point, respectively. For all cases the straight line $Y=1.4X$, has been drawn. Forecasting by this method, considering the scattering of dots from the graphs, would be equally successful in clear or cloudy weather.

It will be noted that this method is essentially a modification of my maximum-minimum temperature method (described in Monthly Weather Review Supplement No. 16 and elsewhere) by considering the effect of moisture in retarding cooling.

551.515 (73)

THE TORNADO

By W. J. HUMPHREYS

[U. S. Weather Bureau, Washington, January, 1927]

The tornado discussed in what follows is the typical "twister" of the American prairies, and may be defined as a slightly funnel-shaped, or flaring, hollow, circular column of upward-spiraling winds of destructive velocity. It is the most violent, least extensive, and most sharply defined of all storms. Its appearance and effects often have been described. There is no satisfactory account, however, of its origin. Hence it seems worth while to assemble the more common facts of observation in connection with this type of storm, and to deduce therefrom whatever we can in regard to its genesis. These deductions, being something definite to prove or disprove, will at least help to fix one's attention and thereby hasten, it is hoped, the ultimate solution of this difficult meteorological problem.

Some of the normal, but not all of them invariable, circumstances of place and meteorological conditions connected with the occurrence of tornadoes are the following, the more important, from the standpoint of this paper, being numbered with boldface type.

1. *Geographic location.*—Central and southeastern United States, chiefly; next, perhaps, southern Australia, though Griffith Taylor says, in his *Australian Meteorology*, "tornadoes are not common in Australia"; and several other parts of the world occasionally, except in general the tropical regions. The so-called tornado of tropical west Africa appears to be a violent thunderstorm of the squall type. The tropical waterspout is relatively mild, and of a more or less different origin.

2. *Meteorological location.*—Southeastern section, or, more exactly, east of the wind-shift line, of a LOW, or cyclone, of moderate to decided intensity.

3. *Kind of cyclone.*—The trough or V-shaped, the kind productive of secondary cyclones, is very favorable, especially when the V protrusion points southward, or, more particularly, southwestward. However, tornadoes occur also when this protrusion of the isobars is not conspicuous, if indeed present at all, at the surface of the earth.

4. *Other pressure distribution.*—A moderate anticyclone to the rear, that is, west or northwest, of the cyclone, appears to be an invariable condition; but even if this pressure distribution be essential, as we believe it is, to the genesis of the tornado there is no proof of it from statistical evidence alone, since normally the extratropical cyclone has an anticyclone to its rear.

5. *Surface pressure gradient in region of tornado.*—Usually moderate to steep in comparison with the average cyclone.

6. *Horizontal temperature gradient.*—Usually steep along a portion of the border between cyclone and anticyclone.

7. *Previous wind.*—Moderate to fresh southerly, often southwest.

8. *Following wind.*—Moderate to fresh, northerly, often northwest.

9. *Previous temperature.*—At 8 a. m. 70° or over and increasing.

10. *Following temperature.*—Distinctly lower than just before the storm.

11. *Previous humidity.*—Excessive—making the air, at its high temperature, sultry and oppressive, from hours to even days before.

12. *Clouds.*—Heavy cumulo-nimbus, from which a funnel-shaped cloud depends. Sometimes this cumulus is isolated and very towering, but, when not isolated, often preceded briefly to an hour or longer by mammato-cumuli.

13. *Precipitation.*—Rain and usually hail 10 to 30 minutes before; light precipitation at instant of storm (funnel cloud often clearly seen and occasionally photographed); deluge of rain, mixed at times with small hail, shortly after.

14. *Lightning.*—Nearly, or quite, invariably lightning accompanies the tornado, but seldom, if at all, occurs in the funnel cloud.

15. *Sounds.*—There always is a loud rumbling or roaring noise while the whirling pendant cloud is in touch with or even closely approaches, the earth.

16. *Direction of tornado wind.*—Spirally upward around a traveling axis, and in the same sense as the accompanying cyclone—counterclockwise in the northern hemisphere.

17. *Horizontal velocity of wind in tornado.*—Unmeasured, but destructively great.

18. *Vertical velocity of wind in tornado.*—Also unmeasured, but sufficient to carry up pieces of lumber and other objects of considerable weight—say 100 to 200 miles per hour.

19. *Location of initial and sustaining whirl.*—Above, probably close above, the general cloud base.

20. *Velocity of storm travel.*—Usually 25 to 40 miles per hour.

21. *Length of path.*—Anything up to possibly 300 miles, usually 20 to 40 miles.

22. *Direction of travel.*—Roughly parallel to travel of the center of the general or cyclonic storm, hence usually northeastward.

23. *Width of storm.*—Anything from 40 to 50 feet up to, rarely, a mile or even more, but averaging around 1000 feet. Many are only 500 to 600 feet across and others, as stated, even much less.

24. *Number.*—Usually several, often in groups, in connection with the same low-pressure system, and on the same day.

25. *Time of year.*—Mainly spring, and early to mid-summer, but occasionally also at other seasons.

26. *Time of day.*—Usually midafternoon, or 3:00 to 5:00 p. m.

All the foregoing meteorological conditions are inferred from observations at the surface of the earth, and not in the free air one or two kilometers above the surface, where the tornado seems to have its origin. Data from this obviously desirable upper level appear to be very scanty. However, through the kind assistance of the Climatological and the Aerological divisions of the United States Weather Bureau, 26 cases were found where observations by sounding balloon or kite, or both, were made less, to much less, than six hours from the time of and nearer—some far closer—than 100 miles from, a tornado. These observations indicate (they are too few to prove anything) that when tornadoes occur the wind, whatever its value at the surface, is strong (around 20 to 25 meters per second or, say, 50 miles per hour) at the height of one to two kilometers. In some cases the direction of the wind is nearly constant throughout at least the lower two kilometers, the approximate depth explored. Sometimes it backs, turns counterclockwise, perhaps 30°, but usually veers at this height, roughly 45°.

Mid-air temperature inversions appear to be quite common and the lapse rates next above these inversions very rapid, often nearly or quite of adiabatic value. In short, so far as one can infer from these few observations, the atmosphere in the neighborhood of a tornado appears to be unusually stratified, and tending to become unstable at one or more levels. But we must remember that even these observations, the best we have, were taken at distances too great to give reliable information about so very local a disturbance as the tornado. They may be suggestive in this connection, but they are not conclusive.

As implied, several of the above circumstances and meteorological conditions are only usually, and not invariably, associated with the tornado, nor perhaps are they all that have any importance in respect to its genesis and maintenance. Nevertheless, they are among the more conspicuous and sufficient, it would seem, to restrict explanations to those that contain elements, at least, of the truth.

a. Since the linear velocity in whirls frictionally created between passing currents, whether liquid or gaseous, cannot exceed that of these currents relative to each other, it follows that the tornado, whose winds far surpass this limiting value, is generated in some way that is not purely mechanical.

b. The only other way by which vortical motion is produced naturally in the atmosphere is that of drawing closer together, through vertical convection, masses of air the algebraic sum of whose angular momenta about the center of that convection is greater than zero, whether positive, rotation in one sense, or negative, with opposite rotation. Here the Principle of Conservation of Angular Momentum, or conservation of areas, is operative, by virtue of which the linear velocity, except as reduced by friction, so increases as the distance from the center decreases that the product of this distance and the velocity is a constant.

In this way, and in no other, persistent whirls in the air of great linear velocity can and do occur naturally where the interference, frictional and turbulent, is quite small. That is, in the free air, from where they may, and often do, feed down to the surface.

c. The production of a violent whirl in the air, through the conservation of angular momentum, requires (1) a central or localized vertical convection at the level at which the whirl begins; and (2) that the currents drawn into the ascending column have initially either different directions, or different speeds if originally in the same direction. Local convection does not produce rotation in still air, nor in wind that has the same direction and speed throughout except, in each case, to the slight extent caused by the rotation of the earth. The ordinary dust whirl is induced by convection over a surface across which the flow of air is so disturbed as to miss the center of convection and start a spin. This spin may be in either sense, clockwise or the contrary, from which it follows, as also from other considerations, that the dust whirl and the tornado, which always turns in the same sense, are radically different in origin.

d. Kite, pilot-balloon, and cloud observations all show that the winds one or two kilometers above the surface are moderately swift in the neighborhood of a tornado, and increased over the surface winds more than commonly is the case at that level. These observations also indicate that the rapid velocity increase frequently, at least, begins at some intermediate level where a greater or less change in direction also usually occurs.

We infer, therefore, that there are adjacent, presumably superjacent, currents of air of different sources where and whenever tornadoes are likely to occur.

e. From the rather common occurrence of the mammato-cumulus cloud shortly before the development of a tornado, it would seem that at the level at which this storm originates there is a superjacent wind cold enough to be unstable with reference to the air just below it. From this fact, and from the approximate to full adiabatic lapse rates that have been found at such times at the cloud level, we infer that on these occasions vigorous convection might be expected—started by gravity instability and intensified by vapor condensation. Furthermore, from the lightning that accompanies the tornado we are sure that there then is strong convection within the clouds, and from the hail that so frequently falls well to the front of a tornado it is evident that the convection is up to great heights and into strong winds.

Now, the southerly winds over the lower and mid-Mississippi Valley, especially, often have rather small lapse rates, very much less than the adiabatic, and therefore are comparatively stable, or difficult to upset convectionally. Over such lower air an upper wind might blow, sinking down only to that level at which its adiabatic warming brings it to the temperatures of the under air at that same height. Presumably, then, in this region the mid-level winds of the southeastern portion of an anticyclone to the west or northwest may flow out over a lower stratum of southerly winds belonging to the adjacent cyclone. In this case there would be a cold front, or squall line, in mid-air, a kilometer, perhaps, above the surface, with a shift of wind direction similar to that which under otherwise like circumstances occurs at the ground when the anticyclonic air extends to the surface, as it usually does.

When the cold front is along the ground the slope of the under surface of the anticyclonic wedge, in the direction normal to this front, is very gentle—a rise of one or two kilometers, say, in a hundred. This condition is due largely to the fact that the velocity of the air near the surface is much less than that at a considerable height, owing, of course, to turbulence and surface drag. Along the mid-air cold front, however, the slope between the two wind systems, the cyclonic and the anticyclonic, presumably is much steeper, as there is no excessive drag at a strata interface.

If now, as seems certainly possible, a cold front should occur some distance above the surface of the earth, it is probable that local convections would develop here and there along it, much as, under similar circumstances, they do along the squall line. Owing, however, to the steeper ascent of the interface between the two wind systems there would be this difference: Convection from the ground, the usual case, would be of overrun or entrapped masses of the warmer and humid cyclonic air up *through* the anticyclonic air above, and would not produce much vorticity no matter how different the directions of the two systems of winds. On the other hand, local convection on a mid-air cold front could be *between* the two wind systems (their interface being steep, as explained) and consist of roughly equal parts from each.

This convection would produce rotation at cloud level, at least in those cases in which the cyclonic winds had a strong southerly component and the anticyclonic, at the same height, a considerable northerly component. Such winds, if both are being carried bodily with the same velocity, as may be the case, eastward, or, for that matter, along any other course (the principle is general), might differ in direction over the surface of the earth, that is, as seen from the surface of the earth, by almost any angle from 0° to 180°, as determined by the values of their north-south and east-west components, and yet, *with reference to each other, have exactly opposite directions*—be flowing beside and past each other at the same level. In this case they would tend to develop swirls along their more or less vertical interface, of the nature of miniature secondary cyclones, after the fashion of the greater cyclones along any polar "front." In either case, that is, whether convection were of the squall-line type, or started by a swirl like a miniature cyclone, if the air of the major or great cyclone were very humid, and it always is where tornadoes develop, the heat liberated by the incident condensation would increase the convection and consequent spin. This spin, in turn, would drag in the air from lower and lower levels until under favorable circumstances, particularly the existence of a rather rapid lapse rate in the lower air, the surface of the earth was reached. Furthermore, since the rotation of the earth requires the southerly wind to lie east of the northerly, this spin has always to be counterclockwise in the Northern Hemisphere and clockwise in the southern.

Where the two streams, cyclonic and anticyclonic, are drawn together, presumably at or about the cloud level, the velocity of the whirling wind tends to follow the law of the conservation of areas, or to be inversely proportional to the radius of curvature. At lower levels, however, where the spin is the result of a drag from above, the decrease of velocity with increase of radius appears to be much more rapid. Indeed the path of destruction shows so little shading off that generally it is described as being sharply defined, a condition that proves the wind velocity to drop off exceedingly rapidly with increase of distance beyond this boundary.

A familiar detail of the tornado is its pendent, funnel-shaped cloud, caused, as is well known, by the dynamical or expansional cooling of the air under the decreased pressure within the vortex. This decrease of pressure causes houses, in a measure, to burst open as the tornado passes over them. However, it is not very great, probably of the order of one-tenth of an atmosphere, as is readily computed from the spin of the vortex and the rapid decrease of velocity beyond the path of destruction.

The spinning air constitutes a dynamical wall that keeps the outer atmosphere from getting into the region of lower pressure.

The above, or something more or less like it, appears to be the physical explanation of the origin of the tornado. But if so, why then, one asks, are tornadoes so much more frequent in the central Mississippi Valley than elsewhere, and why most frequent there in the spring of the year? Because there, and especially at that season, certain of the conditions listed above are best developed and most frequent; such as very humid southerly winds (having come from over the Gulf of Mexico); a strongly encroaching anticyclone to the west or northwest, and the formation of a mid-air cold front. Why also, one further asks, does the tornado rarely occur in tropical countries? Because, as explained above, it is a joint product of cyclone and anticyclone, one of which, the anticyclone, is there practically unknown.

A complete discussion of the tornado obviously would involve the liberal use of vortex equations. But the data necessary to such a discussion are not avaliable, nor is the theory of the vortex in viscous fluids sufficiently devoloped to be readily applicable to this case.

THUNDERSTORMS AT LANDER, WYOMING

551.515 (787) By McLin S. Collom

[U. S. Weather Bureau Office, Lander, Wyoming]

The mountainous topography of the Lander district is exceptionally favorable for the occurrence of convectional thunderstorms, and of the recorded storms fully 80 per cent appear to have been of this class.

During the 20-year period 1906–1925, inclusive, a total of 408 thunderstorms occurred at or close to the Lander station. A graphical representation of their diurnal distribution indicates that 75 per cent occurred from 11 a. m. to 7 p. m., 14 per cent from 7 p. m. to midnight, and 11 per cent from midnight to 11 a. m., and that the hour of greatest frequency was from 2–3 p. m., with 51 storms, or 12 per cent of the total number. July was the month of greatest frequency, with 26 per cent of the total, and June a close second, with 25 per cent; for December, January, and February not a thunderstorm was recorded.

The storms, as a rule, develop over the mountainous region a few miles from the station. They are frequently intense, but in most instances the greater portion of their energy is expended in the mountains; intense thunderstorms over the adjacent valley are exceptional. Of the storms of record 81 per cent were classed as light, 14 per cent as moderate, and but 5 per cent as heavy.

The prevailing movement was from the southwest, 43 per cent moving from this direction; 19 per cent moved from the west and 18 per cent from the northwest; or, in all, 80 per cent from a westerly (mountain) direction.

Strong winds accompanying the thunderstorms were exceptional. A maximum velocity of from 30 to 40 miles an hour occurred in 14 instances during the 20-year period; but 5 storms were attended by a wind velocity in excess of 40 miles an hour.

Hail attended but 11 of the 408 storms. In all instances the fall was light and except in a few instances caused no damage to tender vegetation.

The thunderstorms of the Lander region are important as factors in both the starting and stopping of fires on the Washakie National Forest. Here the season of greatest hazard (the season which, on account of relatively high temperature and low humidity, most favors extreme dryness of timber and duff) extends normally from about mid-June to September. It is during this season that thunderstorms are most probable. Approximately 10 per cent of all fires that have occurred on the Washakie Forest have been caused by lightning; but the spread of the fires has been limited by the amount and duration of the precipitation attending the storms. During the 20-year period under consideration 55 storms, or 13 per cent of the 408, were recorded as "dry"; 275, or 67 per cent, gave a trace to 0.10 inch precipitation; 48, or 12 per cent, 0.11–0.25 inch; 19, or 5 per cent, 0.26–0.50 inch; and 11 storms, or 3 per cent, gave precipitation in excess of 0.50 inch.

The average height (base) at which thunderstorms pass over the Lander station, computed from the two constants—adiabatic rate of cooling and rate of lowering of the dew point due to expansion—for a limited series of observations was found to be 2,896 feet.

The average rate of movement of the storms selected for special observation, computed by ratio, was 24.6 m.p.h.

Owing to the limited number of thunderstorms which could be observed for determining the foregoing values,