portion of the cloud or the rate at which the interval between the thunder and lightning decreases may be used to determine the speed. The distance in miles when the thunderstorm is within hearing is very nearly the number of seconds between a flash of lightning and its subsequent thunder divided by five.

CONCLUSION.

The visible development of the local thunderstorm, its compactness, the power of its self-contained action, the grandeur of its towering cloud masses, and its commanding flashes of lightning and peals of thunder attach to it an unique interest, especially to meteorologists, who see in the thunderstorm a wide range of atmospheric phenomena easily observed.

DISCUSSION.

In connection with the part played by a cold layer of air aloft, H. H. Clayton showed how local convection might proceed in an ordinary manner in the layer of air below the cold one, until reaching the base of the layer in which the gradient was adiabatic. Then rapid ascent of cloud tops would take place and thunderstorms probably result. The occurrence of a cold stratum of this nature is often indicated by turreted alto-cumulus clouds formed by convection taking place independently within cold layer.[9] C. F. Brooks called attention to the occurrence of columnar or turreted cumulus when local convectional columns entered such a layer.

[9] Cf. T. R. Reed, Some observations of a bombing pilot in France, Mo. Weather Rev., April, 1920, 48: 216-217.

THE TOPOGRAPHIC THUNDERSTORM.[1]

By Cleve Hallenbeck.

[Weather Bureau Office, Roswell, N. Mex., June, 1922.]

It would seem that nothing new could be added to the voluminous literature of the thunderstorm, but in all discussions of this phenomenon that have come to our notice the influence of topographic features in modifying and in actually producing thunderstorms has been neglected, presumably for the reason that meteorologists who have directed their attention to the thunderstorm have studied it in regions where the topographic factor was negligible.

One type of cyclonic thunderstorm is generated by the underrunning of humid air by a colder current; in fact, the strictly underrunning current produces more thunderstorms than it usually is credited with. It seems reasonable to assume, therefore, even in the absence of supporting data, that when instead of the underrunning stream of cold air we have a long, comparatively steep slope facing the direction of the rain-bearing winds, condensation and consequent convection may occur in an upslope flow of air.

Such a slope is found immediately west of the Pecos River in New Mexico. The ground rises a vertical distance of 1,460 meters through a horizontal distance of 113 kilometers, a rise of about 13 meters per kilometer (69 feet per mile). The valley as a whole has a southward grade of 2 meters per kilometer (11 feet per mile), so that the steepest slope is east-southeast to west-northwest, thus exactly facing the direction of the moisture-bearing winds. In this direction the rise from river to crest is over 1,500 meters, and air moving up this slope would be subjected to a mechanical cooling of about 14° C. This is about 2° less than the normal depression of the dew point at Roswell on summer afternoons. But in the case of an easterly or southeasterly wind of a general circulation, and which in the Pecos Valley is emphatically the rain-bearing wind, the depression of the dew point is much less than normal, frequently no more than 5° or 6° at midday; consequently condensation normally occurs in an upslope wind of a general circulation. Also on midsummer mornings the depression of the dew point usually is no more than 4°, and an upslope wind during the early morning hours, whether local or of a general circulation, is attended by condensation over the west slope in the form of an irregular belt of cumuli or strato-cumuli (most frequently the former) paralleling the valley, and which varies in dimensions from a row of small, detached cumuli to an unbroken, greatly elongated thunderstorm. Such a thunderstorm, observed at 6 a. m., August 16, 1921, was about 50 kilometers distant and subtended an angle of 70°, which gave it the remarkable length (or width, strictly speaking) of nearly 70 kilometers (42 miles).

It is assumed by many that condensation caused by the mechanical cooling of an upslope wind is in the form of fog or low stratus cloud. Such rarely occurs in this district, even in winter, presumably on account of the overrunning of the lower air by the upslope flow and the decreasing depression of the dew point with increase of elevation above the ground, whereby condensation in an upslope wind usually begins at a considerable elevation.

While condensation normally occurs in air of a general circulation moving up the west slope of the valley, it is delayed until the wind has persisted long enough to import moisture a distance of 500 to 1,000 kilometers. An exception to this rule obtains when there has been general precipitation over eastern New Mexico, following which the air for a day or two is humid enough for condensation to occur promptly in an upslope wind of whatever character.

It has been observed that thunderstorms, which form over the west slope under the conditions stated, nearly always move down grade in a direction more or less opposed to that of the prevailing wind. This clearly is due to gravity. A considerable mass of air under the storm cloud is cooled much below the temperature of the surrounding air, and starts downhill, plowing its way through the opposing flow of warm, humid air, part of which is deflected upward and part turned to one or both sides. That deflected upward corresponds to the rising inflow on the front of the "heat" thunderstorm. The reversal in direction, whereby the rear of the storm becomes the front, evidently occurs soon after precipitation begins, for while thunderstorms sometimes pass over or near Roswell moving west, none has ever been observed to form on the west slope and move westward. However, since the average distance at which these storms form west of the station is 40 or 50 kilometers, an upslope movement of a few kilometers probably could not be detected from the station.

The storm now becomes somewhat analogous to one type of cyclonic thunderstorm, except that the colder underrunning stream of air is quite limited as to length and is moving under the influence of gravity rather than of a pressure gradient. (Strictly speaking, it is a pressure gradient in each case.)

[1] Presented at the meeting of the American Meteorological Society at Salt Lake City, Utah, June 22, 1922.

During its progress down the slope this air is subjected to mechanical heating, but moving at the rate of 30 kilometers per hour, which is not far from the average velocity of the thunderstorm, this heating would amount to but 3° C. per hour (for dry air) and is doubtless more than counteracted by the continued cooling effect of evaporation, etc. Consequently the arrival of the storm in the lower valley is attended by an abrupt fall in temperature of 10° to 16° C. or more. An extreme fall of 20.5° C. is of record.

It would be assumed that since the storm in its downward course encounters a progressive increase in the depression of the dewpoint, it would gradually weaken and finally die. This is what happens to a great majority of the storms of this type. Few of them deliver as much as 0.6 centimeters (0.25 inch) of precipitation at the lower valley stations; nearly half of such as reach Roswell deliver no more than a trace, and many of them break up before reaching the lower valley. Yet they frequently present a majestic and awe-inspiring front when they first start on the downward path that leads to their dissolution, and the deception practiced on newcomers by this type of storm is a standing jest among the initiated. In August, 1921, for example, 19 thunderstorms yielded a total of but 1.9 centimeters (0.77 inch) of rain. Consequently, while these storms are of frequent occurrence, and yield abundant precipitation over the upper, uncultivated portion of the west slope, they are nearly negligible so far as the farming belt of the lower valley is concerned.

The circulation in a typical storm of this class is essentially that which would be expected of a mass of cold air flowing down a slope through an opposing upslope movement. It is not known how much of the opposing warmer air is deflected aloft, but part of it certainly is turned to one or both sides; the former when there is a considerable angle between the opposing currents, and the latter when they are meeting approximately "head-on." There is thus a circulation around a vertical axis on one or both sides the underrunning mass—when on but one side this horizontal circulation appears to be the predominating feature of the air movement near the ground, but no similar circulation has ever been observed with certainty at the cloud level. It seems, therefore, that the underrunning stream of air is being spread out and scattered on its front, and constantly renewed on its rear, as long as the storm continues.

During 1918 and 1919 observations of horizontal wind direction attending the passage of thunderstorms were made at two points in addition to the automatic record at the Weather Bureau station, the three points being in a nearly straight line, separated by intervals of nearly 2.5 kilometers. Only thunderstorms traveling approximately normal to this line and including at least two of the three points of observation in its path were considered. Of the 113 thunderstorms recorded at Roswell during the two years only 14 entirely conformed to these conditions; nevertheless some interesting data were secured. The probable horizontal circulation near the surface of the ground is shown in Figure 1 for three of these storms. The short arrows along the lines A–A and B–B are the observed directions at five-minute intervals. The long arrows indicate the interpolated directions. Entire accuracy is not claimed for these assumed circulations, as any one of them could have changed materially while passing over the points of observation. It is believed, however, that they are approximately correct, as it would be difficult to construct any other rational system of purely horizontal wind that would conform to the observed data: It also is generally known that at a comparatively short distance each side of a thunderstorm the prevailing flow of air is not materially disturbed.

The first of the three charts shows a well-developed circulation about a vertical axis on each side the central stream of cooled air. From this chart the idealized circulation in this type of storm could easily be visualized.

In the second, one of the gyratory circulations is greatly predominant; the secondary one may be either just forming or dying out. In the third, only one circulation appears, although there may have been a secondary one to the left, outside the storm's path.

In each case, the circulation as a whole has a progressive movement from right to left approximately opposite to the direction of the prevailing flow of air. The dotted lines represent the front of the precipitation.

It seems to the writer that some form of horizontal circulation must be assumed for most thunderstorms, since the front of the underrunning stream—the "thunderstorm gust" or "squall wind," as it often is misnamed—has a velocity considerably greater than that of the storm as a whole; nevertheless it never outruns the front of the storm more than a few minutes; it lags behind as often as it outruns. At Roswell its maximum velocity averages twice the velocity of the storm; it can not, therefore, be a straight horizontal wind.

It will be understood that we are speaking only of typical storms of this class. Many thunderstorms occurring in this district are hybrid and can not be classified positively under any head. In some the air circulation is very chaotic. The changes in wind direction in a severe hailstorm of April 25, 1919, were recorded at three points in the storm's path, the observation points being in a nearly straight line approximately normal to the path of the storm, and no system of purely horizontal winds could be reconciled to the observed data, although the storm belonged to the topographically generated class.

It frequently has been observed that in their course down the slope the storms follow a curved path; due probably to the deflecting effect of the prevailing wind. They may curve either to the right or left. The hailstorm above referred to blazed an enormous question mark through the farming district, thus adding insult to injury, as it were.

It may be interesting to note that often, when the thunderstorm breaks up before reaching the lower part of the valley, its cool stream of underrunning air continues on its way, and, if it passes over the Weather Bureau station, leaves its record in the form of a sudden fall in temperature accompanying an abrupt change in wind direction and velocity. There are instances where this air reached the station more than an hour after the storm had broken up. The writer recalls one instance when the meteorologist in charge of the Lander (Wyo.) station was his guest at a Saturday-afternoon ball game, during which there came a sudden, cool wind out of the southwest which raised sufficient dust to temporarily suspend the game. The visitor peered out in all directions to discover the impending thunderstorm, and found nothing but a few tattered clouds in the southwest—the only visible remnant of a thunderstorm that had been making its way down the slope two hours earlier. An explanation was requested and furnished.

This cooled air is, of course, warmed after the storm has ceased, and the fall of temperature attending its arrival in the lower valley is not large—usually 3° to 8° C. Nine of these "phantom thunderstorms" occurred at Roswell in 1916 and eleven in 1917; all were apparently traceable to thunderstorms that had broken up and disappeared.

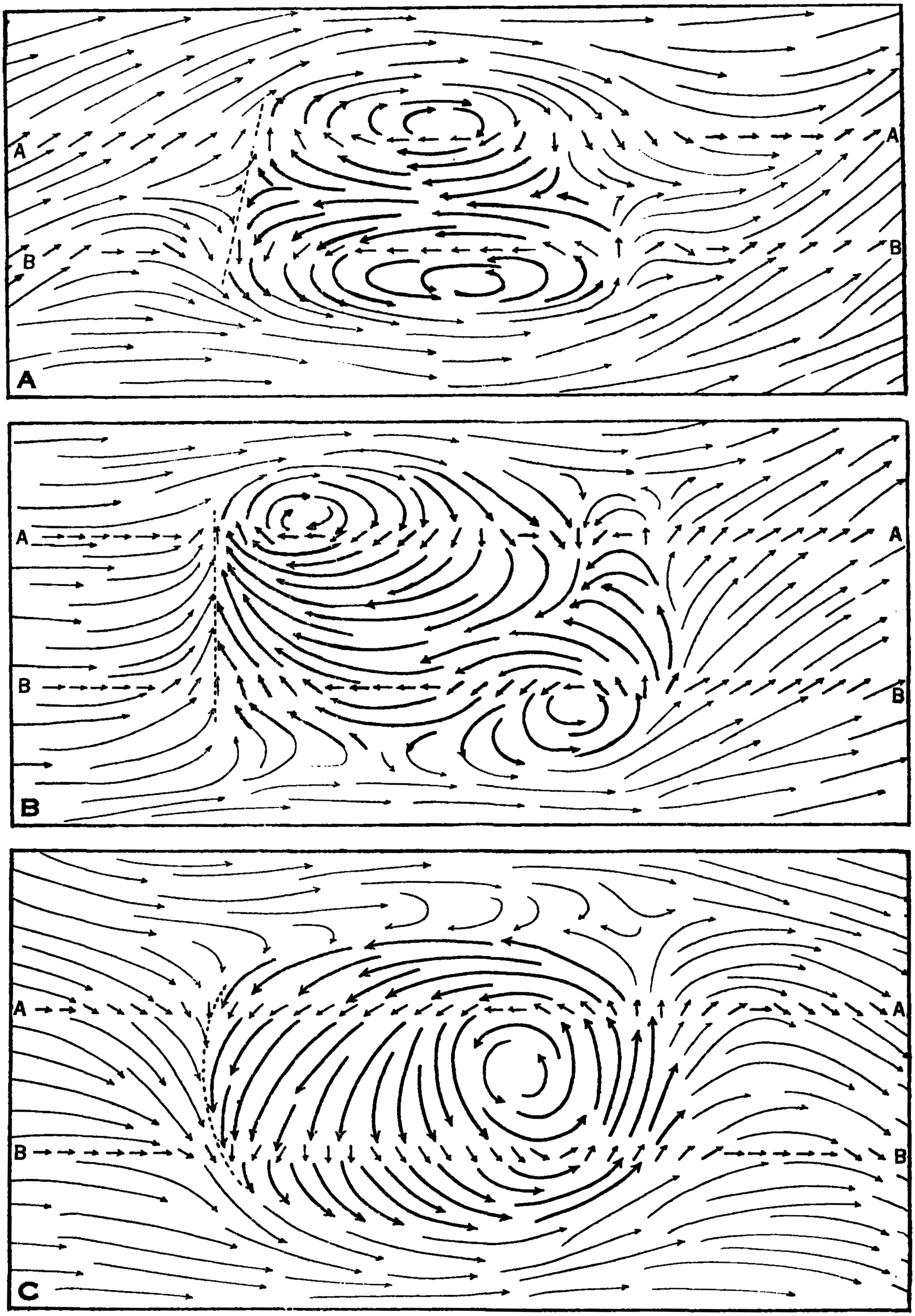

FIG. 1.—Progressive stages of the horizontal circulation about thunderstorms near Roswell, N. Mex.

It may be argued that this so-called topographic thunderstorm may really be of the "heat" variety, since any thunderstorm, however generated, would tend to gravitate down hill. Possibly some that we have classed as topographic were really "heat" storms. But since approximately 80 per cent of all thunderstorms observed at Roswell form on the west slope in an upslope wind, it is certain that this slope is a vital factor in their genesis. Also, both the number of thunderstorms and the total precipitation therefrom increase with increase of elevation westward from Roswell.

A second type of topographically generated thunderstorm occurs in the Pecos Valley, and is decidedly the most interesting phenomenon the writer ever has observed. Its most marked characteristics are as follows: (1) It invariably moves directly up the valley (south to north); (2) it usually occurs at night; (3) two, three, or more such storms sometimes travel in file; (4) there is a stratum of low cloud, nearly always continuous, *below* the thunderstorm circulation; (5) the wind at the Weather Bureau station shows no material change in direction or velocity.

Air moving directly up the Pecos Valley has, at Roswell, an elevation of 1,100 meters above its starting point on the Gulf coast. Reference is made to the Gulf of Mexico because it is only when moisture is imported directly from there that the type of storm under discussion occurs. The air has, therefore, been subjected to a mechanical cooling of about 10° C. The fact that such thunderstorms occur mostly at night may be due to additional cooling by radiation and to the development of an underrunning flow in the form of air drainage.

There seldom is any material change in the velocity of the wind immediately before, during, or immediately after this storm, and its direction is usually southerly at the start, shifting to northerly at some time during the rain; this shift clearly is due to the cooling of the air, whereby it starts to flow down the valley. The direction, however, may be from any point of the compass. The thunderstorm itself is completely hidden from view by an intervening screen of low cloud; this screen covers the entire visible sky, and moves smoothly northward. The storms can be followed only by their thunder and precipitation, but many of them seem to outrun the lower cloud screen. Literally, this is a thunderstorm "above the clouds."

Often two such storms move in file; several cases of three following closely in file are on record (one case occurred while this paper was being prepared, on May 14, 1922), and on June 4, 1921, four thunderstorms followed so closely on each other's heels that the thunder of one had not died away in the north before the rumbling of the next was audible in the south. All were completely screened from view, but the middle of their path apparently was along the river.

On April 15–16, 1915, there occurred a thunderstorm of this type which evidently was composed of five, or possibly six, initially individual thunderstorms that had coalesced into one. The originally distinct storms could be distinguished only by the rise and fall in the volume and frequency of thunder and the contemporaneous increase and decrease in the rate of precipitation. In fact, practically every stage of development has been observed, from two or more separate storms moving in file to a single greatly overgrown thunderstorm in which the original units could no longer be distinguished.

A thunderstorm which delivers excessive precipitation over an area 270 kilometers long and 115 kilometers wide, an area nearly equal to Massachusetts and Connecticut combined, with lightning and thunder lasting nearly ten hours, is a sizable thunderstorm for an arid region, yet the storm of April, 1915, fitted these dimensions. And at that it was not the largest thunderstorm that has occurred in the Pecos Valley.

The following explanation of the formation of this type of storm is offered: The upvalley flow of air—very humid, as it came from the Gulf of Mexico—is cooled mechanically to its dew point simultaneously, or nearly so, at widely separated points. Since the valley slope is but 2 meters per kilometer (11 feet per mile) a difference of 1° in the dew point of two parts of the upflowing air would mean a distance of more than 50 kilometers between the points at which condensation would begin. Unless the dew point were remarkably uniform throughout, condensation would occur at different elevations. There would therefore be a series of local condensation areas, and, consequently, a series of convections moving in file. With continued progress up the valley, with the consequent additional cooling, the areas of condensation would spread, and would eventually join each other, forming one continuous sheet of cloud. The individual convections arising from the upper portions of this cloud also would grow, but it is probable that each maintains its integrity to some extent, for a single convection covering 25,000 square kilometers is unthinkable.

It is further apparent that a final stage in the life of this storm is the total cessation of convection, or, at least, the total cessation of lightning and thunder, although preciptation may continue for some time at a heavy and even excessive rate. An example of this occurred on August 7–8, 1916, which delivered over 13 centimeters (5.5 inches) at both Roswell and Carlsbad, 120 kilometers apart. This storm was attended by lightning and thunder at Carlsbad (the lower of the two points) but not at Roswell, although at the latter point it delivered excessive precipitation for nearly two and a half hours without a break.

While such storms are infrequent, they always yield heavy precipitation, and are responsible for most of the floods that have occurred in the Pecos and its tributaries.

Some objection may arise to the idea of a thunderstorm occurring "above the clouds," but the writer has been assembling his data for six years and is sure of his position in this. An invisible thunderstorm, which approaches and passes overhead, with no movement of the leaves on the trees other than that produced by the falling rain, would certainly be a novelty in districts where every thunderstorm is attended by a high or violent wind. Only one such case has been observed here but as a rule the wind is light. Sometimes the thunderstorm circulation apparently affects the lower air, but these are exceptions to the rule.

There is no reason why a thunderstorm may not develop and run its course wholly removed from the surface of the earth. A convection can, theoretically, start at almost any elevation above the surface. The fact that nearly all thunderstorms are based on the ground is due to the fact that most convections start from the ground.

It has been noted that when such widespread thunderstorms as have been described occur in the Pecos Valley, similar storms occur at the same time in the Canadian Valley in the northeastern part of the State—similar, at least, as regards the amount and extent of precipitation. Possibly both types of thunderstorms discussed herein may be observed in other districts of the West where a long slope is presented to the direction of the moisture-bearing wind.