Principal Results of a Comprehensive Investigation of the Structure and Dynamics of the Thunderstorm

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Abstract

Certain intensive investigations into the nature of thunderstorms in the United States have resulted in a new model of thunderstorm structure, life cycle and thermodynamics. Thunderstorms and their effects have been investigated by airplanes, radar, surface micronetworks and swarms of balloons. Some of the more significant aspects of these measurements are described. A comprehensive final report will be published soon by the U. S. Government.

Introduction

In 1945 the United States Weather Bureau, Air Force, Navy and National Advisory Committee for Aeronautics organized a project to investigate the structure and dynamics of the induvidual thunderstorm by means of a concentrated program of observations and measurements. A description of the observation system has beenpublished in various articles (WHITE, 1946, 1948; U. S. WEATHER BUREAU, 1946, 1947). It will suffice here to state that it has been the largest project ever directed at the study of a single atmospheric phenomenon. Airplanes, balloons, radar, surface micronetworks and certain specialized equipment were used to investigate the structure and dynamics of thunderstorms during two summers of pronounced thunderstorm activity. In the summer of 1946 observations were carried out over the Florida Peninsula, and in 1947 south-western Ohio was the scene of operations.

Analysis of the data has been completed to the point of making a general report of the scientific results. This report, prepared with the collaboration of ROSCOE R. BRAHAM, JR., LOUIS J. BATTAN, HARRY L. HAMILTON, JR., HARRY M. MOSES and others of our Weather Bureau group, is expected to appear in printed form early in 1950. It is being printed by the U. S. Government Printing Office under the direction of the U. S. Weather Bureau, which organization had charge of the scientific investigations. The report, under the title "The Thunderstorm" will be available from the Superintendent of Documents, Washington, D. C.

At the suggestion of the Editor of TELLUS, a summary of the findings of the Project is presented on the following pages in order to acquaint meteorologists and geophysicists in general with the more important new facts about thunderstorms without waiting for the full report. The difficulty of this task can be measured by considering that the printed report will consist of some 300 pages of a size somewhat larger than this journal and including 254 illustrations. This summary, therefore, can only state conclusions, so the reader is referred to the full report to ascertain the nature of the data and reasoning leading to these conclusions. The results will be summarized here in conformance with and in the order of the ten chapters that form the report, with the exception that the last two, covering thunderstorm conditions affecting flight operations, will be omitted. The preliminary results of these two have already been published by the U. S. WEATHER BUREAU (1948) and the AIR WEATHER SERVICE (1949).

1. Thunderstorm Structure and Circulation

The BÉNARD cell (BÉNARD 1901) is rejected as a model of convective circulation in the cumulonimbus cloud partly because steady-state convection cells rarely, if ever, are duplicated in deep atmospheric layers. The atmosphere with strong convection is in a very disturbed state. Radar scans over a large area having thunderstorms show either a random distribution of the storms or a concentration in squall lines. Downflow spreads over areas many times greater than the areas of upflow. The large areas of return settling are cloudless or have only growth-arrested cumuli. The energy released by condensation exceeds the energy of the simple BÉNARD-cell type convective motion.

As indicated by previous investigators, it is found that the thunderstorm consists of several units of convection, called cells. Many of these units are initially detectable as separate echoes appearing on a radar 'scope, but even after they have formed a conglomerate thundercloud mass they can be distinguished through a study of the data measured in airplanes flying through them. The patterns of vertical motions serve to identify the cells. Between the cells is found "connective tissue" of inactive, i.e., nonturbulent, cloud.

As described in a previous article (BYERS and BRAHAM, 1948), the life cycle of the thunderstorm cell is divided naturally into three stages depending upon the direction and magnitude of the predominating vertical flow. They are:

1. Cumulus stage—characterized by updraft through the cell.
2. Mature stage—characterized by the presence of both updrafts and downdrafts, at least in the lower half of the cell.
3. Dissipating stage—characterized by weak downdrafts prevailing throughout the cell.

Cumulus Stage—Measurements made in cells in this stage show that throughout the entire cell there is an updraft. The strongest updrafts are found at the higher altitudes and toward the end of this stage. The surface air converges to feed the updraft, but air also flows into the cloud from the unsaturated environment. This mixing of surrounding air or "entraining" is made possible through the evaporation of some of the liquid water carried in the updraft. The entraining is characteristic of all stages of the thunderstorm.

Within the developing cloud the temperatures are everywhere higher than in the environment at corresponding heights. The greatest differences between the in-cloud and environment temperatures are found in areas of greatest updraft speeds, at the upper levels, reaching a maximum toward the end of the stage.

A distinguishing feature of the cumulus stage as contrasted with the other stages is the absence of precipitation falling out of the bottom of the cloud. The flight crews flying within the clouds reported rain or snow, particularly near the end of the stage, but these hydrometeors appeared to be suspended, since no precipitation was observed at that time at the ground. The greatest concentrations of hydrometeors—liquid, solid, or both—occur at the freezing level and somewhat above it. The depth of the transition zone in which the water passes from a liquid to a solid state varies, depending upon the speed of the updraft.

Mature Stage.—The initial occurrence of rain at the ground has been chosen as the beginning of the mature stage. Apparently this happens when the size and concentration of the drops or ice particles becomes so great that they can no longer be supported by the existing updraft and begin to fall relative to the earth. The drag exerted by the precipitation upon the ascending air is an important factor in forming a downdraft and, as a matter of observed fact, the beginning of rain at the surface and the initial appearance of a downdraft are coincidental. The downdraft, which at first is found only in the lowest 15,000 feet, gradually increases in horizontal and vertical extent. (Fig. 1.)

Throughout the mature stage, an updraft still persists. Its magnitude is usually greatest at the highest levels flown (25,000 feet). It is also strongest in the early part of the mature

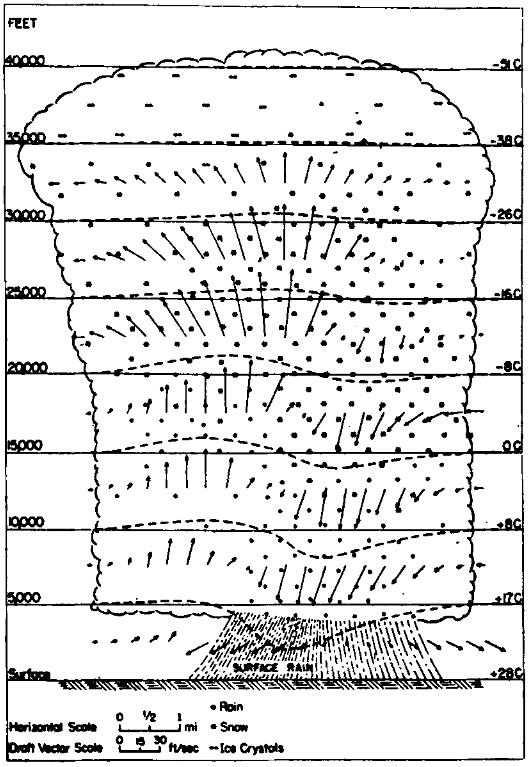


Fig. 1. Vertical cross section sketch of a thunderstorm cell in the mature stage with updrafts and downdrafts represented vectorially, typical hydrometeors and temperature distribution for summer thunderstorm conditions in the eastern United States.

stage when speeds may locally exceed 100 ft/sec. The downdraft is usually weaker than the updraft and has its greatest speeds in the lower part of the cloud. At the ground it is forced to spread out. Thus areas of downdraft, rain and lateral divergence coincide.

Low temperatures are associated with the downdraft, with the greatest negative temperature anomalies in the lower levels. The updraft is still warmer than the clear air surrounding the cloud and, of course, has considerably higher temperatures than the downdraft at corresponding heights. The warmest regions at each level are found in the area of maximum updraft speed, and the coldest areas occur where the downdraft is the strongest.

As discussed in the 1948 Journal article, the updraft air follows an adiabatic reduction in temperature with ascent which is modified both by condensation and by mixing with entrained air, two processes which act in opposite senses. The result is that the updraft or "entraining-wet-adiabatic" rate is greater than the simple wet adiabatic. Therefore the updraft air is permitted to become only slightly warmer than the environment air. In the downdraft, evaporation is the principal process besides compression, and this appears to occur essentially reversibly and wet-adiabatically. At the low levels, then, the downdraft appears as a small cold-air mass. It forms the well-known pseudo-cold front as it advances along the surface of the earth.

The greatest intensities in all aspects of the thunderstorm are reached in the mature stage. Heavy rain and strong winds are observed at the ground and severe turbulence, including short, intense gusts as well as updrafts and downdrafts are found in the clouds. It is during this stage that hail occurs, although this hydrometeor is not found in every storm. Above 26,000 feet no direct observations have been made of hydrometeors, but from radar echoes returned from cells in the mature stage, it is concluded that the size and number of particles are large to heights as great as 60,000 feet in some cases. With extraordinarily strong updrafts (up to 100 ft/sec), it is possible for liquid water to be carried well above the freezing line. One case of heavy rain at 26,000 feet, nearly 10,000 feet above the freezing level, was reported.

Dissipating Stage.—The downdraft spreads over the entire area of the cell to start the dissipating stage. As the updraft is cut off, the total amount of liquid water released becomes smaller, finally reducing the mass of water available to accelerate the descending air. Then complete dissipation occurs or only stratified clouds remain. The entire cell is colder than the environment as long as downdrafts and rain persist. With decreasing downdraft speeds the temperature within the cell rises to a value approximately equal to that of the environment at corresponding levels. The disturbance of the wind field at the ground also disappears.

II. Thermodynamics of Entraining

Reference is made to the work of STOMMEL (1946) and AUSTIN (1948) in showing the thermodynamic results of entraining of environment air in the updraft of a convective cloud. Computations of inflow rates from the swarms of balloons sent aloft around thunderstorms show that the cumulus cloud which develops into a thunderstorm entrains at a rate of approximately 100 per cent per 500 mb of ascent, that is, it doubles its mass as it rises through a pressure decrease of 500 mb. This is considerably less than the entrainment rates of tradewind cumuli found by STOMMEL and perhaps is related to the lack of development of the latter.

It is shown that when entraining takes place the properties of the updraft are considerably different from those to be expected from the conventional considerations of parcel ascent. In general, it may be said that an updraft undergoing entraining has less liquid water and a lapse rate steeper than the moist adiabatic. The rate of temperature decrease with ascent and entraining depends on the temperature lapse rate and water-vapor content of the environment, as well as on the rate of entraining. The drier the environment or the more rapid the entraining, the steeper will be the updraft entraining-moist-adiabatic lapse rate. With high rates of entraining the updraft might theoretically be colder than the environment. This was not found to be the case except in isolated or transitory conditions in the Thunderstorm Project observations.

The conditions of free convection based on temperatures higher in the updraft than in the surroundings, place limitations on the rates of entraining that can exist. A series of charts, of which fig. 2 is an example, was constructed showing the difference in temperature between updraft and environment for a group of different environments and different entraining rates. For each environment is shown the effective temperature difference between the updraft and the environment that would result from each of the several rates of entraining. The effective temperature difference is the difference between updraft and environment reduced by the amount which is required to produce a buoyancy force equivalent to the drag force exerted by the contained water. It is therefore the temperature difference available for overcoming other retarding forces and for accelerating the air. The examples show that entraining rates greater than 100 per cent per 250 mb are unfavorable for the growth of cumulus clouds to heights great enough to produce thunderstorms in American maritime tropical air.

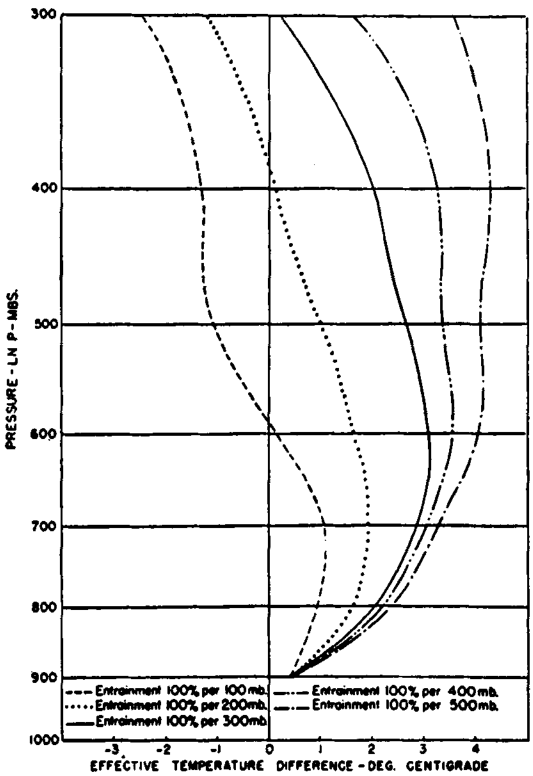


Fig. 2. Plot of distribution with height of computed effective temperature difference between updraft air and environment air under the specified rates of entrainment. In this case the environment lapse rate is assumed to be midway between the dry and saturated adiabatic rates with a convective condensation level at 900 mb and 23°C. Relative humidity in per cent in the environment is considered to be 1/10 of the pressure in mb., *i. e.*, 90 % at 900 mb., 80 % at 800 mb., etc.

The lapse rate in a typical, well-developed, bulging cumulus cloud is represented by line A′ B′ in fig. 3, and the lapse rate of the environment by line AB. If a saturated parcel is displaced downward from point C, it warms at the moist-adiabatic rate CD, if no environment air is entrained. If environment air is entrained, the parcel warms at some other rate, such as CE. If the parcel is displaced downward beyond D or E, it will be colder than the environment and sink. The mass of liquid water provides the means whereby a parcel in a

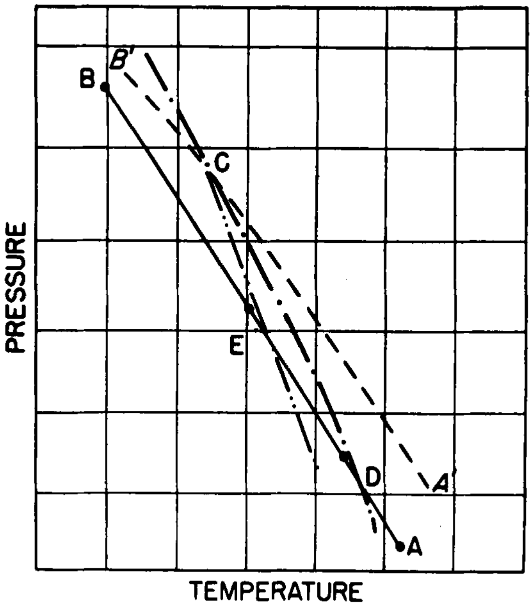


Fig. 3. Graphihal representation on a section of an adiabatic chart of the thermodynamics of the downdraft. AB is the environment lapse rate, while A′B′ is the updraft lapse rate. CD is a moist adiabat and CE represents the downdraft lapse rate. If the downdraft reaches below E, it is colder than the environment. In U. S. thunderstorms, the pressure interval from C to E is usually less than 100 mb.

thunderstorm can thus be forced below point D or point E, whence it continues as the thunderstorm downdraft. With sufficient liquid water available to maintain saturation, the parcel continues to the ground, reaching the surface with a temperature several degrees lower than the surface environment wet-bulb temperature.

III. Thunderstorm Weather Near the Surface

Rainfall.—It was found that the rainfall pattern follows closely the arrangement of the cells and reflects to a considerable extent their stages of development. A single, isolated thunderstorm cell is comparatively rare in the regions studied and when it does occur, it is generally weak and not representative of the average thunderstorms. Usually a thunderstorm consists of a group of three or more cells adjacent to each other, each manifesting itself in the rainfall pattern. The first rain reaching the ground from a newly-developed cell is limited in area to a few square miles. Later, as the cell develops further, the rain area expands along with the increase in horizontal extent of the downdraft with which the rain is associated. The cold air of the downdraft spreads out after reaching the surface, while the rain falls directly to the ground, so an ever-expanding outer area of cold air without rain develops. In the dissipating stage of the cell, the rain area contracts while the cold air continues to spread.

As would be expected, under a moving cell the area of rain advances approximately at the speed of movement of the cell itself. If the rainfall is considered with respect to the moving cell, it is found that the duration of moderate or heavy rain from a single cell may vary from a few minutes in the case of weak, short-lived cells, to almost an hour in the large, active ones. However, the duration of the rain period at a surface station depends upon such factors as the number, size and longevity of the cells passing over the station, the position of the station with respect to each passing cell and the rate of translation of the cell. Without separating the above factors, one finds that the average duration of rainfall at Florida as well as Ohio stations is about 25 minutes.

The maximum rainfall rates occur at the location of a cell core within 2 or 3 min. after the first measurable rain from the cell reaches the ground and the rain usually remains very heavy for a period of 5 to 15 min. Thereafter the rainfall rate decreases, but much more slowly than it increased. Lesser rates occur around the edges of a cell.

Wind Field.—When a cell is in the early building stage there is a gentle inward turning of the surface wind, forming an area of weak horizontal convergence under the updraft. Except for changes in the electric field, this change in wind is the first surface manifestation of the usual type of thunderstorm. As the cell grows and a downdraft develops, the surface winds take on an entirely different character, becoming strong and gusty as they flow outward from the downdraft region.

In the mature stage, the outward-flowing cold air underruns the warmer air which it displaces, and a discontinuity in the wind and temperature fields is established. This discontinuity or discontinuity zone moves outward with the spreading cold air of the downdraft. Strong horizontal divergence is measured in the surface winds of the downdraft outflow. Values as high as 29 hr^{-1} ($8.06 \cdot 10^{-3}$ sec^{-1}) have been evaluated from the surface micronetworks.

In the slowest-moving storms, the outflow is almost radial, but in most cases the outflow field is asymmetrical, with wind speeds substantially higher on the downwind side. This is due to the reinforcement or cancellation, as the case may be, of the radial flow by the prevailing air movement in the lower layers. Thus the wind discontinuity in most cases is easily detected only in the forward portions of the storm, where it appears as a micro-cold front.

The cold dome of outflowing downdraft air has a form illustrated schematically in fig. 4. In this sketch the thunderstorm cell is considered to be in the mature stage and is moving from left to right. The cold air is represented as having spread out considerably farther on the downwind side of the cell than on the upwind side, as would be expected in a moving system.

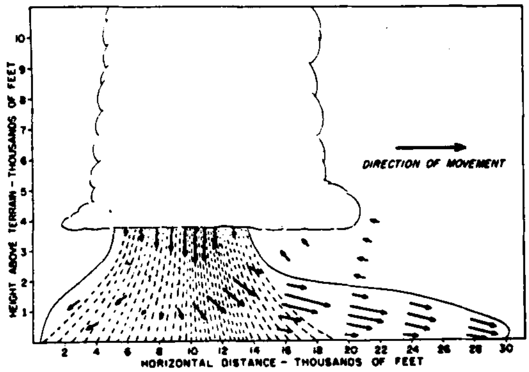


Fig. 4. Schematic vertical cross section through the lower part of a thunderstorm cell in the mature stage showing the spreading cold dome and typical pattern of air flow.

After the outflow has been spreading for 15 to 20 minutes, the discontinuity zone will have traveled about 5 or 6 miles from the cell center. The surface winds near the discontinuity surface are still strong and gusty, but farther behind, inside the cold-air dome, the surface wind speeds have decreased so that the strongest winds are no longer underneath the cell itself. This increase in the wind speed as one approaches the discontinuity zone from the cold air side results from a continued settling of the outflow air, bringing high horizontal momentum downward.

The discontinuity zone, which everywhere marks the limit of the cold downdraft air, is one of the most interesting of all surface weather features associated with the thunderstorm passage. With the passage of this zone at a station directly underneath the center of a cell in the early mature stage, there is a sharp increase in the wind speed, occasionally to destructive force, and a marked reduction in temperature. The sharp increase in wind has been termed the "first gust", since it often appears as the first major gust of a period of high, gusty winds. After the cold air spreads outward, the wind speeds near the boundary of this air decrease. It is found that, at least during some stages of the storm, the discontinuity zone at the ground moves faster than the normal component of the winds immediately behind it. This may be explained by the fact that there is rapid downflow of colder air toward the ground along the boundary zone which thrusts it forward.

In direction, the wind shows clockwise shifts in most cases. This was especially true in Ohio where the winds were usually southwest or south and shifted to west or northwest at the discontinuity.

Temperature.—The "first gust" and the "temperature break", i.e., the point on the thermograph where the temperature suddenly starts its drop, are two of the most pronounced features observed at the surface, and they occur essentially together. At the time of formation of summer afternoon thunderstorms in the areas studied the temperature is usually above 85°F, often in the 90's. As a result of the rain and the downdraft, the temperature may reach a value as low as 65°F. without a change in air-mass. As the thunderstorm activity dies down after sunset, the temperature usually has recovered to an intermediate value representing a mixture of strongly cooled and less cooled or uncooled portions of the air-mass.

The area affected by the cooling is many times greater than that over which rain falls, but the temperature change is, of course, most marked in the rain core (downdraft center).

Cooling may be detected as much as 15 to 20 mi. downstream. Near the center of a mature cell the temperature reaches a minimum within 10 to 15 minutes after the temperature break; farther from the cell the temperature drop is much slower. The amount of the temperature decrease observed in any given storm varies inversely with the distance of the observation point from a cell core. The temperature discontinuity is sharp and well defined under the core but is less pronounced farther away. Since the downdraft is only a few miles in diameter, the area over which the first and most rapid temperature fall occurs is relatively small. As a result, strong horizontal temperature gradients are created after the downdraft first reaches the ground. Gradients exceeding 20°F per mile have been observed. As the storm ages, the cold air spreads out and the magnitude of the horizontal temperature gradient decreases. Regardless of the spread of the cold air, the area of minimum temperature remains in the general location where the cold downdraft made its first appearance at the surface, except in those cases where a new cell with its own downdraft and rain core develops over another part of the cold dome.

Pressure.—Early in the cumulus stage a fall in surface pressure almost invariably occurs. This fall is observed before the radar echo forms, and it is recorded over an area several times the maximum horizontal extent of the echo. When the radar echo appears, the pressure trace levels off in the region directly underneath it, but continues to fall and frequently at a more rapid rate in the surrounding areas. The pressure drops in the cumulus stage are usually small in magnitude — less than 0.02 in. (0.67 mb) below the diurnal trend — and take place over a period of 5 to 15 minutes. Following the fall, the pressure trace remains steady for as long as 30 minutes.

The pressure falls appear to be caused by the combined effects of vertically accelerated air motions, the expansion of the air due to the release of the latent heat of condensation and the failure of the convergence near the surface to compensate fully the expansion or divergence aloft. Wind patterns in the vicinity of thunderstorms showed velocity convergence in the developing stages with divergence above 20,000 feet, suggesting a mass balance.

In the mature stage, two features of the pressure trace—the "dome" and the "nose"—are recognized. The dome is registered at all stations to which the cold outflow air penetrates. The pressure nose, the abrupt, sensational rise that some meteorologists regard as typical of the thunderstorm, really occurs only at stations that happen to be passed by the main rain and downdraft just after they have first reached the earth in the beginning of the mature stage. It is superimposed upon or may mark the start of the pressure dome.

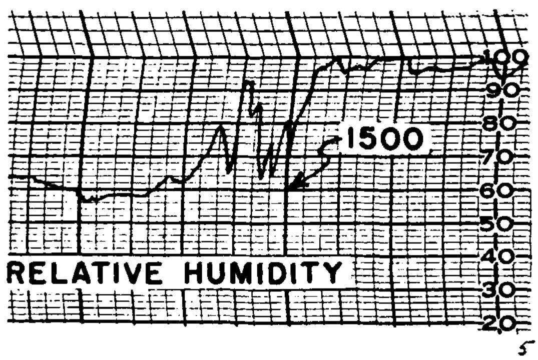
The displacement of the warmer air by the cold outflowing air from the downdraft results in the pressure rise initiating the pressure dome. A study of 206 thunderstorm pressure records from the surface micronetwork showed that in 182 of the traces there was a pressure rise associated with the arrival of the cold outflowing air. Since the rate and total amount of pressure rise depend on the slope of the cold air mass, the temperature difference between the cold air and the displaced warm air, the depth of the cold air itself and the speed with which the system travels, the most marked pressure changes are found near the cell core and decrease with distance from it. The areal extent of the pressure dome is similar to that covered by the cold air. Therefore the pressure remains high for a period of from one-half hour to several hours, depending on the amount of cold air involved.

The distinction between the pressure nose and the pressure dome can be made only with difficulty on the conventional week-long barograph traces, but on the twelve-hour recording drums used on the Thunderstorm Project the distinction is clear.

At any given time the pressure nose was usually detected by but one station per cell in Ohio, indicating that the maximum diameter of the area in which it occurred was less than 5 mi. It is thus apparent that it is caused by a transitory process which exists for only a brief period, namely the time of commencement of the mature stage when rain and downdraft reach the ground. Two effects which are thought to be important in creating the pressure nose are the weight of the suspended and falling water, and a lack of balance between convergence and divergence. Both of these effects are at a maximum at this time. An accumulation of an average of 1 gm of liquid water per cubic meter from the cloud base to 35,000 feet, a conservative value, would increase the surface pressure by about 1 mb, other factors being equal. When the downdraft becomes established, it reverses at least part of the vertical circulation pattern and reduces the divergence above 20,000 feet, or perhaps even reverses it to convergence. Should this happen before the divergence (outflow) in the surface layers becomes well established, a net increase in mass convergence could result in a substantial surface pressure rise. For example, an uncompensated convergence of 1 hr^{-1} (a conservative value for thunderstorm convergence) within a layer only 1,000 feet thick at 20,000 feet would increase the surface pressure at a rate exceeding 1 mb in 3 min. Relationships of pressure changes to vertical motions in thunderstorms which have been a favorite subject for theoretical treatments by meteorologists could not be confirmed by data of the Project. One of the difficulties is that a downdraft at the lower levels is under an updraft at a higher level, so that the vertical accelerations are opposed and tend toward compensating each other.

After the brief pressure nose, the pressure remains at the value of the pressure dome which prevails for the particular thunderstorm. The dome persists through the dissipating stage of the cell, after which the pressure returns to the trend prevailing before the passage of the storm. In the case of a thunderstorm associated with a cold front or a fast-moving squall line, the pressure remains high or even continues to rise as a result of cold-air advection or the passage of a wave in the pressure and wind field.

Humidity.—An extraordinary phenomenon is noted in the hygrograph traces from the surface micronetworks in the form of a sharp decrease in the relative humidity in the midst of the heaviest downpour of rain. With the onset of rain, the relative humidity rapidly approaches but usually does not quite reach 100 per cent, then, in many cases, drops suddenly to values as low as 60 or 70 per cent, returning to near saturation again in a few minutes. Such a fluctuation, termed the humidity dip, and illustrated in fig. 5, is associated with the rain area. In practically



Fip. 5. Example of humidity »dip» as shown on hygrograph during heavy rain under thunderstorm of August 14, 1947 near Wilmington, Ohio. The time divisions indicated on this hygrograph trace are for 5-minute intervals.

all cases the humidity dip occurred in a region of divergence in the surface wind, therefore in the outflowing downdraft. The temperature was usually decreasing, but if it had already reached its lowest point, as was sometimes the case, a rise in temperature of 2 or 3°F would sometimes accompany the humidity dip.

The failure of surface air to become saturated during the heavy rain, together with the frequently observed relative-humidity dip, suggest that the downdraft air fails to maintain saturation as it descends, even in the presence of large concentrations of liquid water. Two processes are suggested: first, dessication of the air by condensation on cold precipitation particles; second, a time lag in the evaporation of the water drops so that there is insufficient accomodation to the increase in the saturation mixing ratio as the air descends to lower levels.

The only measurements of raindrop temperatures were made by the Project at 3 feet above the ground. There it was found that in afternoon thunderstorms the rain temperature in the first few minutes of the rain period is several degrees lower than that of the ambient air. This would be sufficient to keep the relative humidity from reaching 100 per cent. If the second process mentioned above is taking place, one would expect that the air of the thunderstorm downdraft would be heated at a rate between the moist- and dry-adiabatic and would reach the ground in an unsaturated state.

Development of New Cells.—From a study of numerous cases of new cell development, the action of the cold outflowing air appears unmistakably as causing or contributing to the new growth. When two cells in the mature stage are within a few miles of each other, the cold outflows collide. The greatest frequency of new cell development was in the area between two existing cells whose edges were three or less miles apart. A three-mile band downwind was next in importance, then the lateral edges and least frequently the upwind or rear side.

In some cases the time interval between the beginning of the outflow and the appearance of the new cell on the radar 'scope was too short to permit explanation of the new development as a result of the underrunning cold air or similar time-consuming process. There are cases in which one or a cluster of new cells came into existence, as indicated by the radar echoes, almost simultaneously with the initial or parent cell, which suggests that a preferred region of updrafts favors the development.

IV. Electric Fields in Thunderstorms

Owing to a lack of suitable equipment and qualified personnel, the electrical data of the Thunderstorm Project left much to be desired. However, by means of recording electric field meters mounted on top and bottom of the fuselage of the airplanes which operated satisfactorily on a few occasions, some data on the electrical configuration of thunderstorms were obtained and some crude ground measurements gave further information.

The predominant charge distribution was that reported by previous investigators, namely a positive charge in the upper part of the cloud and a negative charge in the lower part, with the field reversed under the cloud to indicate the ground as positive relative to the cloud base. In five low-level airplane traverses under a thunderstorm in Ohio, interesting changes in the electrical field were measured. The first traverse showed an almost neutral field. Only eight minutes later, with increased cell height and heavy rain, a strong positive gradient (directed earthward) was recorded in the rain area and a strong negative gradient outside the rain area. Then, with dissipation of the cell and decreased rain intensity, the later traverses showed the positive field vanishing and being replaced by a negative one. The finding of the positive charge in the rain core on the second and third traverses appears to bear out the findings of G. C. Simpson and his co-workers (1927, 1941) that a positively-charged region may occur near the base of the thundercloud. The more commonly observed charge distribution with the cloud base negative with respect to the ground, was found under the updraft of the cell and under the entire cell after the time of maximum rain. The first result is in conformance with well-known measurements by a number of investigators showing that raindrops falling to the ground usually carry a net positive charge.

In a study of conditions in 7 areas of marked vertical velocities in thunderstorms occurring on three different days in Ohio, negative gradients were found in all except the two traverses mentioned above. These negative gradients were characteristic of both updrafts and downdrafts. The two traverses showing positive gradients, noted above, recorded this sign only in the downdraft portion.

From a study of point collectors located on the ground and a height-finding radar scanning the thunderclouds from a point about 20 miles away, the following conclusions concerning lightning were reached:

1. The cloud tops (echo tops) reached a height where the environment temperature was around —20° C before the first lightning occurred.
2. The maximum lightning frequency occurs at the same time as the cell reaches its maximum height.
3. As the height of the cell top decreases, the frequency of lightning also decreases.
4. It appears that a greater cell height (or lower temperature of the cloud top) is necessary to initiate lightning than is required to maintain it once it has started.
5. The maximum frequency of lightning precedes the time of the maximum 5-minute rainfall.

V. The Thunderstorm as Disclosed by Radar

From the photographic records of the range-height-indicating (RHI) radar 'scope it was possible to obtain data on the altitude of first formation of 66 radar echoes from convective clouds. A graph was made of the frequency distribution of the differences between altitudes of the tops of the initial echoes and the concurrent heights of the freezing level. The distribution showed a pronounced mode at 1,000 feet above the freezing level but the mean was at +2,200 feet. In convective clouds the echoes appear abruptly after the cloud has been visible to field observers for some time, suggesting a sudden release of large quantities of large water drops after penetration above the freezing level, in accordance with the Bergeron theory.

It was found that the rate of vertical growth of the top of a radar cloud echo agrees closely with the updraft velocity measured in that portion of the cloud if a correction factor of about 3 feet per second is added to the radar growth rate to account for the relative free fall of the attenuating snowflakes or other particles. The use of radar in this manner for measuring updrafts appeared to have a practical application in detecting hail possibilities, since all observed cases of hail accompanied strong updrafts.

It was noted that the thunderstorm tops ascended in a series of steps, appearing as the growth of new protuberances or »turrets» from the cloud top. Large clouds usually exhibited several turrets during their growth and, as a matter of fact, in 32 cases studied, the maximum height reached was correlated with the number of turrets formed by a coefficient of $+0.67 \pm 0.10$. Each successive turret was higher than the preceding one and the mean lapse of time between successive turret peaks was 17.8 minutes. It is believed that each turret makes it easier for the following ones by increasing the moisture content in the cloud-top environment air which must be entrained in further growth. Less heat of condensation is robbed from the new turret by entraining than would be the case if it were standing alone in a dry environment. Each turret underwent a growth period followed by an interval of subsidence. The growth period averaged about 16 minutes in duration. The average vertical growth rate was about 18 feet per sec. and the subsidence rate about 12 feet per sec.

The mean of the maximum heights reached by 199 Ohio storms as indicated from the radar was 37,500 feet. There was no significant difference in this respect between different types of thunderstorms, such as air-mass, squall-line or frontal.

The boundaries of the radar cloud echoes were found to agree closely with the visible cloud limits except in the levels near the cloud base where non-echo-producing "outrider" clouds were common. Also the anvils and other layer-type lateral extensions usually did not return a radar echo. The horizontal and vertical extents of thunderstorms were found to be correlated, that is, the taller the cloud the broader it was. The greatest areal coverage was at an altitude around 10,000 feet. The cross-sectional area was slightly less at the lower level and tapered at the top, forming a total cloud echo shaped like a rosebud.

From radar scans covering an area of over 55,000 square miles, it was found that on average thunderstorm days in Ohio 10 per cent of the area would be covered by cloud echo and on a day of maximum thunderstorm activity, 40 per cent of the area would be covered. It is found from indirect comparison that at 20,000 feet the in-cloud areas would average 5 per cent, and have a maximum of 22 per cent, indicating the better chance of avoiding thunderstorms by flying high. (Other measurements showed that these high levels are the worst for flights *within* thunderstorms).

VI. Effect of Environment Wind Field

The causes and effects of vertical shear, including effects of entraining and momentum transfer in the drafts, are investigated. Some of the results have already been published by BYERS and BATTAN (1949) and MALKUS (1949), so it is not necessary to summarize them here, although much new material is contained in the final report.

With the aid of long-range radar and abundant upper-air wind data, the movements of thunderstorms are studied in relation to the wind fields in which they are embedded. A method was devised whereby the translational component of the motion could be separated from the growth or dissipative component.

It was found that the motion of the storm corresponded most closely to the mean vector wind between the gradient level and 20,000 feet. The correlations were better in Ohio than in Florida owing to a stronger, more consistent wind flow in the former region. In direction, the correlations were 0.95 or better in both regions. It was found that the speed of the cloud was less than that of the vector mean wind from gradient to 20,000 feet. When the two speeds are plotted, a nearly straight line is formed, but the relationship is better represented as

$$U_w = 1.9 + 0.65\ U_c + 0.020\ U_c^2$$

where U_w is the vector mean wind speed and U_c is the cloud speed.

VII. Preferred Areas of Thunderstrom Development

Both areas studied were essentially flat, although the plain to the west and southeast of the Ohio network was sharply dissected. The radar made it possible to find out why thunderstorms formed where they did.

In Florida the only topographical effects were the alternation of land, small lakes and swamps which are characteristic of the Central Florida landscape. By making proper allowance for displacement of a cumulus cloud downwind before it produced a radar echo, it was found that the number of new echoes per square mile of land was one-third more than the number per square mile of water. A qualitative estimate of the effect of swampy areas was made by plotting a map showing isolines of number of new echoes, again allowing for an appropriate displacement. Although there are some exceptions, the map shows a definite tendency for the preponderance of new echoes to be over the dry land.

A study of the diurnal distribution of thunderstorms in the Florida area showed a distinct maximum of temperature and rate of thundercloud development from 1230 to 1630, 75th-meridian time. The effect of the sea breezes from the two sides of the peninsula in causing the thunderstorms has already been covered in an article by BYERS and RODEBUSH (1949).

In Ohio, a study of the initial appearance of 584 radar clouds on 21 days showed a larger number of echoes from day to day over the rougher parts of the terrain, especially to the northwest and southeast of the surface micronetwork area. However, plenty of new echoes formed over the flat area of the network.

Neither in Florida nor in Ohio was it possible to find a well-marked region from which the first thunderstorm of a series would develop. The thunderstorm hearth (Gewitterherde) so aptly described by VON FICKER (1932) was not readily apparent.

VIII. Squall Lines

During the 127-day period from May 17 to September 21, 1947 there were in Ohio 56 thunderstorm days on which extensive radar data were obtained. On 32 of these days lines of thunderstorms were observed. The lines on 6 days occurred along surface fronts, on 19 days were ahead of surface cold fronts and on the remaining 7 days apparently had no connection with the surface fronts. As is usual throughout the eastern United States, the pre-cold-front squall line was the predominating scene of thunderstorm activity.

It was found that the pre-cold-front squall lines are not quite parallel to the cold front but have an orientation averaging 13 deg. clockwise from that of the front. Their orientation is somewhat counterclockwise from the orientation of the overlying 700-mb contour lines. The movement of the squall line, as distinct from the movement of the individual storms composing the line, is not very closely related to the speed of the following cold front; in many cases it moves faster than the front. The individual elements of the line, or storms, move with the prevailing upper winds as described in the preceding section.

The pre-cold-front squall line on the synoptic chart is frequently observed to last for periods as long as 24 hours, during which it may travel several hundred miles. When viewed on the radar, it was found that there is usually a zone of convective activity comprising several lines and, although the zone may persist for a considerable period of time, the lines within it are constantly undergoing change—new lines forming and older ones dissipating.

The elements in a line range from a single isolated echo 1 to 2 mi. in diameter to a large aggregate of storms appearing on the 'scope as a single, more or less homogeneous echo having a maximum dimension of over 30 mi. The number of separate elements in a line varied from 4 or 5 small echoes in the early stages to as many as 40 or 50 at the time of maximum echo intensity. For the most part, elements were found to form and dissipate on a given squall line, suggesting the existence of a preferred line formation.

The squall line or, more properly, the squall line zone was found to be at an average distance of 170 mi. ahead of the cold front, with extreme values of 80 and 325 mi. Generally there was an area of relative inactivity between the cold front and the trailing edge of the squall zone; but on one or two occasions the convective activity finally extended back to the front itself.

Generally the thunderstorms associated with the squall lines were little different from any others except for a tendency for them to be more severe, especially in producing effects at the surface, such as strong, gusty winds. Since the storms come in a line, there is a more or less connected discontinuity line from the cold outflowing downdrafts which is often mistaken for a true front. The return to tropical air-mass conditions afterward shows the local character of the discontinuity. The pressure "dome" of the combined storms often results in the creation of a long pressure ridge along the squall line. Sometimes a squall line of this character may after a time produce a true frontal discontinuity involving more cold air than can be accounted for by the downdrafts.

Of the seven squall lines that were not associated with fronts, three were related to some type of large-scale cyclonic disturbance, two were on the west side of a warm anticyclone and the other two were in rather flat, uniform pressure fields. These lines were usually short compared with the prefrontal types and seemed to be less well defined.

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Note: The complete report contains 63 references to previous literature on the subject of thunderstorms, but the list is by no means considered exhaustive. The references given below are only those used to clarify the discussion in this brief summary.

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