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# Improved measurements of the drop size distribution of a freezing drizzle event

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**Abstract**

Airborne measurements from a new digital holographic camera are compared with PMS 2D-C measurements during the Canadian Freezing Drizzle Experiment. The digital holographic camera is not affected by drop sizing errors associated with out of focus particles in the same way as the 2D-C probe. Recent theoretical simulations of 2D-C particle sizing errors and approaches for statistically correcting the measurements are discussed. The theoretical simulations predict that in freezing drizzle with drop diameters from about 50–200 $\mu$m, uncorrected PMS 2D-C measurements can produce an artificial tail in the drop size distribution that extends out to about 325 $\mu$m. The digital holographic camera does not see the artificial tail. 2D-C measurements of drop size distribution in freezing drizzle that have been statistically corrected show an improved agreement with the digital holographic measurements. Some digital images of drizzle drops and ice crystals from a recently improved version of the instrument, called a cloud particle imager (CPI), are also shown. 

*Keywords:* Freezing drizzle; Aircraft icing; Drop size distribution; Instrumentation

## 1. Introduction

The Glossary of Meteorology defines freezing drizzle as supercooled water drops with diameters from 200 to 500 $\mu$m (Huschke, 1959). The performance of typical turboprop aircraft (including many commuter aircraft) with pneumatic boots can be severely affected by supercooled drops $\gtrsim 50$ $\mu$m in diameter (Cooper et al., 1984; Politovich, 1989, 1996). This has led some investigators (e.g., Jeck, 1996; Cober et al., 1996) to consider freezing drizzle associated with aircraft icing encounters as super-

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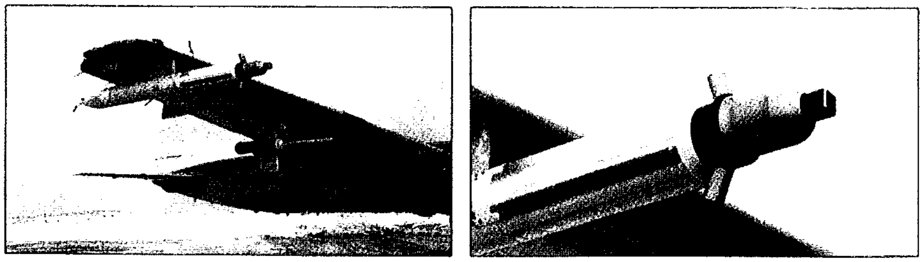

*Digital Holographic Camera*

Fig. 1. Photographs showing (left) installation of PMS probes and digital holographic probe mounted under the right wing of the NRC Convair-580 and (right) close up of the digital probe on the right wing tip.

cooled drops with diameters from about 50–500 $\mu$m. In the lower end of this size range, Korolev et al. (1991, 1997) have shown that the Particle Measuring Systems (PMS) imaging probes are capable of significant (up to about a factor of two) errors in both sizing and counting drops. Here we present measurements in freezing drizzle using a new imaging probe with a novel measurement technique. The measurement errors associated with this instrument are significantly smaller than those associated with PMS probes, particularly for particles in the range from 50 to 200 $\mu$m.

The Canadian Freezing Drizzle Experiment (CFDE) field program, conducted near St. John's, Newfoundland in March 1995, focused on improving understanding of the meteorology associated with freezing drizzle and making improved in situ observations (Isaac et al., 1996). A Convair-580 research aircraft operated by the National Research Council (NRC) and the Atmospheric Environment Service (AES) of Canada was extensively equipped with microphysical instrumentation. The instrumentation on the Convair-580 included a new optical imaging probe that makes 3.7 $\mu$m size resolution digital images of particles from about 10 $\mu$m to 2 mm in diameter. The new probe can use digital holography to reconstruct in-focus images from in-line holograms (Lawson and Cormack, 1995; Lawson, 1995). Photographs of the Convair-580 with PMS probes and the new digital holographic probe installed under the right wing are shown in Fig. 1.

New data collected in freezing drizzle during the CFDE support theoretical calculations (Korolev et al., 1991, 1997) and recent laboratory work (Reuter and Bakan, 1997) showing that size measurements of drops up to about 200 $\mu$m diameter using the PMS 2D-C imaging probe (Knollenberg, 1981) can be overestimated by up to 125 $\mu$m. A statistical correction applied to the 2D-C data (Korolev et al., 1997) can improve the measurements somewhat, but does not correct for all of the measurement deficiencies of the older imaging probes. In this paper, we compare measurements in freezing drizzle using the new digital holographic probe and the Particle Measuring Systems (PMS) 2D-C. Statistical corrections following Korolev et al. (1997) are presented.

## 2. 2D-C measurements

Korolev et al. (1991) present theoretical arguments and laboratory measurements which suggest that the PMS 2D-C can overestimate by up to 125 $\mu$m the size of spherical objects up to about 200 $\mu$m in diameter. Recently, Korolev et al. (1997) and Reuter and Bakan (1997) have strengthened both the theoretical and laboratory results. Basically, the 2D-C measurement problems stem from two inadequacies.

(1) Particles that do not pass exactly through the focal plane (usually in the middle of the probe arms) are out of focus. The probe provides only a one-bit (black/white) digitization of the shadow size, so that the image size of the particle will vary depending on the distance $Z$ the particle passes from the focal plane. For $Z = 3$ to $8r^2/\lambda$ (where $r$ is radius and $\lambda$ is the wavelength of laser light) drops are mis-sized by about 20–80%.

(2) At aircraft (100 m s$^{-1}$) speeds, the probe electronics detect only a fraction of the particles that are $\lesssim 100$ $\mu$m in diameter.

Fig. 2 shows examples of numerical simulations of Fresnel diffraction of 100 $\mu$m diameter spherical particles seen by the PMS 2D-C probe as a function of distance ($Z = Z_d\ r^2/\lambda$) from the focal plane. The simulation on the left shows the diffraction pattern with infinite size resolution and on the right with 25 $\mu$m pixels. The numerical simulations show that the 100 $\mu$m particles are oversized as $Z_d$ increases until about $Z_d = 8$ where they are missed altogether or severely undersized. The patterns in Fig. 2 only take into account the effects of discrete pixel size and thresholding inadequacies of the 2D-C probe and not latency in the electronics. Recent laboratory tests at the GKSS in Geesthacht, Germany by two of the authors (AVK and JWS) suggest that the number of particles with diameters $\lesssim 100$ $\mu$m that are missed or undersized increases dramatically with particle velocity.

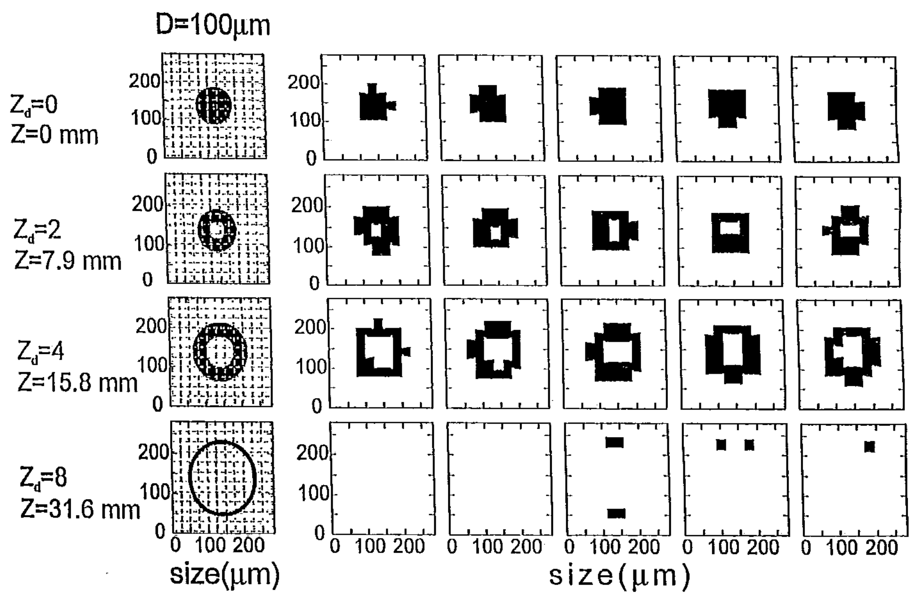


Fig. 2. Korolev et al. (1997) numerical simulations of Fresnel diffraction of a 100 $\mu$m spherical particle. Patterns on the left are for 1-bit shadow images with infinitely small pixels and on the right as seen by the PMS 2D-C with 25 $\mu$m pixels resolution. Moving down the figure, the patterns vary as a function of distance from the focal plane.

## 3. Holographic measurements

Both off-axis and in-line holography have been used for cloud particle measurements for nearly 30 years (Trolinger, 1975; Brown, 1989). These older measurements used optical holography, where the hologram is cast on a holographic (film) plate. The holographic plate must then be processed by recreating the hologram using laser(s) in a darkroom. The optics are adjusted so that the focal plane is moved incrementally through the sample volume, typically about half a liter. Manual processing of one hologram typically requires days or even weeks (Brown, 1989). Previous attempts to automatically process optical holograms (e.g., Bexon et al., 1976; Zarschitzky, 1985) have often yielded unreliable results because of the inherent low signal to noise (Borrmann and Jaenicke, 1993). [1]

The digital holographic process used here differs from the older method in that the hologram is cast directly on a digital CCD camera instead of a holographic plate. Lawson and Cormack (1995) describe the theory and methodology of the digital holographic technique in detail. Here we give a brief overview of the instrument used in the CFDE. Interruption of the beam from an upstream laser diode triggers another laser diode which is pulsed for 30 ns to cast a Fresnel diffraction (shadow) pattern of the particle on a $512 \times 512$ solid state camera. The sample volume of the individual digital holograms is less than optical holograms, about 1 $cm^3$ compared with 500 $cm^3$. However, digital holograms can be recorded at rates of 30 $s^{-1}$ and higher.

The shadow pattern of the digital hologram, actually an in-line (Gabor, 1949) hologram, is computer-processed by numerically propagating the particle through the sample volume until the best in-focus image is obtained. This differs from optical holography where this process must be accomplished by re-creating the hologram in a darkroom. An example of the numerical process used to process a digital hologram is depicted in Fig. 3. The first panel in the figure shows the 256 grey-level (8 bit) hologram and a cross section of shadow depth of a $100 \pm 1\sigma = 4.2$ $\mu$m glass bead that is $Z = 13.5$ mm $(4r^2/\lambda)$ from the focal plane. Casting the Fresnel equation in terms of Fourier transforms, the image was propagated through the sample volume in 0.5 mm steps until the best in-focus image was found. The second panel in Fig. 3 shows the result of propagating the image and the cross section of the resulting shadow. The processed size of the drop, 103 $\mu$m, is determined by thresholding the propagated image at the 65% (of full shadow) level. [2]

Processing of data from the digital holographic probe used in the CFDE is computationally intensive and requires some operator interaction to reject artifacts. The process-

[1] A recent processing advancement using a CCD camera to capture and view optical holograms was achieved by Borrmann and Jaenicke (1993). They found that this reduced analysis time slightly and the minimum detectable droplet diameter from about 12 $\mu$m (Brown, 1989) to about 6 $\mu$m. However, the signal noise was still inadequate to automatically identify the particles and drops with diameters $< 10$ $\mu$m and required increased post-processing magnification and special human attention.

[2] By thresholding the original hologram (the top left image in Fig. 4) in a way analogous to the processing done in the PMS 2D-C probe (i.e., sizing the particle by measuring the width of the shadow at the 50% level), the 100 $\mu$m bead is measured to be 125 $\mu$m in diameter, which is in good agreement with the theoretical simulation shown in Fig. 4.

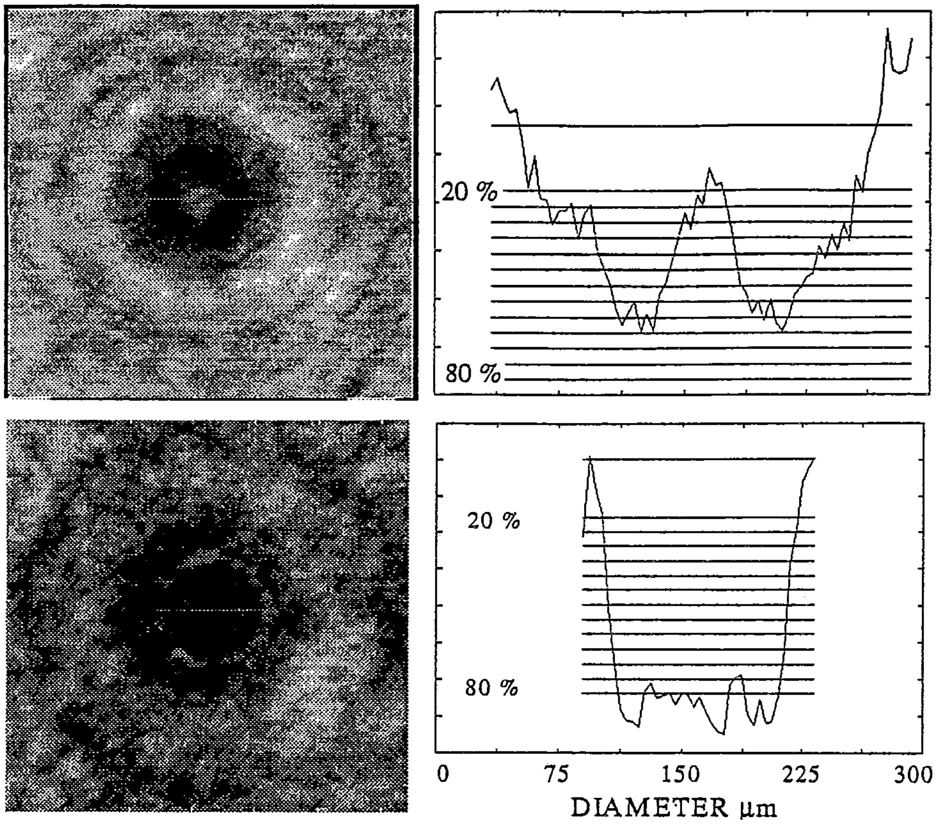


Fig. 3. Example of (top) digital hologram of 100 $\mu$m bead taken at $Z_d = 4$ and cross-section with shadow intensity labelled at 20% and 80%, and (bottom) image and shadow cross-section of bead after digital holographic processing.

ing requirements are not fundamental to the basic measurement technique because the probe used in the CFDE was a prototype and more recent technology has improved many features, as described by Lawson (1997).

In order to increase processing speed of data collected during the CFDE, an alternative to the digital holographic processing technique was developed which uses a software neural net to size spherical particles. A cross-section of the hologram with shadow widths at thirteen thresholds ranging from 20–80% of shadow depth is fed into the neural net algorithm. The neural net was first trained using polystyrene beads and water drops generated by a TSI 3450 drop generator and then tested on another data set.

Fig. 4 shows laboratory measurements using both the holographic technique and the neural net algorithm for various diameter polystyrene beads and 45 $\mu$m water drops produced by the TSI device. The manufacturers' standard deviations in diameters of the actual size distributions of the beads and drops differ for different sizes, but are on the order of 4%. Both the holographic and neural net algorithms produced good results; the

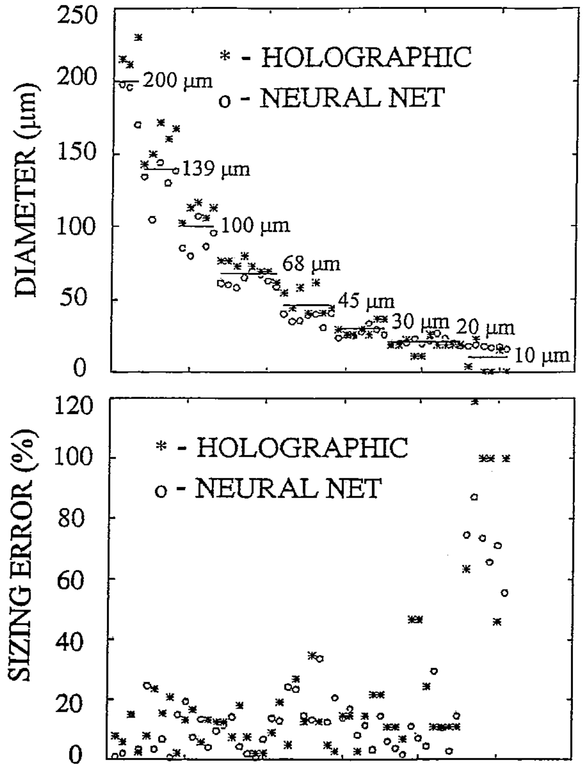


Fig. 4. Top graph shows results of holographic (∗) and neural net (∘) sizing where solid horizontal lines represent 200, 139, 100, 68, 30, 20, 10 $\mu$m beads and 45 $\mu$m diameter drops. Bottom graph plots sizing error on the vertical axis vs. particle diameters which register with the horizontal lines on the top graph.

RMS sizing errors over the range of diameters from 30 to 200 $\mu$m is 11% for the neural net algorithm and 12% for the digital holographic technique. The RMS error increases for both techniques to about 35% at diameters $\lesssim 30$ $\mu$m. The neural net approach takes less computer time and facilitates data processing.

The holographic data from the CFDE were processed using a hybrid approach. Holograms where the drops were noisy or far out of focus (i.e., $Z \gtrsim 20r^2/\lambda$) were flagged and processed using the full holographic algorithm while the bulk of the drops were processed using the neural net algorithm. Periodic comparisons between the holographic and neural net techniques provided a quality check. The measurement of particle concentration using the holographic probe involves corrections for probe activity and dead time. These corrections are currently being refined.

## 4. Measurements in freezing drizzle

The numerical simulations of Fresnel diffraction for discretized pixels shown in Fig. 2 were used as a basis to develop a technique to statistically correct the PMS 2D-C


Fig. 5. Examples of holograms containing in-focus and out-of-focus freezing drizzle drops observed on 15 March 1995.

measurements. A theoretical basis for this technique is given in Korolev et al. (1997). Fig. 5 shows examples of holograms with in-focus and out-of-focus images of freezing drizzle drops observed on 15 March 1995. Simultaneous measurements from the 2D-C and the new digital holographic probe were made in freezing drizzle during the CFDE. Both probes have a sample volume on the order of 41 $s^{-1}$ at 100 m $s^{-1}$. Fig. 6 shows a comparison of drop size distributions from the two probes along with the Korolev et al. (1997) theoretical correction. The measurements were made on 15 March 1995 near cloud top from 1943–1947 UTC. The drizzle drops formed through a collision coalescence mechanism (Cober et al., 1995; Isaac et al., 1996). The uncorrected 2D-C data

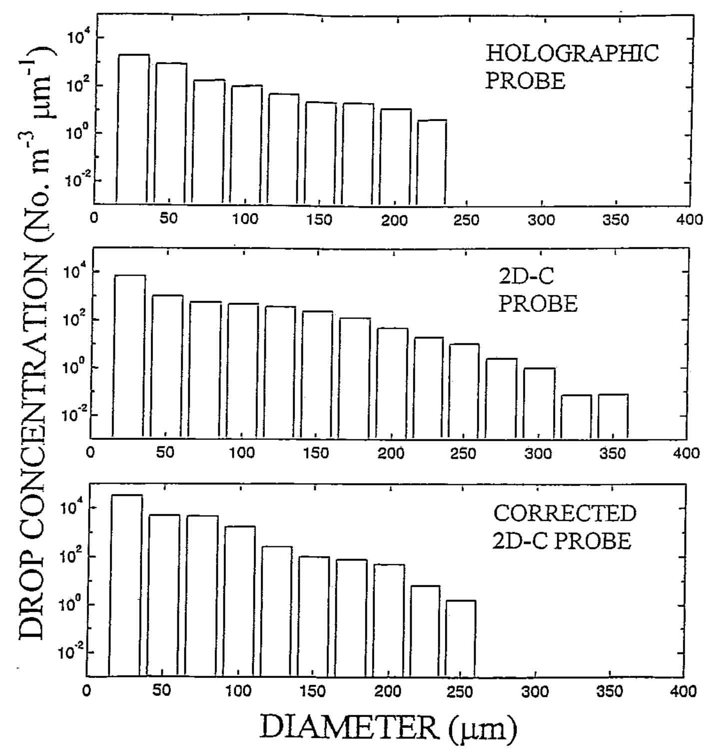


Fig. 6. Comparison of digital holographic, uncorrected and corrected 2D-C measurements collected in freezing drizzle from 1943–1947 UTC on 15 March 1995.

suggest that drops with diameters out to 350 $\mu$m were observed, while the holographic probe measured drops only as large as 225 $\mu$m. The apparent oversizing in the 150–350 $\mu$m range by the 2D-C is in general agreement with the Korolev et al. (1997) theoretical correction, also shown in Fig. 6. The agreement in the overall shape of the holographic and corrected 2D-C distributions is very good, although the PMS 2D-C numbers still require an airspeed correction which should substantially increase the concentrations at sizes less than 100 $\mu$m. The large (artificial) tail seen in the uncorrected 2D-C measurements is shifted to smaller sizes by the Korolev et al. (1997) correction scheme.

The artificial tail of the hydrometeor spectra could cause a significant change in calculated parameters such as median volume diameter, which is commonly used in determining aircraft icing severity (Politovich, 1989, 1996). Using data from the CFDE, a comprehensive comparison of drizzle spectra measured with FSSP, 2D-C and 1D-C probes and the Holographic camera are the subject of on-going research.

## 5. Observations of ice crystals

In addition to making accurate measurements of the sizes of freezing drizzle drops, the 3.7 $\mu$m pixel size of the digital holographic probe provides excellent reproduction of in-focus ice crystals. Fig. 7 shows examples of in-focus images of ice crystals observed during the CFDE. The images clearly show crystal habit and the effects of riming. For example, a hex-plate center can be seen inside of a dendrite and frozen drops can be seen on some of the needles. The detail of the riming process helps to identify microphysical processes and to determine the amount and size of supercooled liquid water drops that may have existed at the time of riming. Two of the needles observed at $-6°C$ showed split ends typical of needles observed in melting conditions on the ground by Knight (1979). It is difficult to explain how melting could have occurred in these clouds at $-6°C$; however, the crystals may have sublimated after being exposed to a region which was subsaturated with respect to ice.

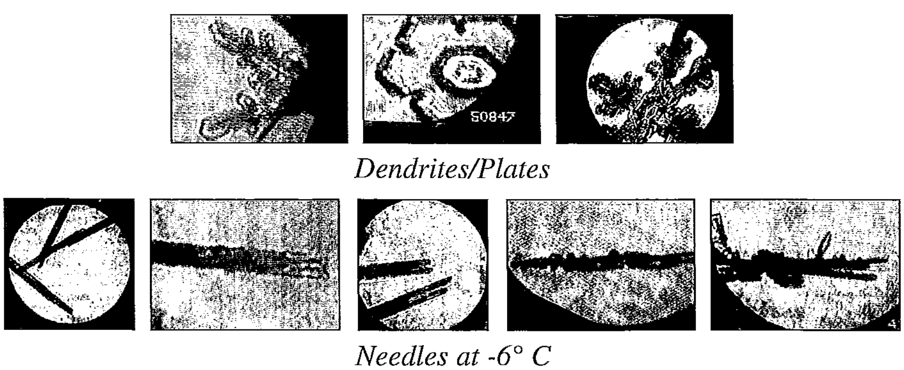


Fig. 7. Examples of (top) dendritic and sector plate ice crystals and (bottom) needles with and without riming observed at $-6°C$ during the Canadian Freezing Drizzle Experiment. The circular field of view is about 1.8 mm in diameter.

Because the in-focus images seen in Fig. 7 provide such excellent detail, the optical system in the probe was re-designed and a new instrument was built which assures that the particle detected by a system of perpendicular laser beams will always be in focus. The new probe, called a cloud particle imager or CPI (Lawson, 1997), has improved optics and a 1 million CCD camera with 2.3 $\mu$m pixel resolution. The CPI was flown in freezing drizzle in an upslope cloud near Boulder, CO on 5 April 1997. Fig. 8 shows examples of a mixture of freezing drizzle drops, pristine ice crystals and rimed ice crystals observed in various regions of the upslope cloud. The excellent clarity of the

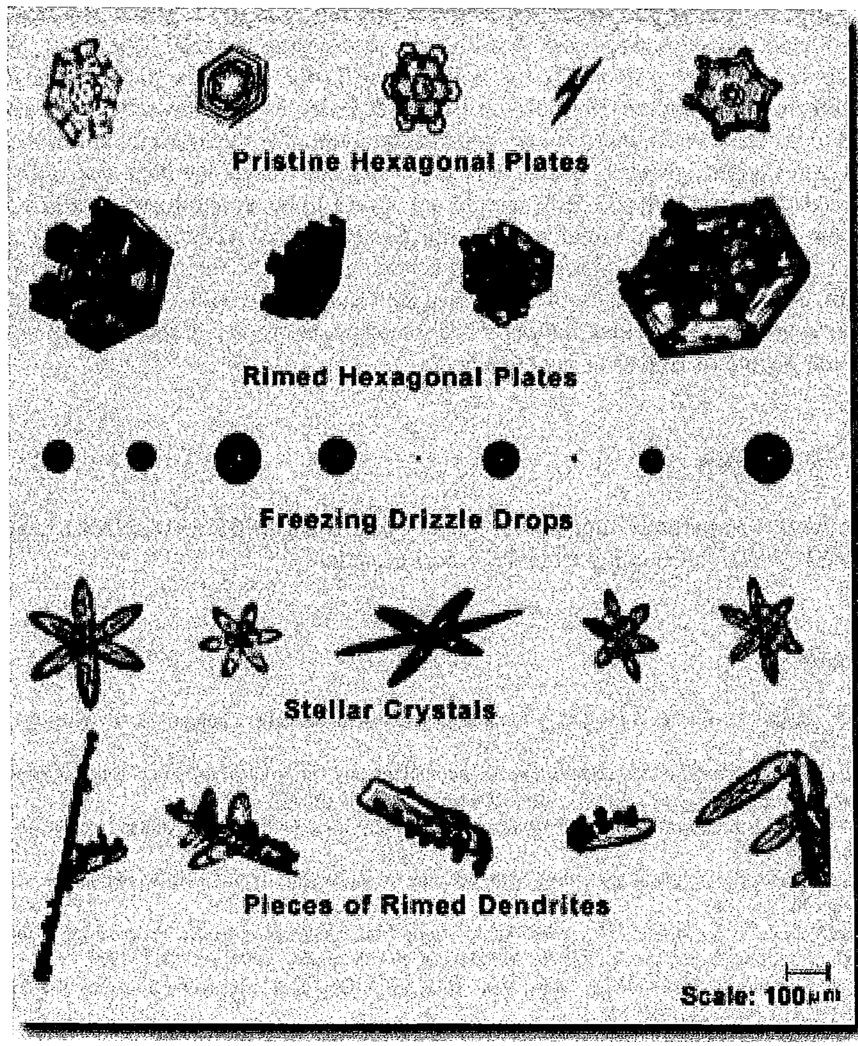


Fig. 8. Examples of images of ice crystals and water drops observed by the SPEC cloud particle imager (CPI) in an upslope storm from 24–26 February, 1997 in Boulder, CO.

images facilitates the identification of crystal habits, riming from individual drops and discrimination of ice crystals from water drops.

## 6. Summary and discussion

Measurements made in freezing drizzle of drop size distribution and LWC from some selected portions of the Canadian Freezing Drizzle Experiment (CFDE) are discussed. Measurements from a new airborne instrument, a digital holographic imaging probe with 3.7 $\mu$m pixel size resolution, are compared with the standard PMS probes. Numerical simulations, laboratory and flight data indicate that the PMS 2D-C probe can create an artificial 'tail' in the drop size distribution of freezing drizzle. The new digital holographic probe does not create the artificial tail in the drop size distribution. For a measurement on 15 March 1995 during CFDE, Korolev et al.'s theoretical corrections applied to the 2D-C data appear to be statistically correct for the artificial tail in the 225 to 350 $\mu$m region; however, due to effects of airspeed and noisy data, corrections to 2D-C measurements in the 25–100 $\mu$m do not appear to be straightforward at this time.

A new instrument, the cloud particle imager (CPI), has recently collected data in freezing drizzle and mixed phase clouds (Lawson, 1997). The unprecedented clarity of detail of the digital images from this instrument suggests it will provide even better measurements of the size distribution of freezing drizzle drops and identification of the habits and degree of riming of ice crystals.

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