Some Properties of Convective Plume and Small Fair-Weather Cumulus Fields as Measured by Acoustic and Lidar Sounders

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ABSTRACT

Results of a preliminary experiment are described in which a lidar-acoustic sounder system was used to measure plume and cloud width and depth. These parameters are shown to be lognormally distributed. By applying the theory of the genesis of the lognormal to the formation process of convective cells it is suggested that clear air plumes and small cumulus clouds grow by the merger or agglomeration of smaller elements.

1. Introduction

In spite of considerable progress in the formulation of models of cloud growth and development, the initiation of cumulus clouds is not clearly understood at this time. the existence of convective plumes and bubbles in the planetary boundary layer has been confirmed by various sensing devices. Among these the following examples can be mentioned: instrumented towers (Kaimal and Businger, 1970; Taylor, 1958), instrumented aircraft (Vul'fson, 1961; Warner and Telford, 1963), acoustic sounders (Hall, 1972), and ultrasensitive radars (Hardy and Katz, 1969). It is generally supposed that water clouds are formed when these plumes and bubbles somehow break through the stable layer that usually caps the well-mixed layer in convective situations. However, the exact mechanism by which this occurs is imperfectly understood.

In a recent paper Coulman and Warner (1976) concluded from aircraft observations that successions of parcels of air from the convective layer produce the larger parcels of cooler, moister air present in the stable layer beneath cloud base. These larger parcels were often found to be associated with fair weather clouds. The implication is that convective elements agglomerate in the formation of larger parcels, which can eventually form water clouds. On the other hand, López (1976) analyzed cumulus cloud populations for many different geographic and climatic situations around the world and found that cloud and radar echo diameter, height and duration are distributed lognormally. By extending the stochastic process that determines the genesis of this probability law to the formation process of clouds, he concluded that cumulus clouds of all scales are probably formed by the progressive union of smaller elements. Thus, these two sets of observations would indicate that cumulus clouds ranging in size from the small fair-weather cumuli through cumulus congestus and cumulonimbi are formed and grow by a process of agglomeration of smaller convective elements. An example of this agglomeration in the case of cumulus congestus is the merging of clouds very often observed in undisturbed and disturbed shower production (e.g., Woodley *et al.*, 1971; López, 1976).

The present paper presents some preliminary results of an experiment designed to improve the understanding of cloud initiation. A high-power (5 J) ruby lidar firing at one pulse per second and using a 71 cm telescope was utilized. In addition, an acoustic sounder and a movie camera were employed.

2. The experimental setup

The data was obtained at a site in Boulder, Colo., during a day in August 1976. The lidar, the acoustic sounder and the movie camera employed were pointed at the zenith. Thus, clouds and convective plumes were monitored as they drifted over the site with the ambient wind. The lidar was fired once every second and the acoustic sounder once every 12 s. The lidar provided precise measurements of the heights of cloud base and cloud top above ground and of the time during which the clouds were over the instrument (± 1 s). Similarly, the acoustic sounder provided measurements of the time during which the convective thermals were overhead (± 12 s). An estimate of the wind speed at cloud base of 7 m s^{-1} was obtained from cloud motion vectors calculated from the movie photographs and the range obtained from the lidar. From this wind estimate the time intervals during which the clouds were overhead were translated into cloud transect lengths. The winds in the well-mixed layer, where the convective plumes were observed, were estimated at 3 m s^{-1} by extrapolating the winds at cloud base with an exponential wind profile (Smith, 1973). Thus, convective plume transect lengths were also estimated.

It is possible that on many occasions the clouds and plumes did not go directly overhead of the acoustic sounder and lidar. By assuming a geometrical model for the plumes and clouds and by using a statistical model, it is possible, as Vul'fson (1961) has done, to obtain a better estimate of the plume and cloud diameter. For the purposes of this preliminary note it can be assumed that the plume and cloud fields are populations of vertical cylinders which are transected along a straight line oriented with the mean wind direction by the acoustic sounder and lidar. Using the statistical scheme and tables developed by Vul'fson (1961) the plume and cloud transect lengths distributions have been converted into plume and cloud diameter distributions.

3. Results

A frequency distribution of plume widths was obtained from the acoustic sounder observations. The data were derived from fascimile records which provide a time history of the strength of the returned signal with height. The estimate of the time interval during which a plume was overhead was obtained by counting the number of contiguous fascimile traces making up an identifiable element and multiplying this number by the time interval between traces (12 s). Using the wind speed calculated for the well-mixed layer (3 m s^{-1}) an estimate of the plume transect length can be finally obtained assuming Taylor's hypothesis. The system results in an uncertainty of ± 36 m in all the measurements. In addition, some of the plumes with widths less that 36 m might not be detected. This is not felt to cause a severe bias in the distribution of plume sizes since the average diameter of plumes as recorded in the literature (see above) ranges from 50 to 300 m.

Fig. 1 shows the frequency distribution of plume transect lengths (large dots). The data have been plotted on logarithmic probability paper—the ordinates on a logarithmic scale and the abscissas on a normal probability scale. A lognormal distribution would thus describe a straight line on this coordinate system. As can be seen from the graph the data points closely approximate a straight line. The straight line in the figure corresponds to the lognormal distribution that minimizes the value of chi-square for the present sample. This minimum value is 1.15. The value of chi-square at a 5% level of significance corresponding to this data is 9.49, so that the hypothesis of lognormality would not be rejected at the 5% level. In fact the probabiltity of obtaining a value of chi-square as high or higher than the value obtained for the observations is 88%.

It is interesting to note that the lognormal distribution obtained shows no indication of truncation or biasing. If a distribution is obtained from a lognormal population by truncating it at the low end (not including elements below a certain size), the resulting log-probability graph would curve away from a straight line at the lower end indicating lower frequencies of the smaller elements than called for by the pure lognormal distribution. No such truncation or biasing is apparent in the present distribution.

The triangles in the graph correspond to the distribution of plume diameters obtained from the transect length data using Vul'fson (1961) techniques. Again the hypothesis of lognormality cannot be rejected at a level of 5% or better. In fact the best lognormal fit yields a value of chi-square of 0.31 compared to 1.15 for the uncorrected distribution. The geometrical mean of the original distribution (54.5 m) (intersection of the 50% ordinate axis) is seen to be higher than the mean of the diameter distribution (28.0 m). This seemingly contradictory result (also noted by Vul'fson in his data) is due to the fact that the statistical model includes the very small convective elements that are unlikely to be intercepted by the acoustic sounder, and which contribute in a negligible amount to the frequency distribution of transect lengths. In the derived distribution of diameters they will appear significantly, thus lowering the mean diameter for the entire population. If only those plumes which were intersected were considered, however, their average diameter would be larger than the average length of the intercepted chords.

Cloud transect lengths were obtained from the lidar observations. The data were derived from a height vs time display of the strength of the returned signal. A procedure similar to that employed with the acoustic sounder was used to obtain cloud transect lengths. The uncertainty in the measurements was ± 7 m. In some cases of considerable vertical wind shear, cumulus clouds tend to tilt with height. Under those conditions the method employed in this study to measure cloud transect lengths would result in an overestimate of the real values. An inspection of the height vs time lidar display of the data as well as of the movie photographs

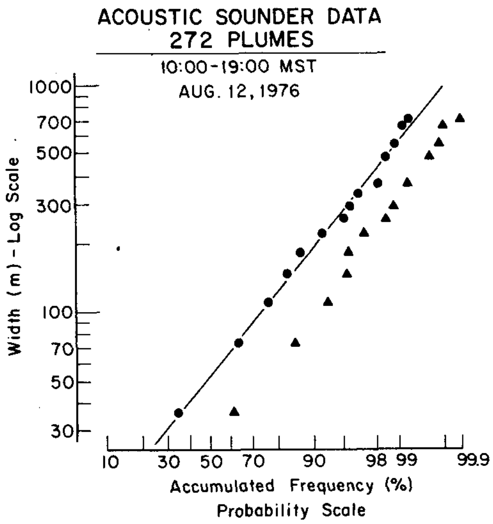

FIG. 1. Logarithmic probability graph of the accumulated frequency distribution of the convective plume transect lengths measured with an acoustic sounder. The straight line corresponds to the lognormal distribution that best fits the data. The triangles represent the distribution of plume diameters obtained from the transect length data.

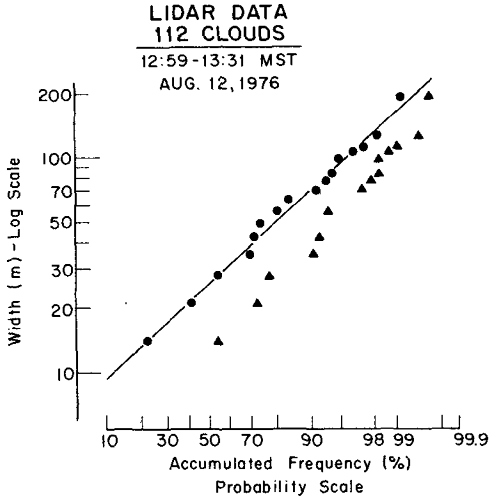

Fig. 2. As in Fig. 1 except for cloud transect lengths measured with a lidar plotted on logarithmic probability paper. The triangles represent the distribution of cloud diameters obtained from the transect length data.

taken at the same time did not indicate any apparent tilting of the clouds. Actually because of the small depths of these clouds (80% had depths under 100 m) a strong vertical wind shear would be necessary to show appreciable tilting.

The frequency distribution of cloud transect lengths is displayed in Fig. 2. It can be seen that the widths of the clouds detected by the lidar are also lognormally distributed. Applying a chi-square test again shows that the hypothesis of lognormality for the distribution would not be rejected at the 5% level of significance. Again, the distribution of cloud diameters obtained from the cloud transect length data is shown by triangles. This corrected distribution is also lognormal at better than the 5% level of significance and yields a smaller chi-square value for the best fit than the original distribution. The diameters in the mean are also smaller than the transect lengths due to the inclusion of smaller clouds which were less likely to be intercepted by the lidar.

The depths of the clouds were obtained by noting the greatest depth observed for each particular cloud from the lidar records. In general, the attenuation of visible lidar beams is considerably high. For a ruby lidar, for example, the penetration in a dense cloud would only be a few hundred meters. However, in many cases a lidar beam can penetrate several layers of cloud which together obscure the sun. Derr (1977) has computed from Mie scattering theory the penetration of different types of clouds by a ruby lidar beam. For a newly formed low-density cloud he obtained penetration depths of 357 m for a signal-to-noise ratio of 10 and 715 m for a signal-to-noise ratio of 100. The clouds observed in this study were very small, incipient thin clouds. On the basis of Derr's computations we would expect penetrations of around 400 m. Actually, a few hours after the small clouds were measured, a larger, denser cumulus congestus cloud drifted over the site from the mountains. The returned signals from this cloud were in general 2–3 times as intense as in the case of the early clouds and came from depths of up to 400–700 m inside the cloud. The small clouds used in this study were under 300 m in depth and about 80% of them were under 100 m. According to the above considerations we feel confident that the cloud depths measured were real and were not penetration depths.

The frequency distribution of depths is portrayed in Fig. 3. It also describes very closely a lognormal distribution, and the hypothesis of lognormality would not be discarded at a level of significance of 5% or better.

The lognormal distribution can be considered (Aitchison and Brown, 1957) the frequency distribution of a variate that is subject to the law of proportionate effects, i.e., a variate whose change in value at any step of a process is a random proportion of the previous value of the variate. Thus, something that forms, grows or changes according to the law of proportionate effects will yield a lognormal size distribution. López (1976, 1977) has hypothesized that large cumulus clouds grow and develop by a process which follows the law of proportionate effects, thus producing the observed lognormal distributions of cloud characteristics. Such a process can be postulated as follows: In a given region many small convective elements are randomly generated throughout the subcloud layer. These agglomerate randomly into larger elements. The larger elements, covering a greater area, intercept a larger number of other elements and thus grow more rapidly than the smaller ones, i.e., growth proceeds according to the law of proportional effects. In this way a cloud population develops where the eventual size

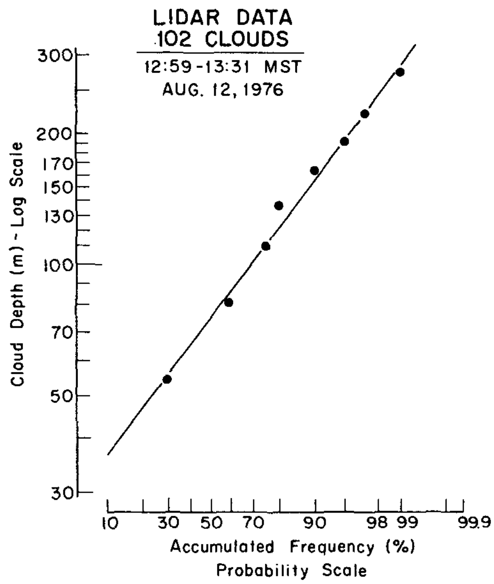

Fig. 3. As in Fig. 1 except for the depths of clouds measured with a lidar.

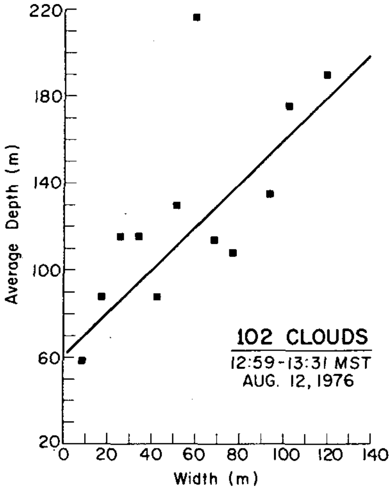

FIG. 4. The average depth of all the clouds within each cloud transect width interval as measured with a lidar.

distribution is lognormal. On the basis of that interpretation, the lognormality of plumes in the boundary layer and small fair weather cumuli as revealed by the present measurements suggests that the convective plumes and small clouds also grow by the merging or agglomeration of smaller elements.

It is interesting to notice from these distributions that on the average the small clouds are 2–3 times deeper than they are wide. This is more evident in Fig. 4 where the average depth of all the clouds within each cloud transect width interval is portrayed. Notice that

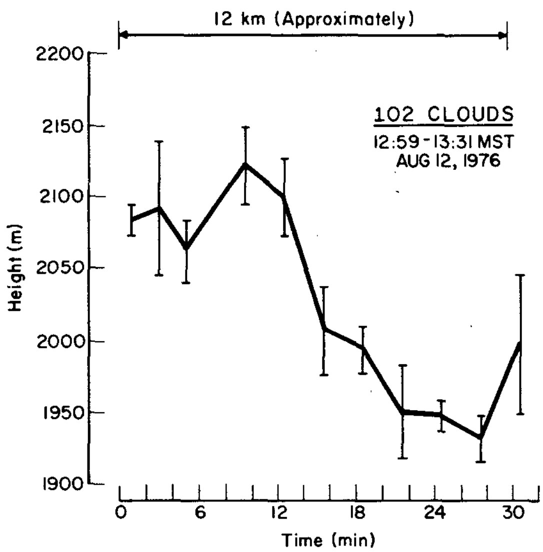

FIG. 5. The height of the average cloud base above ground as a function of time. The vertical bars represent ±1 standard deviation of cloud base height around the corresponding average. Time has been equated to horizontal distance by using the wind at cloud base and by assuming that the cloud-base height patterns remained constant as the clouds were advected by the wind over the site.

those clouds with smaller widths tend to have large aspect ratios of depth to width, while the wider clouds tend to be as deep as they are wide. In other words, the small clouds (supposedly formed by a few convective elements) tend to look like plumes, whereas the larger ones (supposedly formed by the merger of many convective cells) tend to look like bubbles.

Fig. 5 shows as a function of time the height of the base of the clouds above ground measured with the lidar. A fluctuation with a duration of about 30 min can be seen. This time interval can be equated to a horizontal distance of about 12 km by using the wind estimate at cloud base and by assuming that the pattern of cloud-base height remained constant as the clouds were advected over the site by the wind. This mesoscale variation could have been due to wavelike perturbations in the subcloud layer on the scale of about 12 km, or due to time changes in the thermal structure of the boundary layer on the scale of 30 min.

4. Summary and discussion

It has been shown here that both clear air convective plumes and small cumulus clouds yield lognormal size distributions. Similar distributions for larger cumulus clouds have been interpreted by López (1976, 1977) as an indication of growth by the agglomeration of smaller cloud elements. Applying the same interpretation to the present data it is suggested that both convective plumes and small fair-weather cumuli are formed by the agglomeration of smaller elements.

The relationship between the plumes and the clouds cannot be ascertained from the present data. However, the concept of growth by agglomeration in both clear air plumes and very small cumulus clouds is suggestive of a continued process of grwoth from the clear air convection to the cloud stage. In any case, the preliminary data presented in this note are an indication of the capability of a lidar-acoustic sounder system to study the problem of cumulus cloud initiation by convective plumes in the boundary layer. A more extensive and complete experiment is planned where this system will be supplemented with instrumented tower and aircraft observations.

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