The Effects of Precipitation on Cloud Droplet Measurement Devices

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ABSTRACT

Aircraft in situ observations of precipitation during the Rain in Cumulus over the Ocean (RICO) field project are used to study and parameterize the effects of precipitation on cloud probes. Specifically, the effects of precipitation on the Forward Scattering Spectrometer Probe, the King cloud liquid water hot-wire probe, and the particle volume monitor are parameterized as linear functions of the precipitation water content.

1. Introduction

The effects of precipitation on three cloud probes are presented: the Forward Scattering Spectrometer Probe (FSSP; Knollenberg 1981), particle volume monitor (PVM; Gerber et al. 1994), and liquid water hot-wire probes (King et al. 1978). Each of these probes is intended to respond to cloud droplets. For example, the nominal diameter range of the National Center for Atmospheric Research (NCAR) FSSP used during the Rain in Cumulus over the Ocean field project (RICO) is 1.4–45.75 μm, for the PVM it is 3–50 μm, and the King hot wires begin underestimating LWC for drops larger than 40 μm (Biter et al. 1987). These probes, however, do have some response to larger drops that may be considered a source of error in the measurement of the bulk cloud droplet parameters. The goal of this work is to quantify that error.

Baker et al. (2009) show that there is a lack ($<$0.001 cm^{-3}) of hydrometeors smaller than about 100 μm in diameter in rain shafts measured over the ocean near Antigua during RICO (Rauber et al. 2007a,b). This result facilitates the quantification of the effects of raindrops on the FSSP, PVM, and King probes that also flew on the National Science Foundation (NSF)/NCAR C-130 research aircraft during RICO. These droplet probes measured orders of magnitude above the two-dimensional stereo probe (2D-S) estimates. Therefore, essentially everything they measured in those rain shafts is an effect of the precipitation. The 2D-S probe has been shown to be sensitive down to about 10 μm (Baker et al. 2009; Lawson et al. 2006). Splashing effects on the 2D-S are minimized via a number of methods, primarily by removing closely spaced events (Cooper 1978; Korolev and Isaac 2005; Field et al. 2006). The uncertainty in the 2D-S measurements in this situation (droplets smaller than 100 μm in below-cloud rain shafts) are as great as the measurements themselves, which does not cause a problem since the cloud probe measurements are orders of magnitude greater.

The effects of precipitation on the FSSP, PVM, and King probes are parameterized via least squares linear regression as functions of the precipitation water content (PWC), which was estimated from the 2D-S probe. We use LWC to refer to the liquid contained in cloud droplets and PWC to refer to liquid contained in precipitation drops. In as much as the interpretation of these cloud probe measurements is of cloud droplet parameters and response to precipitation may be considered error, the results presented here may be used to estimate those errors in the bulk microphysical parameters measured by FSSP, PVM, and King probes in precipitating liquid clouds.

2. Results from about 600 ft (180 m) MSL

The backbone of this analysis is the automatic determination of relatively uniform regions of precipitation, herein loosely referred to as rain shafts. Rain shafts

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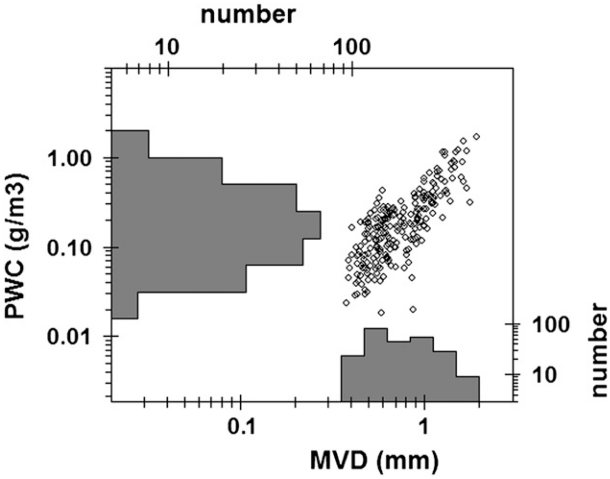

FIG. 1. Scatterplot of PWC vs MVD for the 237 rain shafts observed at about 600 ft MSL on 19 Jan 2005. Also shown are histograms of the PWCs and MVDs.

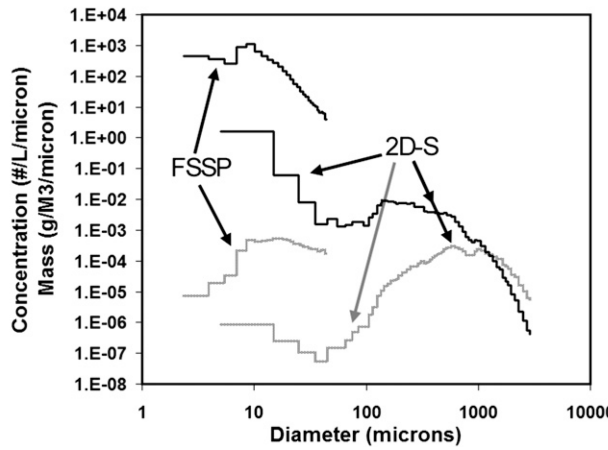

FIG. 2. Mean 2D-S and FSSP drop size distributions, both concentration (black) and mass (gray), averaged over 237 rain shafts. Note that here and in subsequent figures 1.EXXX indicates 10^{XXX}.

were determined by the following criteria: (i) the segment must be at least 3 s long (~300 m); (ii) the FSSP concentration remains within 0.8 and 1.2 times the mean FSSP concentration for the period; and (iii) the PWC, estimated from the 2D-C (cloud) and 2D-P (precipitation) probes (Knollenberg 1981), remains within 0.5 and 1.5 of its mean for the period. These criteria allow the automation of the processing, remove human biases, and insure some degree of uniformity over the averaging regions. NCAR 2-D data are used for this rain shaft determination. These data have incomplete artifact rejection and thus absolute values tend to be erroneously high. However, the data are adequate for the purpose of defining the rain shaft segments. The algorithm determined 237 such rain shaft regions at about 600 (538–666) ft MSL on 19 January 2005, which was a RICO flight dedicated to precipitation measurements below cloud base. These 237 data points represent a variety of PWCs, which is important since our goal is to parameterize the effects in terms of the PWC. A histogram of the measured PWCs is shown in Fig. 1, along with a histogram of the median volume diameters (MVDs) and a scatterplot of the two parameters, which as expected are reasonably well correlated.

Figure 2 shows the mean 2D-S size distribution averaged over the 237 rain shafts as well as the average FSSP cloud droplet size distribution. The FSSP measurements are two to three orders of magnitude greater than the 2D-S droplet concentrations. The 2D-S data have been processed to reduce splashing effects (Baker et al. 2009) while the FSSP data are not processed to remove effects of splashing. Thus, we conclude that the FSSP measurements are primarily an effect of the precipitation, presumably caused by precipitation splashing on the sample tube leading edge. The FSSP is designed to respond to drops in the size range from 1.5 to 46 μm. While some attempts to understand the response of the FSSP to larger drops at aircraft speeds have been attempted, no definitive results have been published. Jensen and Granek (2002) suggest that drizzle drops splashed from the tips of a Particle Measuring Systems, Inc., 260X probe and created small drops. Baker et al. (2009) show images of splashing events on the 2D-S demonstrating the production of small drops. High-speed video photography resulting from a cooperative effort of the National Aeronautics and Space Administration and Environment Canada shows that large drops splashing on a Nevzorov hot-wire probe produce copious small drops (Isaac et al. 2006). It seems likely then that the spurious FSSP measurements in precipitation are caused by impacts of raindrops with the inlet sample tube. The impacts cause the precipitation drops to break up into small droplets, some of which then pass through the sample volume.

Figure 3 shows a scatterplot of the FSSP LWC, extinction, and concentration versus PWC determined from the 2D-S probe. Least squares linear fits to the data are also shown. The correlation coefficients are 0.94, 0.93, and 0.84, respectively, suggesting that the effects may be fairly well estimated as simple linear functions of PWC.

Biter et al. (1987) studied the response of the King probe to water drops of different sizes. They showed that the response of the King probe depends on drop size and that it underestimates LWC for drops larger than 40 μm. For a spray with an MVD of ~150–200 μm the measured LWC decreases to 50% of the actual value. Similar results were obtained by Strapp et al. (2003). The

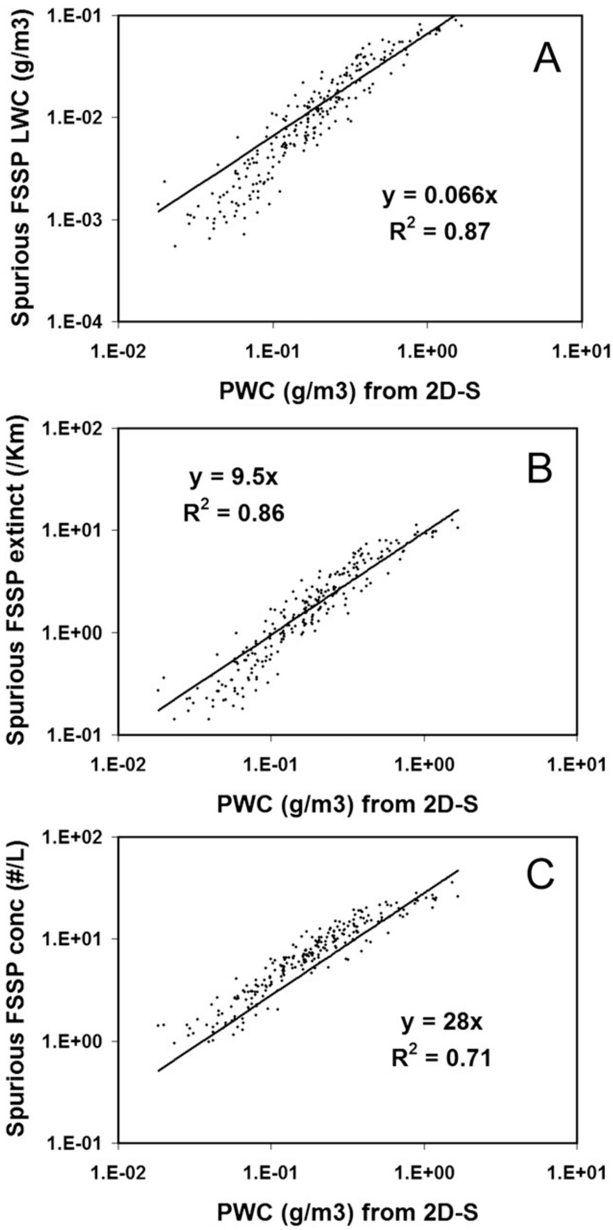

FIG. 3. FSSP LWC, extinction, and concentration vs 2D-S PWC for 237 rain shaft penetrations made at 600 ft MSL on 19 Jan 2005. The equation of the linear least squares best-fit line, through the origin, and the square of the correlation coefficient are shown.

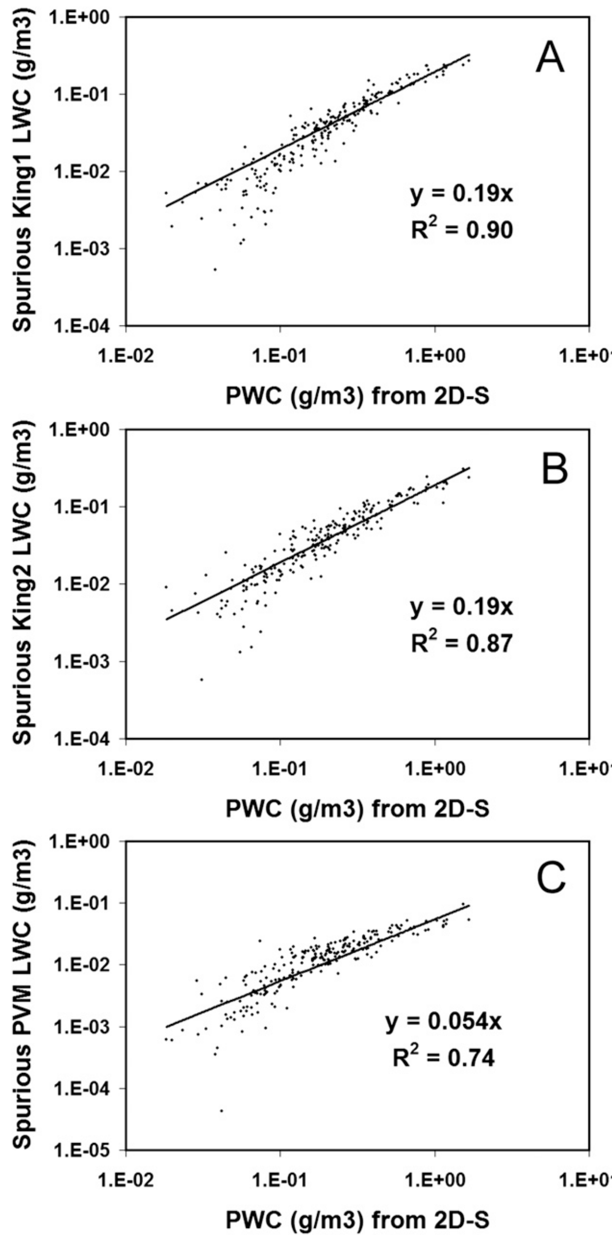

FIG. 4. King and PVM probe LWCs vs 2D-S PWC for 237 rain shaft penetrations made at 600 ft MSL on 19 Jan 2005. The equation of the linear least squares best-fit line, through the origin, and the square of the correlation coefficient are shown.

undercounting of LWC by the King probe is related to incomplete evaporation of large drops. As shown in Fig. 4, for the raindrop distributions during RICO, the LWCs measured by the King probes were approximately 20% of the estimated PWC from the 2D-S measurements. This implies that inside precipitating clouds (e.g., above cloud base), if the King probe measurements are interpreted as LWC associated with cloud droplets, they would be overestimated by 20% of the PWC.

The mechanism for generating measurements on the PVM is likely the same as for the FSSP (i.e., raindrops splashing from the inlet tube). Since the PVM inlet tube has a larger diameter than the FSSP, the effect on the PVM might be less than on the FSSP. Both probes have beveled inlet tubes to deflect splashes away from the sample volumes. Figure 4c shows the PVM LWC versus PWC. The slope of the linear fit (0.054) is slightly less than that for the FSSP (0.066; Fig. 3a).

TABLE 1. Results of analysis of rain shafts at four different altitudes, including $\overline{k}$, the coefficient of proportionality between PWC and the spurious effect, $\Delta k/\overline{k}$, an estimate of the uncertainty in $\overline{k}$, and the correlation coefficient.

	256–367 ft MSL; $N = 98$	538–666 ft MSL; $N = 237$	720–876 ft MSL; $N = 72$	900–1100 ft MSL; $N = 221$
$\overline{k}$				
FSSP concentration [No. L^{-1} $(g\ m^{-3})^{-1}$]	22	28	35	39
FSSP extinction [km^{-1} $(g\ m^{-3})^{-1}$]	7.4	9.5	12	12
FSSP LWC	0.052	0.067	0.083	0.082
King1	0.21	0.19	0.30	0.21
King2	0.20	0.19	0.25	0.23
PVM	0.045	0.055	0.066	0.069
$\Delta k/\overline{k}$				
FSSP concentration [No. L^{-1} $(g\ m^{-3})^{-1}$]	0.11	0.053	0.066	0.024
FSSP extinction [km^{-1} $(g\ m^{-3})^{-1}$]	0.088	0.039	0.062	0.025
FSSP LWC	0.081	0.035	0.063	0.028
King1	0.052	0.032	0.15	0.029
King2	0.085	0.038	0.064	0.028
PVM	0.10	0.050	0.046	0.024
Correlation coef				
FSSP concentration [No. L^{-1} $(g\ m^{-3})^{-1}$]	0.84	0.90	0.88	0.77
FSSP extinction [km^{-1} $(g\ m^{-3})^{-1}$]	0.88	0.93	0.90	0.86
FSSP LWC	0.89	0.94	0.90	0.88
King1	0.95	0.95	0.92	0.89
King2	0.90	0.94	0.91	0.90
PVM	0.81	0.89	0.87	0.77

3. Results from various altitudes

The examples shown above are from 237 rain shafts, all at about 600 ft MSL. Table 1 presents the results of analysis for four altitude levels. The coefficients k in the equations $y = kx$, where y is the spurious quantity and x is the 2D-S PWC measurement, are shown. A bootstrap method (Efron and Tibshirani 1993) was used to estimate k as the mean of the bootstrap values ($\overline{k}$) and an uncertainty in k ($\Delta k/\overline{k}$) as the standard deviation of the bootstrap k values divided by $\overline{k}$. The correlation coefficients are also presented.

While the results for all altitudes are similar, some coefficients $\overline{k}$ differ more than would be expected due only to random sampling from the same population. That is, the differences between some of the $\overline{k}$ values between altitudes are larger than the corresponding uncertainty estimates ($\Delta k/\overline{k}$). We speculate that this may be due to differences in the precipitation sizes between the different altitude datasets and a dependence of splashing effects on the precipitation size. Figure 5 shows the distributions of MVDs at each altitude, which demonstrates that the precipitation sizes vary to some degree with altitude. In addition, Fig. 6a shows a scatterplot of k, the ratio of the value of FSSP LWC to PWC versus MVD, where one point is plotted for each rain shaft. This suggests that the effect of precipitation on the FSSP is dependent on precipitation size, since a trend is detectable as a function of MVD. The plot suggests an optimum size for splashing effect, as might be expected. We speculate that smaller-sized drops may create splashes that tend not to reach the FSSP sample area in the center of the sample tube, while larger drops create splashes that extend beyond the sample area. Figure 6a shows a polynomial fit suggesting the possibility to include MVD in the parameterization of the splashing effect. SPEC, Inc., will make the data available to investigators interested in pursuing this. There is much less dependence on MVD for the hot-wire probes (Fig. 6b), which is consistent with the above speculation since the hotwires are more likely to be directly affected by the precipitation, instead of being affected by splashing reaching the sample area. The effect on the PVM (Fig. 6c) is intermediate between the

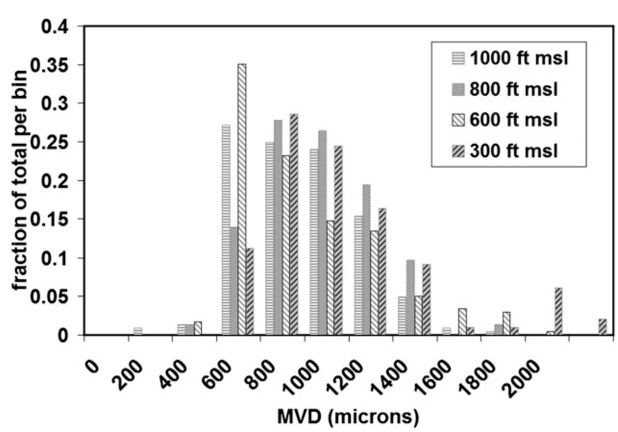

FIG. 5. Distributions of MVD at each of the altitude levels.

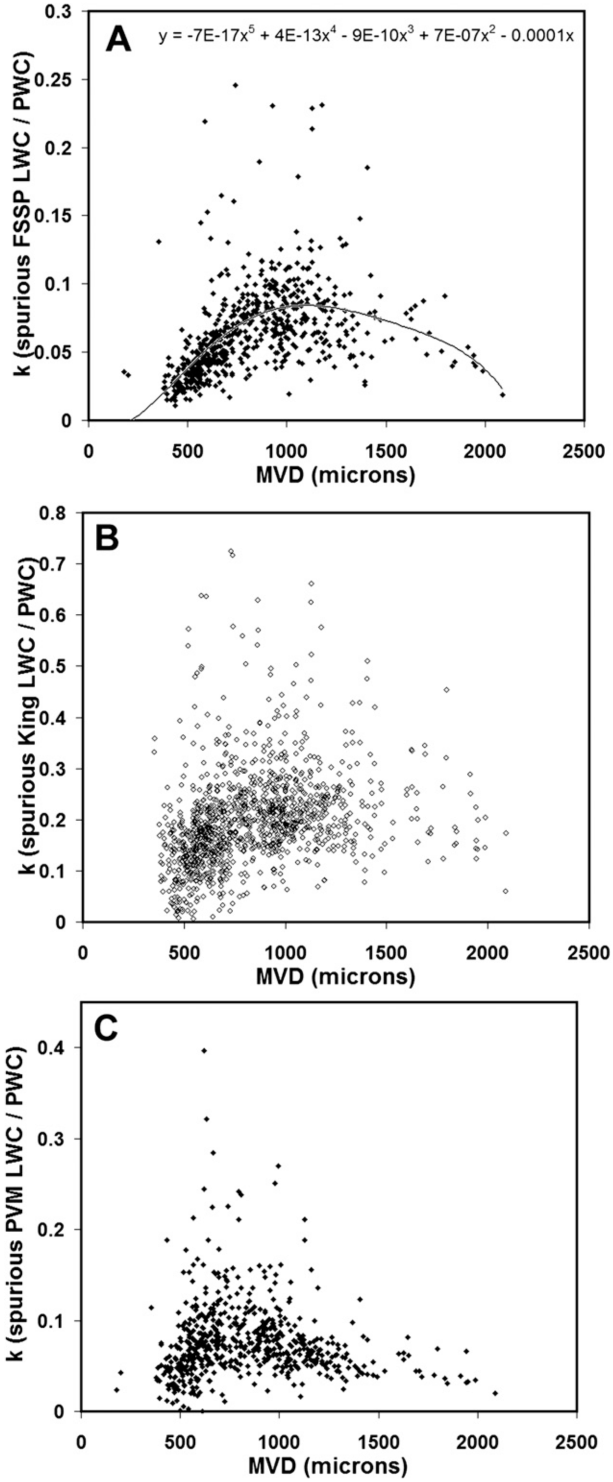

FIG. 6. Scatterplots of k (spurious effect/PWC) vs MVD calculated for each rain shaft (all altitudes). (a) The spurious effect is FSSP LWC and a fifth-degree polynomial fit is also displayed. (b) The spurious effect is King LWC (both probes); (c) the spurious effect is the PVM LWC.

effects on the FSSP and hot wires. Perhaps this is because the effect on the PVM is due in part to splashing like the FSSP and, in part, to direct partial sensitivity to drops larger than 100 μm.

4. Conclusions

The dearth of particles smaller than 100 μm in RICO rain shafts (Baker et al. 2009) supports the conclusion that measurements in those same rain shafts from the FSSP, King probes, and the PVM are effects of precipitation. These effects are spurious in the sense that measurements from these devices are generally interpreted as being due to cloud droplets and not precipitation. The effects of precipitation, on each of these probes, are reasonably well parameterized by simple linear regression as functions of the precipitation water content. Keeping in mind that in other situations both real and spurious droplets smaller than 100 μm coexist, corrections based on these parameterizations may be applied where the estimated spurious effect is a significant fraction of the total measurement. For example, suppose 1 g m^{-3} of PWC is measured in a cumulus near cloud base where the cloud LWC is 0.2 g m^{-3}. From Figs. 3 and 4 we can estimate that the FSSP (King; PVM) cloud LWC measurement would be about 0.07 (0.2; 0.05) g m^{-3} too high, because of the precipitation. In this situation, corrections based on the estimated effect of the precipitation are worth applying. Alternatively, the information provided in Figs. 3 and 4 can be used to determine when the effects of precipitation on these cloud probes may be ignored, that is, when the corrections would be smaller than the measurement uncertainties due to other causes.

Evidence for a size dependency of splashing effects on the FSSP was found and discussed. These results are most applicable to the RICO dataset on which they are based. Other rain shafts may have greater differences in drop size distributions and therefore parameterization coefficients could vary. The possibility for further parameterization based on MVD to account for this was discussed. Additional data from clouds with larger MVDs are desirable to continue that effort. Similar effects must be expected in ice phase precipitation as well. However, we expect the quantification may vary considerably more, because of differences between splashing and shattering.

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REFERENCES

Baker, B., Q. Mo, R. P. Lawson, D. O'Connor, and A. Korolev, 2009: Drop size distributions and the lack of small drops in RICO rain shafts. *J. Appl. Meteor. Climatol.,* **48,** 616–623.

Biter, C. J., J. E. Dye, D. Huffman, and W. D. King, 1987: The dropsize response of the CSIRO liquid water probe. *J. Atmos. Oceanic Technol.,* **4,** 359–367.

Cooper, W. A., 1978: *Cloud Physics Investigations by the University of Wyoming in HIPLEX 1977, Final Report*. University of Wyoming, 320 pp.

Efron, B., and R. J. Tibshirani, 1993: *An Introduction to the Bootstrap*. Chapman and Hall, 436 pp.

Field, P. R., A. J. Heymsfield, and A. Bansemer, 2006: Shattering and particle interarrival times measured by optical array probes in ice clouds. *J. Atmos. Oceanic Technol.,* **23,** 1357–1371.

Gerber, H., B. G. Arends, and A. S. Ackerman, 1994: New microphysics sensor for aircraft use. *Atmos. Res.,* **31,** 235–252.

Isaac, G. A., A. V. Korolev, J. W. Strapp, S. G. Cober, F. S. Boudala, D. Marcotte, and V. L. Reich, 2006: Assessing the collection efficiency of natural cloud particles impacting the Nevzorov total water content probe. *Extended Abstracts, AIAA 44th Aerospace Sciences Meeting and Exhibit*, Reno, NV, AIAA, Paper AIAA-2006-1221.

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

King, W. D., D. A. Parkin, and R. J. Handsworth, 1978: A hot-wire liquid water device having fully calculable response characteristics. *J. Appl. Meteor.,* **17,** 1809–1813.

Knollenberg, R. G., 1981: Techniques for probing cloud microstructure. *Clouds, Their Formation, Optical Properties, and Effects,* P. V. Hobbs and A. Deepak, Eds., Academic Press, 15–91.

Korolev, A. V., and G. A. Isaac, 2005: Shattering during sampling by OAPs and HVPS. Part I: Snow particles. *J. Atmos. Oceanic Technol.,* **22,** 528–542.

Lawson, R. P., D. O'Connor, P. Zmarzly, K. Weaver, B. A. Baker, Q. Mo, and H. Jonsson, 2006: The 2D-S (stereo) probe: Design and preliminary tests of a new airborne, high speed, high-resolution particle imaging probe. *J. Atmos. Oceanic Technol.,* **23,** 1462–1477.

Rauber, R. M., and Coauthors, 2007a: Rain in shallow cumulus over the ocean: The RICO campaign. *Bull. Amer. Meteor. Soc.,* **88,** 1912–1928.

——, and Coauthors, 2007b: Rain in shallow cumulus over the ocean: The RICO campaign. *Bull. Amer. Meteor. Soc.,* **88** (Suppl.), doi:10.1175/BAMS-88-12-Rauber.

Strapp, J. W., and Coauthors, 2003: Wind tunnel measurements of the response of hot-wire liquid water content instruments to large droplets. *J. Atmos. Oceanic Technol.,* **20,** 791–806.