THE VALIDATION OF DRIZZLE PARAMETRIZATIONS USING AIRCRAFT DATA

Robert Wood

Meteorological Research Flight, The Met. Office, Farnborough, Hants, UK

1. INTRODUCTION

The climatological impact of precipitation formation in marine stratiform clouds is poorly understood. In order to improve our knowledge of the connections between drizzle and stratocumulus cloud climatology, better representation in climate models of the processes of precipitation formation in warm stratocumulus cloud is required. In this paper a number of commonly used parametrizations of autoconversion and accretion are examined using aircraft data from 11 flights. Only flights in which the cloud deck was sampled with good vertical and horizontal resolution were chosen for this study. In several of the cases improved vertical sampling was obtained using sawtooth runs from cloud-base to cloud-top. These data were obtained in marine stratocumulus cloud spanning a wide range of cloud thickness h, liquid water paths LWP and droplet concentrations N_d (see table 1). Also in the table is given the cloud-base height z_b and the ratio of the liquid water path observed to that in an adiabatic cloud with the same thickness. The droplet concentrations range from 25-710 cm^{-3} and liquid water paths from 80-360 g m^{-2}.

2. DRIZZLE LIQUID WATER CONTENTS.

The drizzle liquid water content q_D is defined as the liquid water content in droplets larger than 20 μm radius. Droplets smaller than this do not contribute significantly to the precipitation rate. Drizzle liquid water contents were calculated for each 1km section of flight. Figure 1(a) shows that the drizzle liquid water content is generally greater in the cleaner (low N_d) clouds. Figure 1(b) shows that clouds with high drizzle liquid water contents are more depleted in liquid water content.

Table 1: Details of C-130 flights used. Values given are mean values for entire flight.

Flight Month; Location	z_b [m]	h [m]	N_d [cm^{-3}]	LWP [g m^{-2}]	LWP/LWP_{adiab}
H511 April; UK	950	320	710	120	0.93
H526 July; UK	400	400	100	170	0.65
H564 Dec; UK	200	670	35	205	0.44
A049 Dec; UK	750	700	285	260	0.52
A209 Jun; Azores	275	425	120	170	0.79
A439 Feb; UK	750	400	90	115	0.66
A641 Dec; UK	400	750	320	360	0.83
A644 Dec; UK	150	1600	55	90	0.07
A648 Feb; UK	200	850	25	85	0.22
A649 Feb; UK	450	300	60	80	0.61
A693 Jul; UK	100	300	200	80	0.64

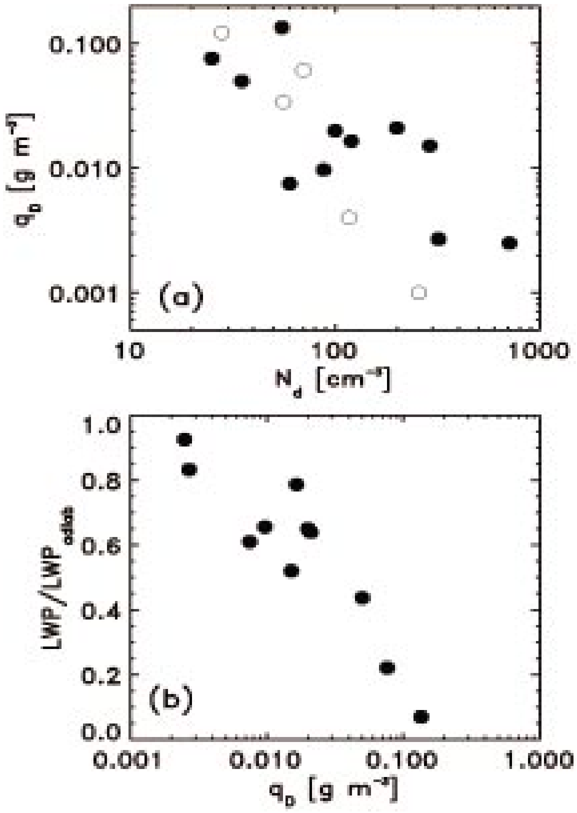

Figure 1.(a) Mean in-cloud drizzle liquid water content against cloud droplet concentration (solid circles). Results from Yum et al. (1998) are also shown (open circles). (b) Degree of adiabaticity as a function of drizzle liquid water content.

Figure 2 shows the mean vertical distribution of the drizzle liquid water content within cloud for flights A049-A693. Height-partitioned data were not available for cases H511-H564 as data for these flights is from Nicholls and Leighton (1986). The height in cloud is normalised using the cloud-base and top heights so that 0 represents cloud-base and 1 cloud-top. The abscissa is plotted using a logarithmic scale to show the large range of drizzle liquid water contents encountered. Table 2 shows the mean and standard deviation in-cloud drizzle liquid water content over the normalised height range 0.2-0.8 (to avoid the inclusion of cloud-free regions), which ranges from 2.7×10^{-3} to 7.5×10^{-2} g m^{-3}. The standard deviation gives an idea of the variability of the drizzle liquid water content within the cloud. The ratio of the standard deviation to the mean drizzle liquid water content (Table 2) ranges from 0.46-1.89 and this variability is mainly a result of horizontal variability rather than any systematic trend of the drizzle liquid water content with height. The parameter $F_{v/h}$ (Table 2) is the ratio of the standard deviation in the linear regression of drizzle liquid water content with height to the total standard deviation. In all cases except

---

Corresponding author's address: Robert Wood, Meteorological Research Flight, Y46 Building, DERA, Farnborough, Hants, GU14 0LX, UK; email: robwood@meto.gov.uk

A644 the systematic variation with height represents less than 20% of the total variability. In the case A644 there was a considerable increase in the drizzle liquid water content with height in cloud.

Table 2. Mean and standard deviation of observed in-cloud drizzle liquid water content. Standard deviations are not available for flights H511-H564. Also shown is the ratio of the standard deviation to the mean. The final column shows $F_{v/h}$ which is the ratio of vertical to horizontal variability in q_D.

Flight	$\overline{q_D}$ [x10^{-3} gm^{-3}]	σ_{q_D} [x10^{-3} gm^{-3}]	$\sigma_{q_D}/\overline{q_D}$	$F_{v/h}$
H511	2.5	-	-	-
H526	20.0	-	-	-
H564	30.1	-	-	-
A049	15.1	12.1	0.80	0.20
A209	16.5	15.4	0.93	0.01
A439	9.7	6.9	0.71	0.12
A641	2.7	5.1	1.89	0.06
A644	92.9	162.2	1.75	0.48
A648	76.0	123.0	1.62	0.10
A649	7.5	13.1	1.75	0.03
A693	21.0	9.6	0.46	0.15

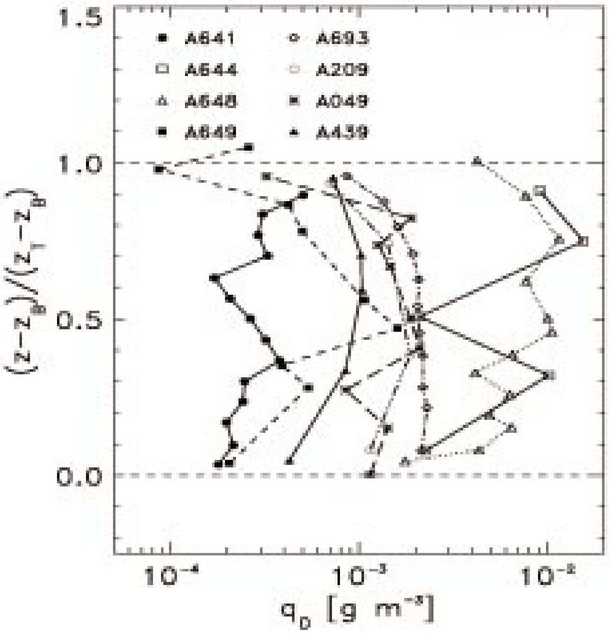

Figure 2. Variation of drizzle liquid water content with height in cloud (0=base; 1=top) for cases A049-A693.

3. HETEROGENEITY of DRIZZLE LWC

Table 2 indicates that the ratio of the standard deviation of q_D to the mean is roughly constant. Clouds with high drizzle liquid water contents exhibit considerable inhomogeneity, with regions of relatively weak drizzle interspersed among strongly drizzling regions. The probability distribution function (pdf) of drizzle within cloud is of considerable interest because the coupling between microphysical and dynamical processes is strongly affected by precipitation formation (Stevens et al., 1998). We find that the cases examined here have pdfs of drizzle liquid water content that are approximately lognormal in character with geometrical mean and standard deviation fitted well using

$$\text{geometrical mean} = 0.034\left\{1-\exp\left(-27.0\overline{q_D}\right)\right\}$$
$$\text{geometrical s.d.} = 2.43 + 51.12\overline{q_D} \qquad [1]$$

This indicates that if the mean drizzle liquid water content in a grid-box is known then the subgrid variability is predictable to a reasonable accuracy.

4. PRECIPITATION RATE

The precipitation rate is of prime importance to the prediction of drizzle in both large and small scale numerical models. The precipitation rate P (g m^{-2} s^{-1}) of a population of drops can be written as

$$P = w_{FALL}\, q_D \qquad [2]$$

where w_{FALL} is the fall speed (m s^{-1}). The precipitation rate is derived from observed droplet size distributions using the terminal velocity relationships of Rogers and Yau (1989). We find that the mean fall velocity for all our clouds is 0.37 ± 0.09 m s^{-1}.

5. MODEL

A simple model is used to predict drizzle liquid water contents. The model assumes that the removal of precipitation from the cloud-base is balanced with an equal turbulent flux of water vapour into the cloud from below. It is also assumed that the depletion of CCN by drizzle drops falling to the surface is negligible over the timescale of the observations (3-6 hours). There was no evidence of a systematic reduction in droplet concentration during the course of the observations in any of the cases. The equilibrium assumption therefore allows the use of a constant liquid water and droplet concentration profile. The input profiles are obtained from the entire observational dataset at 20 levels from the surface to the inversion. At each level the rate of change of drizzle liquid water content is given by

$$\frac{\partial q_D(z)}{\partial t} = Auto(q_C, N_d) + Acc(q_C, q_D) + \frac{\partial P}{\partial z} \qquad [3]$$

where *Auto* is the autoconversion rate, a function of cloud liquid water content (q_C, r<20 μm) and Acc is the accretion rate, a function of both the cloud and drizzle liquid water contents.

All microphysical data were averaged over 10 second intervals to allow for sufficient sampling of the larger drizzle-size particles. The precipitation rate P is calculated as function of q_D using the fall speed from equation [2]. Autoconversion and accretion are parametrized using three different commonly used schemes shown in table 3.

The observed and model drizzle liquid water contents are shown in table 4 and for T+C and K+K in figure 3. All results were taken in-cloud from normalised height 0.2-0.8. There are several important features to note:

(i) The T+C scheme overestimates the drizzle liquid water content by a large amount in almost all cases apart for those clouds with low liquid water path and low droplet concentration. Especially poor are the predictions for thick polluted clouds for which q_D may be overestimated by up to three orders of magnitude. The observed drizzle liquid water contents are strongly influenced by droplet concentration but those of T+C are not.

Table 3. Details of the formulations for autoconversion and accretion used in the different parametrizations examined in this study. The values of A-F are approximately constant having only some weak dependency upon air density. H(x) is the Heaviside step function and ρ is the air density. *All liquid water contents expressed in kg kg^{-1} and droplet concentrations in m^{-3}.*

Scheme	$\left.\frac{dq_D}{dt}\right\|_{Auto}$ [kg kg^{-1} s^{-1}]	$\left.\frac{dq_D}{dt}\right\|_{Acc}$ [kg kg^{-1} s^{-1}]
Kessler (1969) [KES]	$A.max(q_C - q_{thresh})$ A=10^{-3} s^{-1} q_{thresh}=5x10^{-4} kg kg^{-1}	$D\rho^{7/8}N_d^{1/8}q_C q_R^{7/8}$ D=0.29
Tripoli and Cotton (1980) [T+C]	$Bq_C^{7/3}N_d^{-1/3}H(q_C - q_{thresh})$ B=3268$\rho^{4/3}$ (E_C=0.55) q_{thresh} assumes r_{cm}=7µm	$Eq_C q_R$ E=4.7
Khairoutdinov and Kogan (2000) [K+K]	$Cq_C^{2.47}N_d^{-1.79}$ C=7.42x10^{13}	$F(q_C q_D)^{1.15}$ F=67.0
Beheng (1994) [BEH]	$Gd^{-1.7}q_C^{4.7}N_d^{-3.3}\rho^{3.7}$ d is width parameter (d=9.9 for N_d<200 cm^{-3} d=3.9 for N_d>200 cm^{-3}) G=4.8×10^{14}	$Jq_C q_R\rho$ J=6.0

(ii) The K+K scheme generally underpredicts the drizzle liquid water content, although the agreement is far better than that of T+C. In addition, the highest predicted drizzle liquid water contents are in the clouds with the highest observed drizzle liquid water contents suggesting that the K+K scheme has a realistic dependency upon droplet concentration.

(iii) The Beheng scheme generally underestimates the drizzle liquid water content as does K+K, but the discrepancies are generally worse than K+K but in general, BEH accounts reasonably well for the wide range of droplet concentrations. There appears to be too large a dependence upon liquid water content as the A641 drizzle liquid water content is considerably overpredicted.

(iv) The Kesler scheme, having an autoconversion threshold of 0.5 g m^{-3}, results in no drizzle production at all in most of the clouds. In the cases where drizzle is predicted by KES the rates are far too high and would in reality result in a complete depletion of the cloud liquid water within 10-20 minutes in cases A049 and A641. The lack of a dependence upon droplet concentration is also a limiting feature of this parametrization.

6. EFFECT OF HETEROGENEITY UPON AUTOCONVERSION AND ACCRETION

The three formulations presented here were intended for use in cloud-resolving models (CRMs). As such they represent the production of drizzle liquid water content on a *local* scale (the resolution of the CRM). In contrast, GCMs have grid-boxes which may be many times the scale for which the autoconversion and accretion parameterizations were intended. It is therefore important to assess how heterogeneity in the cloud on scales from 1 km upward would affect the production of drizzle liquid water content. This has been investigated previously (Larson et al., 1999) for clouds observed during the ASTEX campaign. Because there is sub-grid variability in liquid water content and droplet concentration, applying the autoconversion and accretion parametrizations to the grid-box mean parameters leads to biases in estimates of autoconversion and accretion rates. It is shown in Larson et al. (1999) that such biases can in some cases be large.

To give an idea of the bias caused by having a distribution of liquid water contents and droplet concentration at a model level, we examine the autoconversion and accretion using all the 1km data over a short height range close to the cloud-top.

Table 4. Observed and predicted mean in-cloud drizzle liquid water contents using the three different autoconversion and accretion schemes.

Flight	$\overline{q_D}$ [x10^{-3} g m^{-3}]				
	OBS.	K+K	T+C	KES	BEH
H511	2.5	0.04	0.0	0.0	0.003
H526	20.0	3.8	320.9	182.4	2.4
H564	30.1	6.2	145.8	0.0	3.3
A049	15.1	1.2	1407	23230	5.2
A209	16.5	2.3	329.4	685	0.1
A439	9.7	0.9	85.8	0.0	0.1
A641	2.7	2.9	2882	38310	16.5
A644	92.9	40.0	37.2	0.0	22.0
A648	76.0	32.8	15.7	0.0	51.8
A649	7.5	2.0	49.7	0.0	1.2
A693	21.0	0.2	31.5	0.0	0.02

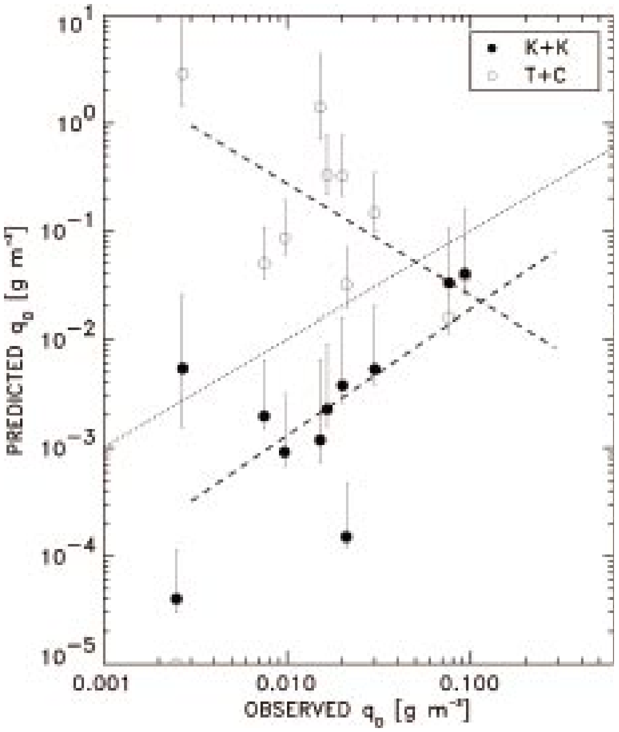

Figure 3. Observed and predicted cloud-mean drizzle liquid water contents. Only the T+C and K+K results are shown as KES predicted zero q_D for most of the cases. The error bars represent both the uncertainty in the fall speed, the droplet concentration and the liquid water content. In addition, the upper limit of the predictions has been extended to account for the effect of heterogeneity in the clouds (see section 6). The dotted line represents perfect agreement. The dashed lines are the best fits for the T+C (upper line) and K+K parametrization (lower line).

The ratio between the mean value of the autoconversion and the value of the autoconversion calculated using the level mean parameters varies from 1.15 (A439) to 1.80 (A644) with a mean of 1.58. For the accretion this ratio varies from 1.01 (A209) to 2.11 (A648) with a mean of 1.36. For all flights these ratios are greater than unity indicating that a model estimating the mean autoconversion and accretion at a level will underpredict these rates, with the greatest discrepancy being in the autoconversion. Inclusion of the effects of these biases (by raising the autoconversion and accretion rates) in the model increases the mean in-cloud drizzle liquid water contents by a factor of 2.2 for the K+K parametrization. The mean autoconversion and accretion ratios for T+C are 1.42 and 1.18, which would lead to a mean increase in the predicted drizzle liquid water contents of approximately 60%. The biases for BEH are also significant and result in a mean increase in drizzle liquid water content of some 80%.

The biases are somewhat less with the T+C and KES formulations because there is less dependency upon the droplet concentration. The error bars in figure 3 have been adjusted to account for this systematic underprediction. Inclusion of the heterogeneity of the clouds reduces the discrepancy between K+K and the observations, but increases it in the case of T+C and KES.

7. DISCUSSION

Eleven flights have been intensively observed to study the processes involved in drizzle formation in warm stratocumulus clouds. The results suggest that the production of drizzle is highly dependent upon the cloud droplet concentration and that parametrizations of autoconversion and accretion should account for this dependency. In addtion, this paper has reported an attempt to validate three autoconversion/accretion parametrizations used in GCMs using aircraft data from 11 intensively observed cases of stratocumulus cloud which varied considerably in cloud thickness, droplet concentration and drizzle liquid water content.

A simple equilibrium model of drizzle autoconversion, accretion and fallout was initialised using the observed, height resolved values of droplet concentration and liquid water content. The same fallout relationship was used throughout but the accretion and autoconversion terms differed. The most accurate predictions were those made by a scheme (Khairoutdinov and Kogan, 2000) derived using LES with explicit microphysics, but results from Beheng (1994) are also encouraging. The Tripoli and Cotton (1980) scheme generally predicted drizzle liquid water contents which were too high and the dependence of autoconversion upon droplet concentration appears to be too weak. The Kessler (1969) scheme either did not predict any drizzle at all (due to the inclusion of a threshold cloud liquid water content) or values far too high. This scheme is fundamentally limited for predictions the climatological impact of increasing aerosol loadings due to the lack of dependence of drizzle production upon cloud droplet concentration. This dependence appears to be significant – the observed drizzle liquid water contents (and hence precipitation rates) correlate strongly and negatively with the cloud droplet concentration as shown in figure 1(a). The autoconversion rate depends strongly upon droplet concentration in K+K (exponent = –1.79) and Beheng (exponent = –3.33), which accounts for the better predictions. However, these exponents still differ considerably.

The scaling up of a parametrization of local processes for use in climate and large scale numerical models requires considerable further attention. The use of mean liquid water contents and droplet concentrations in the simple model presented here results in sizeable underpredictions of the autoconversion and accretion rates. This bias is expected to be a function of both the observational averaging length (in this case 1 km) and the grid-box length. This bias is also expected to depend crucially upon cloud morphology, i.e. how variable the liquid water content and droplet concentration are in space.

ACKNOWLEDGEMENTS

Thanks to all staff and aircrew of the Met. Research Flight for their dedication in obtaining the data presented here.

REFERENCES

Beheng, K. D., 1994: A parameterization of warm cloud microphysical processes. Submitted to *Atmos. Res.*, **33**, 193-206.

Larson, V. E., Wood, R., Field, P. R., Golaz, J.-C., Vonder Haar, T. H., and Cotton, W. R., 1999: Systematic biases in the microphysics and thermodynamics of numerical models that ignore subgrid-scale variability. Submitted to *J. Atmos. Sci.*, November 1999.

Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulations. *Meteor. Monogr.,* **32**, Amer. Meteorol. Soc., 1-84.

Khairoutdinov, M. and Kogan, Y. L., 2000: A new cloud physics parametrization in a large-eddy simulation model of marine stratocumulus. *Mon. Wea. Rev.,* **128**, 229-243.

Nicholls, S. and Leighton, J., 1986: An observational study of the structure of stratiform cloud sheets: Part I. Structure. *Quart. J. Roy. Meteorol. Soc.,* **112**, 431-460.

Stevens, B., Cotton, W. R., Feingold, G., Moeng, C.-H., 1998: Large-eddy simulations of strongly precipitating, shallow, stratocumulus-topped boundary layers. *J. Atmos. Sci.*, **55**, 3616-3638.

Rogers, R. R. and Yau, M. K., 1989: A first course in cloud physics. Third edition, Pergamon Press, Oxford, UK.

Tripoli, G. J. and Cotton, W. R., 1980: A numerical investigation of several factors contributing to the observed variable intensity of deep convection of south Florida, *J. Appl. Meteorol.*, **19**, 1037-1063.

Yum, S. S., Hudson, J. G. and Xie, Y., 1998: Cloud condensation nuclei and drizzle. *Proc. AMS Conf. Cloud Phys.*, Everett, USA, 1998, 267-270.