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VISIBILITY WITHIN AND ELECTROMAGNETIC TRANSMISSION THROUGH NATURAL CLOUDS AND FOGS

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January 1979

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A substantial amount of field data obtained in recent cloud and fog experiments conducted at Great Dun Fell (GDF) is currently under analysis, and will be reported subsequently. In this report we concentrate on two activities falling within the scope of grant AFOSR-78-3511A. The first is an analysis of the meteorology and water characteristics of some clouds and fogs enveloping the GDF laboratory, which were examined by the UMIST group, in collaboration with scientist from the Meteorological Office. The second is the development of a theoretical model of droplet evolution in fogs and clouds under the influence of

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INTRODUCTION

A substantial amount of field data obtained in recent cloud and fog experiments conducted at Great Dun Fell (GDF) is currently under analysis, and will be reported subsequently. In this report we concentrate on two activities falling within the scope of grant AFOSR-78-3511A. The first is an analysis of the meteorology and water characteristics of some clouds and fogs enveloping the GDF laboratory, which were examined by the UMIST group, in collaboration with scientists from the Meteorological Office. The second is the development of a theoretical model of droplet evolution in fogs and clouds under the influence of inhomogeneous turbulent mixing with undersaturated environmental air. This theoretical work has been performed in conjunction with Dr M B Baker of the University of Washington, Seattle. Some complementary laboratory investigations currently being performed at UMIST will be reported at a later date.

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PRELIMINARY ANALYSIS OF DATA OBTAINED IN FIELD STUDIES AT GREAT FELL DURING THE PERIOD 12 to 16 DECEMBER 1977

In this brief report we present preliminary findings emerging from analysis of meteorological and microphysical data obtained in experiments made at Great Dun Fell (GDF) in December 1977. These were performed in collaboration with scientists from the Meteorological Office (MO), but the comprehensive droplet measurements made by the MO group are not discussed herein, owing to shortage of time. The primary objective in this first round of analysis is to examine the changing relationships between the meteorology and the droplet size spectrum over continuous extensive periods (1630 to 1700 hrs on 12/12, 1930hrs on 15/12 to 0021 on 16/12 and 1000 to 1115 hrs on 16/12). A particular goal had been to establish whether, in some circumstances, there is evidence for the influence, on the spectrum, of mixing-in of environmental undersaturated air - and if so, to see whether these effects are 'classical', based on a description of mixing as a homogeneous process, or whether they conform better with the model of inhomogeneous mixing which has been developed under Grant GR3/3007. An outline of this new model has been presented to the AAPS committee in the note by Baker and Latham (1978) which has been submitted for publication. Figure 1 presents a characteristic spectral evolution emanating from this model, which has already been shown to fit well with observations made by Warner (1969). It is included herein in order to establish whether its predictions are in accord with our measurements at GDF. These measured spectra were obtained by integrating over several minutes, in order to obtain good statistics on the concentrations of the larger droplets. It is probably useful to mention here that in the absence of mixing the spectral shapes within clouds formed over GDF are narrow and generally very close to that displayed in Figure 3, curve A.

EXPERIMENT I. 1630 to 1700 hours on 12.12.77

A westerly airflow covered Northern England. A weak ridge extending Northwards from a belt of high pressure stretching through the Bay of Biscay, was approaching from the West, followed by a weak warm front. During the run the axis was just off the East coast of Ireland and the surface warm front was between 100 and 150 miles to the West of Ireland.

During the 48 hours prior to arriving at GDF during the run, the air had been involved in the circulation of a deep depression over the Eastern Atlantic. Hence although the air was advected to GDF from higher latitudes it had spent a considerable time over the ocean and had not been sufficiently far North to pass over any land or sea ice. Hence the temperatures were relatively high although the air was somewhat unstable in the lower layers (more so than at any other time during the experiments conducted) due to the passage over progressively warmer sea as it was advected SE to GDF.

Cloud cover was generally well broken over NW England during the run with between $\frac{1}{8}$ and $\frac{7}{8}$ cumulus with base at 540m (this was dispersing due to slight radiative cooling at the surface) and $\frac{3}{8}$ to $^{6}/8$ stratocumulus at about 1km. Several stations had reported light rain showers during the afternoon.

It was decided that the temperature sounding obtained at Long Kesh at 1100 on 12th was representative of GDF during the run. This ascent showed that the air was conditionally unstable from the surface 1008mb to 915mb (1100m). At this level there was a shallow weak inversion, probably associated with slight subsidence due to the ridge, above which the air was much drier.

The wind profile for the GDF region (ignoring the presence of the mountain) was deduced from the data obtained from several sonde stations at 0500 and 1700 on the 12th. Analysis was then performed as before.

The drop size distribution observed in the cap cloud at 16.33 hours on 12/12 is shown in Figure 2. The estimated cloud base is at around 600m (approximately 2km upwind) and the observed windspeed near the ground at the summit was about $10 m s^{-1}$. It was considered unlikely that droplets from the broken overlying stratocumulus would have been mixed down to the observation area at the mountain summit, and thus it is probable that all the droplets observed developed within the cap cloud in the time taken to reach the summit from cloud base.

As discussed, the atmosphere was moderately unstable with a small amount of natural cumulus present and therefore the interaction at the edge of the cap cloud, well away from the mountain, may be expected to be somewhat similar to that for a cumulus cloud, although modified by the mountain. The likelihood that significant mixing occurred is reinforced by the observation of substantial short-term fluctuations (in excess of 50%) in the measured liquid water content. The spectral shape displayed in Figure 2 is distinctly non-classical, but it is similar to those presented in Figure 1, which were derived from our model of inhomogeneous mixing.

EXPERIMENT II. 1930 hours on 15/12 to 0021 hours on 16/12 and 1000 to 1230 hours on 16.12.77

During the period of the runs an anticyclone situated over the North Sea at 1800hrs on 15/12 moved slowly South-East into North Germany and slowly intensified.

During the earliest part of the run the air trajectories to Great Dun Fell were slightly to the East of the Pennines where lowland stations were reporting between $\frac{1}{8}$ and $\frac{3}{8}$ cover of stratocumulus with base at 600m. After 2200 hrs the wind had veered sufficiently for the air trajectories to be somewhat to the west of the Pennines and remained so for the remainder of the period. At 1800 hours stations in this area reported a similar stratocumulus cover at 450m.

During the period up to midnight the cloud cover over NW England became more complete, most stations reporting $^{8}/_{8}$ stratocumulus cover at between 300m and 400m. A nearly total cover of stratocumulus ($\frac{7}{8}$ to $^{8}/_{8}$) then persisted at most stations for the remainder of the period. By 0600hrs on 16/12 cloud base was generally somewhat higher (around 600m) before falling again to around 400-500m by 1200 hrs.

The Aughton temperature ascents were considered to be representative of Great Dun Fell throughout the period and the ascents for 1100hrs 15/12, 2300hrs 15/12 and 1100hrs 16/12 were studied in some detail.

The period of the runs was characterised by a gradual cooling of the air between 1000mb and 950mb pressure levels together with an increase in relative humidity and a decrease in stability from the surface up to 950mb (between 700m and 800m a.s.l). During the same period the inversion associated with the developing anticyclone intensified substantially and lowered from 980m at 1100 on 15/12 to 900m by 2300 on 15/12 and then to about 600m by 1100 on 16/12 over lowland regions in the vicinity of GDF.

For the period of the run air trajectories were used to estimate the arrival at GDF of air of the changing characteristics. The data on the tephigrams was then used to lift the air mass to the GDF summit, making use of observed wind profiles at Aughton and an estimated profile for above the mountain. The results of this will be discussed concurrently with the observed data.

At the start of the run a vertically thin and tenuous cap cloud was observed through which the moon could be clearly seen. This cloud was observed to be highly inhomogeneous with some completely clear patches, lasting for several seconds. By 2100 hours the cap cloud was thicker, much more homogeneous and the moon was totally obscured.

Figure 3 shows the drop size distribution and mean liquid water content obtained for the early, highly inhomogeneous cap cloud (this showed variations of liquid water content of a factor of 50 with a period of 60sec) with the thicker more homogeneous cap cloud. It is apparent that more large droplets are present in the earlier spectrum.

To explain this apparently anomolous effect the following was done. The lifting, deduced from the tephigram for Aughton at 1100 on 15/12, resulted in a shallow layer, less than 100m deep that was slightly supersaturated at the mountain top above which was a layer of undersaturated highly stable (inverted) air with a strongly positive Richardson number ($\sim$70) up to the main subsidence inversion. A gradual transition to the air on the 2300 tephigram resulted in a cap cloud of progressively greater vertical depth - finally reaching the main inversion layer - and a gradual decrease in stability. It is clear then that the air immediately above the cap cloud was highly stable throughout the early part of the run.

Shortly after 19.30 however, the cloud top was clearly very close to the ground and the point of observation. In the highly stable conditions it is in this region that surface induced turbulence will be a maximum and some entrainment of dry air was expected and observed, with its effect at instrumental height.

Slightly later, as the cloud became deeper, the top of the cloud was away from this more turbulent region and any slight entrainment effect well away from the instruments. From 2100 hours to around 2245 hours the spectrum was narrower than at first, indistinguishable from the classically expected spectrum based on observed CCN concentrations, and remained almost completely unchanged in shape as the cloud gradually thickened.

It would therefore seem likely that the entrainment of undersaturated air when the cloud was very thin was responsible for the broadening of the spectra revealed in Figure 3. We cannot explain the observed spectral shape on the 'classical' picture of mixing as a homogeneous process, but comparison with Figure 1 shows that the spectrum measured at 1930 hours closely resembles that predicted on the inhomogeneous model for a similar liquid water content. It is highly unlikely that any significant change in air trajectory occurred between 1930 hours and 2100 hours, which might have resulted in a sufficiently different CCN activity spectrum.

As mentioned, observations remained unchanged until around 2245 hours. At this time intermittent slight rain was observed at GDF which gradually up to midnight became somewhat heavier and more continuous. No precipitation was reported from any nearby lowland stations. This could not have occurred from higher cloud as the air aloft was very dry and largely cloud-free. At the same time the liquid water content began to rise and the drop size distribution became progressively and appreciably broader, as shown in Figure 4. These last two effects continued into the morning of the 16th by which time the rain had stopped.

To explain this the development of an extensive strato-cumulus cover with base below the mountain summit is probably highly significant. The rainfall observed may be explained qualitatively as follows:-

Taking the summit of the stratocumulus to be the base of the subsidence inversion it may be estimated that a droplet of initially around 20μm radius may grow by coalescence as it falls through the stratocumulus and then grow further to a size of perhaps 1mm as it falls through a few hundred metres of cap cloud, facilitated by the lifting of the stratocumulus close to the mountain. The smaller drops from the stratocumulus above could evaporate before reaching the ground.

The cessation of precipitation by 1000 hours on 16/12 may be accounted for in terms of the lowering of the main inversion layer overnight.

The broadening of the drop size distribution observed in the cap cloud is probably to be accounted for by the progressively greater degree of entrainment of the long lived stratocumulus cloud (which would be expected to contain larger drops due to radiative cooling, coalescence and mixing) as the stability of the air below the inversion decreased and so a degree of turbulence increased. (The lowering of the inversion away from the mountain is unlikely to affect this latter process.) Tephigram analysis shows that this is probably also the case for the observed appreciable rise in liquid water content as the distribution widened. This would not be expected if entrainment of dry air was the cause.

It should be noted that the stratocumulus base-altitude agreed well with mixing condensation levels estimated from the tephigrams.

CONCLUSIONS

The preliminary analysis presented in the preceding paragraphs appear to provide strong evidence for a profound influence of mixing-in of undersaturated environmental air on the cloud droplet spectra. Over one extensive period the entrainment of stratocumulus residue into the air forming cloud over Great Dun Fell appears to be responsible for the spectral shape. In the other two cases studied we conclude that mixing produced spectral broadening, and spectral shapes which cannot be explained classically, but do appear to fit with the predictions of our model of inhomogeneous mixing.

THE EVOLUTION OF DROPLET SPECTRA AND THE RATE OF PRODUCTION OF RAINDROPS IN CUMULUS CLOUDS

Despite considerable effort (1,2,3,4 & 5) and some progress, no generally accepted solution has been provided to two important problems in cloud physics involving the population of cloud droplets produced by condensation. The first is that the measured times required to produce raindrops in water clouds may be appreciably shorter than values calculated on the basis of classical theory for growth by condensation followed by stochastic coalescence. The second is that the predicted size distributions of cloud droplets within the condensational stage of growth are inconsistent with those observed in cumulus clouds. In this note we outline the results of some recent calculations, based on a new model of inhomogeneous mixing, which appear to offer a solution to both of these problems.

The basic idea, based on laboratory experiments, has already been reported (6). It is that when undersaturated environmental air is entrained into a growing cumulus some cloud droplets are profoundly affected while others - at the same level, but more remote from the blobs or filaments of entrained air, - are scarcely influenced. This is clearly distinguished from the homogeneous description of entrainment employed by other workers, where it is assumed that the reduction in supersaturation produced by entrainment is, at any level, the same at all points.

A prediction of our inhomogeneous model is that natural clouds should contain adjacent regions of strongly different water content but similar mean droplet size and dispersion -

defined as the ratio of the standard deviation to the mean size. Confirmatory evidence for this prediction has been obtained in several field studies (7, 8, 9).

The calculations described below were based on the simplest possible picture of inhomogeneous mixing - which, however, the laboratory experiments (6) suggest is reasonably accurate. It is that when a region of cloudy air is infiltrated by a blob or filament of undersaturated environmental air some droplets are completely removed by evaporation - with equal probability - from all size categories, while the remaining droplets at that level are unaffected.

The calculations were based on those of Warner (3). An updraught of constant speed $U = 1 m\ s^{-1}$ produced a cloud of base temperature $T_B = +15^{o}C$ in an environment of constant relative humidity 80% and constant lapse rate of $\Gamma = 7.5^{o}C\ km^{-1}$. Condensation occurred on a distribution of NaCl nuclei consisting of N = 200 particles per cubic centimetre in 5 mass classes (based on (3) and (5)). The subsequent evolution of the cloud as it moved upwards at $1 m\ s^{-1}$ and cooled was calculated from the standard equations (3)

for three different conditions. (H), an homogeneous case, in which entrainment of outside air occurred steadily and uniformly in the manner assumed by other workers (3,5). This the classical picture described earlier. (I), an inhomogeneous case, in which undersaturated blobs of constant size V_o are drawn into the cloud, either at random intervals or regularly, (with frequency λ) and evaporate completely droplets (of all size classes) until the humidity rises to 100%. (A), an adiabatic case, in which the cloud did not interact with its environment. In models H and I the entrained air contained nuclei of the same activity spectrum as those at cloud base. As the cloud volume v grows the mean frequency λ is set equal to $\mu v/v_o$ where μ, the effective entrainment parameter, was taken to be 10^{-3} m^{-1}, equal to that assumed in the homogeneous model; v_o is the original cloud volume.

Figure 5 shows a typical size distribution observed in cumulus by Warner (2) at a stage where the liquid water content was around 0.4 g m^{-3}. It also displays two calculated spectra. (H) is based on the homogeneous model, and is very similar in shape to those calculated by Warner (1) on his classical model of mixing. It is seen to bear little resemblance to the observed spectrum (W). However, the size distribution (I), based on our inhomogeneous model, with $\lambda_o^{-1} = 10s$, is seen to agree closely with that observed; λ_o is the initial frequency of infiltration. The spectral shapes on the inhomogeneous model were found to be insensitive to λ_o so the agreement appears quite general.

Table 1 presents values of liquid water content L_H, L_A, L_I, supersaturation S_H, S_A, S_I and maximum radius of droplets in the spectrum, R_H, R_A, R_I, after various growth times t for the homogeneous, adiabatic and inhomogeneous models respectively. Also presented are values of the concentration N_T of droplets of maximum radius R_T. The striking observation is that the largest droplets grow much faster on the inhomogeneous model than on either the inhomogeneous or adiabatic models - even though, in the latter case the liquid water content is about twice as great. For example, we see that about 150 seconds are required on the inhomogeneous model for the largest drops to achieve a radius of 13µm, while about 400 and 500 seconds respectively are required on the adiabatic and inhomogeneous models. For R = 15µm the figures are about 200 seconds for the inhomogeneous model, 700 seconds on the adiabatic model and 800 seconds on the homogeneous. We see that on our inhomogeneous description of the entrainment process the largest droplets move through the condensational stage about three times as fast as is predicted classically - and it appears, therefore, that this finding may resolve the long-standing question, referred to earlier, of the rate at which raindrops can be produced in cumulus. In this connection, it is interesting to note that the values of N_T ($\sim 1\ l^{-1}$) are of the right order of magnitude for raindrop concentrations.

The reason for the greatly enhanced growth-rates on the inhomogeneous model is apparent from the inspection of Table (1) - the values of supersaturation are much greater. This is because, on the inhomogeneous model, a substantial proportion of the droplets are small, having been formed above cloud base by re-activation of nuclei contained within completely evaporated droplets or activation of entrained nuclei. These smaller droplets consume water vapour relatively ineffectively, thus allowing S to rise, and the largest (unaffected) droplets to grow more rapidly.

The absolute growth rates of droplets will depend on factors which may vary greatly from cloud to cloud, but we believe that the difference in growth rates (between homogeneous and inhomogeneous mechanisms) will generally be close to those presented in Table 1. Our major conclusions were found to be insensitive to variations in λ_o^{-1} (from 10 to 100s) and to the choice of CCN spectrum. It is difficult to imagine that they would be sensitive to variations in T_B, U, Γ and other meteorological parameters. It appears to us to be sensible, as the next stage in this study, to devote our principal effort, through field, laboratory and theoretical work, to establishing more precisely the processes involved in mixing, on a scale comparable with the drop spacing. This will involve consideration of the various time constants governing droplet evaporation, vapour diffusion, and the creation of interfacial area between cloudy and undersaturated air.

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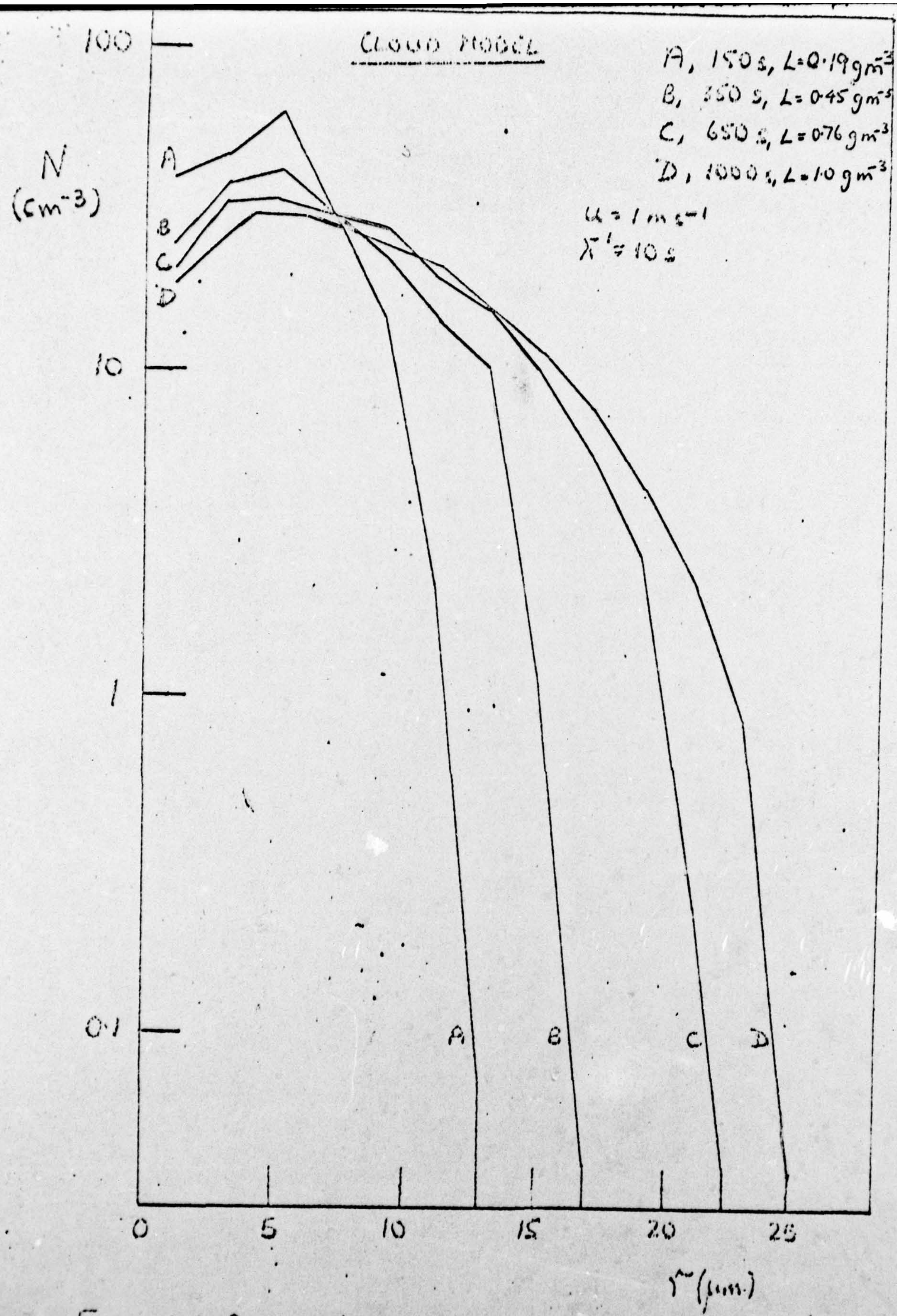

Figure 1. Droplet spectra calculated from our model of inhomogeneous mixing

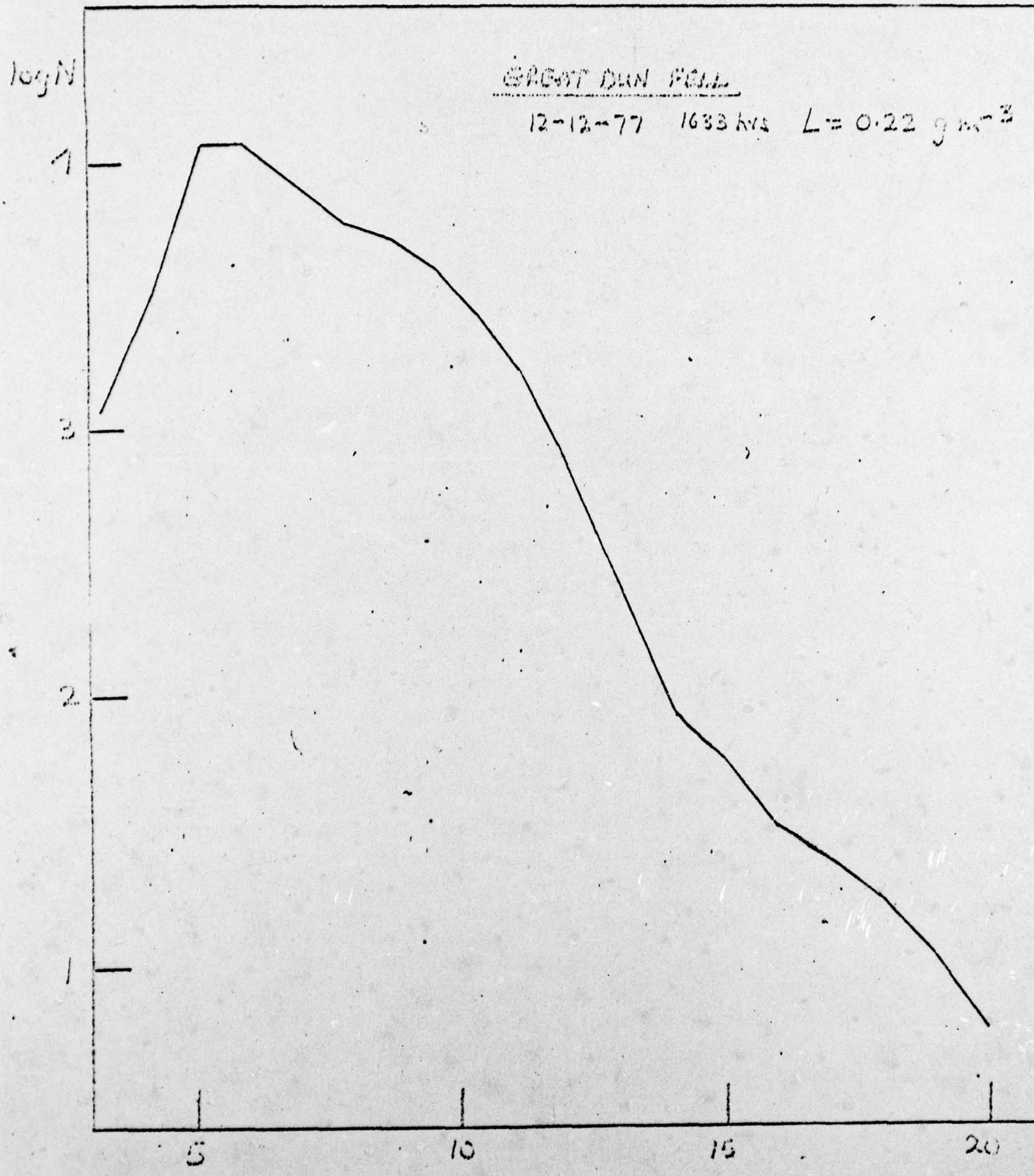

Figure 2. Measured droplet spectrum at Great Dun Fell.

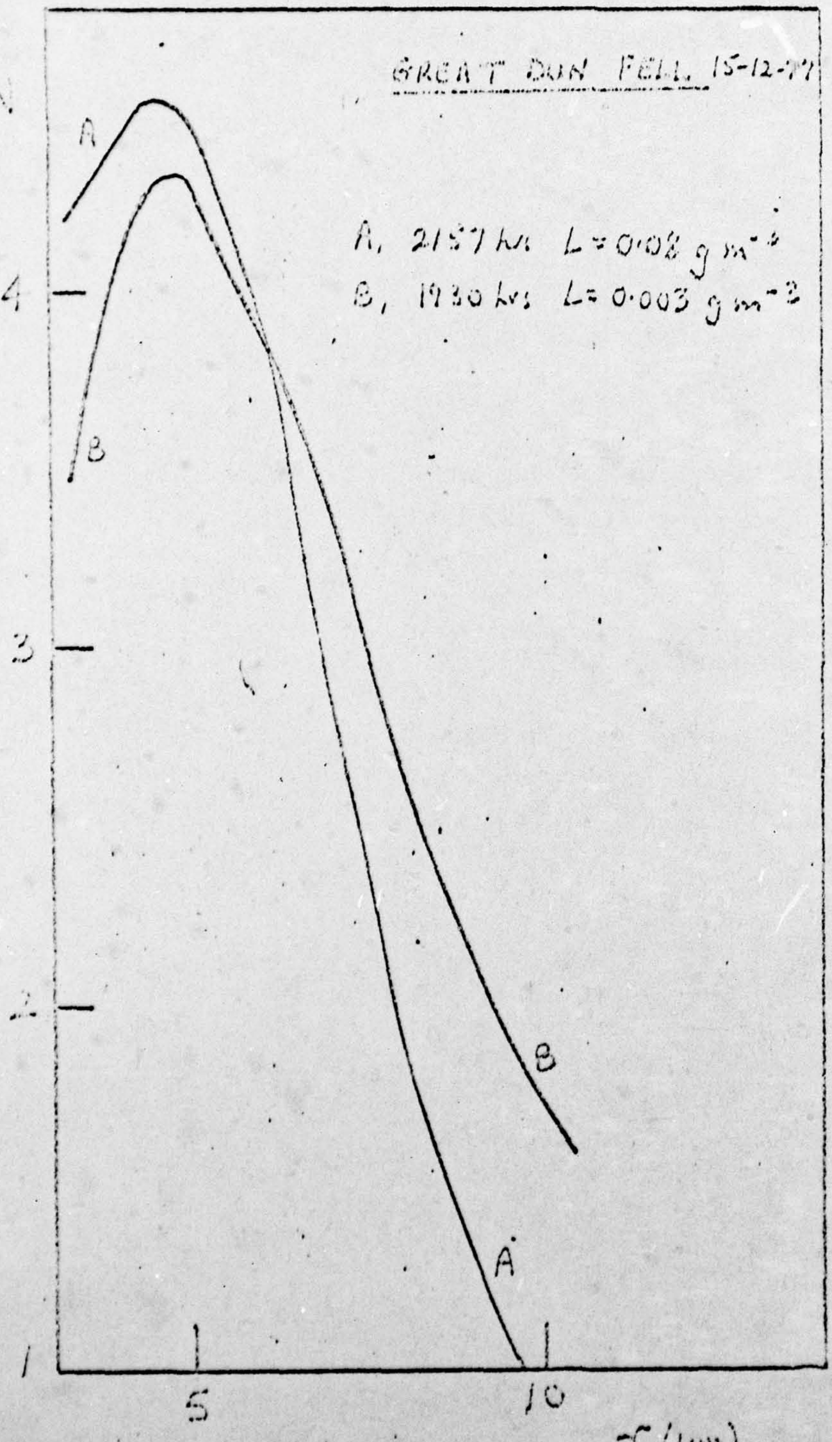

Figure 3. Measured droplet spectra at Great Dun Fell.

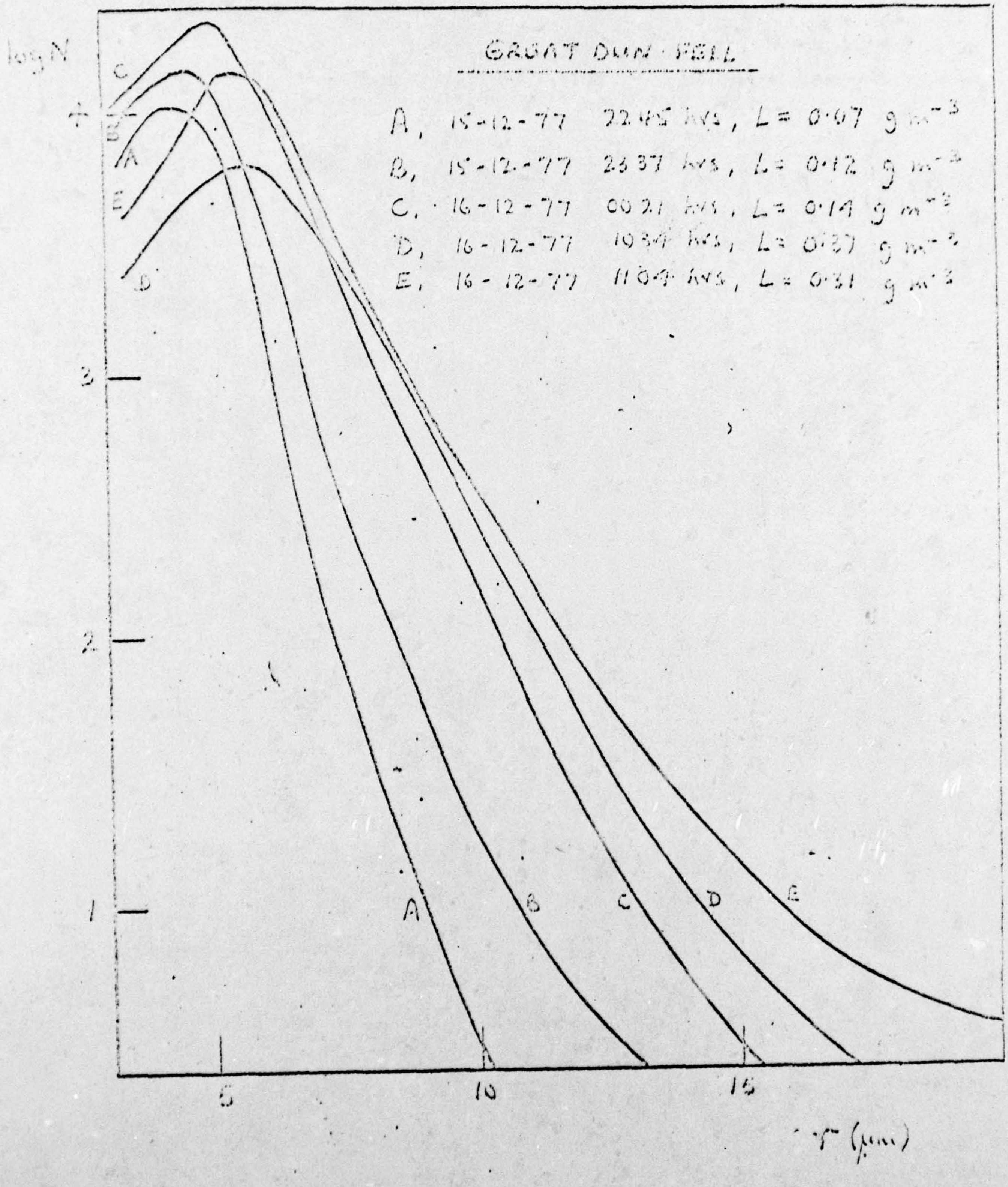

Figure 4. Measured droplet spectra at Great Dun Fell

FIGURE 5: Size distributions in cumulus. W, measured by Warner (2). (Note that he could not detect droplets of radius $r < 2\mu m$); H, calculated on the homogeneous model; I, calculated on the inhomogeneous model. $N = 200 cm^{-3}$; $\lambda_o^{-1} = 10$ sec; $L_H = 0.45 g\ m^{-3}$; $L_I = 0.42 g\ m^{-3}$.

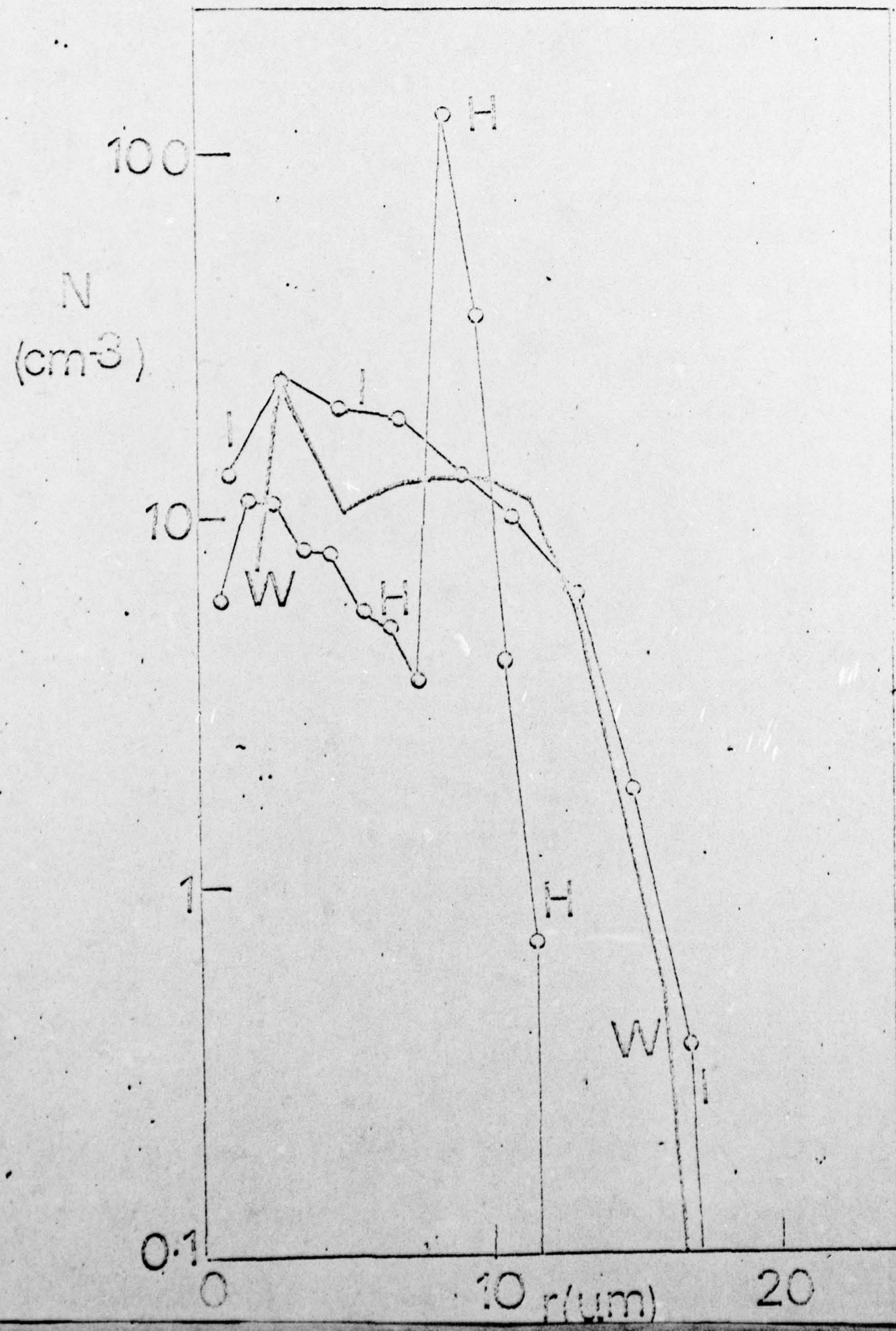

TABLE 1

t(s)	100	200	300	400	500	600	700	800	900	1000
T_c (°C)	14.4	13.7	13.0	12.3	11.5	10.8	10.0	9.3	8.5	7.7
T_e (°C)	14.2	13.5	12.7	12.0	11.2	10.5	9.7	9.0	8.2	7.5
R_H (μm)	8.5	10.2	11.3	12.2	13.0	13.8	14.5	–	–	–
R_A (μm)	9.3	11.0	12.1	12.9	13.6	14.2	14.8	15.3	15.8	16.2
R_I (μm)	10.5	15.2	17.6	19.4	20.5	22.2	23.3	24.3	25.2	26.1
N_T (ℓ^{-1})	58	6.3	2.6	1.4	0.57	0.53	[illegible]	0.26	0.19	0.15
L_H (g m^{-3})	0.10	0.26	0.39	0.51	0.62	0.72	0.80	–	–	–
L_A (g m^{-3})	0.20	0.46	0.71	0.94	1.18	1.41	1.64	1.86	2.09	2.31
L_I (g m^{-3})	0.06	0.27	0.41	0.52	0.62	0.71	0.79	0.88	0.93	1.00
S_H (%)	0.37	0.20	0.17	0.16	0.15	0.14	0.14	–	–	–
S_A (%)	0.37	0.21	0.17	0.15	0.13	0.12	0.11	0.10	0.10	0.09
S_I (%)	1.12	0.55	0.42	0.41	0.38	0.39	0.38	0.33	0.38	0.34

Calculated values, at various times t, of liquid water content (L), supersaturation (S), maximum drop radius (R) and concentration of droplets of radius R, (N_T). The suffices H, A and I refer respectively to the homogeneous, adiabatic and inhomogeneous models. $\lambda_0^{-1} = 10s$.