Ice Particle/Water Droplet Discrimination with an Optical Ice Particle Counter

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ABSTRACT

The capability of a Mee Industries Model 120 ice particle counter (IPC) to differentiate between ice particles and water drops was investigated in laboratory and field studies. The threshold voltage setting as well as the particle size were found to be critical in determining counting efficiency. The results show that ice crystals are counted with an efficiency more than ten times as high as are water drops of the same average size. Increasing the threshold voltage setting of the instrument increases the discrimination factor but also results in a decrease in the absolute number of particles counted. The availability of concurrent information on particle sizes and concentrations from other probes allows the Mee IPC phase determinations to be made with much greater confidence. Methods for utilizing data from the Mee IPC as well as the limitations of the instrument are discussed.

1. Introduction

The presence of ice in a cloud has traditionally been detected visually or by means of a collection or impaction device. In the latter instrument, a suitably prepared slide or ribbon is exposed to the ambient flow past the aircraft and then examined microscopically for evidence of ice crystal impacts. Because this type of analysis is tedious and largely qualitative, a number of attempts have been made to develop an automatic, airborne ice particle counter using optical techniques.

Both the Mee Industries (Sheets and Odencrantz, 1974) and the University of Washington (Turner *et al.*, 1976a) ice particle counters (IPC's) use optical polarization techniques to discriminate between ice and water particles. Although these instruments differ in optical design, both have the ability to count particles but not to measure size.

A number of optical imaging probes (Knollenberg, 1970, 1972) are produced by Particle Measuring Systems (PMS) for the airborne measurement of the size distribution of particles between 20 μm and ~6.5 mm in diameter. The one-dimensional probes are able to count and size particles but cannot distinguish between ice and water. The two-dimensional probes produce a cross-sectional image of each particle detected and allow nonpsherical ice particles to be distinguished from water drops by either manual or automated means.

A variety of instruments were used by Holroyd *et al.* (1978) to determine ice crystal concentrations in their cloud seeding experiments. The different concentrations obtained underline the requirement for a clearer understanding of the sizes and types of particles to which the different probes react. This paper describes laboratory and field experiments, in which the capability of a Mee IPC to discriminate between ice particles and water drops, is examined and documented as a function of threshold voltage and mean particle size. Criteria are established for using the Mee IPC alone, or in conjunction with other instrumentation such as a system of PMS probes, to distinguish ice from water in mixed-phase clouds.

2. Operation of the Mee IPC

The Mee Industries Model 120 IPC is an aircraft-mounted instrument designed to produce a real-time readout of ice particle concentrations. Discrimination between ice particles and water drops is made on the basis of a cross-polarization technique (Sheets and Odencrantz, 1974). Light from an incandescent source passes through a polarizing infrared filter to a free-stream sample area, where it is scattered from a target particle in a manner which depends on the size, shape and phase of the particle, as well as on its internal and surface properties. A semiconductor photodetector is placed at a 90° viewing angle and is screened by a second polarizing infrared filter adjusted for maximum signal (ice) to noise (water) response (i.e., maximum extinction). An ice particle passing through the sample area produces a signal pulse which is substantially greater than that produced by a water drop of equivalent size. By adjusting the triggering threshold of the counting circuitry, it should be possible to eliminate the low-level pulses due to water drops and to count only those produced by ice particles.

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Prior to the experiments described in this paper, several modifications were made to the commercial IPC in order to facilitate inflight control and to increase its operational stability. The most significant of these were 1) the provision of a digital output signal which was recorded as a counting rate; 2) the installation of a digital panel meter for the continuous readout of the threshold voltage; and 3) alterations to the wiring, components and component layout in the sensor pod in order to reduce background noise and spurious counts.

The manufacturer's specifications indicate that the IPC should count ice particles $\gtrsim 40$ μm in diameter. The laboratory work of Sheets and Odencrantz showed that the lower detection limit for ice crystals was probably ~100 μm. Sax and Willis (1974) used a Mee IPC to make measurements in Florida cumuli and deduced an operational lower size limit of ~250 μm. These various size limits for ice crystal detection may be the result of operation at different threshold voltages. Turner *et al.* (1976a) found that the counting efficiency of the IPC increases with increasing ice particle size and is greater than zero for water drops above a certain minimum size. Thus, the IPC is not capable of absolute discrimination between ice and water over the entire range of sizes with which particles occur in natural clouds.

Turner *et al.* (1976b) compared the University of Washington (UW) IPC to the Mee IPC operating at 100, 300, 500 and 700 mV. They concluded that the Mee IPC operating at ~400 mV produced ice particle concentrations comparable to those of the UW IPC and that at lower threshold voltages large counts due to the presence of water may be produced by the Mee IPC. Isaac *et al.* (1977) also noted higher than expected sensitivity of the Mee IPC to water at threshold voltages <100 mV. In the latter case this was found to be due to an amplifier instability in the sensor-pod electronics. Upon resolution of the problem, the ice/water discrimination at low threshold voltages was markedly improved to the level documented in this paper.

3. Laboratory measurements

Laboratory investigations of the response characteristics of the Mee IPC were carried out using both liquid and solid particle populations having known properties. Individual water drops of known size were obtained using micropipettes, while a spray containing a broad spectrum of small drops was generated by a continuously driven atomizer. Since preliminary tests showed that the response of the instrument to water drops could be effectively duplicated using spherical glass beads, the latter were used extensively in the calibration experiments. Known quantities of glass beads were propelled through the IPC sample area at velocities of 10–30 m s^{-1} using a specially constructed pneumatic gun (Curry and Schemenauer, 1978) so that it was possible to determine counting efficiency (the fraction of all particles passing through the sample area which is counted by the IPC) as a function of mean particle size.

Because of the difficulty of generating and accelerating large ice crystals of known size, solid crystalline particulates were used to simulate ice. Ordinary table sugar proved to be an acceptable ice crystal substitute, having many flat crystal faces and a range of particle sizes appropriate for IPC operation at typical threshold voltages. This does not imply that ice and sugar crystals are similar crystallographically, indeed they are quite different. However, the need was not to duplicate ice crystals in the laboratory but to work with a material where specular reflection off external crystal faces would be an important light-scattering mechanism. It would be expected that instruments employing a forward scattering ice/water discrimination technique may find different relative responses to ice and sugar than those reported below, due to the marked differences in the birefringent properties of the two materials. The sugar particles used had a broad log-normal size spectrum with a mean size of 290 μm. The measured sugar size distribution is shown in Curry and Schemenauer (1978).

Trials with actual ice crystals were limited to those sizes which could be generated in a 18 m^3 cold room. Ice crystals were produced by nucleating a fog at temperatures -10 to -18°C and were subsequently drawn through the IPC sample area at ~45 m s^{-1}. Crystal habits as determined by slide replication in the sample stream were generally hexagonal plates and broad-branched crystals. Sizes ranged from 30 to 175 μm in concentrations that were ~1000 ℓ^{-1}. Comparing the IPC concentration measurements to the size distributions and concentrations from the slides, it was apparent that crystals with sizes <100 μm were rarely counted at threshold voltages of 50 or 90 mV. The comparisons generally indicated that all particles greater than some size between 100 and 150 μm were being counted. The lack of control over the production of ice crystal size distributions, the difficulty of producing crystals >150 μm in size, and the uncertainty inherent in the concentrations obtained from the slides limited the conclusions that could be derived from the cold room data.

Fig. 1 shows that the percentage of water drops counted increases gradually as the average diameter increases and the threshold voltage (V_t) is kept constant. It is also evident that the V_t setting is very important in determining whether millimeter sized water drops are counted. For water drops <1 mm diameter the V_t setting is not as critical, since only a few percent of the drops would be counted in any case. This figure also gives the percentage of sugar crystals counted as a function of threshold voltage. Clearly, for any V_t a much higher percentage of sugar crystals are counted than drops of the same size. However, even at low V_t settings not all of the sugar crystals are counted.

For example, at a V_t of 50 mV 37% of the sugar was counted. The sugar distribution has a median size of 270 μm with 37% of the particles >310 μm. In contrast, the work in the cold room implied that almost all crystals >150 μm were counted. This difference may be due to differences in the shape of sugar and ice particles or to differences in surface or internal structure. It does imply, though, that ice/water discrimination should be as good as or better than the sugar/water discrimination.

The IPC does not contain any circuitry to reject particles passing through the edge of the sample area and as such the effective sample area will increase with particle size. For example, the effective sample area for a 2.2 cm particle can be as much as 50% larger than for a 0.2 cm particle. This effect, however, is much smaller than the increase in counting efficiency with average size seen in Fig. 1 and is in any case precluded from entering the results due to the aiming accuracy inherent in the laboratory apparatus. It may be important in calculating the concentrations of millimeter sized particles in-cloud but these rarely occur in the absence of much higher concentrations of submillimeter particles for which the change in effective sample area is small.

If the assumption is made that the percentage of sugar crystals counted at a given V_t is directly related to crystal size, then a plot of minimum detectable size (MDS) versus V_t can be obtained as in Fig. 2 from the cumulative sugar size distribution. Fig. 2 shows that above 20 mV the MDS is a linear function of threshold voltage. All crystal sizes greater than the MDS should be counted. This figure shows the importance of V_t in the measurement of ice particle concentrations. The × at 235 μm is the mean MDS for nine cloud penetrations where all of the large particles were known to be ice. On the average ice is seen more effectively than sugar, though the spread of MDS values (shown by the vertical bar) does encompass the sugar value for 50 mV.

Table 1 illustrates the change in the ratio of sugar to water drop counting efficiencies with threshold voltage for particles with a mean size of 290 μm. For each particle size, raising V_t increases the capability to discriminate between particle phases but this is done at the expense of the absolute number of particles counted. In addition, for each V_t there is a particle size above which all the particles are counted, i.e., the ratio of efficiencies is 1. For particles smaller than a certain size neither sugar nor water drops are counted and the ratio is undefined.

The data in this section point out the tradeoffs involved in using the IPC in mixed-phase clouds. If one wishes to completely eliminate counts due to water drops >1 mm diameter from the IPC data, then the threshold voltage must be raised to the point where a portion of the counts due to ice particles >150 μm will also be lost. If the threshold voltage is lowered, then it must be recognized that a certain fraction of the counts may be due to large water drops. The exact fraction depends on the size distributions and respective con-

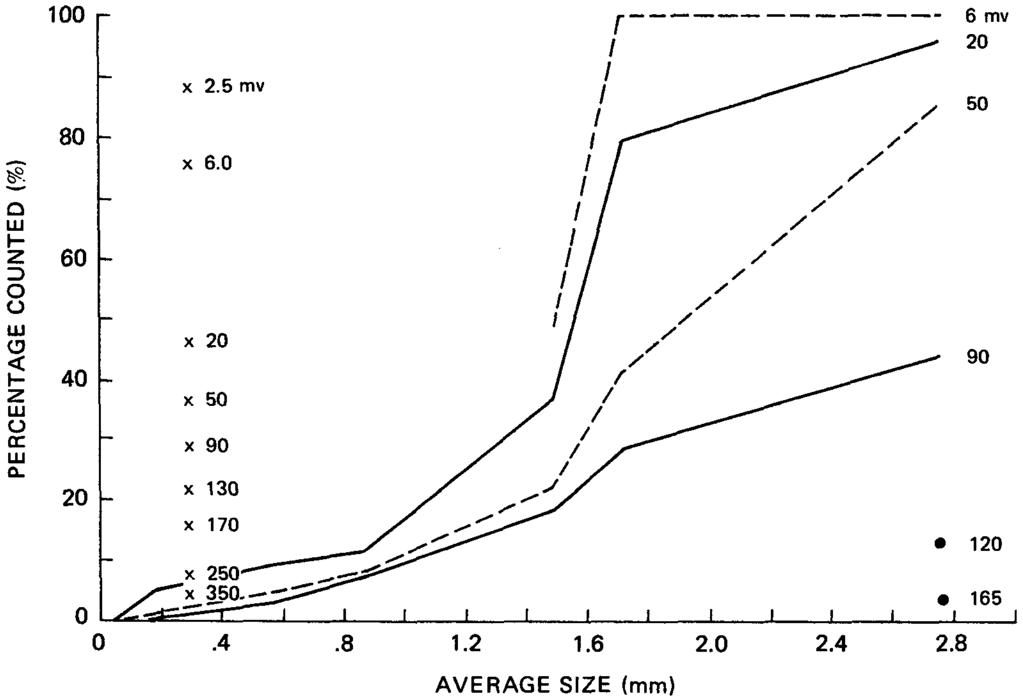

FIG. 1. Percentage of particles counted by the IPC as a function of size and threshold voltage. The crosses are for a crystalline material (sugar); the dots and lines are for a non-crystalline material (water drops or glass beads).

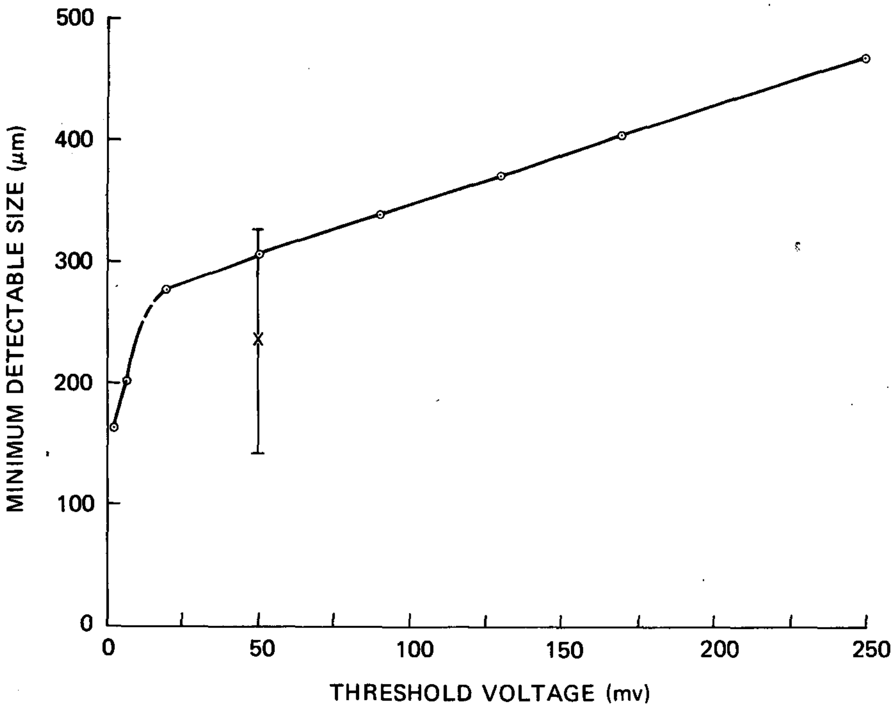

FIG. 2. The minimum detectable crystal size as a function of threshold voltage. The circles are for sugar; the cross is the mean of nine ice crystal observations.

centrations of the water drops and ice particles. However, as long as the threshold voltage is >20 mV, ice particles should be counted with an efficiency at least an order of magnitude higher than for submillimeter water drops.

4. In-cloud measurements

a. Comparison of measurements from different systems

As a result of the laboratory tests it was decided to fly the IPC at a V_t setting of 50 mV. This value would allow ice crystals $\gtrsim 150\,\mu$m to be counted with a moderate to high efficiency and at the same time yield a good ice/water discrimination capability.

The IPC was mounted on a DHC-6 Twin Otter aircraft along with a complement of cloud physics instrumentation that included a Johnson-Williams liquid water content meter, a Mee Industries continuous replicator, a PMS FSSP probe, a PMS 1D-C probe and a PMS 1D-P probe (Isaac *et al.*, 1977). The PMS probes measured concentrations of particles in the size range 1–4500 µm and were used to determine the concentration of particles >150 µm. The undercounting in channel 1 of the 1D-P probe was corrected for, as in Curry and Schemenauer (1978).

TABLE 1. Relative counting efficiencies for sugar crystals and water drops of the same average size (290 µm) as a function of threshold voltage V_t.

V_t (mV)	Counting efficiency (%) Sugar	Water	Discrimination Sugar/Water
20	46	6.0	8
50	37	2.0	19
90	29	0.8	36

As ice particles <150 µm are not counted effectively by the Mee IPC, the mean size of particles >150 µm has been used to characterize the distribution in each data set.

The following sections describe the results of operating the IPC in a variety of cloud and precipitation regimes.

b. High droplet concentrations

Penetrations were made in many clouds where the Johnson-Williams (JW) meter measured liquid water contents of 1–4 g m^{-3} and the PMS probes indicated that almost all of the particles were <50 µm in size.

Fig. 3 shows the JW liquid water content and IPC particle concentrations for a cloud penetration on 11 July 1976 at a temperature of −7°C and an altitude of 4450 m. This cloud had the highest liquid water content values of any observed in 1976. Analysis of the continuous replicator film showed no evidence of ice crystals. The average particle concentration >150 µm from the PMS probes was 2.3 ℓ^{-1} with an average particle size of 250 µm. A few particles as large as 2 mm were also recorded. As can be seen from Fig. 3, the IPC concentration deviated from zero for only 1 s of the 30 s penetration and for that second gave a reading of 0.4 ℓ^{-1}. This corresponds to counting three particles in that second. The average IPC concentration for the penetration was 0.01 ℓ^{-1}.

These results agree with what would be predicted from Section 3. Cloud droplets $<50\ \mu$m diameter are not seen by the IPC even in high concentrations ($\sim 10^6\ \ell^{-1}$). If water drops are present in sizes 1–2 mm then a few counts will be observed. In this case the average IPC concentration is 0.4% of the total particle concentration $>150\ \mu$m. From Fig. 1, one would predict that 1–2% of water drops with a mean size of 250 μm would be counted at a V_t setting of 50 mV. The difference from the observed value may be due to differences in the shapes of the laboratory and in-cloud particle distributions or to a somewhat lower counting efficiency for water drops than for glass beads. This example illustrates what is seen in other water clouds of this type. The IPC yields a very low but nonzero particle concentration. It is only in cases where all the cloud droplets are $<150\ \mu$m and no ice is present that one can be assured of getting a zero IPC reading.

c. *Rain*

At 2024 GMT 5 July 1976 the aircraft flew in rain below cloud base at an altitude of 1615 m and a temperature of +12°C. The particle concentrations, as measured by the PMS probes and the IPC, are plotted in Fig. 4. One minute of data is shown with concentrations plotted every second.

The concentration of particles $>150\ \mu$m ranges from 1 to 12 ℓ^{-1} with an average of 4.3 ℓ^{-1} over the minute. The average drop size $>150\ \mu$m is 300 μm and the average rainfall rate 3 mm h^{-1}. The IPC concentrations range from zero to 2 ℓ^{-1} with an average value of 0.055 ℓ^{-1}. The IPC average is 1.3% of the PMS average. Fig. 1 gives an expected counting percentage of 2.3% for drops of this average size. Again, the laboratory data slightly overestimate the percentage of water drops counted. The fact that the IPC will count only the largest of water drops is likely the reason for lack of correlation between the IPC readings and the total concentrations of particles $>150\ \mu$m.

d. *Ice crystals*

Two cases will now be examined where the observed particles were known to be ice.

1) 17 JULY 1976 CASE

The fifth penetration in this cloud was made at 2128:23 GMT, at −7.4°C and 3750 m at a time when the cloud top was dropping rapidly and the cloud was breaking up. For ~ 5 s during this penetration particles $<150\ \mu$m were seen by the PMS 1D-C in concentrations of $\sim 10\ \ell^{-1}$. The replicator data show that these particles were ice: $\sim 52\%$ miscellaneous ice particles, 31%

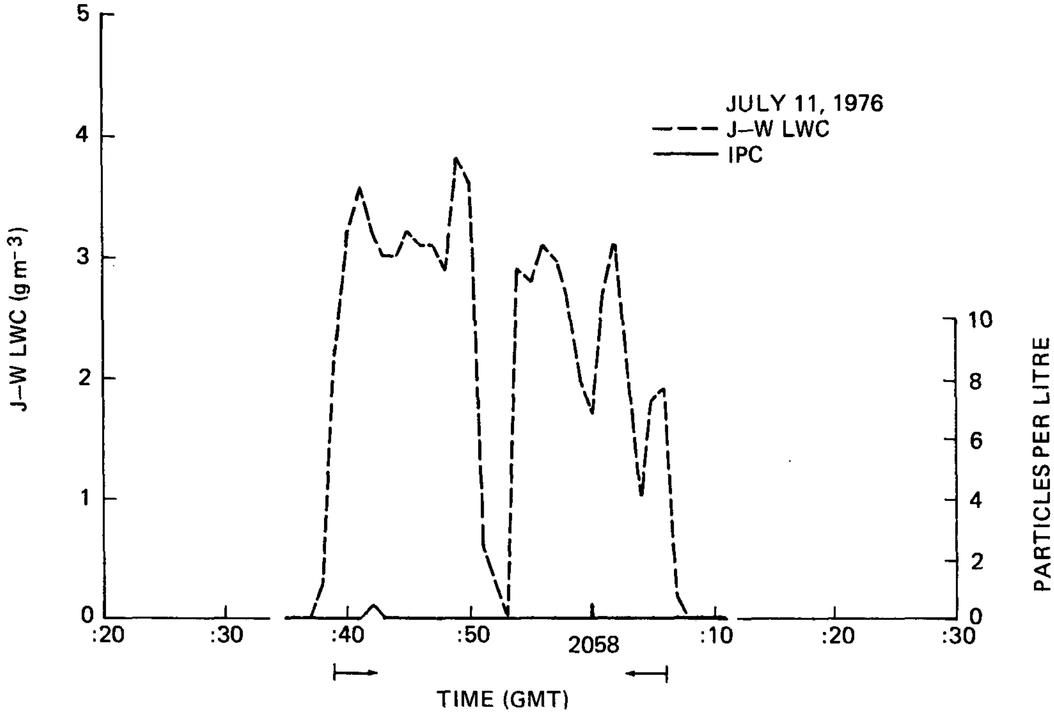

FIG. 3. Variation with time of the liquid water content as measured by the Johnson-Williams probe and of the particle concentration as measured by the Mee IPC. The measurements are for one pass through a cloud at −7°C at an altitude of 4450 m.

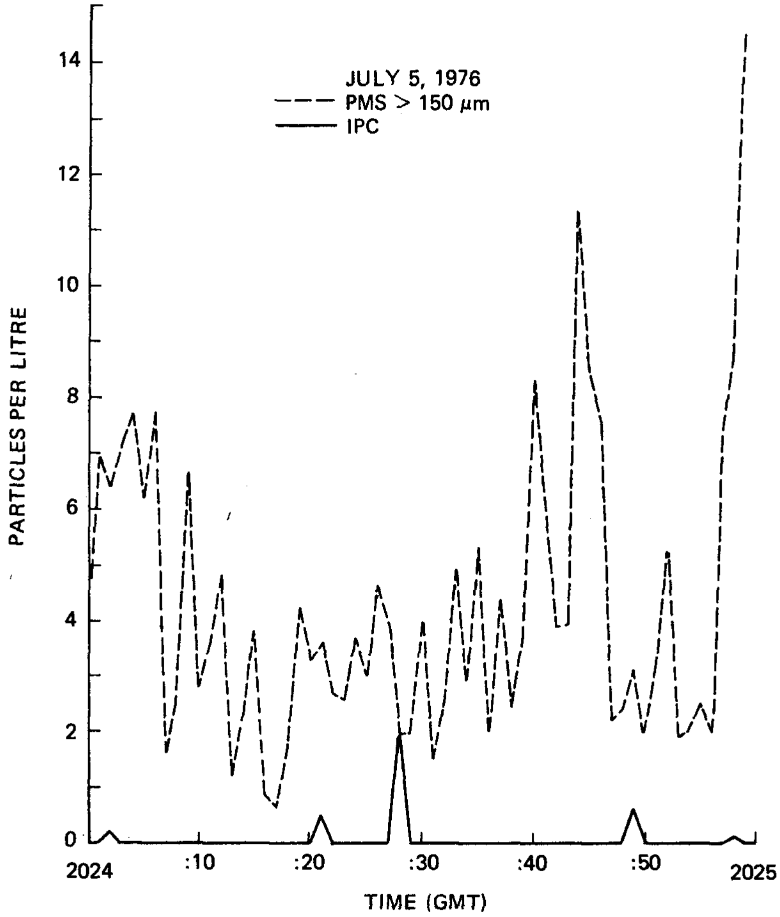

FIG. 4. Particle concentrations as a function of time as measured by the PMS probes and the Mee IPC. The aircraft is flying in rain at a temperature of +12°C and an altitude of 1615 m.

hexagonal plates and ~17% columns. The IPC did not count any of these particles. This is in agreement with the laboratory data discussed above, i.e., the ice particles should have maximum dimensions >150 μm in order for them to be counted at a threshold voltage of 50 mV.

2) 16 JULY 1976 CASE

At 2225:03 GMT, a cloud penetration was made at −9.6°C and 4310 m. Millimeter sized ice particles were observed in a particle collection tube during this penetration and fragments of ice particles as well as irregular ice particles were observed on the replicator film. The PMS and IPC data for this penetration are plotted in Fig. 5. The relative agreement between the two instruments is very good and the average particle concentrations for the penetration are similar. The average PMS particle concentration >150 μm was 32 ℓ^{-1}; the average IPC concentration was 25 ℓ^{-1} which is 78% of the PMS concentration. The average particle size >150 μm was 380 μm. Fig. 1 predicts that one would see 3% of the particles if they were water. The percentage actually counted is 26 times higher than this figure which is in agreement with the particles being ice.

This second case is typical of the results obtained when ice particle concentrations were a few tens per liter. That is, both the absolute and relative concentrations from the two types of probes were in good agreement. In cases where the ice particle concentration was <5 ℓ^{-1} the relative agreement of the probes was not nearly as good but the IPC still counted 50–100% of the ice particles >150 μm. The reduced relative agreement is probably a reflection of inadequate sample volume, particularly for the PMS 1D-C probe.

5. Use of the Mee IPC in mixed-phase clouds

a. General comments

If the IPC is flown through clouds or precipitation shafts where one can infer the phase of the large particles, then the IPC concentration data can be interpreted with little ambiguity. A few counts in rain at +15°C do not indicate the presence of ice but rather that some large drops were counted. Counts in a cirrostratus deck at −25°C can be expected to be a reasonable measure of the concentration of ice particles >150 μm in size (at $V_t = 50$ mV). One would not have to consider the possibility in this case of the counts being produced by raindrops. It is the intermediate temperature range, perhaps +5 to −10°C, where the possibility of misinterpreting the data exists.

Table 2 gives the average PMS (>150 μm) and IPC concentrations for seven consecutive penetrations in a cloud on 16 July 1976 at about −10°C. Initially the IPC is counting only a small percentage of the particles >150 μm. However, while the concentrations measured by the PMS probes are fairly constant with time after the second penetration, the concentrations measured by the IPC are clearly increasing with time. In fact, the percentage of particles counted by the IPC increases approximately exponentially with time from 2215 to 2225 GMT. This effect could be produced either by a change in phase of the particles or by significant changes in the particle size distributions. That it was not due to a change in phase is demonstrated by the replicator data which showed that the large particles in penetrations 2–5 were ice.

The size distributions averaged over each of five of the penetrations are shown in Fig. 6. As time progresses there are fewer small particles and more large particles in the cloud. From 2217 to 2231 GMT, the average particle size (>150 μm) increased from 215 to 400 μm. This major change in the size distribution is undoubtedly the cause of the increase with time of the percentage of ice particles counted by the IPC. This is a somewhat unusual event since the crystals were produced by AgI seeding in the cloud at 2213 GMT, but it does illustrate the strong dependence of IPC concentration on particle size and the value of having particle size information in conjunction with IPC concentrations.

Table 2. Average IPC and PMS concentrations measured during seven consecutive penetrations of a cloud on 16 July 1976.

Time (GMT)	Temperature (°C)	Average IPC (ℓ^{-1})	Average PMS >150 μm (ℓ^{-1})	IPC÷PMS (%)
2215:43	−9.2	0.0	0.1	0.0
2217:35	−9.8	0.1	59	0.2
2220:25	−9.7	2.5	67	3.7
2222:43	−9.5	9.9	90	11
2225:03	−9.7	25	32	78
2228:12	−9.9	27	58	47
2230:51	−9.9	39	45	87

b. *Application of the data*

If particle size and concentration information is available for use with the IPC data, then the method

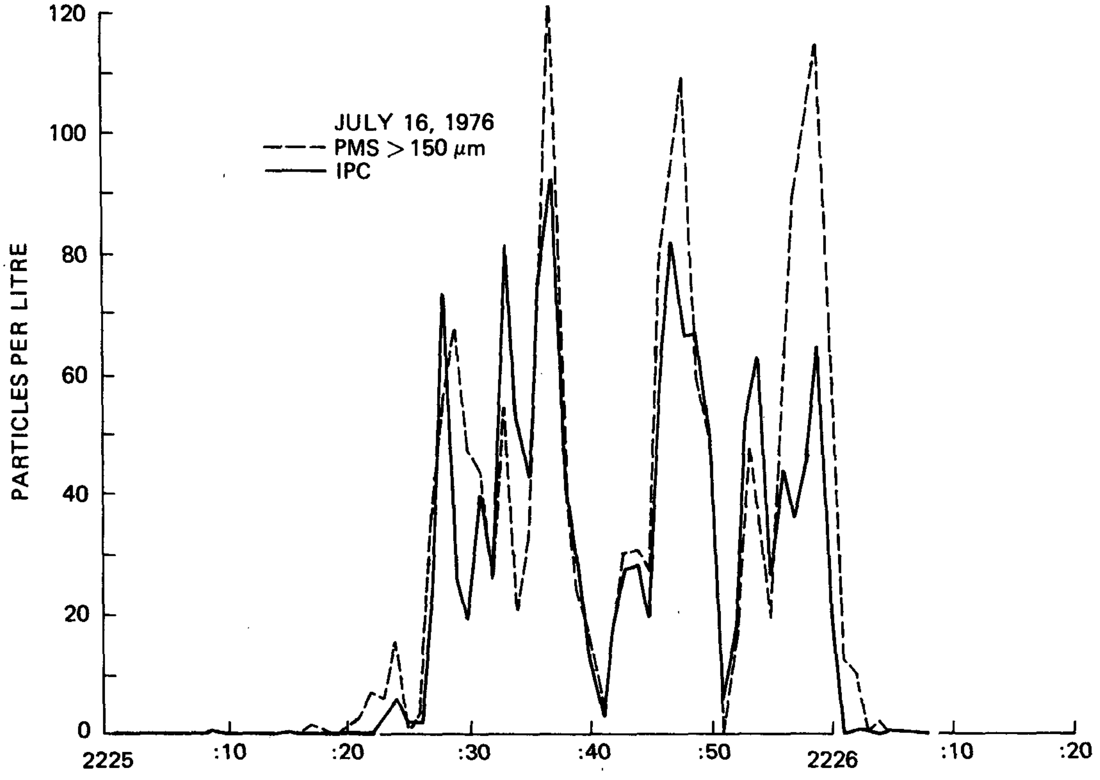

Fig. 5. Particle concentrations as a function of time as measured by the PMS probes and the Mee IPC. The measurements are for one pass through a cloud at a temperature of −9.6°C and an altitude of 4310 m.

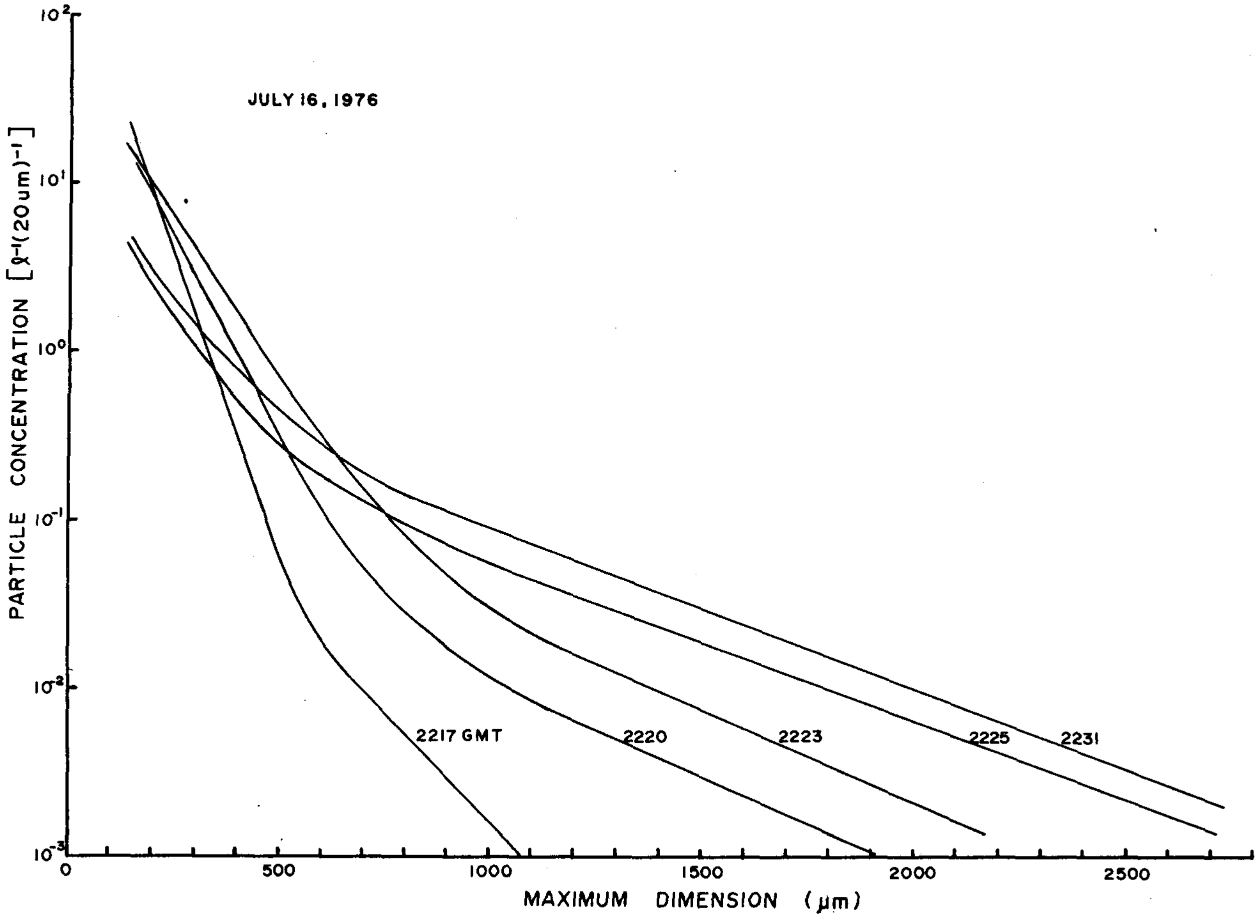

FIG. 6. Average particle size distributions for each of five penetrations on 16 July 1976.

of Fig. 7 should be used to decide on the ice/water content of the cloud. The phase of the cloud particles is presented as a function of the ratio of the IPC and PMS (>150 µm) particle concentrations and the average size of the particles >150 µm. The averaging period used to determine the concentration ratio can be of any length, though it is usually the duration of a cloud penetration. This figure represents data gathered during 27 cloud penetrations on 5 days in 1976 at a threshold voltage of 50 mV. Changing the threshold significantly would result in different boundaries on the figure. For each of the penetrations the phase of the large particles could be definitely verified by another means (replicator, sampling tube, visual observations, etc.).

The basic premise used in constructing Fig. 7 is that it has been adequately shown that where the particles >150 µm are ice the IPC and PMS concentrations will agree and where the particles are water the concentrations will be greatly different.

Fig. 7 is divided into three basic regions: 1) particles producing a data point to the left of the solid line labeled I on the figure were all ice; no decision can be made on particle phase in the hatched region, since the particles are too small to be counted by the IPC; 2) particles producing a data point to the right of the line labeled W were water drops; 3) particles producing points between the I and W lines were a mixture of ice particles and water drops or possibly partially melted ice particles in a precipitation shaft; in practice few observations fall into this region.

The ice particle region can be subdivided on the figure according to cloud type as follows: (i) Layer cloud (temperature 0 to −2°C); (ii) Convective cloud (temperature −9 to −10°C); (iii) Convective cloud (temperature 0 to −8°C). These regions are the result of a small data set and should only be used as an indication that the crystal habit and the degree of riming affect the efficiency with which the particles are counted by the IPC. Heavily rimed particles produce points which fall in region Ic. They are counted more efficiently than unrimed crystals, which are usually found in regions Ia and Ib.

The data point for sugar from the laboratory experiments would fall in region Ic of Fig. 7. The numerous crystal faces on a sugar crystal may be the reason for it being counted with an efficiency similar to that for graupel particles.

The water drop region can be divided according to concentration as follows: (i) drop concentrations $>3\ \ell^{-1}$, (ii) drop concentrations $<3\ \ell^{-1}$. Region Wb generally results in an IPC concentration of $0\ \ell^{-1}$ since only a very low percentage (say 1%) of a low concentration could possibly be counted.

Due to the steep slope of the I line between 210 and 265 μm great care should be exercised in deciding whether particles of this average size are all ice or water and ice combined.

Fig. 7 was used to determine the phase of particles $>150\ \mu$m for 101 cumulus cloud penetrations in 1976. These are discussed by Isaac and Schemenauer (1978). Continuous replicator data were available for 13 of the 101 penetrations and a sampling tube for large particles similar to that of Schreck *et al.* (1974) was operated during each penetration. In none of the cases did a phase determination from these two sources disagree with that from the IPC.

If coincident PMS 1-D or similar data are not available, then it is more difficult to make a definite decision on the cloud's ice/water content. The following guidelines do, however, apply for a threshold voltage of 50 mV:

1) If the particles are all water, the average IPC concentration for the penetration will be $\leqslant 0.2\ \ell^{-1}$, usually $0\ \ell^{-1}$.

2) If the average IPC concentration for the penetration is nonzero, then some ice could be present; if it is $>0.2\ \ell^{-1}$, ice is present.

3) If the average IPC concentration is $>5\ \ell^{-1}$, the particles are all ice.

Obviously these guidelines cover a wide range of cloud conditions. In reality, if operating in one particular type of cloud the observer will develop a more refined set of criteria for use with the IPC results.

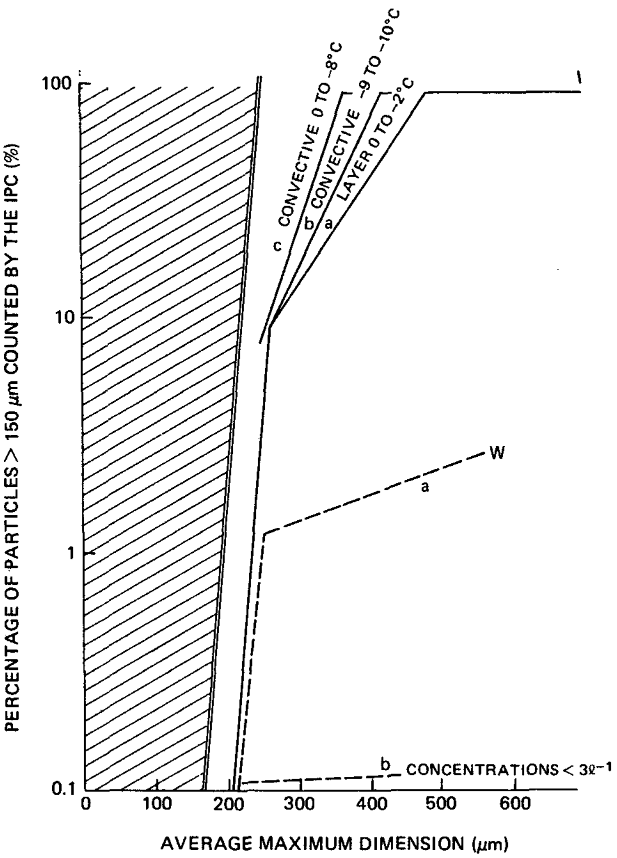

FIG. 7. Phase of particles counted by the Mee IPC as a function of particle size and the percentage counted. Percentage counted is the ratio of the IPC concentration to the PMS concentration of particles $>150\ \mu$m. Observations of ice particles fall into the region to the left of the line labeled I; observations of water drops to the right of the line labeled W. Particles to the left of the double line are too small to be counted at a threshold voltage of 50 mV.

6. Discussion and conclusions

The response of the Mee Industries Model 120 ice particle counter to crystalline and non-crystalline substances has been examined in the laboratory. A strong increase in counting efficiency with decreasing threshold voltage and increasing size was found for all materials and sizes investigated. The counting efficiency for crystalline materials is a factor of 10 or more higher than for non-crystalline materials, the exact ratio depending on the threshold voltage. The IPC can usefully serve as an ice particle detector in-cloud with the qualification that for a given penetration average concentrations $\leqslant 0.2\ \ell^{-1}$ can be produced by raindrops alone.

The IPC is capable of reliably measuring the concentration of ice particles $\gtrsim 150$–$200\ \mu$m when operated at a threshold voltage of 50 mV. This detection size cannot be lowered significantly, since in order to do so the threshold voltage must be reduced, resulting in increased counts from water drops. Optimum usefulness of the IPC is obtained by operating it in conjunction with a particle size measuring system such as a series of PMS probes. This is particularly valuable in mixed-phase clouds at relatively warm temperatures and in cases where the concentration of particles $>150\ \mu$m is only a few per liter.

It is possible that more information can be obtained from the Mee ice particle counter by analyzing the pulse heights produced by the particles as they pass through the sample area, i.e., operating with multiple-threshold voltages. This may result in a lower detection size for ice crystals as well as a greatly improved capability to reject water drops. This is presently being evaluated in laboratory and field experiments.

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