A Preliminary Assessment of the Importance of Coalescence in Convective Clouds of the Eastern Transvaal

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ABSTRACT

For the past three years, a Learjet has been making microphysical measurements in new cloud development on the flanks of multicellular storms in the eastern Transvaal area of South Africa. Data from an imaging probe and a forward scattering spectrometer have been averaged for each storm for all first cloud penetrations between −8° and −12°C. Clear images of drops of diameters greater than 300 μm are found in 40% of the 42 storms measured.

Most of the observed drops are associated with the more "maritime" droplet spectra. Also, the appearance of coalescence around −10°C appears to be related to cloud base temperatures and buoyancies, rather than changes in air masses, suggesting that cloud thermodynamics may play a dominant role in determining cloud microphysics in the Nelspruit area.

1. Introduction

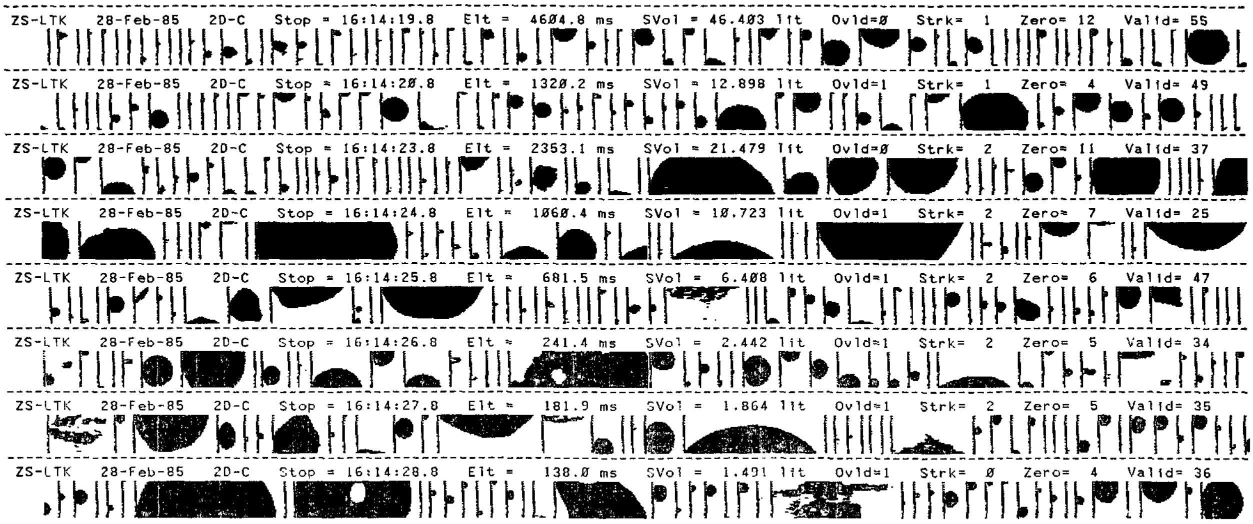
Convective clouds supply about 90% of the annual rainfall over the eastern Transvaal of South Africa (Schulze, 1965). As part of the weather modification research for the Programme for Atmospheric Water Supply (PAWS), microphysical measurements using an instrumented Learjet have been conducted over the past several years on vigorous cumulus congestus towers growing on the flanks of multicellular thunderstorms. Most of the cloud sampling has been focused around the −10°C level since this is the level that is being targeted for glaciogenic seeding. These measurements frequently show the presence of large supercooled water drops implying that the condensation-coalescence mechanism often plays an important role in the local precipitation formation processes.

Dynamic seeding is an attempt to invigorate cloud growth by suddenly releasing large amounts of latent heat. Studies indicate that significant heat release may depend on the presence of large supercooled water drops (Lamb et al., 1981). Several studies (MacCready et al., 1957; Nelson, 1979; Knight, 1981; Johnson, 1982) have suggested that cloud base temperature is a good indicator of whether ice crystals or large water drops will be the dominant graupel embryos in convective clouds. Other factors are liquid water content, air mass of origin (cloud base droplet spectra) and updraft speed. Attempts to relate an active coalescence process to local air mass types in the PAWS experimental area have not been successful using synoptic analyses. More promising is a relationship found between the presence of large drops around the −10°C level, temperatures at cloud base and some measure of updraft potential. This suggests that cloud thermodynamics may be the predominant control over cloud microphysics in this area.

2. Data

The microphysical data used in this study were obtained from a Particle Measuring System (PMS) Forward Scattering Spectrometer Probe (FSSP) and a PMS two-dimensional cloud particle imaging probe (2D-C). The FSSP measures the size distribution and concentration of cloud droplets from 2 to 47 μm. Corrections for electronic dead time and variable velocity acceptance ratio (Baumgardner and Dye, 1982) have been applied to the FSSP data. The 2D-C probe produces shadow images of cloud particles larger than about 35 μm at a resolution of 35 μm. These data are processed to obtain information on particle concentrations and sizes using the particle weighting technique and standard artifact rejection procedures (Cooper, 1978; Heymsfield and Baumgardner, 1985). Smooth circular images with diameters greater than 300 μm encountered at −10°C provide unambiguous evidence of large water drops produced by a condensation-coalescence mechanism (Fig. 1). Very smooth, round, but clearly rimed particles are often observed, indicating the birth of graupel as large frozen drops. These, too, could be taken as evidence of the importance of coalescence, but have not been considered in this note.

Cloud base temperatures (CB_T) are determined from



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ZS-LTK   28-Feb-85   2D-C   Stop = 16:14:28.8   Elt =   138.0 ms   SVol =  1.491 lit   Ovld=1   Strk=  0   Zero=  4   Valid= 36
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FIG. 1. Images recorded with 2D-C probe on 28 February 1985. Vertical dimension of image frame is 1.12 mm. Average static temperature for this penetration was −10.6°C.

the points at which the average equivalent potential temperatures in the lowest 60-mb layer intersect the lines of average mixing ratios for the same layers. The distribution of cloud base temperatures for convective storms in the Nelspruit area is shown in Fig. 2. On average, cloud base temperatures at Nelspruit are colder than those in Florida and the Midwest, but considerably warmer than those found in the Great Plains (Johnson, 1982). The differences between the pseudoadiabats through cloud base and the environmental temperatures at 500 mb (ΔT_{500}) are a measure of potential buoyancy. Cloud base temperature and ΔT_{500} are computed from the Learjet ascent to 300 mb, which is taken close in time and space to the sampled storms.

Measurements from first passes made within 1000 m of the tops of unseeded turrets growing on the flanks of 42 convective storms have been arithmetically averaged for each storm. Only those passes that commenced in environmental air between −8° and −12°C inclusive are considered in this sample. These measurements are listed in Table 1 and summarized in Table 2. The numbers in Table 2 are storm-averaged 2D-C concentrations of particles whose diameters exceed 105 μm. The numbers in parentheses indicate those storms where clear images of drops greater than 300 μm were found. There is a greater frequency of observed water drops as the FSSP concentrations decrease and mass-weighted mean diameters increase (towards the upper right-hand corner of Table 2). Another way of saying the same thing is the more maritime the FSSP spectra around −10°C, the greater the likelihood of observing coalescence-grown water drops. (This follows the tradition of using the terms "maritime" and "continental" to describe relative degrees of colloidal instability in clouds.) Calculations reported by Young (1974) indicate a rapid decrease in the number of cloud droplets with the onset of coalescence. This opens the question, How much of the observed "maritime" appearance of the droplet spectra at −10°C is caused by the coalescence? It can be informally reported that, in general, the FSSP-measured droplet concentrations at Nelspruit decrease with height on a given flight, sometimes quite dramatically.

Imaging probe data cannot provide unambiguous discrimination between ice crystal and frozen drop graupel cores. We are tackling this measurement problem at Nelspruit by measuring graupel reflectivities using the on-board aircraft X-band radar and comparing these with reflectivities calculated from the 2D-C probe for various density assumptions. Care must be taken here to stay within the 2D-C size range (35–1120 μm). There is also a big disparity between the sample vol-

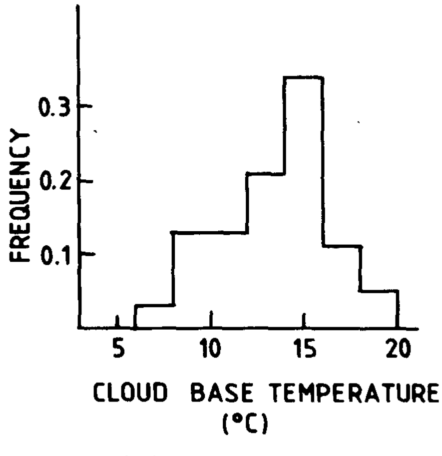

FIG. 2. Frequency distribution of cloud base temperatures (CB_T) computed from 38 Learjet soundings close in time and space to sampled storms.

TABLE 1. List of calculated cloud base temperatures (CB_T) and 500-mb potential buoyancies (ΔT_{500}). Also listed are observed averages of FSSP droplet concentrations (N_c), mass weighted mean diameters (D_M), 2D-C particles concentrations > 105 μm l^{-1} and observations of large (>300 μm) drops.

Date	CB_T (°C)	ΔT_{500} (°C)	N_c (cm^{-1})	D_M (μm)	Conc > 105 μm (l^{-1})	Remarks
19 Nov 1982	11.1	3.6	435	18.2	0	
24 Nov 1982	9.4	3.1	417	18.6	1	
29 Nov 1982	16.5	4.9	470	19.9	2	
8 Dec 1982	13.0	2.9	425	19.4	8	Drops
20 Dec 1982	8.7	2.9	452	18.0	1	
7 Mar 1983	18.8	5.4	337	21.7	0	
18 Mar 1983	11.7	4.2	355	21.6	4	
22 Mar 1983	17.7	2.8	220	24.6	18	Drops
15 Apr 1983	14.1	4.5	336	21.0	0	
12 Oct 1983	9.0	0.7	377	18.2	0	
13 Oct 1983	9.1	1.8	284	21.9	0	
24 Oct 1983	6.6	2.6	375	18.2	2	
4 Nov 1983	10.8	1.3	289	22.2	7	Drops
5 Nov 1983	12.0	2.3	384	18.1	0	
6 Nov 1983	15.3	2.4	307	22.9	9	
12 Nov 1983	15.0	3.4	235	23.1	18	Drops
14 Nov 1983	15.2	6.4	347	22.1	0	
1 Oct 1984	10.5	5.8	348	20.0	0	
26 Oct 1984	*	*	304	19.5	0	
30 Oct 1984	*	*	331	22.0	0	
16 Nov 1984	12.8	0.1	197	23.0	10	Drops
27 Nov 1984	13.8	3.0	331	22.4	1	
28 Nov 1984	13.5	2.7	319	19.3	0	
29 Nov 1984	*	*	216	23.1	8	Drops
10 Dec 1984	15.1	6.7	399	19.5	0	
12 Dec 1984	*	*	294	22.0	5	Drops
13 Dec 1984	13.1	3.3	315	19.5	0	
13 Dec 1984	11.9	3.3	388	22.1	4	
14 Dec 1984	14.1	5.2	346	17.8	3	
14 Dec 1984	14.5	5.0	280	17.5	2	
19 Dec 1984	14.0	3.4	328	21.5	2	
20 Dec 1984	16.1	4.1	214	23.5	6	Drops
20 Dec 1984	14.2	2.9	331	22.0	4	Drops
15 Jan 1985	12.5	1.5	276	23.9	5	Drops
15 Jan 1985	9.0	−0.1	326	22.3	1	
18 Jan 1985	18.2	2.4	181	24.1	13	Drops
23 Feb 1985	14.7	2.1	229	21.1	4	Drops
28 Feb 1985	15.2	1.3	254	21.1	13	Drops
1 Mar 1985	17.1	5.2	266	23.1	8	Drops
12 Mar 1985	13.8	1.4	336	22.1	11	Drops
12 Mar 1985	14.2	1.6	313	23.1	4	Drops
13 Mar 1985	14.9	2.1	305	21.6	1	Drops

* Missing data.

umes of the 2D-C probe (about 10 L s^{-1}) and the radar (5×10^6 m^3 sec^{-1}). Keeping these two caveats in mind, some surprisingly good results are emerging from these comparisons. Indications are that most of the graupel that we are seeing in the high liquid water content cloud regions have densities that are compatible with large frozen drop cores.

Figure 3 shows a plot of CB_T vs ΔT_{500} from Table 1. Circles represent measurements from those storms in which clear images of drops were recorded. A discriminant function L, defined by

$$L = b_0 + b_1 CB_T + b_2 \Delta T_{500}, \qquad (1)$$

where the coefficients b_1 and b_2 are chosen so as to maximize the difference between the two groups, best discriminates between drops and no drops when $L = 0$ (Panofsky and Brier, 1958). The use of this function here clearly demonstrates that the appearance of drops at the −10°C level is a function of cloud buoyancy as well as cloud base temperature.

3. Discussion

It is unlikely that the supercooled drops observed at around −10°C are a result of the recycling and melting of ice particles for at least two reasons. Such a mechanism would tend to produce random observations of drops which could not be related in any systematic

TABLE 2. Storm-averaged 2D-C particle concentrations (per liter) >105 μm vs averaged FSSP concentrations and mass-weighted mean diameters. Numbers in the table in parentheses are those storms in which clear images of water drops were recorded.

Concentrations (cm^{-3})	Mass-weighted mean diameters (μm) 16–17.9	18–19.9	20–21.9	22–23.9	24–25.9	
170–199				10	(13)	
200–229			(4)	(6), (8)	(18)	
230–259			(13)	(18)		
260–289	2		0	(7), (5), (8)		
290–319		0, 0, 0	(1)	9, (4), (5)		
320–349	3		0, 0, 0, 2	0, 1, (4), 1, (11), 0		
350–379		0, 2	4			
380–419		0, 1, 0		4		
420–449		0, (8)				
450–479		2, 1				
Total	2	12	9	17	2	42
Frequency	0.05	0.29	0.21	0.40	0.05	1.0

way to cloud thermodynamics and other cloud physics observation. Secondly, drops have been observed in isolated cumulus cloud towers on days when they also have appeared in cloud turrets on the flanks of convective storms.

Since CB_T is related to the distance between cloud base and the −10°C level, and ΔT_{500} to the average updraft between the two levels, the ratio $CB_T/\Delta T_{500}$ is proportional to the time it takes for a parcel to ascend to the sampling level from cloud base. Since coalescence is a time-dependent process (Leighton and Rodgers, 1974), the air parcel ascent rate should also be an important variable in the prediction of the occurrence of large supercooled drops, as well as the cloud base temperature.

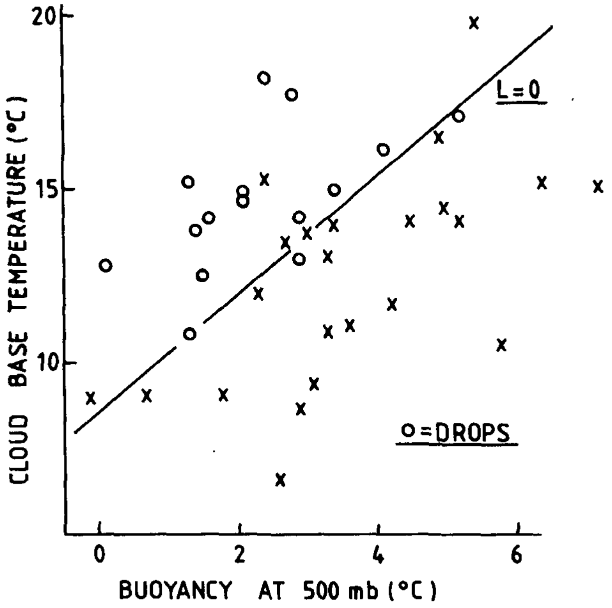

FIG. 3. Plot of cloud base temperatures (CB_T) vs potential buoyancy at 500 mb (ΔT_{500}) for the storms in this study. Those cases in which clear images of cloud drops > 300 μm were encountered are plotted as open circles (O). The oblique line in the figure is the discriminant function plotted for $L = 0$.

Many of the sampled clouds show a mixture of drop and round graupel images. We believe that the round graupel originates from drops that freeze at levels below the aircraft penetration level. Indeed, some of the clouds that fall into the "drop" region in Fig. 3 exhibit only images of round graupel. Pristine images of ice crystals (columns, plates, dendrites, etc.) are only seen occasionally in the relatively "dead" regions at the edge of clouds, never in the high liquid water regions that are sampled by the Learjet. Any ice crystals nucleated in these regions would almost immediately come in contact with a water drop. The prediction of the formation of ice in cumulus clouds remains one of the most important problems in cloud physics and weather modification.

If dynamic seeding is dependent on the water contained in the large supercooled drops found at glaciogenic seeding levels (Lamb et al., 1981), then a "coalescence window" may exist for effective dynamic seeding; too large a $CB_T/\Delta T_{500}$ ratio and drops will have grown to such a size that they will overcome a relatively weak updraft and fall out of the cloud before reaching subzero temperature levels; too small a ratio and the time in the cloud will be too short for coalescence to become significant before the cloud air parcel reaches the level where natural ice nucleation becomes important.

Since coalescence is also dependent upon liquid water content, any entrainment would delay the onset of coalescence (Leighton and Pissimanis, 1975) so best seeding opportunities might be found in those clouds with unentrained cores. Measurements at Nelspruit indicate that cloud turrets rising on the flanks of multicell convective storms often exhibit such unentrained updraft cores. If the storms in Table 2 are a representative sample from the population of large convective Nelspruit clouds, then at least 45% of the clouds in the area are likely to have an active coalescence mechanism contributing to the precipitation formation processes (those with number concentrations < 350 cm^{-3} and mass-weighted diameters > 22 μm at the $-10°C$ level).

A complete climatological description of the microphysical characteristics of the clouds in the Nelspruit area will follow in another paper.

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