Stereo Measurement of Thundercloud Kinematics

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The cumulonimbus to be described was stereo-photographed mostly at two-minute intervals by special cameras, from close to its initial (15:43 CET) to nearly its decay stage (17:05 CET), on 7 Sept. 1954 in Berlin. The distance from the cloud face to the stereo base-line – some 5.5 km – and the size of the cloud are close to optimum for good measurement.

The surface weather at 13 CET strongly favoured local thunderstorm occurrence.* A survey showed that this cb represented, at this time, the only thunderstorm within a radius of some 30 km. Moreover the rise of isolated towers turned out to have occurred over large industrial plants and housing areas. This corroborates that industrial areas, located close to water or woods, pronouncedly favour the release of thunderclouds in calm air [2].

Rain from this cloud first touched ground (at station 5) at 16:30, with a steep rise to 46 mm before a sudden stop at 16:55. For the total rain from this cloud see Fig. 1.

Essential data of the cb and its close surrounding are summarized in Table I. Repeated cloud ascent occurred over nearly constant locations A, B, C, D (Figs. 1, 4a..d). All four of these «sources» were located within the 5 km broad corridor of housing districts (between woods), where in addition, at A and C, large industrial plants exist.

The vertical motion components of buoyant cumuli and the altitudes of surrounding cloud shreds and stratus are condensed in Fig. 3 (for denotations, see legend); Table I renders supplementary numerical values and horizontal vectors. Successive rises of groups of towers from the origin to peak altitude suggest that these constitute stages of the clouds development; they will be described separately.

The first stage was close to its final phase when photography started at 17:43: At this time a tower, roughly in the middle of what at 15:49 formed an anvil at D (Fig. 4a), had arrived at 0.2 km below ac lager I 2 (Table 1). Possibly this peak bubble may be classified as having emerged as a «protected core» [1]. Cloud parcels D 1 and D 2 became part of the anvil edge at 15:49 (Fig. 4a). Due to the change in wind vector within the layer 3.3 to 3.8 km the now asymmetrical anvil drifted with a motion vector close to that of I 2 (Table I).

Nearly simultaneous with the main cloud at D, the single tower B 1 had attained its top altitude also at 0.3 km below the level of I 2 (below the face edge of B 1, the dapples of sheet I 1 can be recognized in Fig. 4a).

The second stage is marked by the penetration of the level of strata I 2, I 3 by towers D 4 und D 6 of the main cloud; the buoyancy of the single towers A, B, C again was too little for them to attain that level.

At 15:43, the second stage cumulus field above D (compare Fig. 4a) roughly fitted a (horizontal) rectangle of 1.0 km × 2.0 km. The average altitude of cu tops in this field then was some 1.3 km, the average altitude of the cumulus' upper surface 1.1 km (the mean planes of both ascend by some 15° from S to N). At 15:50 (Fig. 4a), the corresponding values were 1.7 and 1.5 km. Only from 15:49 til 15:53, a thin sheet of stratified fog existed above the middle of the field, at 1910 m. (The

* Within a radius ≈1000 km, horizontal pressure gradient $|\delta p/\delta r| < 10^{-5}$ mb m^{-1}; a weak Low trough terminated at Berlin.

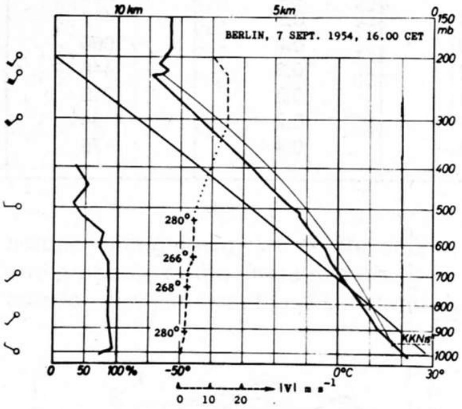


Figure 2. Sounding at Tempelhof (loc. «T» in fig. 1), in temporal coincidence with thundercloud occurrence.

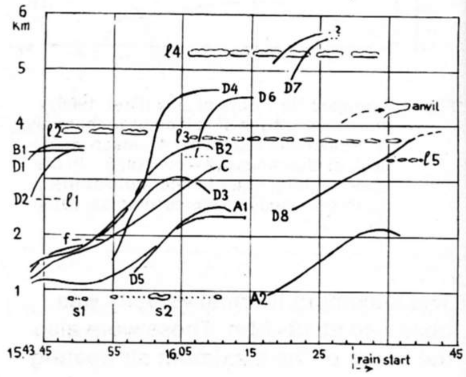


Figure 3. Altitude of prominent cloud bubbles – capital letters denoting their origin position – versus time. Stratus clouds, denoted by small letters l and, in one case, f, are depicted for the respective span they occupied the photographs. The respective life span of two convective shreds, s, is also shown. They were approx. 2.5 km in front of the edges of the main cloud at D.

Table I
Essential data of cb and environment (compare with figures and text).

subject (and time)	properties as measured by photogrammetry	data known from aerol. sounding or map	comment
surface altitude (underneath cb)	–	50 m	
CCL of cb at 16 CET	altitude 880 m		
small cu shred s 1 (15:49–51)	altitude 860 m		
small cu shred s 2 (15:55–16:10)	altitude 900 m motion vector 280°, 1.8 m s^{-1}		
ac layer 1 (15:43–16:01)	altitude 2600 m motion vector 268°, 2.4 m s^{-1}		small-dappled sheet, extent of order 1 km, near B 1
ac layer 2 (15:43–16:05)	altitude of lower surface 3800 m motion vector 266°, 4.4 m s^{-1}	layer 3.7 km–4.2 km, $\gamma \approx -0.3 \times 10^{-2}$ °C m^{-1}	note sharp reduction of humidity from 3.7 km upward (Fig. 2)
ac layer 3 (Figs. 3, 4b)	altitude of lower surface 3700 m	as before	
ac layer 4 (Figs. 3, 4b)	altitude of lower surface 5240 m motion vector 280°, 4.2 m s^{-1}	isothermal layer 5.5 km–5.6 km	
cb, max. peak alt. (attained at 16:26)	5.7 km		As peak towers were hidden behind other towers and ac dapples, defin. path and alt. were not determined
cb, fastest of (visible) towers D 4 and D 6	max. rising speed 8 m s^{-1} (see Fig. 3)		
Stratus sheet f (15:49–53), upon lift of stable layer	altitude 1910 m covering roughly 0.6 km^2	layer 1.0 km–3.8 km $\gamma \approx -0.6 \times 10^{-2}$ °C m^{-1}	

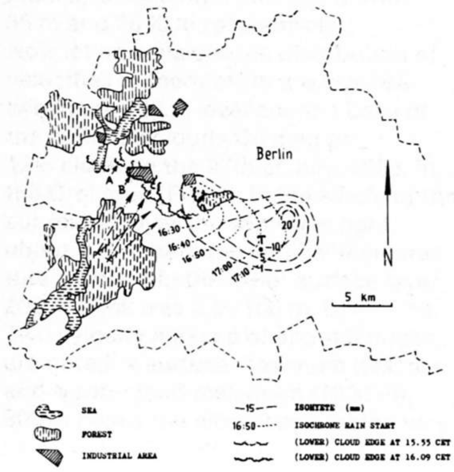


Figure 1. General map of cumulonimbus and essential environment.

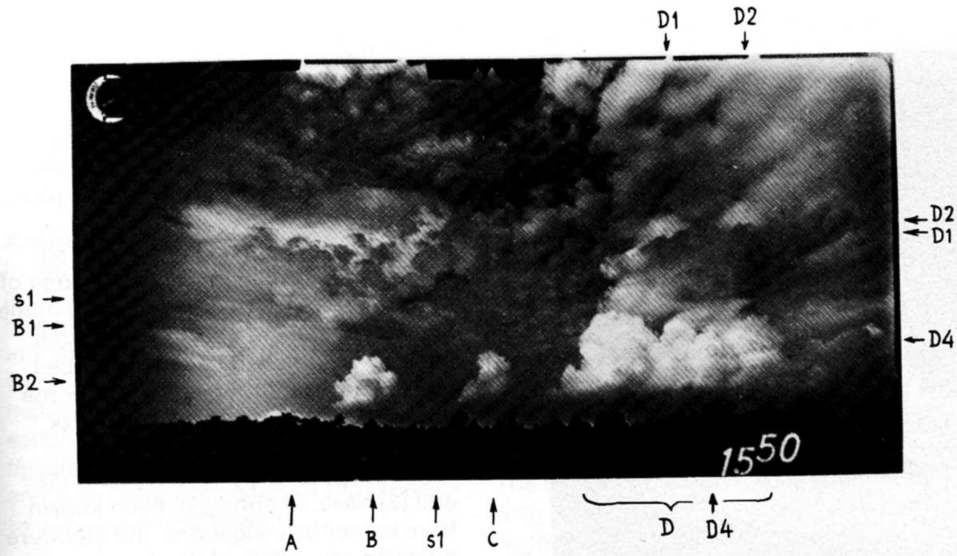
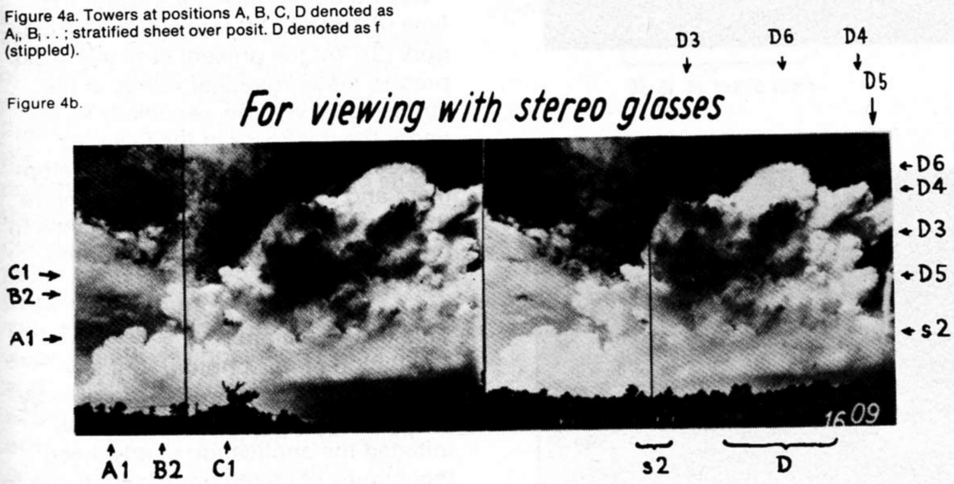


Figure 4a. Towers at positions A, B, C, D denoted as A_i, B_i . . ; stratified sheet over posit. D denoted as f (stippled).

Figure 4b.



complete extent of this sheet can be recognized only in stereo.)

This implies that lift occurred in a layer of increased stability at 0.4 km above the mean cloud surface level.

If the sounding is representative also for this layers humidity, a dry adiabatic lift of 300 m would have been needed to attain saturation (at 15:49). Yet apparently in the later visible sheet the original humidity had already exceeded that of lower and higher clear air layers – which would mean a correspondingly smaller lift necessary to attain saturation.

This specific state of a layer at least 0.4 km thick being lifted suggests discussion of the dynamic aspect: It suggests the need to modify the Malkus-Scorer equation ((1) in [1]), which describes the dynamics of rise of thermals with a spherical cap, to make it applicable to a largely coherent field of towers (or for one large, «flat» cap, which may represent a whole congestus and attain a diameter up to 5 km). In this equation, $\frac{dw}{dt} + Kw^2 = gB$, the first term means the actual acceleration upwards attained by the thermal; K is the friction coefficient of its rounded cap, and gB represents the potential acceleration.

Since additional lift of dry air above the field of towers would hardly add to friction but rather imply an increase in the share taken by buoyancy necessary to accelerate also the (inertial) dry air mass overhead, the real state now would be approximated by

$$\frac{dw}{dt}(1 + n) + Kw^2 = gB,$$

where $n = m_{dr}/m_{cl}$ means the ratio of the dry air mass m_{dr} to be lifted overhead, to the buoyant cloud mass m_{cl}. It appears that in the initial stage of the present case n approximates unity.

Considerations suggest that the vertical thickness of the clear air lifted is proportional to the square root of its horizontal plane area; it further depends on the horizontal edge shape and its stability γ; while the speed of lift depends on the buoyancy of the cloud layer. The parameter K will have to be determined anew upon these variables.

At 15:53, a fish-like, horizontal fog band reached out (towards S) from between two neighbouring towers. Apparently the lateral momentum is bundled into a direction determined by a «valley» between towers when they squeeze the stable layer overhead.

Since for periphery thermals, exposed to dry air, the stable layer I 2, I 3 reduced the difference between the actual surrounding temperature and that of the mixing adiabate, their buoyancy suffers additional diminution. For some of the towers at the periphery of the main cloud, like D 3, the phase of the zero vertical acceleration set in even below I 2 (figs. 3, 4b). Such towers of reduced buoyancy were lifted and pushed aside by a central propulsion, thus conveying, at 16.09 (Fig. 4b), the impression of an explosion of the cloud.

From 16:05 to 16:09, the horizontal component of D 3 (directed towards the left camera) kept nearly constant at 1.9 m s^{-1}; within the same interval, the upper part of tower C was blown WNW by the main cloud, at an absolute horizontal component of 0.8 m s^{-1}. (With a basic horizontal wind of approximately 2 m s^{-1} in the opposite direction, the relative horizontal component is correspondingly greater). Even the more distant thermal B 2, which had separated from its base tower at 16:05, was blown WNW at an absolute horizontal component of 0.5 m s^{-1}. On the other (southeastern) side, D 5 held an absolute horizontal component of 1.6 m s^{-1} ESE.

Having risen to the level of 3 km, the front towers of the area above discussed formed a nearly vertical (though not straight) wall, while only a small edge of very low cloud tops had formed anew. Only at 16:21, within stage 3, had another considerable layer of low cu formed.

The third stage is characterized by the top altitude having been attained at about 16:30, and by rain which simultaneously reached the surface.

The isohyete of rain onset advanced ESE at 1.9 m s^{-1}. Although even now the largest bubble at D, D 8, did not alter the position of its origin, both the lower and the higher cloudiness grew towards the ESE.

Measurement towards the end of this stage was disturbed by several causes: Stereo photography was interrupted from 16:26 to 16:34 when cameras had to be turned to the right to follow the growth of the cloud. Also, stereo photography was not successful all the time. Finally, the main cb became hidden, to a large extent, behind lower or higher sheets.

A narrow garland of cumuli, their mean upper surface at altitude 1.1 km, again lay in front of the main cloud at 16:21. Above them, at altitudes between 1.2 and 1.4 km, small and thin fog sheets and apparently stratified dapples existed.

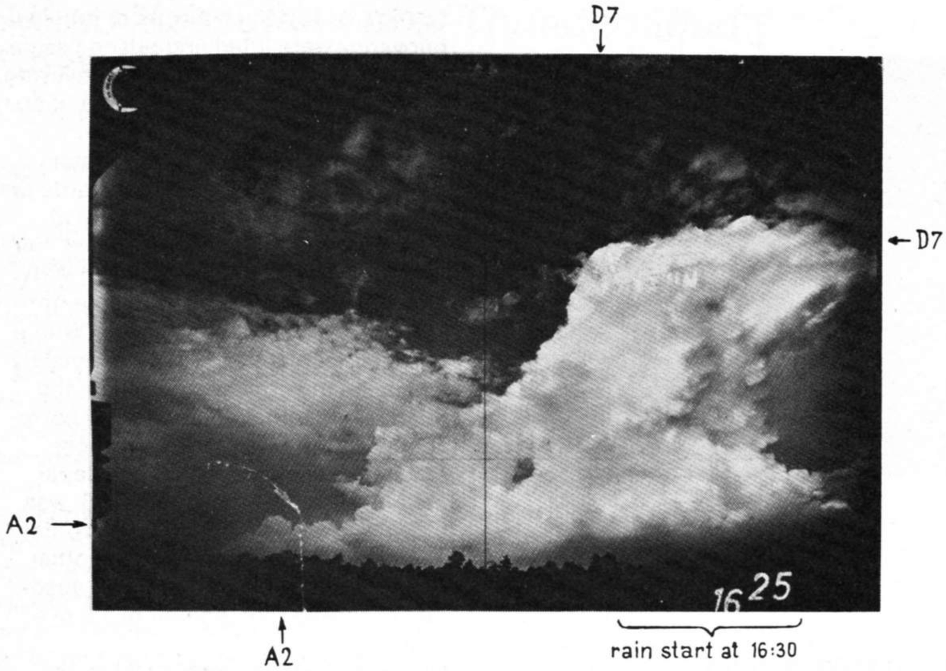
Conclusions

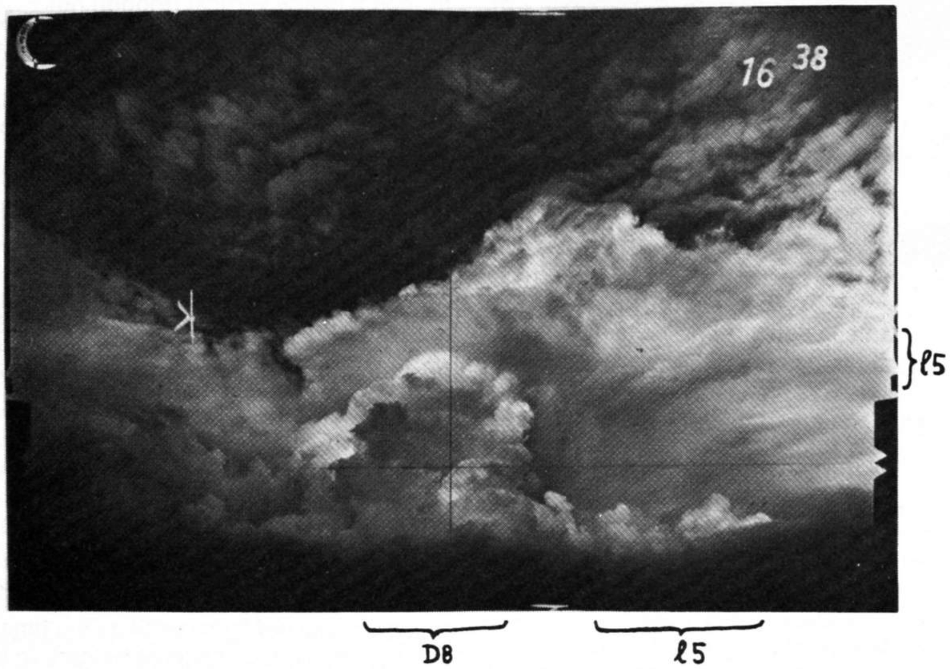
From this case study we can distinguish three categories of lift.

These were:

(1) Separated, individual towers (A, B, C) at the northwestern outskirts of the main cloud, their tops rising at 1 to 3 m s^{-1}. The horizontal diameters d of these towers are not inconsistant with results obtained by Saunders [3], according to which $d \leqq 0.4\Delta h$ (Δh = height of bubble above its virtual origin).

The comparatively small diameter of the separated tower limits both its vertical





acceleration and the altitude attained.
(2) Towers in the vicinity of the cloud (D 6, D 7, «protected cores» [1]), which attain high altitudes by great rising speeds. Although this was generally speaking a small thundercloud, these towers, in the visible parts of their paths, attained 8 m s^{-1}.
(3) Towers, in general low ones in an early stage, formed in a common area of considerable extent (as found at D in the second stage), are able to lift a stable layer of dry air overhead as described above (clear air lift). Averaged over the entire field, the speed of this lift was only some 1.5 m s^{-1}.
While properties of the categories (1) and (2) have, in principle, been known from earlier investigations, the literature holds no quantitative data about the type of clear air lift represented by category (3). Yet the present case still lacks precise meteorological values of the strictly local volume, especially as regards the thickness of the layer, its degree of stability, the safe of development and endurance of lift. To explore this gap in precise knowledge seems to be a task suited for an instrumented sailplane.

Acknowledgement
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References:
[1] J. S. Malkus and C. Ronne: On the structure of some cumulonimbus clouds which penetrated the high tropical troposphere; Tellus VI (1954), 351–366.
[2] J. H. Reuss: Ein Gewitter bei Windstille; Beitr. Phys. Atmosph. 34 (1961), 259–273.
[3] P. M. Saunders: An observational study of cumulus; J. M. 18 (1961), 451–467.