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THE LOCAL, OR HEAT, THUNDERSTORM.[1]

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GROWTH AND DECAY OF A LOCAL THUNDERSTORM.

The development of a local thunderstorm from a clear or nearly clear sky proceeds by well-marked stages in the course of but a few hours. At first small bodies of air here and there are warmed more than those over surrounding areas, and as a result convection in small units occurs. The upward currents in the early morning when the air is still humid do not need to rise very high before cooling by expansion results in cloud formation. The sky becomes dotted with a number of small cumulus clouds at low elevation. As the heating continues the convectional currents become stronger. At the same time, however, the rise of temperature increases the depression of the dewpoint and, therefore, the height at which condensation will occur. When there is abundant moisture the increased strength of convection carries the convectional columns upward at a higher rate than that at which the level of condensation rises. On account of the greater heating and greater height to which convection must go, however, before a cloud will form only the larger columns can reach the cloud stage, so the clouds become larger and their number decreases. This process continues until there are great cumulus clouds interspersed by large clear spaces.

If the supply of warm air that is being displaced by colder air from aloft is sufficient and if the air at moderate heights is enough colder to make this warm air rise rapidly through an appreciable layer, the cumulus cloud grows to a great height and a large amount of condensation takes place within it. Up to a certain stage the upward current is sufficient to prevent any of the raindrops from falling out of the cloud. But when the load of accumulated rain becomes too great for some part of the rising current it breaks down and the first rain descends suddenly to the ground. As this rain falls it cools the air by evaporation, and, to some extent, the raindrops drag the air along with them, thereby establishing a descending current. This downward current spreads laterally at the ground and becomes the outblowing squall of the thunderstorm. Where this squall underruns the air that is rising in the periphery of the great cloud, a new, outward growing ring of cloud lower than the original cloud base is formed. (See lower projection on right of Figure 1.) Figure 1 shows the probable distribution of winds, hail, and rain and snow within a well-developed thunderstorm.

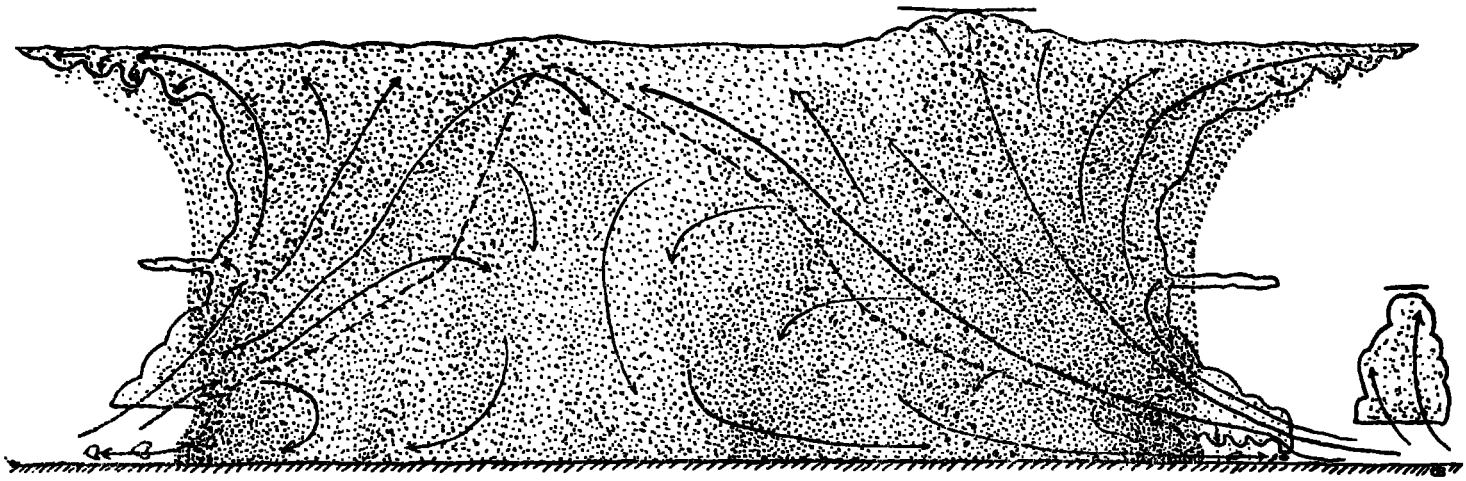

FIG. 1.—Idealized, diagrammatic, cross section of a well-developed local thunderstorm. The lines represent cloud outlines, the dots raindrops, the black spots hail-stones, and the arrows winds. The dotted line within the body of the cloud marks the boundary between ascending and descending winds and, therefore, roughly the position of the cloud base. It will be noted that winds may concentrate lines of falling raindrops in such a way as to bring more intense rainfall than is occurring by virtue of the precipitation falling from the same area at a height of a kilometer or two. The most intense rainfall is shown near the borders of the thunderstorm where there is most active condensation and release of the raindrops. With a given rate of fall from the thunderstorm or any part of it the amount of rainfall at any place passed over will increase in proportion to the decrease in the velocity of the storm. Thus, when a moderate or intense shower becomes stalled on a mountain slope a cloudburst occurs. A description with diagrams, of the details of the front of a thunderstorm was published in the MO. WEATHER REV. June, 1919, 47: 398-400.

The physical make-up of the thunderstorms now changes from the simplicity of a central rising column of air surrounded by descending air to the complexity of a central descending and outflaring current of cold air, surrounded by a cone of rising warm air and still farther out by a zone of descending air, as at first. By the process of lateral expansion the thunderstorm may become so large that no more rain is carried to the center. Then the middle falls out, leaving a doughnut-shaped thunderstorm or a ringlike series of small thunderstorms attached to a common overflow sheet at the top. A moving thunderstorm develops a crescentic or half-

[1] Presented before American Meteorological Society, Washington, D. C., Apr. 26, 1922. Reference should be made to Prof. W. M. Davis's unexcelled description of local thunderstorms, in his *Elementary Meteorology*, Boston, 1894.

doughnut shape, representing the front half only, for it scoops up large masses of warm air in front, but has little except its own wake of cool air behind. Further expansion of these smaller units may now be limited by the coolness produced by neighboring storms, and so with the life-giving warm air exhausted, the storms wane and the clouds evaporate.[2]

CAUSES OF LOCAL THUNDERSTORMS.

A thunderstorm is the result of relatively large streams of air in violent convection attended by abundant condensation of moisture. Even in the smallest of local thunderstorms the air volumes involved amount to many cubic kilometers. The maximum strength of the upward movement of air within any thunderstorm must be considerable, for the electrical separation which causes the lightning is probably the result of the splitting of raindrops (or snowflakes) and the rapid carrying aloft of the smaller, negatively charged fragments while the larger, positively charged ones descend. That abundant condensation of moisture is an essential feature of a thunderstorm is evident from the invariably attendant great mass of cloud and the usually accompanying intense rainfall.

Large local streams of air in convection.—Any observer of clouds has noticed the failure of promising-looking large cumulus clouds to become cumulo-nimbus, evidently from the lack of a large enough flow of ascending air. Furthermore, a cloud of considerable dimensions must develop before a thunderstorm originates. Strong winds are adverse to the collection of sufficient, continuous volumes of warm air to form large enough convectional units. Even if the requisite volumes can be forced upward from the surface stratum of air, a marked diversity of relative air movement at different levels within the lower 4 or 5 kilometers of the atmosphere is likely to draw them out or blow them apart before a thunderstorm can form. Thus a small wind movement at the surface and a lack of marked diversity of relative wind movement aloft are conditions essential to the formation of large local streams of air in convection.

Violent convection.—Why does the air in cumulus clouds that are growing into cumulo-nimbus rise so rapidly? A cloud will grow from insignificance to towering height in only a few minutes. On different occasions rough, angular measurements of mine have shown upward motions of 3, 4, and 7 meters per second in such tops. In addition, the sides of such cumuli bulge perhaps half as fast as the top rises. It is evident that the upward current within the cloud must be more rapid than the rise of its summit. After the thunderstorm is formed, the occurrence of enormous drops of rain and the occasional fall of hail of appreciable size indicates the presence of great uprushes of air within the cloud. Furthermore, such unfortunate aviators and aeronauts as have been inside active portions of cumulo-nimbus clouds have experienced great bumpiness owing to the strong up-and-down currents.[3]

Violent convection is caused by the instability accompanying a large lapse rate in temperature.[4] A large lapse rate may be caused by heating below, cooling above, or both. The formation of a relatively hot, surface stratum in the early afternoon is favored by (1) a lack of clouds, (2) dry ground, (3) a small lapse rate to 2 or 3 kilometers, which prevents convection from sending up the surface air till it becomes very warm, and (4) a high, morning minimum temperature, induced, perhaps, by nocturnal cloudiness. The occurrence of relatively cold air aloft is favored by (1) cloudy weather for some days, (2) northerly wind (in Northern Hemisphere) recently begun or a southwesterly wind which has continued for some time,[5] and (3) either a lack of upper clouds, resulting in cooling by radiation, or the presence of heavy cirrus with the lower ends of its snow trails cooling the air by evaporation. The part played by the falling, dense clouds of snow from the top sheets of old thunderstorms is often a highly important one. This snow by melting and evaporating not only keeps cold the air down to an altitude of about 3 kilometers, but also adds considerable moisture to it. Thus the drifting, old tops of thunderstorms help to provide conditions favorable for thunderstorms in the districts they invade. Convection will take place in cloudless air if the lapse rate exceeds about 1° C. per 100 meters, the adiabatic rate of temperature change with change in volume attending change in height, and in cloudy air if the lapse rate exceeds the retarded adiabatic, about 0.5° to 0.7° C. per 100 meters, in the lower half of the troposphere at ordinary temperatures. Violent convection will occur if the lapse rate in cloudless or cloudy air markedly exceeds the adiabatic or retarded adiabatic, respectively.

Any condensation at all is thus likely to increase the speed of convection; and the lower the level at which condensation occurs the faster and the farther will the air be forced upward. Thus, not alone as yielding water does condensation favor the formation of a thunderstorm.

Abundant condensation of moisture.—Abundant condensation of moisture is essential to the start of a thunderstorm, for without the great numbers of drops or snowflakes large enough to break on falling through the rising air there would not be the separation of the larger from the smaller fragments which seems to be necessary to the production of lightning. Abundant condensation is also necessary to the maintenance of the mechanical strength of a thunderstorm. The falling rain evaporates and keeps cool the air descending with it. Without its cold element coming to the ground, where it can run under and force upward the warm element, the power which the thunderstorm derives from being a self-cooling heat engine could not arise. Plenty of moist air is, therefore, needed in the production and maintenance of a thunderstorm. A high moisture percentage (e. g., 2 or 3 per cent) in the surface air, even if it prevails through a layer a kilometer thick, will not be sufficient if the air aloft is dry, for the early convection rapidly dissipates this moisture by mixing the moist air with the dry air above. Thus, the moist layer should extend up to 2 or 3 kilometers, at least, to insure it against loss of effectiveness before convection can form a thunderstorm. A wind blowing for several days from a warm source of moisture, with attendant daytime convection to spread the moisture through an appreciable vertical layer, is,

[2] In an article on "Clouds in east Texas, June 8, 1918" (MO. WEATHER REV., March 1919, 47: 151-154), I have described in some detail the development and decay of cumulus clouds and local thunderstorms. The characteristics there described are typical of local weather in many parts of the United States under similar conditions of generally clear upper air with warm, moist lower air.

[3] See MO. WEATHER REV., August, 1919, 47: 523-532.
The degree and volume of upward motion within a growing cumulus or cumulo-nimbus cloud could be observed and computed. A corps of observers with plenty of pilot balloons, theodolites, and base lines could obtain data as to the amount of air per minute inflowing under the cloud base, and by successive angular measurements of the upward and lateral expansion of the cloud could provide themselves with a check on the computation of inflow. The actual upward speeds would be indicated to some extent by the rate of rise of balloons entering the cloud base at different points, thus providing a way for distributing the total upflow as computed from the inflow and the area of the cloud base. In making the computations of the upward motion of the air the increase in the volume on account of expansion would not be neglected.

[4] "Lapse rate" is being used as a substitute for the cumbersome "rate of vertical decrease" or "vertical temperature gradient."

[5] Cf. H. W. Clough, The sequence of changes in wind direction, pressure, and temperature in the free air (synopsis in), Bull. Am. Metl. Soc., July, 1922.

therefore, usually a necessary precedent to thunderstorm formation.[6]

Local indications of conditions favorable for local thunderstorms.—Since there are three essentials to the formation of thunderstorms—plenty of warm air, rapid ascent, and much moisture—taking each of these elements separately into account simplifies the difficulty of attempting to consider all the factors at once in predicting whether or not local thunderstorms will occur. One, or even two, of the factors may be very favorable to the formation of thunderstorms, while another may be adverse. Under such conditions local thunderstorms do not occur. The following outline questionnaire may be helpful in showing the complexity of any attempt at forecasting local thunderstorms even only six hours in advance and in providing a guide to making predictions of afternoon, heavy, local showers:

QUESTIONNAIRE FOR PREDICTING LOCAL THUNDERSTORMS.

A. Will large units of warm air become available?
   1. Will the wind this afternoon be light? and
   2. Will there be a lack of marked diversity of relative air movement up to 4 or 5 km.?

B. Will there be violent convection?
   1. Will the air at the surface become hot relative to that aloft?
      (a) Will there be a lack of cloud sheets most of the morning?
      (b) Is the ground dry (dryness and low specific heat favors rapid heating)?
      (c) Is the lapse rate small up to 2 or 3 km. (so that considerable heating will take place before convectional overturning occurs)?
   2. Is there, or will there be, relatively cold air aloft?
      (a) Has the weather been cloudy for some days?
      (b) Is the wind at 3 or 4 km.
         Northerly, since only recently? or
         Southerly, since some time ago?
         } For Southern Hemisphere use opposite directions.
      (c) Was the night free of upper clouds? or
         Has there been appreciable cooling of the air at these levels by evaporation of heavy cirrus trails?

C. Will there be abundant condensation of moisture?
   1. Is the surface air moist (i. e., with high absolute and high relative humidity)?
   2. Is there, or will there be, a plentiful supply of moist air up to 2 or 3 km., the height from which return currents of air can come before a thunderstorm can form?

If the answers to these questions are tabulated somewhat as follows, their indications may be readily summarized:

PROBABLE CONDITIONS AT NOON OR 2 P. M. (DETERMINED AT 8 A. M.).

Date.	Large streams of air.		Violent convection.		Abundant condensation.	
	Light wind.	Lack of diversity aloft.	Large lapse rate because—		High absolute and relative humidity.	Moist up to 2 or 3 km.
			Hot at surface.	Cold aloft.		

Under each of the six headings a plus, a zero, or a minus may be used to indicate answers of "yes," "moderately so," or "no," respectively. A minus in any column will show a probability of no local thunderstorms. Furthermore, at least one plus under each of the principal three headings will indicate that local thunderstorms are probable, while 5 or 6 plusses will show that thunderstorms are to be expected and that they will probably be violent.

WHERE THE LOCAL THUNDERSTORMS ORIGINATE.

Local thunderstorms tend to originate most often where large volumes of moist air are readily warmed and forced upward, e. g., broad expanses of meadowland or river flats, and over cities,[7] hills, and mountains. From places of origin the storms grow laterally and move forward. As lateral growth largely depends on local supplies of hot air, and as the general winds about the body of a thunderstorm are usually fairly constant in direction, it follows that the frequency of thunderstorms rains must be markedly different within even a relatively small area, such as a State, or even a county.[8] Within a homogeneous area, however, the wetting of strips by local showers temporarily makes the dry strips the loci of thunderstorm formation. At College Station, Tex., during a rainy week in the latter part of August, 1918, this phenomenon was noted very clearly, and local forecasts of thunderstorm rains were successfully based on the widths and position of strips wet by thunderstorms on the preceding day. Daily rainfall statistics for stations within a homogeneous region for a period of local showers show marked differences in totals for any day, but less important ones for the period as a whole. Any area that escapes on the first day or two heats more readily than the surrounding wet areas, and so becomes the center of greatest expansion and inflow from the surroundings, and in consequence is wet by the resulting shower. Or even if the shower produced by the local rising air is carried to other fields before discharging, any approaching shower will develop most strongly over the dry area and therefore drench it more than those previously wet.

When winds aloft blow forward, the spreading tops of local thunderstorms, the first effect of this cloudiness is to curb local heating and convection. When these sheets advance along the paths of the storms this curtailed heating and convection starves a weak storm, yet sustains a strong one. The small, weak storm usually needs strongly heated, local air masses, which can not be supplied if the top has cast its shadow over the path of the storm. Thus, it dies, and a considerable strip in advance of it remains dry for the day. The strong storm, on the contrary, is favored by the lack of local convection in its path, for the warm surface air has not been dissipated by small scale convection nor cooled and dried by local thunderstorms. The advancing plow of cold air scoops up a good supply of warm air for miles and miles, and the storm thunders across the countryside with undiminished energy, the same distance as the edge of the thunderstorm top. Once such heights are known it becomes necessary only to determine the actual speed of winds at the intermediate levels. This speed is readily found from the angular motion of alto-cumulus or alto-stratus clouds considered in conjunction with the height of such clouds as found from the cumulus measuring stick. By taking the measured height and the angular height the distance is obtained, and from the speed the time required to traverse this distance is found.

When the thunderstorm is near at hand the rate of increase in the angular elevation of any prominent

[6] For a detailed discussion of the physics of the thunderstorm, see W. J. Humphreys's *Physics of the Air*, Philadelphia, 1920.

[7] See R. E. Horton, Thunderstorm-breeding spots and The beginning of a thunderstorm, Mo. WEATHER REV., April, 1921, 49: 193-194.

[8] A preliminary study of thunderstorm data collected by W. H. Alexander from about 1,000 observers in Ohio in 1917 strongly supports this general statement even for a region as homogeneous as Ohio.

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.