Degradation of In-Cloud Forward Scattering Spectrometer Probe Measurements in the Presence of Ice Particles

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ABSTRACT

Airborne measurements of cloud liquid water content derived from a formvar replicator, a Johnson-Williams probe and a forward scattering spectrometer probe (FSSP) are compared. These show that in the presence of ice crystals the FSSP droplet spectra may be artificially enhanced. Typically the ice produces a flat distribution superimposed on the actual droplet distribution. The concentrations measured by the FSSP in the presence of ice are found to be 2–3 orders of magnitude greater than the actual ice concentrations as measured by the formvar replicator and a 2D-C probe. Possible explanations for the abnormal behavior of the FSSP in the presence of ice particles are discussed.

1. Introduction

The Forward Scattering Spectrometer Probe (FSSP), manufactured by Particle Measuring Systems, is the most widely used instrument for the measurement of cloud droplet spectra (Knollenberg, 1981). Optics collect the light scattered in a forward direction by a droplet passing through a helium–neon laser beam. The particle size is determined from the measured light intensity using the Mie scattering theory. Recently a number of papers (Dye and Baumgardner, 1984; Cerni, 1983) have demonstrated certain limitations of the instrument. These studies were concerned with problems of measurement in clouds containing only the liquid phase. Unrealistic results may also be obtained if a cloud contains a sufficient concentration of ice particles. Measurements at the University of Wyoming field station on Elk Mountain were made by Vali *et al.* (1980, 1981) of the response of both an Axially Scattering Spectrometer Probe (ASSP) and a FSSP to ice crystals. Measurements were made in both naturally occurring ice clouds and with artificially produced ice crystals. They found that both instruments respond to ice particles with a nearly uniform distribution of counts in all size channels which is superimposed on any "true" droplet spectrum that is present. False counts due to the ice particles were registered in concentrations 300–3000 times higher than the actual ice concentrations. These measurements were made with ground-based instruments, at velocities low compared to aircraft speeds. Although experienced users of the FSSP are aware that this problem can also occur when making airborne measurements, this paper documents the effect for the first time.

As part of the Cooperative Convective Precipitation Experiment (CCOPE) the Desert Research Institute operated an instrumented Aerocommander aircraft for the measurement of cloud microphysical parameters. In addition to a FSSP the aircraft was equipped with a PMS 2D-C probe, a Johnson–Williams (JW) hot wire device and a continuous record formvar replicator (Hallett, 1976). The JW device provides a measurement of liquid water content (LWC) independent of that obtained from the integrated FSSP spectra. The formvar replicator may be used to estimate liquid water content as well as providing high-resolution information on ice particle type and concentration.

Examination of the FSSP measurements during passes through glaciated cumuli show that, on occasion, unusually flat spectral distributions are observed which can be attributed to the presence of ice particles. Some possible explanations for the response of the FSSP to ice particles are discussed in the final section.

2. Results

Several passes were made on 21 July 1981 through a line of cumulus congestus lying in an east–west direction 60 kilometers to the south of Miles City, Montana. The passes were generally made at a true airspeed of 110 m s^{-1} and an altitude of 6700 m (MSL), corresponding to a temperature of −21°C.

Figure 1 shows the liquid water contents derived from the JW, FSSP and the replicator and the ice concentration obtained from the formvar replicator. In general during the CCOPE project the JW- and FSSP-derived liquid water contents agree within 30%; Fig. 2 shows good agreement from a previous flight

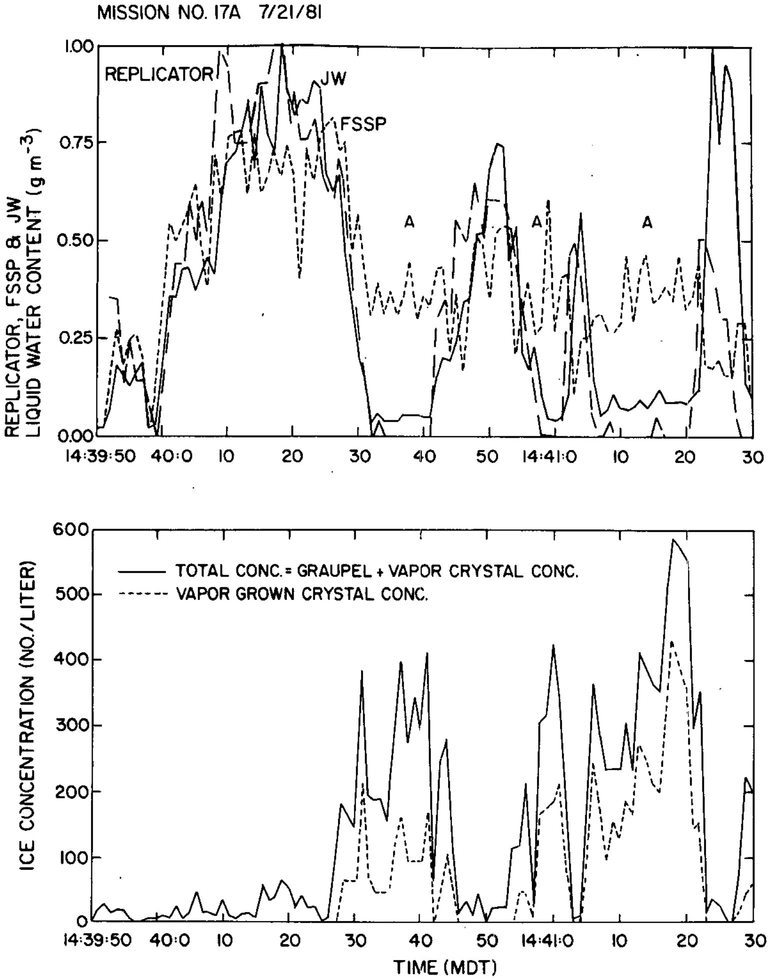


FIG. 1. Aerocommander replicator (long dashes), JW- (solid) and FSSP-derived (short dashes) liquid water contents and total ice and vapor-grown crystal concentrations for Cloud 2, Pass 1 on 21 July 1981.

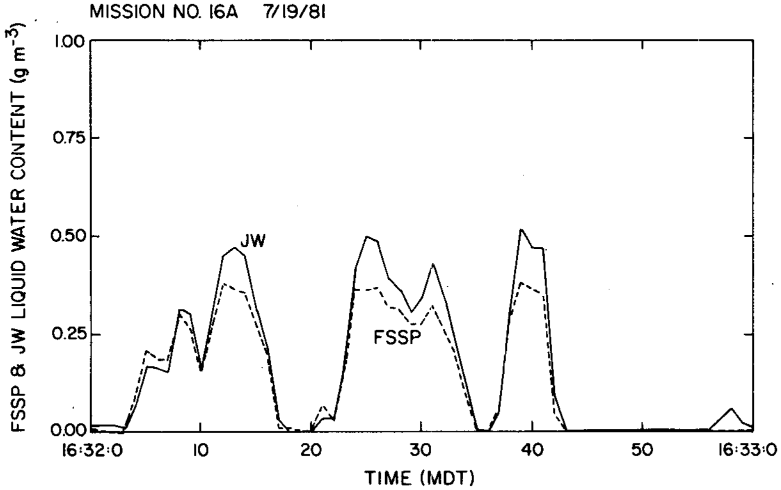


FIG. 2. Aerocommander JW- and FSSP-derived liquid water contents for Cloud 1, Pass 1 on 19 July 1981.

where low concentrations of ice were observed. In contrast, in Fig. 1, apart from the initial 15 s, the JW is much better correlated with the replicator than with the FSSP. In particular, during the periods marked "A" which correspond to regions with high ice concentrations, the FSSP registers liquid water contents of around 0.35 g m^{-3} when the JW shows only 0.05 g m^{-3} and the replicator less than 0.05 g m^{-3}. The JW can give artificially low readings under icing conditions (Strapp and Schemenauer, 1982), often indicated by a tendency to give negative readings. In this case the evidence from the replicator suggests that the JW is not misreading but rather the problem lies with the FSSP. The replicator, although it cannot be relied on to give absolute values of LWC since there are uncertainties in its collection efficiency and in estimates of the spreading factor following impact of the droplets, can indicate whether any droplets greater than 6 μm diameter are present. In the periods marked "A" no droplets were detected. In contrast, Figures 3b and d show typical spectra recorded by the FSSP during these periods. These were recorded in the presence of high ice concentrations (>300 l^{-1}) and show "apparent" droplets with sizes as large as 50 μm diameter. In contrast, spectra 3a and c, from periods of moderate ice (<30 l^{-1}), are more typical of spectra from continental cumuli.

The ice crystal concentrations were obtained from the replicator, which can detect ice particles in the range 10–3000 μm diameter. Typical ice particles detected during this pass are shown in Fig. 4. Evidence from the replicator and the JW suggest that in those periods with high ice concentrations the FSSP produces artificially enhanced spectra. These spectra are characteristically flat and because of the diameter-cubed dependence of LWC can result in high values of apparent LWC. Although it is no surprise that ice particles can trigger the FSSP electronics because it cannot differentiate between the liquid and solid phase, the magnitude of the effect is surprising. The maximum ice concentration of 600 l^{-1} recorded during this pass can only explain an apparent FSSP concentration of 0.6 cm^{-3}, yet concentrations of up to 150 cm^{-3} were recorded. This represents an effective multiplication of 250. From the sample volume of the FSSP and typical ice concentrations during this pass an event would be expected on the average of every ⅕ s. However, Fig. 5 shows the FSSP responding

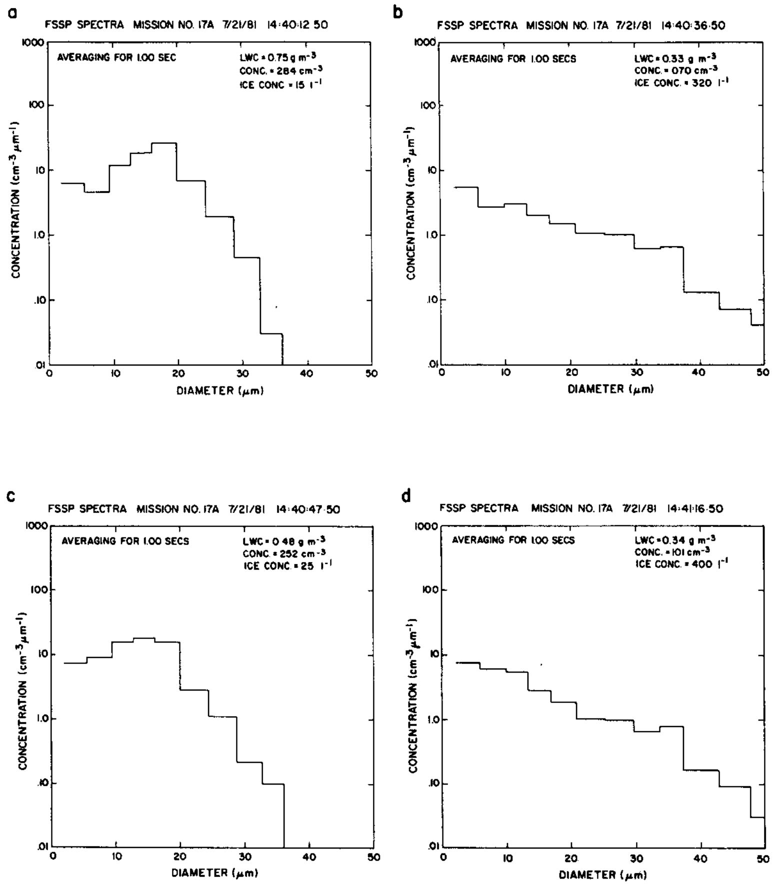
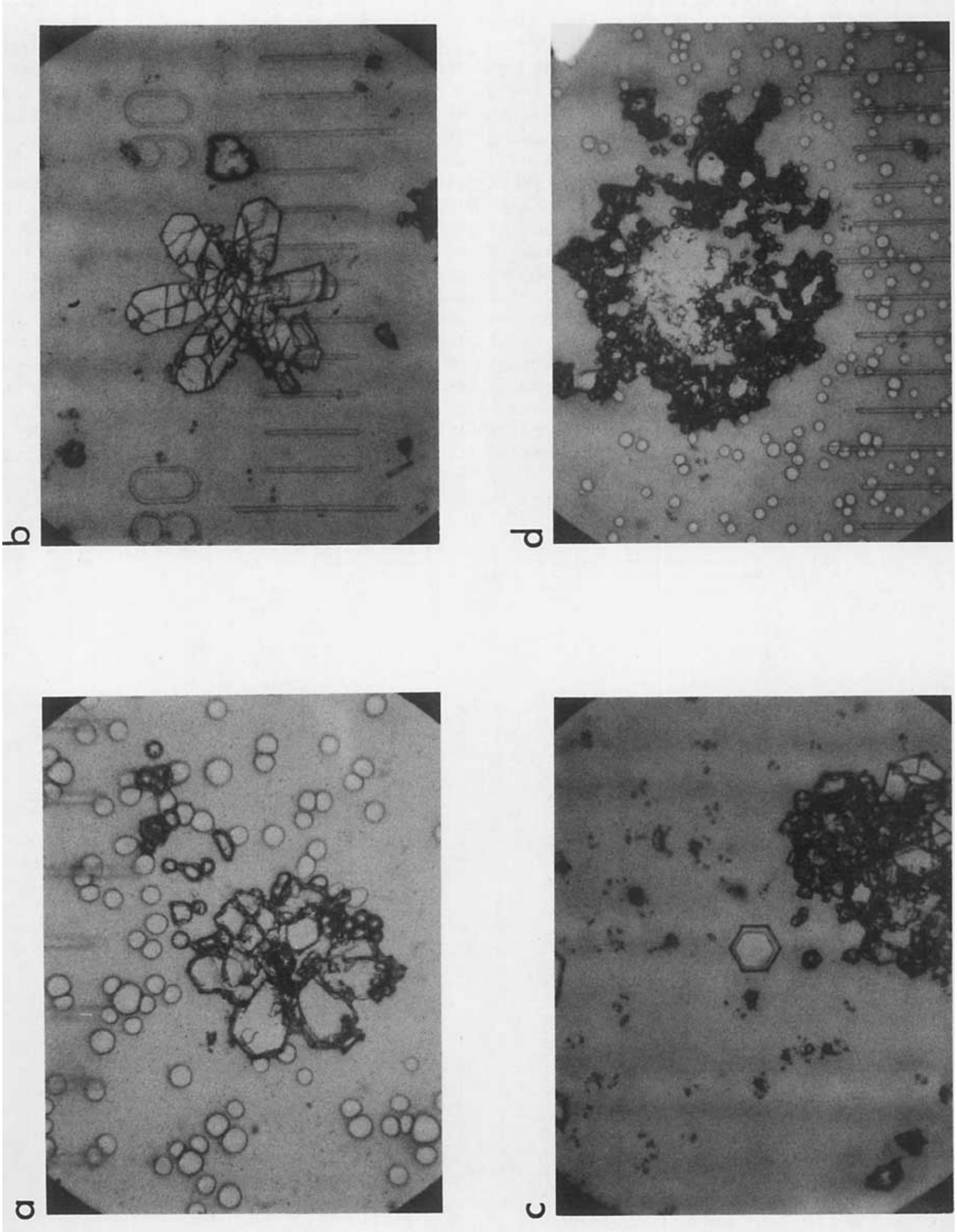


FIG. 3. Aerocommander FSSP spectra observed during Cloud 2, Pass 1 on 21 July 1981. (a) and (c): Low ice concentration; (b) and (d): high ice concentration.


b
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a
c

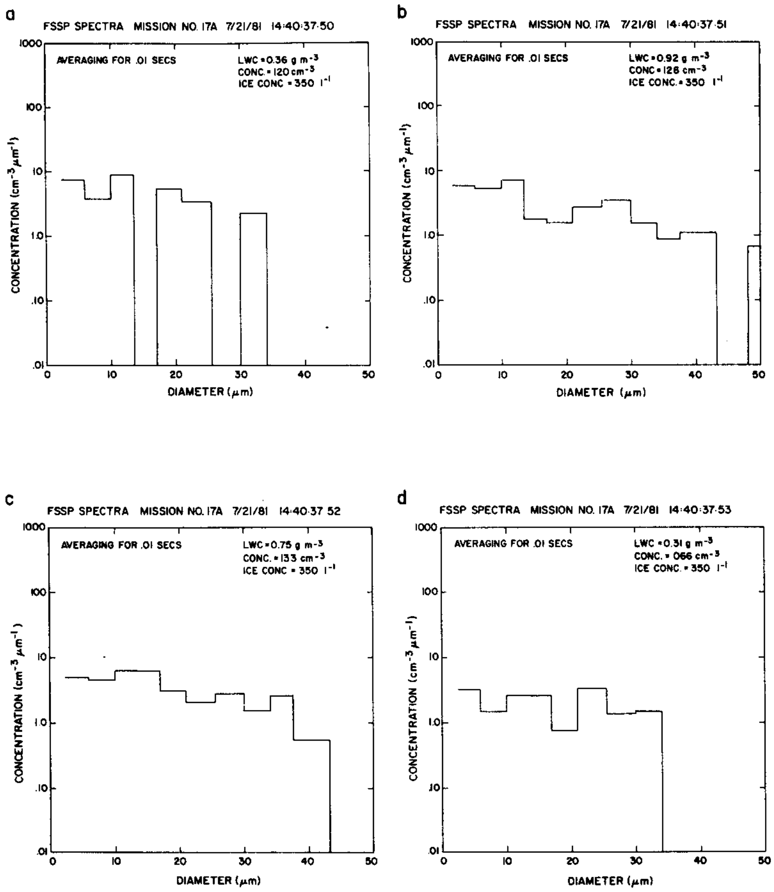

FIG. 5. Aerocommander FSSP spectra observed during Cloud 2, Pass 1 on 21 July 1981 for every 1/100 s between 1440:37.50 and 1440:37.53 MDT. High ice concentration.

to a number of particles every $^1/_{100}$ s during a low liquid water and high ice concentration situation. It is also necessary to explain why there does not appear to be a simple linear correlation between ice concentration and apparent FSSP concentration and why between the periods marked "A" in Fig. 1, where the ice concentrations are much reduced (<30 l^{-1}), the FSSP fails to recover and correlate with the JW measurements.

The FSSP appears to respond to a variety of ice particle types. The second pass through the cloud discussed above is presented in Fig. 6. The JW and replicator showed low liquid water contents (<0.1 g m^{-3}) through much of the pass, yet the FSSP indicated an apparent liquid water content varying between 0.25 and 0.75 g m^{-3}, again associated with the presence of ice. From 1445:00 MDT the ice consisted almost entirely of graupel, which by itself can trigger an exaggerated response by the FSSP. The same appears to be true for vapor-grown crystals. Figure 7 consists of data from part of a pass made on 17 July 1981 through a series of glaciated cumulus congestus at a height of 5700 m (MSL) and a temperature of −14°C. Apart from an initial 10 s period when ice concentrations were low, the JW- and FSSP-derived liquid water contents showed little agreement. This appears to be due almost entirely to the presence of vapor-grown ice, in this case mainly small plates (<100 µm diameter).

To confirm that this problem was not unique to the FSSP used on the Aerocommander or due to the mounting location on the aircraft, data were examined from the University of Wyoming King Air, which also participated in the CCOPE project. The King

FIG. 4. Ice particles recorded by the Aerocommander formvar replicator during cloud passes made on 21 July 1981 (scale 100 µm): (a) vapor-grown crystal with cloud droplets; (b) vapor-grown crystal only; (c) graupel and vapor-grown crystal; (d) graupel and cloud droplets.

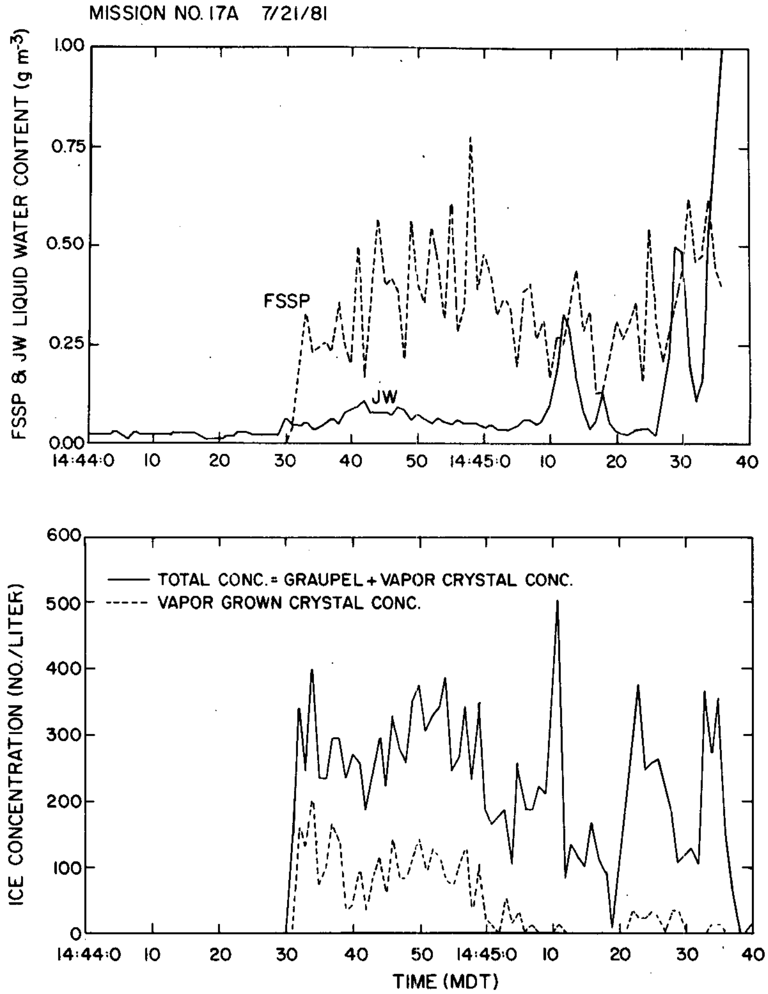

FIG. 6. Aerocommander JW- and FSSP-derived liquid water contents and total ice and vapor-grown crystal concentrations for Cloud 2, Pass 2 on 21 July 1981.

Air FSSP was also found to suffer contamination of the FSSP signal when ice was present. Figure 8 shows two one-second averaged spectra from a cloud pass on 11 July 1981 at a temperature of −14°C. The spectra at 1946:33 MDT (dashed line) was recorded during a period when the 2D-C probe recorded ice concentrations as high as 300 l^{-1}. The spectra shows the flat tail characteristic associated with the presence of ice which is absent from the spectra recorded later in the pass at 1947:50 MDT (solid line) when no ice was observed. During portions of this cloud where ice was present in significant concentrations ($>50\ \mathrm{l}^{-1}$) the FSSP-derived LWC was in general 50–70% higher than the JW value, in contrast to ice-free portions of the cloud where the JW usually read higher. Because the FSSP on the King Air operated on range 1 (nominal 2–32 μm) the effects of ice are not as noticeable as with the Aerocommander which operated on range 0 (nominal 2–47 μm). Any pulses which correspond to an apparent droplet size between 32 and 47 μm are not recorded on range 1, and because of the cubic dependence of LWC on size the introduced discrepancy between the JW and FSSP LWC is not as great as when operating on range 0.

Although in general during the CCOPE project the FSSP spectra from both the Aerocommander and the King Air were affected by the presence of ice particles, there were occasions when no effect was observed, even when ice in significant concentrations ($\sim 50\ \mathrm{l}^{-1}$) was present. There were no obvious differences between these occasions and those in which "contamination" occurred to explain this inconsistency.

3. Discussion

These results indicate that contamination of the FSSP spectrum in the presence of ice noted by Vali *et al.* (1980, 1981) for ground-based measurements is also observed at aircraft velocities. This can lead to an artificially broad spectrum with a corresponding

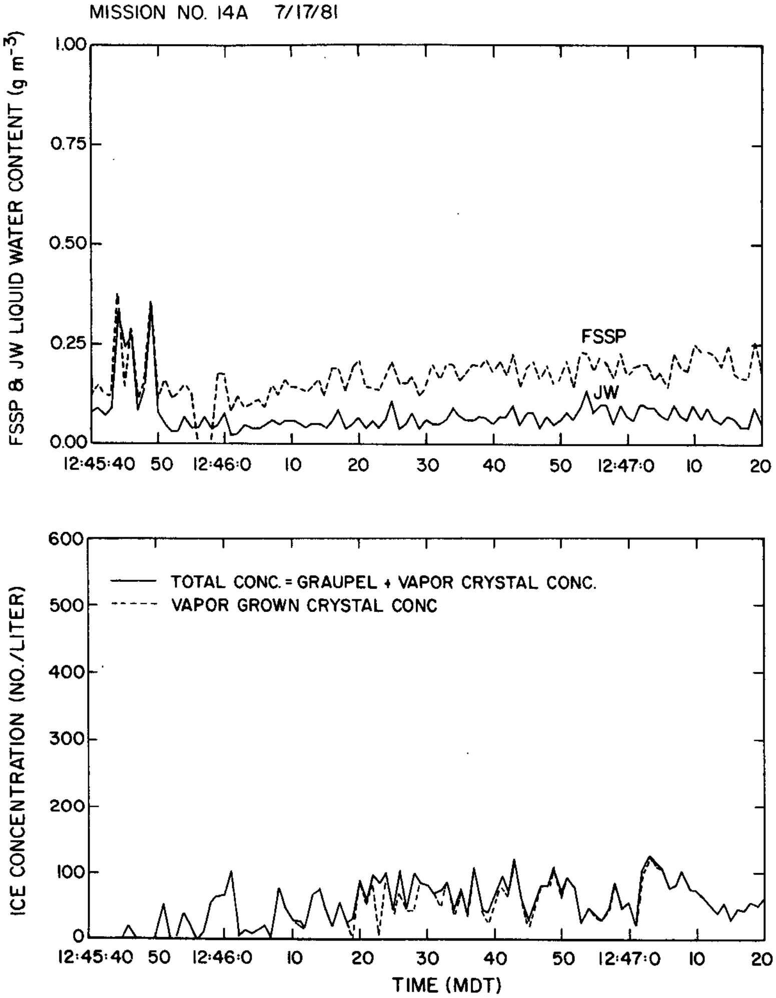

FIG. 7. As in Fig. 6 but for Cloud 1, Pass 2 on 17 July 1981.

increase in concentration and liquid water content. Combined with the degradation of the JW performance in heavy icing conditions this puts an increased uncertainty on LWC measurements in glaciated clouds. Moreover, the artificial broadening of the spectra means that interpretation of spectral shape needs to be made with caution when ice is present.

It would be useful if some limit could be placed on the ice concentration where the problem becomes significant. Furthermore, is there some method for recovering contaminated data? To answer these questions it becomes necessary to attempt to understand better the possible reasons for the exaggerated FSSP response to ice particles.

a. Multiple scattering

Vali *et al.* (1980) suggested that ice particles greater than a certain size (d_l) may produce more than a single pulse during passage through the FSSP laser beam. Following the initial pulse, if the particle is still in the beam after the "reset" time for the probe, a second pulse may occur. For a true airspeed = 100 m s^{-1} and a "reset" time of 6 μs, d_l = 100 × 6 μm. Hence all crystals greater than 600 μm diameter can produce double pulses. However, this cannot explain the 2–3 orders of magnitude increase observed.

b. Ice splintering

Ice impacting on the tip of the FSSP, or inside the sample tube if the airflow is at an angle to the device, may shatter and produce a number of smaller particles. This is particularly true for graupel which on impact at 100 m s^{-1} with the film used in the formvar replicator can produce an average of 200 smaller particles scattered over a radius of 2 cm (see Fig. 9). The breakup of vapor-grown crystals is less dramatic and is size dependent, with larger crystals breaking up more readily. If any vapor-grown aggregates are present they would be expected to break up extremely readily. However, examination of the 100 Hz Aero-

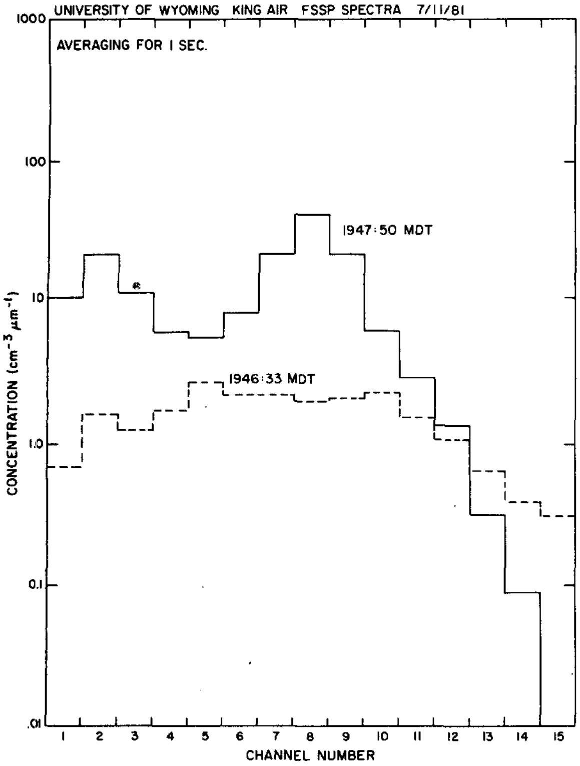

FIG. 8. King Air FSSP spectra observed on 11 July 1981 at 1947:50 MDT with low ice concentrations ($<5\ \mathrm{l}^{-1}$) and at 1946:33 MDT with high ice concentrations ($\sim 300\ \mathrm{l}^{-1}$).

commander FSSP data found no evidence for bunching of the large-size pulses, which one might expect if they were due to individual collision events. Another possibility is that ice sticks to the FSSP inlet, becomes melted due to the sample tube heater and sprays the sample volume with water drops and small pieces of ice. This effect is likely to continue for some time after passage through a glaciated region of the cloud. There is no evidence for this in the data even though during the CCOPE project the Aerocommander FSSP did become covered in ice during passes through heavily glaciated clouds. These possibilities are impossible to quantify as they are likely to depend on ice particle type and environmental temperature.

c. *Increase in FSSP sample area*

Ice particles cannot be expected to behave optically in the relatively simple manner of water droplets during passage through the FSSP laser beam. Generally, if a particle passes outside the depth of field (DOF) of the FSSP the particle is rejected because the annulus photodiode voltage is greater than the signal photodiode voltage. Because of the complicated reflective and scattering properties of ice particles it is conceivable for an ice particle outside the DOF but within the usual sensitive beamlength of the FSSP to provide a stronger signal to the signal photodiode than to the annulus photodiode. This would be interpreted by the FSSP electronics as a particle within the DOF and would be accepted. The ratio of sensitive beamlength to DOF provides a maximum value for the increase in effective DOF for ice particles. This ratio may be obtained from the DOF fraction, measured by Dye and Baumgardner (1984) to have a minimum value of 0.2, a multiplication in effective DOF of 5. Another consideration is that because of their large size, ice particles may be detected even when their centers pass outside the laser beam. So long as that part of the ice particle that intercepts the laser beam takes as long as or longer than the average transit time to pass through the beam it will be accepted by the velocity-averaging circuitry. Assuming a spherical ice particle and a laser beam diameter of 0.17 mm (effective beamwidth = 0.1 mm), calculation shows that a 500 μm particle will take a longer than average length of time to pass through the beam as long as its center is within 300 μm of the center of the laser beam. This increases the effective beam width to 660 μm for a 500 μm particle, a multiplication of 6.6. Combined, these effects could conceivably provide a $6.6 \times 5 = 33$ increase in the FSSP sample area for a 500 μm particle. For the maximum ice concentration of $600\ \mathrm{l}^{-1}$ during Pass 1 on 21 July 1981 (Fig. 1) this could only explain an apparent concentration of $0.6 \times 33\ \mathrm{cm}^{-3} = 20\ \mathrm{cm}^{-3}$, at a time when concentrations of up to $150\ \mathrm{cm}^{-3}$ were recorded. However, when vapor-grown crystals are the predominant ice form present (Fig. 7) this conjectured increase in FSSP sample area is likely to be a more important effect since ice splintering as discussed in Section 3b will be less dramatic.

d. *Impaction on the FSSP optics*

A further possibility is that ice particles enter the laser exit tube from the sampling area and impact on the 90° prism. Certainly glass calibration beads, if not used with caution, can cover the prism face and degrade the performance of the FSSP. If ice particles stuck to the prism face, possibly by breaking up on the edge of the laser exit tube, totally artificial results would be obtained. The prism is heated during flight to vaporize any water particles that do collect, but it is conceivable that ice particles at cold enough temperatures may have a significant residence time. This could explain why in the first pass on 21 July 1981 (Fig. 1) the FSSP did not recover and agree with the JW in the periods between those with high ice concentrations.

These suggestions are speculative and careful laboratory studies to check the suggestion of an increased sample area are needed, as are studies under icing conditions to investigate the possibilities of ice shattering and impaction on the FSSP optics. Such studies

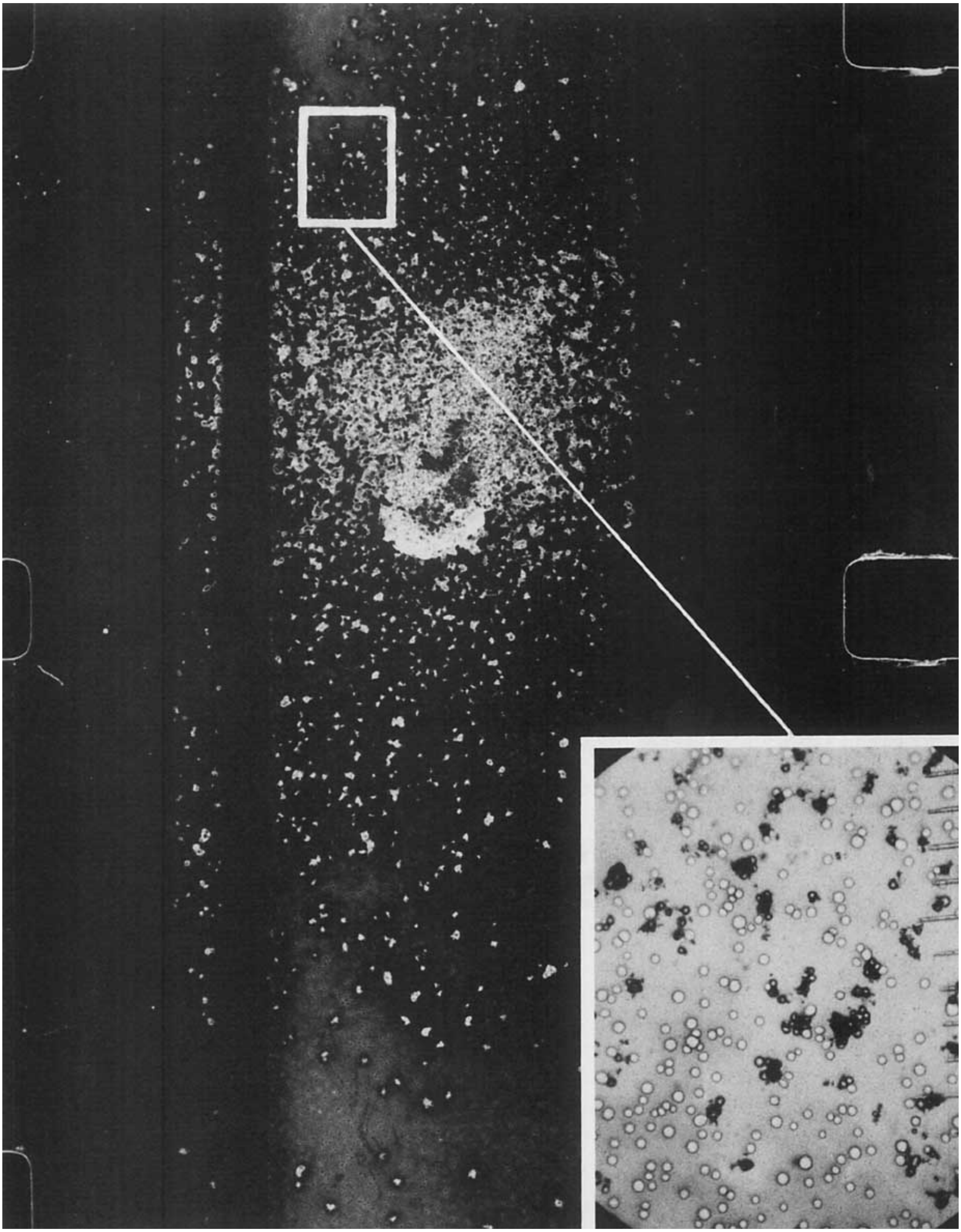

FIG. 9. Breakup of graupel particle on impact with formvar replica on 16 mm film. Several hundred particles ~ 100 μm in diameter are produced. As the particles are collected in the formvar, they freeze supercooled droplets with which they come into contact. These can be distinguished by their darker appearance in the inset (scale 100 μm).

might indicate design modifications that could minimize these problems. Because the mechanism for the enhancement of the FSSP response to ice particles is not understood and may be a combination of a number of effects, it is difficult to devise a scheme for recovering contaminated data. Vali *et al.* (1981) suggest that when flat spectral tails are encountered a rough correction may be made by removing that portion of the spectra. This will probably be reasonable if liquid droplets contribute the majority of the spectral shape and information is required only on droplet concentration and liquid water content. If ice contributes the majority of the pulses recorded by the FSSP it would be dangerous to attempt to recover the liquid droplet portion of the spectra. Furthermore, in the presence of ice particles, interpretations of spectral shape need to be made with caution.

4. Conclusions

It has been shown that ice particles are detected by the FSSP at concentrations 2–3 orders of magnitude larger than the "actual" ice concentration. The contribution of the ice to the spectra is a relatively flat distribution in all channels, superimposed on the "true" liquid water spectra. Contamination of the FSSP spectra may be recognized by an unusually flat tail in the distribution and comparison of the derived liquid water content with other devices such as the JW probe.

The mechanism for the exaggerated response of the FSSP to ice particles is not well understood and further laboratory studies are needed to resolve this question. Furthermore, the problem is likely to be more obvious when operating on range 0 or when the peak of the liquid droplet spectrum is in the lowest channels. Therefore any attempted recovery of the true droplet spectrum by removing the flat tail of the distribution will be dependent on the conjectured contribution made by the ice particles and the particular use being made of the FSSP data. It follows that when ice is present the FSSP may not be the best instrument for droplet spectral measurements in investigations of cloud processes where the details of the spectrum are important; for example, whether the Hallett–Mossop process (Hallett and Mossop, 1974), ice-graupel collisional charging (Jayaratne *et al.*, 1983) or spectral broadening due to dry air entrainment are likely to be important in a particular situation. It also illustrates the value of making microphysical measurements by a variety of methods to expose false results that might otherwise go unnoticed.

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