Assessing the Errors of Microphysical Retrievals Based on Doppler Radar Parameters

Y.L. Kogan, Z.N. Kogan, and D.B. Mechem
Cooperative Institute for Mesoscale Meteorological Studies
University of Oklahoma
Norman, Oklahoma

Introduction

The paper analyzes errors in retrievals of cloud liquid water content (Q_l) and precipitation flux (R) based on three different sets of parameters: a) radar reflectivity, Z, b) radar reflectivity and Doppler velocity, V_d, and c) radar reflectivity and Doppler velocity spectrum width, σ_d. As radar reflectivity represents the sixth moment of the drop size distribution (DSD), one can expect it to be correlated with other moments of the DSD, such as liquid water content Q_l (third moment of DSD), or drizzle flux R, which in stratocumulus clouds is proportional to the fourth DSD moment. Thus, a number of studies have been devoted to retrievals of Q_l and R in boundary layer stratocumulus based on radar reflectivity Z alone. The success of the Q_l retrievals depended on cloud type, but even more on the absence of drizzle, both in the cloud and below cloud base. The retrieval of Q_l is rather straightforward in non-drizzling stratocumulus where cloud spectra are mostly unimodal and the contribution to reflectivity from the large droplet tail of the spectrum is minimal. A simple Z-Q relation in this case is justified (Sauvageot and Omar 1987; Frisch et al. 1995; Fox and Illingworth 1997):

$$Z = a\, Q_l^b \tag{1}$$

Here parameters a and b depend on assumptions about the drop number concentration and the shape (mostly the width) of the drop spectrum. The task becomes more complicated once drizzle drops are present in significant numbers. Drizzle typically contributes little to Q_l yet can profoundly influence reflectivity, which is proportional to the sixth moment of the droplet size distribution and thus sensitive to the large drop tail of the DSD. For this reason, radar reflectivity alone may not be sufficient for an accurate retrieval, especially in drizzling cases where a significant fraction of cloud liquid water is carried by small drops ($r<25$ μm). In order to enhance the accuracy of Q_l retrievals a number of studies have proposed to use Doppler velocity measurements in addition to reflectivity (Frisch et al. 1995, Babb et al. 1999, Kollias 2001a). Others have suggested combining radar observations with other cloud remote sensing instruments such as lidars (O'Connor et al. 2005) or passive microwave radiometers in an effort to constrain the retrieval (Liao and Sassen 1994; Frisch et al. 1998, Ovtchinnikov and Kogan 2000).

Using observable Doppler parameters, such as mean Doppler velocity and the Doppler velocity spectrum width, adds another dimension of complexity, since those parameters depend both on moments of the DSD (which have the direct bearing on microphysical parameters to be retrieved) and on the turbulent air velocity. From the standpoint of *microphysical* retrievals, the turbulent contribution represents noise that must be filtered in order to extract useful microphysical information. The "noise" signals in the mean Doppler velocity and the mean Doppler spectrum width have different magnitudes and will be investigated in more detail elsewhere. Here we will concentrate on the assessment of the accuracy of retrievals based on specified sets of Doppler radar parameters. Specifically we aim to determine 1) which Doppler parameters improve the accuracy of retrievals most significantly compared to retrievals based on Z alone, and 2) the maximum retrieval accuracy that can be achieved based on these parameters.

Our evaluation is based on the concept of the Observing System Simulation Experiments (Parsons and Dudhia 1996). Based on this concept, cloud radar parameters are obtained from data generated by the high-resolution Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) large-eddy simulation (LES) model with Explicit MicroPhysics (CIMMS LES EMP). Applying the Observing System Simulation Experiments framework for stratocumulus clouds, we quantitatively evaluate the errors of several cloud liquid water and drizzle flux retrievals. As both V_d and σ_d are defined as intrinsic parameters of the DSD and, thus, neglect the contribution from air turbulence in the sensed volume, our assessment should be considered as the lower limit on the retrieval errors.

Approach

Model and Data

The study is based on the CIMMS LES model, which combines 3D dynamics with an explicit (size-resolving) formulation of liquid phase microphysical processes. The thermodynamic state is described in terms of virtual liquid water potential temperature and total water mixing ratio. Cloud physics processes are formulated based on prediction equations for cloud condensation nuclei and cloud/drizzle drops (19 and 25 bins, respectively). A detailed description of the model can be found in Kogan (1991), Kogan et al. (1995), and Khairoutdinov and Kogan (1999). Individual case studies and comparison of simulations with aircraft observations (Khairoutdinov and Kogan 1999, Liu et al. 2000) have demonstrated that the model can reasonably well reproduce major dynamical, radiative, and microphysical parameters. Indirect tests of a bulk drizzle parameterization derived from model DSDs (Khairoutdinov and Kogan 2000) showed good agreement with a large number of observational datasets (Wood et al. 2002; Wood 2005).

We simulated several cases of stratocumulus clouds observed during the Atlantic Stratocumulus Transition Experiment (ASTEX) field experiment in clean and polluted air masses. The simulated cloud layers represented cases with different intensities of drizzle *in the cloud* (drizzle is defined as drops larger than 25 μm in radius).

From each simulation we extracted about 4,000 to 6,000 DSDs that were used to calculate cloud parameters, such as, e.g., drop concentration, liquid water content, cloud and drizzle water content, radar reflectivity, and Doppler velocity. The set of DSDs, therefore, served as the source for deriving Q_l and R retrievals using regression analysis and as a benchmark for evaluating them by comparing with the exact values of Q_l and R.

The range of cloud and drizzle parameters for all performed simulations is illustrated in Figure 1 for datasets representing light (LD), moderate (MD) and heavy (HD) drizzle spectra. Since the cloud layer evolves significantly during the three to six hour-long simulations, these datasets were further subdivided into subsets corresponding to a particular time of cloud evolution (e.g. LD5 refers to light drizzle case at 5 hrs into simulation). Table 1 shows cloud parameters and fraction of drizzle in cloud liquid water and reflectivity for subsets of data selected for analysis (LD≡LD1, MD≡MD1 and HD≡HD2).

Table 1. Mean and standard deviation (in brackets) of drop spectra parameters for LD, MD, and HD drizzling cases. Q_l and Q_r is liquid and drizzle water content, N_c and N_d is total and drizzle concentration, R_m and σ is the mean radius and relative dispersion of drop spectrum, R drizzle flux, V_d –Doppler velocity, Z_d – reflectivity in dBZ, FQ_{Qr} and FZ_{Qr} – fractions of Q_l and Z_m from Q_r, respectively.

Parameter	L D	M D	H D
Q_l (g m^{-3})	0.33 (0.15)	0.32 (0.14)	0.34 (0.16)
R_m (μm)	7.5 (1.2)	11.2 (1.7)	12.1 (2.4)
N_c (cm^{-3})	153 (35)	34 (12)	30 (8)
σ	0.25 (0.07)	0.34 (0.06)	0.34 (0.1)
Q_r (g m^{-3})	<0.0001	0.012 (0.018)	0.047 (0.042)
FQ_{Qr}	0.01 (0.03)	3.9 (5.5)	14.1 (9.1)
N_d (cm^{-3})	<0.00001	0.016 (0.22)	0.33 (0.38)
R (mm d-1)	0.31 (0.18)	0.84 (0.45)	2.03 (1.5)
Z_d (dBZ)	-24.8 (3.3)	-17.8 (2.9)	-9.3 (5.5)
FZ_{Qr}	0.31 (0.42)	16.6 (12.7)	77.7 (21.8)
V_d (cm s^{-1})	1.35 (0.2)	4.8 (1.7)	47.0 (26.5)

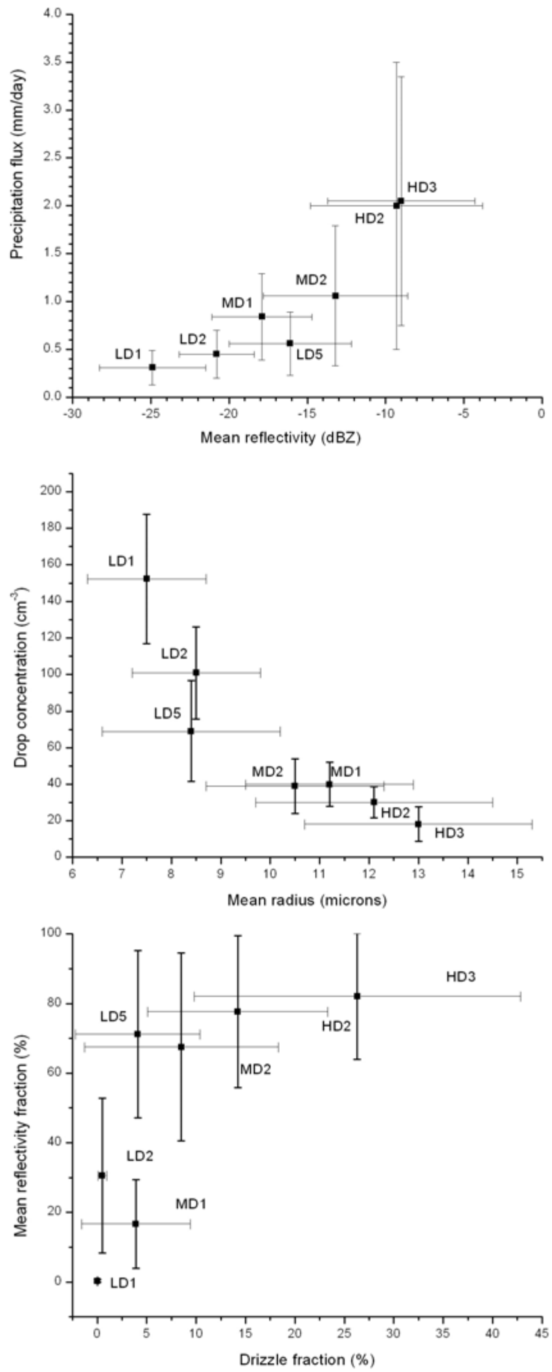

Figure 1. Range of cloud parameters in the analyzed cases of stratocumulus cloud layers. The black square represents the mean and the error bars the standard deviation of a parameter.

Definition of Doppler Radar Parameters

The Doppler velocity measured by the zenith-pointing radar is the sum of the vertical velocity of the air and the Z-weighted droplet terminal fall velocity *averaged over the radar pulse volume*. The mean Doppler velocity of the pulse volume at time t near point x with coordinates (x, y, z) is:

$$\overline{V_{dv}(\boldsymbol{x})} = \overline{w(\boldsymbol{x})} + \int_{r_0}^{r_{\max}} n(\boldsymbol{x},r)\; f_v(r)\, r^6 dr \Big/ \int_{r_0}^{r_{\max}} n(\boldsymbol{x},r)\, r^6 dr \equiv \overline{w(\boldsymbol{x})} + \overline{F_z(\boldsymbol{x})/Z(\boldsymbol{x})} \tag{2}$$

Here $f_v(r)$ is the fall velocity of the drop with radius r, $Z(\boldsymbol{x})$ is radar reflectivity and $Z(\boldsymbol{x})/F_z(\boldsymbol{x})$ is the Z-weighted drop terminal fall velocity at point $\boldsymbol{x}$. The bar denotes averaging over the radar pulse volume. For the K_α-band millimeter wave vertically pointing cloud radar millimeter wave cloud radar which operates at 35 GHz with an 8.77 mm wavelength, the vertical gate size is 45 m. The effective beamwidth for this radar is 0.2°-0.3°, which gives the radar a horizontal scanning dimension of about 10-50 m, depending on range. These radar pulse dimensions are comparable with those of a sampling volume required for a statistically robust determination of the drop size distribution $n(\boldsymbol{x},r)$ in the full range of drop sizes, including drizzle drops. The latter, because of their low concentration require an especially large sampling volume. The radar pulse and the DSD sampling volume dimensions are thus comparable with the grid dimensions in the LES model simulations (25 m in the vertical and 75 m in horizontal). For non-drizzling stratocumulus, the drop size distribution can be determined over a smaller sampling volume; in this case $n(\boldsymbol{x},r)$ in (2) should represent DSDs averaged over the radar pulse volume. The second term in (2):

$$V_d \equiv \overline{F_z(\boldsymbol{x})/Z(\boldsymbol{x})} \tag{3}$$

is the intrinsic microphysical contribution to the Doppler velocity and is defined similarly to O'Connor et al. (2005). Because $f_v(r)$ for droplets in the drizzle size range is a linear function of r, the Doppler velocity is essentially proportional to the ratio of the 7th to the 6th moment of the DSD (M_7/M_6). It is also worth noting that the drizzle flux is proportional to the 4th moment of the DSD (M_4).

The Doppler velocity spectrum variance in a pulse volume is given by:

$$\sigma_{dv}^2 = \int_{r_0}^{r_{\max}} [w' + (f_v - \overline{V}_d)]^2 n(r)\, r^6 dr / Z = \sigma_w^2 + \sigma_{dw}^2 + \sigma_d^2 \tag{4}$$

The observed spectral variance is the sum of variances representing contributions from air turbulence σ_w^2, intrinsic microphysical variance due to the spread of drops terminal fall velocities σ_d^2, and the cross-correlation between fluctuations of air and drop fall velocities σ_{wd}^2. The latter term is difficult to evaluate without information on the subgrid fluctuations in a LES model; however, our estimate based on resolvable scale fluctuations show that this term is on the same order of magnitude as σ_w^2. In addition to the terms shown in (4), the expression for the observed spectral variance also includes other contributions, e.g., due to drop oscillation/wobbling and finite width of the radar beam.

Estimates of these contributions have been made in many studies (see Doviak and Zrnic 1993 for review). Babb et al (1999) derived an expression for the contributions of turbulence, modal diameter, and DSD shape to Doppler spectral density. They demonstrated that characteristic turbulent intensity, represented by the half-width of the vertical velocity distribution, can be recovered via minimization of a cost function. Kollias et al (2001) assumed a turbulence spectrum based on homogeneous energy dissipation, which can be integrated over relevant wave numbers to obtain an expression for variance. This technique provided the best estimate of variance in the interior regions of updrafts and downdrafts, away from cloud boundaries where shear-generated turbulence tends to dominate. O'Connor et al (2005) extended the method of Kollias et al. in order to separate the DSD and turbulent components of the variance. Their estimate of the turbulent contribution was a wind-speed-dependent fraction of the total variance calculated over a 30 s sampling time.

With these methods to constrain the turbulent component under development and improvement, in this study we concentrate not on the retrieval algorithm itself but on assessment of the retrieval errors and the relative informational weight of different intrinsic microphysical parameters. Specifically we will assess contributions from the Doppler velocity V_d and the Doppler spectral width σ_d. For the intrinsic microphysical contribution, the latter is defined as:

$$\sigma_d^2 = \int_{r_0}^{r_{\max}} (f_v(r) - \overline{V}_d)^2 n(r)\, r^6 dr \Big/ \int_{r_0}^{r_{\max}} n(r)\, r^6 dr \qquad (5)$$

Results

The regression expressions are sought in an exponential form where the exponent is a linear combination of reflectivity and one of the Doppler parameters. For instance in the case of a Q_l retrieval based on Z and V_d we seek Q_l in the form:

$$Q_l = exp\,(\alpha + \beta Z_d - \gamma V_d) \qquad (6)$$

In the above expression parameters α, β, γ are determined from a regression analysis of the LES data. By replacing the intrinsic microphysical parameter V_d with the observable Doppler radar velocity $V_{dv} = V_d + w$, we can rewrite (6) in the form:

$$ln\, Q_l = \alpha + \beta Z_d - \gamma(V_{dv} - w) = \alpha + \beta Z_d - \gamma V_{dv} + \gamma w = \alpha + \beta Z_{eff} + \gamma w \qquad (7)$$

In the last expression for convenience we denote the linear combination of observable parameters Z_d and V_{dv} as an "effective" reflectivity $Z_{eff} = Z_d - \gamma/\beta V_{dv}$. Such a formulation is convenient because in the case of stratocumulus topped boundary layer the vertical velocity, horizontally averaged over the large time or spatial interval, is nearly zero, thus permitting in principle a method for estimating the horizontal mean value of $ln\ Q_l$:

$$< ln\ Q_l > = \alpha + \beta < Z_{eff} > \quad (8)$$

Our analysis shows (Kogan et al. 2005) that the regression formulas based on power instead of exponential function, yield similar approximation errors; however, when employing Doppler parameters the use of an exponential function is obviously advantageous for the reasons mentioned above.

Errors in the Retrieval of Cloud Liquid Water

For the LD case, the scattergram of cloud liquid water as a function of reflectivity Z in Figure 2 demonstrates that Q_l can be reasonably well represented as a function of Z_m (Z_m is reflectivity in $mm^6\ m^{-3}$, while Z_d is in dBZ). The best fit in the form:

$$Q_l = 9.7\ Z_m^{0.61} \quad (9)$$

is quite accurate with the correlation coefficient R^2=0.941. Less than 10% of the data has errors outside the (-10%, +20%) interval for the whole range of Q_l (see Figure 3). The success of the retrieval in this case is primarily due to the relatively simple unimodal shape of the rather narrow drop spectra with relative drop spectrum dispersion σ of about 0.25. The mean drop radius, R_m, for the LD case is rather small (7.5 μm) and the mean precipitation flux is 0.3 mm/d. Note that the Q_r fraction in the liquid water content Q_l (FQ_{Qr}) is less than 0.1% and the fraction of reflectivity which comes from the drizzle part of the spectrum (FZ_{Qr}) is <1% (Table 1). Obviously this is the main reason for the success of one-parameter (1P) retrieval in this case.

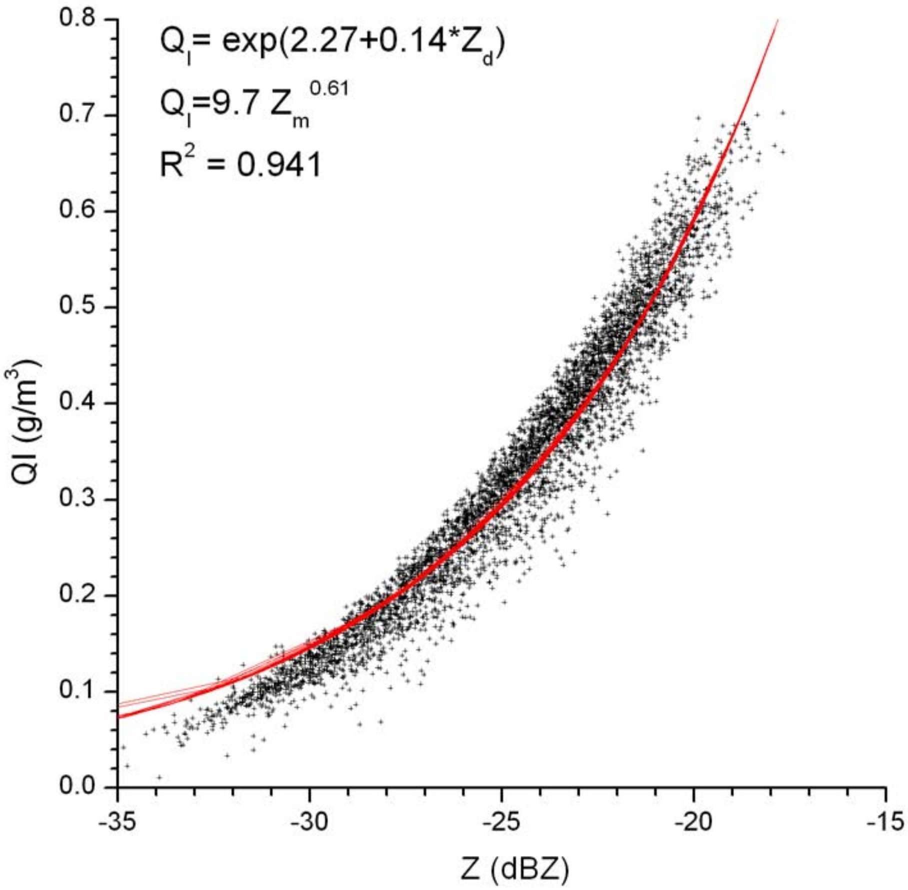

Figure 2. The scattergram of cloud liquid water as a function of reflectivity Z for the light drizzle case LD. Q_l in g m^{-3}, Z_d in dBZ, Z_m in mm^6 m^{-3}. R^2 is the square of correlation coefficient often referred to as coefficient of determination (COD).

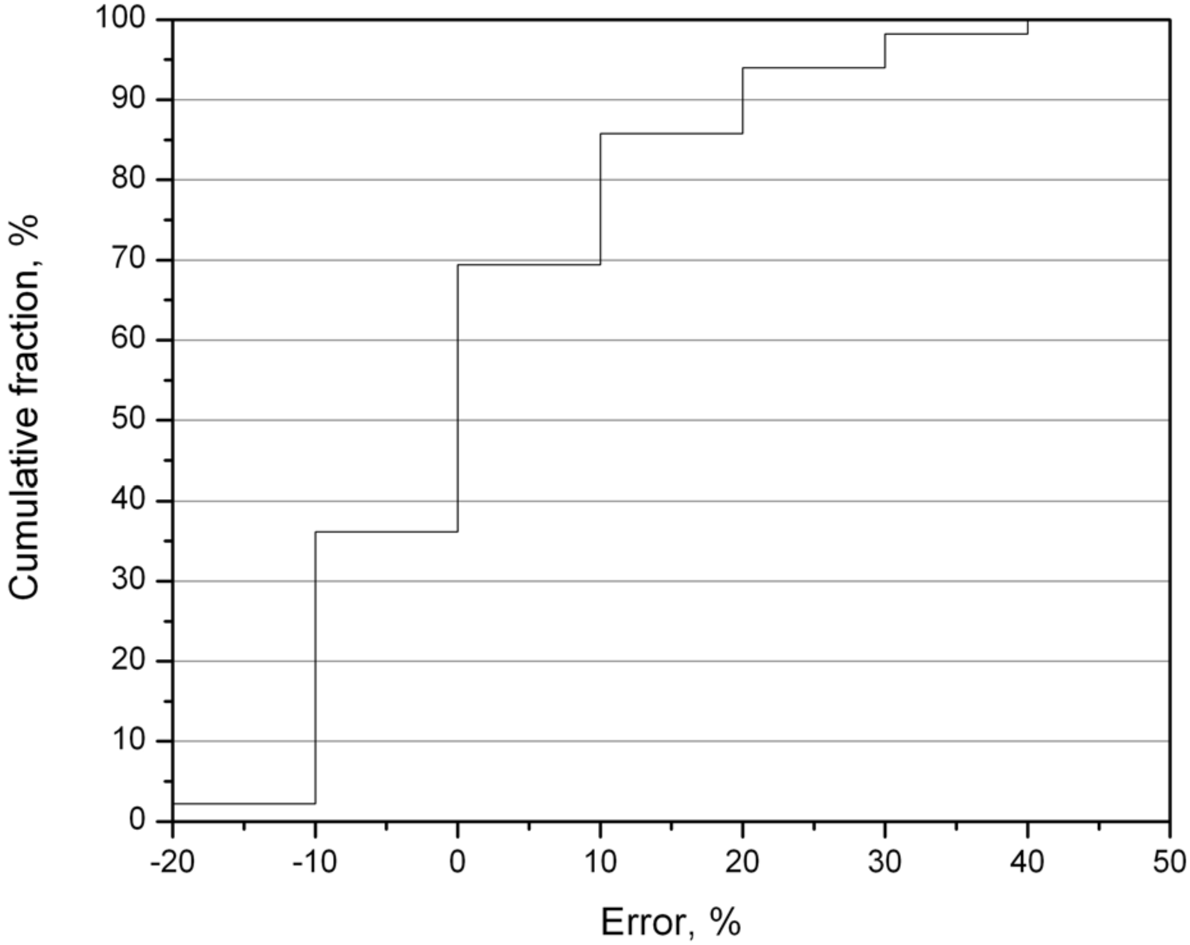

Figure 3. The cumulative distribution of Q_l retrieval errors for the LD case.

The retrieval of liquid water content is more problematic in drizzling clouds, primarily because the correlation between Q_l and Z weakens when DSDs contain a larger fraction of drizzle drops which contribute increasingly to reflectivity (78% for HD, see Table 1). Analysis of the MD dataset reveals a significant scatter in the Q_l - Z scattergram indicating that retrievals of Q_l based on Z alone are rather inaccurate ($R^2 = 0.756$). However, the accuracy of the Q_l retrieval can be substantially increased when information on Doppler velocity is included. The top panel in Figure 4 shows that a relationship in the following form results in a rather small degree of scatter and a quite accurate retrieval of Q_l ($R^2 = 0.969$).

$$Q_l = exp\ (2.63+0.179\ Z_d - 0.146\ V_d) \qquad (10)$$

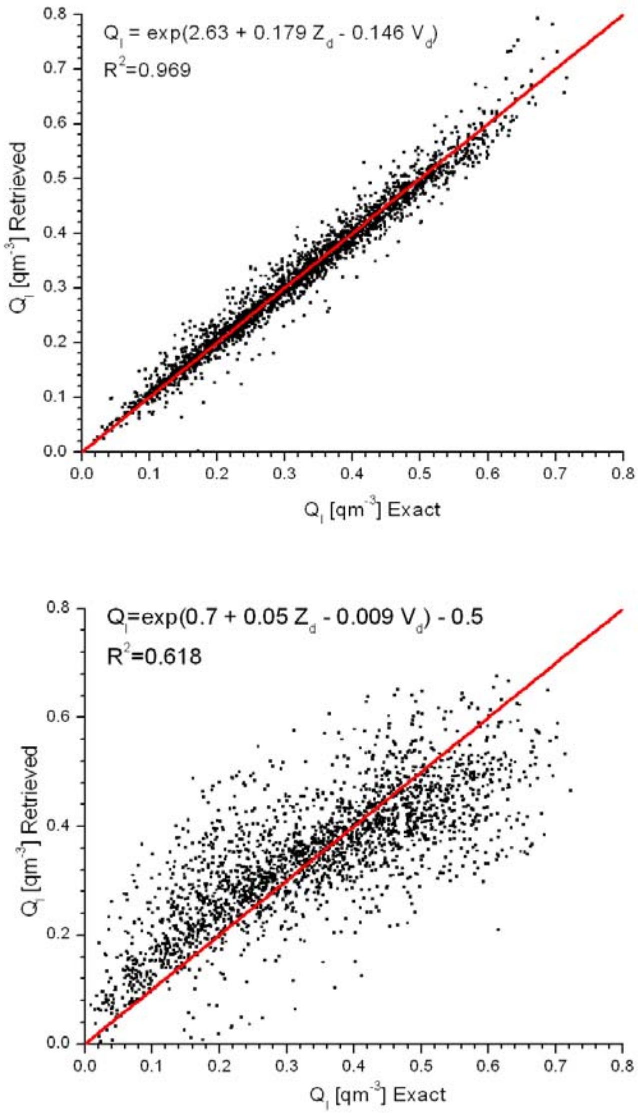

Figure 4. The retrieval of cloud liquid water as a function of reflectivity and Doppler velocity, (V_d). Top – the moderate drizzle case MD, bottom - the heavy drizzle case HD. Q_l in g m^{-3}, Z_d in dBZ, V_d in cm s^{-1}.

The Q_l retrieval based on Z alone in the heavily drizzling case HD is very poor (R^2 = 0.181). Including V_d in the HD case (bottom panel in Figure 4) results in a significantly improved retrieval (R^2 = 0.618) relative to that based on Z alone. However, the scatter in the HD case is larger than in MD case and R^2 has decreased from 0.969 to 0.618. As evident from Table 1, the more numerous and larger drizzle drops in the HD case contribute appreciably both to Z and V_d, (mean fraction of drizzle contribution to Z increased from 17 to 78%); however, the mean fraction of Q_r in Q_l increased only from 4 to 14%. The retrieval errors are not uniformly distributed over the range of Q_l (Figure 5). They can be as large as 100% for small values of Q_l near cloud base; however, for larger values of Q_l the standard deviation of

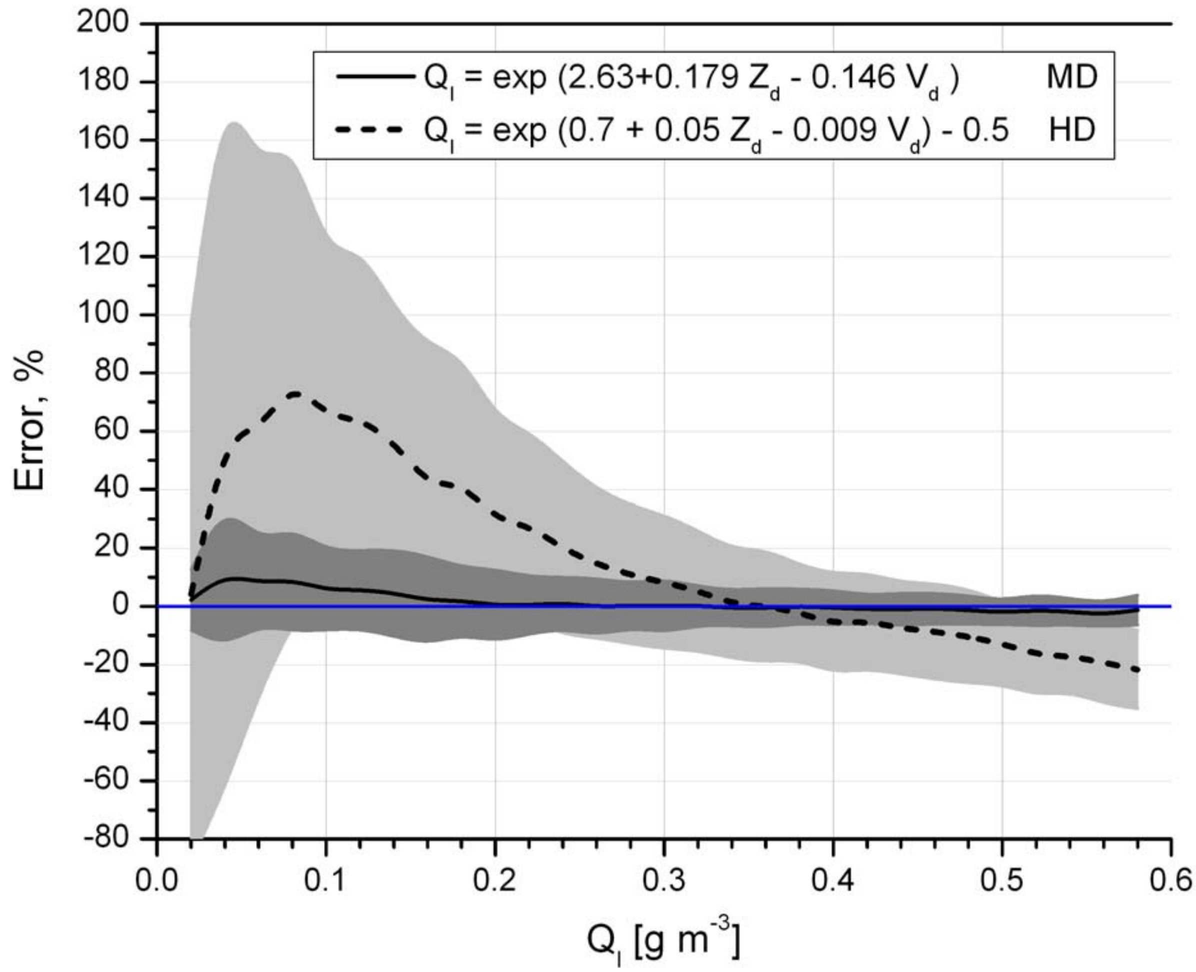

Figure 5. The errors of retrieval of cloud liquid water as a function of Q_l. The solid and dashed black lines are the MD and HD mean errors; the shading areas represent the mean plus/minus one standard deviation. Light/dark gray shading corresponds to the HD/MD case, respectively.

the errors in the HD case is less than 20-30%. For the moderate drizzle case MD the standard deviation of the errors is less than 10% for Q_l >0.2 gm^{-3} and less than 30% for the whole range of Q_l . The dependence of errors on drizzle is quite evident from histograms shown in Figure 6. For heavy drizzle case about 35% of data points have errors larger than 25%, while for the medium drizzle case only 3% have errors this large. The use of Doppler spectrum width σ_d instead of Doppler velocity affects the accuracy of the Q_l retrieval rather insignificantly (Figure 7), thus demonstrating that both Doppler parameters have approximately the same informational potential for microphysical retrieval. The decision which to use should be based on such considerations as, e.g., which parameter has smaller contribution from the air turbulence component, signal-to-noise ratio, etc.

The rather strong effect of Doppler velocity V_d, and Doppler spectrum width σ_d on retrievals of Q_l may at first seem surprising given the fact that these parameters are defined through higher moments of the DSD and, thus, should primarily characterize the tail of the spectrum. However, simple analysis shows that V_d for example correlates well with the lower moments of the DSD. For a drop spectrum characterized by a log-normal distribution with modal radius r_0 and drop spectrum logarithmic width σ, the *k-th* moment of the DSD is given by (see e.g., Frisch et al. 1995):

$$Mk = r_0 \exp(k^2\sigma^2/2) \tag{11}$$

The Doppler velocity is then:

$$V_d \sim M_7/M_6 = r_0 \exp(13\sigma^2/2) \sim M_4/M_1^3 \tag{12}$$

The latter ratio defined by the 1st and 4th moments is obviously sensitive to the left, as well as to the right end of the DSD and, thus, is important in the determination of Q_l as Eq. 6 and the results in Figures 4-6 demonstrate. The drop spectra in the LES simulations deviate from idealized log-normal distributions, and the relation between V_d and M_4/M_1^3 is not as straightforward as in Eq. 12; nevertheless, our estimates based on LES derived DSDs demonstrate that correlation between V_d and M_4/M_1^3 is substantial. In the HD case, for example, R^2=0.461.

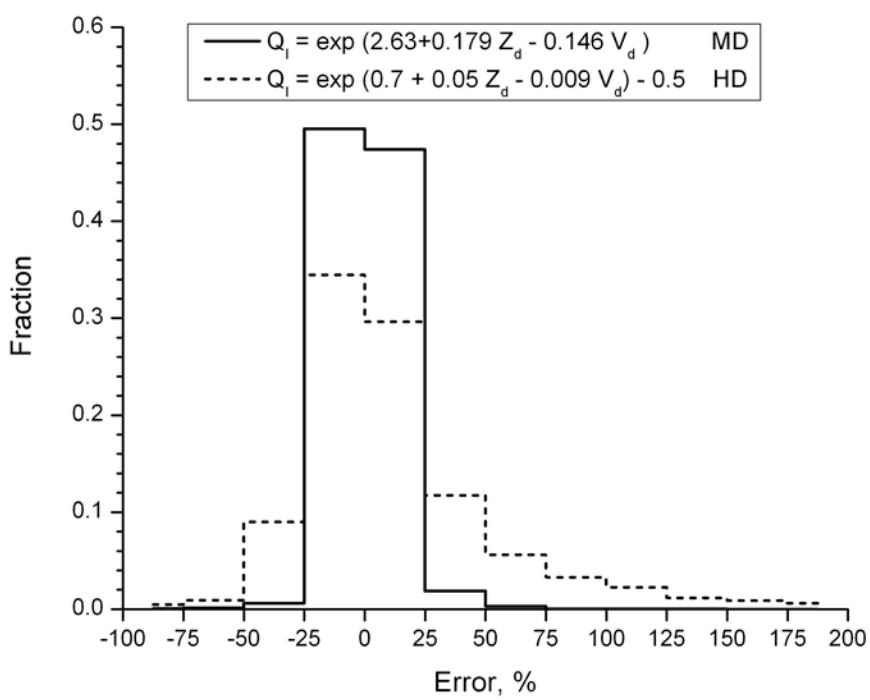

Figure 6. The comparison of Q_l retrieval errors in the MD and HD cases based on two-parameters Z_d and V_d.

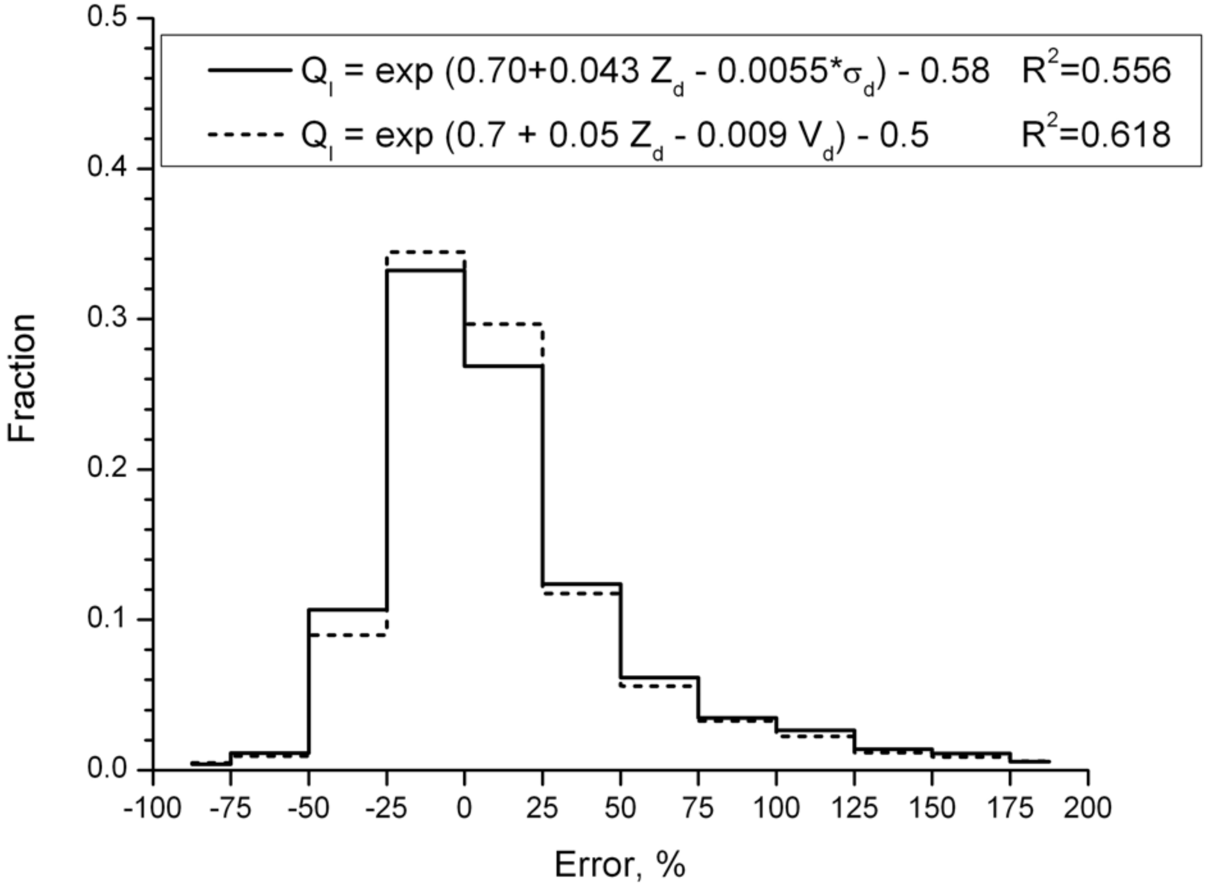

Figure 7. The comparison of Q_l retrieval errors in the HD case based on two-parameters: Z_d-V_d (dased) and Z_d-σ_d (solid).

Errors in the Retrieval of Drizzle Flux

The retrieval of drizzle flux R using Z and V_d, is more robust than retrieval of Q_l, obviously because R, Z, and V_d, all represent higher moments of the DSD (M_4, M_6, and the ratio M_7/M_6, respectively). Thus, strong correlations between them are expected, and this is indeed the case for MD and HD datasets. In the moderate drizzle case MD the use of a 2P retrieval based on Z and V_d yields a nearly perfect correlation (R^2 = 0.997) (Figure 8, top panel). The errors of the 2P retrieval for the MD case are shown in the bottom panel of Figure 8. In this moderate drizzle case the errors are less than 5% in the whole drizzle flux range, except for drizzle rates less than 0.2 mm d^{-1}.

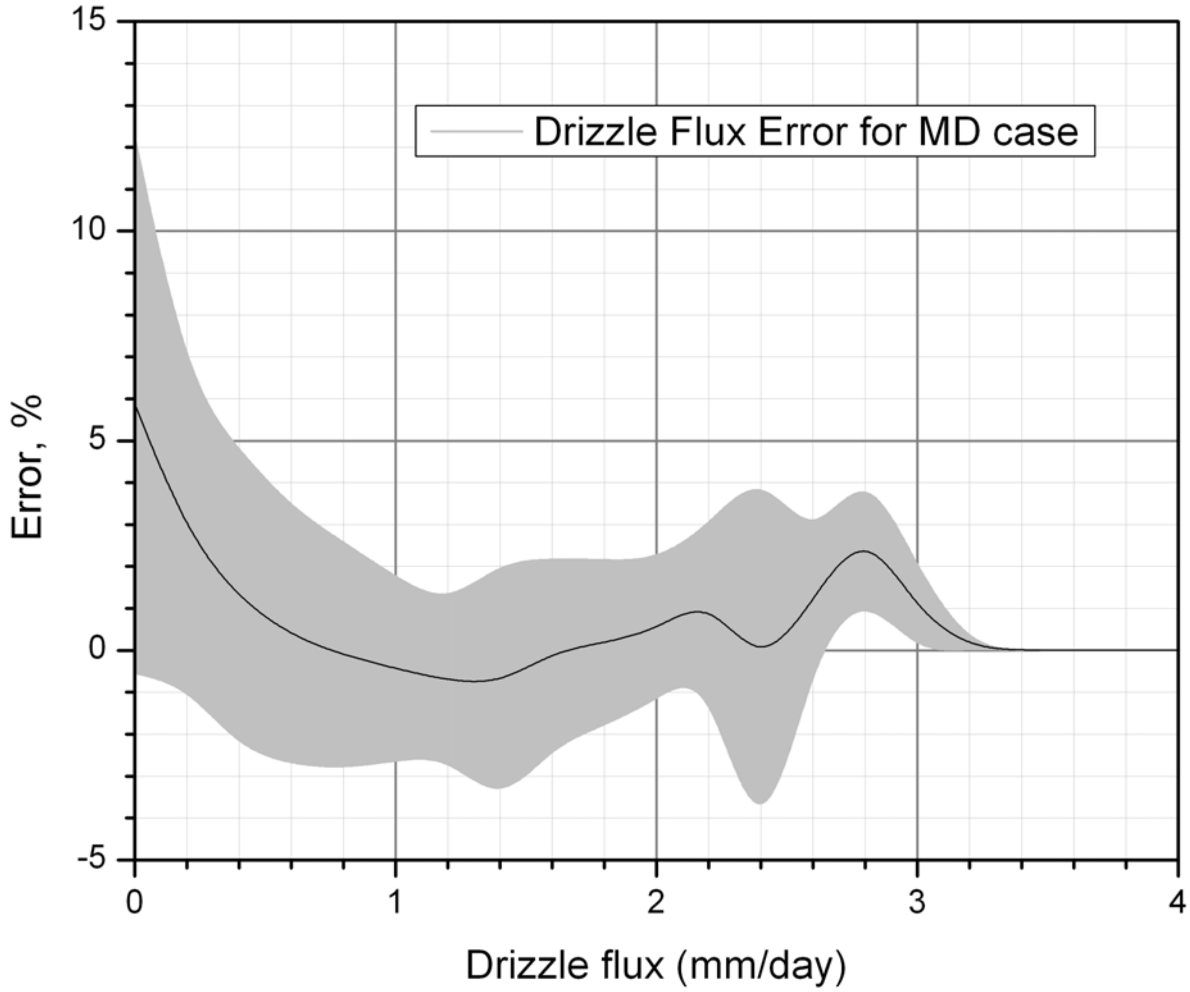

Figure 8. Top: the scatter plot of the retrieved vs exact drizzle flux for the MD case. Bottom: the errors of the 2P (Z-V_d) retrieval. The black line shows the mean error; the shading area represents the mean plus/minus one standard deviation.

For the heavy drizzle case HD R^2 increased from 0.794 for the 1P retrieval based on Z only to 0.962 when the 2P retrieval based on Z and V_d is used (Figure 9). The standard deviation of errors in this case is approximately in the 20-40% range for the 1P retrieval but decreases to about 10% for the 2P retrieval (Figure 10). As in the case of Q_l retrieval, the errors of 2P retrievals based on Z-V_d and Z-σ_d (not-shown) fall approximately into the same range.

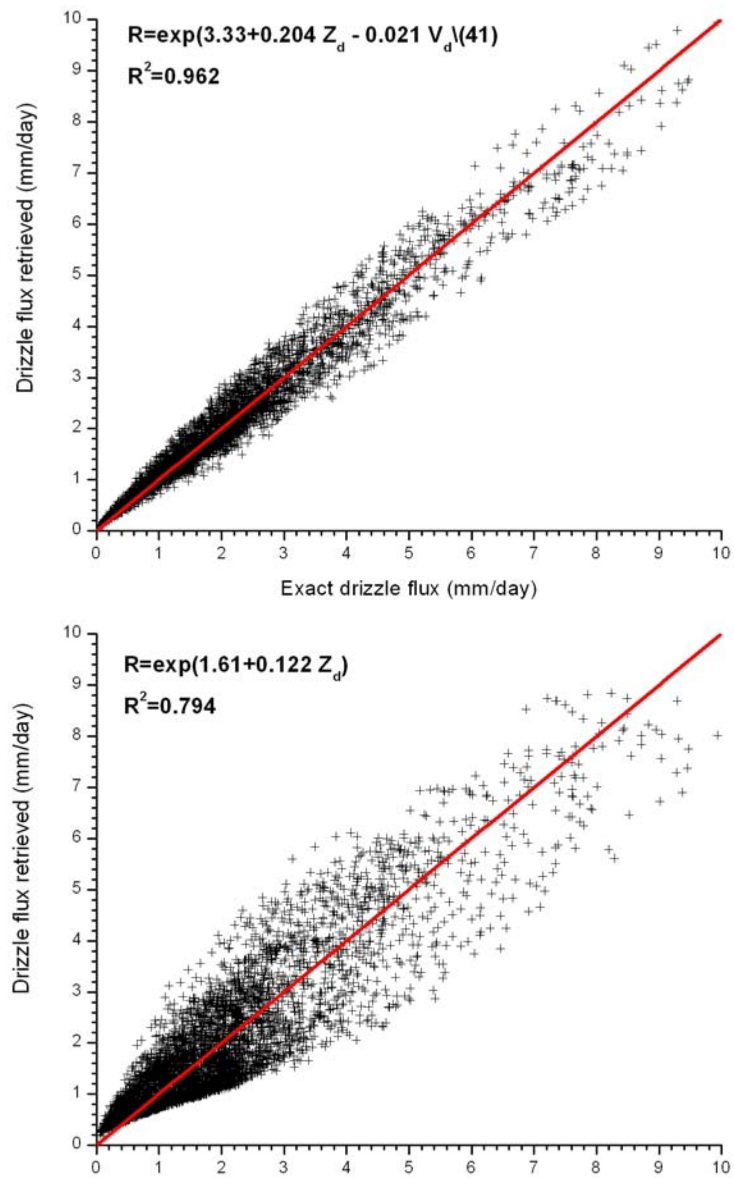

Figure 9. The scatter plot of the retrieved vs exact drizzle flux for the HD case based on one and two (Z-V_d) parameters (to reduce clatter only a fraction of data points is shown).

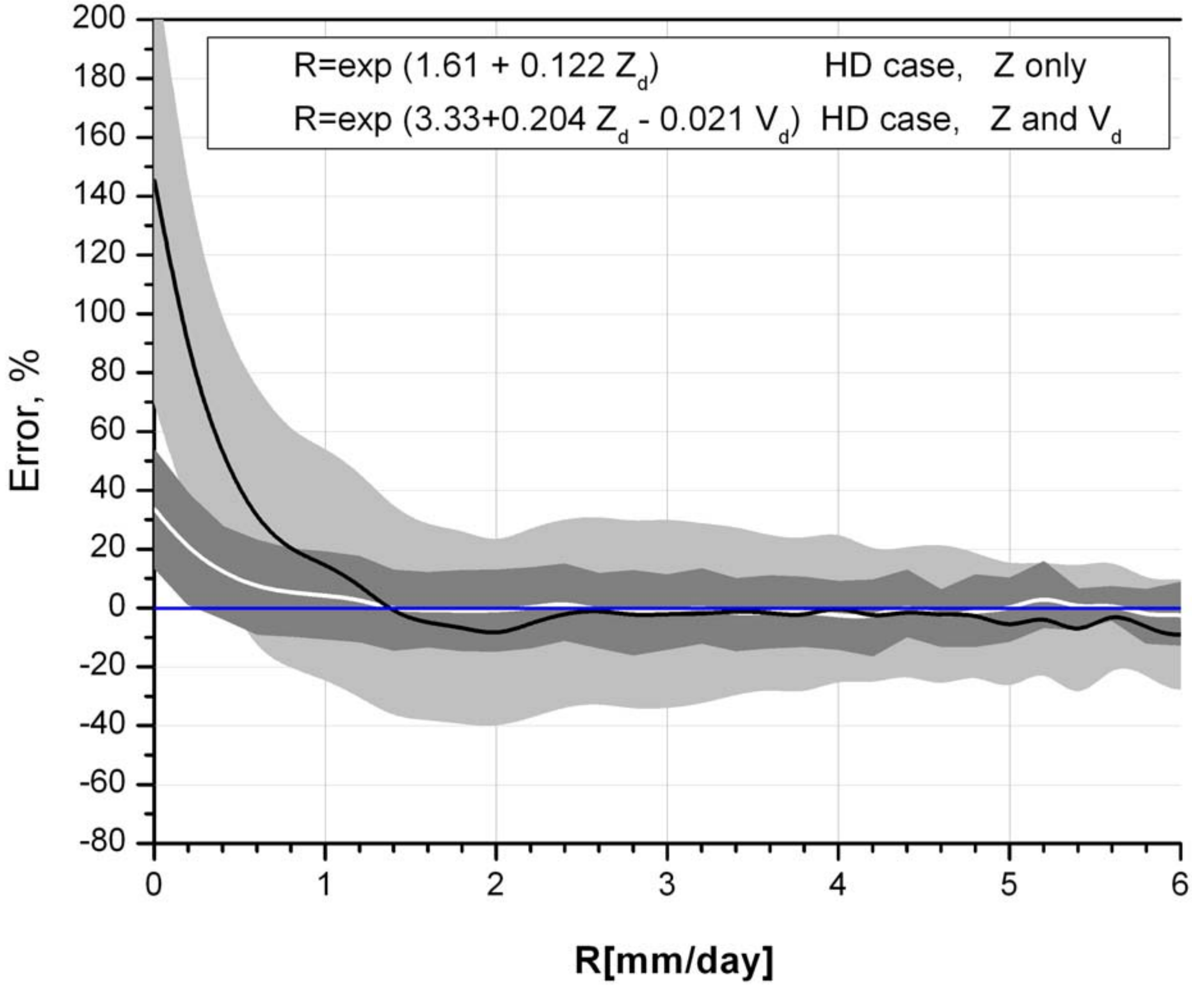

Figure 10. The errors of drizzle flux retrieval for the HD case. The black and white lines are the 1P and 2P mean errors; the shading areas represent the mean plus/minus one standard deviation. Light/dark gray shading corresponds to the 1P and 2P retrievals, respectively.

Comparison with Observations

Limited data are available for comparison of model with observations. Observations during ASTEX occasionally indicated the presence of drizzle drops within thin, nearly invisible stratocumulus clouds (D. Lilly, personal communication 1999). Even though the concentration of drizzle drops is very low, they dominate the reflectivity and can cause liquid water content retrievals based on reflectivity alone to perform poorly. This may explain why most of the Q_l retrievals were developed and tested for non-drizzling clouds.

Fox and Illingworth (1997) analyzed data collected in non-drizzling stratocumulus during ASTEX near the Azores and in a series of flights around the British Isles. The flights covered 11 separate days and over 4000 km of cloud penetrations. Based on this data they suggested the following relationship between Q_l and Z:

$$Q_l = 9.27\, Z_m^{0.64} \tag{13}$$

Expression 13 is very close to the one obtained using LES model data (Eq. 9), as the comparison in Figure 11 demonstrates. The LES data provides somewhat higher (~20%) values of Q_l, which may not be surprising as the simulation was based on one particular ASTEX case A209 which represented a rather deep, 350-400 m thick cloud layer. The observations collected during 11 days of flights on the other hand, included data from penetrations of thin clouds with samples of very low liquid water content.

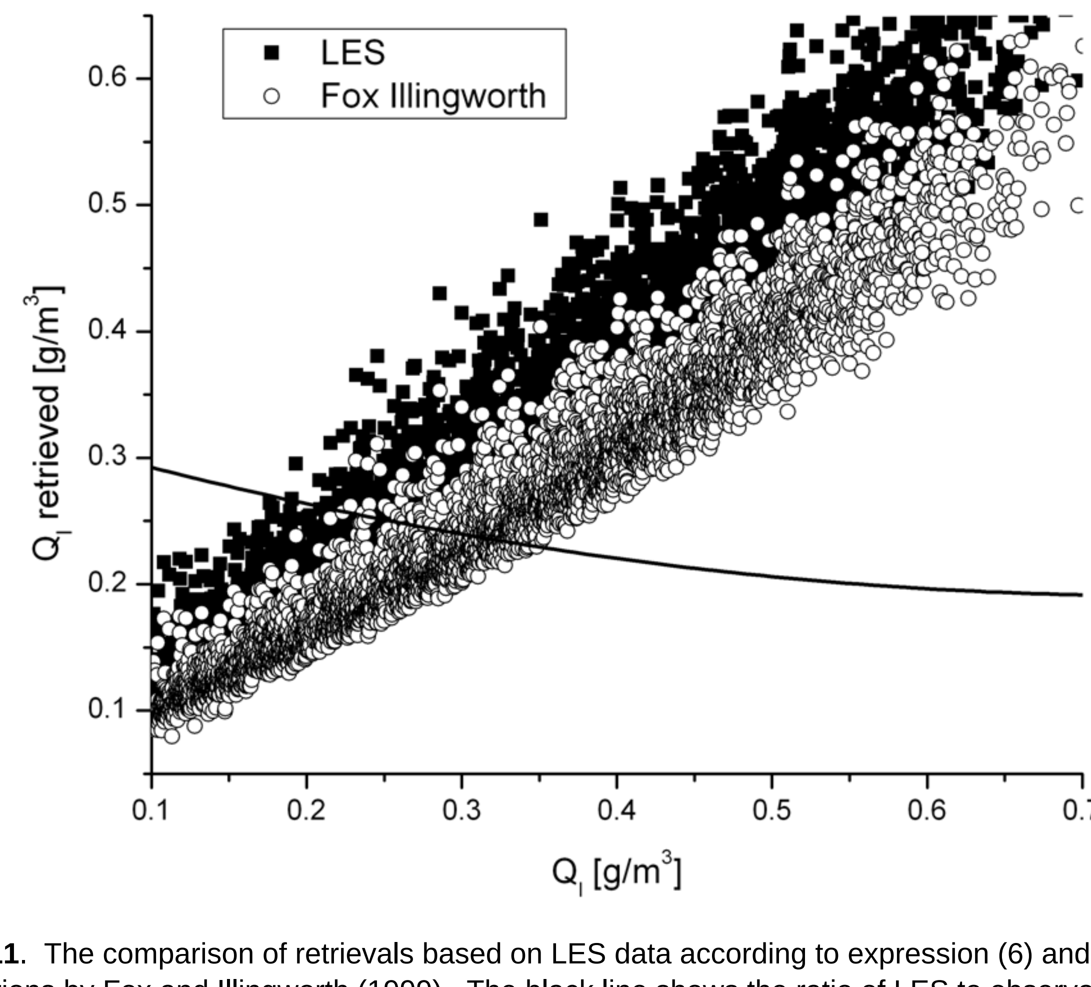

Figure 11. The comparison of retrievals based on LES data according to expression (6) and ASTEX observations by Fox and Illingworth (1999). The black line shows the ratio of LES to observational data.

Conclusions

We performed simulations of marine stratocumulus clouds observed during the Atlantic Stratocumulus Transition Experiment using the CIMMS large-eddy simulation model with size-resolving microphysics. DSD from these simulations represented a wide range of drizzling conditions and were used to evaluate the errors of retrievals of cloud microphysical parameters based on radar reflectivity, Doppler velocity and Doppler spectrum width. For stratocumulus clouds with negligible amount of drizzle, the retrieval of cloud liquid water based on radar reflectivity alone is quite accurate and the parameters of the Q_l-Z relationship are in good agreement with the retrieval obtained from ASTEX observations by Fox and Illingworth (1997). When drizzle is present, Q_l is poorly retrieved based on Z alone; however the retrieval is substantially improved when Doppler velocity or Doppler spectrum width is included. For Q_l values larger than 0.2 g m^{-3}, the standard deviation of errors is less than 10% in the moderate drizzle case; in the heavy drizzle case the errors are less than 20-30%. The use of Doppler spectrum width σ_d instead of Doppler velocity decreases the accuracy of the Q_l retrieval only insignificantly, demonstrating that both Doppler parameters have approximately the same potential for improving microphysical retrievals.

The retrieval of precipitation flux R is generally more robust than Q_l, evidently because R (proportional in stratocumulus clouds to the fourth moment of the DSD) is more closely correlated with the drizzle portion of the DSD than is Q_l. In stratocumulus with heavy drizzle ($R > 2$ mm d^{-1}) Z-R relationships can also be substantially improved by using the two parameter retrievals. Errors of the two parameter retrieval for the moderate drizzle case are less than 5%. For the heavy drizzle case, employing the two parameter retrieval reduces the standard deviation of errors of the 1P retrieval from the 20-40% range to about 10%. We emphasize that our error estimates represent the theoretical lower bound on retrieval errors, because the actual errors will inevitably increase, first and foremost, from uncertainties in estimation contributions from air turbulence. If the latter can be constrained and minimized (as in Babb et al. 1999; Kollias et al. 2001b; O'Connor et al. 2005), then the informational potential of radar reflectivity and Doppler parameters may be sufficient for substantial improvement in retrievals of cloud liquid water and precipitation flux under a wide range of drizzling conditions.

Acknowledgments

This research was supported by the Office of Science (BER), U.S. Department of Energy, Grant No. DE-FG02-05ER64062, the ONR Grants N00014-03-1-0304 and N00014-05-1-0550.

References

Babb, DM, J Verlinde, and BA Albrecht. 1999. "Retrieval of cloud microphysical parameters from 94-GHz radar Doppler power spectra." *Journal of Atmospheric and Oceanic Technology* 16:489–503.

Doviak, RJ, and DS Zrnic. 1993. Doppler Radar and Weather Observations. Academic Press, page 562.

Fox, NI, and AJ Illingworth. 1997. "The retrieval of stratocumulus cloud properties by ground-based cloud radar." *Journal of Applied Meteorology* 36:485-492.

Frisch, AS, CW Fairall, and JB Snider. 1995. "Measurements of stratus cloud and drizzle parameters in ASTEX with a Ka-band Doppler radar and a microwave radiometer." *Journal of Atmospheric Science* 52:2788-2799.

Frisch, AS, G Feingold, CW Fairall, T Uttal, and JB Snider. 1998. "On cloud radar and microwave radiometer measurements of stratus cloud liquid water profiles." *Journal of Geophysical Research* 103(23)195-23,197.

Khairoutdinov, MF, and YL Kogan. 1999. "A large eddy simulation model with explicit microphysics: validation against aircraft observations of a stratocumulus-topped boundary layer." *Journal of Atmospheric Science* 56:2115-2131.

Khairoutdinov, MF, and YL Kogan. 2000. "A new cloud physics parameterization in a large-eddy simulation model of marine stratocumulus." *Monthly Weather Review* 128:229-243.

Kogan, YL. 1991. "The simulation of a convective cloud in a 3-D model with explicit microphysics. Part I: Model description and sensitivity experiments." *Journal of Atmospheric Science* 48:1160-1189.

Kogan, YL, MP Khairoutdinov, DK Lilly, ZN Kogan, and Q Liu. 1995. "Modeling of stratocumulus cloud layers in a large eddy simulation model with explicit microphysics." *Journal of Atmospheric Science* 2923-2940.

Kogan, YL, ZN Kogan, and DB Mechem. 2005. "The Enhancement of Radar Retrievals by the Use of Higher Moments of Drop Spectrum." Presented at the Thirty-second Conference on Radar Meteorology, 24—29 October 2005, Albuquerque, New Mexico.

Kollias, P, BA Albrecht, and FD Marks, Jr. 2001a. "Raindrop sorting induced by vertical drafts in convective clouds." *Geophysical Research Letters* 28(14)2787-2790.

Kollias, P, BA Albrecht, R Lhermitte, and A Savtchenko. 2001b. "Radar observations of updrafts, downdrafts, and turbulence in fair-weather cumuli." *Journal of Atmospheric Science* 58:1750–1766.

Liao, L, and K Sassen. 1994. " Investigation of relationships between Ka-band radar reflectivity and ice and liquid water contents." *Atmospheric Research* 34:231-248.

Liu, Q, YL Kogan, DK Lilly, DW Johnson, GE Innis, PA Durkee, and K Nielson. 2000. "LES modeling of ship track formation and its sensitivity to boundary layer structure." *Journal of Atmospheric Science* 57:2779-2791.

O'Connor, EJ, RJ Hogan, and AJ Illingworth. 2005. "Retrieving stratocumulus drizzle parameters using Doppler radar and lidar." *Journal of Applied Meteorology* 44(1)14–27.

Ovtchinnikov, M, and YL Kogan. 2000. "Retrieval of cloud liquid water profile in stratiform clouds from radar reflectivity measurements: Algorithm assessment using large-eddy simulations." *Journal of Geophysical Research* 105(D13)17,351-17,359.

Parsons, DB, and J Dudhia. 1996. "Observing system simulation experiments and objective analysis tests in support of the goals of the Atmospheric Radiation Measurement Program." *Monthly Weather Review* 125(10)2353–2381.

Sauvageot, H, and J Omar. 1987. "Radar reflectivity of cumulus clouds." *Journal of Atmospheric and Oceanic Technology* 4:264-272.

Wood, R, PR Field, and WR Cotton. 2002. "Autoconversion rate bias in stratiform boundary layer cloud parameterizations." *Atmospheric Research* 65:109-128.

Wood, R. 2005. "Drizzle in stratiform boundary layer clouds. Part II: Microphysical aspects." *Journal of Atmospheric Science* 62:3034-3050.