise between making no measurements at all and attempting to use some more elaborate and still not fully satisfactory technique. Filter samples are taken during flights, over periods of few minutes to longer. Subsequent exposure of the filters (in a laboratory chamber) to known supercooling and supersaturation yields a count of IN. The use of several filters in parallel can provide a spectrum.

The prototype instrument of Rogers (1994) has undergone some field use installed in aircraft and appears to show some promise but further tests are needed.

Where the requirement is only to detect the presence of some artificial ice nucleating aerosol then it may be warranted to use devices which are inadequate for the characterization of IN concentration and mode of activity in general. Such instruments use continuous airflow through a refrigerated chamber and count the ice crystals that develop by optical or other means. In these cases one deals with a qualitative 'tracer' detection, that perhaps also yields an indication of the relative amount of ice nucleating aerosol present. No quantitative conclusions can be drawn from such data about the actual initiation of ice in the clouds.

Another approach that can help fill the gap left by the lack of instrumentation for IN is to take samples of air in the cloud inflow, or other region of interest, in some large container (metallized mylar bag, for example) and deliver the sample within as short a time as possible to a laboratory cloud chamber (e.g. Rogers and DeMott, 1995; DeMott et al., 1995). This approach requires a large effort, has to be accompanied by careful studies of potential losses of IN in the container, and are subject to the limitations which are inherent to cloud chamber measurements of IN.

It is clear that the development of better methods of IN measurements is of considerable urgency.

Tracers.

Since analysis of many cloud processes is most meaningful in Lagrangian reference frames, and the aircraft provide intermittent snapshot descriptions of the measured parameters, the use of tracers is a natural complement to airborne observations. Approximate air parcel trajectories can be constructed *post hoc* on the basis of thermodynamic and other information but direct determination of such trajectories by tracers is undeniable more definitive. In cloud seeding activities, the ability to follow the transport and diffusion of the seeding material is specially valuable.

Several tracer methods have been developed in various combinations of release from the ground and detection by an airborne instrument and vice versa, or with both release and detection done by the aircraft.

The two most productive methods are the release of radar-reflective chaff from the aircraft and tracking of the chaff with a ground-based radar, and the use of a tracer gas like sulfur hexaflouride (SF_6). Chaff release requires a dispensing apparatus and a chute to the outside of the aircraft. The times of release are recorded on the aircraft data system. Chaff has been successfully tracked to periods over 30 min during which time the transport and spreading of the chaff through the cloud volume can be well documented (Martner et al., 1992). Spatial and temporal resolution depend on the radar characteristics and scanning sequence used. The SF_6 gas is released form pressurized tanks; detection is with a fast-response electron-capture device. The analyzer has a response time of near 1 s with a lag-time of a few seconds, so that spatial resolution of few hundreds of meters can be achieved. Stith and Benner (1987) demonstrated the potential of this technique and Stith et al. (1990) show interesting results on the transport of seeding material in cumuli.

Navigation and winds.

Precise positioning of the aircraft is crucial to meaningful interpretation of the collected data. Position and velocity need to be measured both with respect to some fixed (ground) coordinate system, and with respect to a reference frame moving with the air volume being sampled. Knowledge of both of these enables the winds (horizontal and vertical) to be derived.

Ground-referenced position may be obtained from radio-beacon signals (DME/VOR, TACAN, for short range; LORAN-C for long range), from Inertial Navigation Systems (INS) and from the Global Positioning System (GPS). The radio-beacon and GPS systems yield direct position data; with the INS, position is derived by double integration of the accelerations of the aircraft with respect to the ground. On the other hand, the INS yield better acceleration and velocity information that are inherently more precise than what can be obtained from differentiation of the position data.

Reliance on the sparse radio-beacon networks of the air transportation authorities often produced less-than desirable coverage and accuracy. Augmentation of these networks with installations for specific projects has been done infrequently, although at least one system (Johnson and Fink, 1982) was assembled with that sort of flexibility in mind. Rodi et al. (1991) developed a procedure which takes advantage of the INS for continuous data and short-term accuracy, and combines it with the precision to be gained from reference to ground-based (fixed) DME. Major improvements are being realized with the use of GPS. This positioning system is based on receiving signals from several satellites simultaneously. It permits position to be determined with accuracies of the order of meters (or better) using small and relatively inexpensive equipment on the aircraft.

Motion with respect to the air is derived from air speed, pitch and yaw. Air speed is obtained from dynamic and static pressure measurements (Pitot and static pressures) along with temperature measurement (for the determination of air density). Deviations between the direction of motion of the aircraft and its axis is determined from pressure differences across a near-hemispherical surface (at the tip of a noseboom, or the nose radome) or with the use of small vanes.

Radars mounted on aircraft.

The traditional role of aircraft in cloud physics research is to collect in-situ observations and this is reflected in instrumentation development efforts. However, the large gap between the sample volumes of in-situ sensors on the one hand and of ground-based remote sensing devices on the other, has increasingly stood in the way of obtaining comprehensive descriptions of cloud-scale processes. Aircraft-mounted remote-sensing devices can serve to fill the gap.

Aircraft have been used for some time as platforms for remote sensing instruments (lidars and radars), but these uses were directed, for the most part, at examinations of clear air processes (winds, aerosols, etc.) and for deriving surface (ground) characteristics. Also, some large, four-engine aircraft are used to carry weather radars. Developments over the 10 years or so have led to the construction of smaller, less expensive remote-sensing devices that can be carried on twin-engine aircraft and can therefore be expected to be more widely used. Reference was made already to the potential of passive microwave radiometers for the determination of column water content. Two other, active sensors are worth mentioning here.

A Doppler lidar system, useful for the examination of air motions at cloud boundaries, has been developed (Schwiesow et al., 1989) and flown on a King Air aircraft. This system should provide additional insights into the characteristics of mixing and entrainment.

A 95 GHz (3-mm wavelength) radar has been in use for cloud studies for about 5 years. This unit is small enough to mount in a twin-engine aircraft. With a fixed antenna that is relatively easily mounted in a cabin window a 0.75 beamwidth is achieved. Data are collected to distances of 3-5 km from the aircraft with 30-m resolution along the beam and better than that along the flight path. Reflectivity, velocity and polarization data are recorded. Results obtained with this radar to date (Pazmany et al., 1994; Vali et al. 1995) indicate the usefulness of the instrument. At least two other research groups are in the process of installing similar radars in aircraft.

Data systems.

Fast and powerful digital computers now available make the processing and recording of data a considerably lesser problem than it has been even a few years ago. Limitations in data recording capacity and speed have practically disappeared. The need for special purpose signal processing units has also diminished.

An important aspect of aircraft data systems is the ability to provide real-time analyses and to make the data available for immediate use by the flight crew. Quick recall of data from previous periods, and the display of time trends, correlations, integrated, filtered data, or of derived parameters using data from several sensors are among the tools that can be accessed with modern data systems.

Data communication between ground stations and aircraft, or between two aircraft, can also be implemented. Observations taken by the aircraft system can be telemetered to a ground station for monitoring and real-time analysis, or for recording. Similarly, data can be made available on the aircraft (satellite images for example).

As a complement to the data collected by the special sensors installed on the aircraft, it has been found very useful to record video data of the visual appearance of the clouds being examined. Installed in the cockpit of the aircraft and equipped with a time reference signal, such video records provide a great deal of useful information for relatively little expense and effort. In a similar vein, recording of voice communication in the aircraft, among the crew and with the ground, is of great help in deciphering the data after the flight.

While not strictly part of the aircraft instrumentation system, it is a matter of overall utility of the observational program to also consider the production of 'quick-look' data sets within hours after flights. With such data there is a much better chance to quickly detect subtle instrument problems that otherwise might escape notice. Review of these data also facilitates better utilization of the aircraft in subsequent missions of an experimental series.

Looking ahead.

The development of aircraft instrumentation is a continuous process driven by the need for more detailed and more accurate information about cloud processes. Thus, at any one time, instruments of various degrees of maturity are in use, from proven to experimental. The decision what instruments to apply in a given situation need to consider scientific, engineering and cost factors. Even beyond the decision what hardware to use, the demands on calibration facilities and the ease of data processing are further factors to take into account. As stated before, this review summarized the characteristics of proven systems; it is to be anticipated that newer instruments, and improved understanding of those already in use, will continuously change the assessments here given.

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