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METEOROLOGY OF THE GREAT DUN FELL CLOUD EXPERIMENT 1993

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Abstract—Synoptic and local meteorological conditions during the Spring 1993 Ground-based Cloud Experiment on Great Dun Fell are described, including cloud microphysics, general pollution levels and sources of air, especially for five case studies selected for detailed analysis. Periods when air was flowing across the hill are identified and the extent to which air mixed into the cloud from above reached the ground is estimated. To aid the interpretation of cloud chemistry and microphysics measurements, the horizontal and vertical extent of the cloud are used to estimate droplet lifetimes and to comment on the influence of complex terrain on peak supersaturation. © 1997 Elsevier Science Ltd.

Key word index: Meteorology, Great Dun Fell, cloud formation, orographic cloud, hill cap cloud, fog, air flow, advection, cloud droplet lifetime, aerosol nucleation scavenging, nitrogen dioxide.

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1. INTRODUCTION

The Ground-Based Cloud Experiment was performed on and around Great Dun Fell (GDF) in Spring 1993 to investigate the partitioning of aerosol material between cloud droplets and interstitial particles, the modification of the aerosol spectrum as air is processed by passage through cloud, the budget of ammonia and ammonium in the air, and the atmospheric chemistry of oxides of nitrogen and sulphur, metals and carbon (Choularton *et al.*, 1997). Before these objectives can be met, it is necessary to study the meteorology relevant to the experiment. In this paper, the results of such a study are presented all together, to avoid having to repeat them in other individual papers. Examples of similar studies carried out for previous experiments are Winkler *et al.* (1994), Wobrock *et al.* (1992), Hahn *et al.* (1992), and Shipham *et al.* (1992). A meteorological analysis of a field experiment can also help to identify ways in which conclusions may be drawn from the measurements and thus aid the design and planning of future experiments at the same site and at different sites.

Many field experiments utilise some special property of the field site to study processes in the atmosphere. An example of this is the sampling of boundary-layer air in up-slope winds and free tropospheric air in down-slope winds on Mauna Loa (Hahn *et al.*, 1992). At a similar site in the Alps but in very different meteorological conditions, Collett *et al.* (1993) describe the use of three sites on one steep slope on mount Rigi as like a 1500 m high tower from which to study the evolution of precipitation as it falls towards the ground. For the GDF field site, the special property, which was utilised in the 1993 experiment and previous experiments, is the two-dimensional shape of the Pennine Ridge in its vicinity. This enables the orographic cloud on the hill to be used as a flow-through reactor (Choularton *et al.*, 1986, 1996; Gay, 1986). The functioning of this reactor cloud will be demonstrated and discussed in this paper. This will be in the context of the synoptic meteorological situation, the horizontal and vertical extent of the cloud, and the flow of air over the hill during selected case studies during which intensive measurements were made. Also the droplet lifetime will be computed. The meteorological analysis includes some discussion of sources of pollution, both distant sources affecting all the sites where measurements were made and local sources affecting only one or more sites, although more details about distant sources may be found in Swietlicki *et al.* (1996).

2. SYNOPTIC METEOROLOGY

During the measurement period 22 April–13 May 1993, three types of weather may be identified: (1) Primarily 22–23 April but also partly applicable to 25 April, 2 and 10 May: Hill cap cloud in warm sector of depression or associated with frontal activity (Fig. 1). The GDF experiment is designed for these conditions with prevailing southwesterly winds, (2) 25–28 April, 5–13 May: Cool, moist air from the North Sea penetrating inland; sea fog or low cloud evaporating on lee side of Pennines or sometimes on hills further east. Cloud on GDF increased as the pressure gradient became steeper and the winds freshened (Fig. 2). This period ended when wind backing to northerly brought heavy snow on 13 May. (3) Clear, anticyclonic conditions on 29–30 April and 3–5 May.

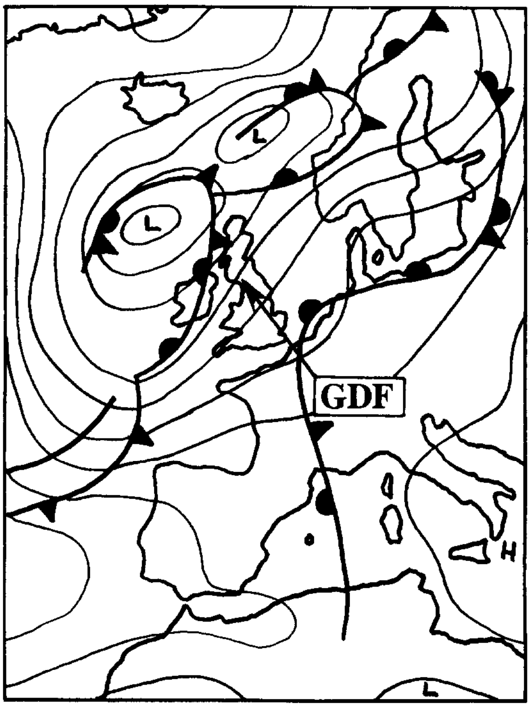

Fig. 1. Surface synoptic chart at 13:00 on 22 April 1993, showing GDF in the warm sector of a depression. Isobars are drawn every 4 mbar. Cold fronts are shown by triangles, warm fronts by semicircles and occluded fronts by semicircles and triangles together.

3. VALIDITY OF FLOW-THROUGH REACTOR CLOUD MODEL

In Choularton *et al.* (1997), the GDF Ground-Based Cloud Experiment design is described, which assumes that the hill cap cloud can be modelled in two dimensions. This enables air to be sampled before, during and after passage through cloud in a variety of wind directions at sites positioned across the Pennine Ridge but not necessarily in a straight line. The sites at which measurements were made in 1993 were Wharley Croft 206 m above sea level in the Eden Valley to the south of GDF, Fell Gate 430 m and Mine Road 670 m above sea level on the south-west slopes of GDF, GDF Summit 850 m above sea level, and Moor

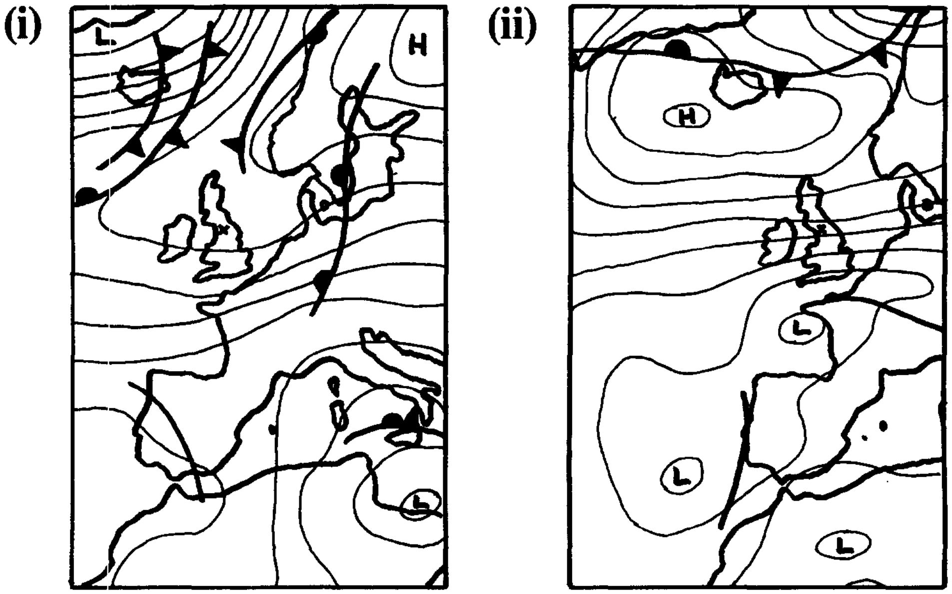

Fig. 2. Surface synoptic charts at 13:00 on (i) 6 May and (ii) 11 May 1993, showing how the northeasterly winds across Northern Britain freshened as the pressure gradient increased. Key is the same as for Fig. 1.

House 550 m above sea level in Teesdale to the east of GDF. For details of the locations of these sites and also of the instruments used to make the measurements shown here, see Choularton *et al.* (1997). Before using a comparison between measurements made at different points on the hill to draw conclusions concerning the cloud processing of gases and aerosol material, it is necessary to verify that the air sampled at Wharley Croft, Fell Gate, Mine Road, GDF Summit and Moor House was indeed the same and to remove from the data set any periods of time at one or more sites where this is not the case. If the atmosphere is stably stratified or there is a temperature inversion below the level of GDF Summit and the wind is light, cold air can stagnate in either valley. Under such blocked conditions, most comparisons between measurements made in the blocked valley and those made on the hill are meaningless.

Temperature differences between sites given by the wet adiabatic lapse rate, wind blowing across the valleys, and O_3, NO_2, conserved ionic species and numbers of particles the same at all sites are a signature of connected flow. The best example of a conserved ionic species is Na^+, although even ions such as SO_4^{2-} and NO_3^-, which have sources in the cloud, may be used on the many occasions when the amount produced in cloud is a small fraction of that entering the cloud (Chandler *et al.*, 1988; Colvile *et al.*, 1994; Laj *et al.*, 1997), especially in cases of Na^+ being unsuitable as a tracer due to being present only at low concentrations. Conversely, blocked flow may be identified by its signature in the valleys of low wind speed, low temperature, low O_3 caused by deposition to the ground (PORG, 1987), high NO_2 and high particle concentrations from local sources, when the valley measurements are compared with those on the hill. For example, Fig. 3 shows a transition from disconnected to connected then to blocked again in the Eden Valley on 29 April 1993. Figure 4 shows the disconnection of the flow of air from Teesdale to GDF during the night of 6–7 May 1993 with reconnection at dawn. Table 1 shows when the flow of air was disconnected between the Eden Valley, GDF and Teesdale. The periods have been identified using the above signatures, as listed in the table. Of the times listed, only three, marked by asterisks, occur during the periods listed in Section 4 which were selected for detailed study. Question marks denote insufficient observations made to determine connection of flow. At all times during the experiment other than those listed in Table 1, the same measurements as those used to detect disconnected flow show that the flow of air across GDF was connected between Moor House and Wharley Croft. During all the case studies, other than the short exceptions mentioned above, it is therefore possible to use the measurements made at the five sites across GDF to study the evolution of the air mass as it was processed by passage through the hill cap cloud.

4. CASE STUDIES

In order to maximise efficiency of use of resources, most measurements were made during discrete periods several hours in length when it was forecast that

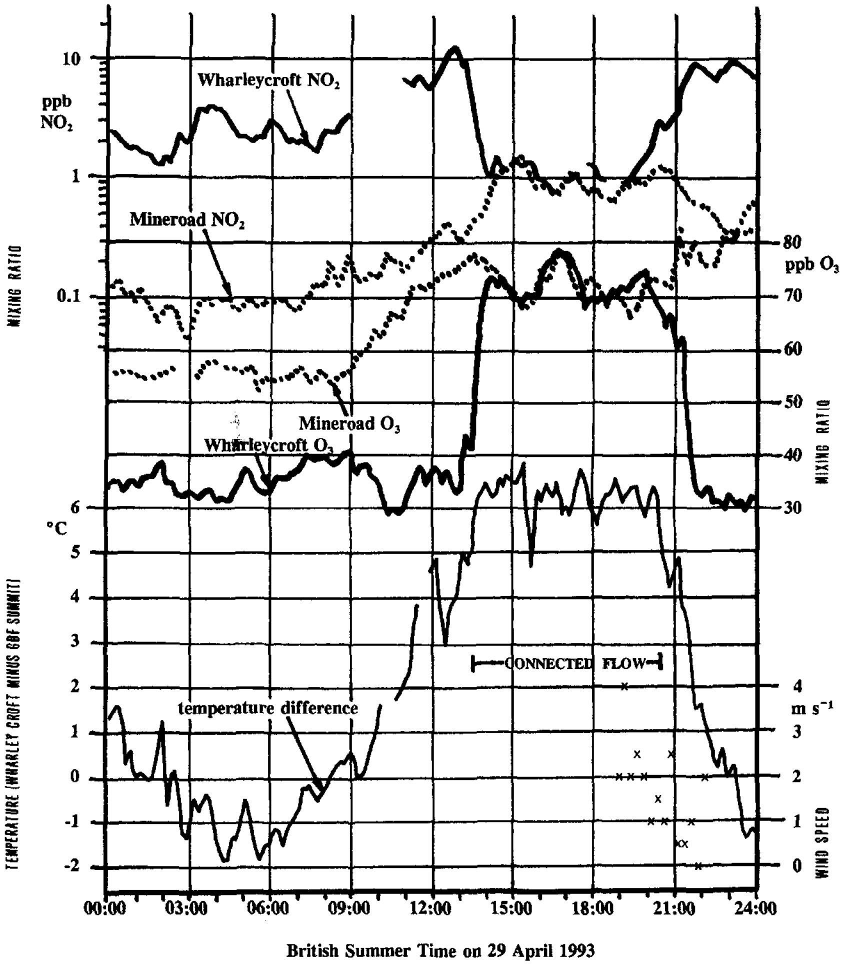

Fig. 3. Measurements of ozone and nitrogen dioxide at Wharley Croft and Mine Road, for comparison with the difference in temperature between Wharley Croft and GDF Summit, showing connection and disconnection of flow of air down off GDF into the Eden Valley on 29 April 1993. Spot measurements at Wharley Croft also show decreasing wind speed there as flow disconnected after sunset.

weather conditions would be suitable for the flow-through cloud experiment. During the first weeks of the experiment, cloud on GDF occurred infrequently and was not persistent. It was therefore possible to study each cloud event in a single case study. Conversely, during the final 84 h of the experiment, cloud was in contact with the ground on GDF for 80% of the time. To allow for instrument calibration and rest periods, this cloud event was divided for intensive study into three case studies separated by rest periods. Here, however, it is more convenient to describe the whole 84 h as a single event because the division into case studies does not correspond to meteorological changes which occurred during that period of time.

The periods studied are shown with traces of water vapour mixing ratio, temperature and cloud liquid water content at the summit of GDF in Fig. 5. For each case study, the presence of cloud will be described, along with a brief description of general levels of pollution typified by the NO_2 mixing ratio and, when a measurement is available, the number of cloud droplets (see also Choularton *et al.*, 1997). For selected case studies, these parameters will be related to the source of the air using calculations of 4-day isobaric back-trajectories from the Europa model of the German Weather Service, at surface pressure and at 850 mbar. Rain will be noted on the occasions when it fell.

4.1. *Evening of 22 April*

GDF Summit was already in cloud when intensive measurements started at 16:00 on 22 April. The liquid water content there increased from 400 mg m^{-3} to a maximum of 800 mg m^{-3} in the small hours of the morning. Cloud remained in contact with the ground after the intensive measurements had stopped around midnight. Back-trajectories come from the North Atlantic then turn left off the coast of southwest England to approach GDF from the southwest, showing how the air passed over the conurbations of northwest England. It therefore picked up levels of pollution which are moderate to high compared with typical

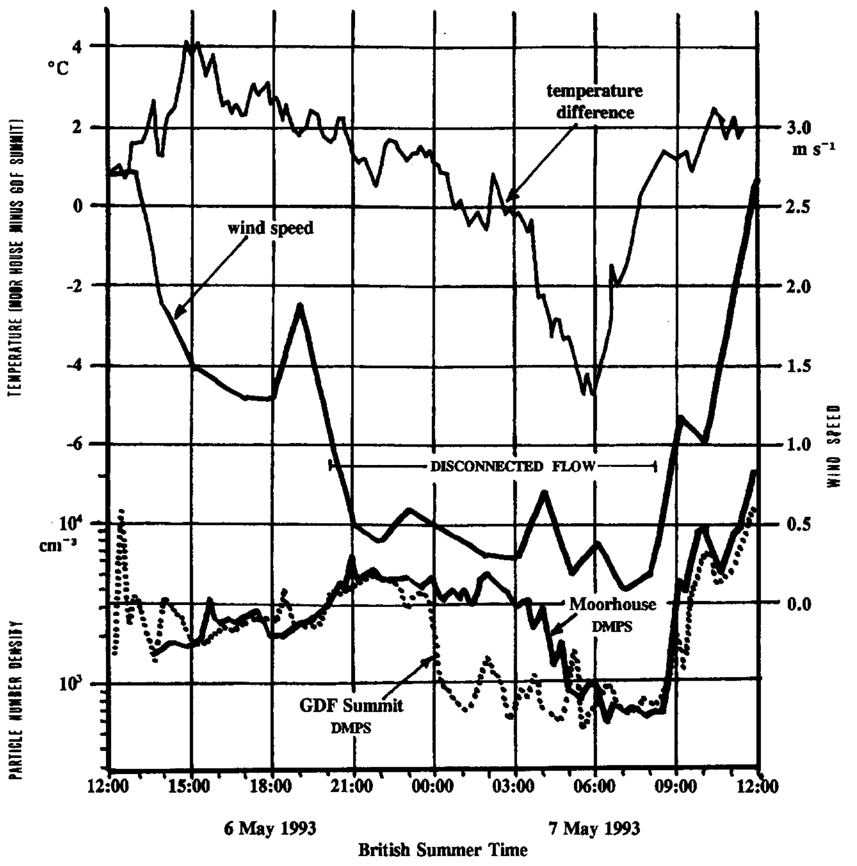

Fig. 4. Disconnected flow in Teesdale during the night of 6–7 May 1993, shown by measurements of wind speed at Moor House compared with differences in the number of particles measured by the DMPSs and in temperature at Moor House and GDF Summit.

levels in the North Pennines, with 5–10 ppb of NO_2 and 500–570 cloud droplets per cm^3. Most meteorological variables and measures of pollution levels remained similar throughout this case study, except for SO_2, non-marine Cl^- and cloud-water acidity, which increased markedly at 20:00 (Swietlicki *et al.*, 1997; Schell *et al.*, 1997). After 20:00, the SO_2 mixing ratio was higher than the NO_2 mixing ratio, which is quite unusual for this site (Choularton *et al.*, 1997). This is the only case study for which Wharley Croft was the upwind site and Moor House the downwind site. Some intermittent light drizzle was seen at GDF Summit and Moor House but was too fine to be measured by the automatic weather stations.

4.2. *Night of* 5–6 *May*

During the afternoon and evening of 5 May the temperature fell steadily while the total water mixing ratio was rising to reach its maximum value at about 18:00. This caused GDF to be enveloped in cloud from 15:30 onwards. Thereafter, fluctuations in both the temperature and the total water mixing ratio of the air approaching the hill from the east caused a series of cloud events, each several hours in length, separated by a few minutes in thin or absent cloud, until temperatures rose again in the late morning of 6 May. Cloud was observed in contact with the ground at Moor House and it was possible to forecast changes in liquid water content at GDF Summit a few minutes ahead by communicating when Moor House entered or left cloud. Liquid water contents up to $1\ g\,m^{-3}$ were observed at GDF Summit. Back-trajectories approach the British Isles from the North Atlantic, the low-level trajectories from near Iceland and the 850 mbar trajectories from further south. After crossing Scotland they then turn right over the North Sea to approach GDF from the east. During the early evening, the low path crosses Northern Ireland and the Central Lowlands of Scotland, where there are several sources of pollution. Later trajectories follow a more northerly path where industry and population are much more sparse. This change is reflected in the NO_2 mixing ratio, which fell steadily from 5 ppb at 16:00 on 5 May to less than 0.5 ppb by 24:00, then remained low during the morning of 6 May. The number of cloud droplets varied between 160 and $370\ cm^{-3}$, with a minimum at 19:00.

4.3. 9–12 *May*

During the period 8–12 May there was some correlation between the speed of the northeasterly wind and the total water mixing ratio. From 00:00 on

Table 1. Times when the flow of air between Wharley Croft, GDF and Moor House was disconnected. At times between those listed, the flow was connected.

Wind direction	Date	Wharley Croft		Moor House	
		Times	Signatures[a]	Times	Signatures[a]
Variable	24–25 April	21:00–07:00	O_3, T, NO_2	23:00–05:00	ff
NE	26 April*	02:00–16:00	O_3, T, NO_2	?	none
Variable	26–27 April	20:00–12:00	O_3, T, NO_2	02:00–10:00	ff, T
NE	27 April*	17:30–21:00	O_3, NO_2	?	none
NE	27–28 April*	23:30–09:00	O_3, NO_2	?	none
NE	28–29 April	19:00–13:30	O_3, T, NO_2	22:00–07:30	T, ff
NE	29–30 April	20:30–14:00	O_3, T, NO_2, ff	19:30–10:00	T, ff
SW	30 April to 1 May	17:00–10:00	O_3, NO_2	18:00–04:00	T, ff
W	2–3 May*	21:00–10:00	O_3, T, ff	24:00–09:00	ff, T
W	3–4 May	22:00–11:00	O_3, T, ff	24:00–08:00	ff, T
N	4–5 May	20:30–11:00	O_3, T	20:00–09:00	T, ff
NE	6 May	03:30–08:30	O_3, T	04:00–05:30	ff
NE	6–7 May	23:00–09:00	O_3, T	20:00–08:00	T, ff, p
E	8 May	00:00–09:00	T, O_3	19:00–09:00	ff, T
E	12 May	18:00–	O_3, T	19:00–	T, ff

[a] T = temperature difference, ff = wind speed, p = particles > 6 nm diameter.

Table 2. Periods (shaded) when cloud was present at different sites on GDF

Date	British Summer Time		Fell Gate 550 m	Mine Road 670 m	GDF Summit 850 m	Moor House 550 m
	From	To				
23 April		09:00		▨	▨	
23–24 April	09:00	09:00			▨	
25 April	05:50	08:30		▨	▨	
25 April	08:30	12:30			▨	
25 April	12:30	16:00		▨	▨	
25–26 April	16:00	06:00		▨	▨	▨
26 April	06:00	10:00		▨	▨	
27 April	18:00	20:00		▨	▨	
27 April	20:00	23:00		▨	▨	▨
27–28 April	23:00	07:00		▨	▨	
28 April	07:00	10:15		▨	▨	▨
28 April	10:15	12:15			▨	
2 May	02:00	23:30	▨		▨	
5 May	15:00	18:00		▨	▨	
5 May	18:00	20:30		▨	▨	▨
5 May	20:30	23:30			▨	
5–6 May	23:30	01:15		▨	▨	
6 May	01:15	02:30		▨	▨	▨
6 May	02:30	05:20		▨	▨	
6 May	05:20	09:30		▨	▨	▨
6 May	09:30	11:00			▨	
8–9 May	23:00	11:00		▨	▨	
9 May	18:30	21:00		▨	▨	
9–10 May	21:00	12:00		▨	▨	▨
10 May	12:00	14:00		▨	▨	
10 May	14:00	23:30		▨	▨	▨
10–11 May	23:30	01:00		▨	▨	
11 May	01:00	04:00		▨	▨	▨
11 May	04:00	09:00			▨	
11 May	18:30	21:30			▨	
11 May	21:30	23:30			▨	▨
11–12 May	23:30	01:00		▨	▨	▨
12 May	01:00	02:40			▨	
12 May	02:40	05:00		▨	▨	
12 May	05:00	10:00			▨	

8 May to 14:00 on 10 May the wind speed and total water mixing ratio both increased steadily, from $5\,\mathrm{m\,s^{-1}}$ and $4\,\mathrm{g\,kg^{-1}}$ to $20\,\mathrm{m\,s^{-1}}$ and $7\,\mathrm{g\,kg^{-1}}$ at GDF Summit. This caused cloud to be present on the hill from 23:00 on 8 May to 12:00 on 12 May, interrupted only by temporary increases in temperature from 12:00 to 18:00 on 9 and 11 May. Cloud liquid water contents up to $900\,\mathrm{mg\,m^{-3}}$ were observed at

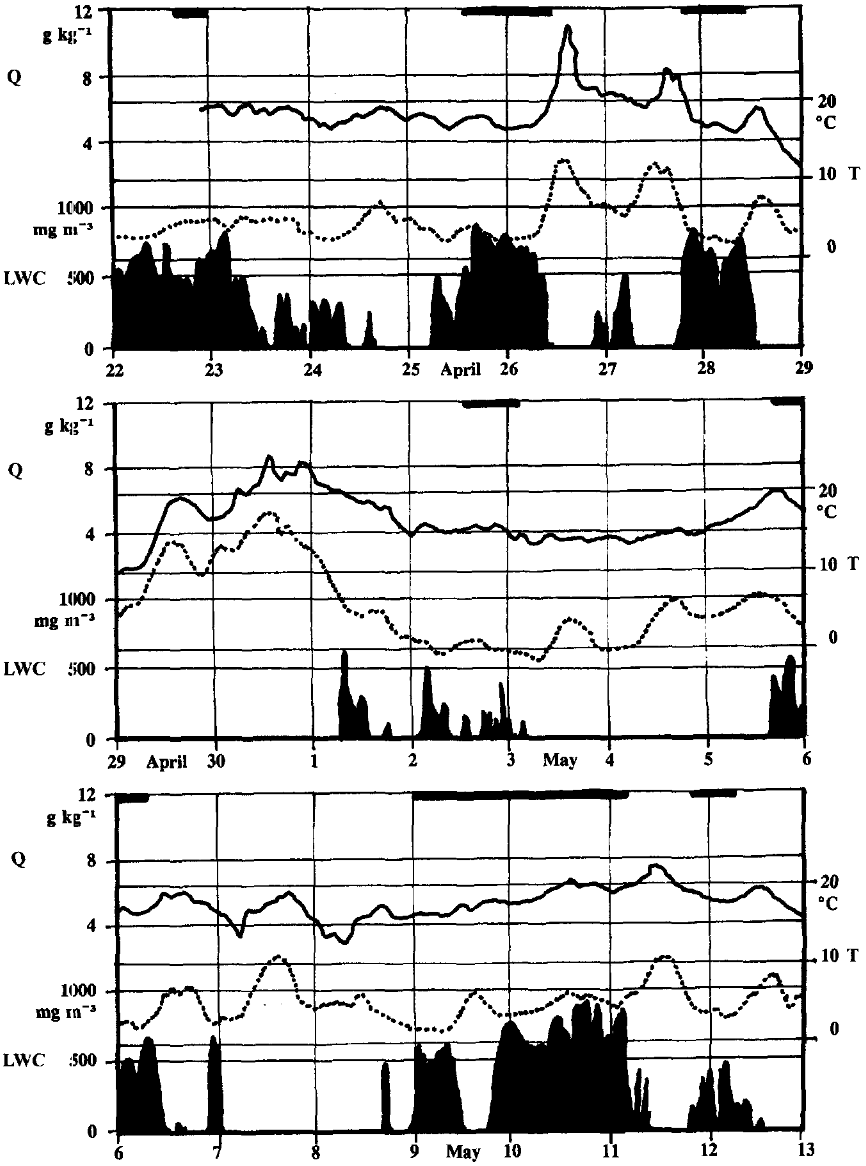

Fig. 5. Water vapour mixing ratio, Q (——), temperature, T (·········) and cloud liquid water content, LWC (solid black) at GDF Summit during the whole of the Ground-based Cloud Experiment 1993. Periods of intensive measurement are shown by a solid line along the top of the panels. The date numbers are at 00:00 British Summer Time at the beginning of each day.

GDF Summit. The wind speed, direction and atmospheric temperature profile were such that there was also a helm bar cloud (Manley, 1945; Stromberg *et al.*, 1989) to leeward of GDF during the evening of 9 May. Cloud was often observed in contact with the ground at Moor House, yet there were several cloud-free periods with a clear starry sky at Mine Road.

During the morning of 9 May, the back-trajectories follow a path which is entirely over the sea, starting over the Bay of Biscay, then circling the British Isles in a clockwise direction before coming on-shore from the North Sea to the east of GDF. Under these conditions, the air was at its cleanest for this case study, with only a fraction of a ppb of NO_2. Thereafter, the back-trajectories show a change in the source of the air. The surface trajectories come from the west coast of Sweden while the 850 mbar trajectories come across Denmark from eastern Europe. It is not certain what the implications of this for the GDF cap cloud might be, but it is possible that the surface trajectory shows the source of the air flowing into the base of the cloud upwind of GDF while the 850 mbar trajectory may show the source of any air which is mixed into the top of the cloud. If this was the case, eastern European air mixed into the top of the cloud should have been considerably more polluted than the Swedish air in the body of the cloud. It is true that on the evening of 10 May, when there is the most evidence of mixing of air from above (Section 6), the levels of pollution in the air arriving at GDF reached their highest values for this case study, with up to 6 ppb of NO_2. This is despite only very small changes in the wind directions on the hill and in the paths of the back-trajectories.

The number of cloud droplets reached nearly 700 cm^{-3} on the evening of 9 May, then decreased to a steady 550 to 600 cm^{-3}. On 10–11 May, the number of cloud droplets was between 400 and 500 cm^{-3}, and on 11–12 May it varied between 300 and 600 cm^{-3}. No rain fell, except for a few hours before dawn on 10 May and some drizzle at Moor House on the evening of 10 May.

4.4. *Other periods studied*

During the night of 25–26 and 27–28 April incomplete measurements were made, in the former case because rain was falling during the evening and in the latter case because cloud was not forecast. The rain stopped soon after sunset on 25 April, leaving the cloud liquid water content of 700 $mg\,m^{-3}$ which decreased gradually with the humidity of the air until noon the following day, with roughly constant temperature and winds as strong as 20 $m\,s^{-1}$ down the lee slope of GDF. On 27 April, the cloud formed when a change in wind direction brought a drop in total water mixing ratio but also a drop in temperature, again with strong down-slope winds. On both these nights, NO_2 mixing ratios were around 1 ppb.

During the evening of 2 May, a full set of measurements was attempted, but was discontinued when several layers of cloud were observed as the variable wind blew around the hill instead of over it.

5. CLOUD TYPE

Figure 6 shows a typical cloud field computed by the Clark model (Wobrock *et al.*, 1997) in easterly winds at Great Dun Fell. The asymmetric shape of GDF can be seen clearly, with the more gentle slope on the upwind side. This causes the horizontal position of the upwind cloud-base to be sensitive to its height above sea level, and also gives a transit distance of several kilometres in cloud to GDF Summit. In the following sections, field measurements are used with the model results to confirm best estimates of the vertical and horizontal extent of the cloud.

5.1. *Vertical extent of cloud*

In clouds where the effects of entrainment are negligible near the ground, the height of the base of the cloud may be estimated simply using the 2 $mg\,m^{-3}$ per metre of height increase in liquid water content which is expected during adiabatic changes in the temperature of air parcels flowing over the hill. For the purposes of interpreting measurements made using the GDF flow-through reactor cloud it is necessary to identify periods when either of the valley sites were in cloud. To this end, variations in estimated cloud-base height may be compared with times when the measurements made at those sites show evidence of the presence of cloud, even though liquid water

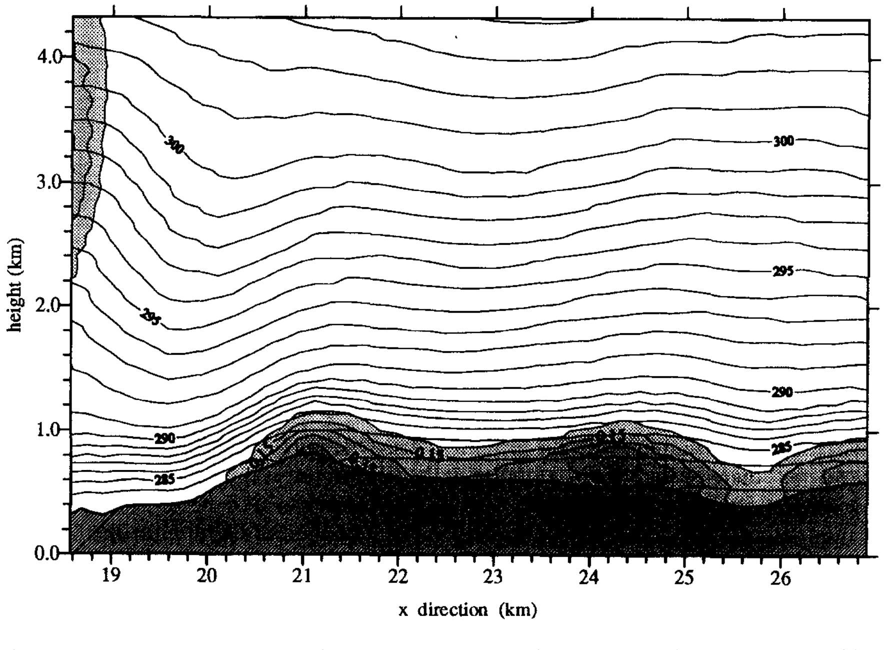

Fig. 6. Vertical cross-section through GDF along the mean wind direction, showing cloud liquid water content ($g\,m^{-3}$, shading) and potential temperature (K) computed by the Clark model for the night of 5–6 May.

content itself was not measured at these sites. These measurements include number of aerosol particles with dry diameter greater than 0.3 μm that grow to wet sizes too large to be sampled, measurements of relative humidity, or simple observations of the attenuation of car headlights. These different indicators all coincide well with times when the liquid water content measured on the hill predict low cloud bases, with the exception of number of large particles which indicates the presence of some cloud but not all. The times when cloud was in contact with the ground are shown in Table 2. The times are accurate to the nearest 30 min, changes more frequent than this being ignored. There may have been some times outside of those tabulated when cloud was present in Teesdale but no measurements were made at Moorhouse and entrainment might have caused a lower liquid water content on the hill than would otherwise be expected with such a low cloud base.

On certain occasions, it was possible to observe from the ground that the layer of cloud on GDF was only tens of metres deep above the observation site. During the early evening of 5 May, the sun could be seen from GDF Summit, shining into the top of the cloud. After sunset, it is usually very dark inside the cap cloud, but later on 5 May the interior of the cloud on GDF assumed the beautiful silvery quality of moonlight. During the nights 8–12 May, the sonde measurements at Boulmer, on the East Coast about 90 km away from GDF, just manage to resolve an inversion only tens of metres above the ground upwind of GDF. This is consistent with the fact that stars were seen above while cloud was blowing by on the ground at Moor House during the evenings of 10 and 11 May, as the top of the cloud was delineated by the low inversion.

The Flowstar airflow model (Wobrock *et al.*, 1997) and the Boulmer radiosonde measurements of atmospheric stratification and humidity may be used to make more general estimates of the height of the top of the hill cap cloud. For the night of 5–6 May, Flowstar calculates that only air within about 500 m of the ground was lifted from Teesdale to rise over GDF; air approaching the hill at greater altitude passed horizontally over the ridge or even was deflected downwards. This is consistent with the observations that the top of the cloud was close to GDF Summit. For other case studies, Flowstar calculates that a much deeper layer of air was lifted over the ridge, and only at heights greater than 1 or 2 km were streamlines deflected downwards. Therefore, it is possible for a much deeper cloud to form on these days than on 5–6 May.

The Clark Model on 5–6 May, however (see Fig. 6), predicts cloud extending several hundred metres above GDF Summit. It is possible that the depth of the cloud varied on Great Dun Fell, as did the liquid water content, such that observations (for example of moonlight) were made during periods while the top of the cloud was lower than during the period represented by the Clark Model. An alternative explanation for the discrepancy is that the amount of moisture in the Boulmer sounding, which is what determines where cloud will be predicted by the model, was locally perturbed by coastal effects.

It may be concluded that the height of the top of the cloud above the ground ranged from tens of metres to several hundred metres. The top of the cloud was low on the nights of 5–6 May and 8–12 May, but higher during the day from 8 to 12 May and much higher on 22 April. For the other case studies, there are insufficient observations to comment on the height of the top of the cloud. The low cloud-top on 5–6 May was caused by downward deflection of streamlines at moderate altitude, while that on 8–12 May was caused by a low inversion. These periods when the top of the cloud was close to the ground are of interest because of the possibility that entrainment of dry air into the top of the cloud affected the cloud studied near the ground (Section 6). When the top of the cloud is several hundred metres up, entrainment can still occur in the upper parts of the cloud, but may be ignored for the purposes of a ground-based experiment. The height of the base of the cloud varied from close to the top of GDF down to below the level of the floor of the windward valley.

5.2. *Horizontal extent of cloud*

The orographic cloud on GDF may be an isolated cap cloud or part of a more extensive cloud layer. When the base of the cloud is above the floor of Teesdale, whether or not the cloud is isolated has little bearing on the interpretation of the flow-through reactor cloud experiment (Choularton *et al.*, 1997). However, when the cloud is in contact with the floor of Teesdale, the horizontal extent of the cloud influences the droplet lifetime, so must be considered.

The satellite photographs taken at 15:09 and 16:50 on 22 April, 16:13 on 25 April and 16:32 on 10 May show an extensive sheet of low cloud of which the GDF cap cloud was probably a part. These three clouds are all associated in some way with frontal activity (Section 2). On 22 April, the base of the cloud was above the floor of the valleys on both sides of GDF, so the part of the cloud in contact with the ground on GDF had much of the character of an isolated hill cap cloud. For a number of hours on 25 April and 10 May, the base of the cloud was in contact with the floor of Teesdale and the cloud continued out for hundreds of kilometres to windward over the North Sea, so this cloud might show some features which are quite unlike an isolated hill cap cloud.

On the many occasions when a layer of low cloud extended from the North Sea as far as GDF, the satellite images show cloud the eastwards horizontal extent of which varied from tens to hundreds of kilometres. During these times, the satellite evidence that the Pennine ridge marked the limit of western extent of the cloud and fog is confirmed by observations of clear skies above Wharley Croft.

The satellite images show isolated cap clouds during the final few hours of some of the cloud events, as cloud from the North Sea during the night became patchy and restricted to high ground before burning off completely with increasing solar heating (see Fig. 5). Examples of this are 09:00 on 26 April, 6 May and 11 May.

The location of the point where air enters the cloud can have a profound influence on the nucleation scavenging of aerosol particles. When the base of the cloud is on the slopes of the hill, it is the orographic updraught which produces the supersaturation required for the aerosols to grow. The most extreme case of this was on 22 April, when the base of the cloud was close to the steepest part of the south-west slopes of GDF. With a hill slope there close to 1:1 and a horizontal wind speed of 5 m s^{-1}, the updraught could have been as high as 5 m s^{-1}, leading to very efficient nucleation scavenging. At the other extreme, when North Sea fog or low cloud was advected to GDF, the supersaturation had been developed by cooling of air flowing over cold sea water not adiabatic cooling in an orographic updraught, so the nucleation scavenging might have been a lot less efficient. However, if the initial scavenging is very inefficient, further droplet activation may occur when the already cloudy air is forced to rise up the eastern slope of GDF, especially when the wind is strong. This is discussed further in Bower *et al.* (1997). Figure 7 shows the points where air sampled at GDF Summit and Mine Road entered the cloud on the occasions when the base of the cloud was above the floor of the upwind valley, assuming an adiabatic liquid water content profile from the base of the cloud to the measurement at GDF Summit. The width of each ellipse along its minor axis is therefore estimated from the variability in wind direction during each period indicated plus the width of the cone of air which undergoes turbulent mixing to reach the observation points on the hill; the length of the major axis of each ellipse is estimated from the variability in the liquid water content during each period indicated. Shorter intervals within each case study have been distinguished from each other according to whether the liquid water content was close to the maximum for that period ("high LWC") or significantly lower ("low LWC"); the time history of liquid water content for a typical cloud event makes it possible to distinguish clearly between these two situations.

5.3. *Droplet age*

The droplet age is important in a study of the chemical evolution of the cloudwater, for example in Sedlak *et al.* (1997) and Laj *et al.* (1997). Estimates of the amount of time parcels of air have spent in cloud before reaching GDF Summit are therefore shown in Table 3. For times when the base of the cloud was above the floor of Teesdale (see Section 5.1), this may be calculated simply using the Flowstar or Clark airflow models (Wobrock *et al.*, 1997; Bower *et al.*, 1997). When the base of the cloud was in contact with the floor of Teesdale in an easterly wind, it is necessary to use the satellite images of the horizontal extent of the cloud, with measurements of the wind speed. Some consideration of droplet loss mechanisms in such fog could reduce the average droplet lifetimes somewhat from the cloud parcel lifetime, and some droplets may be freshly formed on the slopes of GDF (Bower *et al.*, 1997). Conversely, when cloud above the floor of both valleys is part of an extensive cloud sheet, a minority of droplets arriving at GDF Summit can have lifetimes longer than the transit time from the base of the cloud, because of

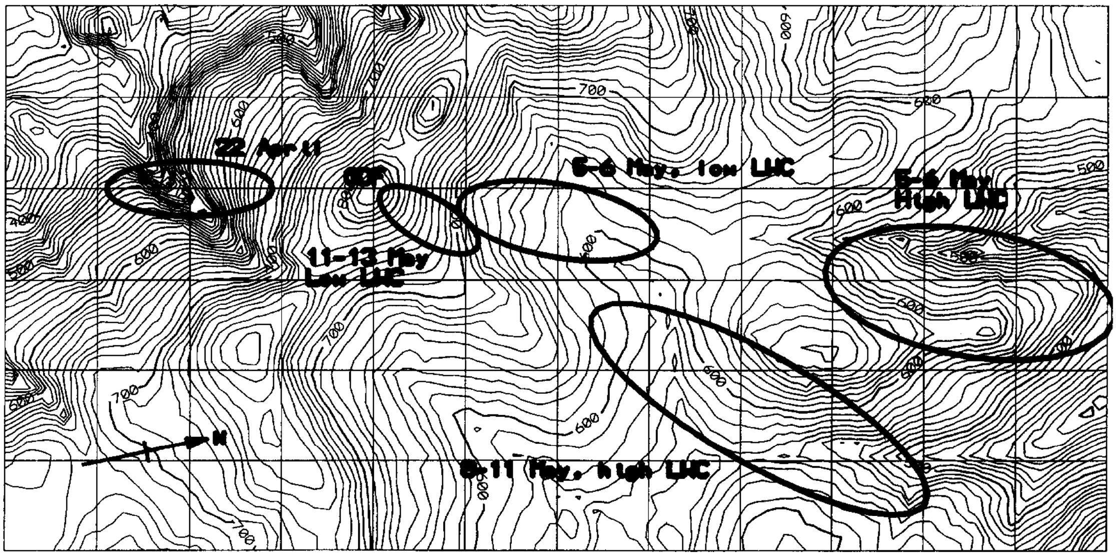

Fig. 7. Map of GDF, showing the approximate locations of the areas where air entered the cloud en route to being sampled at GDF Summit and Mine Road.

Table 3. Droplet ages. Ages calculated are transit times between air entering the base of the cloud to windward of GDF and the same air being sampled at GDF Summit, taking into account variation of wind speed and height of base of cloud. The data shown here are intended to illustrate the range and variations of droplet lifetime: for detailed temporal variations, it is necessary to look at short-term changes in cloud liquid water content at GDF Summit

Date in 1993	British Summer Time	Droplet age (minutes) at GDF Summit	
		GDF cap cloud	Previous cloud
22 April	18:00	1–2	0
23 April	03:00	4–6	0
25–26 April	18:00–12:00	10–15	100–200
28 April	21:00	20–30	30–60
29 April	04:00	10–20	30–60
5 May	16:00	10–20	100–400
5 May	21:00	20–30	100–400
5 May	22:00	2–5	100–400
6 May	03:00	20–30	100–400
9 May	02:00	18–25	100–200
9 May	10:00	10–15	60–180
9 May	21:00	18–25	100–200
10 May	01:00	10–15	60–180
10 May	12:00	10–15	100–200
11 May	00:00	18–25	180–300
11 May	22:00	5–10	200–300
12 May	02:00	15–30	200–300

mixing from the extended cloud into the region of orographic uplift. In easterly winds, all the air passed over the hills 10 km upwind, which are only about 200 m less high than GDF, so orographic cloud on these hills needs to be considered whenever its base is low enough. In westerly winds, however, the nearest high ground to windward is the Lake District, some 30 km away, and it is difficult to predict how much of the air reaching GDF passes through cloud there instead of approaching up the Lune Valley to the south, from the Solway Firth to the north or passing over the top of any cloud.

6. ENTRAINMENT

Even when the air is flowing across the hill (Section 3), it is common for some air from above the cloud to be mixed into the top of the cloud (Baker *et al.*, 1984; Gallagher *et al.*, 1991). Often, the influence of this mixing is restricted to the upper reaches of the cloud. When the entrained air is mixed down to the ground, however, it is necessary to take this into account in the interpretation of ground-based measurements. Six indications may be used to identify times when this was happening: (1) Differences in trace-gas mixing ratios between sites: Ozone has been used because it is consumed slowly in cloud compared to the inter-site transit time. Entrainment of ozone-rich air from above the cloud can therefore be identified as an increase in ozone mixing ratio from one site to the next. (2) Differences in number of small aerosol particles: The production or loss of such particles in cloud, with sizes too small to be nucleation scavenged, is discussed by Wiedensohler *et al.* (1997). In the absence of such production or loss, changes in number of particles may indicate entrainment. (3) Ions: When entrainment is not reaching the ground, dilution of ions in cloud water occurs from one site to the next according to the adiabatic change in liquid water content. When entrainment causes droplets to evaporate in the cloud to sizes smaller than the cut-off of the cloud-water collectors, this is seen as a drop in ion loading at the downwind site. This is accompanied by an increase in the amount of ionic material found in the interstitial aerosol. (4) Liquid water content: Evaporation of water caused by entrainment of dry or warm air may be detected by comparing liquid water contents made at the two sites in cloud. Owing to the observed drift in instrument calibration during the campaign, only differences in excess of 20% from the adiabatic profile can be taken as indicative of entrainment. (5) Number of droplets: In an adiabatic cloud, the number density of droplets is conserved. When entrainment occurs, the number of droplets may decrease due to droplet evaporation or increase due to activation of additional condensation nuclei. Comparison between cloud droplet measurements at the two sites therefore provides an indication of entrainment after the data have been carefully inter-compared and corrected for instrumental sizing and counting differences. (6) Droplet size spectrum: Adiabatic droplet growth produces narrow, monomodal droplet size spectra. In entraining clouds, bimodal spectra are often observed. These are often highly variable.

All these indications are summarised in Table 4. This shows that entrainment influenced the ground-based measurements during the early hours of 9 May and during the night of 10–11 May. On the evening of 5 May, all the measurements indicate that the flow of air over the hill near the ground was not only connected but also adiabatic without mixing, despite the observed proximity to the top of the cloud (Section 5.1). During all the other cases, the measurements provide no consistent evidence of entrainment, although the fact that individual measurements are consistent with the presence of entrainment implies that some entrainment may have been occurring but that its influence near the ground was very slight.

7. SUMMARY

From the Ground-based Cloud Experiment performed on and around Great Dun Fell (GDF) over four weeks in Spring 1993, five periods have been selected for detailed study. It can be shown that, during all of these periods except for 2 May and parts of 25–28 April, the same air was sampled in the valleys upwind and downwind of GDF and at three sites

Table 4. Indications for entrainment during the five case studies

Day time	22 April 20–22:00	5 May 19–21:00	6 May 00–10:00	9 May 01–05:00	9 May 19–24:00	10 May 00–12:00	10 May 12–24:00	11 May 00–04:00
Ozone	Peaks in some LWC dips	Same at all sites	Greater at Mine Road than at Summit	Measurement not available	Greater at Mine Road than at Summit	Greater at Mine Road than at Summit, higher in LWC dips	Greater at Mine Road than at Summit, higher in LWC dips	Greater at Mine Road than at Summit
Small particles	Not measured	Same at all sites	Same at all sites	Greater at Moor House than elsewhere	Same at all sites	Same at all sites	Highest at Moor House	Increasing from windward to leeward
Ions	Not available	Conserved until 21:00	No indication of entrainment	Not available	No indication of entrainment	Much NaCl in small droplet fraction	Aqueous sulphate greater at Mine Road than Summit; interstitial sulphate	Not available
Liquid water	Summit 18% lower than adiabatic	Mine Road 13–15% lower than adiabatic	Mine Road 13–15% lower than adiabatic	Mine Road 18–20% lower than adiabatic	Mine Road 17–19% lower than adiabatic	Mine Road 17–19% lower than adiabatic	Mine Road up to 33% lower than adiabatic	Mine Road up to 33% lower than adiabatic
Droplet number	Summit and Mine Road approximately equal	Summit and Mine Road equal	Mine Road greater than Summit	Not available	Mine Road greater than Summit	Mine Road and Summit approximately equal	Mine Road significantly greater than Summit	Mine Road and Summit approximately equal
Droplet spectrum	Close to adiabatic	Adiabatic	Small second mode	Not available	Small second mode	Second mode	Clear bimodal distribution	Strong variations
Indications	Slight	None	Slight	Strong	Slight	Slight	Strongest	Strongest

on the hill, enabling the processing of aerosols and gases by their passage through the hill cap cloud to be studied. The experiment was designed for westerly winds, but also works in the easterly winds which blew during all of these periods except the evening of 22 April. Maximum cloud liquid water contents for individual cloud events were typically 500–1000 mg m^{-3} at GDF Summit. Pollution levels were lowest (fraction of a ppb of NO_2, 100 cloud droplets per cm^3) during 25–26 April and 5–6 May, variable during 9–11 May and highest on 22 April (10 ppb of NO_2, more than 400 cloud droplets per cm^3). Entrainment of air into the top of the cloud influenced the measurements made at the ground only very slightly, except during the early hours of 9 May and during the night of 10–11 May when its effects were clearly observed, and the evening of 5 May when no evidence for any entrainment was found. The length of streamline along which parcels of air travelling close to the ground remained in cloud varied from about 100 m during periods of low liquid water content to tens of kilometres, leading to cloud droplet lifetimes ranging from a few minutes on 22 April possibly to hours during some of the May case studies. This varied meteorology also caused the microphysics of the orographic cloud to vary by determining the locations on the hillside where droplet activation was occurring and hence the supersaturation history of the air parcels.

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