A Method for Validating FSSP Measurements Using Observational Data

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(Manuscript received 16 February 1990, in final form 11 May 1991)

ABSTRACT

A validation method of measurements from the forward-scattering spectrometer probe (FSSP) allowing preliminary analysis and verification of rough data is presented. It is based on the comparison of observed spectral distributions from undiluted cloudy air with theoretical adiabatic ones. The latter are obtained using an ascending adiabatic cloud-parcel model and the corresponding cloud-base conditions. A two-step approach is used to correct observed spectral distributions and is illustrated with data collected during the 1985 Joint Hawaii Warm Rain Project (JHWRP). The procedure provides an alternate way of obtaining the response matrix for an FSSP and can be used to validate the laboratory-derived response matrix. The results obtained (spectral characteristics and liquid water contents) agree well with the ones calculated from the laboratory characterization, which was made after the experiment, taking into account the laser beam nonuniformities.

1. Introduction

The forward-scattering spectrometer probe (FSSP) is widely used as the principal method for measuring cloud-droplet sizes and concentrations from an aircraft. Liquid water contents deduced from these measurements are often used in thermodynamic analysis when the ones obtained by hot-wire probes (Johnson–Williams, CSIRO, King probe) are unreliable as a consequence of instrumental defects or erratic behavior. The FSSP operating characteristics and limitations have been described and evaluated extensively by several authors (e.g., Cerni 1983; Baumgardner 1983; Dye and Baumgardner 1984). Measurement errors in droplet sizes and concentrations are partly due to the probe's electronic response and optical limitations. With a good knowledge of the operating characteristics of individual probes, correction schemes have been developed (Cooper 1988; Baumgardner and Spowart 1990; Kim and Boatman 1990) to compensate for measurement errors.

During the 1985 Joint Hawaii Warm Rain Project (JHWRP), the comparison of results obtained from different liquid water measuring instruments and cloud-droplet–sizing probes flown on the University of Wyoming King Air showed some important discrepancies. The FSSP liquid water contents were systematically lower than the Johnson–Williams (JW) values, and the transition in the overlap region between the size distributions obtained by the FSSP and the OAP-260X was discontinuous. A further evaluation of the FSSP operating characteristics was made by Baumgardner (1987, 1988) following the experiment. This investigation revealed that a nonuniform intensity distribution in the laser beam contributed to distortions of the measured droplet sizes. This author estimated the real droplet sizes from the measured ones and suggested a new correction scheme for the FSSP, by mapping the laser beam intensity and modeling the electronic response of the FSSP. A complementary validation of the droplet measuring device may be made by comparing experimental results from undiluted cloudy-air regions with those obtained by a cloud-parcel model with the assumption of adiabatic ascent from the observed cloud base. Such a method allows the rapid detection of any abnormal behavior of the FSSP as well as a check on data consistency.

The main goal of this work is to present the methodology and compare the results obtained for a selected cloud sampled during JHWRP to the ones determined by using the FSSP laboratory calibration.

2. Methodology

If the FSSP systematically missizes the droplet radii, one may assume that the droplet concentration in a given FSSP channel i is the result of the respective contributions of droplets, which would be distributed,

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if correctly sized, in different FSSP channels. The contribution to the droplet concentration measured in channel i of droplets with true radii belonging to channel k can be written as

$$N_{ki} = M_{ki}N(k) \quad (1)$$

where M_{ki} and $N(k)$ are, respectively, a proportionality coefficient and the true droplet concentration in FSSP channel k.

The measured droplet concentration in channel i obtained according to Eq. (1) can be expressed as

$$N_M(i) = \sum_{k=1}^{15} M_{ki}N(k) \quad (2)$$

and more generally, the (15×1) matrices $\mathbf{N}_M$, $\mathbf{N}$ corresponding, respectively, to the measured and true FSSP spectral concentrations are related according to the equation:

$$\mathbf{N}_M = \mathbf{MN} \quad (3)$$

where $\mathbf{M}$ is the (15×15) FSSP response matrix whose elements, M_{ki}, define the contribution from each FSSP bin to all other bins.

The components of this matrix have been first derived by Baumgardner and Spowart (1990) by combining both theoretical considerations and laboratory measurements.

For a given measured spectral distribution, if the M_{ki} values are known, the true droplet spectral concentrations could be obtained by inverting matrix $\mathbf{M}$. However, since this matrix is often ill-conditioned, the problem may be solved by guessing an initial "true" droplet spectral concentration matrix $\mathbf{N}$ followed by a progressive adjustment of the $N(k)$ values to fit Eq. (3), thus, obtaining an "estimated measured" spectral distribution. This procedure may be accomplished by following any of several different numerical schemes. The technique of Markowski (1987) has been used as suggested by Baumgardner and Spowart (1990). Since the accuracy of the final "true" droplet spectral distribution obtained is sensitive to the choice of the first guess of this distribution, the method implies the use of a two-step procedure. It consists primarily of determining both the first guess of the true droplet spectral distribution $\mathbf{N}$ and the FSSP response matrix $\mathbf{M}$ (step A), and second of the adjustment of the $N(k)$ values (step B).

a. Step A

This step requires the presence of undiluted regions at levels far from cloud base. Measurements of the dynamical, thermodynamical, and microphysical characteristics both at cloud base and in these undiluted regions are necessary. The observed droplet-size distributions in the adiabatic cores may be compared to the predicted ones obtained from model calculations in order to provide a means of deriving the first guess of the true droplet spectral distribution and the FSSP response characteristics. Observed cloud-base parcels are raised to the level where undiluted parcels have been detected, with an adiabatic ascent cloud-parcel model in a Lagrangian frame. It shall be further shown that the FSSP missizing errors at cloud base, where spectral distributions extend mainly over the first three or four FSSP channels, have only a negligible influence on the final result. The equations of the model are well known and are not reported here. Cloud-base characteristics (pressure, vertical velocity, temperature) are used for the model initialization in association with the corresponding clear-air sounding. The resulting theoretical adiabatic spectral distributions are compared (in terms of mean radius) to the observed ones with similar droplet concentrations.

If $\Delta R(i)$ is the difference between the true mean radius $R_T(i)$ of a given FSSP channel and the manufacturer's one $R_M(i)$, the true mean radius of an observed spectral distribution may be written as

$$\overline{R_T} = \overline{R_M} + \sum_{i=1}^{15} P(i)\Delta R(i) = \overline{R_M} + \overline{\Delta R} \quad (4)$$

where $P(i)$ is the droplet percentage in the corresponding channel.

Since there are 15 FSSP channels, the accurate determination of $\Delta R(i)$ can only be obtained by solving a system of 15 independent equations similar to Eq. (4) for which $\overline{R_T}$ and $\overline{R_M}$ are known. This requires the presence of 15 different sampled levels, each containing at least one undiluted parcel for which the true mean radius of its spectrum, $\overline{R_T}$, is the mean radius of the theoretic adiabatic spectrum calculated for the corresponding level. However, under usual experimental conditions, the number of sampled levels in a cloud is limited and undiluted samples are not found at all levels, thus, seriously restricting the number of independent equations available to determine $\Delta R(i)$. Empirically, the corrective term $\Delta R(i)$ can be approximated by an nth-order polynomial and with increasing number of sampled levels, a more precise corrective term can be estimated.

If only one undiluted region has been observed throughout the cloud, one has to assume that each $\Delta R(i)$ value is the same and corresponds to the difference between the mean radius of the spectral distribution of an observed undiluted sample and the one calculated for the corresponding theoretic spectral distribution:

$$\Delta R(i) = \overline{\Delta R} = \overline{R_T} - \overline{R_M}. \quad (5)$$

If undiluted samples have been measured at two different levels, an approximative way to determine $\Delta R(i)$ is to assume that there is a linear relation between the corrective term $\Delta R(i)$ and the corresponding true mean radius $R_T(i)$ of each FSSP channel:

$$\Delta R(i) = AR_T(i) + B \quad (6)$$

where A and B are constant coefficients. Taking into account relation (6), Eq. (4) becomes

$$\overline{R_T} = a\overline{R_M} + b \quad (7)$$

where a and b are two constant coefficients that may be determined by using two independent equations established for two different cloud levels containing undiluted samples, where the true mean radius of the spectra of observed undiluted parcels corresponds to the mean radius of the theoretic adiabatic spectral distributions.

With the knowledge of the terms a and b, the estimated correction is:

$$R_T(i) = aR_M(i) + b. \quad (8)$$

The measured droplet spectral distribution once corrected is referred to, hereafter, as $\mathbf{N}_{G,l}$.

Further, the comparison between the theoretic spectral concentrations and the observed ones in undiluted samples allows the determination of the M_{ki} values, which correspond to the fraction of droplets measured in size class i originating from the actual size class k.

b. Step B

The measured droplet spectral distribution corrected according to step A, may be used as the first guess of the "true" droplet spectral distribution to start the best-fit procedure of Eq. (3) according to

$$\mathbf{N}_{M,l} = \mathbf{M}\mathbf{N}_{G,l}$$

where l is the iteration step index. At each iteration step, a new estimate of the droplet spectral distribution $\mathbf{N}_{M,l}$ is calculated and compared to the measured one, $\mathbf{N}_M$. The result of this comparison is used to determine a new true droplet spectral distribution $\mathbf{N}_{G,l+1}$, initializing the next iteration step. The square sum $S = \sum_{k=1}^{15} [N_{M,l}(k) - N_M(k)]^2$ is used as the best-fit criterion. The procedure is stopped when S reaches its minimum value or is lower than unity.

The method is similar to the one presented by Baumgardner and Spowart (1990), where the determination of the corresponding matrix elements requires detailed knowledge of the FSSP optical and electronic characteristics. In this case, the knowledge of the specific instrumental probe characteristics is not necessary; however, the data used should be obtained at the same aircraft speed. Note that the results obtained by both methods may only be used to correct a specific FSSP. An example illustrating the aforementioned approach using data from a cloud sampled during the JHWRP, is given in the following section.

3. Validation of the FSSP operated during JHWRP

a. Cloud characteristics

The cloud selected for this study was sampled on 10 July 1985 between 0820 and 0833 LST. Six penetrations were made at regular pressure intervals (957, 907, 860, 810, 780, and 727 mb) starting from cloud base. The mean cloud-base characteristics were p = 963.3 mb, T = 19.9°C, Q = 15.39 g kg^{-1}, and N = 204 mg^{-1}.

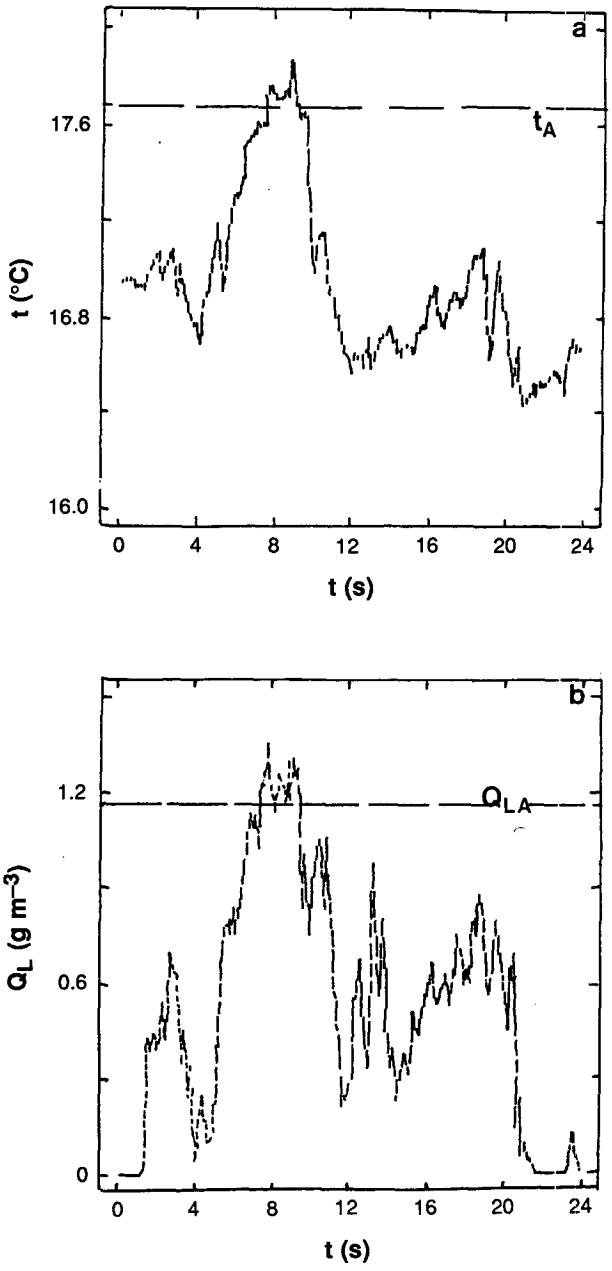

FIG. 1. (a) Time series of reverse-flow temperature and (b) JW liquid water content allowing the identification of an undiluted cloudy-air region at the 907-mb level (t_A and Q_{LA} denote, respectively, adiabatic temperature and liquid water content values).

TABLE 1. Measured temperatures (reverse-flow and Lyman α–derived) and FSSP liquid water contents of undiluted parcels sampled at three different levels compared to the corresponding theoretic adiabatic values (A).

p (mb)	t_{RF} (°C)	$t_{L\alpha}$ (°C)	t_A (°C)	Q_L (FSSP) (g m^{-3})	Q_{LA} (g m^{-3})
957.2	19.6		19.6	0.04	
907.3	17.6	17.8	17.7	0.49	1.14
857.7	14.5	15.4	15.6	1.06	2.18

Undiluted parcels were observed on a 10-m scale at 957 (130 samples), 907 (28 samples), and 860 mb (1 sample). They were identified by using the criteria established by Jensen et al. (1985), that is, the simultaneous presence of adiabatic temperatures and liquid water contents, maximum vertical velocity values, and minimum turbulent dissipation rate values. Droplet concentrations in the undiluted samples ranged between $N_{min} = 187$ mg^{-1} and $N_{max} = 225$ mg^{-1}. At 907 mb, for the corresponding samples, the reverse-flow temperatures and JW liquid water contents were adiabatic, whereas, at 860 mb where the reverse-flow probe was most presumably subject to wetting, only the Lyman α–derived temperature value satisfied this condition. Figures 1a and 1b show the time series of the reverse-flow temperature values and the JW liquid water contents for the 907-mb level on which the corresponding adiabatic values have been reported, thus, allowing the identification of an undiluted region. As may be seen in Table 1, which summarizes the temperature and liquid water content values of three undiluted samples observed at the three lowest sampled levels, the calculated FSSP liquid water contents are subadiabatic, thus, suggesting a serious underestimation of the droplet radii.

b. Experimental validation

1) STEP A

The illustration of the two approaches considered in step A, section 2, corresponding, respectively, to the presence of undiluted parcels at a single level, or at two different levels, will be given hereafter.

If undiluted parcels had only been detected at the 907-mb level, the unique corrective term $\overline{\Delta R}$ to be applied to each mean FSSP channel radius would be obtained from Eq. (5), for each undiluted parcel of this level. The mean value of $\overline{\Delta R}$ thus obtained is $\overline{\Delta R} = 2.68 \pm 0.06$ μm.

However, since undiluted parcels have been detected at two different levels far from cloud base (907 and 860 mb), a system of two independent linear equations can be solved to determine the coefficients a and b, involved in Eq. (7). Equation (8) may then be written, in this case, as

$$R_T(i) = 1.189 R_M(i) + 1.167. \quad (9)$$

As an example, Figs. 2a and 2b show the measured spectral distributions of specific undiluted parcels, respectively, at 907 and 860 mb, as well as the theoretical ones and those corrected according to Eq. (9). The corrected spectra are broader than the theoretical ones, at least partially as a consequence of both the FSSP artificial spectral broadening (Baumgardner 1983; Cerni 1983) and the correction scheme. The small radii are most affected by the artificial spreading, which is consistent with Baumgardner's (1988) laboratory observations. Figure 3 presents the 1-Hz FSSP and OAP-260X droplet spectral distributions of a diluted parcel at 810 mb. The transition in the overlap region between the FSSP and 1DC droplet spectra is improved if each

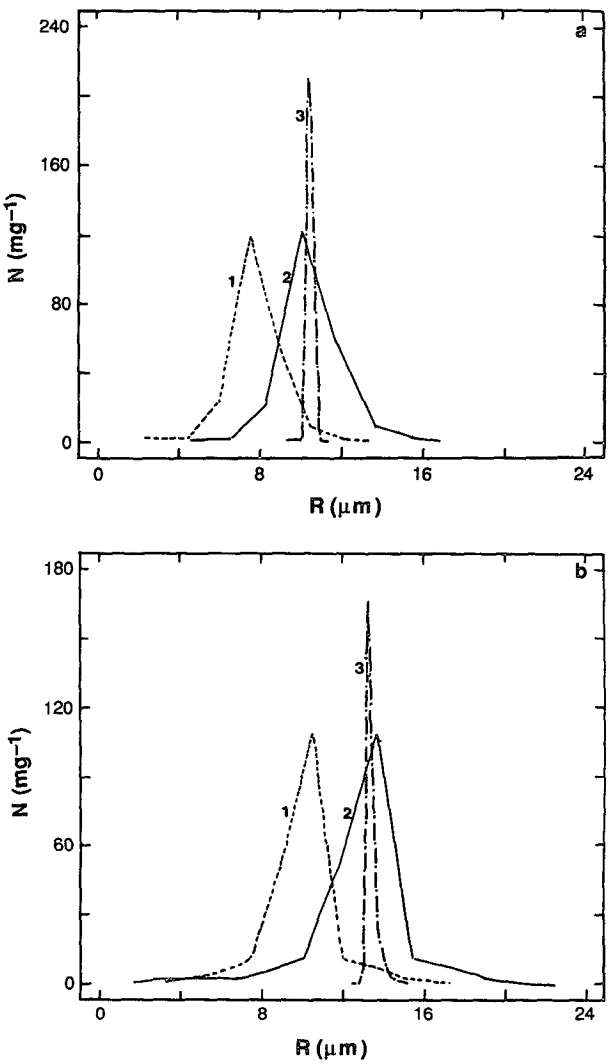

FIG. 2. 1) Measured, 2) corrected, and 3) theoretical spectral distributions of specific undiluted parcels sampled, respectively, at (a) 907 mb and (b) 860 mb.

FSSP mean channel radius is corrected according to Eq. (9).

Further, the set of values for the M_{ki} matrix elements in Eq. (2) are determined by comparing the mean observed spectral distribution of the undiluted samples at the 907-mb level to the theoretical adiabatic one. The latter is either monodispersed or extends over two FSSP bins (usually, more than 98% of the total droplet concentration is in one bin and the remaining percentage of droplets in the following one). In the second case, the simplifying assumption is made that all droplets are contained in the most populated bin. Thus, for each observed undiluted sample at 907 mb, the M_{ki} values are easily obtained from Eq. (1) in which $N(k)$ is the total droplet concentration. An average set of M_{ki} values is finally calculated using the results obtained from all 28 undiluted samples observed at 907 mb and the matrix **M** is established with the assumption that the artificial spectral broadening of the FSSP is independent of the droplet size.

2) STEP B

The M_{ki} matrix elements and the corrected measured spectrum [Eq. (9)], used as the first guess of the true droplet spectral distribution, allow the determination of the final true spectral distribution, which fits Eq. (3). As an example, Fig. 4 presents a measured spectral distribution of a diluted parcel observed at 860 mb compared to both the deduced final true spectral distribution and the "estimated measured" one obtained according to the procedure defined in section 2. It can easily be seen that the FSSP used in Hawaii undersized droplet radii. The shift of the true radii toward smaller sizes corresponds roughly to two FSSP channels that agree well with the correction obtained for the mean radii shift during step A. Moreover, the effect of artificial spectral broadening is reduced since the droplet spectral concentrations are redistributed in the appropriate FSSP bins. This may be seen in Table 2, which contains the measured and true microphysical spectral characteristics (mean radii $\bar{R}$, corresponding standard deviation σ, and dispersion $\sigma/\bar{R}$) for three undiluted or minimally diluted parcels sampled, respectively, at three different levels of this cloud.

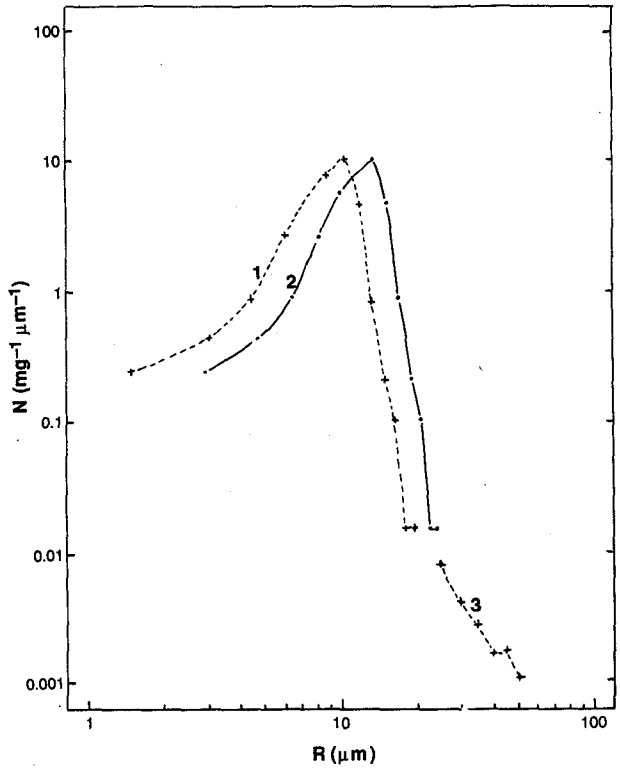

FIG. 3. 1) Uncorrected and 2) corrected FSSP spectral distributions, and 3) the corresponding OAP-260X spectrum of a diluted parcel sampled at 810 mb.

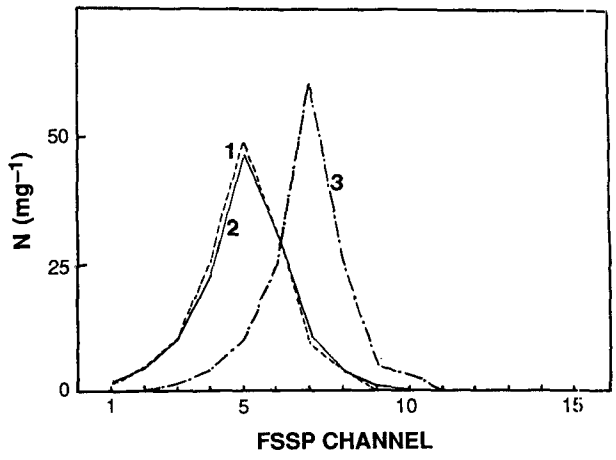

FIG. 4. 1) Measured, 2) "estimated measured", and 3) final "true" spectral distributions of a diluted parcel at 860 mb.

c. *Comparison with the laboratory calibration*

Baumgardner (1988) and Baumgardner and Spowart (1990) derived a laboratory correction for the FSSP measurements used in this study. This correction

TABLE 2. Comparison between some microphysical characteristics (mean radius $\bar{R}$, standard deviation of the mean radius σ, and dispersion, $\sigma/\bar{R}$) of measured (M) and corrected (T) spectral distributions corresponding to undiluted or minimally diluted parcels of three different levels.

p (mb)	$\overline{R_M}$ (μm)	$\overline{R_T}$ (μm)	$\overline{\Delta R}$ (μm)	σ_M (μm)	σ_T (μm)	$\sigma_M/\overline{R_M}$	$\sigma_T/\overline{R_T}$
907.3	8.18	11.15	2.97	1.44	1.06	0.18	0.09
857.7	10.05	13.02	2.97	2.04	1.73	0.20	0.13
810.2	10.76	13.63	2.87	2.77	2.51	0.26	0.18

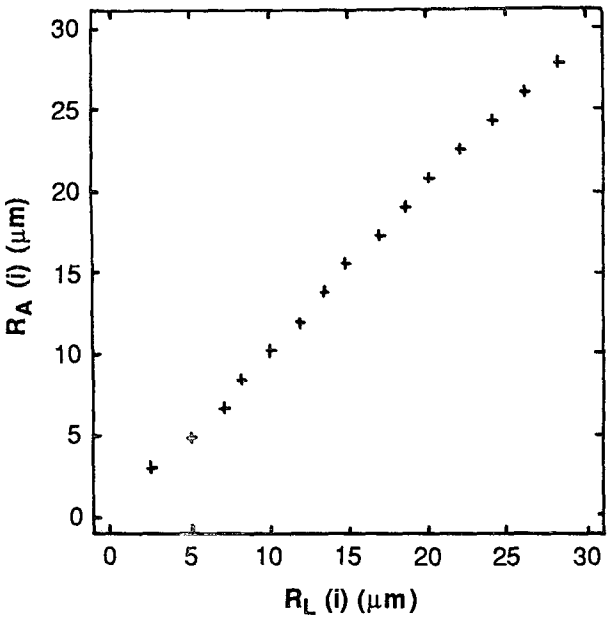

FIG. 5. Comparison between mean FSSP class radii determined from the laboratory studies, $R_L(i)$ and the ones deduced from the procedure described in step A, $R_A(i)$.

accounted for laser beam intensity variations and electronic time response limitations. Figure 5 compares the average radii of the FSSP channels obtained from this correction and the radii corrected according to step A [Eq. (9)]. Slight differences in the mean radii may be noticed for the intermediate FSSP channels. However, this plot reveals that a linear algorithm provides a satisfactory correction for the mean channel radii of this FSSP. The FSSP liquid water contents calculated by using the assumption of a constant corrective term $\overline{\Delta R}$ according to Eq. (5) (mean or extreme values) or a variable term depending on the FSSP mean class radii [Eq. (9)] are compared in Figs. 6a and 6b to the liquid water contents obtained after the laboratory correction. The data points correspond to measurements made at all sampled levels of this cloud. In both cases, the differences remain lower than the 30% error limit announced by Baumgardner (1988) for the liquid water contents calculated with the laboratory correction. This behavior suggests that the procedure presented in this work allows useful conclusions even if undiluted cloudy-air parcels are only detected at a single level. The mean radii and the liquid water contents calculated after having applied step B are plotted against the corresponding values obtained by using the laboratory correction, respectively, in Figs. 7a–7e and Figs. 8a–8e for each sampled level. Despite the slight discrepancies in the low radii and high liquid water content ranges, the results obtained by both methods generally agree well, thus, attesting the validity of the physical approach.

4. Discussion

The two-step approach used in this work to correct the FSSP measurements during the JHWRP led to results that agreed well with those obtained from the laboratory correction, thus, giving confidence to this procedure and to that developed in the laboratory. The

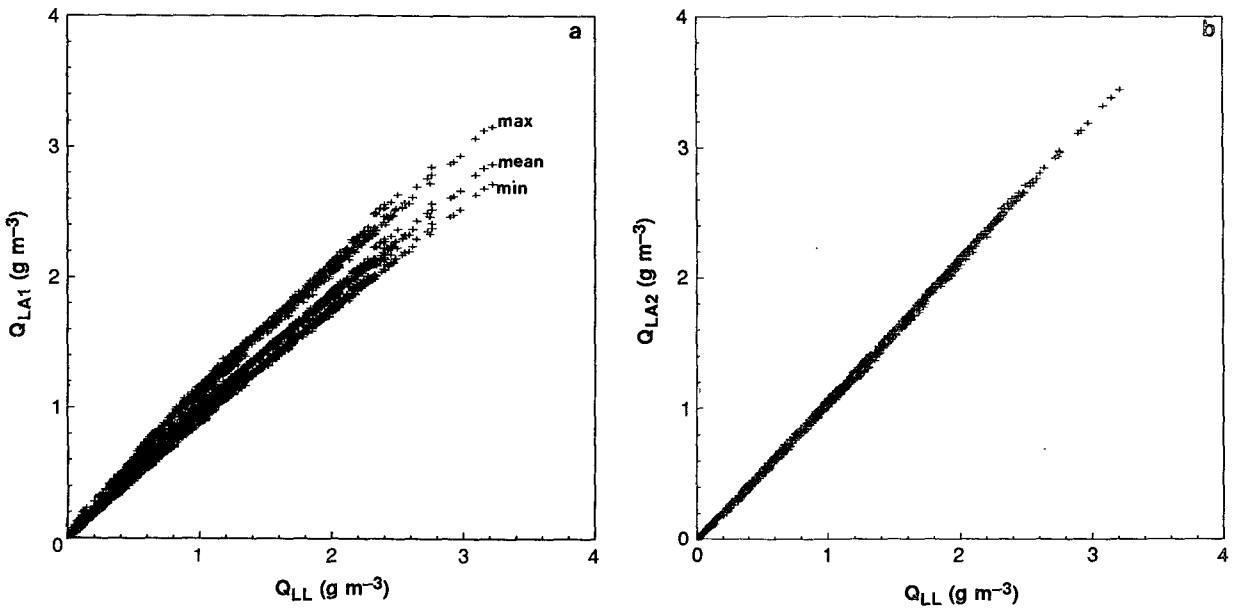

FIG. 6. Comparison between the liquid water contents calculated by using the laboratory correction, Q_{LL} and the one corresponding to step A [Q_{LA1}: $\overline{\Delta R}$ = constant; Q_{LA2}: Eq. (9)].

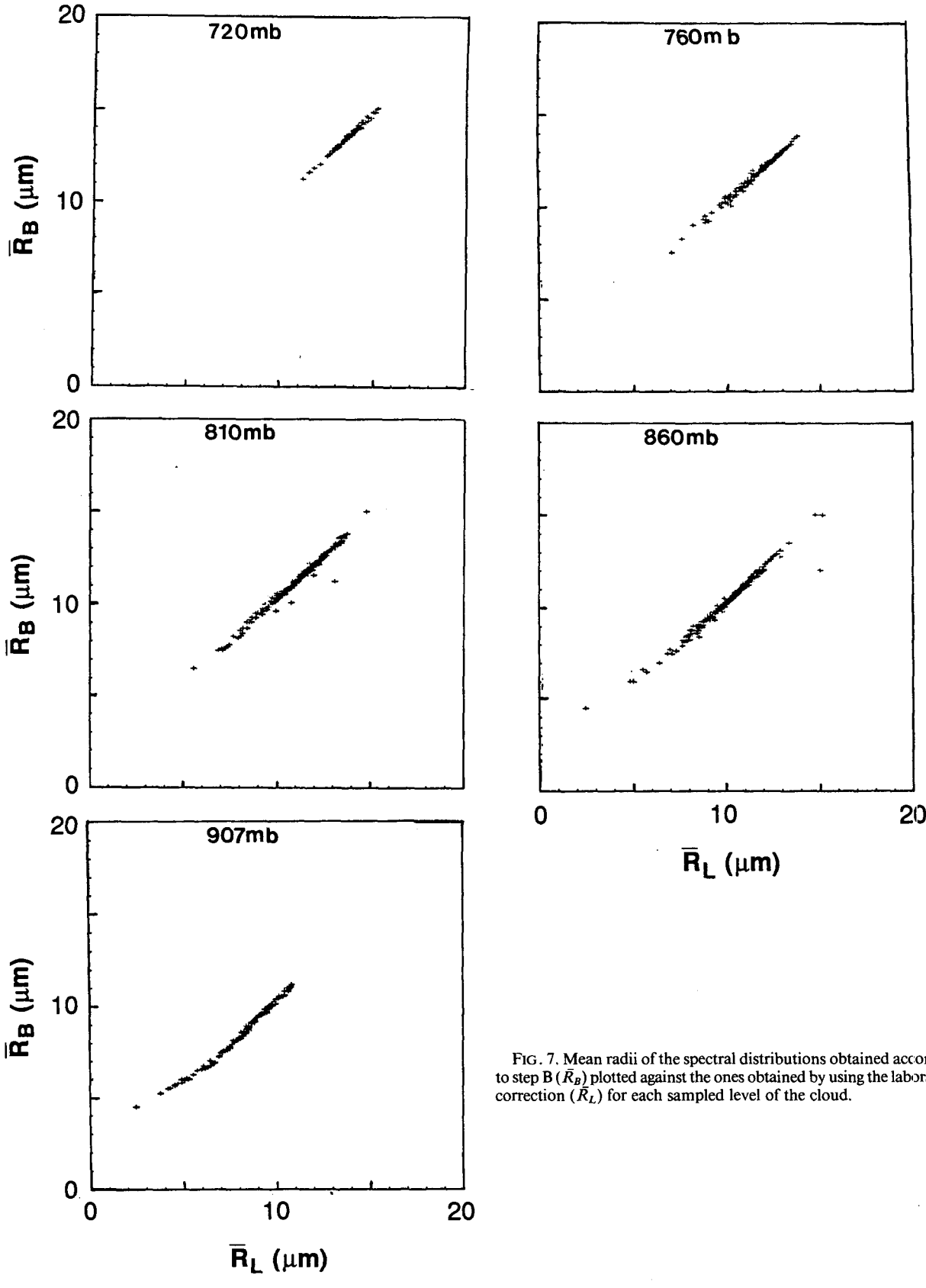

FIG. 7. Mean radii of the spectral distributions obtained according to step B ($\bar{R}_B$) plotted against the ones obtained by using the laboratory correction ($\bar{R}_L$) for each sampled level of the cloud.

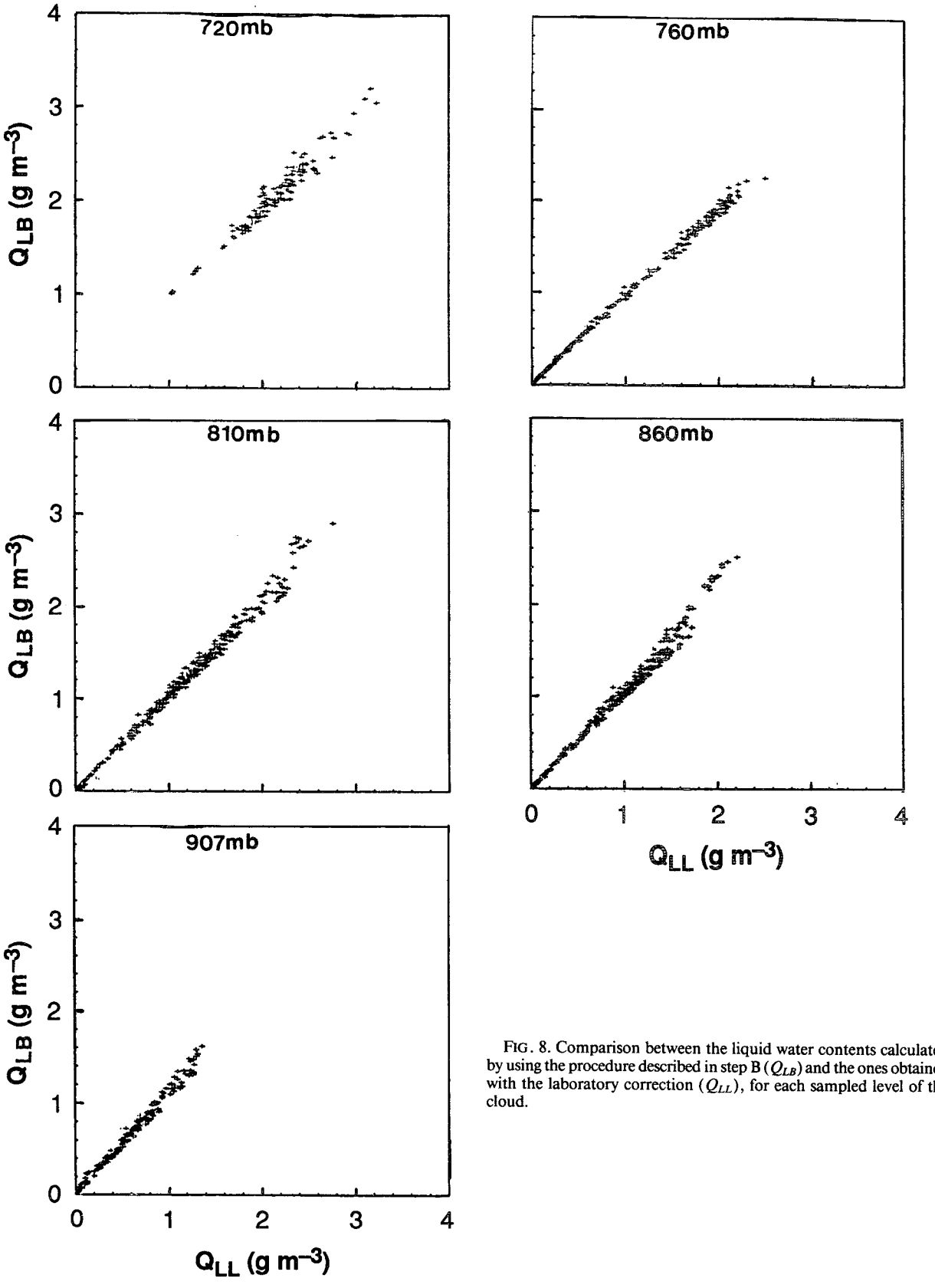

FIG. 8. Comparison between the liquid water contents calculated by using the procedure described in step B (Q_{LB}) and the ones obtained with the laboratory correction (Q_{LL}), for each sampled level of the cloud.

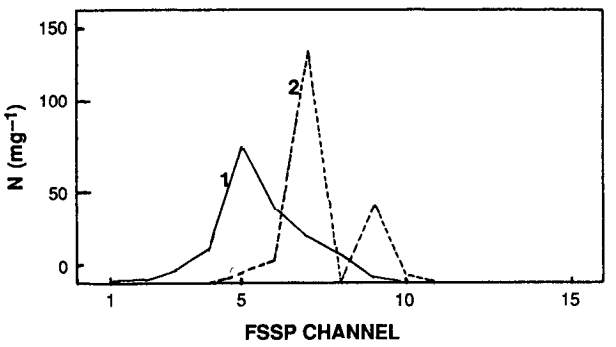

FIG. 9. Measured spectral distribution 1) corresponding to a diluted parcel that has activated new nuclei compared to the corresponding final true spectral distribution 2) showing a bimodal character.

first step relates each FSSP mean channel radius (manufacturer's calibration) to a corrective term $\Delta R(i)$, which is considered either as a constant or linear function of the mean channel radius. A possible error could be introduced during this process if some parcels considered as undiluted were slightly diluted. In the worst case (clear-air entrainment at the observation level and homogeneous mixing), the error in the mean radius has been evaluated to 1%. Further, this approach does not correct the spreading caused by the laser beam inhomogeneities. Therefore, although this procedure can be used to provide useful information for mean radii and liquid water contents, it maintains the artificial overestimation of the spectral width.

The second step improves the previous approach since it takes into account the contribution of each populated FSSP channel to the measured spectral concentration of a given channel. This approach corrects both the sizes and concentrations of droplets in the FSSP bins. In this case, the true spectral distributions are narrower than the measured ones. The fact that some undiluted droplet spectral distributions observed at 907 mb could have developed on wide cloud-base ones (however, with negligible droplet concentrations beyond FSSP channel 3) and the simplifying assumption of a monodispersed theoretic spectral distribution made for the calculation of the matrix elements M_{ki} could lead to a slight underestimation of the true droplet spectral width. In agreement with Baumgardner and Spowart's (1990) observations, it appears that the FSSP shifts spectral distributions toward smaller radii. It is therefore clear that if there were droplets outside the FSSP range, the spectral droplet concentrations in the extreme FSSP bins would be affected. However, such droplets are in low concentrations when compared to the medium-sized ones, and their presence would not lead to significant changes in the deduced true droplet spectral distributions, thus, not seriously affecting the calculated liquid water contents.

From a theoretical point of view, this approach should lead to better results if CCN distributions were used to initialize the model calculations. Since such distributions were not available in the case study discussed here, uncorrected measured cloud-base spectral distributions were used for the model initialization. This possibly results in errors in the calculated droplet spectral distributions at higher levels. The influence of these errors should decrease with increasing distance from cloud base. The effect of FSSP missizing errors at cloud base has been evaluated. A CCN activity spectrum, deduced from an observed droplet-size distribution measured in the undiluted region of the lowest sampled level, was used in relation to the model, to calculate a theoretical adiabatic distribution at 907 mb. The mean radius of the latter distribution was compared to a corrected spectrum from an undiluted parcel from this level. The difference was less than 0.1 μm. One may therefore conclude that the FSSP missizing errors at cloud base have negligible effect on the mean characteristics of the corrected spectral distributions at higher levels. The laboratory results and the ones obtained by using our procedure agree well, which strengthens the aforementioned conclusion.

This corrective procedure may also lead to additional useful microphysical information. For example, the presence of bimodal true spectral distributions corresponding to single-peaked measured ones could be a further confirmation of secondary activation in diluted samples well above cloud base. Such diluted samples are characterized by positive vertical velocities, important small-droplet concentrations, and total droplet concentrations, which are equal to or larger than the ones observed in undiluted samples. Although one would expect the corresponding spectral distributions to be bimodal, this feature is often masked by the artificial spectral broadening when both modes are close. The true spectral distribution should restore the bimodal character of the spectrum, since it reduces the artificial spectral broadening effect. As an example, Fig. 9 presents the measured and final true spectral distributions of a diluted sample which satisfied the previous secondary activation criteria. Under certain conditions, the algorithm used in this approach could produce sharp changes at both extremities of the true spectral distribution leading to multimodal spectral features. This behavior is associated with the absence of droplet size information beyond the FSSP extreme values. However, in this case, since the approximation degree S was less than unity, it seems reasonable to conclude that the bimodal character of the final true distribution is the result of secondary activation and not an artifact of the iteration procedure.

5. Conclusions

A method has been presented in this paper allowing an alternative correction and validation of FSSP measurements by using data obtained in undiluted cloudy-air regions. It is based on the comparison between the

theoretical and observed droplet spectral distributions of undiluted cloudy-air samples and allows preliminary aircraft data analysis using rough FSSP data. Although this method will not replace FSSP laboratory calibrations and corrections based on studies of the probe response, it provides an alternative consistency check for verification of correction algorithms.

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