

## Assessing the Errors of Cloud Liquid Water and Precipitation Flux Retrievals in Marine Stratocumulus Based on Doppler Radar Parameters

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### ABSTRACT

The errors of formulations of cloud retrievals based on radar reflectivity, mean Doppler velocity, and Doppler spectrum width are evaluated under the controlled framework of the Observing System Simulation Experiments (OSSEs). Cloud radar parameters are obtained from drop size distributions generated by the high-resolution Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) large-eddy simulation (LES) model with explicit microphysics. It is shown that in drizzling stratocumulus the accuracy of cloud liquid water ( $Q_l$ ) retrieval can be substantially increased when information on Doppler velocity or Doppler spectrum width is included in addition to radar reflectivity. In the moderate drizzle case (drizzle rate  $R$  of about  $1 \text{ mm day}^{-1}$ ) the mean and standard deviation of errors is of the order of 10% for  $Q_l$  values larger than  $0.2 \text{ g m}^{-3}$ ; in stratocumulus with heavy drizzle ( $R > 2 \text{ mm day}^{-1}$ ) these values are approximately 20%–30%. Similarly, employing Doppler radar parameters significantly improves the accuracy of drizzle flux retrieval. The use of Doppler spectrum width  $\sigma_d$  instead of Doppler velocity yields about the same accuracy, thus demonstrating that both Doppler parameters have approximately the same potential for improving microphysical retrievals. It is noted that the error estimates herein represent the theoretical lower bound on retrieval errors, because the actual errors will inevitably increase, first and foremost, due to uncertainties in estimation contributions from air turbulence.

### 1. Introduction

Marine stratus and stratocumulus clouds play an important role in global water and energy budget by increasing the local planetary albedo by 30%–50% while having relatively little impact on outgoing longwave radiation. These clouds are widespread and at any given time may cover much of the eastern subtropical Pacific and Atlantic, most of the Arctic Sea in summer, and large regions of the middle latitudes. Charlson et al. (1987) estimate that stratus and stratocumulus clouds are the only cloud type that cover over 25% of the world's oceans. It is estimated (Ramanathan et al. 1989) that an increase of a few percent of cloud cover, or a comparable increase in stratocumulus cloud albedo, would counter the anticipated greenhouse warming of the next century, while similar decreases would double the warming.

Because of the large spatial coverage and persistence of marine stratocumulus, drizzle exerts a powerful influence on the structure and longevity of stratocumulus. The primary effects of drizzle are on vertical redistribution of heat and moisture (Paluch and Lenschow 1991; Feingold et al. 1996). This redistribution then influences microphysical properties and cloud macrophysical characteristics (cloud fraction, liquid water content), which can lead to cloud system breakup (Stevens et al. 1998) and significant changes in the surface radiation and moisture budgets. The latter effects were illustrated by vanZanten and Stevens (2005) who used in situ aircraft data from the Second Dynamics and Chemistry of Marine Stratocumulus (DYCOMS-II) field project to demonstrate that drizzle can be an important term in the water budget for marine stratocumulus. Austin et al. (1995) previously showed that local rain rates can be a significant fraction of the surface hydrologic balance—as much as 4–5 times larger than the local surface moisture flux. Drizzle is also an important component of the hydrologic cycle on climate scales, and an intercomparison of global climate models

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emphasized a systematic underestimate of the frequency of drizzle events over stratocumulus cloud regimes (Lau et al. 1996).

In the current study we evaluate techniques for remote sensing retrieval of important microphysical parameters from marine stratocumulus clouds. Specifically we analyze 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,  $\sigma_d$ . 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 nondrizzling 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):

$$Z = aQ_l^b. \quad (1)$$

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 ( $r < 25 \mu\text{m}$ ). To enhance the accuracy of  $Q_l$  retrievals a number of studies have proposed using Doppler velocity measurements in addition to reflectivity (Frisch et al. 1995; Babb et al. 1999; Kollias et al. 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 (OSSEs) (Parsons and Dudhia 1997). Based on this concept, cloud radar parameters are obtained from data generated by the high-resolution Cooperative Institute for Mesoscale Meteorological Studies large-eddy simulation model with explicit microphysics (CIMMS LES EMP). Applying the OSSE framework for stratocumulus clouds, we quantitatively evaluate the errors of several cloud liquid water and drizzle flux retrievals. As both  $V_d$  and  $\sigma_d$  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.

## 2. Approach

### a. 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 observa-

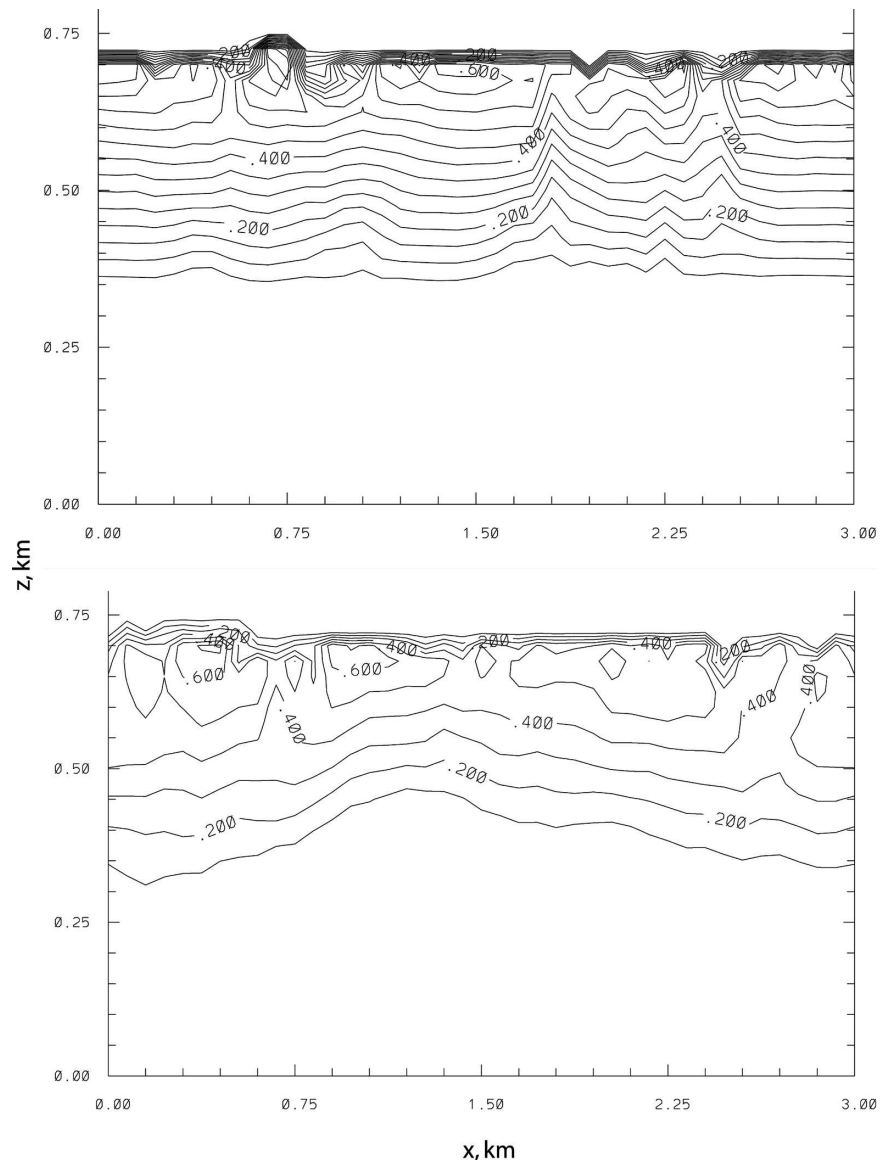


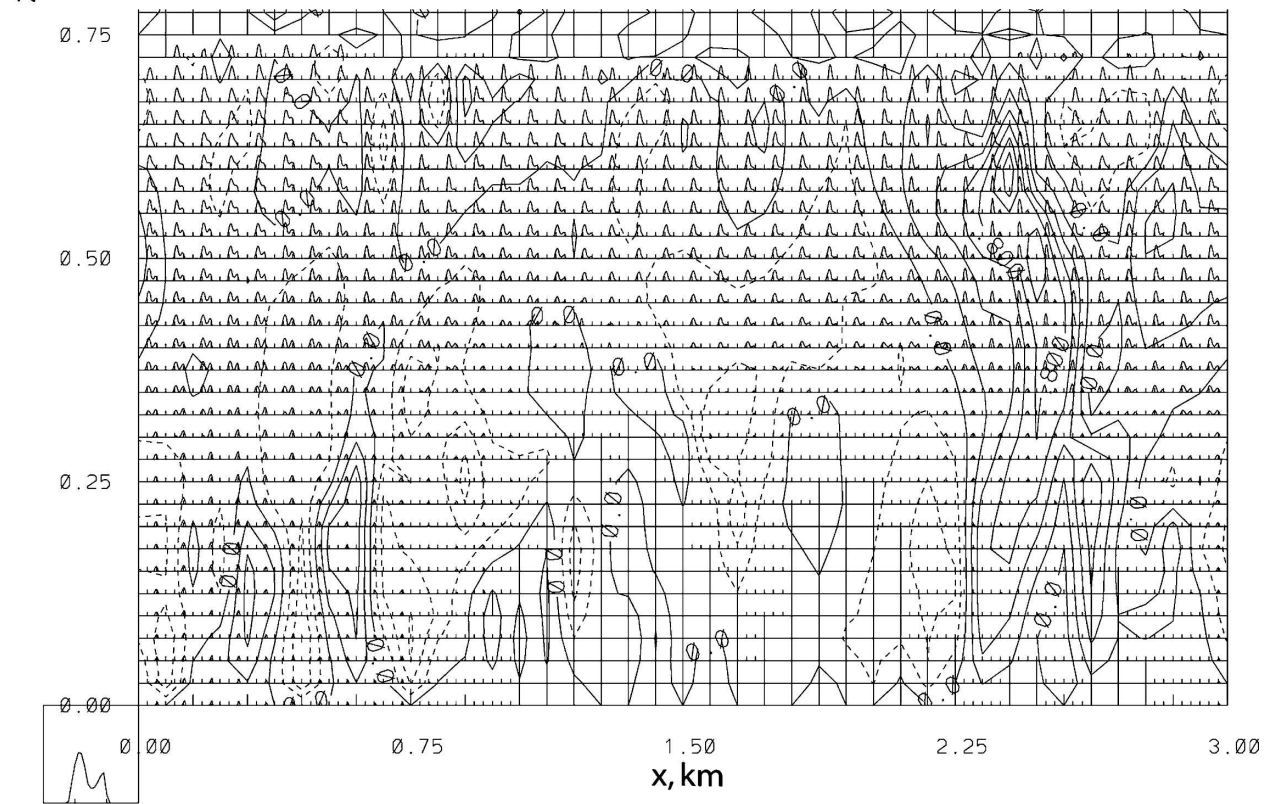
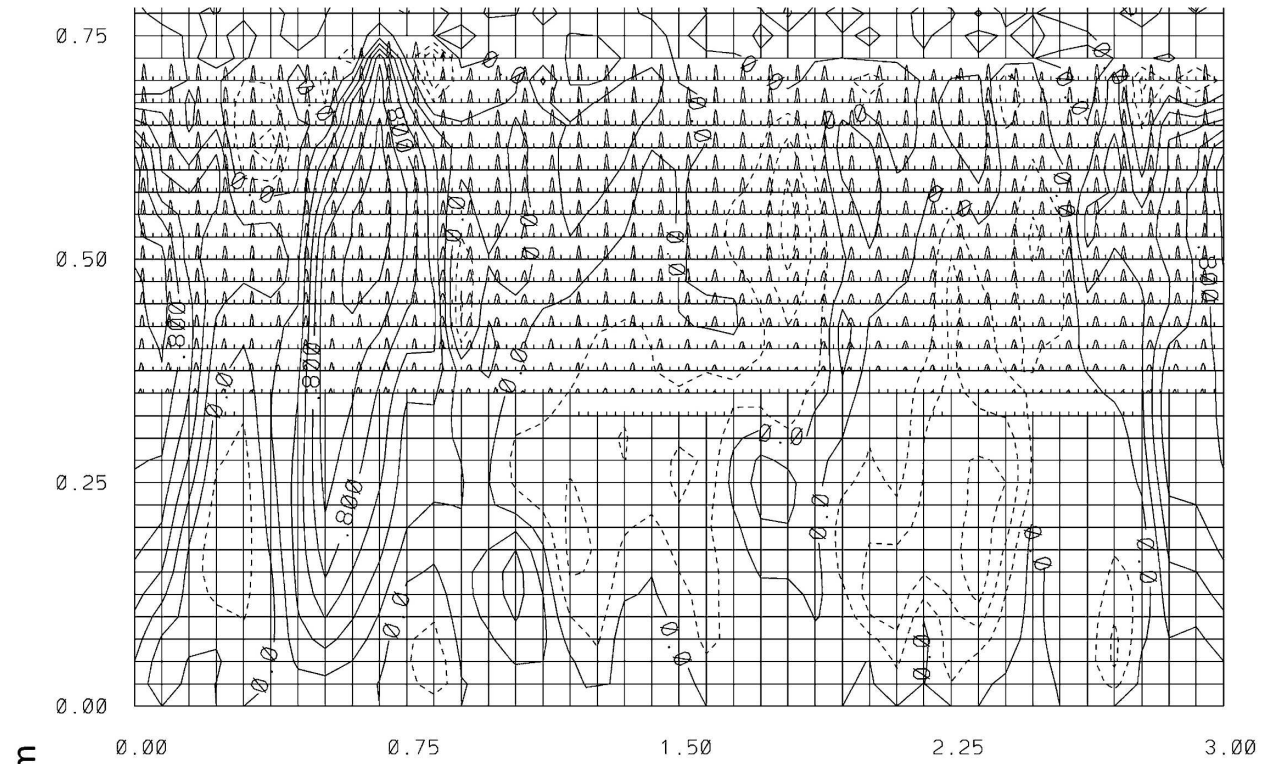
FIG. 1. Isolines of the liquid water content ( $\text{g m}^{-3}$ ) in a vertical cross section ( $y = 1.425$  km) of the cloud. Clouds representing (top) light- and (bottom) heavy-drizzling conditions.

tions (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 in the 25–300- $\mu\text{m}$  radius range). Figures 1 and 2 show examples of cloud liquid water fields and cloud drop spectra superimposed with vertical wind velocities in model simulations for light and heavy drizzling conditions. Note the prevalence of bimodal cloud drop distributions in the heavy drizzle case.

From each simulation we extracted about 4000 to 6000 DSDs that were used to calculate cloud parameters, such as, for example, 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  $R$



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retrievals using regression analysis and as a benchmark for evaluating them by comparing with the exact values of  $Q_i$  and  $R$ .

The range of cloud and drizzle parameters for all performed simulations is illustrated in Fig. 3 for datasets representing light (LD), moderate (MD), and heavy (HD) drizzle spectra. Since the cloud layer evolves significantly during the 3–6-h-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 h 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  $\equiv$  LD1, MD  $\equiv$  MD1, and HD  $\equiv$  HD2).

### b. 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

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

Here  $f_v(r)$  is the fall velocity of the drop with radius  $r$ ,  $Z(x)$  is radar reflectivity, and  $F_z(x)/Z(x)$  is the  $Z$ -weighted drop terminal fall velocity at point  $x$ . The bar denotes averaging over the radar pulse volume. For the  $K_\alpha$ -band vertically pointing Millimeter Cloud Radar (MMCR), which operates at 35 GHz with an 8.77-mm wavelength, the vertical gate size is 45 m.<sup>1</sup> 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  $n(x, r)$  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 nondrizzling stratocumulus, the drop size distribution can be determined over a smaller sampling volume; in this case  $n(x, r)$  in (2) should represent DSDs averaged over the radar pulse volume.

The second term in (2),

$$V_d \equiv \overline{F_z(x)/Z(x)}, \quad (3)$$

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 seventh to the sixth moment of the DSD ( $M_7/M_6$ ). It is also worth noting that the drizzle flux is proportional to the fourth moment of the DSD ( $M_4$ ).

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

$$\begin{aligned} \sigma_{dv}^2 &= \int_{r_0}^{r_{\max}} [w' + (f_v - \overline{V_d})]^2 n(r) r^6 dr / Z \\ &= \sigma_w^2 + \sigma_{dw}^2 + \sigma_d^2. \end{aligned} \quad (4)$$

The observed spectral variance is the sum of variances representing contributions from air turbulence  $\sigma_w^2$ , intrinsic microphysical variance due to the spread of drops terminal fall velocities  $\sigma_d^2$ , and the cross correlation between fluctuations of air and drop fall velocities  $\sigma_{dw}^2$ . The latter term is difficult to evaluate without information on the subgrid fluctuations in an LES model; however, our estimate based on resolvable scale fluctuations show that this term is on the same order of magnitude as  $\sigma_w^2$ . In addition to the terms

<sup>1</sup> A more detailed description of the millimeter wavelength cloud radar parameters can be found in Moran et al. (1998) and Clothiaux et al. (1999).

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FIG. 2. Cloud droplet spectra in (top) light and (bottom) heavy drizzle simulations superimposed with isolines of the vertical velocity ( $\text{m s}^{-1}$ ) in a vertical cross section ( $y = 1.425$  km) through the cloud. At each spatial point the square box representing the drop mass distribution function  $v \log r$  is shown. The big box in the lower-left corner, shown for illustration, has two tick marks at the bottom corresponding to 10- and 100- $\mu\text{m}$  drop radius.

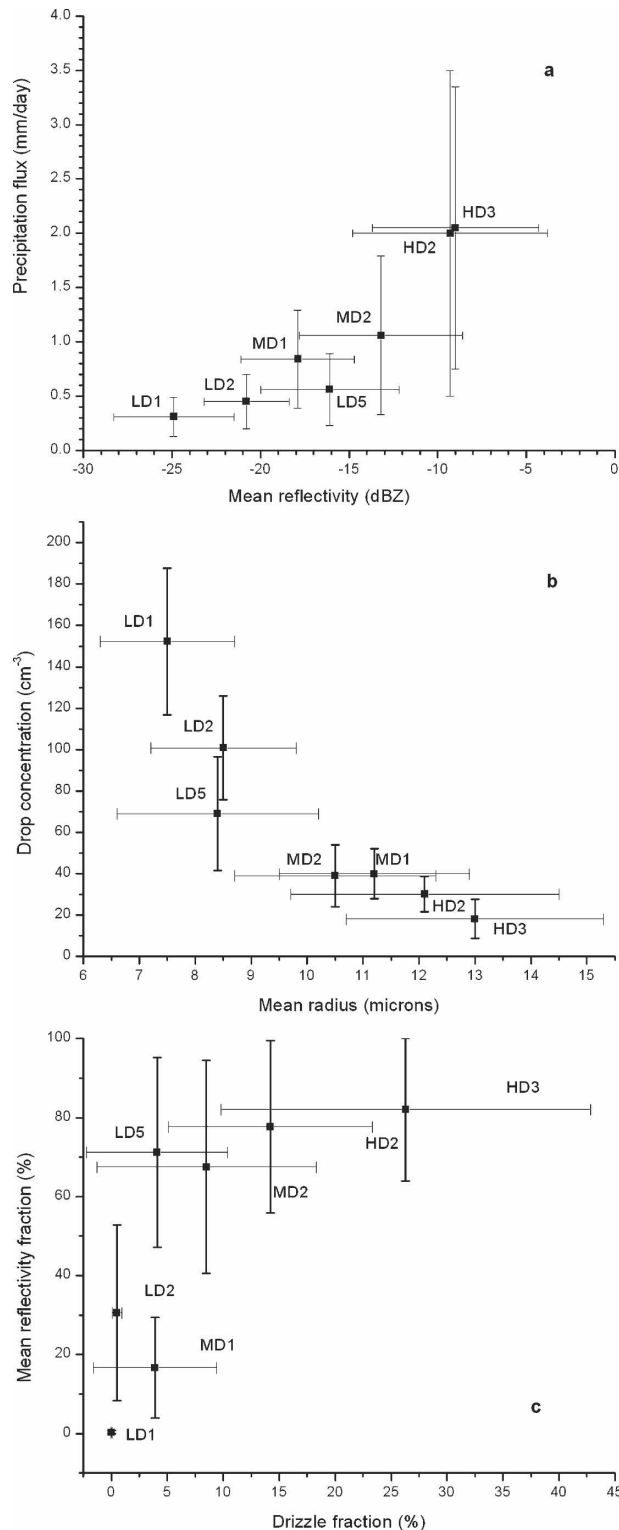


FIG. 3. Range of cloud parameters in the analyzed cases of stratocumulus cloud layers. The black square represents the mean and the error bars the std dev of a parameter.

TABLE 1. Mean and std dev (in brackets) of drop spectra parameters for light (LD), moderate (MD), and heavy (HD) drizzling cases;  $Q_l$  and  $Q_r$ : liquid and drizzle water content,  $N_c$  and  $N_d$ : total and drizzle concentration,  $R_m$  and  $\sigma$ : the mean radius and relative dispersion of drop spectrum,  $R$ : drizzle flux,  $V_d$ : Doppler velocity,  $Z_d$ : reflectivity in dBZ,  $FQ_{Or}$  and  $FZ_{Or}$ : fractions of  $Q_l$  and  $Z_m$  from  $Q_r$ , respectively.

Parameter	LD	MD	HD
$Q_l$ ( $\text{g m}^{-3}$ )	0.33 (0.15)	0.32 (0.14)	0.34 (0.16)
$R_m$ ( $\mu\text{m}$ )	7.5 (1.2)	11.2 (1.7)	12.1 (2.4)
$N_c$ ( $\text{cm}^{-3}$ )	153 (35)	34 (12)	30 (8)
$\sigma$	0.25 (0.07)	0.34 (0.06)	0.34 (0.1)
$Q_r$ ( $\text{g m}^{-3}$ )	<0.0001	0.012 (0.018)	0.047 (0.042)
$FQ_{Or}$	0.01 (0.03)	3.9 (5.5)	14.1 (9.1)
$N_d$ ( $\text{cm}^{-3}$ )	<0.00001	0.016 (0.22)	0.33 (0.38)
$R$ ( $\text{mm day}^{-1}$ )	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)
$FZ_{Or}$	0.31 (0.42)	16.6 (12.7)	77.7 (21.8)
$V_d$ ( $\text{cm s}^{-1}$ )	1.35 (0.2)	4.8 (1.7)	47.0 (26.5)

shown in (4), the expression for the observed spectral variance also includes other contributions, for example, 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 Zrníc 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. (2001b) assumed a turbulence spectrum based on homogeneous energy dissipation, which can be integrated over relevant wavenumbers 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  $\sigma_d$ . For the intrinsic microphysical contribution, the latter is defined as

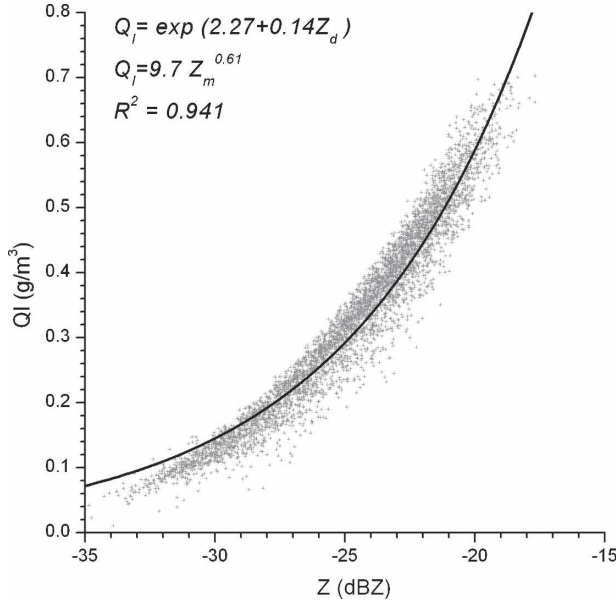


FIG. 4. Scattergram of cloud liquid water as a function of reflectivity  $Z$  for the light drizzle case LD:  $Q_l$  in  $\text{g m}^{-3}$ ,  $Z_d$  in dBZ, and  $Z_m$  in  $\text{mm}^6 \text{m}^{-3}$ ;  $R^2$  is the square of correlation coefficient, often referred to as coefficient of determination (COD).

$$\sigma_d^2 = \int_{r_0}^{r_{\max}} [f_v(r) - \bar{V}_d]^2 n(r) r^6 dr \Big/ \int_{r_0}^{r_{\max}} n(r) r^6 dr. \tag{5}$$

**3. 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

$$Q_l = \exp(\alpha + \beta Z_d - \gamma V_d). \tag{6}$$

In the above expression parameters  $\alpha$ ,  $\beta$ ,  $\gamma$  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

$$\begin{aligned} \ln Q_l &= \alpha + \beta Z_d - \gamma(V_{dv} - w) \\ &= \alpha + \beta Z_d - \gamma V_{dv} + \gamma w \\ &= \alpha + \beta Z_{\text{eff}} + \gamma w. \end{aligned} \tag{7}$$

In the last expression for convenience we denote the linear combination of observable parameters  $Z_d$  and  $V_{dv}$  as an “effective” reflectivity  $Z_{\text{eff}} = Z_d - \gamma/\beta V_{dv}$ . Such a formulation is convenient because in the case of

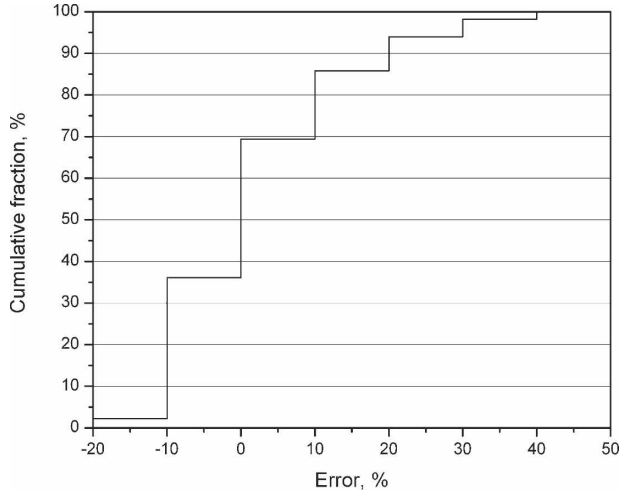


FIG. 5. The cumulative distribution of  $Q_l$  retrieval errors for the LD case.

stratocumulus topped boundary layer the vertical velocity, horizontally averaged over the large time or spatial interval, is near zero (see, e.g., Frisch et al. 1995; Kollias and Albrecht 2000), thus permitting in principle a method for estimating the horizontal mean value of  $\ln Q_l$ :

$$\langle \ln Q_l \rangle = \alpha + \beta \langle Z_{\text{eff}} \rangle. \tag{8}$$

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.

*a. 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 Fig. 4 demonstrates that  $Q_l$  can be reasonably well represented as a function of  $Z_m$  ( $Z_m$  is reflectivity in  $\text{mm}^6 \text{m}^{-3}$ , while  $Z_d$  is in dBZ). The best fit in the form

$$Q_l = 9.7 Z_m^{0.61} \tag{9}$$

is quite accurate with the correlation coefficient  $R^2 = 0.941$ . Less than 10% of the data have errors outside the  $(-10\%, +20\%)$  interval for the whole range of  $Q_l$  (see Fig. 5). 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  $\sigma$  of about 0.25 (see Fig. 2). The mean drop radius,  $R_m$ , for the LD case is rather small ( $7.5 \mu\text{m}$ ) and the mean precipitation flux is  $0.3 \text{ mm day}^{-1}$ .

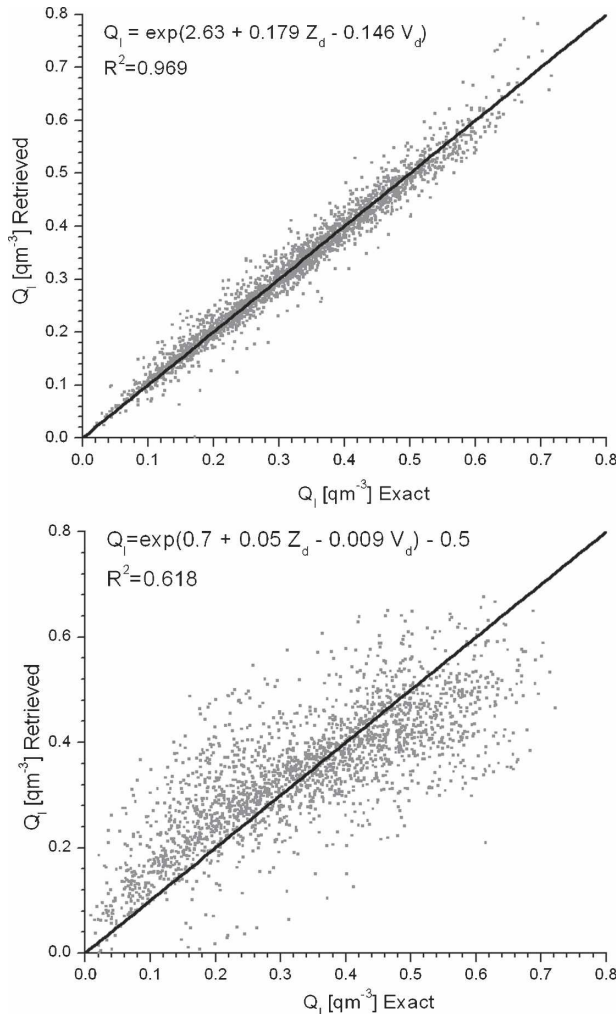


FIG. 6. The retrieval of cloud liquid water as a function of reflectivity and Doppler velocity ( $V_d$ ). (top) The moderate drizzle case MD and (bottom) the heavy drizzle case HD.  $Q_l$  in  $\text{g m}^{-3}$ ,  $Z_d$  in dBZ,  $V_d$  in  $\text{cm s}^{-1}$ .

Note that the  $Q_r$  fraction in the liquid water content  $Q_l$  ( $\text{FQ}_{Q_r}$ ) is less than 0.1%, and the fraction of reflectivity, which comes from the drizzle part of the spectrum ( $\text{FZ}_{Q_r}$ ), is  $<1\%$  (Table 1). Obviously this is the main reason for the success of one-parameter (1P) retrieval in this 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 that 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 ve-

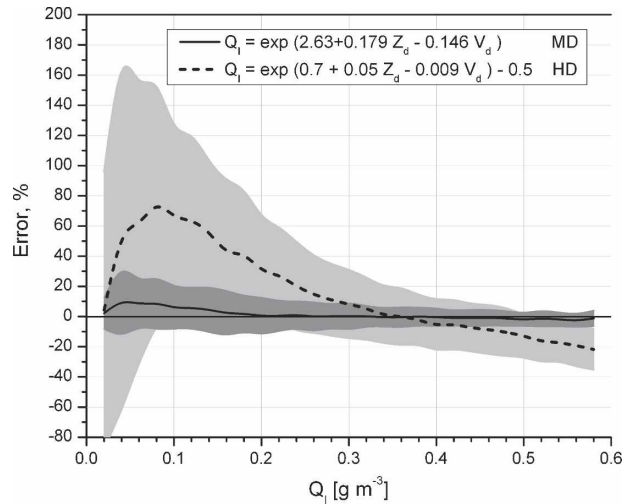


FIG. 7. The errors of retrieval of cloud liquid water as a function of  $Q_l$ . The solid and dashed black lines are the MD and HD mean errors; the shading areas represent the mean  $\pm 1$  std dev. Light/dark gray shading corresponds to the HD/MD case, respectively.

locity is included. The top panel in Fig. 6 shows that a relationship in the following form results in a rather small degree of scatter and a quite accurate retrieval of  $Q_l$  ( $R^2 = 0.969$ ):

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

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 Fig. 6) 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  $Q_l$  (Fig. 7). 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 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  $Q_l > 0.2 \text{ g m}^{-3}$  and less than 30% for the whole range of  $Q_l$ . The dependence of errors on drizzle is quite evident from histograms shown in Fig. 8. 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  $\sigma_d$  instead of Doppler velocity affects the accuracy of the  $Q_l$  retrieval



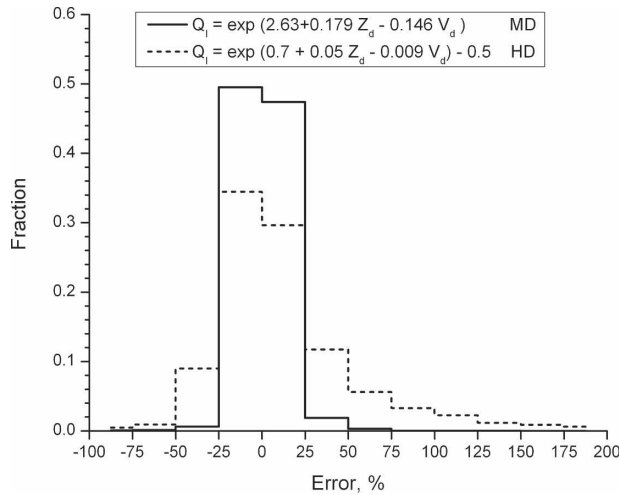


FIG. 8. The comparison of  $Q_l$  retrieval errors in the MD and HD cases based on two parameters,  $Z_d$  and  $V_d$ .

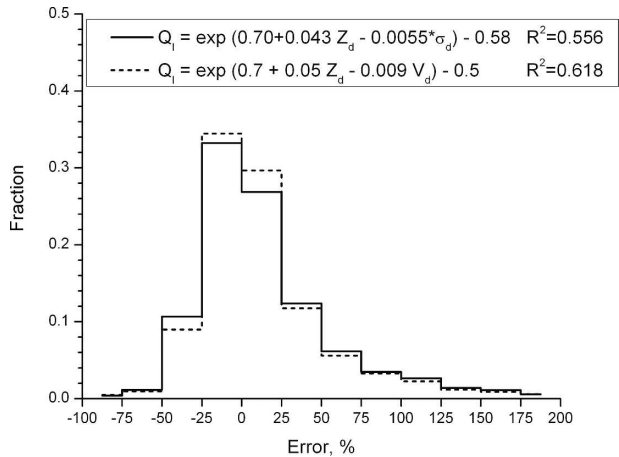


FIG. 9. The comparison of  $Q_l$  retrieval errors in the HD case based on two parameters:  $Z_d - V_d$  (dashed) and  $Z_d - \sigma_d$  (solid).

rather insignificantly (Fig. 9), thus demonstrating that both Doppler parameters have approximately the same informational potential for microphysical retrieval. The decision of which to use should be based on such considerations as, for example, 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  $\sigma_d$  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 lognormal distribution with modal radius  $r_0$  and drop spectrum logarithmic width  $\sigma$ , the  $k$ th moment of the DSD is given by (see, e.g., Frisch et al. 1995)

$$M_k = r_0 \exp(k^2 \sigma^2 / 2). \quad (11)$$

The Doppler velocity is then

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

The latter ratio defined by the first and fourth 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 Figs. 6–8 demonstrate. The drop spectra in the LES simulations deviate from idealized lognormal distributions, and the relation between  $V_d$  and  $M_4 / M_1^3$  are 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,  $R^2 = 0.461$ .

#### b. 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 ( $R^2 = 0.997$ ; Fig. 10, top panel). The errors of the two-parameter (2P) retrieval for the MD case are shown in the bottom panel of Fig. 10. In this moderate drizzle case the errors are less than 5% in the whole drizzle flux range, except for drizzle rates less than  $0.2 \text{ mm day}^{-1}$ .

For the heavy drizzle case HD  $R^2$  increased from 0.794 for the one-parameter (1P) retrieval based on  $Z$  only to 0.962 when the 2P retrieval based on  $Z$  and  $V_d$  is used (Fig. 11). 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 (Fig. 12). As in the case of  $Q_l$  retrieval, the errors of 2P retrievals based on  $Z - V_d$  and  $Z - \sigma_d$  (not shown) fall approximately into the same range.

### 4. Assessing retrievals based on drop spectra from LES, in situ observations, and analytical function approximations

The current study evaluates retrievals based on the OSSE approach using DSDs from an explicit LES

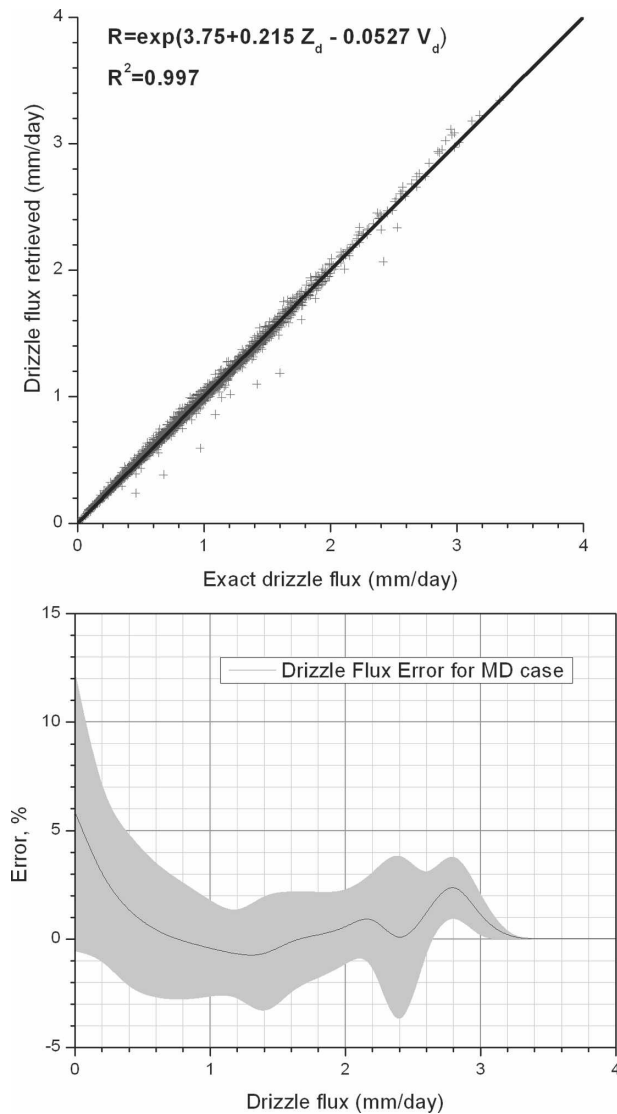


FIG. 10. (top) The scatterplot of the retrieved vs exact drizzle flux for the MD case. (bottom) The errors of the 2P ( $Z-V_d$ ) retrieval. The black line shows the mean error; the shading area represents the mean  $\pm 1$  std dev.

model. The retrieval techniques may be also evaluated either by using in situ observations or approximations of cloud DSD by known analytical functions. Most of observational data are difficult to utilize due to the presence of drizzle drops within thin, nearly invisible stratocumulus clouds (D. Lilly 1999, personal communication). 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 nondrizzling clouds.

Fox and Illingworth (1997) analyzed data collected in

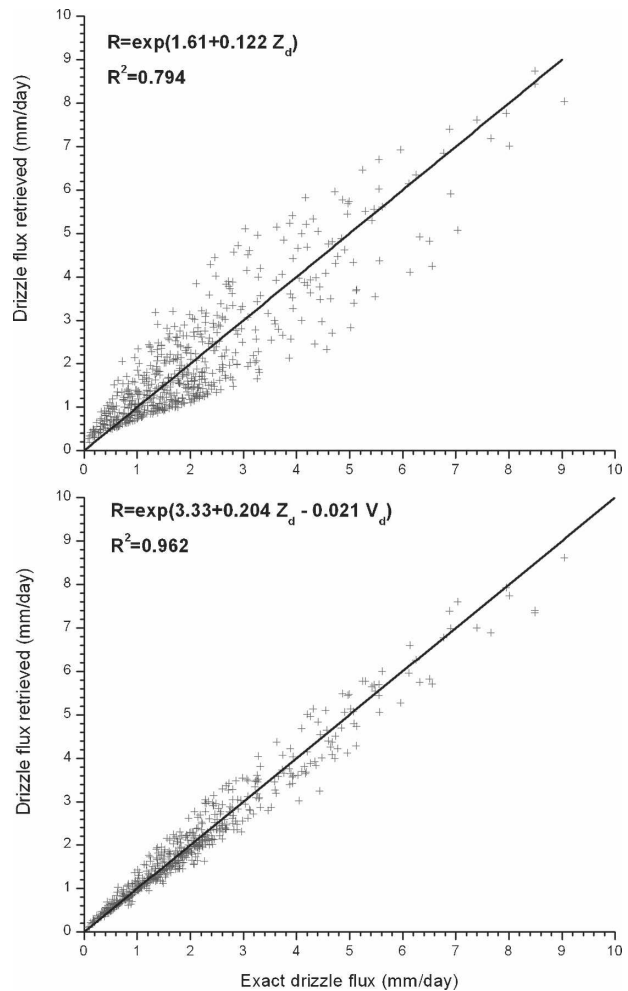


FIG. 11. The scatterplot of the retrieved vs exact drizzle flux for the HD case based on one and two ( $Z-V_d$ ) parameters (to reduce clutter only a fraction of data points is shown).

nondrizzling 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  $Z$ :

$$Q_l = 9.27 Z_m^{0.64}. \quad (13)$$

Equation (13) is very close to the one obtained using LES model data [Eq. (9)], as the comparison in Fig. 13 demonstrates. The LES data provide somewhat higher ( $\sim 20\%$ ) 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 (see Fig. 1, top panel). 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.

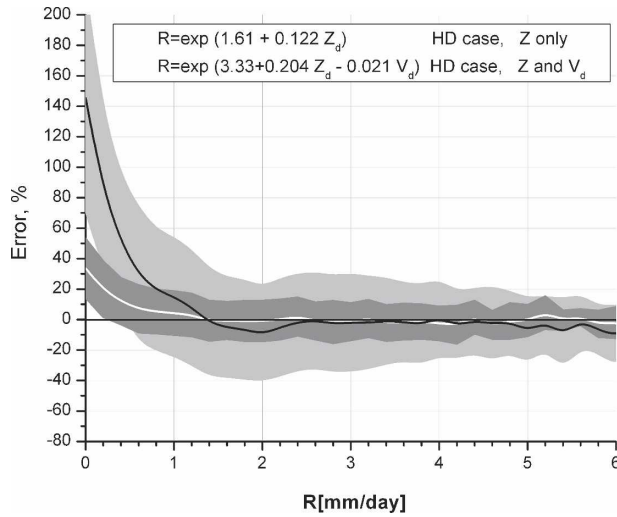


FIG. 12. The errors of drizzle flux retrieval for the HD case. The black and white lines are the 1P and 2P mean errors; the shading areas represent the mean  $\pm 1$  std dev. Light/dark gray shading corresponds to the 1P and 2P retrievals, respectively.

Other retrieval methods can be obtained by approximating cloud DSD by known analytical functions. Frisch et al. (1995) developed a retrieval technique that assumes cloud and drizzle drop spectra are lognormally distributed. Using our LES-derived DSDs, we are able to evaluate the accuracy of the lognormal assumption and thus indirectly evaluate the accuracy potential of this class of retrievals. As the lognormal distribution function is defined by three parameters, we use the zeroth, first, and second moments of the LES-derived DSDs for definition of the lognormal distribution function parameters. We then compare higher moments (liquid water content, rain rate, and radar reflectivity) given by lognormal distribution function with the corresponding moments of the explicit LES-derived DSDs.

Table 2 shows the mean and standard deviation of the relative errors  $\varepsilon$  due to the lognormal approximation

$$\varepsilon = (M_{LN}/M_{LES} - 1) \times 100, \quad (14)$$

where  $M_{LN}$  and  $M_{LES}$  are moments given by the lognormal distribution function and from the explicit LES-derived DSDs, respectively.

Clearly, for lightly precipitating clouds (case 1), the LWC can be rather accurately approximated using the lognormal distribution function (mean  $\varepsilon \sim 3\%$ ). The lognormal distribution function can similarly well represent the drizzle flux, although with somewhat larger error (mean  $\varepsilon \sim 9\%$ ). The representation of radar reflectivity is very sensitive to the amount of drizzle; the

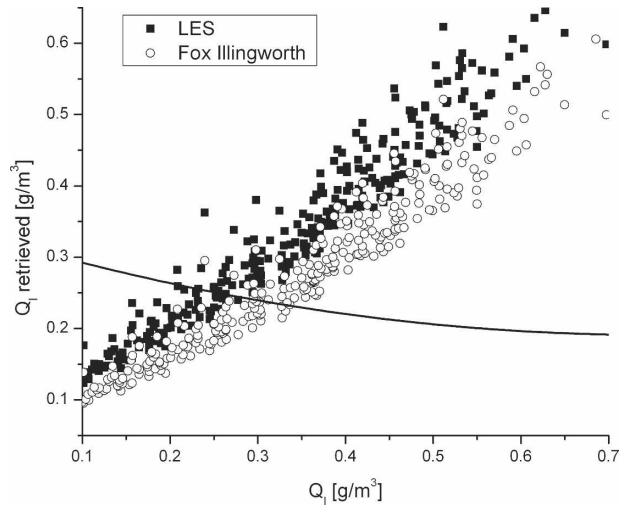


FIG. 13. The comparison of retrievals based on LES data according to expression (6) and ASTEX observations by Fox and Illingworth (1997). The black line shows the ratio of LES to observational data.

error can increase sharply (mean  $\varepsilon \sim 43\%$ ) even with a slight increase in drizzle rate (see Table 2, case 2). In the case of drizzling clouds, the radar reflectivity parameter is predominantly underestimated, obviously due to the fact that a single-mode lognormal distribution function has little or no information on drizzle drops far on the right from the mode.

In summary, the approximation of DSDs by a lognormal distribution function is justified when DSDs contain predominantly small cloud drops ( $r < 25 \mu\text{m}$ ) and only a fraction of drizzle drops. The retrievals of cloud liquid water similar to that of Frisch et al. (1995) should be quite accurate in this case. In cases when cloud drops span over a wide range of sizes, the approximation by a single-mode lognormal function may be inadequate and result in large errors.

### 5. Conclusions

We performed simulations of marine stratocumulus clouds observed during the Atlantic Stratocumulus

TABLE 2. Mean and std dev of errors (%) in the liquid water content, drizzle flux, and radar reflectivity due to approximation of drop spectra by a lognormal distribution function. Case 2 contains more DSDs with larger drizzle rates compared to case 1 (mean and std dev of drizzle rates  $R$  are indicated in the first row).

Parameter	Case 1	Case 2
$R$ (mm day <sup>-1</sup> )	0.84 $\pm$ 0.45	1.12 $\pm$ 0.52
Liquid water content	2.70 $\pm$ 2.66	1.52 $\pm$ 2.93
Drizzle flux	9.64 $\pm$ 6.08	7.51 $\pm$ 8.05
Radar reflectivity	8.22 $\pm$ 4.15	43.39 $\pm$ 61.70

Transition Experiment using the CIMMS large-eddy simulation model with size-resolving microphysics. Drop size distributions (DSDs) 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  $Q_i$ - $Z$  relationship are in good agreement with the retrieval obtained from ASTEX observations by Fox and Illingworth (1997). When drizzle is present,  $Q_i$  is poorly retrieved based on  $Z$  alone; however, the retrieval is substantially improved when Doppler velocity or Doppler spectrum width is included. For  $Q_i$  values larger than  $0.2 \text{ g m}^{-3}$ , 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  $\sigma_d$  instead of Doppler velocity decreases the accuracy of the  $Q_i$  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  $Q_i$ , 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  $Q_i$ . In stratocumulus with heavy drizzle ( $R > 2 \text{ mm day}^{-1}$ )  $Z$ - $R$  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.

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