The influence of the circulation around cumulonimbus clouds on the surface humidity pattern

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1. Introduction

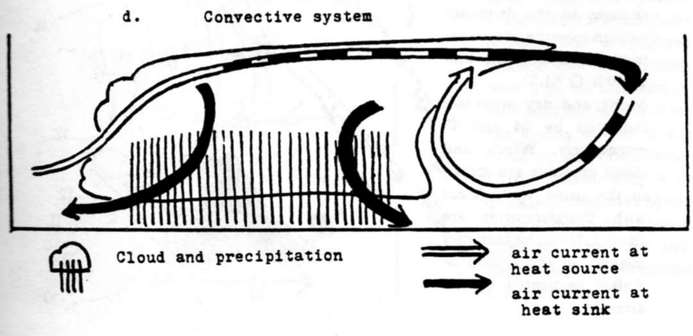
It is well known that on days with thermal convection in relatively dry air, the temperature and the humidity show fluctuations. These are particularly marked when cumulus clouds develop in an atmosphere in which there is a strong hydrolapse. When the humidity decreases with height at a sufficiently large rate, remnants of cumulus bubbles which evaporated in the dry air aloft may sink to the surface as parcels of cold air having a humidity mixing ratio, which is considerably lower than that of the surface layer before the beginning of the first development of cumulus clouds.

On the synoptic scale maps and even at meso-scale maps these fluctuations give rise to a completely incoherent pattern. This is easily understood if one compares the dimensions of cumulus clouds (0,5–1 kilometre) with the spacing of the synoptic stations (10 kilometres in the densest network). However, when the cumulus clouds grow to thunderstorm size, a rather coherent humidity pattern develops, which can be followed up over several successive hourly maps. This pattern shows areas of moist and dry air which are 10 to 30 miles across. In some cases, after storms have developed, the dewpoints may start to show differences of 5 to 10 °C over distances of 40 to 50 miles.

The direction of movement and the velocity of dry areas is difficult to assess when several thunderstorms are developing at the same time, but sometimes they move over the map at the flanks of, or behind thunderstorm areas.

In many cases it is impossible to relate these dry areas to domes of cold air caused by downdraughts, which have spread underneath the storms, particularly when dry areas develop at a considerable distance upwind of the storms. Sometimes this happens even over coastal stations during thunderstorm situations in late summer and autumn, in spite of a continuous inflow of moist air from over a warm sea.

Fig. 1 Main convective circulation systems; schematic vertical cross-sections. After T. Bergeron: The Physics of precipitation, 1960, Publ. No 746, American Geophysical Union, p. 6



One would then be inclined to seek the explanation in compensating downcurrents outside the cloud of the kind which are shown in models of flow in and around cumulus clouds, such as can be found in textbooks of meteorology or in the literature (see fig. 1). It is rather remarkable that in these models very little is said about the scale and the velocity of this sort of circulation. The only paper in which some indications are given of the scale of the circulations around cumulus clouds, is that by Bleeker and André (1950). From pressure data and surface wind data obtained from a network of stations set up by the Thunderstorm Project, they inferred that these circulations could have characteristic dimensions of the order of a few kilometres.

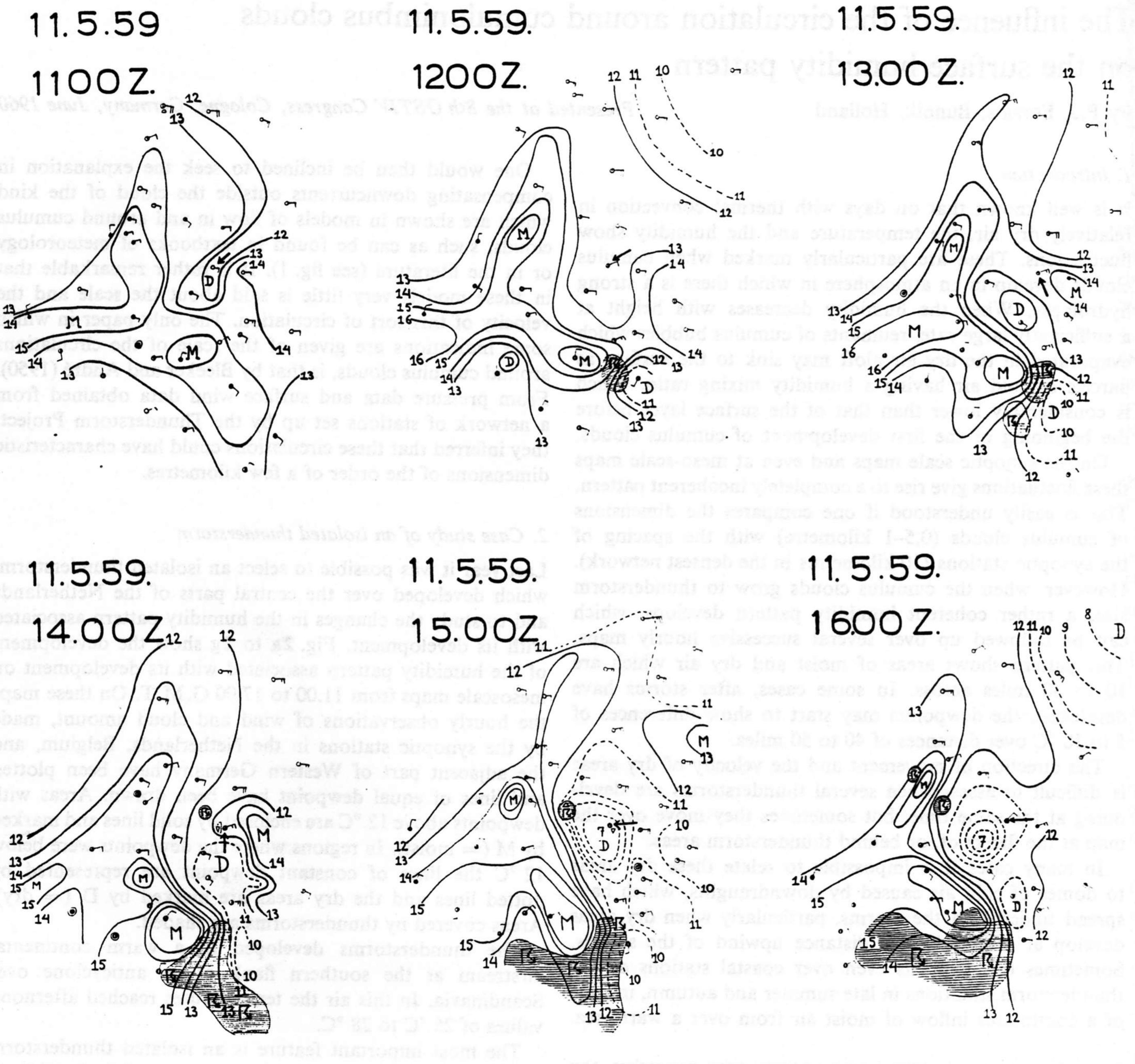
2. Case study of an isolated thunderstorm

Last year it was possible to select an isolated thunderstorm, which developed over the central parts of the Netherlands and to study the changes in the humidity pattern associated with its development. Fig. 2a to 2g show the development of the humidity pattern associated with its development on mesoscale maps from 11.00 to 17.00 G.M.T. On these maps the hourly observations of wind and cloud amount, made by the synoptic stations in the Netherlands, Belgium, and the adjacent part of Western Germany have been plotted and lines of equal dewpoint have been drawn. Areas with dewpoints above 12 °C are enclosed by solid lines and marked by M (= moist). In regions where the dewpoints were below 12 °C the lines of constant dewpoint are represented by dotted lines and the dry areas are marked by D (= dry). Areas covered by thunderstorms are shaded.

The thunderstorms developed in a warm continental airstream at the southern flank of an anticyclone over Scandinavia. In this air the temperatures reached afternoon values of 25 °C to 28 °C.

The most important feature is an isolated thunderstorm which developed between 14.00 h and 15.00 h G.M.T. in the neighbourhood of the airfield Volkel (indicated by an arrow on the maps) and moved with the easterly airstream towards Rotterdam. At Volkel airport the cloud produced a slight shower, but soon afterwards it grew to thunderstorm dimensions. An hour later the dewpoint at this station had dropped from 12 °C to 7 °C and the temperature had risen from 27 °C to 28 °C. At the neighbouring airfield of Eindhoven the dewpoint dropped to 8 °C at the same time but outside the dry area the dewpoints remained at the same level. The recovery of the dewpoint at Volkel airport to 10 °C at 16.00 h G.M.T. and to 12 °C again at 17.00 h G.M.T. is also noteworthy.

It is very difficult to explain this humidity dip by the arrival of air which has spread out in the downdraught underneath the storm. The winds should then have become westerly and temperature should have fallen instead of risen. Neither the synoptic observations nor the records of the volunteer thunderstorm observers gave any indication of strong gusts during the passage of the storm and the wind direction remained generally easterly. Fig. 3 shows the contours of



the cloud, copied from time lapse pictures of the cloud system taken at intervals of a minute between 14.21 h and 14.49 h G.M.T. The distance of the storm could be inferred from the reports of the volunteer thunderstorm observers and from the rainfall pattern. Moreover, during the time-interval in which the pictures were taken aircraft reported the highest tops of the cumulonimbus at 42 000 feet. From these data and the measurements on the photographs the dimensions of the cells and the rate of vertical growth of the tops could be deduced. At the beginning of the series the tops had already grown to a height of about 10 000 metres. The diameter of the cells was about 4 kilometres and the upward velocity of the cloud tops ranged from 10 to 23 metres per second.

Later on the cells had diameters of about 6000 metres and became enveloped by the anvil of the cumulonimbus. A characteristic feature of the storm was, that new cells developed to the west of the cloud system, i.e. downwind from the main body of cloud and that the anvil spread towards

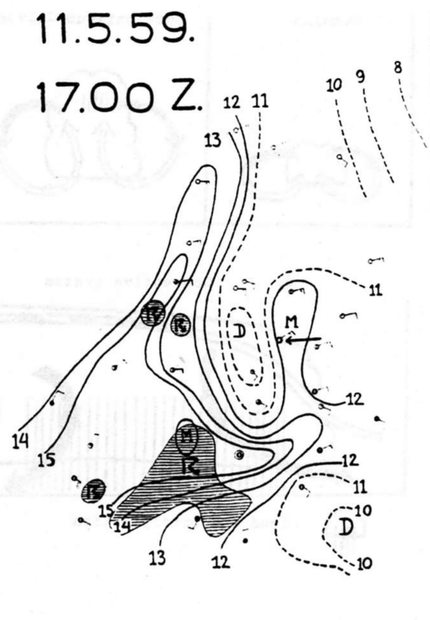


Fig. 2a–2g Meso-scale changes in the dewpoint pattern over the low countries between 11.00 and 17.00 h G.M.T. Moist and dry areas are indicated by M and D respectively. Winds and cloud amounts are shown in the usual way. Areas with thunderstorms are shaded. Note the humidity changes at the airfield of Volkel (indicated by the arrow)

the east. The storm was selfpropagating and could be followed up over more than three hours. It is most remarkable that the development of the dry area between 14.00 h and 15.00 h G.M.T. took place long after the cloud system had produced a shower, i.e. when it had already entered the mature stage and showed the IIId phase growth, described by Ludlam (1957), which occurs after the onset of glaciation of the cumulus towers.

Having the schematic cross-sections of fig. 1 in mind, it is reasonable to suppose that the dry area in fig. 2e was caused by subsidence associated with the development of the anvil of the storm. From the radiosonde ascent, which was made at de Bilt at 12.00 h G.M.T., two hours prior to the development of convective clouds, we can infer the rate at which the air near Volkel airport had subsided during the period between 14.00 and 15.00 G.M.T. We therefore have to assume that the humidity recordings made by means of the gold beaters skin of the radiosonde humidity element can be compared with those made by the Asmann hygrometer in the screen at 2 metres above the surface. This is, in fact, not correct and it would be desirable to have these replaced in future studies by at least a homogeneous record of a good psychrometer system, for example, by aircraft observations. Secondly, we have to assume that the water vapour added to the air by evaporation from the soil can be neglected. During the period from 1st May to 31st July 1959 which was extremely dry and sunny, the evaporation determined at de Bilt, following a method put forward by Penman (1950)

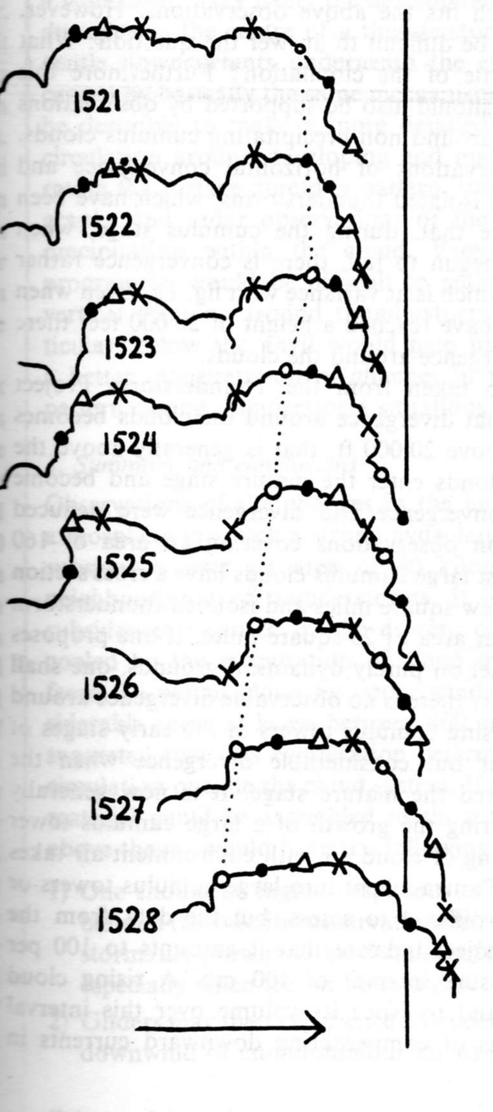


Fig. 3 Contours of the cumulonimbus cloud during its development between 15.21 and 15.28 h local time (14.21–14.28 G.M.T.). The movement of the protrusions at the cloud top (which are indicated by markers) relative to the parent cloud is clearly seen. These protrusions retained their velocity component in the direction of motion of the cloud system, but having arrived at the cloud top at approximately 12 000 metres, they were quickly carried away by the upper winds in the opposite direction. This has also been noted by Hitschfeld (1959, 1960)

was 433 mm. From these figures we can estimate that probably less than a few tenths of grams per kg of water vapour was added to the layer between the surface and the cloud base, (which was at 1600 metres) within an hours time. This is below the limits posed by the accuracy of the measurements.

However, taking the available synoptic information at its face value, we can deduce from fig. 4 that a humidity dip from a dewpoint of 12 °C to a dewpoint of 7 °C corresponded to a subsidence of about 1000 metres, or, roughly 100 mb in the lowest levels of the atmosphere. This would mean that between 14.00 and 15.00 G.M.T. on the average the air would have subsided at the considerable rate of 0,3 metres per second. Even this figure may be an underestimate. A subsidence like this must be desastrous for the development of cumulus clouds, and gliders who would have entered the dry area in fig. 2 might have been forced to give up their flight. In fact, during the development of the cumulonimbus, small cumulus clouds over de Bilt soon disappeared and even a forest fire in the neighbourhood did not succeed to trigger off fresh cumulus growth.

It may be interesting to see whether the subsidence associated with the dry area could have been produced by the isolated storm.

Referring to the model of convection currents presented in fig. 1, one is inclined to wonder why the dry area should appear so far behind the cumulonimbus and not around the cloud system. This has led to the inspection of the hodograph of the upper winds reported by de Bilt at 12.00 G.M.T. This hodograph represents the undisturbed wind profile, which existed before the development of cumulus clouds. Up to 6900 metres the wind was rather steady, both in direction and velocity, but between 6900 and 9300 metres it backed rather sharply to the northwest (fig. 5). This means that the tops of cumulonimbus clouds entering the layer between 6900 and 9300 metres were blown to the southeast. This is consistent with the photographic and visual observations, and it seems reasonable to suppose that the dry area to the southeast of the storm was somehow associated with the third phase growth of the cloud tops after the onset of glaciation.

It can be inferred from the hodograph that an air parcel at a height of 9300 metres would remain 25 miles behind a parcel at 6900 metres in an hours time. Moreover, from the photographic measurements the horizontal tangential velocity of the nodules at the cloud top, which were blown to the southeast could be estimated. From these figures a velocity vector of about 50 kilometres (28 knots) pointed southeastward relative to the main body of cloud could be deduced (see fig. 3). The center of the dry area was found to be about 60 kilometres (or 33 miles) to the southeast of the storm. In view of the uncertainty about the considerable distortions of the wind field in the neighbourhood of a developing storm, a consistency of the above three figures to an accuracy of 25 per cent makes it possible to believe that the subsidence was caused by the evaporation of precipitation particles from the cumulonimbus anvil, which trailed behind in the wind shear. A subsidence of an air parcel from about 9000 metres (300 mb) to 7000 metres (400 mb) within an hour would correspond to an average downward velocity of 2 kilometres per hour or 0,6 metres per second at these levels. This is comparable with the fall speeds which ice crystals, having characteristic diametres of a millimetre, could have at these levels. Jones (1960) reports that particles

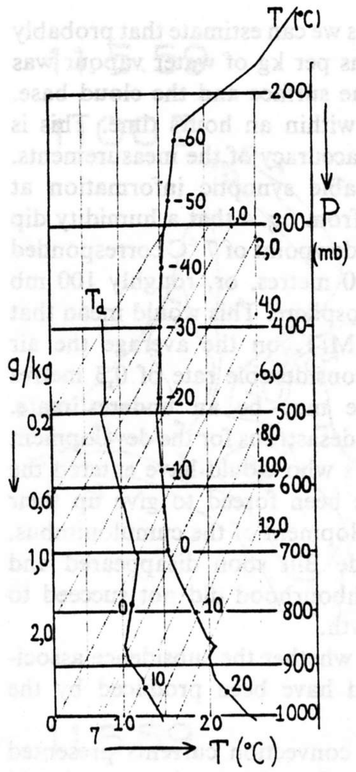
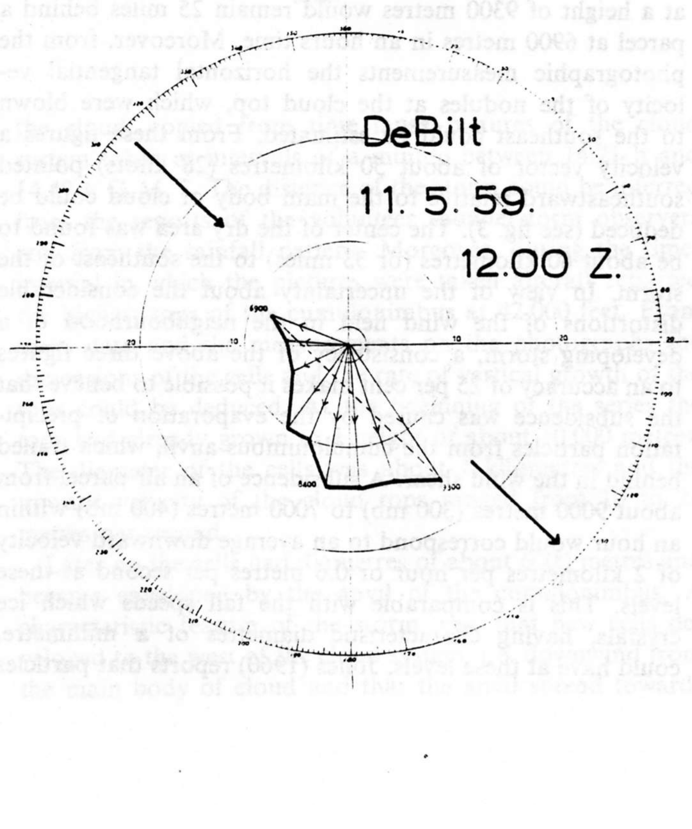


Fig. 4 Radiosonde ascent made at de Bilt at 12.00 h G. M. T. Horizontal lines are isobars, vertical lines are saturated adiabats. Lines of constant humidity mixing ratio are dotted. Temperatures are indicated at the ascent curves

of about a millimetre diameter with terminal velocities of about one metre per second are present in concentrations of 1 to 10 per litre in cumulonimbus anvils well away from the parent cloud. Moreover, air, which subsided from 300 mb (temp. −47 °C) to 400 mb (temp. −32 °C) could take up about 0,6 g/kg of water vapour, or about 1 gram per m³. This value corresponds to the "solid water content" of anvil cirrus well away from cumulus towers, quoted by Jones. He has found 1,25 g/m³ from aircraft measurements of the ice crystal contents in anvil cirrus. Hitschfeld (1960) from his radar studies of plume formation in thunderstorms, deduced fall speeds of anvil particles which ranged from 1 to 7,5 metres per second at the 300 mb level (which corresponds

Fig. 5 Hodograph of the upper winds at de Bilt at levels between 6900 and 9300 metres



to 0,75–4,9 m/sec. near the surface), and concluded that the *melted* diameters of these particles were probably 0,8 to 5 mm. The plume formed at a height of 10 500 metres and subsided to 4500 metres, where it was evaporated.

This evidence strongly supports the hypothesis that the evaporation of ice particles from the cumulonimbus anvil may be a possible cause of the subsidence underneath it, but there will still be the task of designing a circulation model which is not in contradiction with all the evidence which a thorough investigation with modern methods can produce.

For instance, when the air around the anvil is near ice saturation the evaporation of the ice crystals would proceed at a much slower rate or cease altogether and the anvil would then be blown away over a large distance. (Would we observe the same sort of circulation in this case?) Humidity measurements made by the radiosonde element are unreliable at the 300 mb level, and also, the rate at which the anvil cloud air mixes with the environment air is unkown. These data should be incorporated in calculations of the rate of evaporation and subsidence of the anvil.

In the above situation we only have at our disposal the cloud observations which suggest that the air at the level of the cumulonimbus top was rather dry and that the anvil evaporated fairly rapidly.

One could of course argue that not the evaporation of material from the anvil, but the growth of the expanding cloud could already be sufficient to cause subsidence in its surroundings, and one can even suggest a purely mechanical or dynamical model of the circulation, based on the principle of continuity which fits the above observations. However, in this case it will be difficult to answer the question: What determines the scale of the circulation? Furthermore this circulation model should also be supported by observations of the circulation around non-precipitating cumulus clouds. But the few observations of horizontal convergence and divergence around isolated thunderstorms, which have been published, indicate that, during the cumulus stage, when rain has not yet begun to fall, there is convergence rather than divergence, which is at variance with fig. 1a. Even when the cumulus tops have reached a height of 20 000 feet there may still be convergence around the clouds.

Fig. 6a and 6b taken from the Thunderstorm Project clearly indicate that divergence around the clouds becomes important only above 20 000 ft, that is generally above the level where the clouds enter the mature stage and become glaciated. The convergence and divergence were deduced from pilot balloon observations covering an area of 160 square miles, whilst large cumulus clouds have a cross section of the order of a few square miles and isolated thunderstorm cells may cover an area of 25 square miles. If one proposes a circulation model on purely dynamical grounds, one shall have to explain why there is no observable divergence around the summits of rising cumulus towers in the early stages of their development but considerable divergence when the clouds have entered the mature stage. It is now generally accepted, that during the growth of a large cumulus tower considerable mixing of cloud air with environment air takes place. The rate of entrainment into large cumulus towers or thunderstorms is difficult to assess, but the data from the Thunderstorm Project indicate that it amounts to 100 per cent over a pressure interval of 400 mb. A rising cloud bubble may expand to twice its volume over this interval without any signs of compensating downward currents in

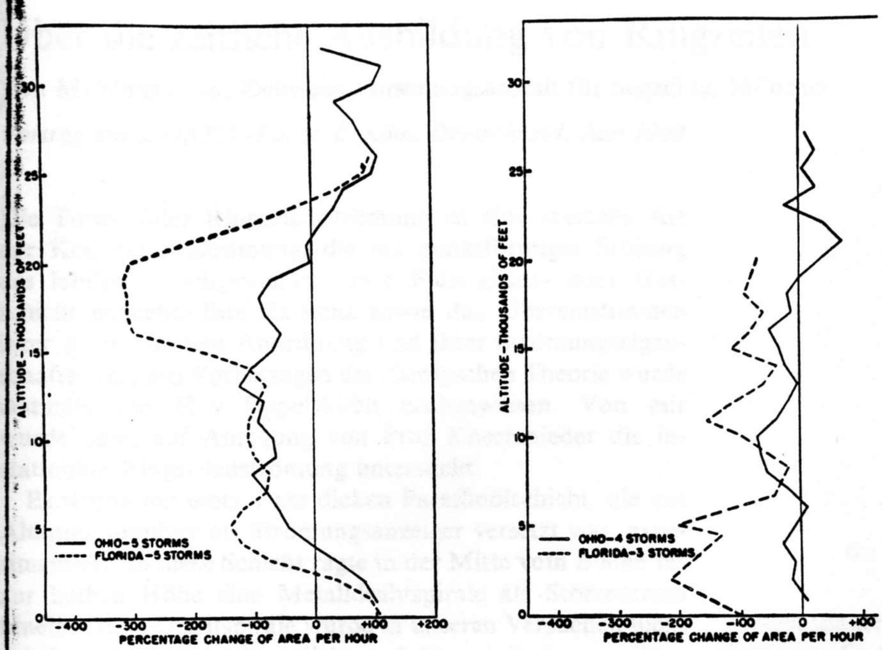


Fig. 6 Thunderstorm structure and circulation (after Byers and Hull, 1949)

a) Graph showing the change with height of the divergence about thunderstorms from which rain was falling. These curves represent averages based upon five thunderstorms in Florida and five thunderstorms in Ohio. The divergence is expressed as the percentage change in area per hour, with a positive value representing divergence. Computations were based on the horizontal displacements of several balloons passing through given levels at approximately the same time

b) Graph showing the change with height of the divergence about growing cumuli from which heavy rain had not been falling. These curves represent averages based upon three sets of observations in Florida and four sets of observations in Ohio. The divergence has been calculated from the horizontal displacements of several balloons passing through given levels at approximately the same time and is expressed as a percentage change in area per hour. A positive value represents divergence

its surroundings. It rather seems that these have to be sought in regions where cloud towers evaporate. As condensation and evaporation have been taken into account in previous studies of the circulation inside a thunderstorm cell or even inside a rising cloud thermal, it seems logical to do the same if we wish to explain certain circulations outside large convective clouds, which grow into a layer where there is a windshear. Very likely the development of vigorous downdraughts in the centre of a thunderstorm cell and the more gentle downcurrents underneath the evaporating anvil are caused by basically the same mechanism. It would, therefore, be desirable to make a more detailed investigation of the circulation around developing and mature storms incorporating the surface humidity pattern, time lapse cloud photographs and radar observations of the development of the precipitation within the cloud. Even if such a research programme would be difficult to realise, gliders reports of vertical motions around thunderstorm clouds and, in particular, below the anvil would help us very much towards a better interpretation of changes in the surface humidity pattern during thunderstorm situations.

3. Summary and conclusions

Observations of the changes in the humidity pattern in an atmosphere in which a strong hydrolapse is present, indicate subsidence over an area of 40 kilometres across in the neighbourhood of thunderstorms. It is suggested that this subsidence is caused by the descent of air which has been cooled by the evaporation of cloud material carried away from the parent cloud by upper winds, which show a considerable shear at levels between 400 and 200 mb. It is also suggested that this evaporation determines the scale of the circulation outside the cloud system. If enough observational material could be assembled to show this conclusively, the above theory would have the following implications:

1) One should be highly suspicious of radiosonde and pilot balloon (theodolite) observations in regions where thunderstorms are present within 50 miles of the radiosonde station especially when the air aloft is dry.
2) Gliders may then experience downcurrents over large areas downwind of cumulonimbus anvils and should be advised to fly upwind of large developing cumulus towers. They then have to know the hodograph of the upper winds, especially at levels between 500 and 300 mb.
3) Thunderstorms would be expected to move or to expand into a direction opposite to that of the windshear vector between the levels of 500 and 300 mb. This may explain the erratic movement of thunderstorms reported by Hitschfeld (1959) which was sometimes at variance with the upper winds at all levels.

However, it must be emphasized, that if the air is moist at cirrus level, evaporation of the cumulonimbus may not take place and consequently, there may be no important change in the surface humidity pattern. Similarly, if the humidity mixing ratio is nearly constant within the first kilometre or so above the surface, the humidity distribution may remain generally the same, but the absence of cumulus clouds over certain areas should be indicative of strong downward motions.

It is important for short range forecasting to know the dimensions and the movement of regions of subsidence associated with the storms. These may, while they pass over the station, delay the arrival of thunderstorms for periods of at least an hour, and in some cases, thunderstorms situated in regions upwind of the station may not arrive at all, in spite of a favourable wind at the 800 or 700 mb level.

The few cases studied so far are consistent with these ideas but a more detailed statistical study will be undertaken in due course.

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