Circulations in large sheared cumulonimbus

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ABSTRACT

The structure of a cumulonimbus cloud subjected to vertical shear is interpreted in light of the horizontal forces acting upon it, and of the varying thermodynamic influences in its different parts. In-cloud horizontal velocities depart greatly from those in the environment, and the forms assumed by draft columns (updrafts typically leaning in a sense opposing the vertical shear) vary with the shear, vertical motion, and speed of storm movement.

The cumulonimbus is viewed as an ensemble of air elements which have undergone varying degrees of mixing with the environment, penetrating upward to different heights. Some of the air in the updraft rises into stratospheric towers, then descends as a vigorous downdraft which, because of mixing-in of heat and of air having no initial vertical momentum, dies out in the upper troposphere. This air, together with air reaching the upper troposphere in the less buoyant outskirts of the updraft, feeds the expanding anvil plume. A separate downdraft in the lower part of the cloud, originating from middle levels where the wet-bulb potential temperature is low, continually regenerates the updraft though mechanical lifting. Estimates of the air and water budgets of squall-line thunderstorms are given.

1. Introduction

One of the many areas in which Professor Tor Bergeron has illuminated our understanding of the atmosphere, is that of convective phenomena. His contributions have ranged from the microphysics of precipitation processes (BERGERON, 1935) to interpretations of the structures of large organized convective weather systems (BERGERON, 1954). An acute observer and interpreter of natural events, he has taught us the great value of deductions from indirect evidence, in an atmosphere wherein direct observations are seldom to be had in sufficient quantity.

Because of the difficulties of making direct measurements in severe thunderstorms, our conceptions of their internal circulations are largely founded on inferences. In this paper, an attempt is made to deduce certain characteristics of these circulations, from the form and dimensions of a cumulonimbus.

2. Persistent storms and ventilation by shear

The most comprehensive description of convective storms to date, resulting from observations in their interior as well as outside them, is that by the Thunderstorm Project (BYERS & BRAHAM, 1949). In recent years considerable evidence has been brought forward suggesting that large severe thunderstorms, growing in environments typified by appreciable vertical shear, differ in important respects from the more common but less destructive air-mass type predominating in these studies.

Shear in the environment plays a twofold role. It largely accounts, by the process of differential advection of heat and moisture in upper and lower levels, for the generation and maintenance of thermodynamic instability. Secondly, for reasons summarized by NEWTON (1963), strong vertical shear is hostile to small clouds with weak convection; but favorable for the survival, through continuous reinvigoration, of a limited number of large storms.

One reason for this is illustrated in the highly-simplified Fig. 1. Radar observations show (HITSCHFELD, 1960) that the heavy-precipitation cores of intense thunderstorms resist being deformed, even when the wind shear between storm base and top is around 100 kt. This condition is possible when the vertical motions in the storm core are intense, with

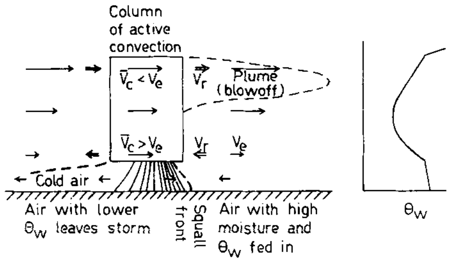

FIG. 1. Principal components of a large sheared thunderstorm. V_r denotes relative wind, the difference between mean wind $\overline{V}_c$ at a given level in storm column and wind V_e in undisturbed environment. At right, schematic vertical distribution of wet-bulb potential temperature in environment.

vigorous vertical transfer of horizontal momentum, and at the same time the drafts are of large lateral extent (NEWTON & NEWTON, 1959; HITSCHFELD, 1960). The massive "plumes", observed to stream along the general direction of the vertical shear, consist of cloud matter eroded from the column of active convection. As the storm advances in the general sense indicated by the upper winds, air disgorged by the downdrafts is left behind as a cold layer. This evaporatively cooled air accounts for the extensive high-pressure cells characterizing organized convective systems (BERGERON, 1954); FUJITA, 1959), and its advancing front plays an essential role in triggering new convection.

Since the intense convective column in a large thunderstorm maintains its form rather than being sheared off, it is evident that such a storm is *ventilated*. Owing to its motion relative to the air in the lower moist layers, the storm sweeps up air having high water-vapor content and high wet-bulb potential temperature. Unlike a storm cell in a stagnant environment, which overturns the air in its immediate locality and perishes, *a storm in a sheared environment has its latent energy continually replenished as it is used up*. This principle has been stressed by WEICKMANN (1953) as an essential feature of the large persistent thunderstorm. The disposal of waste products through the action of shear, in the form of the plume blowoff and the lower-level layer of residual cold air, is also important. If warm air were permitted to accumulate in upper levels and cold air in lower levels in the near environment, the resulting stabilization would soon vitiate the thermodynamic driving mechanism of the storm.

3. Winds in and around storms

In a shear field, rising or descending air tends to conserve its momentum, but only partially, being subjected to forces of interaction with the environment winds. BATES (1961) has formulated principles by which these forces may be analyzed to deduce the configurations of drafts in convective systems. Considering a circular draft of diameter D, a horizontal slice or "wafer" is subjected to a drag force

$$F_D = C_D \varrho D h V_r^2/2 \qquad (1)$$

where C_D is a drag coefficient (here taken as 1.8, corresponding to a rough cylinder), h is the thickness of the wafer, and V_r is the relative motion $(V - \sigma)$, V being the wind speed in the environment and σ the horizontal wind speed inside the draft. The impulse of the wafer mass M is

$$M\dot{\sigma} = \dot{\sigma}\varrho' h \pi D^2/4. \qquad (2)$$

Neglecting the small difference between the density ϱ' inside the draft and the density ϱ outside, combination of Eqs. (1) and (2) gives, according to Bates,

$$\dot{\sigma} \approx 2C_D(V - \sigma)^2/\pi D \qquad (3)$$

for the special case of a two-dimensional wind field (wind not turning with height).

If entrainment of horizontal momentum is neglected, $\dot{\sigma} = w d\sigma/dz$, and the horizontal speed of the air within the draft may be computed from Eq. (3). In some preliminary calculations (BATES & NEWTON, 1965), we have assumed vertical velocity profiles of the form shown in Fig. 2*a*. Although the profile of upward velocity is realistic, it will later be shown that the downdraft profile is not; however certain parts of the calculations based upon it are qualitatively applicable.

For a draft with a uniform diameter of 7.5 km (neglecting the broadening near base and top in Fig. 2*b*), an assumed environmental wind field given by curve V, and varying values of w_{max}, the computed horizontal speed σ in the drafts is given in Fig. 2*c*. The accommodation of σ toward V is, as would be expected, most

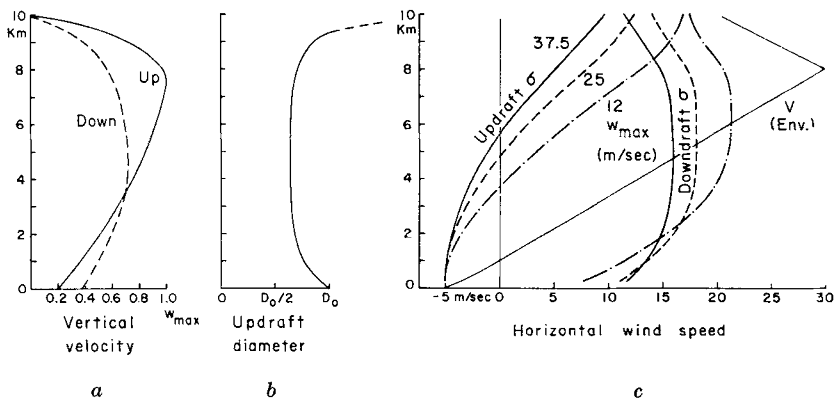

FIG. 2. (*a*) Assumed vertical velocity profile in updraft (solid) and in downdraft (dashed); (*b*) corresponding variation of updraft diameter with height; (*c*) horizontal wind velocity in drafts (σ) and in environment (V), from computations by Bates and Newton (1965).

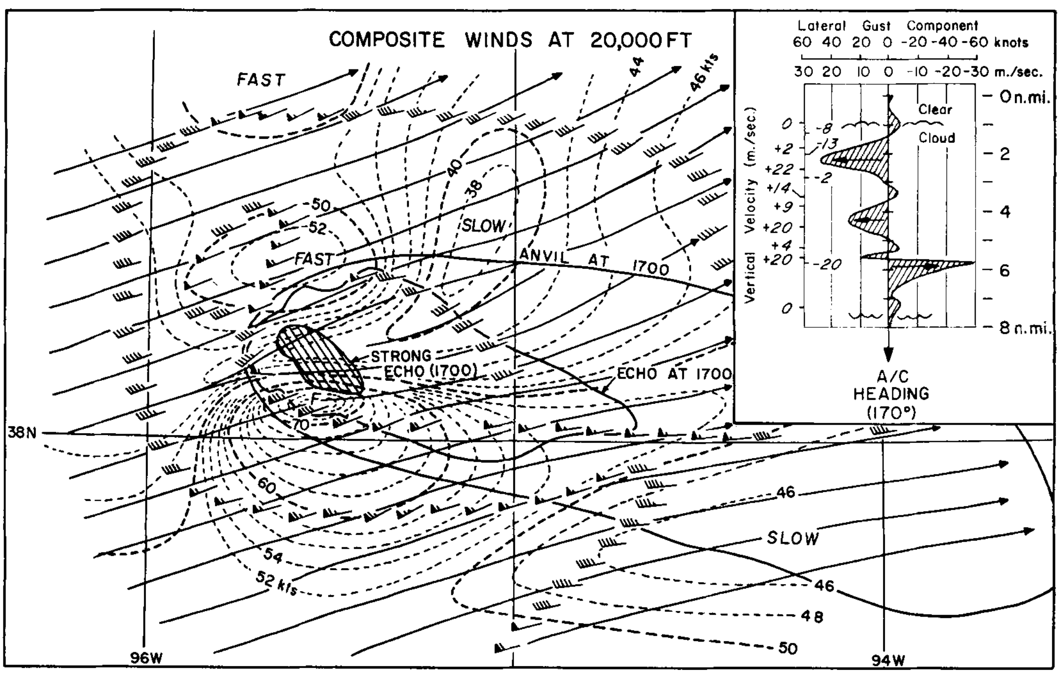

FIG. 3. Composite winds at 6000 m in the vicinity of a thunderstorm over SE Kansas, 1620–1813 CST 21 April 1961, after Fujita and Arnold (1963). Winds, measured by U. S. Weather Bureau DC-6B aircraft, were plotted in a coordinate system relative to the radar-echo center at times of measurement. Dashed lines are isotachs. Anvil boundary was determined photogrammetrically, from nose-camera films taken by B-57 aircraft flying at 13.5 km. Inset shows, based on data from Steiner and Rhyne (1962), a highly-smoothed representation of the lateral gust components measured by a NASA-instrumented Air Force T-33 aircraft traversing a storm in a similar wind environment (peak values from smoothed profile of vertical velocity, at left). Flight altitude was 11.9 km, 2 km below estimated cloud top.

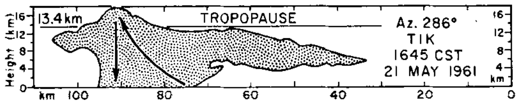

FIG. 4. Profile through a squall-line thunderstorm, represented by full-gain echo of FPS-6 vertical-scan radar (10-cm wavelength) at Tinker Air Force Base, 20 km E of Oklahoma City, Oklahoma. See text.

pronounced when the vertical velocity is small and the draft wafer, while undergoing an acceleration due to drag, takes a longer time to rise or descend through a given layer of the atmosphere.

In the case of the most vigorous vertical motions, the computations indicate a difference of up to 25 m/sec between the horizontal speeds within and outside the draft. Observational evidence supporting such wind deviations within and around cumulonimbi is illustrated in Fig. 3 which shows the wind field in the middle troposphere, in the neighborhood of a large cumulonimbus (FUJITA & ARNOLD, 1963). Ambient winds were southerly 20–40 kt in the subcloud layer, and westerly about 80 kt near the tropopause. This storm was moving eastward with a speed of 22 kt, compared with the WSW wind of about 50 kt in the environment at this level. The isotach field indicates a speeding-up of the flow beside the flanks of the storm core, and a region of weaker winds on its downwind side, suggestive of the pattern of velocities observed around obstacles in wind tunnels.[1]

The inset shows some measurements of the horizontal gust components inside the upper part of a cumulonimbus in a similar wind field. In this case, west-wind velocities 15 and 24 m/sec deficient from the environment winds were associated with moderate updrafts.

4. Storm shape and draft configuration

Fig. 4 shows a vertical section through a large cumulonimbus, in a squall line approaching Oklahoma City on the afternoon of 21 May 1961. Winds were southerly about 30 kt in low levels, and westerly about 60 kt near the tropopause. Fig. 4 is oriented approximately along the direction of the shear through the cloud layer.[2] *Although the anvil plume streams along the general direction of the shear, the highest tower is located on the upshear side of the main convective column.* Visual as well as radar observations (BYERS & BATTAN, 1949) show this to be the characteristic location where high-reaching turrets successively appear. This has sometimes been interpreted as an indication that the updraft originates from an influx of air in low levels on the same side.

The fallacy in this misconception is evident from the fact that in this case, for example, the squall line was advancing southeastward against southerly winds in the subcloud layer, low-level moist air obviously being fed in on the general forward side of the thunderstorms. Since a tropopause-penetrating tower must mark the general location beneath which the updraft has large kinetic energy, it is most reasonable to conclude that *the updraft leans in an upshear sense as it traverses the storm from its region of entry.*

Such a configuration is supported by computations of the draft figure. The draft column may be considered as the locus of the endpoints of trajectories of air parcels which have risen from cloud base at successive times. Although such a *parcel* trajectory may lean in a downshear sense, the *draft* profile does not necessarily do so (Fig. 5). Thus although it is a common observation that small clouds lean downshear, this is not characteristic of the drafts in large travelling storms.

If c is the speed with which a cloud system is moving, the shape of the draft figure may, as outlined by BATES (1961), be computed from

$$x(z) = \int_0^t (\sigma - c)\,dt; \; z = \int_0^t w\,dt \qquad (4)$$

[1] This similarity is particularly striking on the south side, where the *relative* motion of the external air approximately doubles, from 28 kt in the "undisturbed" flow to 50 kt just south of the storm core. This is an indirect indication of a deficit in pressure in that location, whose magnitude would from Bernoulli's equation be about 1.4 mb. The induced pressure varies at different levels, and its vertical gradient contributes significantly to vertical accelerations, which influence the regeneration of convection (NEWTON & NEWTON, 1959).

[2] The important influences of veering of the wind with height have been discussed by BROWNING (1964) in regard to the configurations of storms, and by NEWTON & FANKHAUSER (1964) in relation to their water budgets and movements. For simplicity, only the principal component of the shear is considered here.

where σ is given by Eq. (3), and x is measured horizontally from the locale where the updraft rises from cloud base, in a coordinate system moving with the storm speed c. In the computations shown in Fig. 6 (based on Fig. 2), c has been taken to be the particular storm speed for which the top of the downdraft lies directly above its base. There is no evident theoretical basis for this choice, but it yields a storm speed which is near the mean environmental wind velocity through the depth of the storm, in broad agreement with average observed storm movements.

Fig. 6 shows that the upshear canting of the updraft is least when vertical motions are strong. Similar calculations, in which the shear of the environment wind field was varied by a factor of three, disclosed about the same degree of variation in the draft figure. Varying the draft diameter by a factor of two, although it has a strong influence on σ, has little effect on the configuration of the draft. However, storms with large-diameter drafts are indicated to move significantly slower than storms with small-diameter drafts. This is in accord with observations on the movements of radar echoes of different sizes (NEWTON & FANKHAUSER, 1964).

The solid profile in Fig. 6, computed for conditions most nearly similar to the wind and

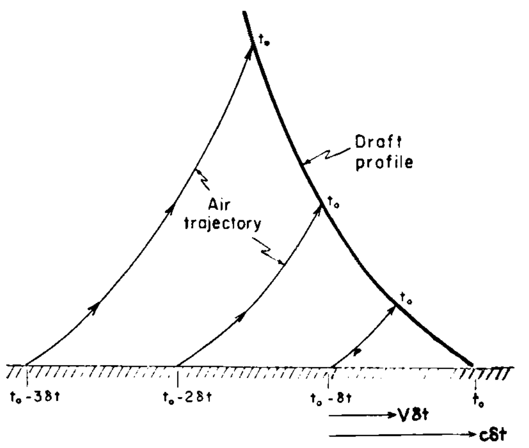

FIG. 5. Showing the tilt of an updraft column which results from displacements of successive parcels upward from the lower layers. The squall front, which triggers their initial rise, is in this example assumed to have a speed c toward right, greater than the horizontal speed V of the air parcels. (Adapted from Bates, 1961.)

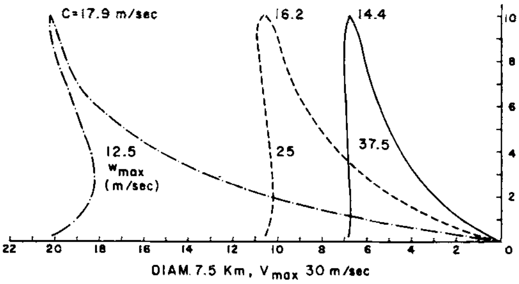

FIG. 6. Computed profiles of updraft and downdraft, for three intensities of vertical motion, based on Fig. 2c. Storm speed c indicated at tops of profiles. See text. (After Bates and Newton, 1965.)

stability environment of the storm in Fig. 4, fits rather well with the storm figure. This demonstrates that *it is physically reasonable for air entering the forward side to emerge at the top of the storm on the rear side.*[1]

Successive tracings of the radar profile (Fig. 7) suggest that this may most properly be called a "pulsating persistent" storm. Such a storm is associated with a squall front (advancing edge of rain-cooled air) which more or less continuously lifts the air ahead of it to maintain an updraft. The variable height attained by the tower, which appears persistently on the upshear side, indicates however that the vigor of the updraft varies in a pulsating manner, the net mass flux through the tropopause being alternately upward and downward.

5. Thermodynamic processes

Although direct evidence as to the degree of entrainment into convective drafts is lacking, it has been convincingly established that the rate of entrainment decreases with increasing lateral dimension of the draft. MALKUS & WILLIAMS (1963) conclude that

$$\frac{1}{M}\frac{dM}{dZ} \approx \frac{1}{D} \qquad (5)$$

[1] The configuration in Fig. 4, while common, does not in all respects typify all storms. Analyses by BROWNING & LUDLAM (1962) and by BROWNING (1965) show that in the most severe phase of some storms the updraft becomes more nearly upright, the stratospheric tower assuming a position farther forward. This is consistent with our computations which show that, *ceteris paribus*, when the speed of storm motion is diminished and the intensity of vertical motion increased, the computed updraft profile becomes more nearly vertical and its upper motion may lean downshear.

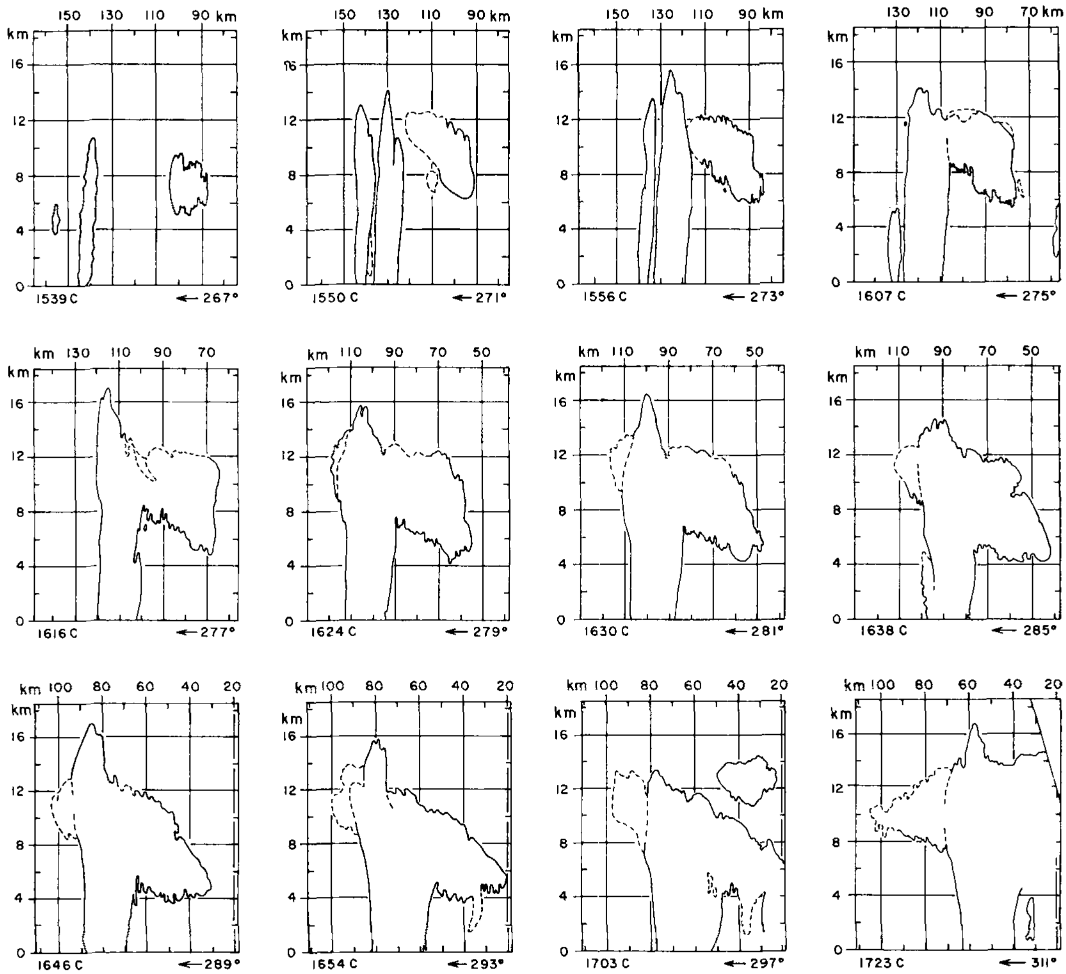

FIG. 7. Successive full-gain radar profiles of storm in Fig. 4 at indicated times, azimuths and ranges from Tinker Air Force Base. Vertical exaggeration is sixfold. Although the shape of the main storm column is adequately indicated, the extent of anvil is only crudely representative. In the first few frames, the radar slices through the anvil plume from another storm, while later on the plumes from several storms were merged into a sheet of the approximate breadth indicated.

where $M(z)$ is the vertical mass flux in a draft of diameter D.

A large cumulonimbus, at an advanced stage of its development, consists largely of "dead air" which has gone through the active vertical drafts and been eroded from them; only a restricted portion of the total cloud volume is likely to consist of thermodynamically active drafts. From Fig. 4, it would seem that the updraft rises mainly through a cloudy-air environment. For lack of a better assumption, it will be presumed that the air in the cloud volume outside the active drafts is non-buoyant, having the same temperature as the clear environment but being saturated. The anvil, at least, appears to be essentially non-buoyant since its downward slope toward the east (Fig. 4) is roughly in accord with the trajectories of small precipitation particles drifting with the wind and falling with speeds of 1 m/sec more or less (HITSCHFELD, 1960).

Fig. 8 shows a composite sounding, based on serial ascents at $1\frac{1}{2}$-hr intervals between 1110 and 1910 CT 21 May 1961, which is considered representative of the undisturbed environment of the storm in Figs. 4 and 7. Curves A show

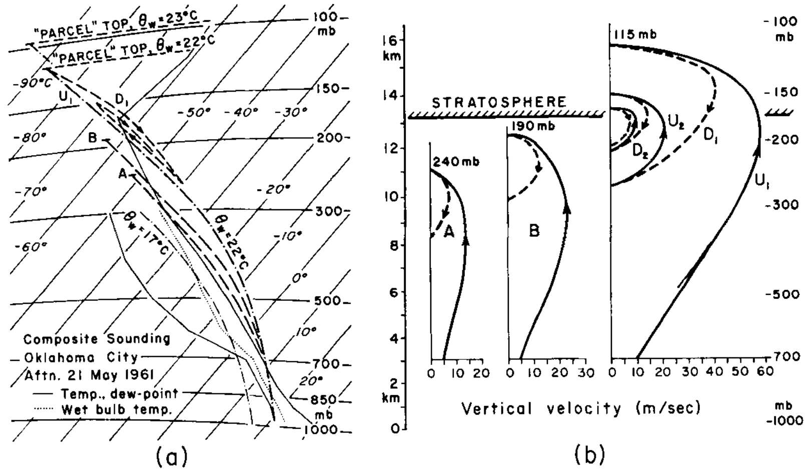

FIG. 8. (*a*) Representative sounding at Oklahoma City, afternoon of 21 May 1961 (thin solid lines temperature and dew point; dotted line, wet-bulb temperature). For meaning of other lines, see text (*b*) Vertical velocities in updrafts (solid lines) and downdrafts (dashed lines), under different assumptions described in text.

the draft temperature and vertical velocity corresponding to entrainment from the *unsaturated* environment at a rate of 1/(6 km).

The computations were made graphically on a thermodynamic diagram, utilizing a procedure outlined by J. M. AUSTIN (1948). Vertical motions were computed from the buoyancy equation, for a parcel having initially the wet-bulb temperature of 22°C which corresponds to the mean in the moist layer below 700 mb. An upward velocity of 5 to 10 m/sec at 700 mb was assumed arbitrarily. Vertical velocities were modified to take into account the incorporation of outside air having initially no vertical momentum. Thus if w_1 is the vertical velocity at one level and w_2 that at a level 1 km higher,

$$w_2 = \frac{k}{k+1}\left(w_1^2 + 2\int_{p_2}^{p_1} R\Delta T\, d\ln p\right)^{\frac{1}{2}} \qquad (6)$$

where $k^{-1} = M^{-1}\, dM/dz$ is the entrainment rate and ΔT the temperature excess over the environment. The top of the updraft in case A is found to be 11 km, in accord with the echo top at 1539 CST in Fig. 7, when the echo diameter was about 6 km [Eq. (5)].

The greatest vertical developments achieved by large storms are often in good agreement with parcel theory, and this has sometimes been taken as an indication that their updrafts may be undiluted. In light of Eq. (5), however, it is unlikely that the vertical drafts (whose dimensions probably do not exceed 10 km) do not experience significant entrainment. This apparent inconsistency can be resolved if *the cores of updrafts are considered to be essentially unmixed, while their outer sheaths undergo strong mixing with the environment.*

In examining this proposition, we may make the crude supposition that an updraft consists of an undiluted core, surrounded by a sheath into which is mixed all the air entrained by the draft as a whole. If the entire draft width is 7.5 km, the effective rate of entrainment into the outer sheath would be 1/(5.6 km), if the core is 1/2 the draft width. The characteristics of the entraining sheath would then roughly correspond to curves B in Fig. 8, for the same conditions as case A but entrainment from the *cloudy* environment through which the draft rises (Fig. 4). In line with the demonstration by AUSTIN (1948), the influence of humidity is pronounced, the updraft in this case rising nearly to tropopause level. If the undiluted core has $\theta_w = 22$°C, the updraft would rise to a height of 15.7 km (curves U_1), while for $\theta_w = 23$°C (corresponding to the mean in the lowest 100 mb) it would rise to 16.7 km. The maximum height attained by the storm of Fig. 7 (allowing for radar beam-width correction) is between these values, suggesting that the innermost core in fact undergoes negligible mixing at times.

At the height of maximum penetration into the stratosphere, a draft parcel, being around 30°C colder than its environment, is subjected to a powerful downward acceleration. Its subsequent behavior depends on the degree of entrainment. It is unlikely that an appreciable amount of updraft air descends again in an undiluted condition. Observations of growing towers (SAUNDERS, 1961) show that their tops rise at speeds very much smaller than the vertical motions within the drafts, indicating that strong divergence is present in their upper portions. Photogrammetric analyses of the movements of irregularities on tower surfaces (ANDERSON, 1960) suggest that the air, after rising in the core, flowers outward and becomes exposed to the environment.

If we suppose that the dilution corresponds to an entrainment rate of 1/(6 km), the properties of the downdraft would be given by curves D_1 in Fig. 8. As a result of mixing with a warm environment in the stratosphere, the downdraft air becomes warmer than the updraft. As a consequence both of this, and of the incorporation of inert air according to Eq. (6), the downdraft would lose all its momentum at 10.5 km. Being buoyant at that level, this air would accelerate upward again, and under the influence of further entrainment undergo a damped oscillation (only the next two excursions of which are shown), *eventually remaining below the tropopause but in the upper troposphere.* Damping in this manner under the influence of drag was discussed by F. H. SCHMIDT (1947).

With a smaller mixing rate the air would gain less heat above the tropopause, and descend to a lower level. Computations from Eq. (6) indicate that with an entrainment rate of 1/(10 km), the downdraft air could descend to the 295-mb level, while with a rate of only 1/(20 km) it could descend to no lower than 360 mb on the first excursion. In the latter case, the temperature in the downdraft differs little from that in the updraft; the buoyancies during ascent and descent are thus nearly equivalent, and the restriction to downward movement is essentially due to the incorporation of air with no initial vertical momentum. These calculations indicate that *only under nearly perfect "unmixed parcel" conditions, not likely to be realized, would it be possible for air which has risen in the updraft to return to the lower troposphere.* It must then be concluded that *virtually all of the air rising in the updrafts remains in the upper troposphere, passing into the expanding anvil of the cumulonimbus.* This statement might be somewhat modified if the weight of liquid water, not taken into account in the buoyancy computations, were included.

If as noted earlier the anvil air has on the whole no appreciable buoyancy, its temperature must approximate that of the environment. From Fig. 8, it is evident that air parcels rising in the core of the updraft, those in the entraining sheath of the updraft, and those rising in cloud elements near the periphery of the storm, would have different properties depending on their varying entrainment histories. It seems likely that the anvil air at 200 mb is made up of a mixture of potentially warm air (D_1) which has circulated through the stratospheric tower, and potentially cool air (B) from the upper part of the entraining sheath. At 250–300 mb, on the other hand, it seems likely that the anvil air originates essentially from strongly-entraining air in the outskirts of the updraft (A, B), which is potentially cool and which has never risen to an appreciably higher level.

6. Mass circulation through stratospheric tower

If all the updraft air behaved according to "parcel" considerations, the updraft would spread out at the top in the manner indicated in Fig. 2*b*; in reality, the dome above the tropopause becomes narrower with increasing height (Fig. 4). This suggests that although the air in the *core* at times rises to heights predicted by parcel theory, only a limited portion of the air in the updraft can do so.

The flux of mass through a given isobaric surface in the tower may be written

$$F_m = \int_A (\varrho w)\, dA \tag{7}$$

where A is the cross-sectional area at the level concerned. The mass of air in the stratospheric portion of the tower may be computed from the expression

$$M_s \int \frac{A(z)}{g}\, dp = \int \frac{\pi r^2(z)}{g}\, dp, \tag{8}$$

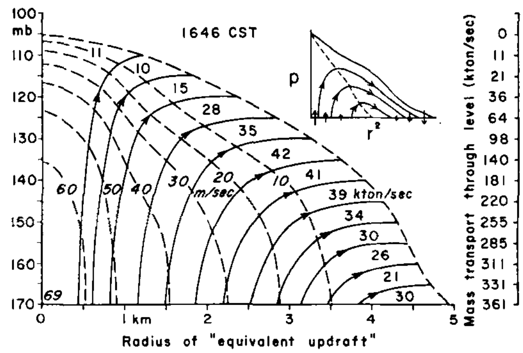

FIG. 9. Isotachs of vertical velocity (dashed), and streamlines, in "equivalent updraft" above tropopause, in storm of Fig. 7 at 1646 CST. See text.

evaluated from the tropopause level to the top of the tower.[1] The alternate inflation and deflation of the tower may be considered as due to the net flux of air through the tropopause, or

$$F_{mT} \approx dM_s/dt. \qquad (9)$$

This quantity was evaluated to be around 0.1 to 0.2 megatons (mton) per second, at times of maximum change in tower mass.

Although this is a measure of the fluctuating *difference* between upward and downward mass transport, it is not a measure of the mass transport itself. In order to estimate this, the fiction is adopted that the flow inside the tower is of the character shown in the inset of Fig. 9. Considering symmetrical flow for computation purposes, Eq. (7) may be written

$$F_m = \int_0^r \varrho w(r) \pi d(r^2). \qquad (10)$$

At times when the tower mass reaches a maximum or minimum, the upward and downward fluxes through an isobaric surface are equal.

In order for an air parcel to reach a given isobaric level, it must have sufficient kinetic energy to overcome the negative buoyancy above the tropopause. For the sake of simplicity, the vertical velocities required are taken to be those prescribed by parcel theory, with $\theta_w = 22°C$. Fig. 9 shows the dimensions and vertical velocity distribution of an "equivalent updraft" computed on this basis, for the time 1646 CST when the stratospheric tower achieved greatest height and breadth.[2] The dimensions portrayed would be valid if the tower were occupied by a single updraft, covering half the whole area of the tower, the other half being occupied by an equivalent downward flow. In reality, as suggested by Fig. 7 and as shown by other studies (e.g. BYERS & BATTAN, 1949), a tower of this sort is likely to be composed of several turrets of smaller dimensions, in varying stages of growth or decay. Thus the individual turrets would, on the average, have the characteristics of Fig. 9 but smaller horizontal dimensions. The total mass flux computed in this manner would be unaffected, however, if the tower were considered to be occupied by one, or by two or more updrafts of smaller dimensions.

Vertical velocity profiles at various levels are shown in Fig. 10*a*, corresponding to Fig. 9. From the mean tower dimensions at 1616, 1624, 1630 and 1638 CST (middle row in Fig. 7),

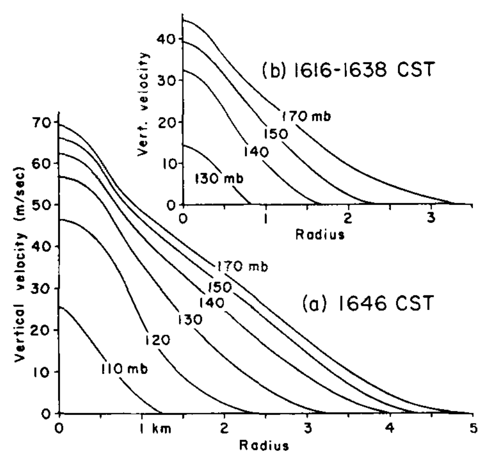

FIG. 10. Profiles of vertical velocity at tropopause and at higher levels in tower, (*a*) corresponding to Fig. 9; (*b*) for earlier period when tower was less developed.

[1] The assumption of a circular cross section of radius *r* is necessary because the lateral beam width of the radar does not permit accurate resolution of the dimensions normal to the line of sight from the observing station. In the computations to follow, the height of the cloud profile, from Fig. 7, was reduced by half the half-power vertical beam width of the radar (0.8°), amounting to 560 m at 80 km range.

[2] The computations were made by drawing successive profiles of (ϱw) *vs.* r^2, working downward from the tower top, at levels 5 mb apart. The mass transport within each streamline channel is constant with height, and the vertical velocity along a streamline is prescribed by parcel buoyancy.

analogous computations give the velocity profiles in Fig. 10*b*. In each case, the vertical velocity decays outward from the updraft core, in a manner similar to that indicated by SCHMIDT (1947) in his entraining-jet model of convective clouds.

The mass transport through the tropopause, in each direction, is evaluated from Figs. 9 and 10 to be 0.10 mton/sec between 1616 and 1638 CST, and 0.36 mton/sec at 1646 CST. Comparing these quantities with the total mass of air in the stratospheric portions of the tower, 15 mton average at the earlier times and 54 mton at the later, the mean residence time for an air parcel in the tower (considering both updraft and downdraft phases) is found to be 5 min in both cases. The mass transport at 1646 CST is probably essentially representative of "steady state" storms of the kind described by BROWNING & LUDLAM (1962) and by BROWNING *et al.* (1965), whose typical tower dimensions are equivalent to those in this case. A rate of about 0.15 mton/sec is probably more representative of a large storm in the pulsating stage.[1] Comparisons in Section 7 indicate that *the mass flow through the stratospheric tower is a significant but minor portion of the flux in the lower portion of the updraft*, consistent with the earlier notion that *although relatively weak dilution takes place in the updraft core, strong mixing of environmental air characterizes the outskirts of the updraft, where the buoyancy is so diminished that most of the air is prevented from rising to the tropopause level.*

7. Air and water budget of squall-line thunderstorm

Fig. 11 shows a schematic section through the squall line as it passed Oklahoma City. The breadth of the storm column in the lower troposphere, made to conform to the duration of moderate to heavy showers, is somewhat greater than the typical width; the dimensions of the stratospheric tower are about the maximum generally observed, and the length of the anvil plume varies according to the stage in the lifetime of the storm. Main branches of the circulation are indicated by heavy arrows. The schematic relative streamlines are intended to suggest that air in different portions of the updraft rises to varying heights, spreading out in the anvil while intermixing.

According to the results in Section 5, no appreciable portion of the updraft air is likely to descend again to the lower troposphere. The presence of a separate downdraft circulation in the lower troposphere is necessary to account for the cold layer which is augmented and left behind as the storm moves along. The lowest wet-bulb potential temperature observed at the ground, 17°C, indicates that this layer was derived essentially from the middle troposphere where there was a corresponding θ_w (Fig. 8*a*).

This general arrangement has been indicated in earlier studies by NEWTON (1950), BATES (1961), FULKS (1962), and BROWNING & LUDLAM (1962) who observe that the main branches of the circulation essentially "turn the atmosphere upside down" on both sides of the storm. Normand emphasized (1938, 1946) that the energy is greatly augmented if a thunderstorm is "organized to take in potentially cool air at high levels as well as potentially warm air at the lower levels".

The in-cloud wind profiles in Fig. 2*c* were computed on the supposition, later demonstrated to be unjustified, that the downdraft extends through the entire depth of the storm. The solution obtained for horizontal velocities in the downdraft is thus only valid for the uppermost levels. However, it is evident in light of Fig. 11 that since the air entering the lower downdraft circulation has an initial momentum characteristic of the middle troposphere, the velocity profile portrayed for the lower troposphere is also essentially realistic. *This downdraft air, reaching the lower layers with excessive momentum, plays an essential role in mechanically lifting the warm air at the intense zone of convergence on its forward side, and thus continually regenerating the updraft.*

Although the available upper-air observations are very limited, these combined with the earlier inferences may be utilized to arrive at an estimate of the fluxes of air and water

[1] This is only a crude estimate, based on the distribution of tower top heights for the observed portion of the squall line, compared with the top heights for the single storm dealt with above. Within a 200-km segment of the line, there were 10 major towers, whose top heights (after beamwidth correction) averaged 1.5 km above the tropopause, with a root-meansquare deviation ±1.5 km (10 % reaching 3.7 km above the tropopause), for 5 scans between 1617 and 1654 CST.

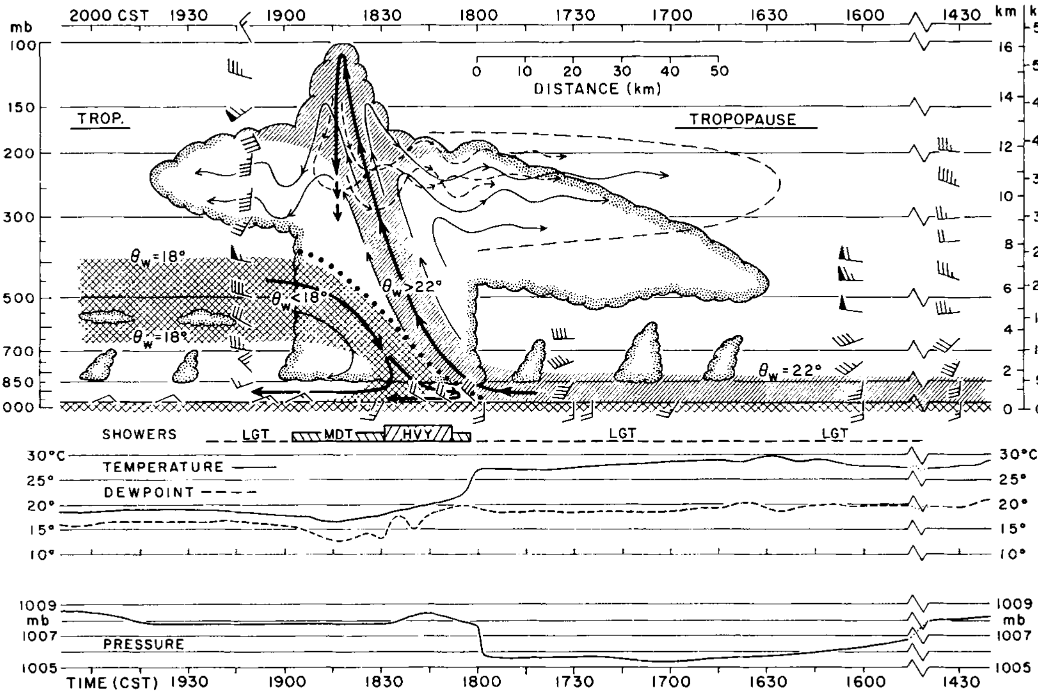

FIG. 11. Partly-schematic cross section through squall line of 21 May 1961, as it passed Oklahoma City (fivefold vertical exaggeration). Winds plotted with directions relative to north at top of figure. Prior to squall-line passage, there were other thunderstorms in the vicinity; these have been omitted for clarity (the balloon released at 1730 oscillated near 650 mb for 14 min, probably having encountered the downdraft of one of the earlier storms; during its further ascent winds were unmeasureable because of low elevation angles). Hatching indicates depth of air with θ_w in excess of 22°C ahead of squall line, and its probable extent in updraft and upper portion of cloud. Cross-hatching indicates extent of air with θ_w less than 18°C, based on sounding behind storm and on surface observations. A similar layer at closely-corresponding heights was present before squall-line passage; this is omitted for the sake of clarity. At bottom, periods of precipitation, and temperature, dew point and sea-level pressure traces (somewhat smoothed) are shown. Heavy arrows, axes of main drafts; light arrows, relative streamlines, dashed where air emanates from core of stratospheric tower. At right, long dashes suggest outline of mass of *air* plume originating in storm and spreading out essentially horizontally; the radar-detected *cloud* plume, at lower elevations, consists of small precipitation particles which have partly fallen out of the air plume.

vapor in the various branches of the circulation. Surface wind and observations were available from the "Beta" surface network of the Weather Bureau National Severe Storms Project, consisting of 36 stations in an area 96 km by 154 km, centered about 85 km south of Oklahoma City. Wind shifts were experienced by all stations, indicating that the squall front was unbroken. The squall line, oriented 047–227°, moved SE with a speed of 11 m/sec over the network.

The mass of air, and of water vapor, entering or leaving an individual thunderstorm may be determined from the rawinsonde observations, from the expressions

$$\int (c - v_n)\, L \frac{dp}{g}, \quad \int (c - v_n)\, Lq \frac{dp}{g} \qquad (11)$$

where c is the speed of the squall line, v_n the wind component along its direction of advance, L is the spacing between thunderstorms (taken to be equivalent to their lateral dimensions), and q is the mixing ratio. Profiles of $(c - v_n)$ and of $(c - v_n)\, q$, behind and ahead of the squall line, are shown in Fig. 12. These indicate a flux

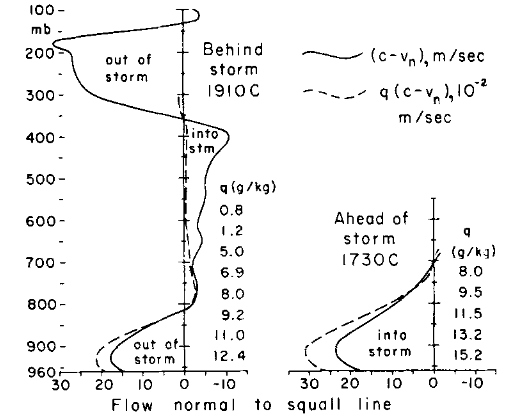

FIG. 12. Vertical profiles of relative velocity components normal to squall line (solid), and of the product of relative velocity and mixing ratio (dashed).

of air (and water vapor) into the forward side of the squall line below 700 mb, a flux outward from the rear side below 810 mb, and a flux into the rear side between 360 and 810 mb.[1]

Radar observations showed L to average about 20 km. From expressions (11), Fig. 12 and the earlier results, the budgets of air and water-vapor flux for a *single* thunderstorm in the line are shown in Fig. 13. Of the 700 kton/sec of air entering the updraft in low levels, the computations in Section 6 suggest that in a well-developed pulsating storm about 20 % may circulate through the stratospheric tower, while in a "steady state" storm with a tower persistently high above the tropopause, up to 60 % may do so. The indication from Section 5 is that essentially all the air originating in the updraft remains in the upper troposphere, spreading out mainly in the anvil plume downshear but appreciably also on the upshear side. Neglecting air entrained from outside the storm, the volume expansion of the anvil would, from the updraft mass flux[2], be about 2 km^3/sec. The lower-tropospheric downdraft, with a mass flux of 400 kton/sec, is equivalent to about 60 % of the updraft flux. A similar ratio was indicated in another squall line example (NEWTON, 1963, Fig. 14).

The mass of water vapor entering the updraft is 8.8 kton/sec. With a mixing ratio of 0.9 gm/kg and an assumed water substance density of 0.3 gm/m^3, 0.6 kton/sec of vapor and 0.6 kton/sec of water are exported in the anvil expansion, leaving 7.6 kton/sec for precipitation aloft. From Fig. 12, the vapor flow aloft into the rear of the storm is 0.7 kton/sec, and the outflow toward the rear in low levels is 4.3 kton/sec, requiring 3.6 kton/sec of this rain to be evaporated into the downdraft. This leaves a residual of 4.0 kton/sec water available for surface precipitation. The mean precipitation indicated by the Beta network stations was 4.7 kton/sec.

In view of uncertainties in representativeness of the various observations, this is a satisfactory agreement, suggesting that the broad

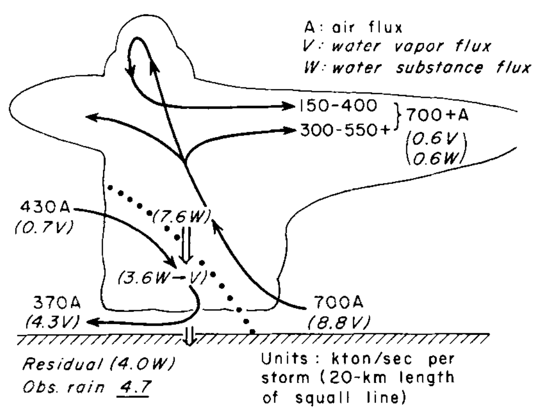

FIG. 13. Principal branches of the circulation, with fluxes of air, water vapor, and water, corresponding to a single thunderstorm in squall line.

[1] The balloon released at 1910 CST passed through a heavily mammatiform shelf of high cloud on the NW side of the thunderstorms. Between 1522 and 1646 CST, the western edge of the radar-detectible anvil near the 11-km level moved eastward with a speed of less than 8 m/sec, 15 m/sec slower than the general west-wind component at that level and half the eastward speed of the storm cores. The extent of the anvil upwind from the storms (eventually reaching 50 km in places), and the slow movement of its western edge, suggest that the in-cloud wind field was disturbed at great distances from the active storm cores.

[2] Data are inadequate to appraise the volume expansion in this case. From figures presented by FUJITA & ARNOLD (1963), the expansion of the anvil connected with the storm of Fig. 3 is estimated at 6 km^3/sec. Two major shower areas were observed by the writer while flying beneath that storm, so that the anvil was probably nourished by more than one convective core. From aircraft wind observations given by Fujita and Arnold, the mass convergence in the lower 200 mb in the near vicinity is estimated at about 2000 kton/sec, consistent with the rate of mass increase in the anvil of that storm but much larger than the inflow indicated for a single storm in Fig. 13.

features of Figs. 11 and 13 are realistic. It may be noted that the mass flux in the updraft of a giant thunderstorm of this type is one to two orders of magnitude greater than that in the typical "air mass" storm described by BRAHAM (1952). The rain reaching the ground amounts to about 50 % of the vapor flux through the updraft, compared with about 10 % for the smaller storm. Considering the reasons for the latter, discussed by Braham, the greater effectiveness of the large storm as a precipitation producer can be attributed to its smaller surface-to-volume ratio (proportionately smaller entrainment and evaporation at cloud boundaries), its greater lifetime, and to some extent to the occurrence of divergence aloft at a lower pressure (with a lower mixing ratio) than is characteristic of smaller storms. Most of the water loss in the large storm is to the downdraft, which because of its smaller mass transport and to some extent also because of its lower θ_w, requires for its saturation the evaporation of considerably less water than is condensed in the updraft. Once such a storm achieves the persistent phase, the loss of water through expansion of its anvil only slightly exceeds the import of water vapor in the middle troposphere, so that *the amount of rain deposited is essentially equivalent to the moisture convergence in low levels.* (Below 700 mb, the vapor accumulation in this case was 4.5 kton/sec, compared with 4.7 kton/sec rainfall). This is consistent with earlier comparisons of rainfall with water-vapor convergence over broader areas encompassing convective precipitation regions, by BRADBURY (1957) and by FANKHAUSER (1965).

8. Conclusion

The above analysis indicates that the squall-line type thunderstorm is a highly organized system whose circulation is so arranged as to make it a peculiarly effective thermodynamic machine. Due to the presence of strong vertical shear, the updraft at least in its lower parts leans in an upshear sense, making it possible for condensed water to fall into the downdraft. Chilling by partial evaporation of this water, with consequent gravitational sinking, is the agency responsible for driving the downdraft whose coldness is due to its origin from middle levels where the wet-bulb potential temperature is lowest. Introduction of the downdraft from the middle troposphere is important also because the air taken in there has relatively high horizontal momentum, which enables it to undercut and continually lift the updraft, causing the circulation to persist once it has begun.

An important feature indicated by the computations is that due to the entrainment of heat and inert air, no significant part of the air rising in the updraft is likely to return to low levels. Thus although a vigorous downdraft must be present near the tropopause level, this rapidly loses impetus, and the downdrafts in the upper and lower portions of the sheared cumulonimbus must be considered as separate entities. In addition, it has been demonstrated that although the core of the updraft may at times be insignificantly diluted, strong mixing from the environment must take place into its outer parts. As a result only part of the air entering the updraft rises above the tropopause, the anvil cloud being made up mostly of air which has never left the troposphere, but also in significant part of air which has circulated through stratospheric towers.

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ЦИРКЫЛЯЦИЯ В БОЛЬШИХ КУЧЕВОДОЖДЕВЫХ ОБЛАКАХ

Рассматривается структура кучево-дождевого облака в поле ветра с вертикальным поперечным градиентом скорости, подверженного действию горизонтальных сил и меняющемуся влиянию термодинамических факторов на различные части облака. Горизонтальные скорости внутри облака сильно отличаются от соответствующих скоростей в окружающей среде. Форма облака, определяемая восходящим потоком, меняется с изменением вертикального градиента скорости ветра, вертикального движения и скорости движения шторма.

Кучево-дождевое облако рассматривается как ансамбль элементов воздуха, в разной степени перемешивающихся с окружающей средой и проникающих до различных высот. Некоторая часть восходящего воздуха образует стратосферные башни, затем опускается в виде интенсивных нисходящих потоков, которые ослабляются в верхней тропосфере вследствие обмена теплом и количеством движения с воздухом, не имевшим вначале вертикальной компоненты количества движения. Эта часть воздуха вместе с воздухом, достигшим верхней тропосферы в менее нагретом окружении восходящего потока, служит механизмом для образования расширяющейся наковальни. Отдельное нисходящее движение в нижней части облака, возникающее на средних уровнях, где низка влажноадиабатическая потенциальная температура, постоянно поддерживает восходящий поток благодаря механическому поднятию. Даются также оценки баланса массы и водности для гроз шквального типа.