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Observations of cloud and precipitation particles on the Avery Plateau, Antarctic Peninsula

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Abstract: Surface-based observations were taken of cloud and precipitation particles on the Avery Plateau (66°50.34'S 65°29.58'W), Antarctic Peninsula from 25 November to 13 December 1995. This paper considers cloud parameters on three days during this period when the cloud base reached ground level and snow was falling. It was found that on all three days more ice crystals were present in the cloud than would be expected from simple theoretical considerations. The rate of snowfall decreased as the number of ice crystals increased, the large number of ice crystals present effectively suppressing the formation of large precipitation-sized crystals. The source of the ice nuclei that allowed the formation of the large number of crystals is not known for certain but is thought to be the snow surface, possibly in the form of very fine ice crystals blown from the surface during blowing/drifting snow episodes.

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Introduction

Clouds play a critical role in the climate system by virtue of their role in radiative processes and the hydrological cycle (Yamanouchi & Charlock 1994), and this is equally true in the Antarctic as elsewhere in the world. When clouds form over the ice-free ocean, which has a low albedo, they have a significant effect on the radiation balance at the top of the atmosphere by reflecting most of the radiation back to space. On the other hand, clouds over the Antarctic continent itself have less of an effect on the short-wave radiation balance because they have an albedo similar to that of the snow-covered surface. Nevertheless, clouds over the continent are important in determining the surface radiation balance by increasing the downward long-wave radiation (Ambach 1974).

A further major role of cloud is in the production of precipitation. In the coastal areas of the Antarctic continent most precipitation comes from frontal cloud bands associated with synoptic-scale weather systems (Bromwich 1988, Turner *et al.* 1995). In certain areas, such as near McMurdo station, mesoscale weather systems are thought to be responsible for a large percentage of the annual accumulation (Rockey & Braaten 1995). However, with increasing distance inland from the coast a greater proportion of precipitation arrives as ice crystals falling from thin, isolated cloud or from an apparently clear sky in the form of 'clear sky precipitation' or 'diamond dust' (Rusin 1961, Radok & Lile 1977).

Very few measurements have been taken within Antarctic clouds because of problems of using advanced instrumentation in the Antarctic and the lack of access to research aircraft. However, measurements are needed to model correctly the effects of possible global climate change in the Antarctic. In particular, to model and understand how global climate change can affect precipitation over Antarctica, it is necessary to understand which cloud microphysical processes are important in controlling precipitation. Also, *in situ* measurements are required to interpret remote sensing measurements of clouds at high southern latitudes. Although measurements of total snow accumulation have been made routinely since the International Geophysical Year (Flowers 1960), it is only in recent years that more details on cloud and precipitation particles have been collected and consideration given to the microphysical processes involved. Several investigations have been carried out into the nature of the precipitation at the South Pole (Hogan (1975), Kikuchi & Hogan (1979), Sato *et al.* (1981)). A lidar system used at South Pole station (Smiley *et al.* 1980) also provided information on the types of ice crystals found in the thin clouds above the station. These studies have helped to describe the type of cloud particles and precipitation found over the high polar plateau but have not been able to determine the mechanisms that are important in their formation.

There have been very few studies of clouds and precipitation in the Antarctic coastal region. A lidar was operated at Dumont d'Urville (66°40'S–140°01'E) for a year to determine the optical and radiative properties of clouds above that location (del Guasta *et al.* 1993). There have also been investigations of precipitation at the Japanese Mizuho station (Takahashi 1985) and Syowa station (Kikuchi 1971). However, these studies have also done little to explain the processes that are important in the formation of clouds and precipitation on the Antarctic. It was therefore decided to carry out an investigation into the nature of the clouds and precipitation found over the Antarctic Peninsula region. This area is very interesting from a climatological point of view since it has experienced a statistically significant rise in surface air temperature of about 2°C since 1956 (King 1994) along with a 50% increase in the number of precipitation reports over the same time (Turner *et al.* 1997). With the area already experiencing climatic change, this paper reports on the first measurements of cloud microphysical parameters for the Peninsula. These data will act as a baseline for further investigations and also assist in the accurate parameterisation of Antarctic clouds within numerical models.

The field campaign and instrumentation used

The investigation was carried out on the central spine of the Antarctic Peninsula at the Avery Plateau (66°50.34'S 65°29.58'W, elevation 1860 m) (Fig. 1) from 25 November to 13 December 1995. This area is situated to the south of the band of maximum cloud cover associated with the circumpolar trough and is crossed by large mid-latitude weather systems (King & Turner 1997). The high ground of the Peninsula acts as a barrier to these systems and only a few cross completely. The cloud climatology (Warren *et al.* 1988) puts the zonally averaged cloud cover at the latitude of the Avery Plateau at 50%. However, the Peninsula is an area where frontal systems tend to become slow moving as they approach from the west so the percentage cloud cover is expected to be higher than the zonal average. During the field campaign the average cloud cover was 83% as determined from local synoptic meteorological observations.

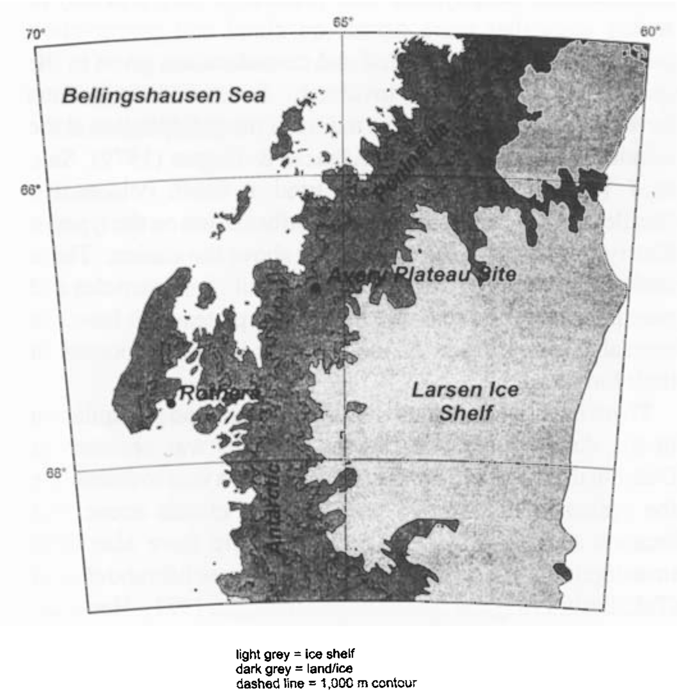

Fig. 1. Map showing the Antarctic Peninsula.

The precipitation at this site comes from many sources, including frontal systems crossing the Peninsula, precipitation from a clear sky and from orographic cloud. A 10 m firn core showed no annual layers, indicating an annual accumulation of greater than 10 m.

Standard meteorological observations

The meteorological observations taken during the campaign comprised surface pressure, wind speed and direction, temperature and humidity every five minutes. These observations were supplemented by standard visual observations of cloud type, visibility and precipitation every three hours during the day. Radiosondes were flown when cloud and precipitation were observed near the ground at the observation site.

The disdrometer

A disdrometer, developed by University of Manchester Institute of Science and Technology (UMIST) was deployed to measure the rate and size distribution of the precipitation (Illingworth & Stevens 1987). This mains powered instrument consists of a halogen bulb and optics to produce a 30 mm diameter annulus of light with a thickness of 0.1 mm. The sample volume is 170 mm long and, after passing through this volume, the light is focussed onto a photodiode. Particles entering or leaving the annulus cause pulses in the signal measured at the photodiode proportional to the part of the annulus obscured by the snow crystal. The particles were counted in one of thirty size ranges, from 0–6.4 mm, to produce a size distribution.

The disdrometer gives good relative readings of the size distribution, the key requirement for this study. An absolute value for the water equivalent precipitation rate has been calculated by assuming spherical crystals with a density of 100 kg m^{-3}. Normally this rate should be viewed with caution. The rate will also change if the shape and structure of the snowflakes changes as this will affect the density of the particles. During this study all the snowflakes observed were in the form of stellar crystals and so any rate changes seen by the disdrometer have been considered to be real.

Formvar replicas

Replicas of the cloud particles near the ground were taken for later analysis. The method used was to coat a slide with a 1% (by weight) solution of Formvar in 1,2-dichloroethane. Enough solution was made up at Rothera before deploying to the field site. It is normally considered better to use a fresh solution and to keep it at a temperature above -5°C to prevent ice crystals forming in the solution, but this was not possible in this case due to the difficult field conditions. A small tent was put up and the Formvar solution and slides were kept in the tent to allow them to reach a temperature close to the outside air temperature. The collection of samples required two people.

One person, in the tent, to coat the slides using a paintbrush. The slide was then passed to the person outside who exposed the slide at around 2 m. In this study it was found sufficient to hold the slide vertically into the wind and allow the cloud particles to be blown onto the slide. The exposure time was varied according to the wind speed and particle density of the cloud and was normally around 10 to 30 seconds. The slides were then passed back into the tent and left to dry. A discussion of a similar method can be found in Takahashi & Fukuta (1988) and it has also been used before by Hogan (1975) to collect samples of diamond dust falling at the South Pole.

A total of 141 slides were collected. Subsequent analysis was limited to the 33 slides taken during precipitation and three control slides; the slides collected in non-precipitating clouds have not been analysed. The analysis was done by taking photomicrographs of the slides and then counting and classifying the particles by eye. It was found that image analysis computer programs were not able to resolve between spherical droplets and hexagonal plates. It was not possible to take a photomicrograph of the whole slide at once and so 10 smaller images where taken at random positions across each slide, the particles were then categorised and sized manually. The size used for the crystals was the average of the largest and the smallest dimensions.

These observations of cloud particle size will be affected by several uncertainties in the measurements. These include errors due to exposure time, variable airflow across the slide and collection efficiency. We shall now consider each of these sources of uncertainty in turn.

The uncertainty in the timing of the exposure of the slides was estimated to be of the order of ± 1.4 seconds for each slide. This gives a percentage error in the number of particles counted ranging from ± 14% for a 10 second exposure time to ± 5% for a 30 second exposure time.

The wind at the time of exposure was measured with the AWS described above. During the observations the one-minute mean wind speed was 4 to 6 ms^{-1}. We can estimate the uncertainty in the wind speed by considering the standard deviation caused by turbulence of the wind blowing over a snow surface (see King 1990). This gives an error in the wind speed of the order of 0.64–0.65 ms^{-1} or in terms of a percentage error in the number of particle counted of between ± 10–16%.

From multiple counts of the same slide the counting errors were found to be around ± 15%. So the total error due to timing, variable airflow and counting is between ± 19–26%, assuming a Poisson distribution of uncertainties.

The collection efficiency of the slide will produce a systematic error with the particles with the smallest sizes being affected to the greatest extent by the airflow around the slide. This will bias the distributions of droplets seen on the slides. To estimate the size of the effect, the theoretical equations derived by Ranz & Wong (1952) for particle collection by an infinite ribbon were used. To do this the coated microscope slide was considered to be an infinitely long ribbon 25 mm wide and two types of particles were considered. These were spherical particles with densities of 0.3 and 1.0 x 10^3 kg m^{-3} representing hexagonal plates and water droplets respectively. Figure 2 shows how the collection efficiency varies with particle size for these two cases in a wind speed of 5 ms^{-1}. It can be seen for the case representing the water droplets no droplets smaller than 15 *μm* should be seen while for the case representing the crystals no particles smaller than 25 μm should be seen. The observed distributions largely agree with this theoretical limit, since very few droplets were seen smaller than 15 μm and few crystals smaller than 25 μm. Some smaller particles than would be expected from the simple theory are seen but in general only around 10% of droplets are smaller than 10 μm and the same percentage of crystals are smaller than 20 μm. Occasional particles are seen on the slides with sizes much smaller than 5 μm, without any structure to enable them to be identified as either crystals or

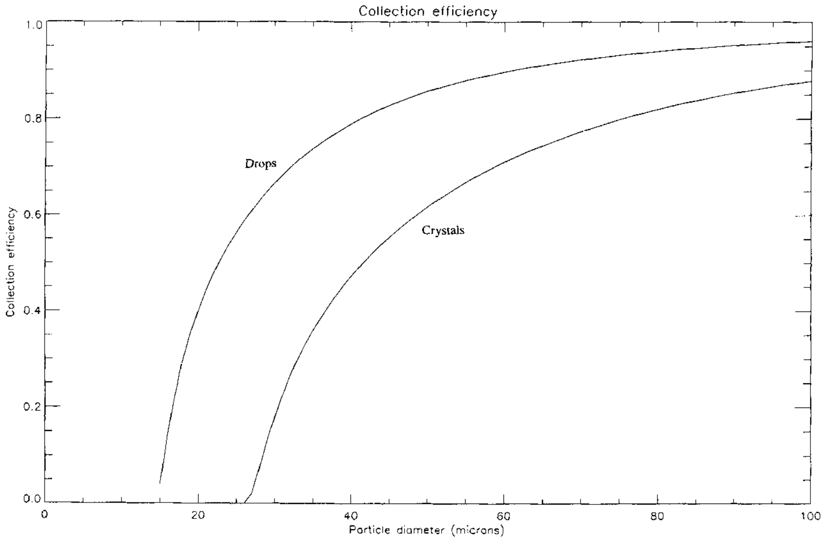

Fig. 2. Collection efficiency of the Formvar coated slides for droplets and crystals.

droplets. Control slides that were treated in the same way but not exposed to precipitation also showed the small particles at the same concentration levels. It is thought that these small particles are contamination in the Formvar solution or dust falling on the slides during the drying process. As a result particles smaller than 5 µm were excluded and particles with sizes between 5 and 10 µm were only counted if they could definitely be identified as either a droplet or a crystal.

As well as the uncertainties in the measurement methods it is necessary to consider how good a representation of the cloud as a whole the measurements are. Clouds have a large natural variability over a temporal scale of a few seconds to minutes and the number of particles collected can vary greatly between slides taken only a few seconds apart. To estimate this variability we have calculated the standard deviation of the particle counts between slides taken on the same occasion.

The synoptic situation during the campaign

29 November 1995

At 0600UTC a low-pressure system with a central pressure of 962hPa was just to the west of the Peninsula where it remained throughout the day. An associated occluded front remained stationary close to, or over, the Avery Plateau. This front caused intermittent light snow to fall throughout the afternoon.

1 December 1995

The mean sea level pressure (MSLP) analysis for 1200 UTC showed a weak ridge over the Avery Plateau with a large low approaching from the west. Although there were large cloud bands associated with the synoptic scale low to the west of the site most of the snow during the day is thought to be due to orographic uplift of the airmass in the north-westerly airflow.

Table I. Number of crystals and droplets for each slide collected. Also shown are the meteorological conditions at the time of collection. Note that slides 12 and 13 were exposed in the drift layer.

Slide	Date	Time	No. of drops	No. of crystals	Vol. sampled (litres)	Drops litre^{-1}	Crystals litre^{-1}	Exposure time	No. of frames
11	29/11/95	1559	4	169	3.75	1.07	45.07	30	10
12			0	228	1.25	0.00	182.40	10	10
13			0	154	1.25	0.00	123.20	10	10
14			0	310	4.13	0.00	75.06	30	11
15			0	124	3.75	0.00	33.07	30	10
16			0	287	4.13	0.00	69.49	30	11
17			0	371	3.75	0.00	98.93	30	10
18			0	344	1.37	0.00	251.09	10	11
19			0	234	1.25	0.00	187.20	10	10
20			0	343	1.37	0.00	250.36	10	11
42	01/12/95	1927	103	14	7.09	14.53	1.97	60	10
43			203	31	5.85	34.70	5.30	45	11
44			291	37	3.55	81.97	10.42	30	10
45			235	45	3.9	60.26	11.54	30	11
46			27	29	3.55	7.61	8.17	30	10
91	07/12/95	1525	175	78	2.15	81.40	36.28	20	11
92			400	81	1.95	205.13	41.54	20	10
93			97	54	2.15	45.12	25.12	20	11
94	07/12/95	1530	299	22	1.47	203.40	14.97	15	10
95			377	41	2.15	175.35	19.07	20	11
96			47	17	1.95	24.10	8.72	20	10
97	07/12/95	1835	206	81	1.37	150.36	59.12	10	11
98			134	116	1.25	107.20	92.80	10	10
99			24	125	1.25	19.20	100.00	10	10
100			270	113	1.37	197.08	82.48	10	11
101			33	71	1.25	26.40	56.80	10	10
103	07/12/95	1922	328	5	0.93	352.69	5.38	10	10
104			475	3	1.02	465.69	2.94	10	11
105			372	11	0.93	400.00	11.83	10	10
106			453	4	1.02	444.12	3.92	10	11
107			77	3	0.93	82.80	3.23	10	10
108			72	3	1.02	70.59	2.94	10	11
109			56	9	0.93	60.22	9.68	10	10

7 December 1995

At 1200 UTC, the MSLP analysis showed a ridge of high pressure lying over the Peninsula with a large area of low pressure moving in from the Bellinghausen Sea. During the day, an area of low cloud, probably orographic in nature, formed over the Avery Plateau.

Results

The ice crystal replicas present on the slides were mostly hexagonal plates although a few columns and the occasional triangular or square crystal were present. On 29 November the surface air temperature was -17.5°C while for the other two days the temperature was warmer being in the range -10.2 to -12.1°C. There did not seem to be a significant difference in the form of the crystals between the two temperature regimes.

Table I shows the number of crystals and droplets, uncorrected for collection efficiency, present on each slide considered in this study. Also in this table is the volume of air sampled, the number of droplets and crystals counted and the time the slides were exposed in the cloud. The main difference between the different days is the number of ice crystals compared with the number of supercooled water droplets. On 29 November when the temperature was lower there were practically no water droplets. On the other days when the temperature was higher the number of droplets per litre is much larger than the number of ice crystals. It was also found that the precipitation rate, as measured by the disdrometer, was higher on the warmer days.

29 November 1995

The slight snow started at around 1550 UTC when the disdrometer (Fig. 3a) was switched on. The mean size of the snow crystals remained around 0.6 mm for the rest of the day.

The cloud replicas for this day (see Table I) showed that the cloud was made up almost totally of ice particles in the form of hexagonal plates. The distribution of crystal sizes at 1559 UTC (Fig. 4a) shows a mono-modal distribution with a peak at around 50 μm. No distribution is given for the droplets in this case, as so few were present. The distributions in Fig. 4 have not been corrected for the collection efficiency. There was some ground drift at the time and a few irregular particles, thought to be drift particles, can be seen on the slides. Two slides (numbers 12 and 13 in Table I) were deliberately exposed, at approximately 5 cm from the ground, in the drift layer. These showed about 2.5 times the number of crystals per litre, far more being irregular, than the slides taken just before and just after and exposed well above the drift layer. The last three slides on this day (18, 19 and 20 in Table I) where exposed when the cloud was observed to become optically thicker for a short time and show a large number of crystals.

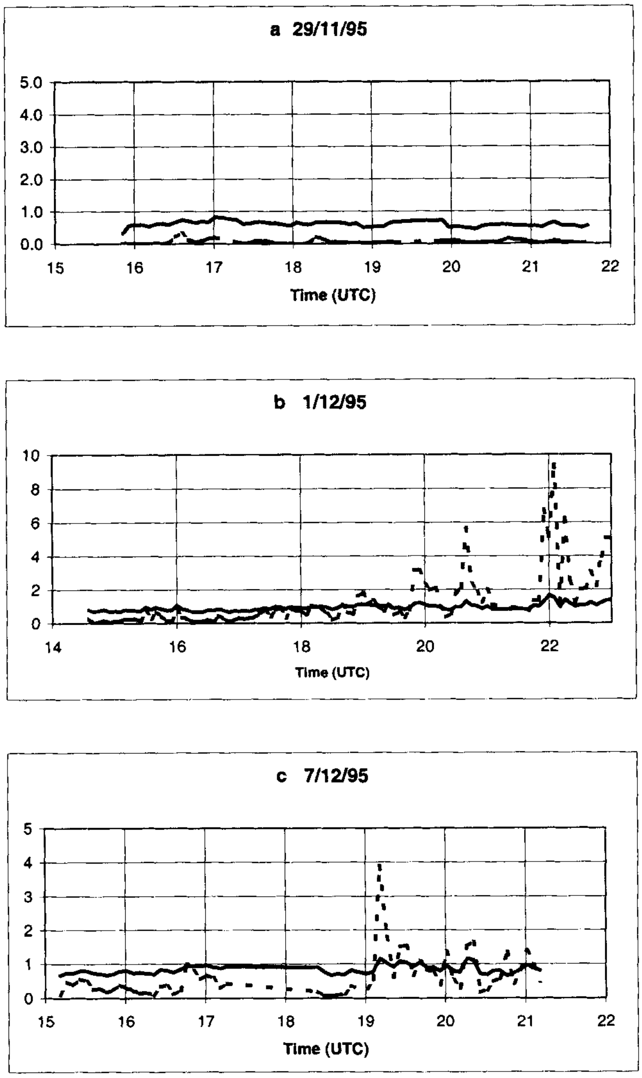

Fig. 3. Disdrometer records showing rate of snowfall in mm hr^{-1} (dashed line) and mean size in mm (solid line) of precipitation particles, **a.** for 29 November 1995, **b.** for 1 December 1995 and c. 7 December 1995.

1 December 1995

The precipitation started at around 1500 UTC and the disdrometer record (Fig. 3b) shows that it increased in amount throughout the rest of the day. Over the same period the mean size of the precipitation particles only increased very slightly being around 1mm for most of the time.

Most of the slides taken on this day show many more droplets present than ice crystals in contrast to the results of 29 November. The distribution of crystal and droplet sizes is shown in Fig. 4b & c. The main peak in the crystal distribution is around 40 μm, and is larger than that for the droplets at around 15 μm. Also in the crystal distribution there is some evidence for a bi-modal distribution with a second peak at around 100 μm. However, the small number of crystals present in this peak means that any conclusions must be tentative.

7 December 1995

On 7 December the snowfall started at around 1500 UTC. The disdrometer record (Fig. 3c) shows that at just after 1900 UTC the rate increased suddenly and became more variable although the mean size of the particles stayed unaltered. The meteorological records did not show any sudden changes at around 1900 UTC, however AVHRR imagery did show that a band of high cloud moved over the site at around this time.

On this occasion the number of droplets usually exceeded the number of crystals. This distribution of cloud particles is similar to that on 1 December (see Table I), though there is a marked drop in the number of crystals per litre between 1835

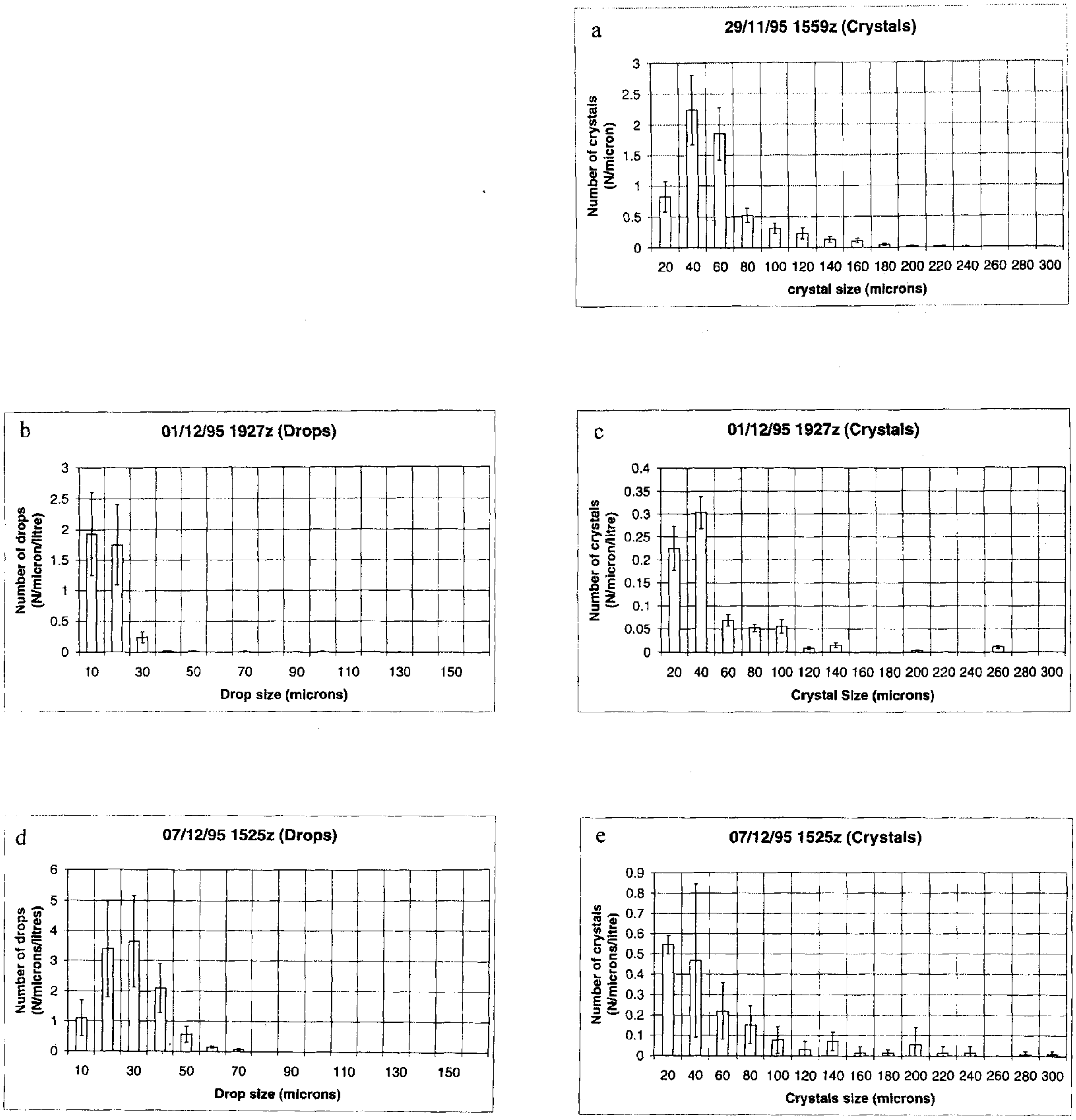

Fig. 4. Crystal and droplet size distributions. The standard deviation is plotted as the standard error and shown as error bars. The observations of droplets smaller than 10 μm and crystals smaller than 20 μm should be taken with caution as the theoretical collection efficiency of the slides is zero for these particles. **a.** Crystals at 1559UTC on 29 November 1995, **b.** droplets at 1927UTC on 1 December 1995, **c.** crystals at 1927UTC on 1 December 1995, **d.** droplets at 1525UTC on 7 December 1995, **e.** crystals at 1525UTC on 7 December 1995, **f.** droplets at 1530UTC on 7 December 1995, **g.** crystals at 1530UTC on 7 December 1995, **h.** droplets at 1835UTC on 7 December 1995, **i.** crystals at 1835UTC on 7 December 1995, **j.** droplets at 1922UTC on 7 December 1995, **k.** crystals at 1922UTC on 7 December 1995

UTC and 1922 UTC and at the same time the number of water droplets increased. The distribution of crystals sizes (Fig 4e, g, i, k) shows some evidence of a bi-modal distribution with a peak at around 50 μm and another at about 160–200 μm. After 1922 UTC the number of crystals counted on each slide was very small and so the complex shape of the distribution is probably due to the small number of particles counted rather than any real structure.

The distribution of the droplets (Fig. 4d, f, h, k) shows a simpler distribution with a single peak at around 20 μm.

The microphysics of the clouds observed

The clouds sampled can be divided into three groups by considering the droplet and ice particle distribution:

a) The data for 29 November showed a cloud completely

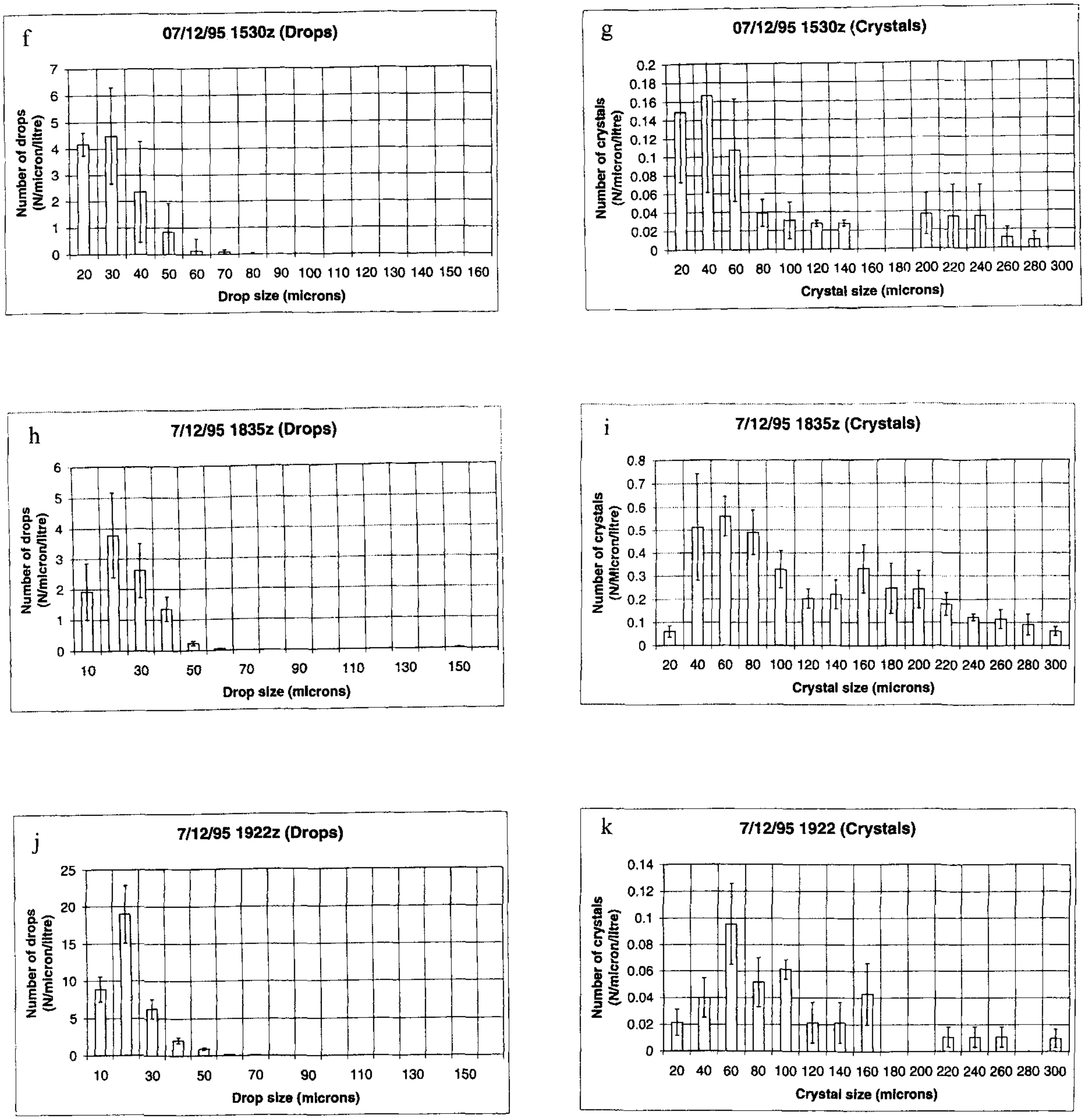

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Table II. Number of ice crystals predicted by Fletcher equation and observed on the Avery Plateau on 29 December 1995, 1 December 1995 and 7 December 1995.

Date	Time	Wind speed (ms^{-1})	Wind direction (degrees)	Temp (°C)	Predicted (number l^{-1})	Observed (mean n l^{-1})
29/11/95	1559	5.5	99	-17.5	0.363	120.0
01/12/95	1927	5.2	311	-11.9	0.013	7.5
07/12/95	1525	4.3	275	-10.2	0.005	34.3
07/12/95	1530	4.3	275	-10.2	0.005	14.2
07/12/95	1835	5.5	288	-12.1	0.014	78.2
07/12/95	1922	4.1	267	-11.4	0.009	5.7

dominated by crystals with virtually no droplets present. The precipitation was lowest from this cloud.

b) On 1 December and on 7 December before 1922 UTC both droplets and crystals are present at the same time, although drops were more common.

c) After 1922 UTC on 7 December the cloud is dominated by droplets with very few crystals being present.

For class a) the temperature was lowest (-17.5°C) and no super-cooled water droplets were present. This means that there was no available source of water vapour for the ice crystals to grow rapidly and so the crystals grow very slowly and few reached a size sufficient to fall as snow.

For class b) the temperatures were higher and the snowfall was heavier (although still in the form of individual snow crystals), probably because the water droplets supplied sufficient water vapour for the crystals to grow more rapidly.

For class c) when the number of droplets per litre was at its highest and the number of ice crystals was lowest the precipitation rate was heaviest, again in the form of individual snow crystals. This could be explained by the few ice crystals present growing rapidly with the water vapour provided by the abundant number of water droplets.

The apparent inverse correlation of the rate of snowfall with the number of cloud ice crystals and the correlation of the rate with the number of droplets is in accordance with the classical theory of precipitation formation (Bergeron 1935). The problem however is to understand why there are so many ice crystals present in most of the samples. Table II shows the number of ice nuclei per litre of air that should be present on the three days according to the equation derived by Fletcher (1962) for mid-latitudes. In all the cases we studied there appeared to be far more ice crystals present than the number of ice nuclei theoretically predicted and that would normally be present at mid-latitudes.

Discussion

Growth mechanism of cloud ice crystals.

There are a number of microphysical processes by which ice crystals may grow within a cloud. Equally, the cloud liquid water content may be depleted in a number of ways. Classically, the Bergeron-Findeisen (Bergeron 1935) process would cause water droplets to evaporate, providing a water vapour source for the growth of ice crystals by vapour deposition. Modelling studies (Davison *et al.* 1998) have shown the dominant processes active within the clouds is indeed the Bergeron-Findeisen process. In model runs that predict the same high numbers of ice crystals as the observations, the Bergeron-Findeisen process occurs at a rate about 20 times greater than the next most active process (the riming of snowflakes).

Source of ice crystals and ice nuclei

The number of ice crystals present in the clouds described here is larger than would normally be expected by simply considering the number of ice nuclei that could be expected in the airmass. Three possible sources of these crystals are considered. These are ice crystals from blowing snow acting as a seed for the growth of cloud particles, (either produced locally or transported from elsewhere), high altitude cloud seeding the low cloud with ice crystals, or the formation of secondary ice crystals via splintering (the Hallett-Mossop process (Hallett & Mossop 1974)) within the cloud or on the surface.

i) *Crystals picked up from the surface*: It is possible that the source of some crystals could be drift or blowing snow. On 29 November drifting snow (that is snow blown by the wind across the surface and close to the surface) was observed, although the slides were exposed well above the layer of drifting snow. The wind speed was 5.5 ms^{-1} which would not normally cause drift, however the surface layer was made up of very small loose snow particles and so some drift was observed. The crystals observed in slides on 29 November, exposed above the drift layer, were regular in shape and did not look like the irregular particles that were found within the drift layer (slides 12 and 13). No drift was observed on 1 and 7 December. It is concluded that the crystals observed are mostly cloud particles with very few being drift particles.

Although the particles are not thought to be drift or blowing snow particles directly it is possible that very small ice particles picked up from the surface, some distance up-wind from the observation site, may act as the seed to allow regular shaped cloud particles to grow. Although measurements of drift at tens of metres above the surface are rare it is thought that small numbers of small drift particle can reach heights in excess of 100m (Budd 1966, Takeuchi 1980) provided that there is locally sufficient upward momentum to keep the particles suspended. This may mean that small changes in the amount of blowing or drifting snow and its relationship with the cloud base could have large effects within the cloud some distance downwind. This may explain the sudden change in ice crystal number at a time when there was no noticeable change in local conditions.

ii) *Seeding from high altitude cloud:* Another possible source of ice crystals is a higher layer of cirrus feeding ice crystals into the lower layer. It is, however, noticeable that on 7 December the number of crystals present decreases from 1835 UTC to 1922 UTC when at the same time a band of high cirrus moves across the observational site, so this explanation seems unlikely.

iii) *Secondary ice crystal production:* Secondary ice crystal production within the cloud by the Hallett-Mossop process (Hallett & Mossop 1974) may be the source of the extra crystals. The Hallett-Mossop process relies on secondary ice crystals forming when cloud particles are rimed; the secondary crystals form as splinters of ice ejected as the water droplets freeze on contact with ice nuclei. This process only occurs between -3°C and -8°C being most efficient at -5°C. However, in the replicas very little evidence was seen of rimed particles, no ice splinters were seen, and the temperature of the cloud base, some distance below the observing site, is thought to be too low for the process to work efficiently. It is therefore unlikely that the Hallett-Mossop process is responsible for the extra ice crystals.

Another possibility is that some direct interaction with the surface, such as the ejection of ice splinters during riming, in a process similar to the Hallett-Mossop process observed in clouds, would produce larger numbers of ice crystals. Rogers & Vali (1987) consider a very similar case when they looked at ice crystal production over Elk Mountain, USA, and they came to the conclusion that although the extra ice crystals were generated near the surface the exact mechanism was not known.

Ice crystals taken up from the surface acting as the seed for further growth appears to be the only possible mechanism that can explain the high numbers of crystals found in the clouds measured. Careful modelling will be required to demonstrate the feasibility of this mechanism.

Conclusions

The sampling of cloud particles in this paper has been made near ground level in cloud that reached the surface and could be considered as hill fog. The clouds sampled contained larger numbers of ice particles than would be expected from a simple consideration of the number of ice nuclei normally found.

The source of the large numbers of ice crystals present is likely to very small (< 5 μm) blowing snow particles, picked up some distance away from the sample site, acting as the seed for further growth. Other possible sources of ice crystals such as seeding from higher cloud and splintering of frozen droplets have been rejected as unlikely.

The effect the number of ice crystals, and by inference the number of ice nuclei, has on the rate of precipitation may have to be considered carefully when using numerical models to study snowfall and accumulation rates in Antarctica. This effect will be particularly important within the coastal area where the accumulation is greatest. Most numerical models will fix the ratio of the number of ice crystals to water droplets according to the air temperature and will not allow large numbers of ice crystals to be present.

To understand the importance of the results reported here it will be necessary to sample clouds throughout their depth and also clouds that do not reach the surface. It is planned to use a kite-based replicator in the future to gain a better understanding of the vertical structure of Antarctic clouds. Work is also continuing into modelling the clouds observed in this study.

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