A Synergy Approach to Estimate Properties of Raindrop Size Distributions Using a Doppler Lidar and Cloud Radar

KATJA TRÄUMNER, JAN HANDWERKER, ANDREAS WIESER, AND JENS GRENZHÄUSER

Karlsruhe Institute of Technology, Karlsruhe, Germany

(Manuscript received 13 August 2009, in final form 15 January 2010)

ABSTRACT

Remote sensing systems like radars and lidars are frequently used in atmospheric measurement campaigns. Because of their different wavelengths, they operate in different scattering regimes. Combined use may result in new measurement options. Here, an approach to estimate raindrop size distribution using vertical velocities measured by a lidar–radar combination is introduced and tested using a 2-μm Doppler lidar and a 35.5-GHz cloud radar. The lidar spectra are evaluated to deduce air motion from the aerosol peak and the fall velocity of the raindrops from the rain peak. The latter is weighted by the area (D^2) of the scatters. The fall velocity derived from radar measurements is weighted by D^6 (Rayleigh approximation). Assuming a size-dependent fall velocity and an analytical description of the drop size distribution, its parameters are calculated from these data. Comparison of the raindrop size distribution from the lidar–radar combination with in situ measurements on the ground yields satisfying results.

1. Introduction

Active remote sensing techniques, such as radar and lidar, are well-established methods for probing the atmosphere. New commercially available small and mobile scanning lidar and radar systems that are operated in an eye-safe and fully automated manner allow for new measurement approaches. Because of the different wavelengths, reflections of lidar and radar radiation depend differently on the scatter's size. These differences can be used, on the one hand, to extend atmospheric measurements of aerosol backscatter and wind velocity in height and time, that is, for providing information under a wider range of weather conditions. On the other hand, the coinciding measurements allow for an estimation of new atmospheric variables, for example, of the liquid water content (Baedi et al. 2000) or droplet concentrations in clouds (Boers et al. 2000), and for a new visualization of atmospheric processes, for example, of convection and convective precipitation (Kottmeier et al. 2008).

Raindrop size distributions (RSDs) are usually measured by disdrometers. They are placed on the ground, where they supply the data continuously and at low cost. To obtain in situ information on higher levels above ground, expensive aircraft-based measurements are necessary. New sonde systems are available, but they only provide a spotlight of the situation when passing through the atmosphere. An overview of different techniques using Doppler radars and wind profilers to determine RDSs is given by Kollias et al. (2002). They also present an approach to using Mie oscillations in the Doppler spectra of a 94-GHz cloud radar in order to estimate vertical air velocity and RSDs. Remotely sensed RSDs based on the relations between (i) drop size and the scattering cross section and between (ii) drop size and fall velocity are also obtained by using a Micro Rain Radar (MRR; Peters et al. 2002).

A synergetic approach to estimate remotely sensed RSDs using vertical velocity measurements performed with a lidar-radar combination is presented here. It represents an usage of a lidar-radar combination beyond the characterization of the turbulent wind field and shall be used in addition to other combined measurements, not as a stand-alone application.

2. Method

Whereas lidars operate in the geometric optics regime and therefore have a measurement dependency on the

Corresponding author address: Katja Träumner, Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany.
E-mail: katja.traeumner@imk.fzk.de

DOI: 10.1175/2010JTECHA1377.1

square of the raindrop size, radars measure in the Rayleigh regime (at least for small raindrops), which implies a dependence on the scatterer size 6th power. Consequently, lidar measurement of radial velocity during rainfall is dominated by the smaller, slower falling drops compared to the radar. Hence, the vertical velocity measured by the lidar is smaller than that measured by a radar. Using this difference, a method based on the vertical velocity of the raindrops as seen by both instruments ($v_{\mathrm{rain,lidar}}$ and $v_{\mathrm{rain,radar}}$) is developed to estimate the RSD. The vertical air velocity v_{air} has to be taken into account, because the velocities of the raindrops observed (v_{lidar} and v_{radar}) are always composed of two components:

$$v_{\mathrm{lidar}} = v_{\mathrm{rain,lidar}} + v_{\mathrm{air}}, \tag{1}$$

$$v_{\mathrm{radar}} = v_{\mathrm{rain,radar}} + v_{\mathrm{air}}. \tag{2}$$

To account for the different scattering mechanisms, a weighted measured velocity is calculated:

$$v_\kappa = \frac{\int v(D)N(D)D^\kappa\,dD}{\int N(D)D^\kappa\,dD}, \tag{3}$$

with drop diameter D, RSD $N(D)$, velocity $v(D)$ of the raindrops having the diameter D [consisting of the fall velocity of the raindrop due to gravity and vertical air movement: $v(D) = v_{\mathrm{rain}}(D) + v_{\mathrm{air}}$], and a parameter κ, depending on the scattering regime. The radar weighting is based on Rayleigh scattering (Ulbrich 1983), that is, $\kappa_{\mathrm{radar}} = 6$. This weighting is reasonable for small raindrops having a diameter much smaller than the radar wavelength. Lidar backscatter occurs as optical scattering, so $\kappa_{\mathrm{lidar}} = 2$, which makes sense for particles with diameters of more than 100 μm. Both approximations are applicable under rain conditions with small drops of up to 1 or 2 mm.

The terminal fall velocity of raindrops is calculated using the formula of Atlas et al. (1973):

$$v_{\mathrm{rain}}(D) = v_1 \exp\left(-\frac{D}{D_v}\right) - v_0, \tag{4}$$

where $v_0 = 9.65$ m s^{-1}, $v_1 = 10.3$ m s^{-1}, and $D_v = 1.667$ mm.

For the RSD, a gamma distribution

$$N(D) = N_0 D^\mu \exp(-\lambda D) \tag{5}$$

with the parameters μ, λ, and N_0 is chosen. The method described here to determine RSDs does not depend on the chosen distribution. Any formulation using three free parameters may be used. Because the gamma distribution is accepted widely for the description of RSDs (Willis 1984; Illingworth and Blackman 2002; Mallet and Barthes 2009), it is used here for demonstrating the technique.

By applying the assumptions concerning the fall velocity and size distribution to Eq. (3), the weighted velocities for the lidar (v_{lidar}) and radar (v_{radar}) may be calculated as

$$v_\kappa = \frac{\lambda^{\mu+\kappa}}{(\lambda + 1/D_v)^{\mu+\kappa+1}} v_1 - v_0 + v_{\mathrm{air}}. \tag{6}$$

Applying Eq. (6) to radar and lidar measurements, the gamma distribution parameters can be determined as

$$\lambda = D_v^{-1}[r^{(\kappa_{\mathrm{lidar}}-\kappa_{\mathrm{radar}})^{-1}} - 1]^{-1} = D_v^{-1}(r^{-0.25} - 1)^{-1}, \tag{7}$$

$$\mu = \frac{\log\left(\dfrac{v_\kappa - v_{\mathrm{air}} + v_0}{v_1}\right)}{\log\left(\dfrac{\lambda}{\lambda + D_v^{-1}}\right)} - (\kappa + 1), \tag{8}$$

where $r = (v_{\mathrm{radar}} - v_{\mathrm{air}} + v_0)/(v_{\mathrm{lidar}} - v_{\mathrm{air}} + v_0)$, and κ may be either κ_{radar} or κ_{lidar}. The parameter N_0 of the gamma distribution depends on the absolute amount of the drops and may be determined from radar reflectivity using the parameters λ and μ:

$$Z = \int_0^\infty N(D)D^6\,dD = N_0 \frac{\Gamma(\mu + 7)}{\lambda^{\mu+7}}. \tag{9}$$

Hereinafter, the parameter N_0 will not be examined, and $\int N(D)\,dD$ will be set to 1.

3. Instrument and measurement description

The lidar–radar combination used in this study consists of two commercially available instruments: a 2-μm WindTracer system produced by Lockheed Martin Coherent Technologies (United States) and a 35.5-GHz cloud radar MIRA36-S designed by METEK (Germany). Table 1 summarizes the properties of the two remote sensing instruments. The lidar as well as the radar are able to measure radial velocity using the Doppler effect caused by the motion of scatterers. For this study, an effective sampling rate of 1 Hz for the lidar (accumulating 500 pulses) and a time resolution of 0.1 Hz for the radar were chosen.

Hard target measurements with the cloud radar and comparative measurements of the lidar and an ultrasonic anemometer indicate that velocity measurements of both instruments are bias-free. To estimate a random error, the autocorrelation function of the measured velocity was

TABLE 1. Instrument specifications.

	Cloud radar	Doppler lidar
Wavelength (mm), (μm)	8.5	2.023
Pulse width (ns)	200	425
Pulse repetition (kHz)	5	0.5
Pulse energy (mJ)	6	2
Unambiguous velocity (m s^{-1})	$\pm$10.6	$\pm$25
Sampling rate (MHz)	50	100
Peak power (kW)	30	4.5
Number of range gates	478	100
Lowest range gate (m)	150	350
Spatial resolution (m)	30	72

calculated. As an upper threshold for the random error due to uncorrelated noise, the difference between lag 0 and lag 1 of the autocorrelation function can be used (Lenschow et al. 2000). Under optimal lidar conditions, that is, a clear but aerosol-loaded nonturbulent atmosphere, the WindTracer has an uncorrelated error of less than 10 cm s^{-1}. In stratiform clouds, the cloud radar shows an error of less than 5 cm s^{-1}. Of course, the uncorrelated noise will increase under less optimal conditions because of a decreasing signal-to-noise ratio (SNR) and, hence, a worse peak estimation (Frehlich 2001), and because of velocity fluctuations within the range gates. For this reason, the uncorrelated noise was also evaluated for periods with uniform rain, which resulted in an estimation of around or less than 20–30 cm s^{-1} for both instruments.

In addition to the remote sensing instruments, a Joss–Waldvogel disdrometer measured RSDs in situ on the ground with a time resolution of 1-min and 20 drop-size classes.

All instruments were collocated during the Convective and Orographically-induced Precipitation Study (COPS; Wulfmeyer et al. 2008) on the Hornisgrinde, a mountain (1160 m asl) in the northern Black Forest of southwestern Germany, and measured from June to August 2007. Both remote sensing instruments performed different synchronized scan patterns. For estimating the RSDs, only the vertical stare measurements were taken into account.

The disdrometer was used to detect rain episodes. A rain period was defined to be a period with at least 10 drops each for at least three consecutive minutes. Using the smallest raindrop size class of the disdrometer $\langle D \rangle$ = 0.3135 mm and a detector area of 50 cm^2, a drop number of 10 results in a rain rate of about 0.002 mm h^{-1}, which is extremely small. For intercomparison of the results obtained from the lidar–radar combination with disdrometer measurements, the remote sensing velocity data were averaged over time intervals of 1 min. During the COPS campaign, the lidar and radar measured in the vertical stare mode during a total of 2617 rain intervals of 1 min. Lidar and radar measurements were evaluated at height levels between 400 and 750 m above ground level. An offset of 2 min between the disdrometer data and the remote sensing data is taken into account to consider the time needed for sedimentation.

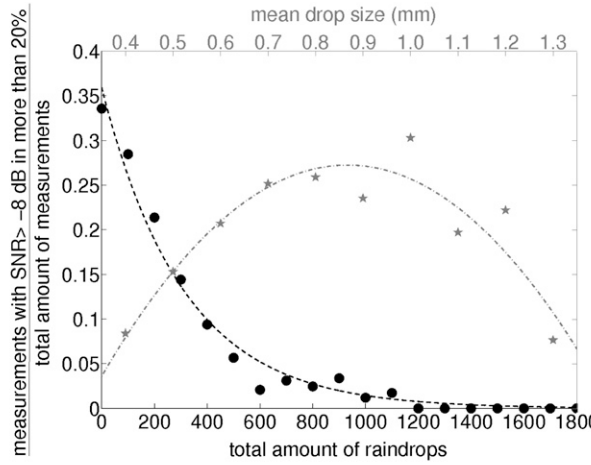

FIG. 1. Fraction of reliable velocity measurements as a function of the total amount of raindrops (black dots) and the mean raindrop size (gray stars).

4. Lidar measurements during rain

Lidars are typically not used for measurements during rain, and very few studies only cover signal characteristics under this atmospheric condition (Lottman et al. 2001). During the COPS campaign, the lidar measured vertical velocities during 6020 rain intervals. For the lowest six range gates (approximately 400–750 m above ground) and the time resolution of 1 Hz, the lidar received 360 individual Doppler spectra within a time interval of 1 min. Using an accumulation of 500 pulses, an SNR better than −8 dB (6-MHz bandwidth) is needed to derive reliable velocities. As a quality criterion, at least 72 of the 360 lidar spectra measured during 1 min (20%) were required to have an SNR better than −8 dB. Figure 1 shows how the fraction of good measurements depends on the total amount of raindrops (from the Joss–Waldvogel disdrometer) and on the size of the drops. It is obvious that the instrument is not able to provide useful data when more than about 1000 drops are counted per minute. A maximum of this fraction is observed for a drop size between 0.5 and 1 mm. It has to be taken into account that more drops do not necessarily mean a higher rain rate. Regarding a possible relationship between the amount of intervals with good SNR and the estimated rain rate, efficiency is constant between 5 and 18 mm h^{-1}, and values are increasing at lower rain rates. In total, 1191 intervals fulfill the above

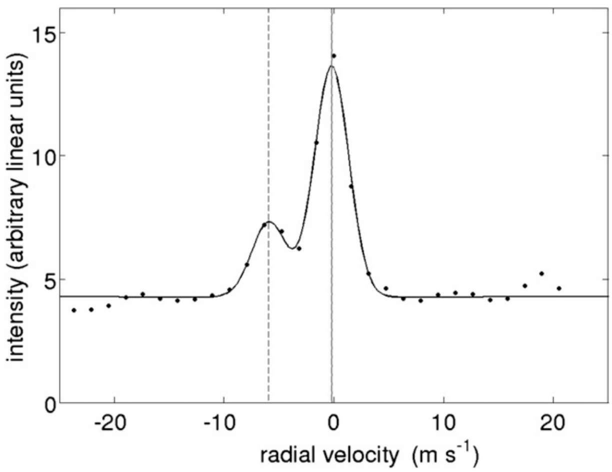

FIG. 2. Lidar Doppler spectra during light rain (dots) and with a Gaussian model (thick solid line). Two peaks could be observed: an aerosol peak (right) and a rain peak (left). The automatic lidar algorithm always detects the higher peak, while the Gaussian model detects both peaks.

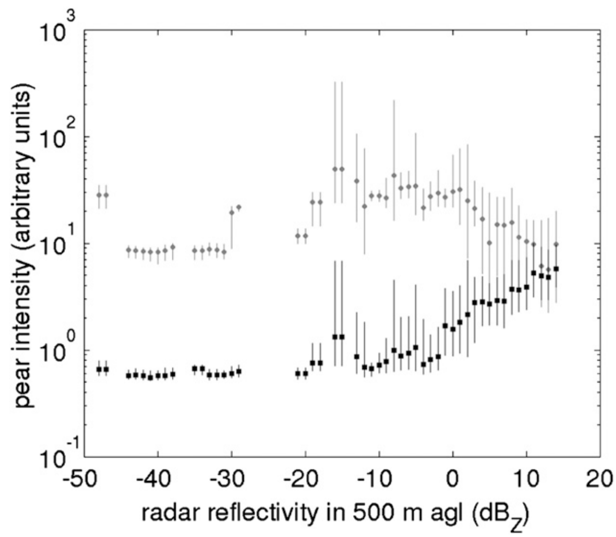

FIG. 3. Comparison of the peak intensity of the two peaks in the lidar Doppler spectra and radar reflectivity. Gray dots represent the aerosol peak and black squares are the rain peak. Vertical lines show the 25th–75th percentile and the symbols show the 50th percentile.

criterion of at least 20% good data, which corresponds to 19.8% of all rain measurements.

During rain events, Doppler spectra with good SNRs always contain at least two peaks (Fig. 2): one belonging to the raindrops (r) and an additional peak located around 0 m s^{-1} due to the aerosol particles (a). A two-component Gaussian model is used to detect two peaks automatically:

$$s(\nu) = a_a \exp\left[-\frac{(\nu - \nu_a)^2}{2\sigma_a^2}\right] + a_r \exp\left[-\frac{(\nu - \nu_r)^2}{2\sigma_r^2}\right]. \qquad (10)$$

Using a least squares fit, the two velocities (ν_a and ν_r) are derived. They are used for further investigation only if the fit parameters of the Gaussian model show significant peak heights for both peaks (lower threshold of 0.5 for both peaks, according to a median aerosol peak height of 11.4 and a median rain peak height of 3.8) and a separation of the two peaks of at least 1.5 m s^{-1}. Around 40% of the Doppler spectra were skipped because of this control mechanism. In approximately 70% of the spectra fulfilling the control criterion, the aerosol peak has an intensity that is higher than that of the rain peak, which supports the fact that only light rain can be detected by Doppler lidar. Comparison of the peak intensities measured by the lidar with radar reflectivities shows an increase of the rain-peak intensity for radar reflectivities exceeding −5 dBZ and a slight decrease of the aerosol peak (Fig. 3). The latter might be explained primarily by attenuation, but scavenging of aerosols might occur as well.

The aerosol peak yields the vertical air velocity υ_{air} during rain. A correlation analysis did not reveal any relationship between υ_{air} and the absolute number of disdrometer counts, neither to the mean drop size nor to the rain rate estimated from disdrometer measurement. So, the vertical air velocity does not seem to be controlled by the falling rain.

5. Application and results

During the COPS campaign, 419 of the possible 2617 rain intervals of 1 min fulfill the criterion of at least 20% useful lidar data (16%). Hence, the attenuation of the lidar signal is the most limiting factor of the method described. Of these 419 intervals, another 58 are lost, because less than 36 (10%) spectra contain double peaks fulfilling the peak criteria. This is a problem if the rain is too weak or the aerosol is scavenged by the rain or the drop size distribution contains more than two distinct peaks.

To determine the RSD parameters, the measured vertical velocities of the raindrops and the vertical air velocity were averaged over the time interval of 1 min and over the lowest 750 m. A study of changing fall velocities at height levels from 750 to 200 m above ground did not reveal any significant trend. The rain velocity ($\upsilon_{\text{rain,radar}}$ and $\upsilon_{\text{rain,lidar}}$) was obtained by subtracting the vertical air velocity from the measured velocity of the raindrops. The standard deviation of the derived velocities within a 1-min interval is up to 80% of the average velocity, which illustrates the high variability of the rain. The parameters of the gamma distribution λ and μ, in turn, show a high sensitivity to variations of the velocities (Fig. 4). To

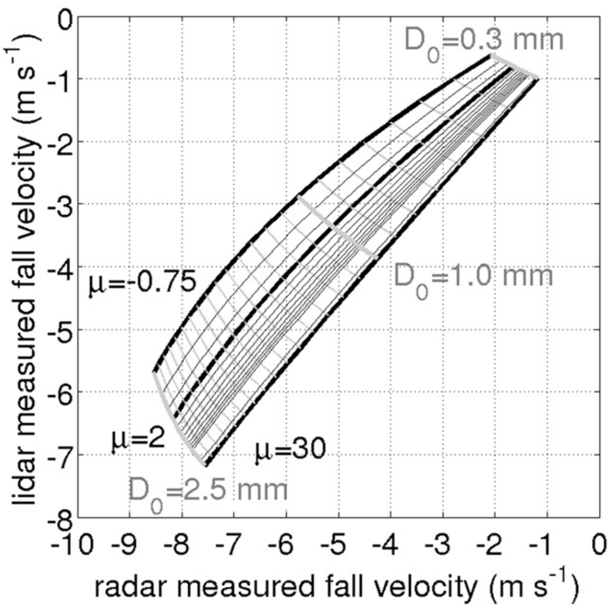

FIG. 4. Effect of a variation of the rain velocity measured by radar and lidar on the parameters μ (black) and $D_0 = (\mu + 4)/\lambda$ (gray).

reduce the scatter and increase reliability, intervals showing a standard deviation of more than 25% were neglected (69%). In the end, a reliable dataset of 111 radar–lidar velocities is available to determine the parameters of the gamma distribution. This corresponds to an overall adaptability of the method of less than 5%.

Figure 5, left, shows an example of a disdrometer measurement (bars), the resulting gamma-shaped fit (based on the first three moments; dashed line), and the distribution estimated from the lidar–radar combination [based on Eqs. (7) and (8); solid line]. The corresponding lidar and radar velocities show the described difference between lidar and radar velocity measurement (Fig. 5, right).

For comparison with in situ measurements, the first and the second moments of the disdrometer distributions were calculated. In 47% the first moments differ by less than 0.2 mm, and in 80% the second moments vary by less than 0.1 mm^2. Both criteria are fulfilled in 45% of the measurements. Figure 6 shows the comparison of the reference drop size $D_0 = (\mu + 4)/\lambda$ from in situ disdrometer measurement and remote sensing estimation, with the correlation coefficient being 0.61.

6. Conclusions

The aim of this paper was to show that RSDs can be estimated from vertical velocities measured by two remote sensing instruments with different wavelengths. To test the algorithm, a dataset obtained from a 2-μm Doppler lidar and a 35.5-GHz cloud radar was used. The lidar measured with a sampling efficiency of around 20% during rain and showed clear double peaks in the Doppler spectra, which allow estimation of the velocity of the raindrops as well as the vertical air velocity. At a total number of more than 1000 raindrops counted on the ground, the lidar signal is attenuated too much to obtain reasonable velocities. This limits the applicability of the method to weak rain events. Other limiting effects are nonseparable double peaks in the lidar Doppler spectra and a high variability of the rain velocity. In this first study, the method was successful in less than 5%. It has to be pointed out that the dataset initially was not created for this study and that the necessary synchronous scan patterns of both instruments were not available in

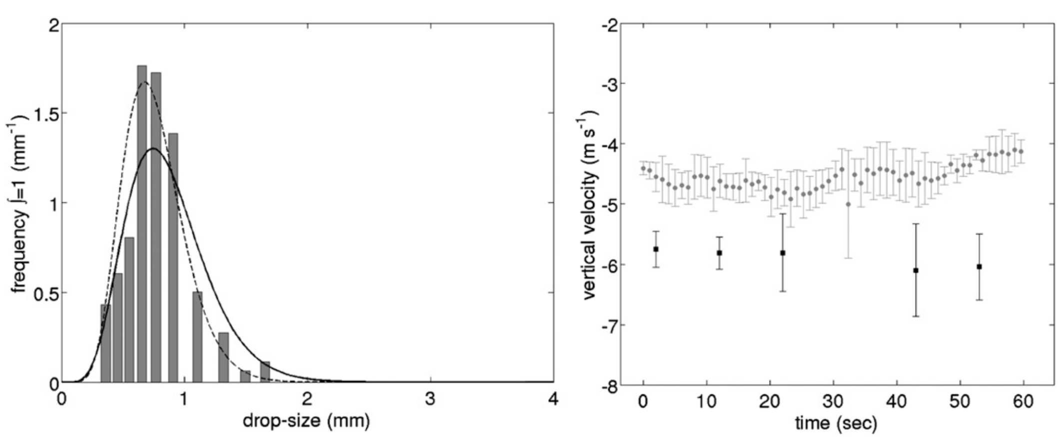

FIG. 5. (left) Example of an RSD measured by a disdrometer and estimated gamma distribution based on the first three moments of the disdrometer measurement (dashed line) and on the method using the radar–lidar combination (solid line). (right) Corresponding raindrop fall velocities show the difference between lidar (gray dots) and radar (black squares) measurement (error bars due to variations along range gates).

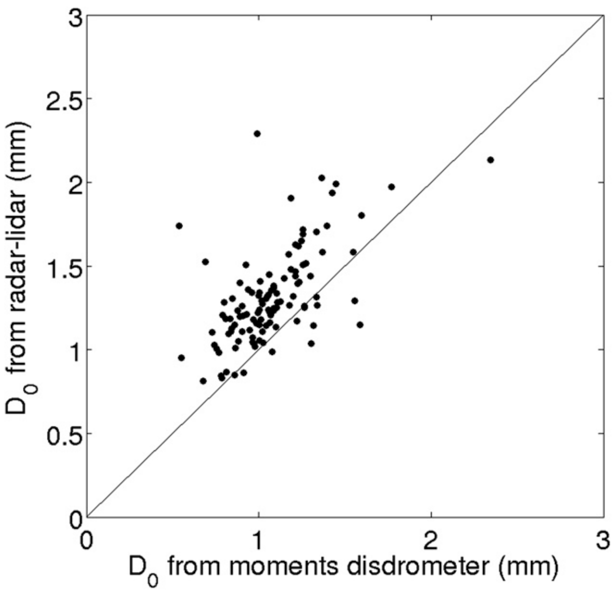

FIG. 6. Reference drop size D_0 from in situ disdrometer measurement vs lidar–radar estimation.

many situations. Additionally, hard control criteria were used.

This study only proves the possibility in principle of deriving information on RSDs by the method proposed. Further improvements should be made: (i) Mie scattering instead of Rayleigh assumption for radar, (ii) the height dependence of the fall velocity of the rain, and (iii) improved methods to derive the velocities from the measurements. These improvements may increase both the reliability and the amount of measurements.

A comparison of the estimated RSDs with in situ measurements on the ground reveals satisfying results. The algorithm can estimate gamma distribution parameters well during weak rain episodes. The differences may result from different measurement locations at high levels of around 500 m and on the ground and from other than gamma-shaped distributions. Generally, the method can be adapted to other distributions.

The method should be investigated further, in particular because the approach has the great advantage of determining RSDs with often-used radar and lidar systems at different height levels without any major expenditure being required.

Acknowledgments. Special thanks go to Dr. Ulrich Corsmeier, Dr. Christian Barthlott, and two anonymous reviewers for all their comments that helped to improve the manuscript.

REFERENCES

Atlas, D., R. C. Srivastava, and R. S. Sekhon, 1973: Doppler radar characteristics of precipitation at vertical incidence. *Rev. Geophys. Space Phys.,* **11,** 1–35.

Baedi, R., J. de Wit, H. Russchenberg, J. Erkelens, and J. P. Baptista, 2000: Estimating effective radius and liquid water content from radar and lidar based on the CLARE98 data-set. *Phys. Chem. Earth,* **25,** 1057–1062.

Boers, R., H. Russchenberg, J. Erkelens, V. Venema, A. van Lammerenb, A. Apituleyc, and S. Jongend, 2000: Ground-based remote sensing of stratocumulus properties during CLARA, 1996. *J. Appl. Meteor.,* **39,** 169–181.

Frehlich, R., 2001: Estimation of velocity error for Doppler lidar measurements. *J. Atmos. Oceanic Technol.,* **18,** 1628–1639.

Illingworth, A. J., and T. M. Blackman, 2002: The need to represent raindrop size spectra as normalized gamma distributions for the interpretation of polarization radar observations. *J. Appl. Meteor.,* **41,** 286–297.

Kollias, P., B. Albrecht, and F. Marks, Jr., 2002: Why Mie? Accurate observation of vertical air velocities and raindrops using a cloud radar. *Bull. Amer. Meteor. Soc.,* **83,** 1471–1483.

Kottmeier, C., and Coauthors, 2008: Mechanisms initiating deep convection over complex terrain during COPS. *Meteor. Z.,* **17,** 931–948.

Lenschow, D., V. Wulfmeyer, and C. Senff, 2000: Measuring second- through fourth-order moments in noisy data. *J. Atmos. Oceanic Technol.,* **17,** 1330–1347.

Lottman, B., R. Frehlich, S. Hannon, and S. Henderson, 2001: Evaluation of vertical winds near and inside a cloud deck using coherent Doppler lidar. *J. Atmos. Oceanic Technol.,* **18,** 1377–1386.

Mallet, C., and L. Barthes, 2009: Estimation of gamma raindrop size distribution parameters: Statistical fluctuations and estimation errors. *J. Atmos. Oceanic Technol.,* **26,** 1572–1584.

Peters, G., T. Andersson, and B. Fischer, 2002: Rain observations with a vertically looking micro rain radar (mrr). *Boreal Environ. Res.,* **7,** 353–362.

Ulbrich, C., 1983: Natural variations in the analytical form of the raindrop size distribution. *J. Climate Appl. Meteor.,* **22,** 1764–1775.

Willis, P., 1984: Functional fits to some observed drop size distributions and parameterization of rain. *J. Atmos. Sci.,* **41,** 1648–1661.

Wulfmeyer, V., and Coauthors, 2008: RESEARCH CAMPAIGN: The Convective and Orographically Induced Precipitation Study. *Bull. Amer. Meteor. Soc.,* **89,** 1477–1486.