Three Types of Horizontal Vortices Observed in Wildland Mass and Crown Fires

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ABSTRACT

Observation shows that three types of horizontal vortices may form during intense wildland fires. Two of these vortices are longitudinal relative to the ambient wind and the third is transverse. One of the longitudinal types, a vortex pair, occurs with extreme heat and low to moderate wind speeds. It may be a somewhat common structure on the flanks of intense crown fires when burning is concentrated along the fire's perimeter. The second longitudinal type, a single vortex, occurs with high winds and can dominate the entire fire. The third type, the transverse vortex, occurs on the upstream side of the convection column during intense burning and relatively low winds. These vortices are important because they contribute to fire spread and are a threat to fire fighter safety.

This paper documents field observations of the vortices and supplies supportive meteorological and fuel data. The discussion includes applicable laboratory and conceptual studies in fluid flow and heat transfer that may apply to vortex formation.

1. Introduction

The occurrence of vertical vortices in wildland fires has been well documented as well as mathematically modeled and duplicated in laboratory experiments (e.g., Byram and Martin, 1970; Church et al., 1980; Emori and Saito, 1982). Conversely, the subject of horizontal vortices in wildland fires is relatively unexplored, even though the occurrence of bent over smoke plumes splitting sideways into two counterrotational regions was described and modeled relatively early, by Turner (1960) and Scorer (1968). Applications of these findings were mostly confined to the field of air pollution, especially smokestack emissions. Initial results from the investigation of horizontal vortices in mass and crown fires[1] were restricted to a few papers concentrating on observation (i.e., Schaefer, 1957; Church et al., 1980), and a two-part paper presenting computer simulations by Luti (1980, 1981).

More recently, Haines and Smith (1983) and Smith et al. (1986) conducted wind tunnel simulations of horizontal vortices applicable to wildland fires. These experiments showed that when air flowed parallel to a heated metal ribbon that simulated the flank of a crown fire, a thin, buoyant plume capped with a vortex pair developed above the ribbon along its length. Nonuniform heating and a subsequent temperature gradient, transverse to the mainstream flow, produced the vortex pair, perhaps through interaction with the boundary layer.

These results suggested that longitudinal vortex pairs may be a somewhat common structure on the flanks of intense crown fires when burning is concentrated along the fire's perimeter. Because these vortices can generate large-scale secondary flows capable of transporting firebrands, they are an important consideration in fire fighter safety. The safety factor is of concern because suppression forces find it difficult, if not impossible, to attack the head of a major crown fire. Consequently, suppression forces tend to concentrate their efforts on the fire's flanks, controlling lateral spread.

In addition to the longitudinal vortex pair, two other distinct types of horizontal vortices have been observed in crown and mass fires, one longitudinal, the other transverse. The longitudinal vortex has been reported only once in the literature (Schaefer, 1957), occurring with intense burning and high winds.

The transverse horizontal vortex consists of a series of rapidly moving vortices that give the appearance of "climbing" the upstream side of the convection column. As with the vortex pair, the transverse type seems to occur during low ambient wind speeds and intense

[1] Crown fires advance from top to top of trees or shrubs. Although they may appear independent of surface fires, they are usually linked with them. Crown fires are most often a phenomenon of conifer forests but also occur in other cover types, principally chaparral and eucalyptus forests. The term *mass fire* characterizes those fires displaying extreme behavior when large amounts of fuels burn simultaneously over a wide area.

burning. Apparently this vortex has not been discussed in the literature, although Luti's (1980, 1981) computer simulations may describe a two-dimensional variation.

The objectives of this paper are threefold. First, we document field observations of the three types of horizontal vortices and supply available (sometimes meager) meteorological and fuel data. Next, we examine selective conceptual and laboratory applications. Finally, we discuss the importance of these observations and list some unsolved problems and unanswered questions.

2. Field observations

Most personnel at the scene of large wildfires, especially mass and crown fires, are totally occupied with suppression; consequently, reliable and extensive documentation of a fire's behavior is somewhat rare. However, without adequate field documentation it is difficult to verify empirically physical theories of extreme fire behavior. The following report outlines three observations of wildland fires displaying smoke column bifurcation and accompanying longitudinal vortex pairs. It also describes three cases where horizontal vortices displayed other types of behavior not associated with bifurcation.

a. Horizontal vortices occurring with smoke column bifurcation

1) A MINNESOTA EXPERIMENTAL BURN

A convective column bifurcation and resultant vortex pair occurred on 1 July 1970 during one of a series of experimental burns conducted by the USDA Forest Service at the Superior National Forest (Haines and Updike, 1971). A prescribed fire was set in 12 ha of heavy slash using simultaneous ignition throughout the fuels. At the time of ignition, skies were mostly clear with a temperature of 30°C, a relative humidity of 22%, and an average windspeed of 3 m s^{-1} with occasional gusts to 5.5 m s^{-1}. About 15 min after ignition, peak ambient gustiness increased to 9 m s^{-1} and continued near that level throughout the burn. The smoke column bifurcated shortly after development, with the counterrotating limbs (each about 30 m in diameter at 75 m above the surface) separated at a 90° angle (Fig. 1). Bifurcation and vortex activity became distorted and ceased with the increase in gustiness. The fire was characterized by unusually high energy release; almost all fuels as much as 9 cm in diameter were completely burned.

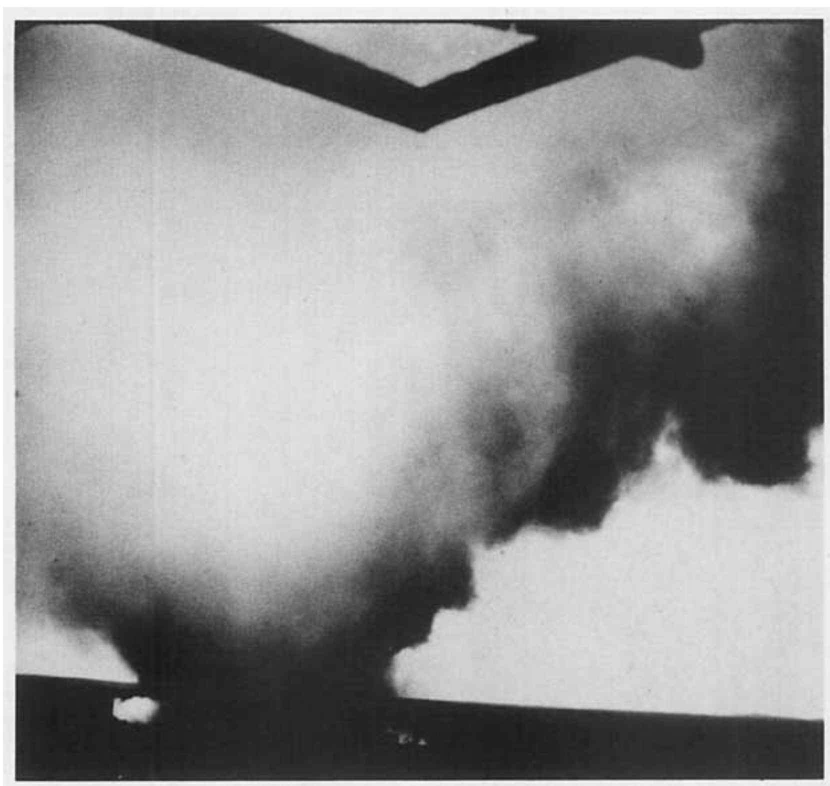

FIG. 1. A Minnesota experimental burn with convection column bifurcation and a vortex pair separated at an angle of 90°. The ambient wind is blowing from the burn toward the observer.

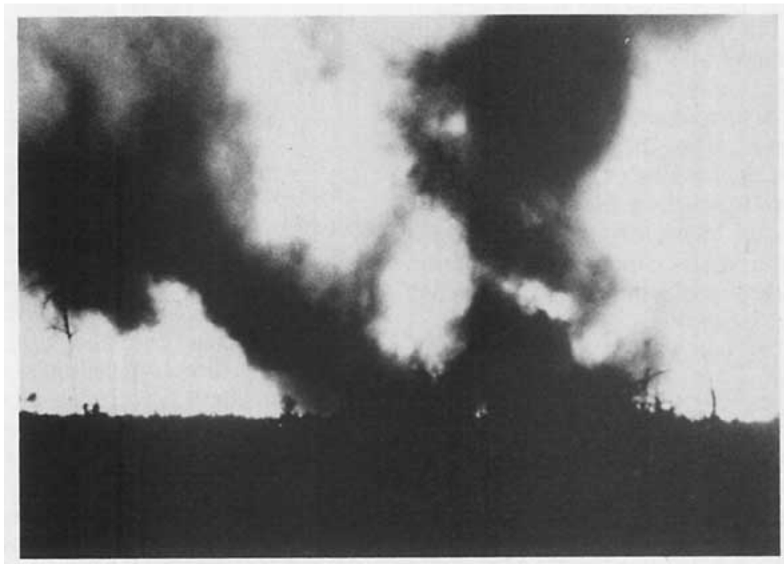

FIG. 2. A bifurcated smoke column and resultant vortex pair during the New Miner Fire in Wisconsin. The ambient wind is blowing from the fire toward a point slightly to the left of the observer. (Photograph courtesy of William Peterson, Wisconsin Department of Natural Resources.)

2) A WISCONSIN CROWN FIRE (THE NEW MINER FIRE)

The New Miner Fire occurred in central Wisconsin on 9–10 May 1976. Primarily a crown fire, it burned 1300 ha of conifer forests with flames as high as 90 m and firebrands spotting 4 km ahead of the main body of fire. Afternoon skies were mostly clear with a maximum temperature of 26°C and a minimum relative humidity of 23%. Winds were low, averaging 2 m s^{-1}. The fire continued into the night with overnight temperatures near 18°C and relative humidities in the middle to upper 20s. This is extreme fire weather for that region of the country.

The smoke column alternately bifurcated (Fig. 2), spilled over the flanks and dropped to the ground (Fig. 3), then reformed. The vortices in Figs. 2 and 3 have initial diameters of about 35 and 25 m, respectively.

FIG. 3. A bifurcated smoke column in the New Miner Fire with the counterrotating vortex on the left side of the picture "collapsing and spilling" over the flank of the fire. The ambient wind is blowing from the fire toward a point slightly to the left of the observer. (Photograph courtesy of William Peterson, Wisconsin Department of Natural Resources.)

FIG. 4. A vortex with a diameter of about 5 m on the flank of the New Miner Fire. Implied airflow is outlined by the curving arrows. Flames are moving out of the main body of fire at 30° to 50° angles and making "rolls" back into the fire. The ambient wind is blowing from the right toward the left in the photograph. (Photograph courtesy of Donald Krohn, Nekoosa Paper Inc., Port Edwards, Wisconsin.)

Vortex activity along the flanks (Fig. 4) threw so many firebrands into unburned fuels (Fig. 5) that, in some sectors, lines were plowed parallel to and 60 m out from the (initial) main body of fire before suppression forces could contain the lateral spread. At one point, a tractor operator plowing along the flanks about 6 m from the main body of fire was trapped as flames from a horizontal vortex came over the top of his unit. His planned escape route was normal to the flank of the main body of the fire, but this would have taken him into a region of intense fire activity. His tractor unit was destroyed, but he escaped by running into a previously burned area of the main fire.

3) A FRENCH EXPERIMENTAL FIRE WITH AN ARRAY OF OIL BURNERS

Church et al. (1980) photographed and reported a bifurcated smoke column and a horizontal vortex pair occurring after ignition of an array of 105 fuel oil burners with a total heat output of approximately 1000 MW. The experimental fire was conducted near the central Pyrenees on 21 October 1978 when the surface winds were 3 to 5 m s^{-1}. The vortices had initial diameters of 30 to 60 m.

b. A single large vortex (the Dudley Lake Fire)

In documenting a 14 June 1956 Arizona fire—the Dudley Lake Fire—Schaefer (1957) described a large horizontal vortex that dominated and acted as a lateral spread mechanism (Fig. 6). Time-lapse movies show the vortex (with a diameter of about 1800 m) rotating counterclockwise (looking downstream) and making a complete rotation in a downstream distance of 1600 m. Maximum height of the smoke structure was 2130 m above the surface. Observers stated that this smoke-outlined cell remained a coherent mass, traveling about 500 km with the prevailing wind. With an afternoon relative humidity of 4% and wind speeds of 16 to 22 m s^{-1}, fire weather conditions were extreme. An average of 34 metric tons of fuels per hectare burned in the 8660 ha burn area during the 48 h of major fire activity (Barrows, 1961).

A photograph, taken from a lookout tower 23 km west of the fire (Schaefer, 1957, with a map of the area), shows clearly delineated banding, indicating both rotation and translation (Fig. 7). On either side of the bands, buoyant smoke plumes partially obscure the activity. This did not appear to be a variation of the vortex pair but rather a single, dominating horizontal vortex. Suppression forces did not observe a counter-rotating vortex in the eastern sector, nor did time-lapse photography, taken at ground level near the western sector, show another vortex. The air photo (Fig. 6) seems to show a single vortex throughout the fire's length, with one possible exception. At the head of the fire (Fig. 6, lower left) there may be an opening along

FIG. 5. A bifurcated flaming front (with counterrotating vortices) on the New Miner Fire in the process of reforming after the right column had collapsed and spilled over the flank leaving a strip of unburned foliage between the extreme right and the main body of fire. The arrows show the presumed action of the approximately 70-m-diameter right vortex during collapse; O marks a 15-m-wide open area between the vortex pair; S marks the 45-m-wide strip of unburned foliage. The ambient wind is blowing from the fire toward a point slightly to the left of the observer. (Photograph courtesy of William Peterson, Wisconsin Department of Natural Resources.)

the centerline with separate smoke columns on either side, but there is no way to confirm or refute that possibility now.

c. The transverse vortex

1) BALD HILL FIRE, MICHIGAN

The Bald Hill Fire occurred on 10 May 1975 in Crawford County, Michigan. Donald Grant, Michigan Department of Natural Resources, in charge of the suppression forces, characterized the head of this 5-km wide crown fire "as a boiling caldron"; often there were no individual sheets of flame, just a buoyant mass of burned and unburned gases. With clear skies, an air temperature of 22°C, relative humidity of 19%, and windspeeds below 3.5 m s^{-1}, surface weather was much the same as during the New Miner Fire, but instead of

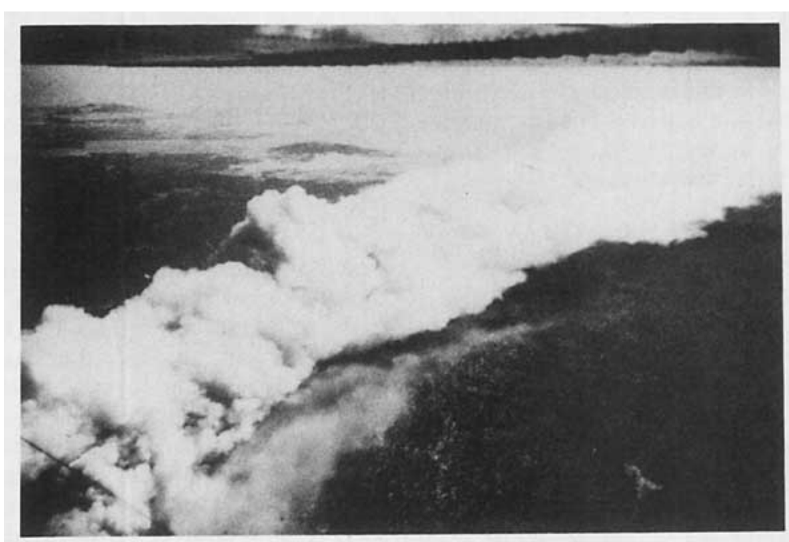

FIG. 6. An air view of the Dudley Lake Fire. A single horizontal vortex dominated the entire fire, moving from the upper right toward the lower left in the photograph. (Photograph courtesy of J. H. Dietrich, USDA Forest Service, ret.)

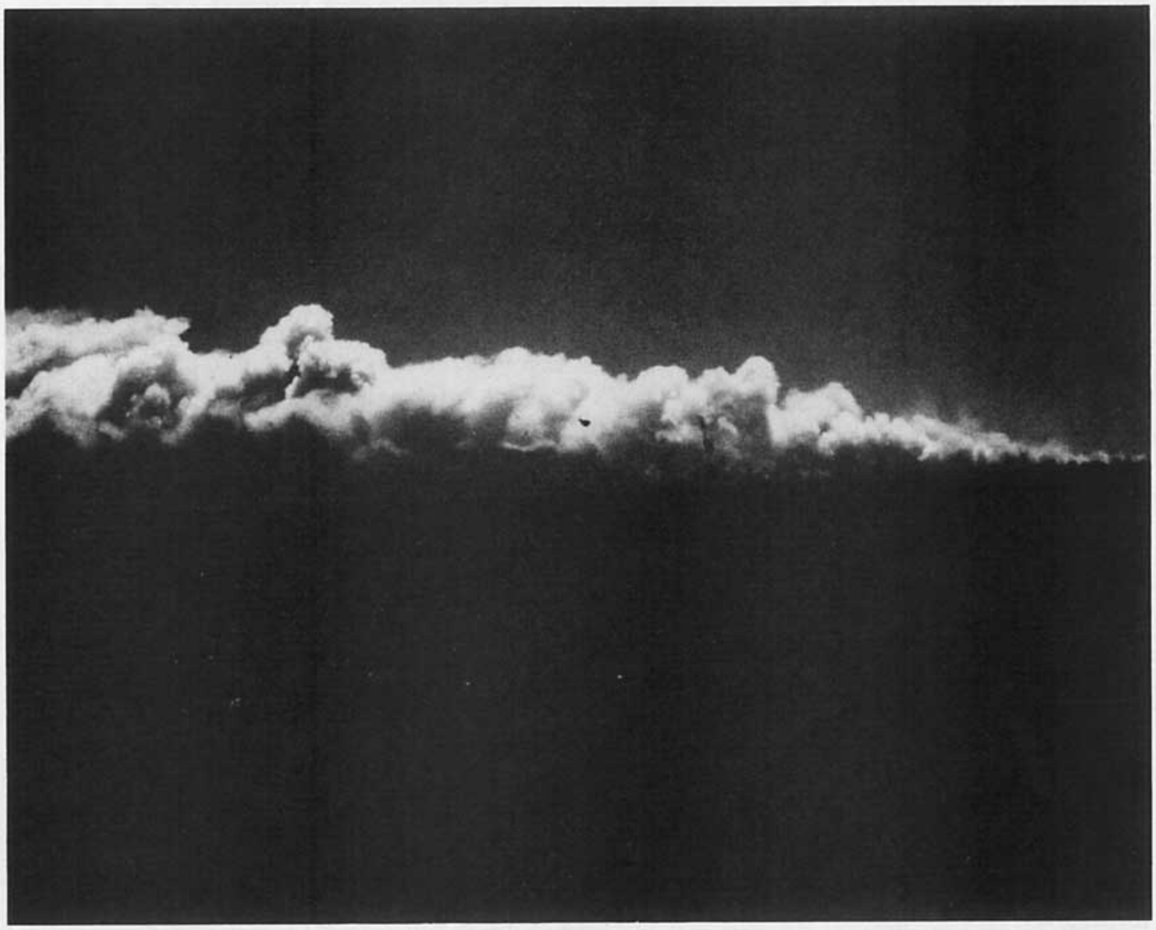

FIG. 7. A side view of the horizontal vortex on the Dudley Lake Fire with banding indicating both rotation and translation. Forest fire spread was from right to left. The top of the vortex was rotating toward the observer. (Photograph courtesy of J. H. Dietrich, USDA Forest Service, ret.)

column bifurcation, transverse vortices, with about 15-m diameters, at times dominated the upstream side of the smoke column (Fig. 8).

Two light-aircraft pilots from the Michigan Department of Natural Resources (Gerald Johnson, personal communication) stated that they flew through the length of a transverse vortex similar to those on the Bald Hill Fire during two other fires. One pilot reported an angular velocity high enough to turn his plane through a 180° roll; the second plane was turned through a full 360° roll.

2) A CALIFORNIA PRESCRIBED FIRE (FLAMBEAU)

On 29 September 1967, the USDA Forest Service conducted this experimental fire (760-12) near the California–Nevada border, one of a series of Project Flambeau fires funded by the Office of Civil Defense (Countryman, 1969). These were well-instrumented fires that included fuel-weighing platforms and three-component airflow towers. Pinyon pine fuels were placed in an 18 × 19 pile array in a 16 ha square of about 400 m on a side. The fuel complex also included four platforms stacked with milled lumber. Simultaneous ignition with moderate ambient wind insured rapid burning and high energy release. Peak fuel mass loss rates approached 10 kg m^{-2} per min, occurring shortly after ignition.

Transverse rolls with radii of up to 45 m formed on the upstream side of the smoke column (Fig. 9). Measurements taken from a film of the fire show that during the most intense period of burning, the buoyant lower portion of the convection column rose at about 18 m s^{-1}. The instantaneous linear speed at the edge of the circular smoke-outlined transverse vortices was about 25 m s^{-1}.

3. Summary of observations

Field evidence indicates that three distinct types of horizontal vortices can occur in mass and crown fires. The first type, the vortex pair, has been observed and photographed often enough so that its existence is no longer in doubt. The second type, the single vortex,

(a)

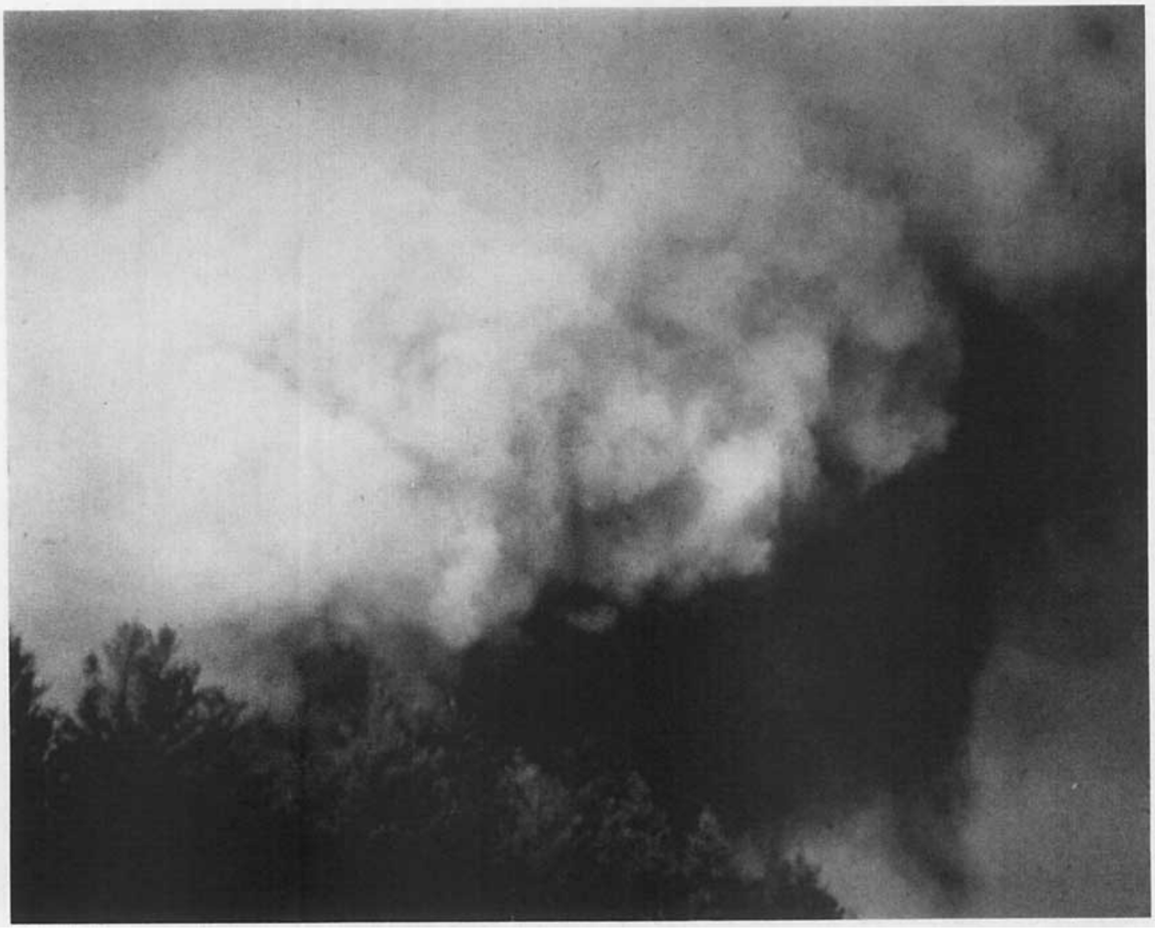

FIG. 8. (a) A photograph of transverse vortices in the smoke column occurring during the Bald Hill Fire in Michigan. (b) A diagram of the vortices seen in the photograph of the Bald Hill Fire. The ambient wind is blowing roughly from the left to the right in the photograph. (Photograph courtesy of Ray Perez, Michigan Department of Natural Resources.)

has been reported only once in the literature. This vortex occurred when strong winds were coupled with exceptionally low relative humidity (and resultant extreme burning); not many fires are observed with this combination of meteorological conditions. The third type, the transverse vortex, is also well documented. Even though we have only four confirmed cases on file, Australian wildfire specialists also have reported its occurrence. Possibly the three types of horizontal vortices occur often, but intermittently, on intense fires but draw attention only when they are dominant. In terms of being noticed by those on the scene, intermittent occurrence of specific behavior tends to "blend in" with a variety of extreme fire behavior.

Extreme burning conditions are a common denominator in the formation of the horizontal vortices documented to date. In interviews with suppression crews, many fire fighters remarked that the fires with horizontal vortices were among the most intense ever encountered. The formation of vortices in a fire is a mechanism for rapidly dispersing large quantities of energy; consequently, it is not surprising to find that vortices are associated with extreme burning situations. Conversely, given the turbulence usually associated with surface airflow, substantial energy might be required to modify the flow field and allow vortex formation.

Ambient wind speed appears to be a second important factor in horizontal vortex formation. The vortex pairs and transverse vortices generally occurred with low to moderate wind speeds, under 6 m s^{-1}. The single large vortex occurred with strong winds, 16 to 22 m s^{-1}.

Topography may be a third factor. The vortex pairs and transverse vortices occurred over flat or very gently rolling terrain. Turbulence associated with rough topography may be sufficient to prevent horizontal vortex formation in those cases.

4. Discussion

A number of laboratory and theoretical studies may apply to an understanding of how the three horizontal vortex types develop. This section discusses those studies and applications.

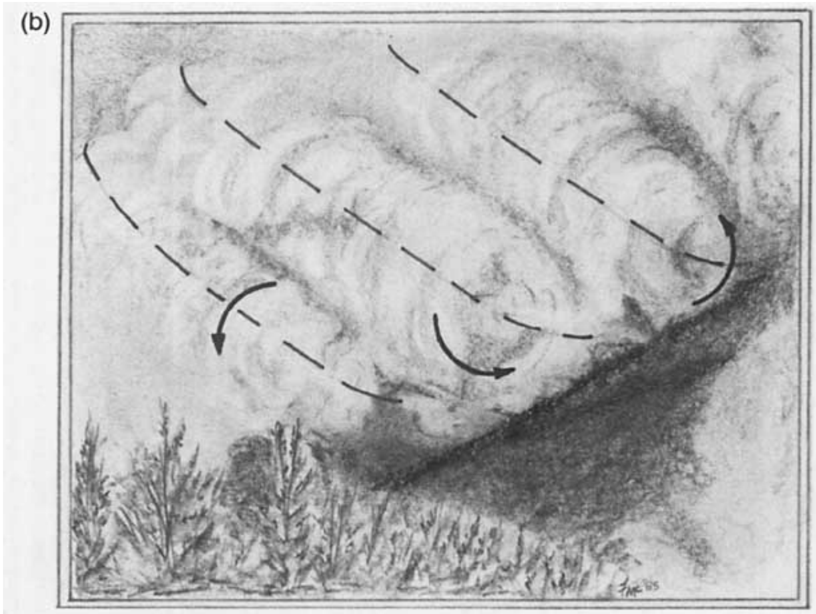

FIG. 8. (*Continued*)

a. The horizontal vortex pair

Longitudinal vortices, sometimes referred to as Bénard cells, have been noted as natural phenomena (e.g., Kuettner 1959, 1971), and as laboratory phenomena by many observers (e.g., Gilpin et al., 1978). In a common situation, the longitudinal vortices form with relatively uniform heating from below and are produced by buoyant forces interacting with a main stream flow. These flows have attracted widespread attention and have been discussed extensively in the literature. The longitudinal vortices described here appear to arise from differential heating in the presence of a boundary layer, and seem significantly different from

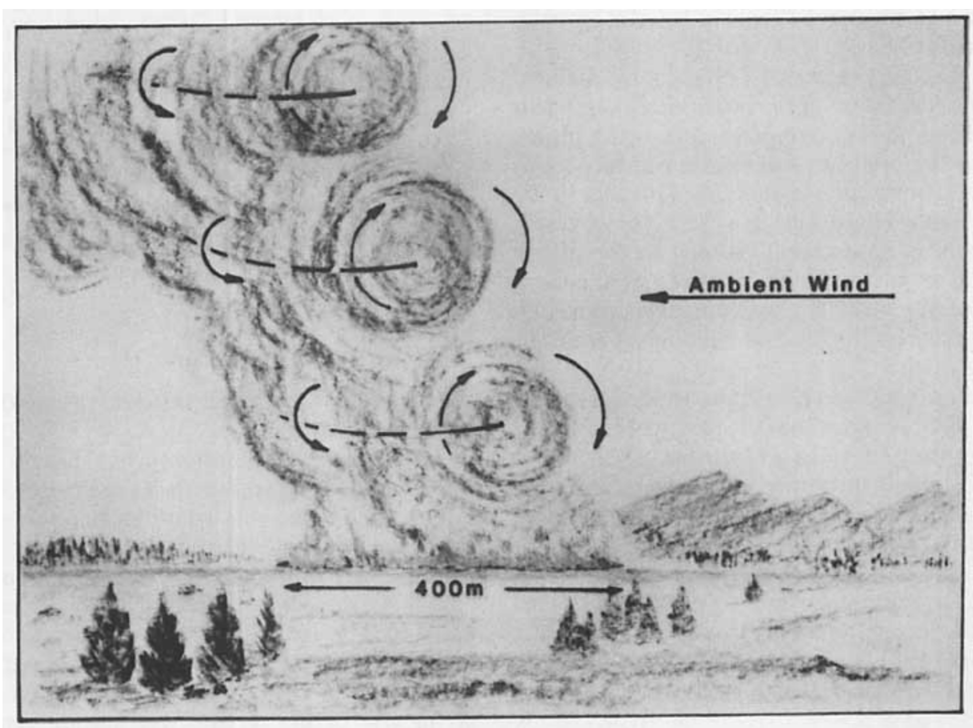

FIG. 9. A diagram of transverse vortices filmed during one of the Project Flambeau fires in California.

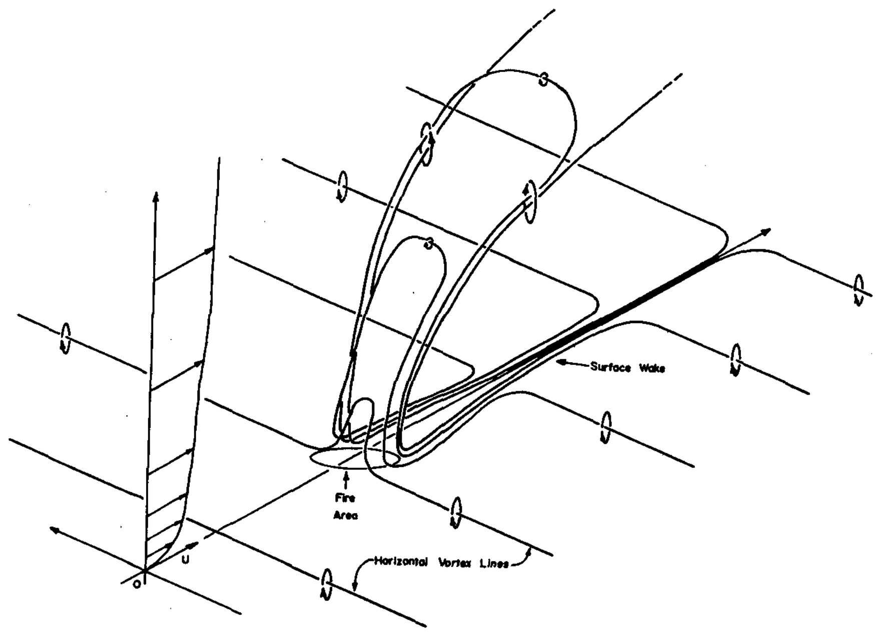

FIG. 10. A diagram illustrating the rising plume acting to produce loops in the horizontal vortex lines present in the environmental wind field. This effect results in a clustering of vortex lines with a strong component parallel to the plume axis along each downwind flank and also a surface wake extending downstream from the plume. Along each flank, mutual interaction twists the vortex lines into an intertwining that is characteristic of a vortex core. (Diagram reprinted from Church et al., 1980.)

those associated with uniform heating from below. In particular, studies of uniform heating are not likely to uncover local and transient effects of interest in wildland fire control.

Church et al. (1980) suggested a physical mechanism involved in the formation of the horizontal vortex pair (Fig. 10). In brief, they concluded that a rising plume of air over the fire area can sometimes produce loops in the otherwise horizontal vortex tubes present in the ambient wind field. This results in a clustering of vortex lines with a strong component parallel to the plume axis along each downwind flank. These along-the-flank components of the vorticity cause the layers to roll up so that the plume bifurcates and becomes a counter-rotating vortex pair.

On the other hand, results from experiments by Tsang (1970, 1971) suggest that the rollup of boundary layer vorticity may be only a contributing factor to vortices associated with plume bifurcation, although his work did not include possible boundary layer effects. Buoyant plumes in a cross flow may spontaneously develop into double vortex flow without boundary layer influence. The argument for this development of vorticity lies in the density gradients, as seen in the vector equation for the time rate of change of fluid vorticity (ω) in a parcel moving with flow ($\mathbf{v}$), expressed by Scorer (1978) as

$$\frac{D\omega}{Dt} = -\omega\, \mathrm{div}\mathbf{v} + (\omega \cdot \mathbf{grad})\mathbf{v} + \mathbf{R} \times (\mathbf{g} - \mathbf{f}) + \nu\nabla^2\omega. \quad (1)$$

In this equation, the left-hand side denotes the change of vorticity with time (t) of a fluid element. The first two terms on the right represent the evolution of vorticity already present due to gradients in the velocity vector, i.e., those in the boundary layer and those resulting from buoyant forces. The last term is decay due to viscosity, while the third term represents vorticity generation due to buoyancy, depending on gravity ($\mathbf{g}$) and fluid acceleration ($\mathbf{f}$) where

$$\mathbf{f} = D\mathbf{v}/Dt. \quad (2)$$

Note that

$$\mathbf{R} = \mathbf{grad}\rho/\rho \quad (3)$$

(where ρ is density) and is unequal to zero due to buoyancy caused by heating.

Wind tunnel experiments by Haines and Smith (1983) tended to support the suggestions of Church et al. (1980) that the roll up of boundary layer vorticity can be an important factor in some plume bifurcation. Haines and Smith (1983) simulated one flank of a crown fire through the use of a heated metal ribbon embedded lengthwise in the tunnel floor. Buoyant forces created an upflow as air streamed above and parallel to the heated ribbon. A vortex pair developed at the top of the plume over a wide range of wind

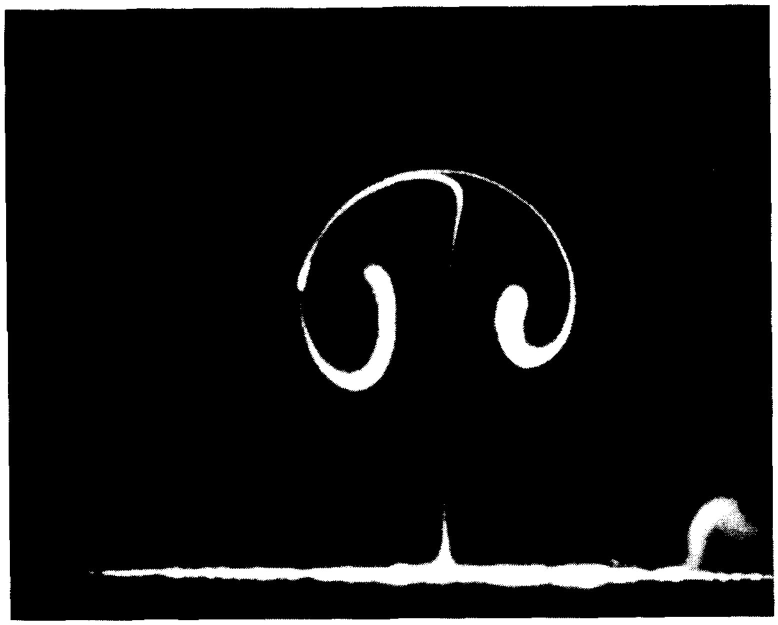

FIG. 11. Laser visualization of a thin cross section of a fully developed vortex pair generated in a wind tunnel over a heated, longitudinally embedded nichrome wire. The photograph was taken with the camera positioned downstream at the tunnel exit directly on the axis of the flow.

speeds and ribbon temperatures (Fig. 11). The experiments supported an hypothesis that an underlying cause for the vortex pair is the reorientation of boundary layer vorticity from a transverse axis to a longitudinal axis.

In comparing these wind tunnel observations to field observations, we note an important point: a pertinent boundary layer length may not necessarily be defined in terms of the total atmospheric boundary layer thickness, but rather as a thickness appropriate to local conditions. For example, the stagnation "line" on the front face of a smokestack will produce a localized boundary layer flow over and around the stack. Stretching and twisting of the vorticity of this flow as it encounters the stack plume should enhance the vorticity already created by buoyancy.

In a wind tunnel, vortex pair development takes place over many boundary layer thicknesses, perhaps 10 to 50 thicknesses. Subsequently, all dimensions of the vortex pair grow with downstream distance. The ratios of dimensions, such as pair height to width, do not remain constant with downstream distance; thus, direct comparisons with field observations are difficult. Characteristics for both laminar and turbulent (grid simulated) flows have been measured by the authors but have not yet been evaluated. However, given the visual similarities between the vortices produced during wind tunnel experiments (Fig. 11) and those observed during crown fires (Fig. 2), Smith et al. (1986) concluded that their laboratory simulations approached conditions in nature. Experimental results have not, as yet, established the importance of such factors as the boundary-layer velocity profile, heat transfer rates, or the transverse temperature gradient.

Haines (1982) formulated a number of hypotheses involving possible behavior of horizontal vortices in crown fires. Fire behavior observed in the cases reported here supports his hypothesis that horizontal vortices form along the flanks of crown fires and, at times, are a major factor in lateral spread. However, these case studies do not support one suggested possibility, that the downward component of air generated by a single vortex may be a primary mechanism involved in "saving" long strips of unburned conifer tree crowns observed after major crown fires. Figure 5 (at "S") shows the formation of a strip of unburned foliage through the action of a horizontal vortex. The vortex carried firebrands laterally over the subsequently unburned strip and started fires beyond it, in the extreme right portion of the area in the photograph. Although horizontal vortex action appears to have saved this strip of tree crowns, the mechanism involved was different from that suggested by Haines (1982).

Preliminary laboratory work shows that two separate pairs of horizontal vortices in close proximity will generate a strong component of downward airflow in the region between the inner vortices (Fig. 12). The two interior bright areas in the photograph are the inner vortices of each pair. Close proximity caused distortion of the adjacent inner vortices within each vortex pair

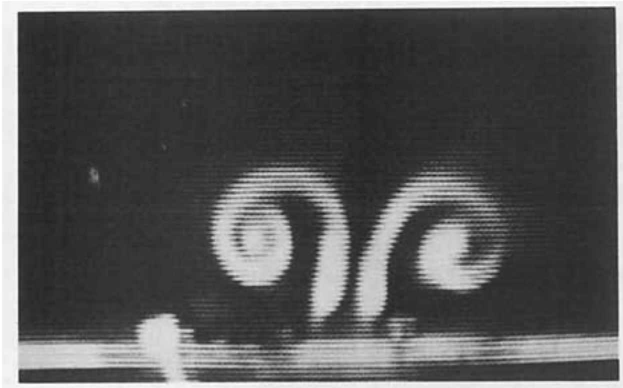

FIG. 12. A wind tunnel cross-sectional photograph of two pairs of horizontal vortices that formed over two longitudinally embedded nichrome wires. The photograph was taken with the camera positioned downstream at the tunnel exit at about a 10° angle off the axis of the flow.

and resultant extremely short radii of curvature. This implies high angular velocities at this juncture relative to the angular velocities occurring within the outer vortex in each pair. The particulars of the flow have not been examined beyond documenting the visual evidence.

Such evidence leads us to postulate a three-stage process in the development of unburned tree crown strips. First, firebrands deposited beyond the flanks of the fire start secondary fires (Fig. 5). Second, the new fires generate another vortex pair which, in conjunction with the previous pair, generates a downward and outward flow of air between the two areas of fire. Third, as the fires back toward each other, there is airflow toward the central plume in the base of each vortex pair and downflow in the unburned area (as opposed to increased upflow when two fires meet under more typical conditions).

Steven Chandler* (personal communication) stated that while between two lines of wildland fire during a 1979 prescribed burn in New Hampshire, he encountered the following situation: As burning increased in both lines of fire, he observed a sudden downward rush of air. Tops of jack pine trees broke off in downflow of about 13 m s^{-1}.

b. The single horizontal vortex

Investigation of the physical mechanism responsible for the single horizontal vortex that dominated the Dudley Lake Fire suggests a number of causal possibilities. One possibility involves a vertical smoke-column vortex that was reoriented because of the unusually strong ambient wind field. Core and entire-column vortices are not the norm in wildland fires, but they do occur. One incongruity at Dudley Lake was the strong winds; most intense core vortices have been observed with calm or low winds. Also there was no apparent source for a sustained, strong, one-direction-only, smoke-column vortex.

A second possibility would depend on ambient wind direction shear, but normally the wind turns to the right in the Northern Hemisphere, tending to produce clockwise rotation. This vortex displayed counterclockwise rotation. Also, during high winds a directional change is usually slight and could not explain such tightly wound spiral flow. Another mechanistic possibility involves the Coriolis acceleration due to vertical motion. However, computation of the factors involved ruled this out as a viable option.

The best causal possibility involves the generation of a horizontal vortex in turbulent shear layers (Lugt, 1983, Chap. 6). Here, a turbulent boundary layer separates from some obstacle in the upstream topography, rolls up, and detaches as a free vortex (Pullin and Perry, 1980). For high Reynolds numbers, the model of a discontinuity line is valid for both laminar and turbulent flows, although the turbulent vortex behaves differently in the core and adjacent annular region with the different flows. The roll up of the discontinuity line at Dudley Lake could have resulted initially from topographical features with the vortex subsequently enhanced and delineated by the fire. Irregularities along the rim of the Mogollon Plateau, about 30 km upstream of the fire, may have been the source since the rise of the rim is comparable to the observed vortex diameter. The fire moved downslope through much of its burning period with unusual steadiness of the wind direction making inducement by fixed topographic features appear plausible. Schaefer (1957) noted spectacular wave clouds over the San Francisco Peaks to the northwest during the fire. This may mean that the vortex was confined to a stable capped boundary layer that was well mixed and nearly neutral due to the high wind speeds.

Figure 13 shows the fluid dynamics configuration that could produce the banding appearance seen at Dudley Lake (Fig. 7). The general flow structure in the figure should be valid for an initiating condition of obstacles in the upstream topography.

c. The transverse vortex

Buoyant, heated air can generate vortex rings; these are often seen with such phenomena as intense explosions and shell bursts. These ring vortices usually decelerate quickly due to friction and entrainment of the surrounding air. A careful examination of 16 mm film, represented by Fig. 9, did not disclose evidence of a complete horizontal vortex ring encircling the smoke column. The downstream unsteady eddies and turbulence could have broken up this portion of a vortex ring (Fig. 9).

* USDA Forest Service.

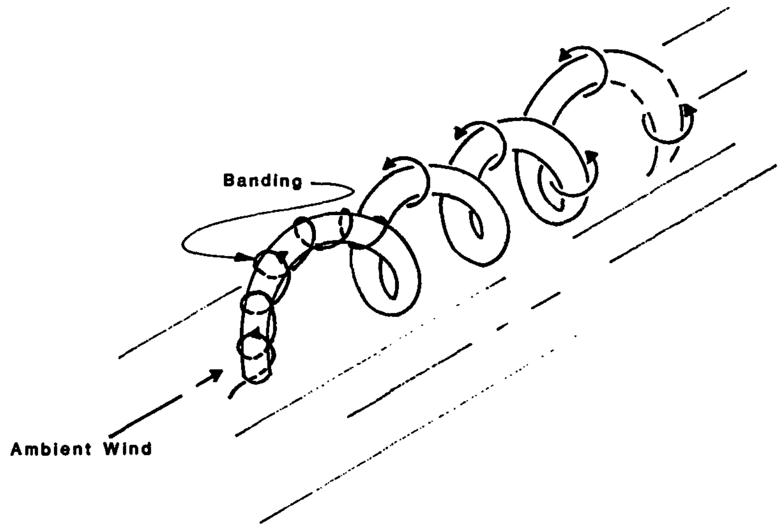

FIG. 13. A single longitudinal vortex under the influence of the ambient wind displays the banded appearance seen in Fig. 7.

While interviewing fire fighters, we received one report of an apparent transverse, downstream vortex. Donald Grant[1] (personal communication) stated that during a high-intensity crown fire, he observed a 15-m, slowly whirling "ashcan" of pure flame coming horizontally out of the head of the fire at treetop height. However, he did not know if transverse vortices were occurring simultaneously upstream of the smoke column of this fire. This could be a case of the downstream portion of the vortex ring separating from the smoke column while maintaining its structure.

The diagrams in Fig. 14 give a postulated fluid dynamic configuration that satisfies both the observational evidence and Helmholtz's principle that a vortex line cannot begin or end in a fluid; the vortex line must go to either a fixed boundary or infinity, or close on itself. Figure 14a shows a typical flow pattern in a ring vortex. The ambient wind causes a distortion of the vortex (Fig. 14b). This leads to a reorientation of boundary layer vorticity and resultant longitudinal vortex enhancement (Fig. 14c). This longitudinal enhancement is of some concern to the integrity of the proposed mechanism because the observed vortices did not include this feature, but, in general, the process appears plausible as it favors continuance of the upstream portion of the vortex and a breakup of the downstream portion through dissipation in the turbulence of the eddies. Note that the sense of the vorticity is the reverse of that of the classical horseshoe vortex occurring when a boundary layer impinges on an obstacle in the flow. This reversal results from domination of the vortex due to buoyancy.

An artist's conception (Figs. 8b and 9) and the concepts illustrated in Fig. 14 form a plausible scenario to explain the photograph in Fig. 8a and the observations discussed previously, provided the vortex formation is transient. If the postulations of Fig. 14 are correct, then the transience is expected, since this is a requirement for the formation of vortex rings. The implication for wildland fires is that periodic bursts of energy release from an unsteady source would produce the observed vortex structure. Laboratory work on pulsating fires by Byram and Nelson (1970) has determined some of the conditions necessary before these periodic bursts will occur.

In a simulation of a massive strip surface fire in a crosswind, Luti (1980, 1981) developed a numerical model for the transient development of a two-dimensional flow field. Because the input parameters were outside the range of natural free-burning mass fires, Albini (1982) commented that it was impossible to judge some results as a test of model validity. However, Luti's general two-dimensional streamline structure appears plausible and germane to the present discussion. The outstanding feature of the simulation was the dominance of the flow field by a horizontal vortex upstream of the convection column. Its size increased with time, although its center showed little horizontal movement. Other activity included counterrotating horizontal vortices just downstream of the convection column. This downstream area was somewhat unstable with vortex generation and shedding. Because his model was two-dimensional, the true transient nature of the vortex phenomenon may well have been dampened. Nevertheless, the results emphasized upstream vortex structural stability and downstream instability.

5. Recommendations

The survey of existing laboratory and theoretical studies that may apply to horizontal vortex generation

[1] Michigan Department of Natural Resources.

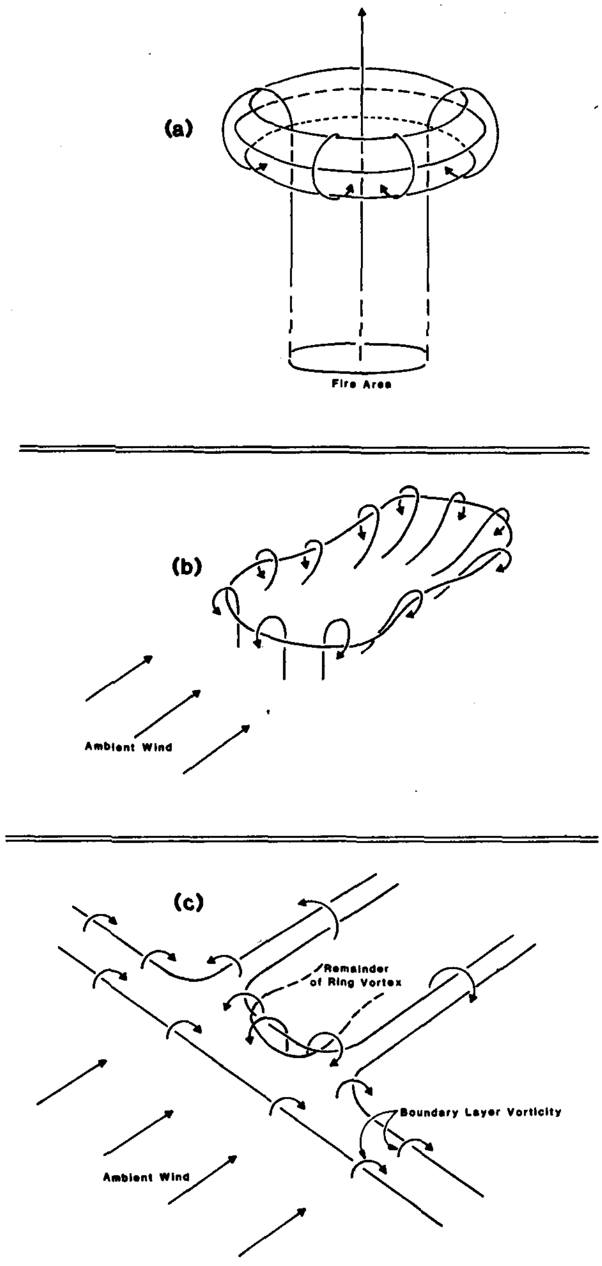

FIG. 14. (a) Typical flow in a buoyant plume during formation of a symmetric vortex ring. (b) Distortion of the vortex ring caused by the ambient wind. (c) A reorientation of boundary layer vorticity and resultant longitudinal vortex enhancement.

and existence in wildland fire indicates that our knowledge of the conditions under which they form and the mechanisms involved is somewhat rudimentary. Before we can hope to predict their formation and behavior, there are a number of problems to solve and questions to answer.

One of the most important basic problems is establishing the relative importance of the boundary layer created by the immediate forest canopy. It can be argued that the boundary layer, viewed as mechanical turbulence produced by local roughness, is not easily distinguished from turbulence produced by upstream roughness, and it should have little additional effect on a buoyant plume produced vortex pair. Perhaps the horizontal vortex pair, associated with a strong buoyant plume, is generated mostly by buoyancy, not by interaction with boundary layer vorticity (Briggs 1974, 1984). It is certainly true that with high or gusty winds it may not be possible to identify a local boundary layer thickness in a wildland setting because of turbulence produced by upstream roughness. However, the vortex pairs and transverse vortices described here were observed only during periods of low to moderate wind velocity. These conditions may allow local boundary layer influence, and, therefore, the authors believe that further experimentation will be required to resolve the issue.

Another fundamental question involves formulating governing equations to describe the mechanism of vortex development. Using well-known, nondimensional numbers would be the most straightforward approach. For example, the Reynolds number, as a ratio of inertial to viscous forces, can be defined in many ways and can include equivalent eddy viscosity (Csanady, 1965). Also, a Reynolds number–Rayleigh number equivalence can be used when the dominant velocity component is buoyancy generated. However, some investigators believe that, although this approach may work on laboratory scales, it may not be as appropriate on atmospheric scales. The issue is unresolved.

Another approach to formulating governing equations involves the exploration of a broad range of the buoyancy flux parameter in the form

$$F_l^{1/3}/\bar{u}, \tag{4}$$

where

$$F_l = (g/c_p\rho T)Q_l \tag{5}$$

and u is a velocity term. Here l denotes length, c_p is specific heat at constant pressure, T is temperature, and Q_l is the total heat release rate per unit length. This approach may depend on expecting buoyancy domination of vortex pair generation.

Finally, an interesting experiment might examine the behavior of the smoke column in the New Miner Fire. As this column bifurcated, the individual arms extended outside the flanks of the fire and then collapsed to the ground (Figs. 3 and 5). Although we have generated a somewhat similar phenomenon in a wind tunnel experiment, laboratory formation was initiated by an upstream obstacle that produced a wake effect. The wake caused the vortex pair to split and extend down and around a wire that had been suspended and heated. Perhaps large trees, clumps of trees, or topography could produce this same effect. On the other hand, this behavior might have been generated by random vorticity in the convective turbulence field advected past the fire, as assumed by Briggs (1974) and reported by Willis and Dearorff (1976).

6. Conclusions

This paper presents observations of horizontal vortices existing in intense mass and crown fires; these vortices are important to the understanding of fire behavior, in fire control, and in firefighter safety. Horizontal vortices appear only in extreme situations, but fires in these situations are the most dangerous and difficult to contain.

As Albini (1984) suggests, horizontal vortices and related phenomena are only the most recent mystery posed by wildland fire behavior. The list of poorly understood phenomena can be expected to lengthen for some time because research in this field is still in its infancy. Nevertheless, applicable results have been produced from the present level of understanding of wildland fire behavior and have yielded rewards in increased safety and suppression procedures.

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