Structure and Dynamics of the Thunderstorm

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MANY TEXTBOOKS OF METEOROLOGY AND PHYSICS contain diagrammatic representations of the structure and vertical circulation of a thunderstorm. They are based mainly on theoretical deductions as to the kind of thermodynamic engine the authors, from laboratory experience, think the thunderstorm should be. Until recently, no precise means of probing the storms to verify or modify the textbook picture was available. Numerous exploratory airplane flights into more or less violent convective clouds or storms had been made, but until the development of the uses of radar, it was impossible to tell where the aircraft were with respect to the storm at any given moment. Free meteorological balloons also had ascended haphazardly into thunderstorms, but again it was not possible to track them until the perfection of radio-direction finding.

Meteorologists knew there were things wrong with the textbook interpretation of the thunderstorm, so with the wartime development of radar and improvements in the art of blind flying, plans were made for a concentrated research program to find out what goes on inside the thunderstorm. Commercial and military aviation interests needed the knowledge for flight safety and all-weather flying programs. With the support of all the interested agencies, the U. S. Weather Bureau organized an intensive campaign of observation and measurement. The undertaking, which came to be known as the Thunderstorm Project, developed into the largest program ever directed at a single atmospheric phenomenon and became a joint project of the U. S. Air Force, the U. S. Navy, the National Advisory Committee for Aeronautics, and the U. S. Weather Bureau.

In the summer of 1946 the observations were carried out in Florida, then in the summer of 1947 a similar program was completed in Ohio. Since that time the analysis of the large amount of data collected has been performed by a group of government and other meteorologists at the University of Chicago, and a comprehensive report of the findings is now in press. It offers solutions of the problems of thunderstorm structure and dynamics which have puzzled meteorologists for years and contains much information of use in flight operations.

In the following paragraphs will be given a brief description of the project and a summary of some of the results.

System of Observations

Basically, the observation program was designed to obtain a complete description of the thunderstorm and to measure its intensity. The turbulence or bumpiness and the broad up-and-down motions of the air were considered the most important items to be investigated, but great stress also was laid on all measurable quantities that could give a clue to the vertical and horizontal air circulations and to the heat exchanges that drive these circulations and produce the rain. Lightning, which has been one of the main subjects of interest in many years of investigation by physicists and meteorologists, was considered to be of secondary importance, although arrangements were made for measurements of the cloud electricity.

In its main details the observation system consisted of the following:

1. Airplanes were used as probes to measure turbulence, updrafts and downdrafts, temperature, and electrical field, and to obtain visual data such as hydrometeors, cloud extent, etc. Northrup Black Widow night fighters (P-61's) were utilized, flown by some of the Air Force's most expert instrument pilots, who volunteered for the task. In a normal mission, five airplanes made simultaneous traverses through the thunderstorms at five different levels, namely, 5000 ft, 10,000 ft, 15,000 ft, 20,000 ft and 25,000 ft.

2. A surface micronetwork was established, consisting of 55 stations located one mile apart in Florida and two miles apart in Ohio. The stations were equipped with gust-recording anemometers and wind vanes, hygrothermograph, weighing rain gage and barograph. The clock speeds on these instruments were fast enough to permit a time resolution to nearly a minute in most cases. The stations were attended daily by observers who traveled through the network in jeeps.

3. In and around the surface micronetwork were set up six radiosonde balloon stations with radio-direction-finding equipment. Outside the network were four radar wind-finding stations, using small radar-

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target-bearing balloons. All these stations made simultaneous balloon releases from which could be obtained, in addition to temperature and humidity data, detailed information concerning the perturbed horizontal wind flow, especially the horizontal inflow and outflow, of the cumulonimbus cloud.

4. Long range radar was used to detect the development of thunderstorms, to select the storms for study, and to guide the pilots and the balloon releases. The airplanes carried transponder beacons by means of which they could be identified separately and traced on the radar 'scopes even when inside the cloud echoes. The pilots were vectored through the storms by the flight controller who, stationed at the ground radar 'scopes, could watch their movements in relation to the thunderclouds. Radar also was used to study the development, growth, movement, distribution, and dissipation of thunderstorms. In this connection, range-height-indicating radar was also employed, giving a vertical crosssection through the clouds and affording an opportunity to study the rates of vertical growth. All 'scopes were photographed every few seconds.

5. Time synchronization afforded the means by which all observations from airplanes, surface, balloon recordings, and radar could be tied together to give the instantaneous and progressive picture of the atmospheric processes.

Structure and Life Cycle

In the analysis of the airplane data it soon became apparent that in the usual large thunderstorm the pilot was encountering areas of strong turbulence, each surrounded by a narrow belt of smooth but cloud-filled air. Roscoe R. Braham, Jr., Thunderstorm Project analyst assigned to this problem, recognized these as distinct convection cells that had become more or less joined together or developed as appendages to an original "mother" cell. For example, a typical Florida thunderstorm that was studied was found to be 20 miles long and about 5 to 8 miles wide, and to have six recognizable cells within it. These were roughly oblong areas measuring 3 to 7 miles across. Between each cell the airplane, although still in heavy cloud, recorded a smooth portion having a width of about a mile or less.

An examination of the photographs of radar echoes returned by the thunderstorms through their life histories verfied the cellular structure by showing the fusion or growth of these cells occurring in much the same way as the growth of masses of certain kinds of bacteria. Where the cells were present over the surface micronetwork, they could also be identified in the rainfall pattern which, at any given moment, had a distribution corresponding to that of the cells. A separate rain maximum would appear under each cell. Other meteorological elements were found to fit the cellular pattern.

The cells were not all alike in structure. Some were found to consist of an updraft only; some had both updraft and downdraft, while others contained only a downdraft. These differences were found to be associated with different stages in the development and dissipation of the cells. From these studies, the life cycle of the thunderstorm cell was worked out, and it was immediately apparent that a thunderstorm usually contains cells in different stages of the life cycle. While every storm must be one-celled at the beginning, the simple unicellular type was found to be rare because its period as a solitary cell lasts only a few minutes after it has reached rainy, thundery conditions. Thus the textbook diagram of a thunderstorm, always unicellular, is misleading.

The life cycle of the cell naturally divides itself into three stages: the *cumulus stage,* the *mature stage,* and the *dissipating stage.*

Cumulus Stage

The first stage of the thunderstorm cell is the cumulus cloud, although only a few cumuli actually build into thunderstorm cells. During this stage two or three cumulus clouds may grow together into one cell, whose diameter may be between one mile and five miles, and whose top usually does not initially exceed 15,000 feet.

The most important structural feature of the cumulus stage is the updraft prevailing throughout the entire cell, balanced by slow settling in the environment. As might be expected, the temperatures in appreciable updrafts are higher than in the environment at corresponding levels. The general updraft varies from only a few feet per second in small and weak cells and cells in earlier stages of development, to almost 100 feet per second in large well-developed cells.

In accordance with well-known precipitation theories, raindrop coalescence occurs when the cloud top has extended some distance above the freezing level. When the accumulation of water exceeds in amount and in drop size that which can be supported by the updraft, the drops begin to fall through the weaker portions of the updraft and the cell passes into the mature stage of development.

Mature Stage

In the mature stage the cell contains in the lower levels a pronounced downdraft adjacent to the updraft. The downdraft reaches downward from approximately 25,000 feet, and throughout the cell above that height the updraft continues. The rain at the surface is associated mainly with the downdraft portion of the cell. The structure is shown in Fig. 1.

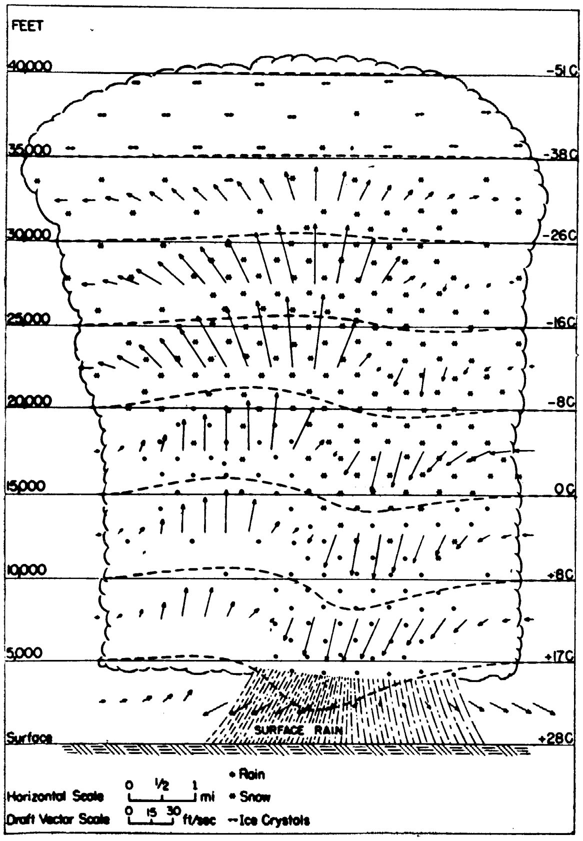

FIG. 1. Sketch of a vertical cross section through a thunderstorm cell in the mature stage, showing vectorially the air circulation. The temperature distribution shown is typical of summer thunderstorms in the eastern United States.

The downdraft results primarily from the presence of falling rain in an area of former updraft. The raindrops become so large and numerous that they exert a frictional drag on the air sufficient to change an updraft into a downdraft.

At this point in the description of the thunderstorm cell it is necessary to insert a few remarks concerning the thermodynamic processes. Classical treatments consider the ascending air from the point of view of the so-called "parcel method." In this process the rising air is regarded as changing its temperature with the expansion and water vapor condensation due to pressure decrease in such a way that it neither affects nor is affected by the environment air. In doing so, its temperature decrease follows the so-called wet-adiabatic rate. Laboratory experience and our atmospheric measurements show that the ascending air of the cumulus cloud behaves in much the same way as a vertical jet stream in the laboratory, in that it frictionally entrains part of the surrounding air. This means that air of less than saturation humidity comes into the cloud and mixes with the cloud air. In the active cumulus, there is enough liquid water being carried in the updraft to preserve saturation, in the face of intrusion of relatively dry air, without completely evaporating. That which evaporates in the mixing process loses part of the heat acquired in the cloud condensation process. As a consequence, the ascending air cools at a rate faster than the wet-adiabatic and at any point is very near the temperature of the environment.

When the frictional drag of the great mass of large raindrops finally changes the updraft to a downdraft, the descent involves increasing temperature at the wet-adiabatic rate, so the rate of warming in descent is less rapid than the cooling in the ascent. Mixing of outside air would tend to make the downdraft even colder, because of evaporation of raindrops. Thus the downdraft becomes a falling current of cold air which spreads out laterally as it strikes the ground.

All of the striking phenomena observed at the ground in thunderstorms are directly associated with the downdraft. Among them are the downpour of rain, the temperature discontinuity, the squall front or "first gust," the barograph "jump," the humidity "dip," and, to a considerable extent, the cloud-to-ground lightning discharge.

Either from the first gust of the wind that reaches out from the downdraft area or from air mass identification in terms of temperature, the outflow of the downdraft air can be traced with precision through the Florida and Ohio micronetworks. The data show that the cold air spreads outward almost equally in all directions in cases of gentle winds, but is carried downwind in a strongly diverging flow when the prevailing unperturbed winds are appreciable. A discontinuity is formed between the outflow air and the surrounding warm air. Although originally formed in the rainy portion of the cell, the downdraft air soon outruns the rain area and its arrival is felt at places several miles from the precipitating cell. The first blast of downdraft air experienced at a station is the strongest, but as long as the outflow continues, strong, gusty winds are observed. The strength of the first and succeeding gusts is less the farther the air has spread, being strongest near where the downdraft first reaches the ground in the early mature stage. There, and elsewhere, the wind speed and gustiness decrease with time as the spreading continues, except in those cases where a new adjacent cell reaches the mature or rain-producing stage.

Computations of the outflow made from a study of the wind field as measured in the surface micronetwork show very pronounced patterns of horizontal divergence centers with the maximum values in the heaviest rain at the point where the downdraft appears to be concentrated. The simultaneous release of balloons at several points around individual storms having mature cells indicated outflow from the ground up to heights between 2000 and 5000 feet, with inflow above. This measured inflow provides a verification of the idea of entrainment of environment air into the vertically moving air of the cloud. In the later mature stage and in the dissipating stage, outflow was measured by the balloons at heights above 25,000 feet, corresponding to the anvil portion of the cloud.

In general, one may say that, heretofore, meteorologists have emphasized too much the thunderstorm updraft. The downdraft is by far the most striking feature, at least in the levels at or near the ground. The inflow winds that feed the updraft are mere zephyrs at the ground, while the outflow from the downdraft produces winds occasionally of destructive force. Other striking changes, such as the temperature drop and the pressure jump, go with the downdraft. Also it is evident that as a thermodynamic engine the thunderstorm does work both through the updraft, which is warmer than the environment, and through the downdraft, which is colder. Temperatures measured from the airplanes amply demonstrated these temperature differences and, in fact, showed that the stronger the draft the greater the temperature difference, in the sense indicated.

Dissipating Stage

When the downdraft has spread across the lower levels of the cell to such an extent that the updraft area becomes of secondary importance, the cell passes into the dissipating stage. As the process continues, the entire lower part of the cell has downdrafts, while in the higher levels there are negligible vertical motions. Slight downdrafts exist as long as light rain continues, although the entraining of environment air at this stage must be a contributing factor in drying up the cloud.

By the time the rain has stopped, large scale vertical motion has subsided and cell boundaries become very indistinct. The storm usually ends up as a dissipating layer of altostratus.

The Outflow and New Cells

One of the effects of the outflowing cold air which was immediately recognized and which was also known to previous investigators, was the action of the pseudo cold front in "triggering" the growth of new cells. It was found that the greatest probability for new cell development is in the region between two cells not more than three miles apart, where two cold outflows meet to squeeze the warm air upward. Downwind three miles or less from an existing cell is another place of importance for cell development.

In some cases the new cells developed before there had been time for the cold air outflow to make its influence felt. It seemed that frequently there was a tendency for cells to grow in clusters almost simultaneously. Some more general features of the dynamics of the air in the vicinity must be a contributing cause in these cases.

Flights Through Thunderstorms

During the two seasons of measurements, the Air Force pilots made a total of 1,363 penetrations through thunderstorms at various altitudes without accident. An effort was made to perform these flights through the most vigorous thunderstorms that could be found in the area of operations. The analysis of these flights furnishes valuable information concerning hazards in thunderstorms.

Turbulence was found to be greatest at the middle and upper altitudes flown, that is, from 10,000 feet upward, with the greatest values appearing between 15,000 and 20,000 feet. The least turbulence was found in the lower layers. Updrafts were strongest in the higher levels, as were also, to some extent, the downdrafts. The lightning and hail hazards were found to be greatest around 15,000 feet. In general, the worst conditions were encountered at the altitudes at which modern airplanes with supercharged cabins are most frequently flown. The use of airborne radar to avoid thunderstorm centers of turbulence, particularly at these upper levels, was indicated to be desirable. With 10-cm radar, it was found that the turbulence outside the cloud echoes was negligible compared with that inside. The possibility of developing radar to the extent that the smooth areas between the cells can be followed should lead to a satisfactory solution of the thunderstorm flying problem at all levels.