Thunderclouds Released by Waves?

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Surveying the hitherto known tropospheric states favourable to the development of thunderclouds, the following can be distinguished:

1. In a state of rather small horizontal pressure gradient (outside a High centre), local release occurs by thermals rising from larger urban or industrial areas [6] or from hill "hot spots" (F. H. Ludlam) in a just stable troposphere.
2. meso-scale chains of thunderclouds caused by and aligned at squall lines or large-scale boundaries of air masses;
3. forced lift at high mountain barriers, possibly combined with the – then secondary – causes (1) or (2).

At a suitable, rare state of the troposphere, a fourth kind of release, by waves at middle or higher levels, might be rendered possible.
Whether this relation exists, and whether waves are cause or effect of thunderclouds, cannot be decided solely by the data here available. Hence this report is restricted to presenting the measurements, with a minimum of interpretation and problem discussion.
The twin thunderclouds illustrated in Fig. 1 were photographed on 20 August 1959, 17.30 GMT at Bruchsal, Germany, from a train. The centre of the cloud on the right (A) is exactly east of Bruchsal, some 23 km distant; cloud B is located in the general winds lee, i. e. 330° of A, at a distance of some 10 km from it.
Both thunderclouds, in turn, were in the lee of the pibal station Stuttgart-Echterdingen, from which the 18 GMT ascent started, 45 km distant from cloud A. Since in addition the balloon on its path approached cloud A within less than half that distance, this wind sounding may well be considered representative for the conditions prevailing at these clouds. However, it must be taken into account that the temperature was measured at 12 GMT, 5 hours before these clouds occurred.
The rate of rise of visible parts of the bubbles at middle heights was found to approximate 8 m sec^{-1}. Taking the mean value from four cases of thunderclouds measured earlier by methods of photogrammetry [6], and with the aid of a diagram relating bubble diameter, altitude and velocity of rise [5], the further conclusions may be drawn that the speed of rise in the clouds' lower half is 7 m sec^{-1} increasing to 10 m sec^{-1} between 5 and 7 km, and decreasing to 8 and less m sec^{-1} when approaching the top.
The theoretical buoyancy as enclosed between the temperature profile (Fig. 2, short dashes) and the moist-adiabatic (solid line) may well be greater, since probably the condensation level is still below that anticipated. With Scorers [7] parameter 1^2 (at right end of Fig. 2) decreasing steeply from altitude 4 km to 7 km at constant wind direction, the state in the layer between was favourable for wave formation. In five other cases of (single) thunderclouds measured by photogrammetry, not even an approximately favourable state was found. Hence the occurrence of twin thunderclouds aligned in the general wind (=vertical shear) direction might be related to that of wave conditions.
If so, the question arises whether the topography – 13 km upwind of cloud A a ridge across the wind up to 440 m high, followed by a 193 m "valley" 8 km upwind from A – participated somehow in releasing the clouds; or if cloud A, perhaps in its congestus stage, caused middle level waves which released convection below the second crest. As Lindemann [4] reports, "it seems that lee waves at higher levels only enhance normal convection underneath the wave crest".
An important distinction is that strictly Scorers parameter criterion [7] and Corbys correlation ([2], applied below) are conceived and hence valid for wave formation at rigid obstacles; while the obstacle effect of a cumulus bubble in a layer of vertical shear is limited to its positive vertical component, its inertial mass [3, 4] and the time of existence of subsequent bubbles. A formula which would include these variables has not been derived to my knowledge.
Further data concerning these questions are as follows:
For comparison with the actual wind profile and conclusions upon the shape of these clouds, the lines connecting the respective bubbles of A and B were drawn (Fig. 2, dashed lines; as cloud A could not be taken normal to its elongation but at an angle of 60°, its length in the picture shrinks to 85% of its true horizontal length; it was rectified correspondingly). The above anticipated velocities of rise of the bubbles were used to draw their paths as they would result from the wind profile neglecting the comparatively great, yet not satisfactorily known effect of their inertia. (The paths would not essentially deviate from these lines if a constant rise velocity of 8 m sec^{-1} through the clouds height had been anticipated.)
Theoretically the following causes of clouds' shape have to be distinguished:

I. In the case of a stationary source of the bubbles, both streamlines and paths of single bubbles would coincide with the profile of simultaneous positions of successively rising bubbles – in principle identical with a photograph. This case is roughly comparable to a smoke plume arising from a stationary chimney.
II. In the case of the source of bubbles moving with the wind at condensation level, the paths of single bubbles and the – then different – streamlines of their centres could be determined only by at least

Fig. 1

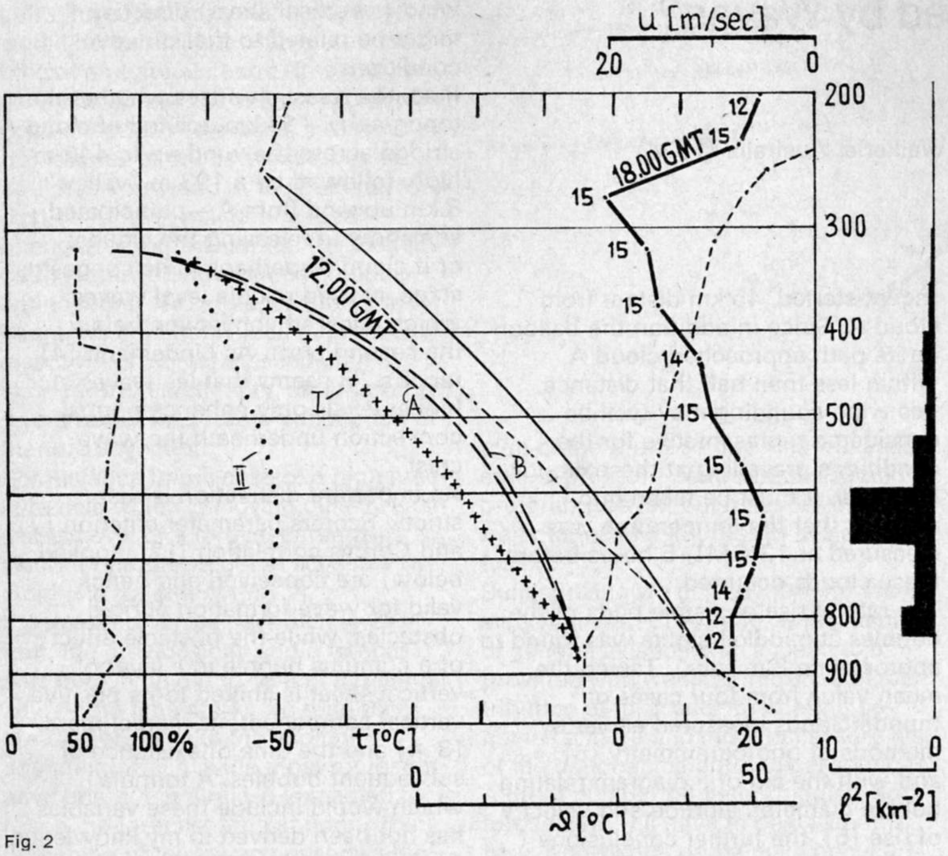

Fig. 2

two successive, but stationary photographs. Any photograph would depict a profile of successively rising bubbles like line II – different from streamlines and individual paths.
In other words: While the profile of bubbles, their individual paths and the streamlines coincide in case I, they differ from each other in case II.

Since the actual profiles of cloud A and cloud B approximate well to line I rather than line II, the source of bubbles obviously was quasi-stationary, as described under (I) in principle, or advancing very slowly compared to the wind at condensation level. This implies that the bubbles grew upwind by a phase velocity which about balanced the synoptic flow.

This fact, along with the occurrence of twin clouds, the agreement with Scorers criterion and Corbys correlation and the restrictive remarks made above, may add to an argument for wave occurrence; yet these statements are not sufficient for a definite conclusion. Direct observations by glider pilots on the flow characteristics in similar cases will be necessary to clear up these phenomena.
A very interesting series involving seven panoramas of periodic clouds was taken from Wolfesing, near Zorneding, Germany by Dr. M. Reinhardt. The time interval between the panoramas is one minute each. Fig. 3 depicts panoramas Nr. 2 and 4, the time interval hence being two minutes. As the date of photography is not known beyond doubt, comparison with the state of the atmosphere has been omitted.
The clouds moved from 130°; assuming a condensation level of 1.2 km above the location of photography, the resulting velocity would be 7 m sec^{-1}, the constant distance from each other 3.4 km. The orientation of the chain coincides with the (above mentioned) direction of motion. These values agree very well with Corbys correlation [2]. Studies of the left zone lead to the assumption of a stationary source of subsequently originating bubbles near Kirchdorf a. H., where the topography, as seen in the direction of cloud motion, rises by 120 m.
Perhaps in some respect an analogy exists between this case with the case of twin thunderclouds.

Fig. 3

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