A PROPOSED SYSTEM FOR PREDICTING, LOCATING AND TRACKING TORNADOES

By

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PREFACE

The work accomplished in this project can be divided into three parts. The first is an introduction of the problem at hand. The second part consists of a summary of material obtained by library research and interviews with authorities on the subject of tornado phenomena. The third part entails a discussion of the results of this research and suggestions for the practical application of the material obtained.

A large portion of this paper has been devoted to a general discussion of weather phenomena. Though not directly concerned with the problem at hand, this part of the work constitutes background material and is one of the important aspects of the problem as a whole. The author has attempted to include sufficient material to give others who carry on the study a general background in the meteorological aspects of the work.

Expression of appreciation is made for the inspiration and help of Doctor H. L. Jones in carrying out this research. Professor Wm. E. Hardy of the Department of Meteorology has given his generous assistance in coordinating the material without which this work could not have been carried on. Captain R. C. Miller of the U. S. A. F. furnished much valuable information on the meteorological methods of tornado prediction. To these men and the others who aided in forming the material, the author expresses his deepest appreciation.

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CHAPTER I

INTRODUCTION

One of the most treacherous and destructive forces arising from natural causes is the tornado. One has only to read the newspapers during a tornado season to realize the great danger and destruction to human life and property due to their formation. At the present time tornadoes cannot be prevented so the resulting damage to property is inevitable. A suitable warning system to give residents time to seek safe shelter would, however, prevent the destruction of human life.

The research, of which this thesis is a portion, is being conducted in the hope of solving the problem of tornado prediction and detection. Mr. Carl Miller initiated a study of possible methods of tornado detection in the autumn of 1947. After considerable research he decided to concentrate on the study of atmospheric peculiarities that might be associated with the storm. As outlined in the thesis prepared by Mr. Miller, equipment was gathered and adapted to the job.[1] The research was restricted to the idea of determining tornado atmospherics which may be distinguished from those coming from ordinary thunderstorm disturbances. Library research narrowed the study to lightning stroke intensity and duration. Additional justification of this basic assumption was obtained by Mr. Stanley

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[1] Carl W. Miller, "A Proposed Method of Identifying and Tracking Tornadoes," Master's thesis, Oklahoma A. & M. College, Stillwater, Oklahoma, 1948.

Hutchison in his study of tornado identification.[2]

The initial equipment designed by Mr. Miller for the identification of tornadoes by lightning flashes has been modified and improved by Mr. Harold Jeske[3] and Mr. T. H. Thomason.[4] The equipment in its present status both measures the intensity of a lightning flash and gives its direction from the receiving station.

This thesis is intended to present a method of predicting the formation of a tornado. Some necessary modifications and additions to the present equipment are suggested so that the tornado may be located and tracked after it has formed and moves over the ground.

When such a system is evolved, tornado warnings can be given to the public and the tornado death toll diminished.

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2 John Stanley Hutchison, "A Study of Tornado Identification," Master's thesis, Oklahoma A. & M. College, Stillwater, Oklahoma, 1949.

3 Harold O. Jeske, "Electrical Apparatus For The Study of Sferic Waveforms," Master's thesis, Oklahoma A. & M. College, Stillwater, Oklahoma, 1949.

4 Thomas H. Thomason, "The Development of A Sferic Direction Finder," Master's thesis, Oklahoma A. & M. College, Stillwater, Oklahoma, 1949.

CHAPTER II

METEOROLOGICAL CAUSES OF TORNADO FORMATION

Tornadoes are almost always associated with cold fronts, i.e., the movement of cold air masses. A cold front is frequently defined as an area along which a cold air mass is overtaking and underrunning a warm air mass. This particular definition, which describes the characteristic action of the normal cold front, is of little use when discussing tornado formation. Let us limit the definition to a dense cold air mass which is overtaking a warm air mass of lesser density or, so that the effect may be implied, a front along which cold air replaces warmer air. The normal action of a cold front is to lift up the warm air it replaces and under such conditions the leading edge of the front is drawn on weather maps as a line on the surface of the ground. Under certain synoptic conditions that will be described later, the cold air mass may temporarily overrun the warm air mass it will eventually replace. Such a tongue of cold air frequently overruns the warm air for a distance of fifty miles and has been known to overrun up to three hundred miles.[1] The position of the front is then usually determined from maps of the upper air. A diagram illustrating such an overrunning cold front is shown in Figure 1.

For the diagram given, the cold air could be polar maritime air that originated over the North Pacific and moved into

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[1] Berry, Bolay and Beers, Handbook of Meteorology, p. 654.

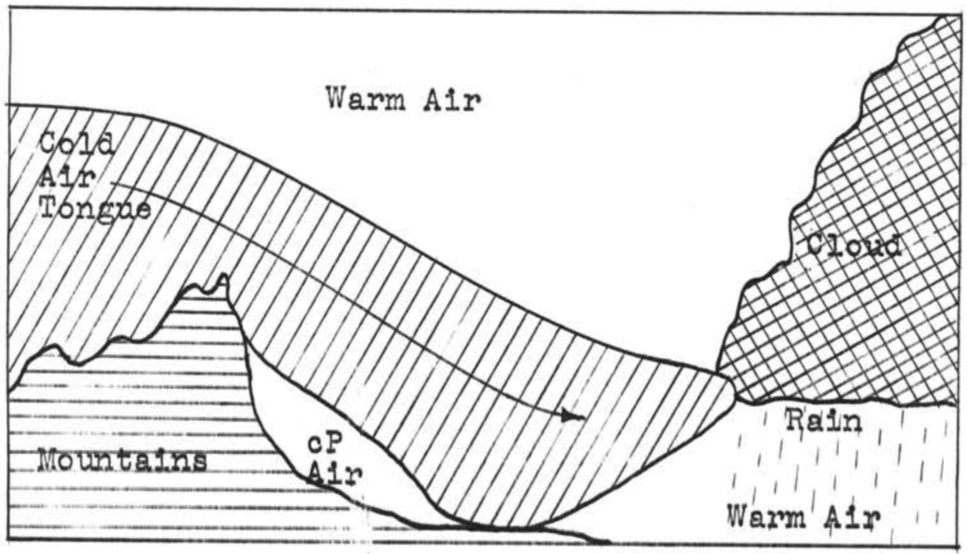

Figure 1

the great plains region from the northwest. The bottom layer of cold air could be polar continental air which originated over the cold northlands and moved southward. It is generally colder and heavier than the polar maritime air. The warm air could be tropical maritime air which started from over the warm waters of the Gulf of Mexico or the Atlantic from near the Tropic of Caner.

The forced lifting by the cold air tongue of the warm air above it will set off convective activity producing heavy showers and thunderstorms. If the warm air trapped underneath the cold air is less dense than the cold air, and it normally is, the boundary zone between the cold and warm air becomes what is termed autoconvectively unstable.[2] This is the condition from which tornadoes may form.

The situation existing is that a mass of warm southerly air lies below a cold north-westerly stratum and a change must soon relieve this unnatural arrangement. The cold air presses down on the warmer lighter air in obedience of the law of convection. Eventually the cold air blanket becomes disrupted allowing the warmer air to surge upward through the break and as this takes place, a rotary motion of the warm air mass will result.[3]

The rotary motion may be explained as follows. As the warm air moves inward and upward from all sides toward the center of the opening the indraughts will fail to follow precise radial lines. As they move inward and to one side or the other of true center, a turning will begin in the direction of the strongest current. If the data available is assumed to be reliable, it can be concluded that all tornadoes in the Northern Hemisphere turn in a counterclockwise direction and those in the Southwen Hemisphere turn in a clockwise direction. Such uniformity points to some factor more regular than the accidental strength of the winds. This point will be explained in some detail in the introduction to cyclones where it will be shown that the direction of rotation of tornadoes is determined by

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2 Berry, Bolay and Beers, Loc. cit.

3 William Morris Davis, Whirlwinds, Cyclones and Tornadoes, p. 83.

the rotation of the earth on its axis.[4]

In explaining the formation of a tornado there are three motions to be considered. These are its general progression over the ground, its spiral rotation, and its central updraft. Chapter four is devoted to a discussion of the first of these. The other two motions can be explained in detail as follows.[5]

> As is well known, the spiral rotation attains great velocities near the center in accordance with the very important mechanical principle of the "preservation of areas." When a whirling body is drawn toward the center about which it swings, its velocity of rotation will increase as much as its radius of rotation decreases: the centrifugal force will also increase, and with the square of the velocity, or inversely as the square of the radius. This law claims obedience from air, as well as solid bodies: hence, if the air of a tornado mass have a gentle rotary velocity of twenty or thirty feet a second at a thousand yards from center, this velocity will increase as the central air is drained upward and the outer particles move inward so that, when their radius is only one hundred yards, they will fly around at the rate of two or three hundred feet a second, or over one hundred and fifty miles an hour. It must be understood, however, that this requires that there should have been no loss of motion due to friction, and hence can be true only for the air at a distance above the ground; and, further, that, in spite of the great horizontal rotary motion, there is still only a moderate vertical current, and consequently we have not yet arrived at the cause of the violent central and upward winds that distinguish the tornado from other storms, but this is close at hand.
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> Admit for a moment that there is no friction between the air and the ground. We should then have a tall vertical cylinder of air, spinning around near the center at a terrific speed, at the base as well as aloft, and consequently developing a great centrifugal force. As a result, the density of the central core of air must be greatly diminished. Most of the central air must be drawn out by friction into

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4 Ibid., p. 30.

5 Ibid., pp. 84-87.

> the whirling cylinder, and prevented from returning by the centrifugal force. The core will be left with a feeling of emptiness, like an imperfect vacuum. If there were any air near by not controlled by the centrifugal force, it would rush violently into the central core to fill it again. Now consider the effect of friction with the ground. The lowermost air is prevented from attaining the great rotary velocity of the upper parts, and consequently is much less under the control of the centrifugal force, which is measured by the square of the velocity. The surface-air is therefore just what is wanted to fill the incipient vacuum: so it rushes into the core and up through it with a velocity comparable to that of the whirling itself; and this inward-rushing air is the destructive surface-blast of the tornado.

There is one other point to be considered. The whirling motion has been described as counterclockwise in direction in the Northern Hemisphere and this uniformity of motion has been ascribed as due to the earth's deflective force. It cannot be assumed that the inward rushing air is drawn from a sufficient distance to show the direct effect of the earth's deflective force. If, however, the entire warm air mass is considered to be rotating in the counterclockwise direction due to the earth's force, then it is logical to assume that a smaller whirl formed within the large air mass would rotate in the same direction. The constant direction of rotation of tornadoes may therefore be taken as evidence that they do not form in a still air mass, but are connected with the air currents of a cyclone.

It is now necessary to consider the sources of frontal movement and cyclonic activity. It is from the resulting motion of air masses that the synoptic conditions necessary for tornado formation result.

The primary cause of all weather changes is the uneven and periodic heating and cooling of the earth's surface. Three major factors cause this large-scale uneven heating and cooling. First, daily heating and cooling result from the earth's rotation. As the earth turns on its axis, the side facing the sun gathers heat. As this side turns away from the sun, it cools, generally reaching lowest temperatures shortly before sunrise. Second, the amount and the seasonable periodicity of solar radiation received by the earth varies with latitude because of the earth's revolution about the sun. This variation is due to the elliptical path of the earth around the sun and to the earth's axis being tilted 23.5 degrees from a perpendicular line to the plane of movement. Since the earth is spherical in form only a portion of the sun's rays strike the earth directly. Areas under direct or nearly direct rays receive more heat than those under oblique rays, since direct rays concentrate their energy on less surface area and so provide more heat per unit area. Also, oblique rays pass through more miles of absorbing, reflecting, and scattering atmosphere. This causes less heat energy to reach the earth's surface. The unequal duration of daylight also contributes to the uneven distribution of heat. The third major factor is that land heats and cools more readily than water. There are several reasons for this. Water surface reflects much more of the solar radiation than land. Hence, less heat remains to be absorbed. The sun's rays penetrate a deep layer of water while land is heated only at the surface. Then, the movement of water distributes the heat while land stays put. The specific heat of water is approximately four times that of land requiring far more heat for a given temperature change. Finally, water evaporates and evaporation is a cooling process. Water retains its warmth longer chiefly because it heats to a greater depth and because it contains more heat per given temperature increment.

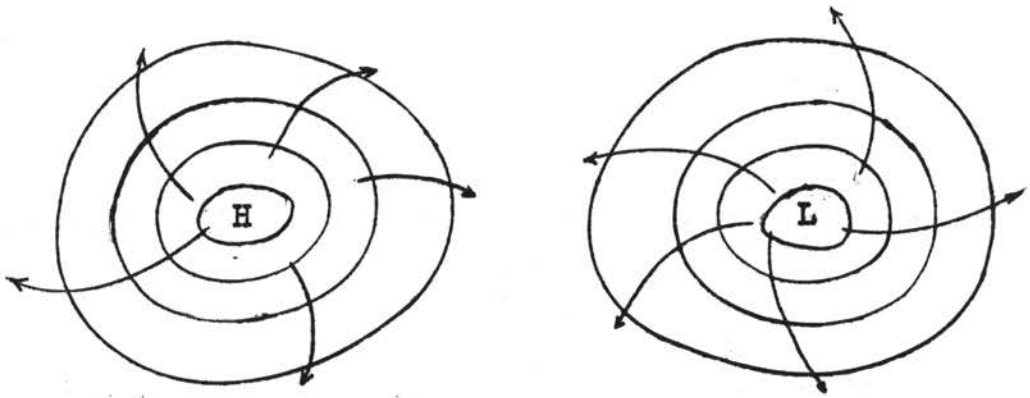
Heat is transferred from the earth to and throughout the air by the three processes of convection, radiation and conduction. Since air is a poor conductor of heat the last of these, conduction, is practically negligible. Radiation from the earth transfers much more heat to the air. Convection transfers heat throughout the atmosphere by moving warm air to higher levels and cold air to levels near the ground where it can absorb heat by radiation and conduction. The transfer of heat from one place to another by air mass movements produces our general pattern of world climate.

Wind, or the movement of air masses, is caused by unequal air pressure conditions over wide areas. Air always moves away from areas of high pressure and into areas of low pressure.

These pressure differences are a result of the unequal heating and cooling of air masses. When air warms and expands, upper layers of the rising column flow off to the surrounding upper colder regions, cooling as they go. The warm area has lost come of its air so its air pressure is reduced and a low pressure area at the surface of the ground results. The upper air that has flown off and away from the expanding air column moves outward and down, stopping over air that is cool and compact. This increases the pressure of the cool air at lower levels and a "high" has been formed.

It would be logical to assume that the air movement at the surface of the ground would be radially outward from a high pressure area and radially inward at a low. Thus, the wind would follow the direction of decreasing pressure gradient and cross the isobars or lines of constant barometric pressure at right angles. If the earth did not rotate, the wind would be perpendicular to the isobars. There is a deflective force however, sometimes called the Coriolis force, that arises from the earth's rotation and tends to deflect all motions in the Northern Hemisphere to the right and in the Southern Hemisphere to the left. This rotational force is not an actual force, it is only an apparent one due to the earth's spinning in the moving air. The deflecting force varies with latitude being zero at the equator and greatest at the poles. In addition there are forces due to the friction of the earth with the atmosphere that deflect air mass movement. As a consequence of the deflective force and friction, wind in the Northern Hemisphere blows counterclockwise toward a low pressure area and clockwise from a "high" at the surface of the earth. As the altitude above the ground increases, the wind blows more nearly parallel to the isobars. They are parallel when the deflective force plus centrifugal force equals the pressure gradient force. The directions of air mass movement from a "high" and toward a "low" are shown in Figure 2.

The speed of the air mass movement, that is, the intensity of the wind is dependent upon the pressure gradient along which



High Pressure Area Low Pressure Area

Air Movement at "Highs" and "Lows"

Figure 2

it moves. On a weather map this is determined from the distance between lines of constant barometric pressure. The closer the isobars are together, the stronger the wind will be.

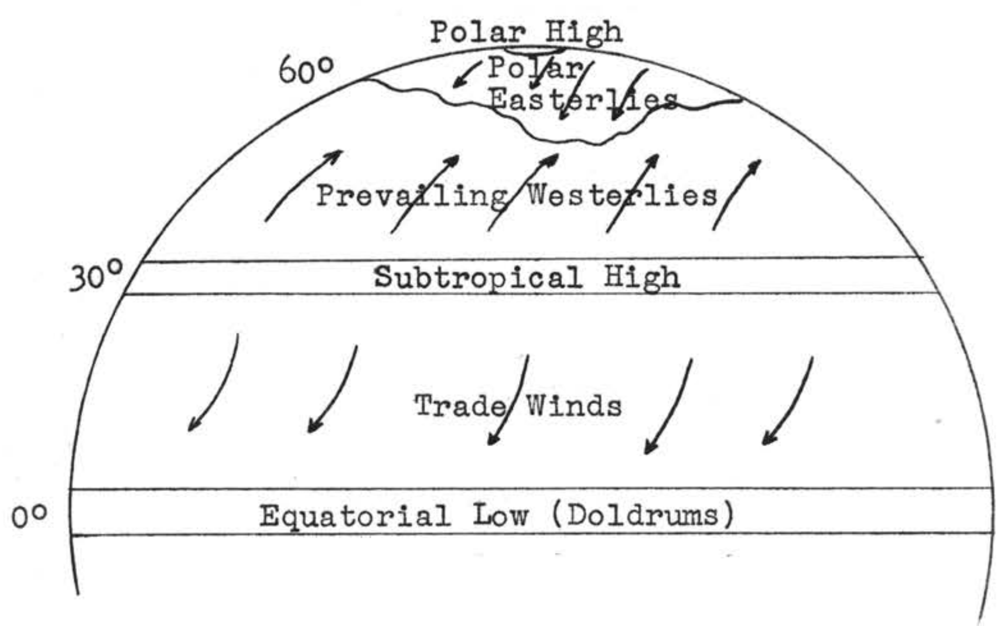
The secret of air circulation is the attempt of the atmosphere to equalize heat distribution. Local turbulence and wind are due to the uneven heating of the earth because of the temperature variations caused by local surface conditions. In the same manner, but on a much larger scale, the latitudinal differences in the earth's heating produce pressure gradients that set air in a general pattern of motion over all the earth.

Equatorial regions heat most. This causes the air to expand, and as a result of the more intense heating, the equatorial expansion extends higher than that of other latitudes. The center of gravity of the equatorial atmosphere is therefore at a higher level. A low pressure area will be formed at the surface of the earth, but at high elevations, the pressure over the equatorial regions is greater than the pressure over the other latitudes, causing the upper air to flow from the equator toward cooler regions. The air that flows from the equator into the Northern Hemisphere generally descends at about thirty degrees North Latitude. The cause is not fully understood, but one popular theory attributes it to the piling up, due to deflection, of the upper air that started northward and is deflected toward the east.

Air flows outward from any high pressure area in all directions. From this high-pressure belt at about thirty degrees North Latitude, lower air blows not only toward the equator but also toward the North Pole. At the North Pole, the air is cold and dense resulting in a high pressure area. Therefore, there is air moving from the pole toward the equator. This cold air moving from the polar high generally meets the warmer air moving toward the poles somewhere between the latitudes of forty and sixty degrees. Along this polar front the warm air, being lighter, must ascend. Some of it moves back overhead to descend again near thirty degrees latitude. Some however, at upper levels, continues poleward and increases the polar high pressure area. The area in which the warm and cold air masses collide is frequently referred to as the polar front "battlefront." Oklahoma lies in this area.

Because the earth's rotation deflects all Northern Hemisphere wind to the right of the pressure gradient, winds moving toward the equator from the subtropical high become what are known as the Northeast trades, and those starting toward the equator from the polar high pressure area become the polar easterlies. Winds starting toward the pole from the subtropical high become our well-known prevailing westerlies. This general circulation pattern is illustrated in Figure 3.

Actually the general circulation does not work just as is shown by the illustration. The uniform circulation portrayed would function if the earth were a homogeneous substance, but the earth's surface is of land and water. The uneven heating of land and water has been previously pointed out as one of the major reasons for uneven heat distribution, and thus one of the major causes of weather. Its effect on the earth's circulation



Theoretical Air Circulation Pattern

Figure 3

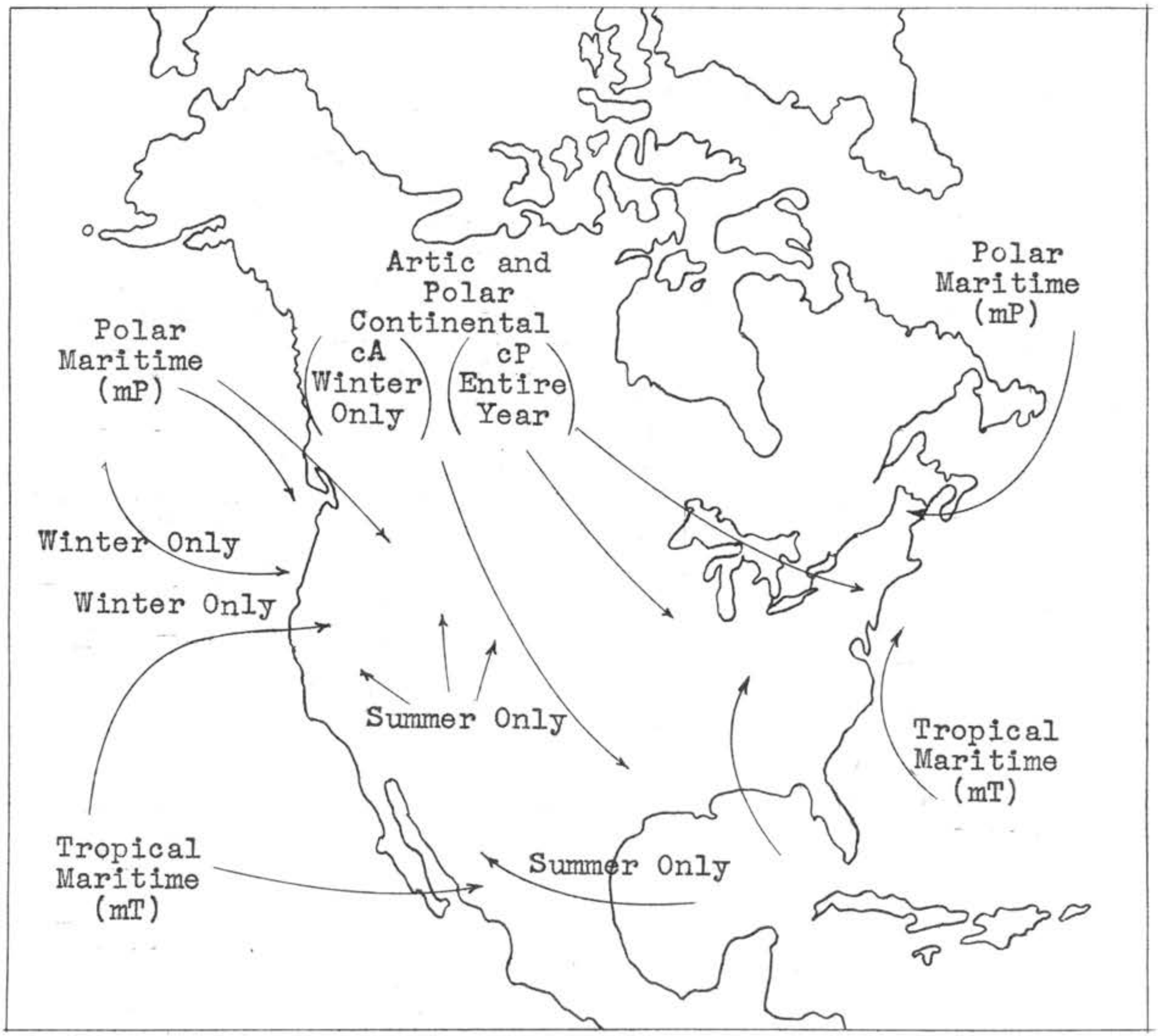
pattern is pictured for the United States by Figure 4.

Let us briefly consider the general characteristics of each of the air masses shown. Three major factors influence the characteristics of an air mass. They are its source, its path and the amount of time spent in transit. An air mass starts its migration endowed with the characteristics of its source region. As it moves across the earth, the air mass is modified by the surface over which it passes. It becomes warm or cold, dry or moist, depending upon the nature of the surface over which it lies. The length of time in passing influences the amount of the modification.

An air mass is classified by its source region and whether it is colder or warmer than the surface over which it is moving. Symbols used on weather maps indicate whether the air is artic (A), polar (P), tropical (T) or "superior" (S) in orgin; whether it gained its properties over a maritime surface (m) or a continental surface (c); and whether it is colder (k) or warmer (w) than the surface over which it is moving. For example, mTw means "warm tropical maritime". Note that it reads backwards.

Of the winter air masses affecting the United States, the most important is the polar continental (cP). It is a cold dry stable air mass that originates over the frozen northlands and surges southward bringing cold waves as far as the Gulf Coast.

Winter air masses originating over the artic icecap require even lower temperatures and greater stability than the cP air. Due to its extreme coldness, it is quite dense, which enables it to move with great force. After moving sufficiently far



Source and Direction of Movement of Air Masses
That Influence North American Weather

Figure 4

southward, usually into the Middle West, it becomes considerably modified and shows the same characteristics as cP air.

Polar maritime air originating over the North Pacific dominates the winter weather of the west coast. This air is usually fairly warm. As it moves, it picks up a great deal of moisture and causes rain and snow particularly in the mountain regions. When mP air moves over the Rockies, it often finds colder heavier cP air over the Great Plains. Since the mP air is lighter, it overrides the cP air and frequently does not reach the ground surface. When the mP air does move down the east slopes of the Rockies, it blows as warm dry winds over the plains having lost its moisture in coming over the Rockies.

A high pressure area is located in the Pacific between California and Hawaii. In the winter this source area is relatively cool, so the winter mT air that moves in on the California coast is comparatively dry and stable. It is the cause of frequent fogs, however.

Over the warm waters of the Gulf of Mexico, mT air masses become warm and moist. When this mT air from the Atlantic or Gulf moves northward over cold land surfaces, deep fog layers cover large areas. It appears over the midwestern states slightly colder and considerably drier.

The summer air masses that appear over the United States differ slightly due to the seasonal effects.

The cP air of the summer comes from a thawed-out northland. It moves southward more slowly than in the wintertime and generally develops fairly high temperatures before reaching the

Middle West.

The high pressure area in the Pacific moves north in the summer. From there it sends mP air to the west coast from the northwest. The lower layers pick up a great deal of moisture and upon reaching the coast, condenses and produces coastal fog.

The subtropical high of the Pacific moves northward for the summer giving the mT air from this source more of the mP characteristics. Little of this air reaches the California coast.

The subtropical high of the Atlantic is best developed in the summer. At the same time there are in general much lower pressures over the continent. Therefore the mT air masses from the Atlantic and the Gulf move farther inland in the summer. This air is hot and moist, possesses a great deal of latent heat energy, and has great potentialities as a thunderstorm maker.

It can be seen that the characteristics of the air masses differ greatly and are continually in motion. When a polar air mass, a polar easterly, moves southward it eventually meets a tropical air mass, a prevailing westerly, moving northward. When these masses meet, with the one exception of an occluded front, they do not mix. Generally one advancing air mass ascends over the other, usually the warmer over the colder. The surface of meeting is called a frontal surface and the line on the earth's surface that separates them is called a front.

Some fronts are stationary with neither air mass replacing the other. Some fronts do not extend down to the surface of the ground. There are two basic types, however, that advance along the surface of the ground. These are the warm front along which warm air replaces colder air and the cold front along which cold air replaces warmer air. Cold fronts normally move faster than warm fronts (20 to 40 m.p.h. to the warm fronts 10 to 20 m.p.h). In addition to traveling faster, the frontal surfaces of cold fronts have much steeper slopes. The normal shapes of warm and cold fronts are shown in Figure 5.

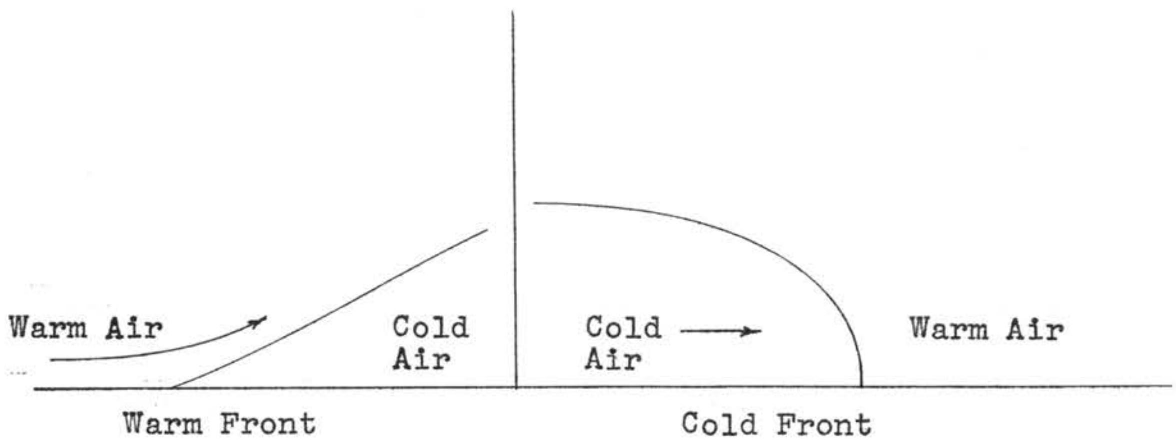


Figure 5

When a warm and a cold front meet, there are atmospheric disturbances. The two fronts act in union and not as individual enities, i.e., they play related parts in the same storm area. Low pressure areas develop along the front of the two air masses due to the rising warm air. The centers of greatest pressure differential form where the greatest quanities of warm air rise over the cold air. Corresponding high pressure areas are formed where the warm air settles and these high pressure areas move in behind the lows. These high and low pressure areas move across the United States in a general eastward direction.

The frontal disturbances are directly connected with the low pressure areas that form where air masses meet. The low pressure areas that bring the frontal disturbances are called depressions or cyclones. The high pressure areas that move in behind the lows bringing clearing skys are called anticyclones. Note that cyclones, or more properly, cyclonic depressions, should not be confused with tornadoes.

The cyclonic depressions are the factors that determine the weather in the area they invade. Although the nature of the frontal activity depends greatly upon the characteristics of the clashing air masses, the cyclones have a standard pattern they follow from beginning to end, as shown in Figure 6.[6]

Theoretically, when the cold air originating from a polar high meets the warm prevailing westerlies, the warm and cold air should move in opposite directions along a smooth polar front as is illustrated in section (a). Such a condition may be present along a stationary front, but is more commonly found in connection with an advancing cold front. In either case, the long smooth front soon becomes disrupted, usually due to the front passing over an obstruction such as a mountain, and the colder denser air surges forward making ripples in the line. This is shown in section (b). Note the associated warm front and the general counterclockwise movement of the air. The solid connecting lines represent the lines of constant barometric

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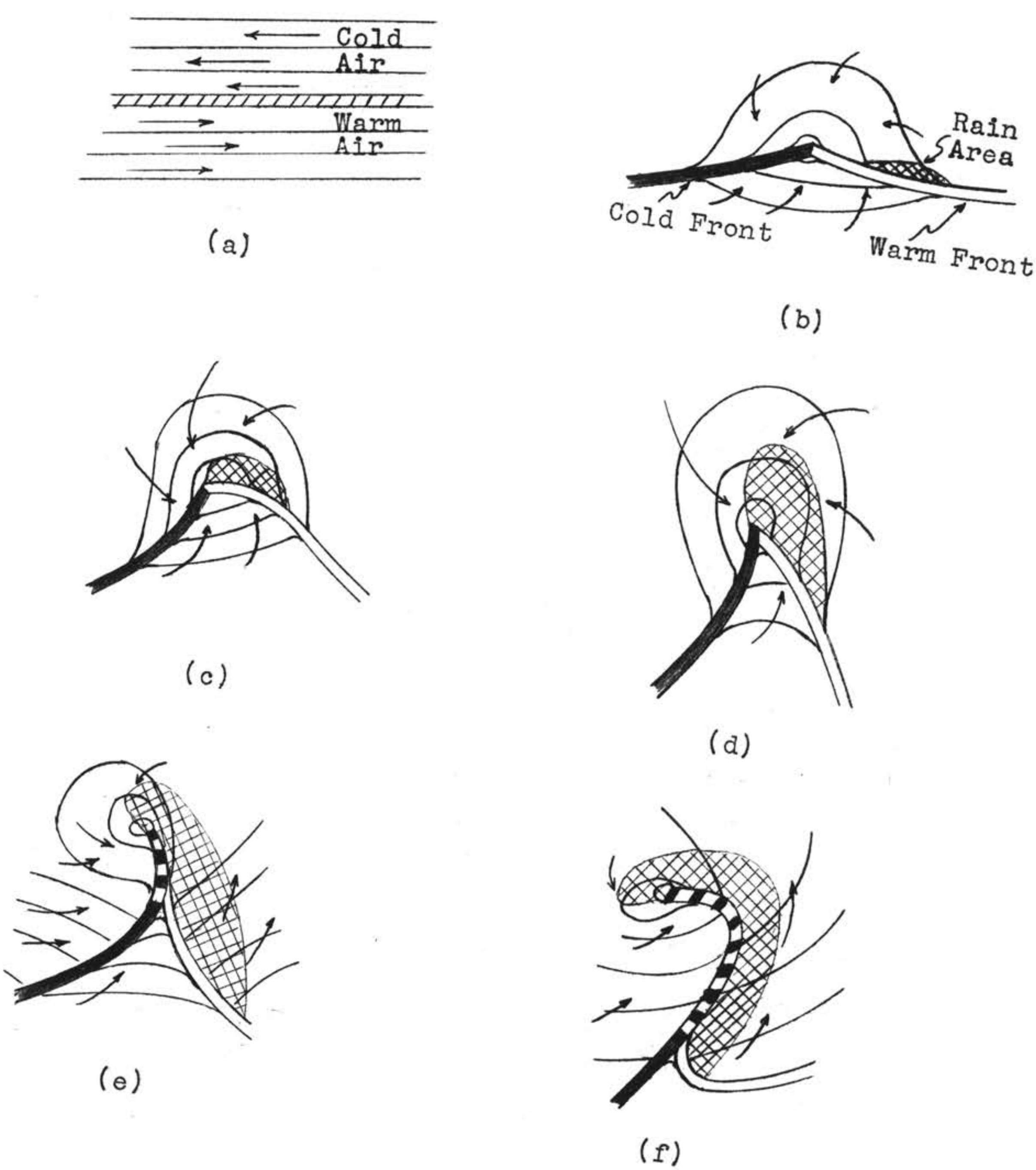
6 William L. Donn, Meteorology with Marine Applications, pp. 288-298.



The Phases of a Cyclone

Figure 6

pressure and are called isobars. As should be expected, the lowest pressure is in the center, thus the name cyclonic depression. These ripples increase in magnitude and become waves (Figure 6c). Cold fronts move faster than warm fronts as can be seen in section (d), and in overtaking the warm front lift the warm air of the ground and up above the cold air producing what is known as a lifted or occluded front (Figure 6e and 6f). When this occluded front dissipates, the cyclone has become a whirl of comparatively homogeneous air, illustrating the condition under which the air masses of cold and warm fronts mix. As the whirl dissolves, a smooth front is again established and the cyclone has disappeared. The development of stages (a) through (c) usually requires less than a day. The continuation from there through occlusion lasts usually from 3 to 4 days. Most of the bad weather is during this latter period. The plan of a cyclonic depression with cross-sections is shown in Figure 7.[7] Note the naming of the various sectors of the cyclonic depression. Reference will be made to these terms later.

This concludes the discussion of tornadoes, cyclones and weather phenomena in general. Application of this information will be made in the following chapter.

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[7] Ibid., p. 292.

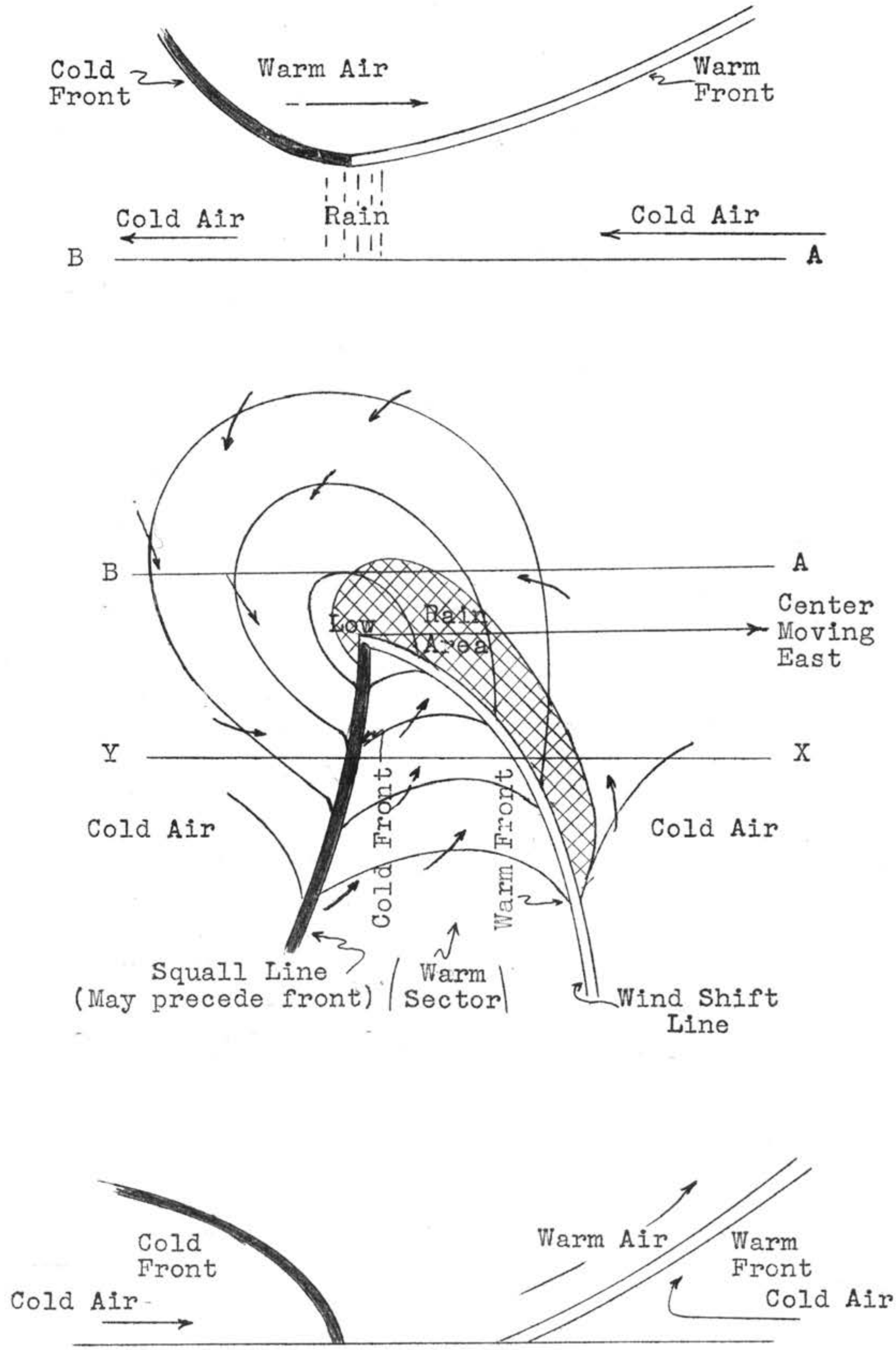
Cold Front
Warm Air
Warm Front
Cold Air
Rain
Cold Air
B
A
B
A
Low
Rain Area
Center Moving East
Y
X
Cold Air
Cold Front
Warm Front
Cold Air
Squall Line (May precede front)
Warm Sector
Wind Shift Line
Cold Front
Cold Air
Warm Air
Warm Front
Cold Air

Figure 7

CHAPTER III

PREDICTING THE FORMATION OF A TORNADO

Set forth in the previous chapter were the synoptic weather conditions necessary for the formation of a tornado. In general, a mass of warm moist air must be trapped underneath a dry cold air mass. The air masses must form or act as the parts of a cyclonic system. Such conditions cause convective instability and the warmer lighter air will rise, if there is an opening in the cold air blanket over it, giving the basis for tornado formation.

Actually such conditions are fairly common and in general produce only thunderstorms. The requirements for tornado formation are more rigid although basically the same.

This chapter is devoted to a method of predicting the formation of a tornado. Although an attempt has been made to keep the explanation readable by laymen, it has been necessary to use the more common meteorological terms.

The system under consideration was developed by Major E. J. Fawbush and Captain R. C. Miller of the United States Air Force. It was presented at a meeting of the American Meteorological Society in St. Louis, Missouri, January, 1950.

This system was selected from several proposed systems offered by other authorities for two reasons. First, it is the only system with which the author is acquainted that has been developed for use in this section of the country, i.e., Oklahoma and its surrounding states. Since the movement and types of air masses vary in the different sections of the country it is quite possible that this system would have to be greatly modified if it were to be used in some other section. Second, this system has been far more accurate than any other system. At the time of this writing, the originators had accurately predicted tornadoes nineteen times in nineteen attempts.

The procedure was devised by a statistical study of past tornadoes and involves determining if the following synoptic conditions are present over a given area.

First, the air in the locality in which the tornado may form must be conditionally and convectively unstable. Conditional instability refers to the fact that a segment of air near the ground in rising may cool more slowly than the air surrounding it. Since it will remain lighter than its surrounding air, it will be accelerated upward. If such a condition exists, it may be determined from pseudo-adiabatic diagrams. These are charts that indicate the lapse rate or variance of the temperature of an air column with altitude and are obtained by taking soundings of the upper atmosphere.

Second, there must be a front of mP air moving into the area from west to southwest. In reference to the cyclonic activity this would be the advancing cold air mass. In connection with this front, there must be a jet of high velocity air moving above and along the face of the front. This jet of cold dry air should exist from the 700 mb. level up to at least the 640 mb. level and should be traveling at a speed greater than 40 knots or 46 miles per hour. The front at ground levels will be lagging behind this jet of air which exists at the higher levels, in general, above ten thousand feet. Millibars or mb. is a measure of atmospheric pressure and is used by the meteorologist as a measure of altitude in place of feet. The information necessary to determine this second condition may be obtained from winds aloft reports.

The final condition is that from the warm sector of the cyclone that causes the movement of the front across the United States, a tongue of warm moist air at least 8,000 to 9,000 feet thick must exist at the higher millibar levels and protrude in such a manner as to cross under the cold air jet. This tongue will be composed of mT air which, as previously mentioned, has great potentialities as a thunderstorm maker. Such a protrusion as is required is caused by the clockwise rotation of the warm air around a high pressure area. It will be indicated by and can be determined from maps showing the dew point of the air at various locations.

When all of the above conditions are present, a tornado will form providing the warm air can find a point of escape through a cold air blanket above it. This break or opening in the cold air mass must occur from some type of triggering impulse. There are a number of conflicting theories as to the exact cause of such an impulse. One general theory concerning tornado formation denys the need for such an effect. For the purposes of this thesis, the following theory, which is one of the latest ones, is presented.

The fundamental assumption in the compression wave theory is that the cold front does not move at a uniform speed across the ground throughout its entire length, but moves with occasional surges.[1] These may be due to the irregular profile of the ground over which it passes. For example, a large hill in the path of the cold front would tend to cause a section of the front to lag a little behind the general line of the front. The high pressure area moving in behind the front would build up pressure on the segment of air lagging behind. As this segment passes on beyond the restraining hill, it would be accelerated by the extra pressure behind it in such a manner as to force it to catch up with the remainder of the front. The action at this time would be much like a piston compressing air. A compression wave would be set up along the temperature-pressure inversion line that would travel faster than the front itself. It has been postulated that this compression wave is the cause of the squall lines preceeding the cold front. If two compression waves, originating at different points along the front should cross, there would be a point of intersection at which their individual effects would add together and cause an intense pressure sufficient to disrupt the cold air blanket above it. If such an action occured in an area where the conditions necessary for tornado formation were present, it would serve as the necessary triggering force.

To predict the place and time of a tornado formation, the

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1 Morris Tepper, "A Proposed Mechanism of Squall Lines: The Pressure Jump Line," Journal of Meteorology, Volume 7, Number 1 (February, 1950), 21-29.

axis of the warm moist tongue of air and the axis of the cold dry jet of air are drawn. The point, or more properly, the area around which these axes cross is the locale of greatest instability and thus the place where tornadoes are most likely to form. The surface, 850 and 700 mb. level charts are checked to determine the movement of the cold air mass. The time for either the squall line or the front to arrive at that location can thus be determined.

This system has several limitations that should be recognized. From the results to date it would appear that the forecasting of a tornado that actually occurs would be fairly certain. It may, however, cause the prediction of a tornado when only severe thunderstorms occur. A second limitation is that it will give only the general area in which the tornado may occur. The minimum area to date has been a sector about 50 miles square and normally the area would embrace about a quarter of a state the size of Oklahoma. Third, since the necessary conditions can develop and disappear in a period of two to three hours, it would be necessary to make hourly checks if extremely accurate results are to be obtained. This would involve a tremendous amount of detail work. Finally it may be necessary to modify the system to take into account the varying characteristics of air masses due to seasonal changes.

CHAPTER IV

THE ACTION OF A TORNADO AFTER FORMATION

The design of suitable equipment for a tornado warning system requires a knowledge of the accuracy with which such factors as the path of the tornado must be determined. Useful information for determining some of these factors can be obtained from a statistical study of the action of past tornadoes. Dr. Edward Brooks of St. Louis, Missouri, has made such a study and presented a general theory concerning the action of a tornado after formation.[1]

Tornadoes, as all meteorologists know, are erratic. They wander around in a rather unpredictable manner, sometimes backing up, then moving sidewise to their previous path, and again moving ahead. Dr. Brooks has come to the conclusion that although their behavior is apparently illogical, tornadoes may move forward inside an imaginary cage, the movements of which are fairly uniform. This cage incloses a circular area from 6 to 12 miles in diameter. The tornado or tornadoes, there may be up to five, prowl around inside of the cage while the cage itself moves in nearly a straight line and usually northeast in direction. It would appear from this information that it would be of little benefit to have equipment capable of locating a tornado from some distance away with an accuracy greater than within 5 to 10 miles.

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[1] Edward D. Fales, "Here Comes a Twister," Science Illustrated, Volume 4, Number 6 (June, 1949), p. 50.

Additional studies have apparently shown that the tornado or cage moves along with the jet of cold air that initially aided in its formation. Since this jet moves approximately along the face of the front, this would explain the general movement of tornadoes in a northeast direction.

The tornado lasts as long as there is a supply of warm moist air to sustain it. As far as is known there has been no attempt to correlate the supply of warm air from the standpoint of area involved, its temperature and humidity, to the active life of a tornado. It would therefore be nearly impossible to predict the distance a tornado would travel with any degree of accuracy.

If warnings to residents of areas that lie in the possible path of a tornado were made on a meteorological basis only, it would be necessary to give delayed warnings if any accuracy were desired, for to warn well ahead of the possible path of the tornado would often entail the dissemenation of false warnings.

CHAPTER V

LOCATING AND TRACKING TORNADOES

There are at least three methods of approach to the problem of locating and tracking tornadoes. These are the use of meteorological information, the use of sferics, and the use of radar.

In the section concerning the predicting of tornadoes, it was pointed out that the area of atmospheric instability in which a tornado could form covered a comparatively large sector of a state. Since the exact point in this area where a triggering pulse will cause tornado formation is unpredictable, it is evident that the location of a tornado cannot be accurately determined by this means.

It would be possible to track, or more properly, predict the path of tornado formation if its location could be determined by some method. One solution would be the dependence upon a ground observer. Since it would be difficult to place sufficent trained observers in a potential tornado area, such a system would have to depend upon the general public phoning in the required information. The system would not, therefore, be very reliable.

There is one other serious objection to the setting up of a warning system based on such a method. The tornado must be developed before it can be observed. This would mean that it could be taking a costly toll of lives and property during its early life before a warning could be given to residents who live in its path.

Since there is no information available as to the accuracy of predicting the path by meteorological means, the question must also be raised as to whether such a system would be satisfactory on this score.

The use of sferics is still in the experimental stage, but on the basis of the present data it appears that most of the disadvantages of the meteorological system can be eliminated. One of its outstanding advantages over either of the other methods is that it may be able to recognize and locate the tornado while it is still in its incipient stage, i.e., that at the time the triggering pulse sets the tornado into its formation, sferics may be able to give the observer this information along with where the formation is taking place. This would make it possible to give a flash warning to residents in the locality where the tornado first strikes.

The problem of locating and tracking tornadoes by sferics resolves itself into a choice of two methods with the various modifications of each. One method would be to use equipment such as is now employed in the tornado research program at two separated stations. Since the present equipment gives the direction from the station of the lightning flash it records, by the use of two such stations, cross-bearings could be obtained that would serve as a means of tornado location. The second method would be to use the direction indication from one station and a knowledge obtained from weather maps of the location of the cold front with which the tornado is associated.

The accomplishment of location and tracking, accurately and quickly, by the first method, would require the setting up of master and slave stations. The function of the slave station would be to transmit to the master station the intelligence it receives as to the intensity and direction of a lightning flash. The master station would take the information received from the slave station and add its own measurements of intensity and direction of the same lightning flash, which were being held in a delay circuit, and record the two measurements simultaneously on film or other recording media. The recorded bearings used in conjunction with a map of the locality would serve to locate the tornado, and of course the tornado could be tracked by the same manner.

There are several disadvantages and problems that arise in considering this first system. The disadvantages are in the extra equipment needed for the slave station, the cost of the equipment, the need of extra personnel to maintain them, and the extra locations required. These disadvantages could be overcome by using only master stations with suitable communications between them. This method will not be considered for reasons given in the analysis of results. The chief problem is in insuring that both stations receive and record the common lightning flash.

This problem may be illustrated as follows. Assume that a tornado is in the process of forming near the master station and some distance from the slave station (or a second master station). The cumbilo-nimbus cloud from which the tornado is evolving is in a state of violent internal agitation and a lightning stroke of sufficient intensity, time duration, and shape to be associated with the incipient tornado is emitted. This lightning flash is received strongly by the master station and after a momentary delay in the hold circuit will be recorded. The electromagnetic radiation from the lightning flash is propagated onward and, in a very small fraction of a second, is received by the slave station. During the course of propagation, the intensity of the electromagnetic wave decreases and its intensity as recorded by the slave station will be much weaker. There are several possibilities that then arise. A weaker lightning flash resulting from an ordinary thunderstorm close to the slave station may arrive at approximately the same time, and since it originated much closer to the slave station and has dissipated little of its energy, may be stronger than the wave received from the originally stronger lightning flash. The slave station will record and transmit back to the master station an entirely false indication that is the resultant of the energy it receives from both waves. It should be pointed out that the electromagnetic radiation received by a station is not an instantaneous pulse but occupies a period of time and is in the form of a train of quasi-oscillations.[1] Thus there is a period of time during which two electromagnetic waves can arrive and be recorded as one. Such an occurrence is not limited to the slave station, but, can also cause inaccuracies at the master station. Since tornadoes are associated with rapidly moving cold fronts

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1 Hutchison, op. cit., p. 41.

which, under the conditions specified, also produce violent thunderstorms, the possibility of the above happening cannot in light of present knowledge be dismissed.

The above problem is not insurmountable. By suitable gating of the receiver the effect can be greatly reduced, and by averaging readings for a period of say a minute, probably eliminated.

The second suggested system using sferics and meteorological information involves the above problem, but it is not of the same magnitude since any such errors would involve only one station instead of the cumulative error of two or more. The meteorological information would also aid in the identification and allowance for false responses. The chief trouble with such a system is that since only the direction and not the distance is known, it would only be possible to say that a tornado is forming somewhere along a line about fifty miles in length. Although the tornado movement is erratic and accuracy closer than ten miles (the approximate diameter of the tornado cage) would be useless, it is evident that this second system would not be satisfactory by itself in locating and tracking tornadoes.

Radar offers several decided advantages over the other methods. The accuracy with which it can give both the distance and direction of a reflecting object is well known to most laymen. Since many weather stations are already employing radar for the observance of the movements of fronts, it would not require the purchase and installation of additional expensive equipment.

Radar has one decided disadvantage in that it cannot distinguish between a tornado and a severe thunderstorm. However, once an operator knows that a tornado has formed within the range of his equipment and approximately where it is located, he can pick it up on his 'scope and watch its progress. Thus, the employment of radar must depend upon outside information as to the tornado formation.

If such information depends upon the actual observance of the tornado by the public, the tornado warning system will be operating under the same severe limitations discussed in the section on warning from meteorological information.

CHAPTER VI

ANALYSIS OF RESULTS

An ideal tornado warning system will have to meet several requirements. First, it must be possible to give a prewarning to the residents of a probable tornado area several hours ahead of time. This will prevent such occurrences as traffic jams and unnecessary panic. Second, it will be infallible, i.e., flase warnings will not be given nor, on the other hand, will tornadoes be missed. Third, it must be possible to give warning to residents of the locality where the tornado first strikes. This is the most difficult of the requirements to meet, but one of the most important if the human deaths caused by tornadoes are to be stopped. Finally, the system must include a means of locating and tracking the tornado with sufficient accuracy to enable a warning to be given to all persons who are in its probable path.

Meteorology makes it possible to meet the first of these requirements, the transmittal of a prewarning, with comparative ease. Although the science of meteorology has made great strides in the last ten years, it is not capable of fulfilling the other requirements of an ideal warning system. Due to the many variables involved in the prediction of tornadoes and the physical impossibility of obtaining sufficient information of various readings, it cannot, at the present time, meet the demand of infallibility nor the third requirement of making it possible to give a flash warning at the time of initial formation. It would be possible to use meteorological means to determine the probable path of the tornado and thus satisfy a portion of the final requirement. The accuracy of this method would be questionable and, since there is not as yet an available method for the determination of the life of the tornado, and the associated distance of travel, warnings might be sent out long after the tornado has dissolved. There is, of course, no method of accurately determining the location of the tornado by meteorological means.

Sferics, satisfactorily developed, would meet the second, third, and possibly the fourth requirement. It would be impossible, in the light of present knowledge, for sferics to serve as the basis for enabling the operator to send out a prewarning. It would, if the present surmise as to the high lightning intensity of a tornado cloud is correct, make a positive identification of an incipient tornado. This would enable the operator to transmit a flash warning to the area first to be hit, particularly if the tornado bearing cloud can be located. In considering the possibility of locating and tracking tornadoes by sferics, the single station and two station systems must be examined separately. One station will give the direction of the tornado from its location but cannot give the distance. A more detailed discussion of this limitation was given in the preceeding chapter. Two stations, or a master and a slave station, would give cross bearing that would enable the operator to locate the tornado. Thus, the use of the two station system would meet the needs of location and tracking. The chief difficulty with the employment of sferics is the danger of obtaining false readings. This, as has been previously pointed out, can be minimized but only at the expense of an increase in working time at a critical interval.

At present it appears that the fourth condition can be satisfied only by the use of radar, after the actual tornado cloud has been identified. This function can be accomplished by radar in far less time and with greater accuracy than by any of the other methods.

From this discussion it is evident that no one or two of the three proposed methods can best satisfy all of the listed requirements. It is therefore suggested that warning stations be set up that employ all three methods.

The proposed system would work in the following manner. Meteorological information would be used, based on the method given, to predict the formation of a tornado. Such a system would make it possible to give a warning several hours ahead of the actual time of development. Since a number of variables are involved, it is suggested that, to eliminate needless warnings, the prewarning be sent out a hour or two ahead of the actual time at which the tornado is expected. This prewarning would be to the effect that a tornado may develop in a given sector. The sferic equipment would be used to give positive identification of the tornado. It is suggested that the sferic equipment be of the single station type. Once the tornado is triggered into formation, the sferic equipment will give the direction of the tornado from the station. The radar can then be trained in this direction to locate the tornado precisely and a flash warning given to the residents in that vicinity. The radar would then be used to track the tornado and a warning could be given to the residents in its path.

This system would meet all the requirements of the ideal system. The meteorological information would be used as a basis for the prewarning and for determining when to put the locating and tracking system into operation. The sferic equipment would give positive information concerning the formation of the tornado and, when the position of the storm center has been determined, permit effective use of the radar equipment. The radar equipment would then give the precise location of the tornado at all times.

Both the meteorological system and the radar equipment are sufficiently developed to be used at the present time. Indeed, trial tornado warning systems are already set up on such a basis. The need for sferic equipment to supplement the system is evident. When development work in this equipment has been completed, it is believed that the main source of error will have been eliminated, and that it will be possible to identify and track the tornado when it is in the process of formation. There will then be sufficient time to warn residents in the zone of probable danger.

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