STATION PAPER NO. 35

APRIL 1954

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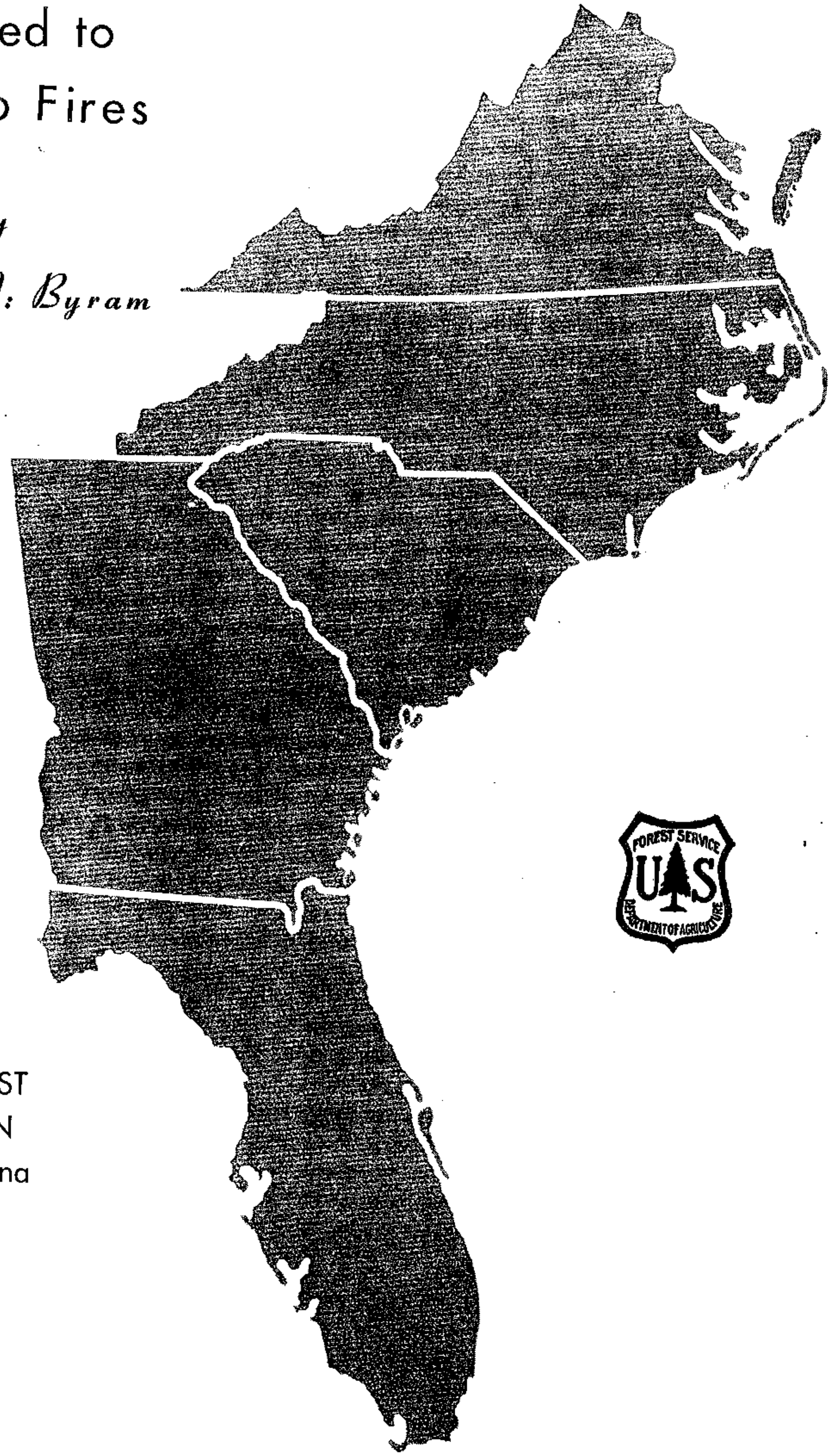

SOUTHEASTERN FOREST
EXPERIMENT STATION
Asheville, North Carolina

U. S. DEPARTMENT OF AGRICULTURE - FOREST SERVICE

Acknowledgment

Grateful acknowledgment is made to personnel of the National Weather Records Center of the U. S. Weather Bureau in Asheville, N. C. Without their assistance in making a large volume of weather records readily available, this study would not have been possible. Thanks are due also to a number of state forestry organizations for valuable help in obtaining fire behavior information, particularly those of North Carolina and Tennessee.

Second printing - July 1954
(Addenda pages 32-34)

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INTRODUCTION

Occasionally a forest fire burns with an intensity that seems far out of proportion to apparent burning conditions. Sometimes it multiplies its rate of energy output many times in a short space of time. Although infrequent, these unusual fires have over a long period of time been responsible for the major loss of life in forest fires and a large part of the losses in property and forest values. Each blowup fire raises the question: What can we do to recognize conditions causing extreme fire behavior and how can we predict them in advance?

From a study of atmospheric conditions that have accompanied a number of blowup fires, there emerges a rather definite picture. Briefly, fires seem most likely to blow up when the following conditions exist simultaneously:

(1) Fuels are dry and plentiful.

(2) The atmosphere is either unstable or was unstable for some hours, and possibly days, prior to the fire.

(3) The wind speed of the free air is 18 miles per hour or more at an elevation equal to, or not much above, the elevation of the fire.

(4) The wind decreases with height for several thousand feet above the fire with the possible exception of the first few hundred feet.

We may have reached the point where we can soon apply our knowledge of extreme fire behavior more effectively than has been possible in the past. Improved fire danger meters, such as the 8-0 and 8-W with a buildup index described by Keetch (6) will give us advance warning when fuels are approaching the point where they will support conflagration-type fires. In a general way the effects of fuel type, stand type, and topography are known. The major unknowns have been certain atmospheric factors which have been the subject of a study at the Southeastern Forest Experiment Station during the last 4 years. This report presents some of the results of that study and is directed primarily toward the group of people who have the responsibility of getting results of fire behavior research into practice. This group includes fire control men who must develop and improve fire suppression techniques and safety methods as fire behavior knowledge advances. It includes the field men who apply these developments on actual fires. It includes, too, the fire weather forecasters on whom must ultimately fall the day-by-day application of a large part of our knowledge of fire behavior and its response to the ever changing elements of the weather.

The terms "blowup" and "conflagration" will be used in this paper without an attempt at precise definitions. In general a blowup fire is one which suddenly, and often unexpectedly, multiplies its rate of energy output many times. Sometimes it does so in a matter of minutes. The blowup fire can be large or small.

A conflagration will be assumed to be any large fire which has taken on storm characteristics.

METHODS OF STUDY--CASE-HISTORY FIRES

The approach used in the present study consisted of case-history procedure accompanied by theoretical and analytical work in fire physics. Data are of two kinds. First are the weather, fuel, and inflammability conditions which existed at the time of a given fire. Second are the details and observations of fire behavior.

From an extensive network of stations the U. S. Weather Bureau has detailed records including (at least for the last 15 years) wind, temperature, and humidity data for the upper atmosphere. It is thus possible to obtain for a specific fire not only fuel and inflammability conditions (either from fire danger records or from Weather Bureau records) but upper air conditions as well.

Some of the observations and details of behavior are written down in fire reports, but most of the information is still in the memories of men who worked on the fires. Fire behavior may, therefore, be difficult to reconstruct at times, especially on fires which occurred a number of years ago. Usually however, a surprising amount of detail can be obtained by talking with men who were on the fires and by going over the fire area with them.

The case-history method becomes much more effective when preceded by or accompanied by analytical work on the energy processes in fire behavior and the manner in which these processes are affected by conditions in the atmosphere. The analytical work indicated in advance some of the fire behavior characteristics one might expect, as well as some of the conditions to look for in the upper atmosphere. For example, work on the energy conversion process indicated that on severe fire days the wind shear should be low; that is, the wind speed should not increase with height as it normally would do. When this condition was looked for, it was found that the wind shear was not only low but was usually negative on the worst days. This meant that the wind speed decreased with height, which is the most favorable condition for the formation of an active convection column in which the conversion of heat energy to turbulent energy takes place. A discussion of energy conversion is outside the scope of this paper, but is discussed briefly in the appendix.

EXTREME FIRE BEHAVIOR

The Facts of Fire Behavior

As more case-history fires are studied, it is possible to assemble a collection of statements about these fires which could be called the facts of fire behavior or, perhaps better, the facts of extreme fire behavior. It seems permissible to call them facts, because most investigators would probably agree on their essential meaning even though different investigators might explain them differently. Possibly the simplest way to define and introduce the problem of extreme fire behavior is to list known conditions associated with blowups. The list contains many seeming contradictions which any effective solution must resolve:

(1) Most severe fires and a considerable number of blowups occur during the middle of the afternoon on sunny days. On such days the atmosphere is often turbulent and unstable to a height of several thousand feet. However, some of the worst forest conflagrations in the United States have either occurred at night or reached the peak of their intensity at night (usually between sundown and midnight). At this time the lower layers of the atmosphere (up to 500 feet or more) are usually stable.

(2) Some of the worst western fires in the past 15 years have been in rough country, which might indicate that topography is a dominating factor. On the other hand, there have been conflagrations, such as those that occurred in the Lake States many years ago, which burned in nearly flat or rolling country. Some of these conflagrations have been compared to "tornadoes of fires."

(3) An intense fire may occasionally spread rapidly across slope or downslope at night in the general direction of the cool downslope winds. Yet this same rapid downslope spread may happen in the middle of the afternoon when the surface winds, if any, would be upslope. Fires have traveled across drainages (upslope and downslope) as though these did not exist.

(4) Turbulence in the atmosphere seems to be closely related to extreme fire behavior; yet on a large proportion of warm, sunny days the atmosphere is unstable. Often, fires do not build up to extreme intensity on such days.

(5) Many intense fires have been accompanied by high winds; but some of the most dangerous and erratic fires have burned when the wind speed was not especially high.

(6) High temperatures and low relative humidity accompany a large proportion of severe fires, but some of the most intense and rapid-spreading fires have burned when the temperature was low and falling. The fires in the East and Southeast in the fall of 1952 are examples.

(7) Prolonged periods of drought and dry weather show a strong correlation with intense hot fires, but the Brasstown fire in South Carolina in March 1953 burned only a week after nearly two inches of rain had fallen on ground well charged with winter rainfall. However, both burning index and buildup index were high on this day.

(8) The amount of fuel available to a fire is an important factor in its behavior. At times the effect of an increase in quantity of fuel on fire intensity appears to be considerably greater than would be expected from the actual fuel increase itself. For example, doubling the amount of fuel might increase the apparent intensity four or five times.

(9) Arrangement as well as quantity of fuel is important. Extreme fire behavior seems most likely to occur in dense conifer stands. Intense fires also build up in stands of evergreen brush, and in the South can readily cross swamps if the brush is dense enough.

(10) On those fires to which one would be most likely to apply the term "blowup" (owing to the sudden and often unexpected buildup of turbulent energy), there is an obvious and well developed convection column which may extend high into the atmosphere.

(11) Large fires exhibiting extreme behavior have been known to put up convection columns to a height of 25,000 feet or more. Since about 70 percent of the total mass of air is below the tops of such convection columns, these fires have literally pierced the atmosphere. They are volume phenomena and have storm characteristics like certain other disturbances in the atmosphere. This in part seems to explain why they do not conform to the "rules" of fire behavior. These "rules" are based on the far-more-frequent ordinary fire, which is pretty much a surface phenomenon.

A Unifying Concept

The preceding statements illustrate the baffling nature of the exceptional fire that does not always conform to the accepted principles of fire behavior. The apparent contradictions in fire behavior facts warn us of the possible futility in attempting to explain each fact, or even certain groups of facts, separately. However, these very contradictions, plus certain basic physical principles, indicate the existence of a single overall unifying concept which would be consistent with all the facts of fire behavior. The recognition of blowup conditions at the time they exist, as well as their eventual prediction several hours in advance, seems to require this type of solution.

Although it may at first appear over-simplified, the energy conversion concept seems to meet the unifying requirements. It can be reduced to three groups of factors:

(1) Stability conditions in the atmosphere.

(2) Wind speed and wind shear in the atmosphere.

(3) Fuel (and stand) conditions.

Strangely enough, topography as such does not appear directly in the above groups of factors; its major effects can be handled most simply by letting them operate through groups 1 and 2.

Turbulence, Instability, and Jet Currents

The terms "turbulence" and "instability" are often used interchangeably without causing confusion, although their meanings are not the same. Instability is a condition of the atmosphere which causes turbulence. If the temperature decreases upward at a rate of 5.3 degrees or more per thousand feet, the atmosphere is unstable. Thermal turbulence is the direct result of instability such as occurs when the earth's surface is strongly heated by the sun, or when cold air passes over warm ground. An unstable atmosphere is in effect "top heavy," and the resulting turbulent air motions tend to restore its balance. Warm surface air will be rising, and cold air from aloft will be falling. These air currents are the updrafts and downdrafts which one experiences when the flying is bumpy.

Turbulence seems to affect the behavior of fires both directly and indirectly. The direct effects are fairly common and are the easier of the two to understand. They are most evident during the afternoon hours when the instability of the atmosphere is greatest. At such times fires show a tendency to crown easily and travel rapidly upslope. Winds are gusty and variable, especially in the vicinity of fires. Small whirlwinds and local updrafts may cause considerable spotting for short distances across fire lines. Fires of all sizes are affected. The direct effects of turbulence reach their peak at the time when relative humidity and fuel moisture are lowest, which makes them difficult to separate from fuel inflammability effects.

The relation of turbulence to fire behavior has been discussed in earlier papers by Crosby (3) and Byram and Nelson (2). Their papers dealt more with the direct effects of turbulence on fire behavior than they did with the indirect effects. The possible existence of these latter effects was not known at that time.

Turbulence appears to exert its most serious and potentially most dangerous effects indirectly. Large fires of high energy output result from a peculiar wind condition which seems to be caused by, or is closely associated with, unstable air. Briefly, this wind condition can be described as a stratum of air in which the lower layers are moving faster than the upper layers. The maximum speed seems to come at an altitude equal to or somewhat above (usually not more than 1000 feet) the elevation of the fire.

A current of relatively fast moving air near the earth's surface can be regarded as a miniature model of the well known jet stream high in the atmosphere. The jet stream1/ usually attains maximum speed between 20,000 and 40,000 feet, and it frequently exceeds 100 miles per hour. The lesser currents near the earth surface, therefore, resemble it only in structure, but for convenience they will be referred to as "jet currents." The height at which the wind speed is a maximum will be referred to as the "jet point." This jet point may be from 100 feet or less above the surface up to several thousand feet.

The Blowup Process and the Convection Column

It is the decrease of wind speed with height which permits a fire to build its "chimney" or convection column. Once this chimney is well started, a violent chain reaction in energy conversion takes place which may not level off until the convection column is several thousand feet high. During this time the fire is converting a part of its heat energy into turbulent energy, which in turn drives the fire on to an ever increasing intensity. This seems to be the physical picture of the blowup process. It can come suddenly and often unexpectedly. It can build up with an accelerating rapidity if there is a plentiful supply of burnable fuel.

The blowup fire is in effect a large heat engine capable of transforming a part of its heat energy into the destructive turbulent or kinetic energy of motion. An essential part of this heat engine is the convection column in which the expansion and cooling of the hot gases complete the energy transformation. From the energy standpoint, it is not surprising that the worst features of extreme fire behavior, such as whirlwinds, updrafts, downdrafts, and long distance spotting are closely related to the convection column, and hence to the decrease of wind speed with height.

The blowup fire, or heat engine fire, bears about the same relation to the ordinary fire that a large railway locomotive bears to a small house furnace. The furnace converts fuel into heat and nothing more. The locomotive on the other hand converts not only fuel into heat but in turn converts a part of its heat energy into the driving or kinetic energy of motion, which is evident in the speed of the locomotive and the cars it pulls. A well-developed blowup fire probably equals or exceeds the efficiency of the coal-burning locomotive in that it may convert a higher percent of its heat into the energy of motion of the gases in its convection column.

1/ More than a year ago Vincent J. Schaefer of the Munitalp Foundation pointed out the possibility that fire behavior might be influenced by the presence of the jet stream. There seems to be no reason, as far as the writer knows, why high winds 20,000 to 40,000 feet aloft should affect fires on the ground. However, in a large number of the case history fires the jet stream was either overhead on the day of the fire, a day or two preceding the fire, or sometimes a day or so after the fire. No attempt was made in this investigation to relate the presence of the jet stream to effects in the lower atmosphere which might bear on fire behavior, but it might be well worth looking into. Possibly both the jet stream and the lesser jet currents are associated with certain pressure systems in much the same way.

Some of the technical aspects of the convection and the energy conversion process are given in the appendix.

Wind speed Profiles on Blowup Days

The peculiar decrease of wind speed with height, or jet current, which is present on days when extreme fire behavior occurs can be illustrated best by showing the profiles which existed near the times and places where some of the blowup or conflagration type fires burned. These are shown in figure 1 for fires that occurred in widely separated areas of the United States, in different topographic locations, and in different types of fuel. Wind speeds are shown for heights up to 14,000 feet above the elevation of the fires. In order to reduce fires which occurred at different elevations to a common base, the wind speed profile curves are plotted with the origin (zero height) taken at the level of the fire. The curves are believed to be good approximations of the profiles which existed at the times and places where the fires burned. The precise elevations of the blowups on the Mann Gulch and McVey fires were not known, so for purposes of comparison they were tentatively placed equal to the height of the jet point. This was about 5600 feet above sea level for the Mann Gulch fire and about 5500 feet for the McVey fire. However, the profiles indicate that the blowups might have taken place as much as 500 feet lower than the jet point and as much as 600 or 800 above. Also, the height of the jet points may have been slightly different at the location of the fires than at the pilot balloon stations (Rapid City, South Dakota, for the McVey fire, and Great Falls, Montana, for the Mann Gulch fire).

Curve A is the wind speed profile over Charleston, South Carolina, 4:00 p.m. on April 17, 1950. On this day intense, erratic fires burned in the coastal plains of both North and South Carolina. The worst of these was the Hofmann Forest fire in which an estimated 30,000 acres burned between 3:00 p.m. and 10:00 p.m. On this day the surface jet current seemed to extend from Georgia to southern Virginia. It seemed to be deepest and most intense over eastern North Carolina.

Curve B in figure 1 is the estimated wind speed profile over Rapid City, South Dakota, at 11:00 p.m. on July 10, 1939, when the McVey fire on the Black Hills National Forest first blew up. This fire is described in greater detail in the appendix.

Curve C is the wind speed profile over Red Bluff, California, at 12:41 a.m. July 10, 1953, a little over two hours after the blowup on the Rattlesnake fire on the Mendocino National Forest.

Curve D is the wind speed profile over Great Falls, Montana, at 8:00 p.m. August 5, 1949 about 2-1/2 hours after the blowup on the Mann Gulch fire.

In addition to the general decrease of wind speed with height, the profiles in figure 1 illustrate another point which may be of considerable importance. This is the close agreement between the curves in speed of wind at an elevation equal to or somewhat greater than the elevation of the fire. The average wind speed for the group is in the neighborhood of 21 or 22 miles

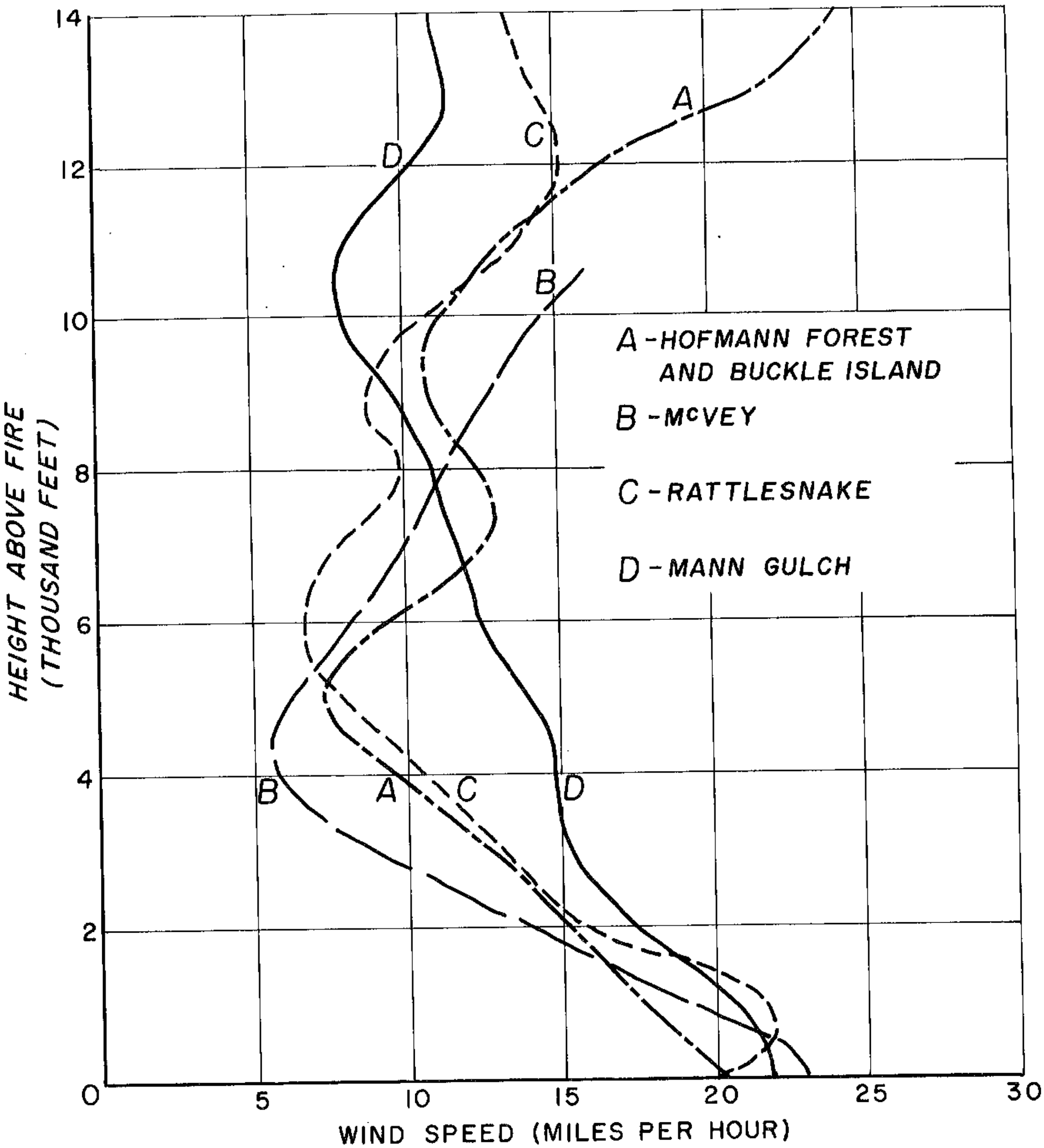

Figure 1.--Wind speed profiles from pilot balloon data for 4 days on which blowup or conflagration type fires occurred. Each curve represents the wind speed profile over the pilot balloon station nearest the fire area and at the time closest to the period when the blowup took place. Wind speed is shown for different heights above the elevation of the fires up to 14,000 feet.

per hour near this elevation, which is not a high wind speed in the free air. It is likely that for the most dangerous fires the wind speed near the jet point will be in the 18 to 24-mile-per-hour zone for light to medium fuels (4 to 12 tons per acre), and possibly somewhat higher, 20 to 28 miles per hour, in heavy fuel (12 to 25 tons per acre).

There appear to be good theoretical reasons for the existence of a critical wind speed zone. It is in this zone that the power of the wind begins to surpass the power developed by the fire heat engine. At high wind speeds the power of the wind controls many behavior characteristics, such as direction of spread and rate of spread. At low wind speeds the fire is dominant in controlling behavior characteristics. Perhaps the critical wind speed zone should be regarded as a "tug-of-war" region in which fire behavior dominance passes alternately from wind to fire. This may be the main cause of the unpredictable behavior of fires in the critical wind speed zone. In addition, the wind speeds in this zone may be those which enable the heat engine to operate most efficiently.

EXTREME FIRE BEHAVIOR AND WIND PROFILE CLASSIFICATION

The tendency of the wind speed profile to fall into fairly definite classes at those times when extreme fire behavior exists, as illustrated in figure 1, suggests the possibility of a rather simple classification system (the method might be numerical or graphical, or it could even be set up in some other symbolic way). However, for the sake of simplicity in a preliminary system, it seems desirable to use either the actual profiles at the time of specific case-history fires, or composites of actual profiles.

This has been done for the type profiles in figures 2 and 3. Figures 4 through 12 give the wind speed and direction profiles for specific fires. There is good possibility that eventually these types (or their equivalent in some other classification method) can be "calibrated" in terms of more definite fire behavior characteristics. At present we can do this only in a general way, and some of the relationships may have to be modified later. Even so, this information may be of considerable help to fire weather forecasters and fire control personnel. Perhaps the type curves in figures 2 and 3, as well as the speed and direction profiles in figures 4 through 12, can be thought of as the beginning of a "rogue's gallery" of extreme fire behavior information. It is known that extreme fire behavior came on days when the wind speed profile could be classed in one of the six types from 1-a to 3-c. It is also known that there was a considerable difference in behavior between certain types. There was a difference in behavior even within a type, depending on the height of the jet point above the ground, the speed at the jet point, and the wind speed near the ground. Jet points are indicated in figures 2 and 3.

It might seem that the temperature profile of the atmosphere should be included in a classification system for extreme fire behavior. More work will be done on this part of the problem, but the study thus far indicates that the complete wind profile (speed and direction) correlates nearly as well with extreme fire behavior as do both the wind and temperature profiles. The correlation of complete wind profile with extreme fire behavior

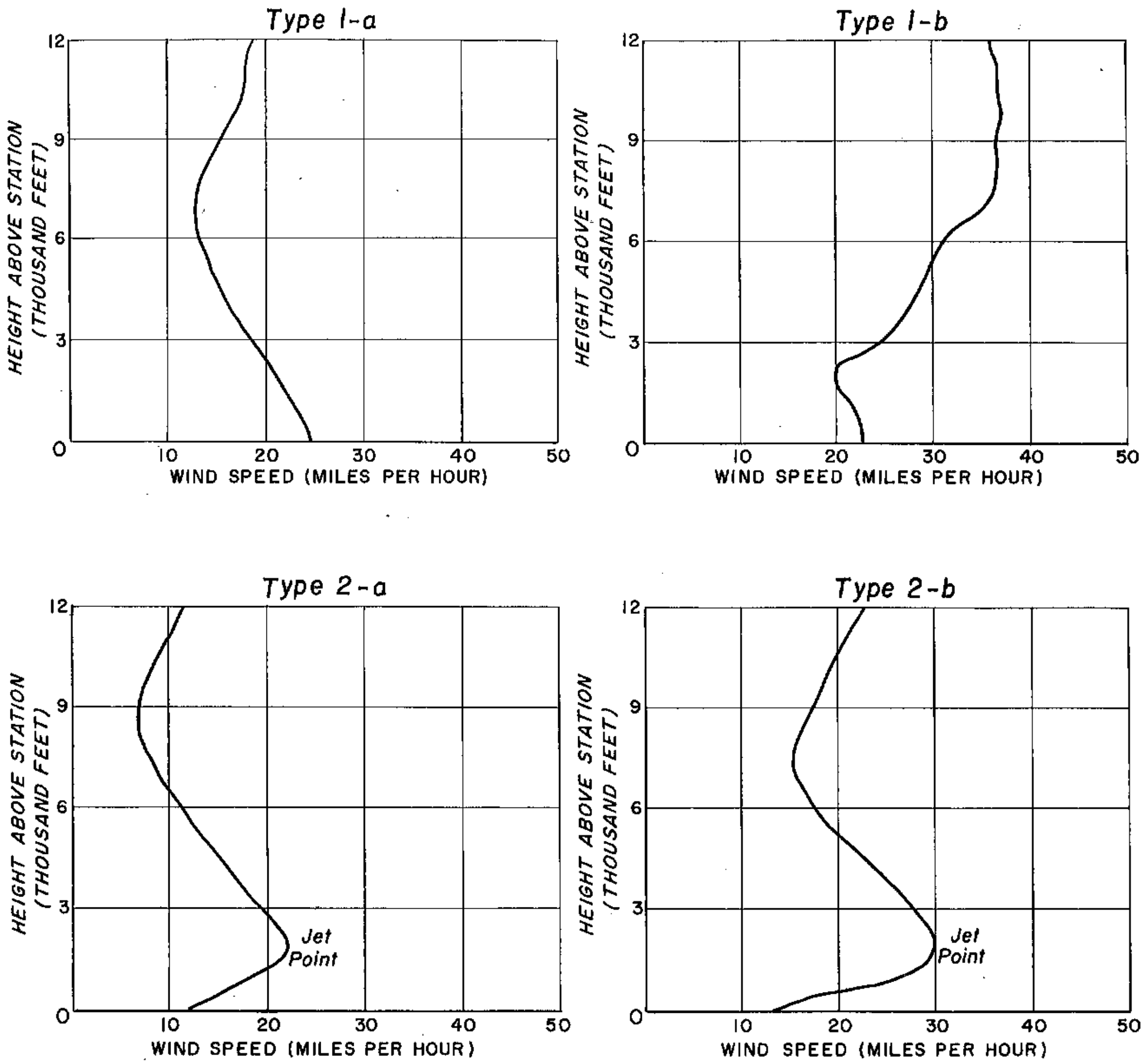

Figure 2.--These curves illustrate four types of wind profiles that appear to be potential trouble makers. Note that wind speeds are shown for different heights above the pilot balloon station rather than height above the fire.

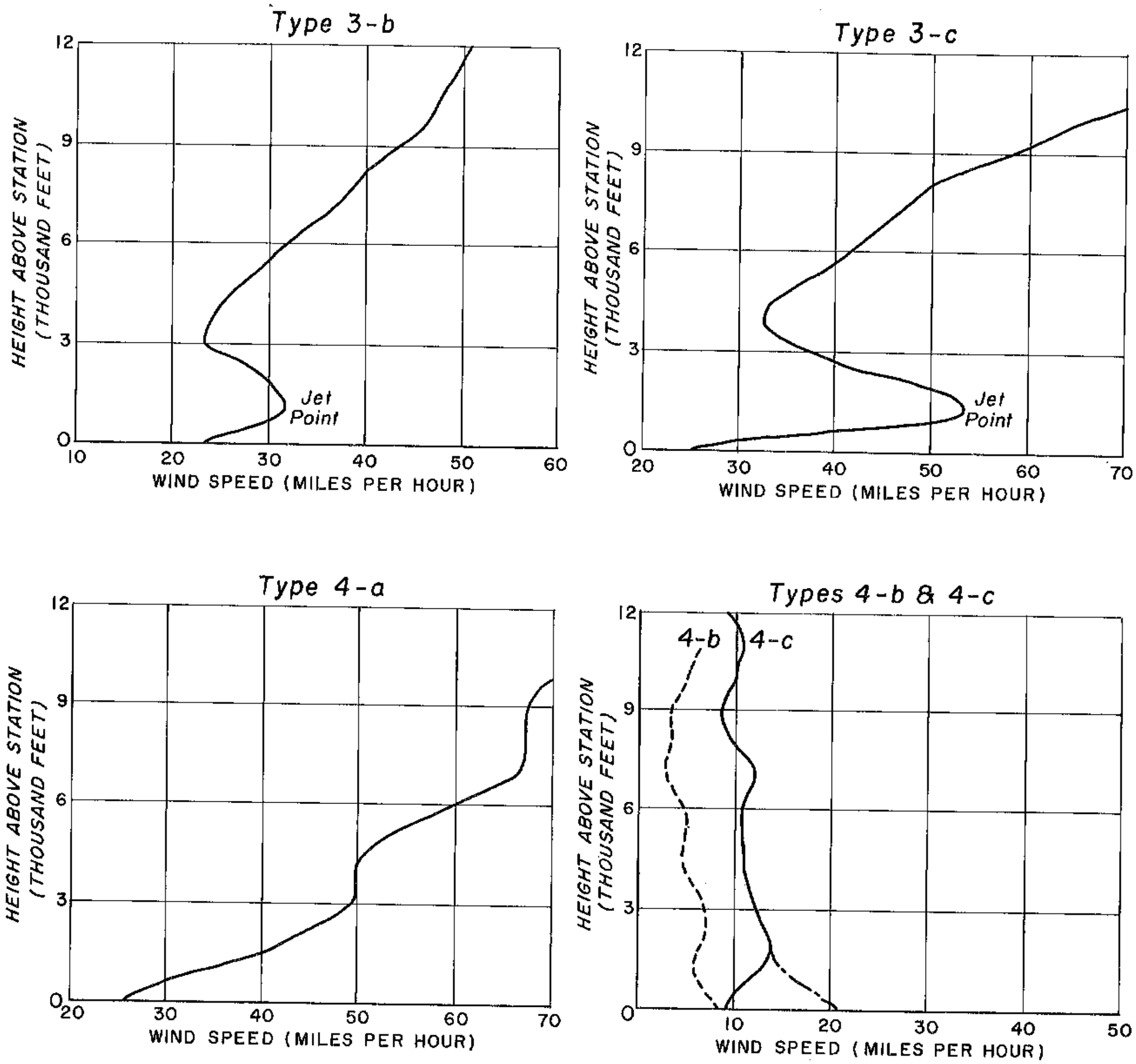

Figure 3.--The two upper curves in this figure represent types that are considered to be trouble makers. The two lower graphs illustrate types that are more common and can be considered safe in flat country. Wind speeds are for different heights above the pilot balloon station.

may reflect the combined effect of existing temperature gradient and previous temperature gradient. Influence of the latter may extend back for a day or more.

The direction profiles were omitted in figures 2 and 3 but were included in the detailed figures 4 through 12. The direction profile is an important part of the complete wind profile. With each of the following type descriptions is given some description of the corresponding fire behavior characteristics which we believe may occur with a given profile type. The fire behavior statements may have to be revised as we get further along in case-history studies, but undoubtedly their main shortcoming now is incompleteness.

In types 1-a through 3-c the wind speed at the jet point is 18 miles per hour or more. If the wind speed at the jet point is 15 miles per hour or less, none of the types may be especially dangerous in flat country. In rolling or mountainous country, however, a fire might run upslope.

Type 1-a

Type 1-a is probably one of the most dangerous types that can exist from the standpoint of personnel safety and erratic and unpredictable fire behavior. Fortunately, it is one of the types least likely to occur. It will be noticed that the jet point is missing in both type 1-a and type 1-b, unless it can be considered to be at the ground level. Actually, both types probably have a jet point but it may be too low to show up on the pilot balloon record. For this reason it will be assumed that the jet point exists and is within 100 feet or so of the ground. There is also considerable variation in the surface winds when the atmosphere is turbulent, so soundings made a short time apart or in slightly different locations might show some variation in the lower part of the profile.

When a type 1-a wind speed profile exists, the worst in fire behavior can be expected if fuels are dry and plentiful. Large whirlwinds (possibly up to 500 feet or more in diameter) may form in the head of the fire and even travel out ahead of the fire into fresh fuel, burning blackened strips as they go. There may also be long distance spotting (600 feet or more). A towering convection column is almost certain to form as the fire becomes larger. This can happen in a matter of minutes if the fire burns into heavy fuel. Although erratic and unpredictable in flat country, fires should move in the general direction of the wind. This will not always be true where topographic features can alter the wind speed and direction pattern and thus affect the direction of spread.

In late afternoon and early evening the lower air layers will become stable and the surface winds will drop. This process converts the dangerous type 1-a into the more common type 2-a. If the jet point is within 500 feet above the fire, type 2-a is nearly as dangerous as 1-a for a large fire already burning. It should be impossible for type 1-a to occur at night.

The illustrative curve for type 1-a in figure 2 is the estimated profile over the Hofmann Forest area at about 5:30 or 6:00 p.m. on April 17, 1950. There were no pilot balloon stations nearby, so the profile was estimated from the 4:00 p.m. and 10:15 p.m. soundings at Raleigh, North Carolina, about 100 miles to the northwest; from the 4:22 p.m. and 10:00 p.m. soundings at Hatteras, North Carolina, about 100 miles to the east; and from the 4:00 p.m. soundings at Charleston, South Carolina, more than 200 miles to the southeast. The profiles for Charleston for both 10:00 a.m. and 4:00 p.m. (including direction profiles) are shown in figure 4.

Type 1-b

This type occurs more frequently than type 1-a. The fire behavior characteristics are similar to type 1-a, but should not be so bad. When the lower air layers cool and stabilize in late afternoon and the surface winds drop, type 1-b converts to the "safe" type 4-a. For this reason fires burning with a type 1-b wind speed profile usually do not cause much trouble after sundown.

The curve illustrating type 1-b is a composite of 4:00 p.m. profiles for March 26 and April 11, 1950 for Charleston, South Carolina (see table 1 for fires which occurred on these days).

Type 2-a

Next to type 1-a, this may be one of the most dangerous types of wind speed profiles that can occur. It may develop either during the day or night, but is more likely to come at night or in late afternoon.

A wind speed profile might be type 2-a with respect to the pilot balloon station, yet for a fire occurring in mountainous or rolling country at an elevation equal to or possibly somewhat above the jet point, the profile would be type 1-a as far as the fire was concerned. This seemed to have been the situation in the Mann Gulch fire and part of the time during the McVey fire.

The fire behavior characteristics for type 2-a seem to be similar to 1-a except that in flat country they should not be as extreme as for type 1-a. Large whirlwinds in particular should be less likely to occur, although the probability of whirlwinds in the convection column aloft might be about the same for both types.

For fires burning in flat country, the height of the jet point as well as the relative wind speeds at the jet point and at the surface are important factors affecting behavior. For light fuels there may be little chance of a fire maintaining a high intensity at night if the jet point is more than 600 feet above the ground. In heavy fuels this figure might be around 1200 to 1500 feet.

The type 2-a profile is more serious in rough or rolling country, where a considerable part of the forested terrain may have an elevation approximating that of the jet point.

It should be remembered that the jet point usually moves upwards at night as the lower air layers cool and stabilize. During the early part of the night, therefore, the terrain between 1000 and 2500 feet above the general land level will be somewhere in the neighborhood of the jet point. In addition the wind speed at the jet point increases when the cooling of the lower air layers diminishes the frictional drag at the earth's surface and the surface winds drop.

This is a somewhat different picture than we have had in the past of wind structure on nights when blowups may occur. We have thought of the strong steady winds as blowing on the higher peaks and diminishing down in the lowlands. Just the reverse seems to be true. On the worst nights the higher mountains may have little wind, and the highest winds will be down in the low country or foothills. Also, the gain in wind speed at the 1000 to 2500 foot level seems to build up from below, not above. For example, the Red Bluff soundings in figure 6 indicate that on the night of the Rattlesnake Fire the wind speed on the higher peaks in the California Coast Range was only about 7 miles per hour but was 21 or 22 miles per hour between 2000 and 2500 feet.

The illustrative curve for type 2-a is a composite of the 12:41 a.m. July 10, 1953 sounding for Red Bluff, California, the 8:00 p.m. August 5, 1949 sounding at Great Falls, Montana, and the estimated 11:00 p.m. profile over Rapid City, South Dakota, on July 10, 1939 (see also figures 5, 6, and 10).

Type 2-b

This type resembles 2-a except that the wind speeds are higher. Not much is known about the fire behavior except that it is undoubtedly dominated by the wind. For this reason it may not be quite so dangerous to experienced fire fighters as types 1-a and 2-a, even though the intensity may be well up in the conflagration range. However, fires burning in heavy dry fuel on a type 2-b day could be very dangerous for towns and villages ahead of the fire.

It is likely that, for a time at least, the wind speed profiles for some of the historic fires may have been of the 2-b type.

The illustrative type 2-b profile is a composite of soundings at Greensboro, North Carolina, for 4:50 p.m. May 6, 1941 and Raleigh, North Carolina, for 10:15 p.m. April 17, 1950 (see table 1 for fires).

Types 3-a and 3-b

These two types have wind speed profiles that are very similar, but the behavior of the fires is quite different. The wind speed for type 3-b is at least 28 miles per hour at the jet point and for type 3-a (not shown) it is in the 18 to 24-mile-per-hour zone. Both types have strong winds at high levels, but for a distance of at least 2000 feet above the jet point the wind speed decreases with height just as for the previous types.

The Brasstown fire on March 30, 1953 (profiles are shown in figure 9) indicated that if a convection column becomes well established above the jet point in the region where wind speed is decreasing, it can also penetrate some distance up into the strong winds at higher altitudes. The surface winds at the time of the Brasstown fire were from the southwest and very light (even lighter than indicated by the 3:53 p.m. sounding at Spartanburg, South Carolina, about 60 miles to the east). The direction profile in figure 9 shows that the wind direction at the jet point was also southwest. However, the fire was spread by showers of burning embers which came from west-northwest. The direction profile indicates that the winds did not veer to this direction until an altitude of 4000 feet or more was reached, which was up in the zone where the wind speed was increasing with height. It seems probable, therefore, that burning embers were carried up to at least 4000 feet and dropped out of the convection column when its active core may have been broken up by the positive wind shear in the higher air layers. This may not be unreasonable because pilots have reported burning embers as high as 4000 feet over other fires such as those in Tennessee in the fall of 1952.

In spite of the low wind speeds on the ground, the Brasstown fire traveled a distance of 3 miles in 1-1/2 hours and cut across drainages as though they did not exist. There is some indirect evidence that there may have been intense whirlwinds high up in the convection column over this fire. So far as the writer knows, whirlwinds of this type have never been seen over a forest fire. However, they have been seen and photographed over an oil fire by Hissong (5) and over a volcano by Dietz (4).

The Wood River Valley fire of May 2, 1951, in Rhode Island, burned when the wind speed profile was of type 3-b. Some of the behavior characteristics of this unusual fire are as yet so little understood that they will not be discussed in detail at this time. There appeared to be distillation effects and oxygen deficiencies such as those that have been reported from time to time on the fires in the eucalyptus forests of Australia. Fire would suddenly appear over a considerable area in advance of the main fire with no apparent direct connection.

The nearness of the jet point to the earth's surface on the afternoon of May 2, 1951 (fig. 8), the high wind speed at the jet point, and the decrease in wind speed for 2000 feet above the jet point, may have contributed to the unusual behavior of this fire, as well as the strong updrafts and downdrafts near the head of the fire. Like the Brasstown fire, the Wood River Valley fire put up a large convection column that probably went above the height of the unstable layer, which was about 9000 feet deep over New England on the afternoon of May 2.

The illustrative type 3-b curve is a composite of the 4:00 p.m. May 2, 1951 sounding for Hartford, Connecticut, and the 3:55 p.m. October 28, 1952 sounding for Spartanburg, South Carolina.

Type 3-c

The illustrative curve in figure 3 is a composite of the 10:35 p.m. October 23, 1947 pilot balloon sounding for Boston, Massachusetts, and the 4:02 p.m. July 31, 1953 sounding for Portland, Maine. Portland would have been a more suitable station for October 23, 1947, but this was the day of the major blowup of the Maine fires. The smoke at Portland was apparently so thick that the balloon was not visible above 1000 feet. Type 3-c resembles 3-a and 3-b except that wind speed at the jet point is extremely high. However, it drops off very rapidly above the jet point for several thousand feet. In the case of the October 23, 1947 soundings at Boston (fig. 7), the wind in the upper levels was very high also, but this was not so marked in the July 31, 1953 sounding at Portland, the day of the fast-spreading Sanford fire in southwestern Maine.

The role of the convection column for fires burning in such extreme wind conditions is not known. It is difficult to see how a fire could build an active convection column when a wind speed profile of type 3-c exists. Also, it would appear that with such a profile a convection column would not be necessary for an intense, rapid-spreading fire. However, the long distance spotting that occurs on some of these fires indicates that strong convection does exist. It may be that convection columns do form for short intervals before being destroyed. The rapid decrease in wind speed above the jet point should increase the tendency for them to form.

Type 4-a

This type is probably the most common of all, although the wind speeds are usually considerably less than shown in the illustrative curve. This curve is the 4:00 p.m. March 27, 1950 pilot balloon sounding at Charleston, South Carolina. For some parts of the East and South this was a very bad fire day, and the profiles in other locations may have been considerably different from that at Charleston. In this area the fires on that day were intense and fast-spreading, but they could not be considered dangerous to experienced crews, nor were there any erratic and unusual aspects to their behavior. Perhaps this was due to a lack of convection columns of any consequence forming over the March 27 fires (at least in the Charleston area). The rapid increase of wind speed with height should keep active columns from forming.

Unless future fires indicate otherwise, it can be assumed that, compared to the previous types, type 4-a is relatively "safe" even for high wind speeds and rapidly spreading fires. If the jet points in type 2-a or type 2-b rise during the night to a height of 2000 or 3000 feet, then for flat country these types have in effect become type 4-a.

Types 4-b and 4-c

The curve for type 4-b is the 10:09 a.m. July 3, 1952 pilot balloon sounding for Raleigh, North Carolina, and for type 4-c it is the 10:05 a.m. July 2, 1952 sounding for Raleigh. Type 4-b resembles type 1-a in that the general wind speed decreases with height. Type 4-c resembles type 2-a. Both of these types are probably "safe" as long as the wind speed at the jet point remains below 14 or 15 miles per hour. However, there is an important exception. This is the case of a fire burning up a slope in which the upslope direction is roughly the same as that in which the general wind is blowing. It should be remembered that the presence of the slope, especially if it is fairly steep, is equivalent to adding several miles per hour of wind in the lower air layers. This means that the presence of the slope may temporarily convert type 4-b or 4-c into the dangerous type 1-a (see the broken line added to 4-c). This is why a fire can rage upslope, build a tremendous convection column in so doing, and then quickly die down (unless it spots over to the bottom of the next slope).

Type 4-b or 4-c can also develop into type 1-a through an increase in wind speed in the lower atmosphere during the afternoon (see the April 17, 1950 profiles for Charleston, South Carolina, in figure 4). However, a more likely possibility is the conversion of types 4-b and 4-c to type 2-a in late afternoon or early part of the night, when the lower air becomes stable and the surface winds drop. Stabilizing of the lower air layers diminishes frictional drag on the earth's surface and results in an increase in wind speed at a height of 1000 to 2500 feet above the general land level. The wind speed could easily be brought up into the critical zone. For this reason type 2-a is more likely to occur at night than in the daytime.

Topography and its Place in Wind Profile Classification

Early in this work, topography appeared likely to become one of the most complex factors in extreme fire behavior. However, this did not prove to be the case as far as basic principles are concerned, although the effects of topography in any specific situation may be very complex. Topography exerts its main effects in two ways. The first of these is the effect on the wind speed profile described in one of the preceding paragraphs and illustrated in figure 3 in the type 4-c curve.

The second main effect of topography is that it permits a fire to occur in, or burn into, zones which may be at elevations corresponding to quite different parts of the wind speed and wind direction profiles. This point is illustrated fairly well in the discussion of the McVey fire in the appendix.

CASE-HISTORY FIRES

For convenience, the case-history fires in this study have been summarized briefly in table 1. These fires have a large range in size as well as in behavior characteristics. The final size is given for the majority of the fires, but for the purpose of this study final size was of much less importance than certain kinds of information such as the time (or times) when a fire made its main run (or runs) or showed other specific characteristics of extreme behavior.

On five of the fires there was loss of life. There were narrow escapes on others. Probably all the fires could be considered potentially dangerous to suppression personnel. A brief statement is given on some behavior highlights for each fire, but no attempt is made here to present any detailed behavior account of any particular fire.

Not given in table 1 is the location and distance of any individual fire with respect to the nearest pilot balloon station, or stations. However, for the majority of the fires there was a station within 50 or 60 miles; for a few there was a station as close as 30 miles.

Table 1.--A summary of principal case-history fires used in studying extreme fire behavior

Name of fire and location	Date, wind-speed profile type, final size of fire	Comments on fire behavior
Hofmann Forest Eastern North Carolina	April 17, 1950. Types 1-a, 2-a, and 2-b.	An estimated 30,000 acres burned between 3:00 p.m. and 11:00 p.m. on April 17. Fire crowned through a dense hardwood swamp at 6:00 p.m.
Mann Gulch Helena National Forest Montana	August 5, 1949. Type 2-a. 5,000 acres.	Behavior erratic in both rate and direction of spread. Blowup came between 5:30 and 6:30 p.m. on August 5.
McVey Black Hills National Forest South Dakota	July 10-11, 1939. Type 2-a on the 10th, types 3-a and 2-b on 11th.	The first blowup or period of rapid spread came at 11:00 p.m. on July 10; continued throughout following day.
Rattlesnake Mendocino National Forest California	July 9, 1953. Type 2-a. 1,200 acres.	A high-intensity fire developed unexpectedly at about 10:15 p.m. on July 9, reaching its peak during the next 30 or 40 minutes.
Bluff Point Eastern North Carolina	July 3, 1952. Probably types 1-a and 2-a.	An estimated 10,000 acres burned on July 3. Backfires crowned at night in pond pine, between 8:00 p.m. and 10:00 p.m.
Maine fires Southern and southwestern Maine	October 23, 1947. Type 3-c. 200,000 acres.	Many fires burned during the last 2 weeks of October, but the major loss seemed to be in the blowup on October 23.
Cherokee Cherokee National Forest Northeastern Tennessee	October 27-28, 1952. Type 3-b.	This was a severe cold-front fire. Major loss came on the afternoon and night of October 27 and day of October 28.
Iron Mountain Jefferson National Forest Southern Virginia	May 6, 1941. Type 2-b. 2,600 acres.	One of the most intense, rapid-spreading fires of the Jefferson National Forest in 15 years.
Blue Jefferson National Forest Southern Virginia	April 6-7, 1942. Type 2-b on 6th, 2-b and 3-b on 7th. 10,000 acres.	Like the Iron Mountain Fire, this was an intense, fast-spreading fire.

Farewell Francis Marion National Forest South Carolina	April 11, 1950. Type 1-b. 470 acres.	Large whirlwinds at least 500 feet in diameter, apparently interacting, formed on this fire during the afternoon of April 11.
Buckle Island 144 Francis Marion National Forest South Carolina	March 26, 1950. Type 1-b. 208 acres.	Behavior characteristics similar to the Farewell fire on April 11, but not quite so severe.
Buckle Island 196 Francis Marion National Forest South Carolina	April 17, 1950. Type 1-a. 260 acres.	This was an intense, whirlwind fire on the afternoon of the 17th. The type 1-a condition probably did not last as long in the vicinity of this fire as it did in the vicinity of the Hofmann Forest fire.
(Name unknown) Southern South Carolina	April 23-24, 1950. Type 3-a and 2-b on the 23rd, 4-b and possibly 1-b on 24th. 1,800 acres.	Whirlwinds on this fire varied from 50 feet to 300 feet in diameter. Whirlwinds were larger in crown fires in dense advanced reproduction than in logging slash. April 23 was the worst day.
Wood River Valley Western Rhode Island	May 2, 1951. Type 3-b. 7,400 acres.	An extremely fast-spreading fire with unusual turbulent effects. There were strong updrafts and downdrafts near the head of the fire.
Hales Lake Eastern North Carolina	October 28, 1952. Type 3-b.	This was a severe fire resulting from the same turbulent cold front which brought severe burning conditions to the Cherokee area on October 27 and 28. About 4,500 acres were burned on the afternoon of October 28.
Sanford Southwestern Maine	July 31, 1953. Type 3-c. 2,300 acres.	The major part of the area was burned from 1:00 p.m. to 11:00 p.m. Greatest run was from about 1:00 p.m. to 4:00 p.m. The wind speed at the jet point, 1,200 feet over Portland, was 55 miles per hour.
Brasstown South Carolina National Forests Northwestern South Carolina	March 30, 1953. Type 3-a. 3,800 acres.	Wind at the ground was very light, but fire ran 3 miles in 1-1/2 hours. Showers of embers caused large areas in front of the fire to ignite almost simultaneously.

If it is eventually used more widely by fire suppression organizations or fire weather forecasters, the pilot balloon may become an effective safety device. The use of pilot balloons on actual fires has been tried in the past and would not be a new technique. The only new feature would be the handling of the resulting data and the use to which it is put. Of paramount importance is recognizing when a dangerous wind profile exists, and next in importance is knowing when an area becomes safe. Usually the dangerous conditions do not last long. For example, the areas where both the Mann Gulch and Rattlesnake fires occurred appear to have become safe within a few hours after the blowups.

The pilot balloon is one of the simplest devices for getting information from the upper atmosphere. With some study of both pilot balloon and radiosonde temperature soundings for a given area, it is often possible to estimate the depth of the unstable air layer with considerable accuracy from the pilot balloon sounding alone. It is sometimes possible to estimate from a 10:00 p.m. sounding what the depth of the unstable layer has been during the previous afternoon. The pilot balloon does, however, have certain sources of error (probably small) and limitations when soundings are made in a turbulent atmosphere with strong updrafts and downdrafts. The magnitude of these erros should be checked before the pilot balloon is given any large-scale trial in fire control work. The Weather Bureau may already have some of this information. Also, the possibility should be considered of making greater use of soundings now taken regularly at official stations.

The prediction of jet currents and their growth and decline is a problem in basic meteorology, a detailed discussion of which is beyond the scope of this paper. When meteorologists understand how the jet stream gets its energy, the explanation of the energy of the jet currents will probably follow soon. That a considerable part of the energy of the jet currents comes from an unstable atmosphere is probably a safe assumption. If so, it is likely that stability and turbulence conditions are important not only on the day when extreme fire behavior occurs but also for a day or two before. In other words, turbulence could have a delayed action in its indirect effects, which could contribute to the strength of the jet currents at a later time. If so, another element for predictions 12 to 18 hours or more in advance would become available. However possibilities for a 12-hour prediction of a jet current condition should be regarded as still unknown.

The prospects for a short range prediction are easier to comprehend. The curves in figure 4 for Charleston, South Carolina, as well as those for Raleigh and Hatteras (not shown), indicate a progressive growth and change in the wind profile for a number of hours on April 17, 1950. The curves in figure 6 show that a similar situation existed over Red Bluff, California, on July 9, 1953. The jet current over the Red Bluff area seemed to build up for at least 8 hours before the blowup. Pilot balloons sent up at 2 or 3-hour intervals would give an even better picture of the profile and its rate of change. The prospect of an accurate 3 to 4-hour prediction of wind speed profile and direction profile seems good.

Even without the use of instruments, there are signs that give warning of unusual burning conditions. A number of indicative conditions, including some suggested by Crosby (3), are given in the following list:

(1) A high burning index and a high buildup index. On most of the severe fires studied thus far, both the buildup index and burning index have been 50 or above on the 8-0 or 8-W meters now used in the eastern states. Even on the Brasstown fire, which came only a week after heavy rains, there had been considerable drying. The soil and lower fuels were moist but the upper fuels were dry. The humidity was very low on the day of the fire, which meant that a relatively large number of embers from spotting would catch in the dry top fuel layer.

(2) Gusty and variable winds from south to southwest with an airport speed of 15 to 20 miles per hour. An airport wind speed will be defined as the wind speed between 30 and 60 feet above a wide expanse of open, clear ground such as exists at the ordinary airport. Temperatures may be somewhat above normal with a rather large rise early in the day, and relative humidity is usually low. Day may be bright and sunny but with a thin overcast.

(3) Conditions similar to (2) but wind with an airport speed of 25 miles per hour or more. Fire may be intense and fast spreading but less erratic than at lower wind speeds.

(4) If a towerman or plane observer viewing a fire from a distance and at right angles to the wind reports that the smoke column tends to curve upward and become nearly vertical in its upper parts, the wind speed is undoubtedly decreasing with height. Such a fire could become dangerous if it burns into heavy fuel. If smoke column has started to "boil" or mushroom up, trouble has probably already happened on this particular fire, although its behavior is less serious if the towering smoke column is caused by a run upslope.

(5) Probably a fire should be regarded as likely to develop extreme behavior if it spots more than 600 feet ahead of the main fire. Long distance spotting means that there are updrafts or whirlwinds strong enough to carry high in the air embers large enough to burn for nearly a minute before dropping to the ground.

(6) Several spot fires that seem to lie along either the same straight line or curve may be a bad sign, especially if they start at about the same time. This pattern may indicate whirlwinds in the convection aloft that are dropping firebrands.

(7) The passage of cold front with northwest winds may cause trouble when it is not accompanied by rain. The cold front fires differ considerably from the warm weather type in that they may burn when the temperature is low and falling. The worst fires of the fall of 1952 in the eastern and southeastern states, as well as the blowup on the Maine fires on October 23, 1947, are examples of this type. Probably the Cloquet fire in Minnesota in 1918 was a cold-front fire. They are often accompanied by high winds and a pronounced jet current. They occur most frequently in the fall and spring.

(8) Just before the arrival of a cold front, fires may sometimes develop turbulent behavior while the wind is shifting from the southwest to northwest. Spotting, whirlwinds, and updrafts may come during this period, which should not last long.

(9) Dust devils or dust whirls over plowed fields are indicators of troublesome burning conditions and difficult fire fighting. However, they are in themselves indicative of the direct effects of turbulence and do not necessarily mean that blowup conditions exist. Possibly a better indication of blowup conditions might be dust whirls on several consecutive days accompanied by the conditions listed in (2).

(10) If lookouts or towermen on the higher peaks from 4000 to 5000 feet above the general land level report lower wind speeds than exist at low elevation, and if anemometers at airport exposures are showing wind speed of from 15 to 20 miles per hour, then an unfavorable wind speed profile may exist. However, this method of estimating the profile is not a good substitute for a pilot balloon sounding.

(11) When the flying is bumpy and if it becomes bumpy earlier than usual in the morning, most of the direct effects of turbulence on fire behavior will be present during the afternoon. This condition may be more significant for extreme fire behavior if flying has been rough for several days in a row and if it is accompanied by the conditions listed under (2).

(12) If it is known that an unfavorable wind speed profile exists and if, in addition, both burning index and buildup index are high, then the only effective period for controlling a fire is when it is small. The probability of the fire establishing a "chimney" and blowing up increases rapidly with increasing size. For fuels of 4 to 12 tons per acre, this critical size may be from 40 to 60 acres. In heavy fuels the size would be smaller. The critical area should be larger for a slow-spreading than for a fast-spreading fire, because it is rate of energy output rather than actual size that determines the probability of blowup.

CONCLUSION

In the study of the behavior of unusual fires which occur infrequently, research must depend to a considerable extent on the observations of the field men who worked on such fires. Up to this time, most accounts of large fires concern more the methods of attack and details of suppression than they do fire behavior description. Many observations that might appear trivial to the casual observer are highly significant to the researcher. Examples of valuable items that should be watched for and included in future descriptions are the maximum distance of spotting, pattern of spotting, estimated height of flame and size of whirlwinds, height and shape of convection column, rate of spread during runs, and brief comments on fuel and stand type. Of special value are the observations of pilots, such as appearance of fire from air, presence of whirlwinds in the fire, shape and size of convection column (or columns), and the bumpiness of flying.

Concepts of what may cause extreme fire behavior are becoming sufficiently developed and specific to be tested experimentally. For example, the higher ground in hilly or rolling country should be well suited for large-scale experimental burns whenever a type 2-a wind speed profile develops after sundown. This type of profile seems to happen often enough to make actual test burns feasible.

How far fire research has come in the solution of the problem of the blowup fire should become fairly clear in the next 2 years. Several research teams are now working on the problem. Some of the results of the work of the group in the West were presented in the Chief's memorandum of November 12, 1953 (these were excerpts from a paper given at the Society of American Foresters' meeting in Denver in September 1953 by R. K. Arnold and C. C. Buck). The Scientific Services Division of the Weather Bureau is also working on the problem.

Even before the final answers are found, the collective effort of groups now studying extreme fire behavior should make increasingly effective guidelines available to the firefighter.

LITERATURE CITED

(1) BROWN, A. A.
1940. Lessons of the McVey fire, Black Hills National Forest. U. S. Forest Serv. Fire Control Notes 4(2): 63-67. April.

(2) BYRAM, George M. and NELSON, Ralph M.
1951. The possible relation of air turbulence to erratic fire behavior in the Southeast. U. S. Forest Serv. Fire Control Notes 12(3): 1-8. July.

(3) CROSBY, John S.
1949. Vertical wind currents and fire behavior. U. S. Forest Serv. Fire Control Notes 10(2): 12-15. April.

(4) DIETZ, Robert S.
1954. The explosive birth of Myojin Island. The Natl. Geog. Mag. 105(1): 117-128. Jan.

(5) HISSONG, J. E.
1926. Whirlwinds at oil-tank fire, San Luis Obispo, Calif. Monthly Weather Rev. 54: 161-163.

(6) KEETCH, John J.
1954. Instructions for using forest fire danger meter type 8. Southeast. Forest Expt. Sta. Station Paper No. 33. 7pp. Jan.

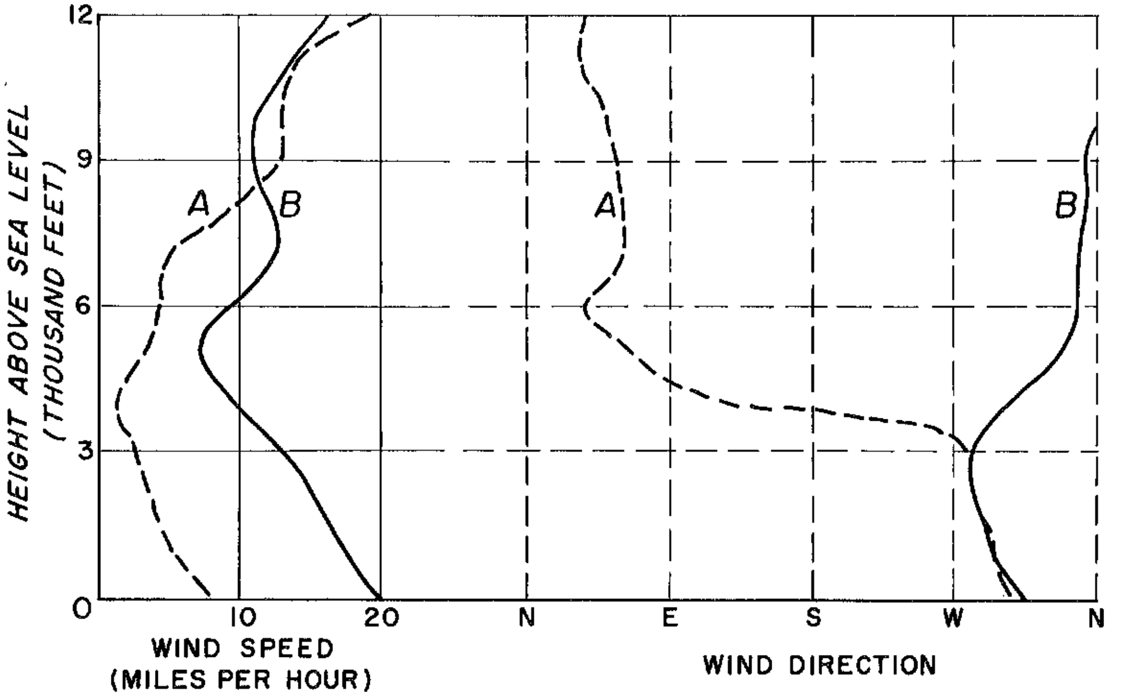

Figure 4.--Wind speed profiles are shown for 10:00 a.m. (curve A) and 4:00 p.m. (curve B) on April 17, 1950 at Charleston, S. C. The corresponding direction profiles are on the right (10:00 a.m. curve A and 4:00 p.m. curve B). Heights are in thousands of feet above sea level rather than above the station level (in this case they are nearly the same).

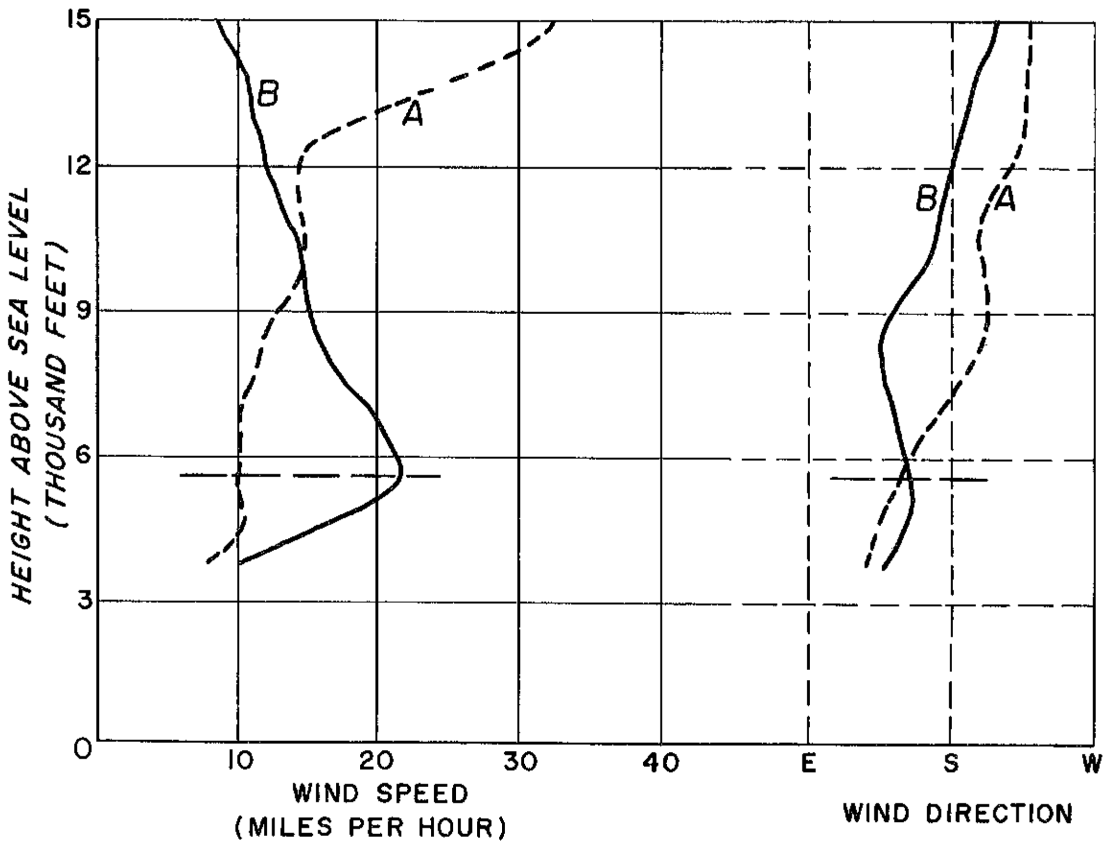

Figure 5.--Wind speed profiles for 2:07 p.m. and 8:00 p.m. on August 5, 1949 for Great Falls, Montana, are shown on the left by curves A and B respectively. The corresponding wind direction profiles are shown in the same manner on the right. The estimated elevation of the Mann Gulch fire is indicated by the broken horizontal lines.

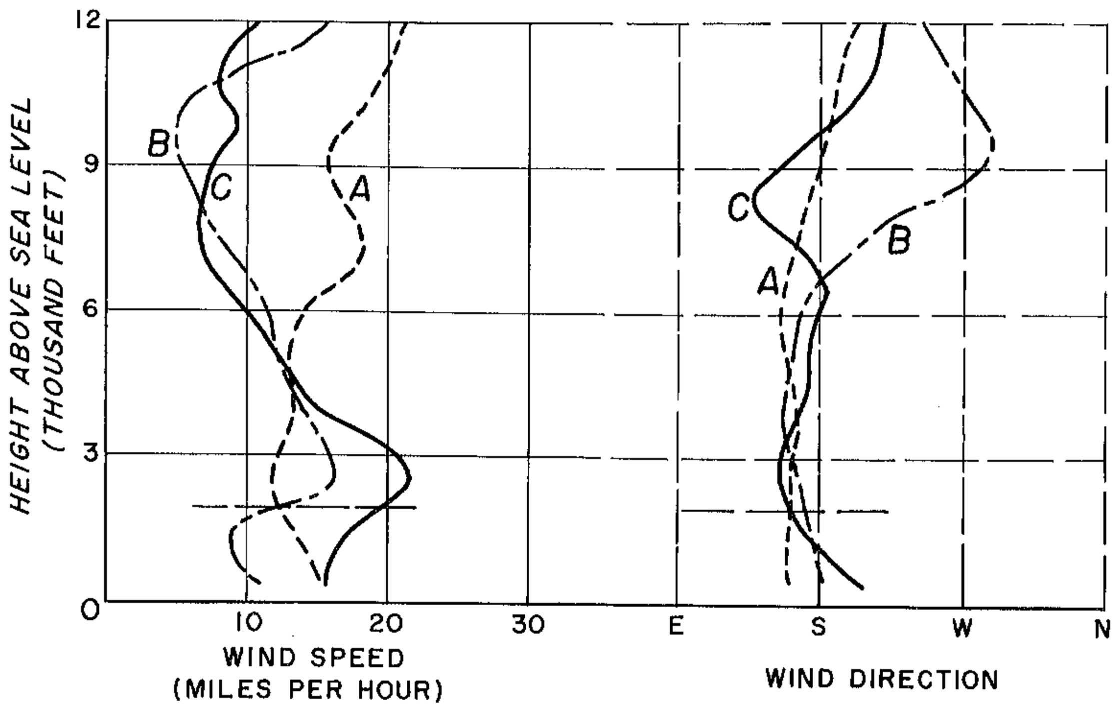

Figure 6.--Wind speed profiles for 12:45 p.m. and 6:55 p.m. on July 9 and 12:41 a.m. on July 10, 1953 for Red Bluff, California, are shown by the curves A, B, and C on the left. The wind direction profiles are designated in the same manner on the right. The approximate elevation of the Rattlesnake fire is indicated by horizontal broken lines.

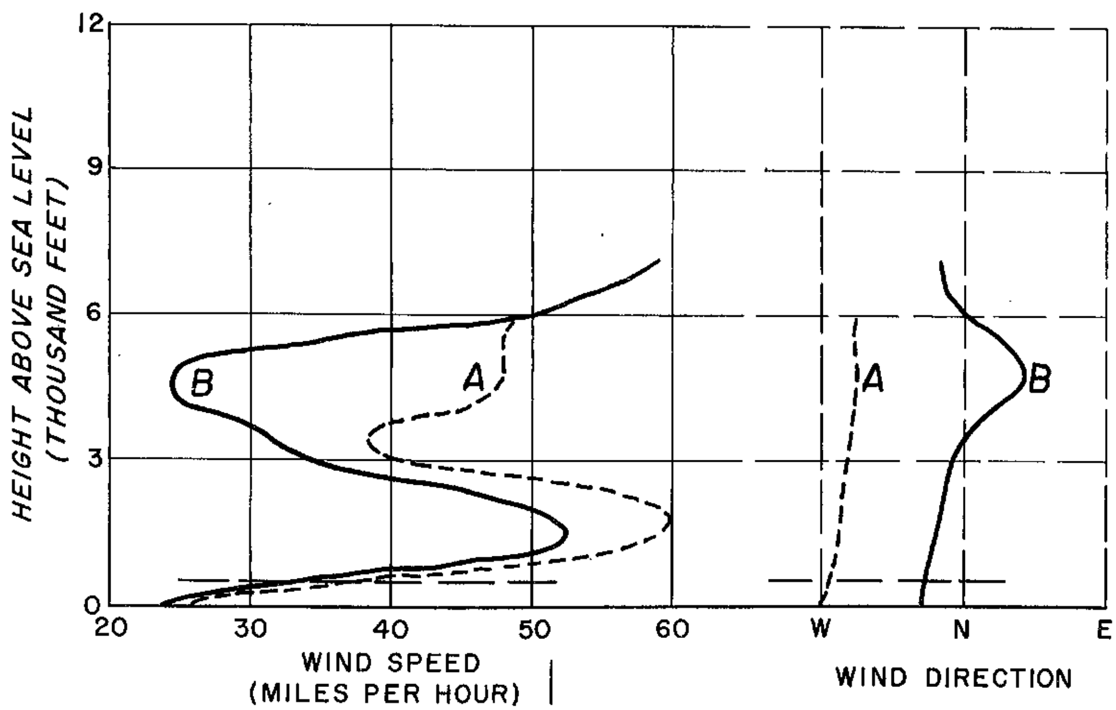

Figure 7.--Wind speed profiles for 4:05 p.m. and 10:35 p.m. on Oct. 23, 1947 for Boston, Mass., are indicated by curves A and B on the left. The corresponding wind direction profiles are shown in the same way on the right. The approximate estimated elevation of the fires in southwestern Maine is shown by horizontal broken lines.

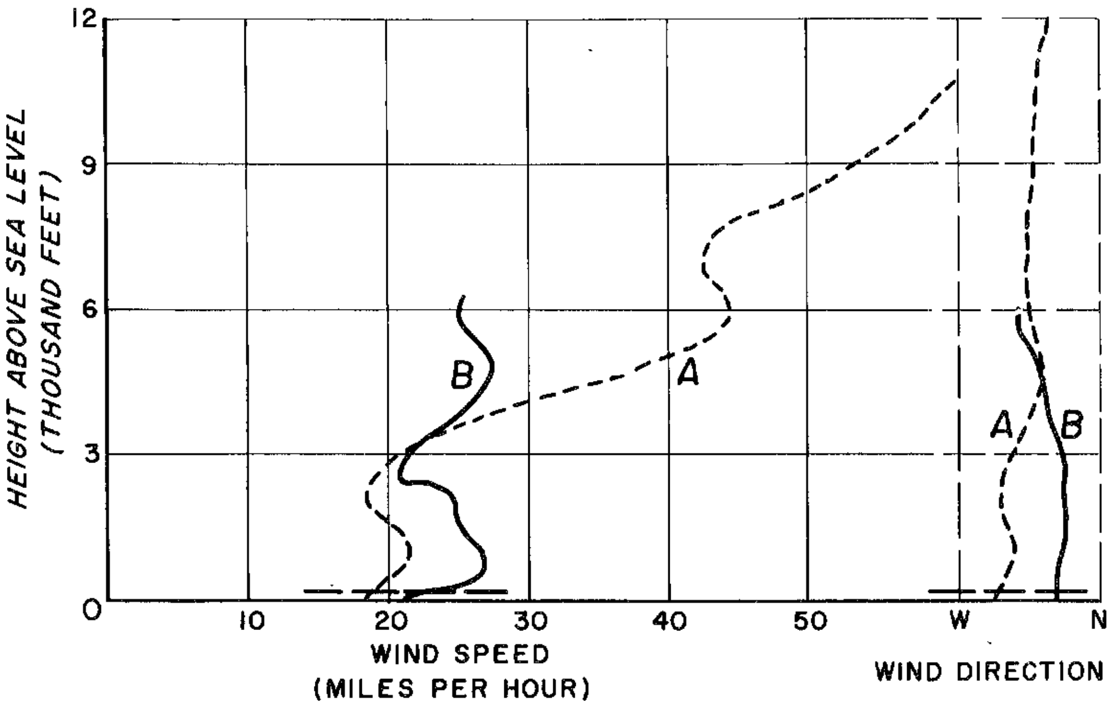

Figure 8.--Wind speed profiles for 10:15 a.m. and 4:00 p.m. on May 2, 1951 for Hartford, Conn., are shown by curves A and B on the left. The corresponding wind direction profiles are indicated in the same manner on the right. The estimated elevation of the Wood River Valley fire in Rhode Island is shown by horizontal broken lines.

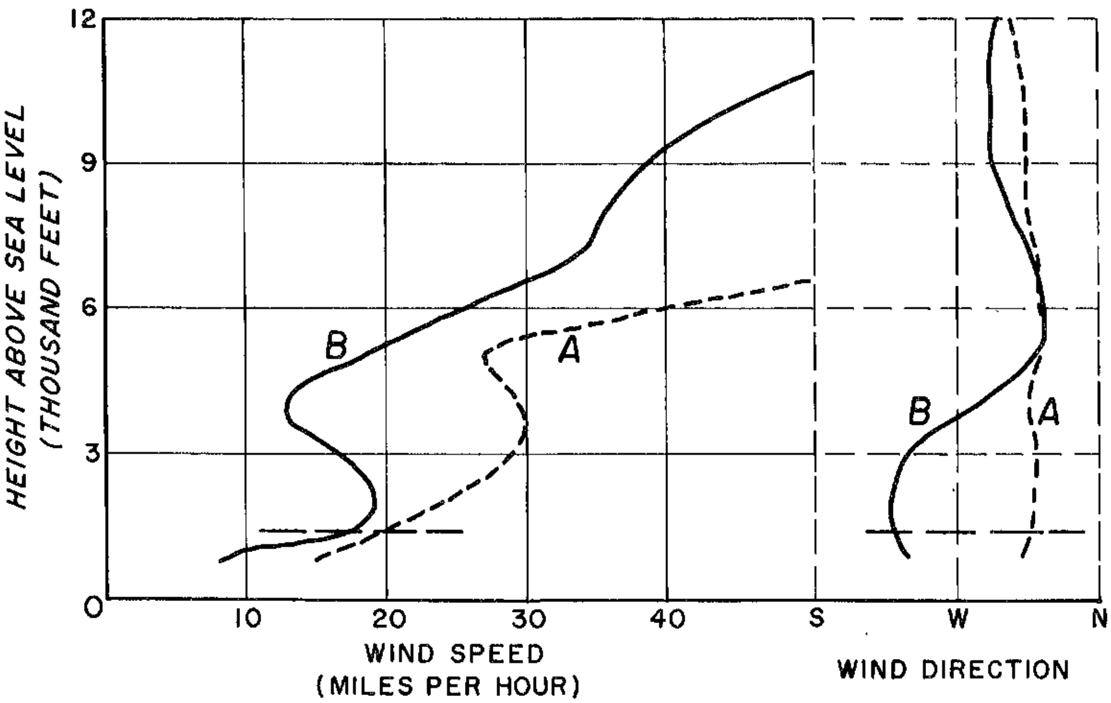

Figure 9.--Curves A and B on the left are the wind speed profiles at Spartanburg, S. C., at 10:00 a.m. and 3:53 p.m. on March 30, 1953. Curves A and B on the right are the corresponding wind direction profiles. The horizontal broken lines indicate the elevation of the Brasstown fire.

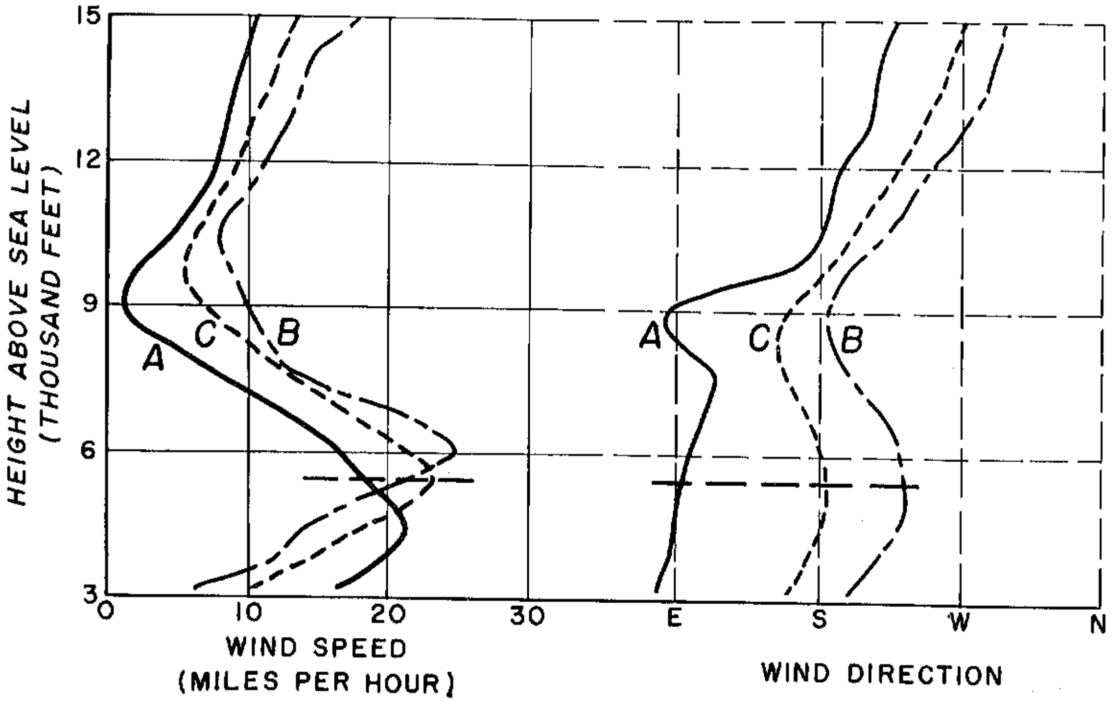

Figure 10.--Curves A and B on the left are the wind speed profiles at Rapid City, S. D., at 7:00 p.m. and 1:00 a.m. respectively on July 10 and 11, 1939. Curve C is an estimated intermediate curve for 11:00 p.m. July 10. The corresponding wind direction curves are on the right. The estimated elevation of the blowup on the McVey fire at 11:00 p.m. July 10 is indicated by the horizontal broken lines.

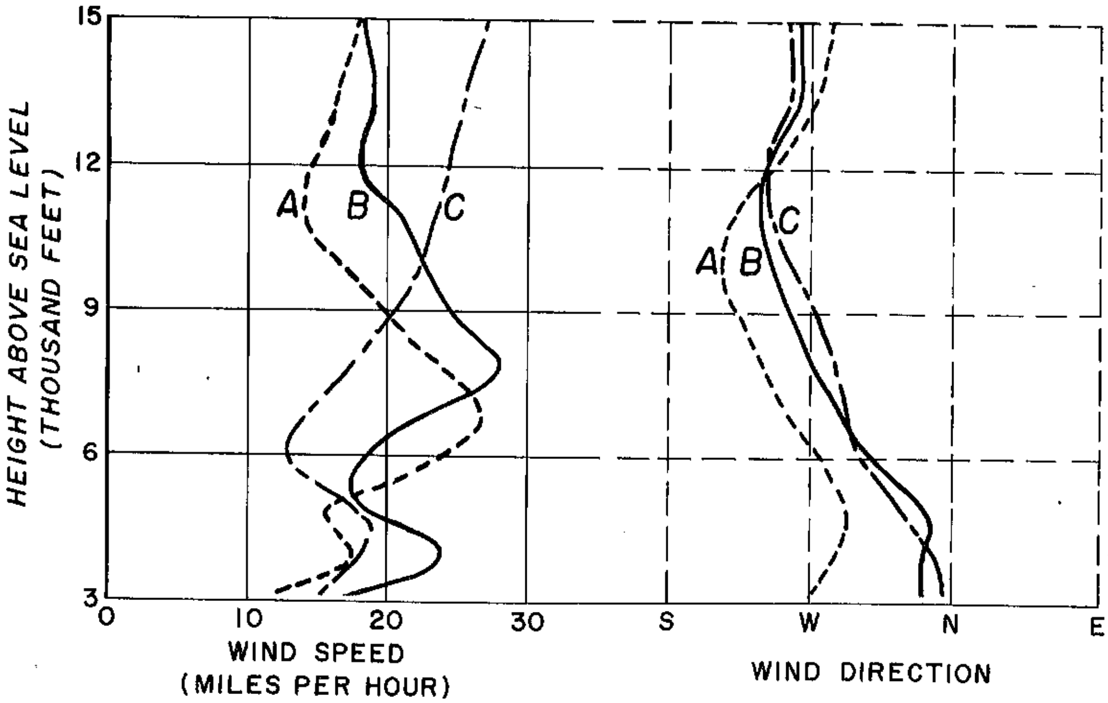

Figure 11.--Curves A, B, and C on the left represent the wind speed profiles at 4:00 a.m., 7:12 a.m., and 10:00 a.m. at Rapid City, S. D., on July 11, 1939. Curve B is a pilot balloon sounding. Curves A and C are estimated intermediate profiles. Curves A, B, and C on the right are the corresponding wind direction profiles.

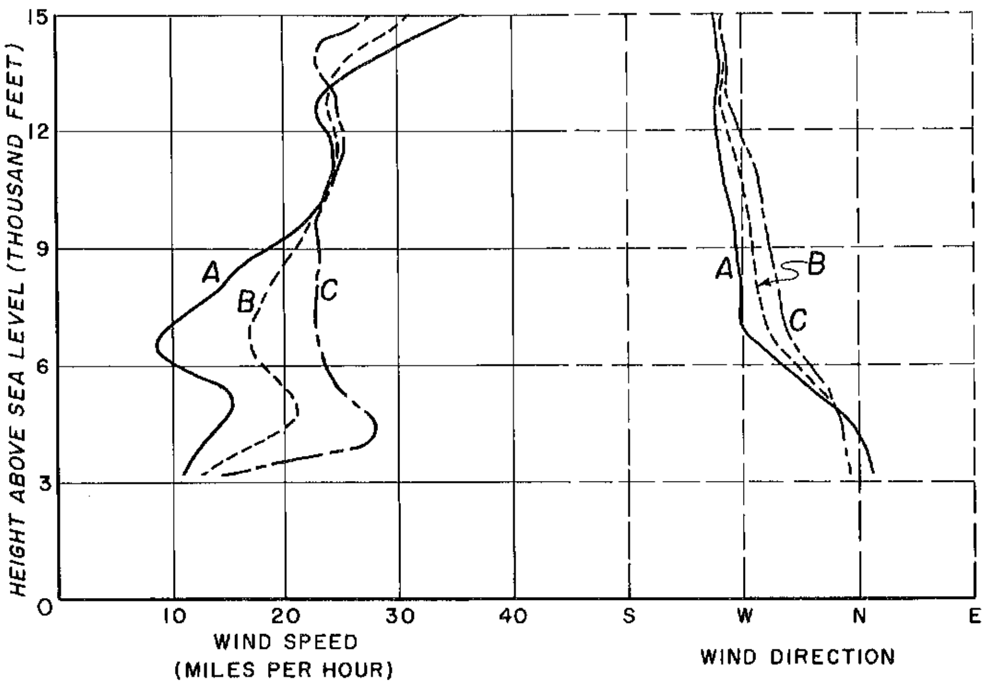

Figure 12.--Curves A, B, and C on the left represent the wind speed profiles at 1:00 p.m., 4:00 p.m., and 7:00 p.m. at Rapid City, S. D., on July 11, 1939. Curves A and C are actual pilot balloon soundings and B is an estimated intermediate curve. Curves A, B, and C on the right are the corresponding direction profiles.

APPENDIX

Wind Speed Profiles during the McVey fire

There are several small areas in the United States which, because of their number of fires, fuel and stand types, topographic features, or close proximity to stations where upper air data are taken, are especially well suited for the study of extreme fire behavior. One of these appears to be the Black Hills of South Dakota, at least from the standpoint of the last two requirements. This comparatively isolated group of mountains probably does not greatly affect the lines of flow in the upper air when wind moves over the region. Jet points probably keep a fairly constant level over the whole area. This may not always be true in the vicinity of more extensive mountain ranges, where general land level can change rather abruptly.

A very good account of the McVey Fire in the Black Hills National Forest in 1939 was written up by A. A. Brown (1). Although not written from a fire behavior standpoint, his account does give some fire behavior description. Thus it seems worth while to present the Rapid City wind speed and direction profiles for a 24-hour period during the McVey fire. These are shown in figures 10, 11, and 12. Actual pilot balloon soundings are given every 6 hours and are supplemented by estimated intermediate profiles.

The first indication of possible trouble in the Black Hills area showed up on the Rapid City 1:00 p.m. sounding on July 10. There was a thin type 2-a jet current (not shown) over the area with the jet point at 4000 feet. The wind speed of 18 miles per hour at the jet point dropped off so rapidly that it was only 9 miles per hour at 5000 feet. For this reason the most troublesome zone during early afternoon would have been a rather narrow strip between about 3800 and 4300 feet. Most of the direct effects of turbulence should have been present on this afternoon and the fire should have been difficult to fight. However, the jet current was hardly deep enough or strong enough to cause extreme fire behavior. There was nothing in the account to indicate unusual fire behavior during the afternoon or early evening of the 10th. By 7:00 p.m. the type 2-a jet current (curve A, fig. 10) was much deeper, and the velocity at the jet point had increased (this increase probably came in late afternoon). Elevations were not given in Brown's report, but the jet current at 7:00 p.m. should have caused considerable trouble in the neighborhood of 4500 feet, the height of the jet point. However, this did not occur, so it may be that the uncontrolled part of the fire was considerably higher than this. The jet point moved up rather rapidly on the night of July 10-11. At 1:00 a.m. July 11, it had moved up to 6000 feet and become somewhat stronger than at 7:00 p.m. (curve B, fig. 10). Curve C is the estimated profile at 11:00 p.m., the time which Brown gives for the first blowup. The estimated profile over Rapid City shows the jet point now at an elevation of 5500 feet. In figure 1 this was assumed to be the elevation of the blowup, but it could have been several hundred feet above or below this point. Some time between 1:00 a.m. and 7:12 a.m. July 11, the jet point moved above the highest peaks in the Black Hills. During this time the surface winds at elevations from 5000 to 6500 feet were decreasing, but what is more important, they were increasing with height. It is significant that Brown speaks of a lull in fire behavior between 2:00 a.m. and 7:00 a.m.

By 7:12 a.m. of the morning of July 11 the original jet current was still higher, with the jet point now at 8000 feet above sea level. However, a new strong jet current had formed near the surface with its jet point at 4000 feet. By 1:00 p.m. the jet point had moved up to about 5200 feet and was much weaker. There might have been a decrease in the intensity of the fire near midday, but this is not mentioned in the account.

Since Brown's paper gives just the fire behavior highlights, we can only speculate on some of the details. There were probably both whirlwinds and long-distance spotting on the night of July 10 and during the day of July 11. Some time during the afternoon of July 11 conditions became considerably worse when the wind speed increased at all elevations. The jet point started to drop, and by 7:00 p.m. it was at an elevation of about 4300 feet. The worst burning conditions were now between 4000 and 5000 feet, but were bad all the way up to the highest part of the Black Hills. If the uncontrolled part of the fire was burning at an elevation between 4000 and 5000 feet, there should have been considerable spotting on the left flank, especially during the early part of the afternoon run. During the night the wind died down at all elevations, and the fire was under control by the morning of the 12th.

Energy Conversion, Convection Column Structure, and Wind Speed Profile

It can be shown from a thermodynamic analysis that almost all the energy of a large fire comes from burning fuel; only a negligible part can come from an unstable atmosphere. It can be shown, too, that a part of the energy is converted into the kinetic energy of motion as the hot gases expand and cool in traveling upward. In this respect a large fire is analogous to a heat engine. An essential part of this fire heat engine is the convection column above the fire.

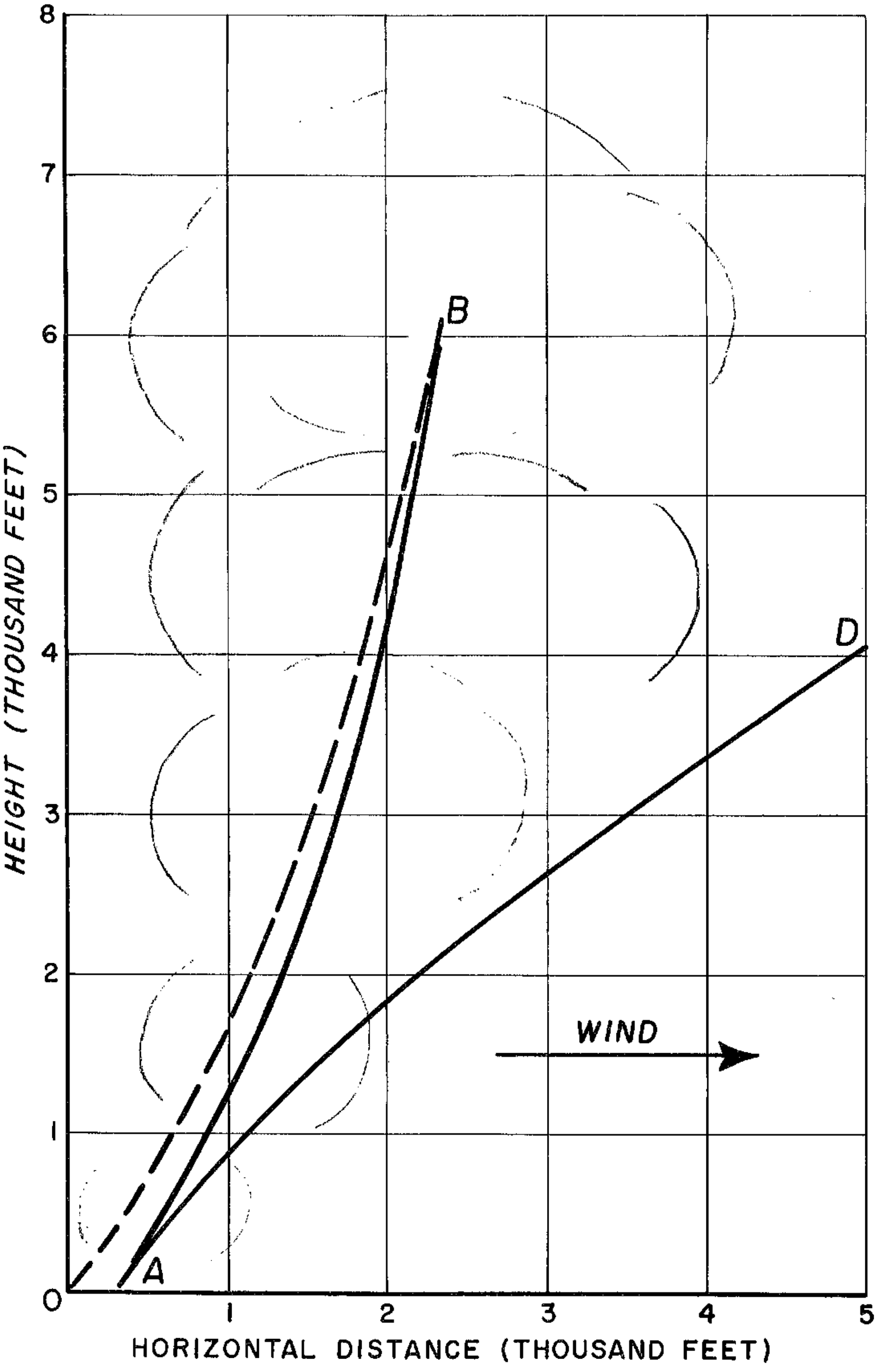

Figure 13.--Curve AB represents the center of a convection column for which the wind is decreasing with height. This curve was computed from wind-speed profile C in figure 1. The dotted curve represents convection column center for a stationary fire. Curve AD represents the center of a convection column which is increasing with height. This curve was computed from wind-speed profile type 4-a in figure 3.

For purposes of this study, a hypothetical model of a dynamic convection column was used. Its principal features are assumed to be as follows:

The convection column model has a hot core which extends well into its upper reaches. The temperature of the core decreases rapidly upwards. Parcels of hot gas do not travel directly up the core, but after traversing the core for a short distance they pass outward, downward, and into the core again. This process is repeated over and over. The convection column thus entrains and re-entrains its own gases. Meanwhile, they are being diluted continuously by mixing with the environmental air. The top of the convection column is a rounded and fairly continuous cap, which may be composed in part of condensed water vapor.

This type of a convection column might be called an active convection column in that it should produce a low pressure area over the fire. To maintain its dynamic properties, this model convection column should maintain a nearly vertical position. To do this and at the same time keep moving over a continuing supply of new fuel, the convection column requires that wind speed decrease with height.

It is possible to reconstruct the general form of a convection column center if the wind speed profile is known and the mean velocity of the updrafts at any height is known. The slope of a line passing up through the center of the convection column core is given by the equation

$$\frac{dy}{dx} = \frac{u}{v-w} \quad ,$$

where u is the average updraft velocity in the convection column at height y, v is the horizontal wind velocity at height y, and w is the rate of spread of the fire along the horizontal distance x.

The illustrative curve AB in figure 13 was constructed from the above equation by using a constant value of 3000 feet per minute for u, 150 feet per minute for w and by letting v at different heights y take on the values of curve C in figure 1. The dotted line represents the position the center of the convection column would have if the fire were stationary.

The illustrative curve AD was constructed in the same way as curve AB, but by letting v at different heights y take on the values of curve type 4-a in figure 3. The velocity u and the rate of spread w were the same for curve AD as for curve AB.

Curve AD, therefore, represents the convection column center when wind speed increases rather rapidly with height. This would probably be an unstable type, in which case the column could not be considered active except in its lower part; the upper parts of the column would contribute little to lowering the pressure over the fire.

Errata

Page 18, column three, first sentence, substitute 10:00 p.m. for 11:00 p.m.

Page 23, line 12, substitute Colorado Springs for Denver.

Page 30, fourth sentence, should read: Curve AD represents the center of a convection column for which the wind is increasing with height.

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Addenda - July 1954

Since the first printing of Station Paper No. 35 in April 1954, the Southeastern Station has received a considerable number of questions and helpful suggestions about the problems discussed in the paper. These comments have brought out points which are worthwhile summarizing to accompany this second printing.

Owing to the interest in convection columns, a few additional statements concerning them are in order. On blowup fires there are two rather distinctive types of convection columns, although there can be some gradation between the two types. Both are associated with a jet current or zone of decreasing winds for several thousand feet above the fire. If the high-level winds above this zone are low, the resulting convection column may be described as "towering." On the other hand, if the high-level winds are strong and increasing in speed, the resulting convection column may be described as "fractured." In the East and South the majority of the severe fires studied thus far appear to have had convection columns of the fractured type. Possibly the reverse is true in the West. Towering columns seem to be associated with wind speed profile types 1-a, 2-a, and possibly 2-b, each of which has a rather deep zone of decreasing wind speed. Fractured columns could also occur with these types when the high-level winds increase rapidly with height. However, they are more closely associated with wind profile types 1-b, 3-a, 3-b, and 3-c, which have shallower zones of decreasing winds but have stronger high-level winds than the preceding wind speed profile types. There may be some question as to whether convection columns can form in the extreme winds of wind profile type 3-c, but there is evidence that they can.

The towering type of convection column illustrated on page 30 curves upward throughout the zone of decreasing wind speed and has a characteristic dome-like cap or "mushroom." If water vapor starts to condense in the upper part of the column, the resulting release of heat may cause the cap to climb rapidly to 15,000 feet or more. On the most intense fires, the height of this moisture-laden cap may exceed 25,000 feet, which is comparable with the heights of the thunderstorm cumulus cloud.

An example of the fractured convection column is that which formed over the Brasstown fire described on page 15. Like the towering column it also curves upward throughout the zone of decreasing wind speed. However, above this zone the wind increases rapidly with height, which should cause the convection column to fracture and drop its load of embers. Possibly the active core of the convection column penetrates 2,000 feet or more into the zone of increasing wind before fracture occurs, but this has not yet been determined. The decreased velocity of the convection column updrafts above the fracture, as well as strong horizontal free air wind speeds, both combine to make a pronounced smoke drift at high levels. Thus, the upper part of the fractured column has a different appearance than that of the towering column. Spotting may be severe with either type of column, but more embers may be dropped with the fractured type.

When there is fire over a large area, extraneous smoke from many smoldering places makes it rather difficult to recognize the form of the convection column, especially at close range. Fires which have reached a size of many thousand acres may have two or more convection columns simultaneously.

To some readers the broken line attached to the lower part of wind profile type 4-c on page 11 has been confusing, because it was not explained until page 16. This broken line does not represent a real wind but rather a virtual or apparent wind to which the slope is equivalent. It merely illustrates one way in which topography can alter the effect of a free wind profile on fire behavior. It should not be confused with the modifying effects of topography (as well as surface temperature) on the actual wind speed itself, such as upslope winds during sunny days and downslope winds on cloudless nights.

The last sentence in the next to the last paragraph on page 16 might possibly be confusing. In effect, this sentence states that if the jet point for wind profile types 2-a and 2-b rises to a height of 2,000 or 3,000 feet above the elevation where a fire might occur, then they are equivalent to the "safe" type 4-a. Therefore, a casual inspection of wind profile types 2-a and 2-b on page 10 might lead to a wrong conclusion as to these types because their jet points are shown at a height of about 2,000 feet. However, this is the height above the pilot balloon station but not above the fire. To develop and maintain extreme behavior, fires would have to be much closer to the level of the jet point (see the third paragraph from the bottom of page 13).

There have been some questions about the relation of the wind profile to the temperature profile of the atmosphere on days when blowup fires occur. Possibly the best way to illustrate this relation (insofar as it is now understood) is from actual examples. Of more than a thousand soundings examined at the National Weather Records Center, those representing the conditions which existed over Great Falls, Montana, on August 5, 1949, are the most striking. The temperature profile (not shown) from the 8:00 p.m. radiosonde flight indicated that during the afternoon the atmosphere had been unstable and turbulent to approximately 16,000 feet above sea level. The temperature would have decreased up to this level at the rate of very nearly 5.3° Fahrenheit per 1,000 feet except for the first few hundred feet where the rate of decrease should have been slightly greater. Figure 1 shows that the wind speed at 8:00 p.m. decreased at a fairly uniform rate throughout a vertical distance of 10,000 feet or up to about 16,000 feet above sea level. Hence, in this instance, the jet current had become established to the top of the exceptionally deep turbulent layer. Flying conditions should have been unusually bumpy for clear air on this day.

More often the zone of decreasing wind speed extends only part way through the turbulent layer. Figure 8 shows that the decrease of wind speed at 4:00 p.m., May 2, 1951, over Hartford, Connecticut, extended to a height of nearly 3,000 feet, or about one-third of the depth of the turbulent layer as indicated by temperature profiles. As another example, figure 9 shows that the top of the zone of decreasing wind speed at 3:53 p.m., March 30, 1953, reached a height of about 3,000 feet above Spartanburg, South Carolina. This was less than one-half the depth of the turbulent layer which the temperature profiles from the nearest radiosonde stations indicated was between 6,000 and 7,000 feet deep over the Piedmont Area.

The wind profile, the temperature profile, and the variations in the pressure field aloft appear to be inter-related in a complex way. Overlooked when Station Paper No. 35 was prepared is a paper entitled "Note on Observed Vertical Wind Shear at Low Levels Over the Ocean" by Donald R. Jones, which appeared in the November 1953 issue of the Bulletin of the American Meteorological Society. This is a timely and significant paper from the standpoint of the relation between wind profiles and temperature profiles. It discusses the decrease of wind speed with height, or "anomalous wind shear" which occurs during conditions of strong turbulence over the sea.

Although it should be emphasized that most of the effects of the temperature profile on extreme fire behavior are reflected (and to a considerable extent integrated) in the simpler wind profile, nevertheless the temperature profile is still an important part of the extreme fire behavior picture. This may be especially true from the forecaster's standpoint. The temperature profile may have even greater significance in forecasting work when more is known about the possible delayed effects of an unstable atmosphere on the wind profile.