Horizontal Roll Vortices and Crown Fires

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ABSTRACT

Observational evidence from nine crown fires suggests that horizontal roll vortices are a major mechanism in crown-fire spread. Post-burn aerial photography indicates that unburned tree-crown streets are common with crown fire. Investigation of the understory of these crown streets after two fires showed uncharred tree trunks along a center line. This evidence supports a hypothesis of vortex action causing strong downward motion of air along the streets. Additionally, photographs of two ongoing crown fires show apparent horizontal roll vortices. Discussion also includes laboratory and numerical studies in fluid dynamics that may apply to crown fires.

1. Introduction

A wildland crown fire is usually short-lived but extremely dangerous and potentially catastrophic. Because most people near crown fires are either totally occupied with fire suppression or with survival, there are few reliable observations of this phenomenon. Van Wagner (1977) found little published on the behavior of crown fires except for reports of rates-of-spread and aspects of fuel arrangements. Without adequate observations, it is difficult to expand on the physical theory of crown-fire spread. Without a more inclusive theory, modeling is difficult and, consequently, reliable fire-behavior prediction is impossible.

This paper compiles information that suggests the horizontal roll vortex (HRV) is a primary mechanism of spread in many crown fires. It presents observational evidence from several fires and also surveys existing laboratory and numerical studies in fluid dynamics that may apply to crown fires.

2. Crown fires

In the classical view, crown fire advances from top to top of trees or shrubs and appears to be more or less independent of surface fire. In a more elaborate model, Van Wagner (1977) suggested that crown fire depends on three simple crown properties: height above ground, foliar bulk density, and foliar moisture content. He proposed classifying crown fires as passive, active, or independent according to their degree of dependence upon surface fire. In the passive classification, the crown phase depends completely on the surface fire, whose spread rate controls the whole fire. If active, the surface and crown fires must travel together as a unit. If independent, the crown fire can supply the required heat flux by itself and no longer depends upon the surface fire.

Crowning is most often a phenomenon of conifer forests, although the broad-leafed eucalyptus forests of Australia and the chaparral of the Southwestern United States are renowned for intensive crown fires. On typical free-burning fires the spread is uneven, with the main spread moving with the wind. This forward fire perimeter is the most rapidly moving portion and is designated the head of the fire. The adjoining portions of the perimeter at right angles to the head are called the flanks, and the slowest portion (that may be backing into the wind) is called the rear.

3. Case histories

Observational support for the activity of HRV's in crown fires consists of evidence from nine sources (Table 1). Crown streets after crown fire are in no sense unique or localized. Two of the discussed fires occurred in the North Central United States, two in the Southeast, one in the Southwest, and the other four were in Canada.

a. The Mack Lake fire

Air reconnaissance of this Michigan crown fire showed long streets of unburned (although often scorched) conifer crowns in an otherwise vast area of blackened ground and trees (Fig. 1) (Simard *et al.*, 1982). These tree-crown streets crossed roads and gently rolling terrain but still essentially maintained their identity, often for 3–6 km and in one case for more than 11 km.

Crown streets were most often parallel to each other, although clusters of parallel streets diverged

TABLE 1. Background information on crown fires that indicate action of horizontal roll vortices.

Fire name/number	Location	Date	Total hm^2 burned	Evidence of vortices	Primary fuels	Surface weather observations (when available) during major crown fire runs	Comments
Mack Lake	Huron National Forest, Michigan	5 May 1980	10040	Videotape of two apparent vortices[a,b]	Sapling to small-pole jack pine	Temp = 28°C RH = 21–26% Wind = 16–29[g] 48 km h^{-1}	Initial 7300 hm^2 burned in 6 hours[c]. FROS[d] = 3.25 km h^{-1} Flame height = 10–25 m
Dudley Lake	Sitgreaves National Forest, Arizona	14 June 1956	8662	Time-lapse film and photographs of a HRV	Mature ponderosa pine	Temp = 31°C RH = 4% Wind = 48–80 km h^{-1}	
Fletcher Road	Kalkaska County, Michigan	8 May 1968	1900	[a,b]	Sapling to small-pole jack pine	Temp = 21°C RH = 24–30% Wind = 24 km h^{-1}	[c]
Air Force Bomb Range	Dare County, North Carolina	22–26 March 1971	11867	[a]	Pocosin, pond pine	Temp = 20–22°C RH = 25% Wind = 24–32[g] 64 km h^{-1}	[c]
Exotic Dancer	Croatan National Forest, North Carolina	23 May 1970	810	[a]	13-year-old pocosin, pond pine	Temp = 31°C RH = 32% Wind = 11 km h^{-1}	
Sioux Lookout—29	Ontario, Canada 50°04′N, 91°22′W	18 June 1979	4960	[a]	Jack pine–black spruce	Temp = 25°C RH = 24–28% Wind = 13–22 km h^{-1}	FROS = 1.6 km h^{-1}
Red Lake—48	Ontario, Canada 50°11′N, 93°07′W	5 June 1976	1700	[a]	Jack pine–black spruce	Temp = 28°C RH = 23–33% Wind = 13–22 km h^{-1}	
Red Lake—37	Ontario, Canada 60 km, NE of Red Lake	5 June 1976	17415	[a]	Jack pine–black spruce	Temp = 28°C RH = 23–33% Wind = 13–22 km h^{-1}	
Red Lake—31[f]	Ontario, Canada Total fires vicinity of Red Lake	29 June–13 July 1974	53874	[a]	Jack pine–black spruce	13 July: Temp = 25°C RH = 28–34% Wind = 16–32 km h^{-1}	FROS = 3–3.5 km h^{-1} [c]
Controlled burn	Everglades National Park, Florida	21–23 Jan 1971	Part of a 32 km line of sawgrass	[e]	Sawgrass, 2–3 m tall		Width of photographed burned area approximately 1000 m (Fig. 11). FROS = 8 km h^{-1}
Controlled burn 7319	Everglades National Park, Florida	21 Feb 1973	11	[e]	Marshgrass (1.5–2.5 m Spartina)		FROS = 0.25 km h^{-1} Flame height = 4.5 m
Controlled burn 8002-C	Everglades National Park, Florida	7–8 Feb 1980	1365	[e]	Muhlenbergia prairie	Temp = 10°C RH = 39–46% Wind = 11–16 km h^{-1}	Intense head fire. FROS = 1.6 km h^{-1}. Flame height = 3 m

[a] Air photographs of tree-crown streets.
[b] Uncharred tree streets.
[c] A low-level jet was evident; when this statement is not included in comments, no upper air information was available.
[d] FROS = Forward rate of spread.
[e] Air photographs of unburned grass banding.
[f] Stocks (1975).
[g] Gusts.

FIG. 1. Approximately straight tree-crown streets resulting from the Mack Lake fire. The ambient wind direction and the forward fire spread were from right to left.

(usually near the fire's origin) or converged (usually near the fire's termination). Individual streets were reasonably straight; a few curved toward the major fire activity. Distance between parallel streets ranged from 45 to 850 m. Width of individual streets ranged from less than 10 to 200 m. From the air, some sides of streets appeared ragged; others were smooth, suggesting strong fire activity along them.

Tree-trunk char and scorch resulting from wildland fires is highest on the downwind side (Fig. 2). Ground examination of the crown-street understory at Mack Lake invariably disclosed that the low-charred sides of tree trunks faced each other (Fig. 3). This phenomenon indicated that fire had spead in opposite directions from winds radiating outward from within all streets (Fig. 4). The char height was generally 0.3–1 m on the insides of the tree trunks and 1.5–3 m on the opposite sides. The center line of opposing spread tended to be offset toward the side where the fire had been most active when streets were formed. Center lines were generally located from one-fourth to one-third the width of the street

FIG. 2. Burning pattern on a tree trunk. The ambient wind is blowing roughly from left to right with resultant char and scorch highest on the downwind (right) side of the trunk. Photograph from Luke and McArthur (1978).

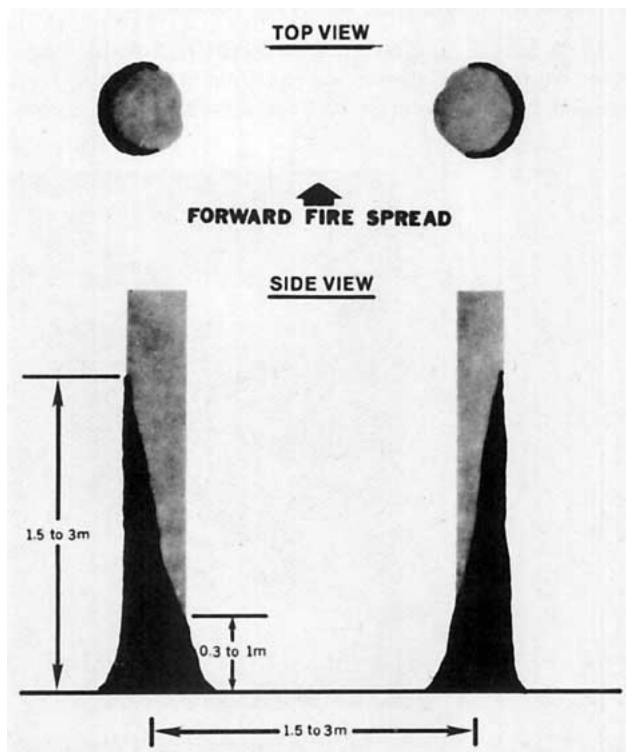

FIG. 3. A typical uncharred tree pattern observed in the understory of tree-crown streets after the Mack Lake fire.

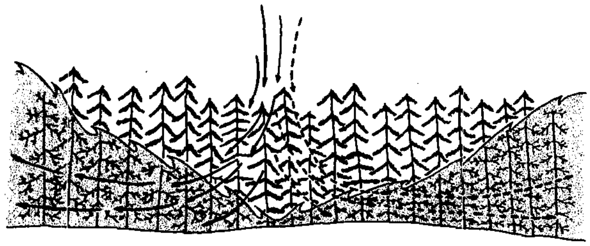

FIG. 4. Suggested action of horizontal roll vortices during the formation of tree-crown streets. Downward streams of air cause the fire (gray shading) to move outward instead of upward, inhibiting the burning of tree crowns and forming the understory pattern of tree char shown in the preceding figure.

from the strong fire side. On wide streets there was often no charring along the center line; even needles suspended a few centimeters from the ground were not burned or scorched. Some trees with char or scorch on opposing sides were less than 1 m apart, but most were 1.5–3 m apart. Char was most prominent in the direction of forward fire spread when trees with opposing patterns were less than 1.5 m apart. These understory patterns continued along all streets examined.

When the crown street and understory pattern became disorganized, it invariably re-formed within a short distance. Investigation showed that it had changed for one of the following reasons:

1) A single, uncharred tree street had re-formed into two or more streets, or multiple streets had re-formed into single streets. This was always accompanied by a change in the overhead tree-crown pattern.

2) The street was 60–90 m upwind of an intersecting road. The street and understory pattern usually re-formed 15–25 m on the other side of the road.

In one instance the uncharred street moved from conifers to hardwoods. Even though there was no crowning in the latter, the uncharred street continued along a sidehill 60 m high with a 25° slope, ~45 m up from the bottom. The pattern indicated that along the length of this hill the fire had burned downslope below the street and upslope above the street.

A portion of the Mack Lake fire was videotaped from the air during the fire's major burning period. The tape shows strong buoyancy on the forward sector of the fire's north flank, as evidenced by heavy smoke rising more than 2 km into the atmosphere. However, toward the trailing sector of the same flank, there appears to be a HRV (Fig. 5). A comparison with ground features indicates that this smoke-outlined eddy is more than 3 km long and 0.4 km in diameter. As shown in Fig. 5, the structure seems to be distinct and uniform.

Videotape taken ~3 h later shows another possible HRV, this one located along the southern flank. Because of poor viewing angle and no ground reference, its diameter or length could not be estimated. Simard *et al.* (1982) give additional information including a synoptic mesoscale analysis of this fire.

b. The Fletcher Road fire

Air photographs of this Michigan jack-pine fire reveal patterns of tree-crown streets similar to those

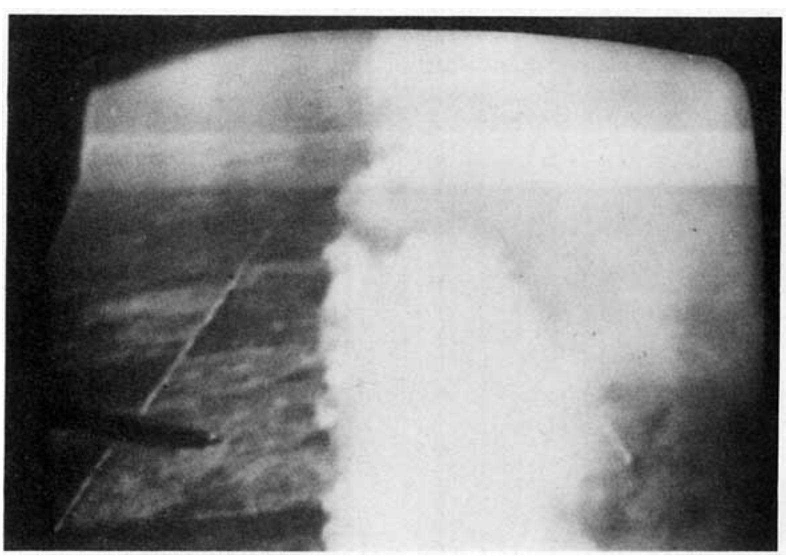

FIG. 5. An apparent horizontal roll vortex on the north flank of the Mack Lake fire. Angle of view is from the rear toward the fire head. This HRV is ~0.4 km in diameter and more than 3 km long. The line on the photograph resulted from videotape reproduction through a television monitor. Photograph courtesy of William Jackson, News Director, WBKB-TV, Alpena, Michigan.

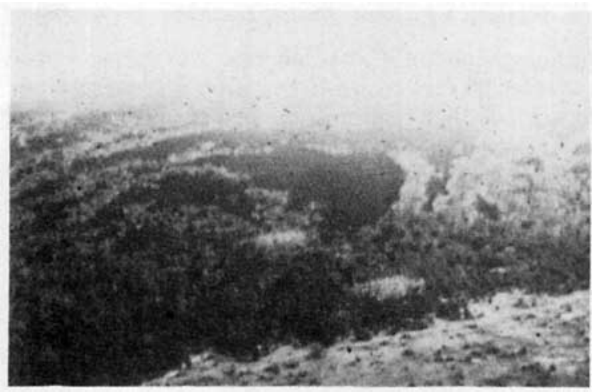

FIG. 6. Curving tree-crown streets at origin of the Fletcher Road fire. Forward fire spread was from lower left to upper right. Photograph courtesy of Steven Such, Michigan Department of Natural Resources, Equipment Development Center, Roscommon, Michigan.

seen at Mack Lake. But one photograph of the Fletcher Road fire shows curved tree-crown streets in concentric bands near the point of fire origin, a feature not nearly as prominent at Mack Lake (Fig. 6).

Twelve years after the Fletcher Road fire, a 1980 ground survey through crown streets where the conifer trees survived revealed faint but still identifiable tree scorch. The pattern was the same as at Mack Lake. We identified streets by walking between trees with char on the backside of the trunks and low branches but no char on the inside, at least above 0.3 m.

We could not locate the curved bands of crown streets seen in Fig. 6. Apparently most crowns in this area were so badly scorched that few trees survived the fire. We were able to identify one curved, uncharred street, but it ended in an area of dead and down trees after a short distance.

c. The Dudley Lake fire

Schaefer (1957) documented this 1956 Arizona fire while attempting to link high-level jet streams to wildfire behavior. He described a large HRV acting as a lateral spread mechanism on the western flank (Fig. 7). Time-lapse movies of this fire showed a HRV, 1.8 km in diameter, rotating counterclockwise (looking downstream). Observers stated that this smoke-outlined cell remained as a coherent mass, traveling ~500 km to the northeast with the prevailing wind.

A photograph, taken from a lookout tower 2 km west of the fire, shows the described vortex (Fig. 7). The clearly delineated banding in the center of this print indicates both rotation and translation. On either side of this feature, buoyant smoke obscures the phenomenon as it did on the downwind sector of the north flank of the Mack Lake fire.

d. The Air Force Bomb Range fire and the Exotic Dancer fire

Wade and Ward (1973) found several types of fuel consumption patterns occurring in both of these North Carolina fires, including concentric bands of tree-crown streets outlining various portions of the fire perimeter (Figs. 8 and 9). Rates of perimeter advance were well documented during the Air Force Bomb Range fire, and a comparison with a photomosaic of the burned area shows that the relatively

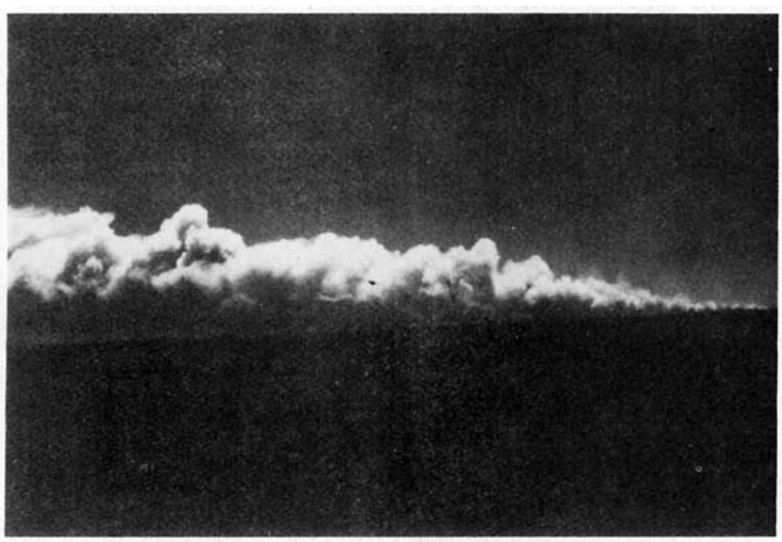

FIG. 7. A large HRV on the Dudley Lake fire with both rotation and translation evident. Forward fire spread was from right to left. Rotationally the top of the roll was moving toward the observer, the bottom away. Photograph courtesy of J. H. Dieterich, USDA Forest Service, Tempe, Arizona.

FIG. 8. Curving tree-crown streets resulting from the Air Force Bomb Range fire. Forward fire spread was from lower left to upper right. Photograph courtesy of Dale D. Wade, USDA Forest Service, Macon, Georgia.

uniform, 15-m wide bands of tree-crown streets were formed ~1 h apart. According to Wade and Ward, detailed observations of this fire show that, "Surges in fire intensity were accompanied by changes in the physical appearance of the convection columns. The columns alternately leaned over and then stood more erect. Smoke color also alternated between yellow when the columns were tilted to black when they straightened." The circular bands outlined the various perimeters of the fire and apparently occurred when the smoke column was upright. Forward sector banding of curved streets did not occur during major fire pulsation.

e. Canadian wildfires, Sioux Lookout 29—1979

Photographs of Canadian and Australian crown fires indicate that crown streets are far more common worldwide than heretofore recorded (Luke and McArthur, 1978; Van Wagner, 1977). Researchers of the Canadian Forestry Service documented a number of Ontario wildfires where streets appeared (Table 1). The Sioux Lookout fire presents a somewhat unusual configuration (Fig. 10). Two major crown streets of mature jack pine-black spruce converge as shown in the upper left corner of the figure. Another photograph of the area shows that the fire crowned again beyond this point and continued briefly until it ran out of fuel in a peat bog.

Minor curved streets radiate outward from the leftmost major street. These narrow minor streets may have outlined perimeters during pauses in fire runs as they did during the Fletcher Road fire and the two North Carolina fires.

f. Controlled grass burns in the Everglades National Park

The fires described to this point all burned in conifer fuels, but air photographs have also shown unburned bands of fuels in grass (Table 1). A photograph taken seven days after a 1971 controlled burn in Florida's Everglades National Park shows obvious bands of unburned sawgrass, 2–3 m tall, in contrast to an otherwise blackened area (Fig. 11). Few details are available, but a published record shows that the fire's forward rate-of-spread was high, ~8 km h^{-1}.

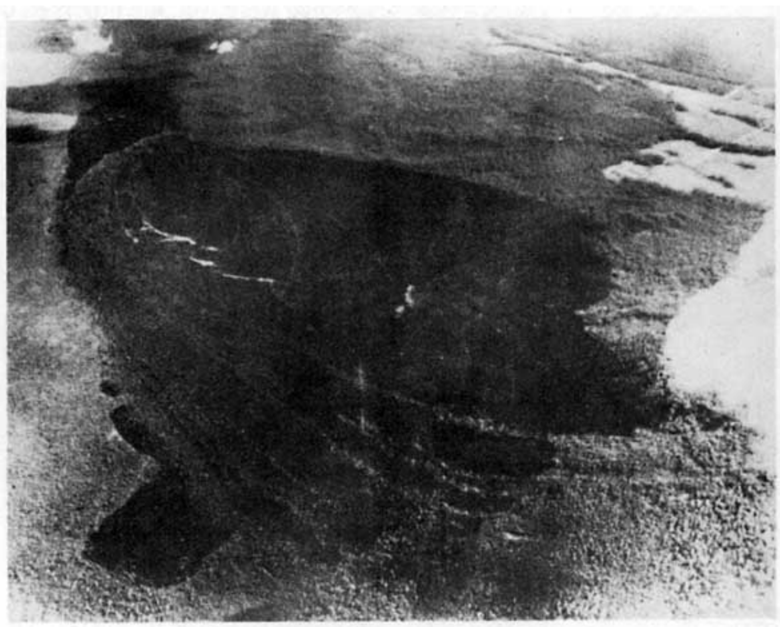

FIG. 9. Tree-crown streets, both curved and straight, resulting from the Exotic Dancer fire. Forward fire spread was from upper left to lower right. Note the repeated banding outlining the burned area perimeters near fire origin in upper left. Photograph courtesy of Dale D. Wade, USDA Forest Service, Macon, Georgia.

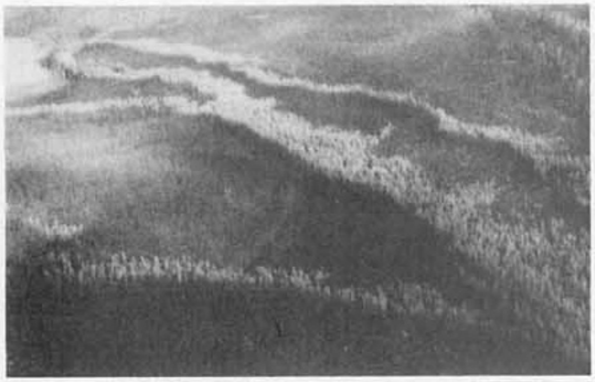

FIG. 10. Tree-crown streets resulting from Sioux Lookout fire 29–1979. Forward fire spread was from lower right to upper left. Photograph courtesy of Martin E. Alexander, Canadian Forestry Service, Great Lakes Forest Research Centre, Sault Ste. Marie, Ontario.

The photographed area, part of a much larger burned tract, is approximately 1 km wide (Klukas, 1972).

A photograph taken in Everglades National Park after a February 1973 controlled burn also shows concentric bands of unburned Spartina marsh grass, similar to patterns in the Fletcher Road fire which involved conifer fuels (Fig. 6).

g. Summarization of observational evidence

In summary, the following observational evidence suggests HRV action as a mechanism in crown-fire spread:

1) Three HRV's may be visible on film, two at Mack Lake and one at Dudley Lake.

2) All fires discussed (except Dudley Lake, for which there are no post-burn photographs) displayed tree-crown or unburned marsh grass streets.

3) There are two post-burn areas with documented uncharred tree understory, the Mack Lake fire and Fletcher Road fire.

Several other fires, not discussed here, also have post-burn crown streets. Gerald Grieve, Fire Science Specialist with the Michigan Department of Natural Resources, states that he has observed healthy crown streets after all Michigan jack-pine fires of 800 hm^2 or more where crowning has occurred. Dale Taylor, Research Biologist at Everglades National Park, states that park researchers see banding patterns on most of their grassland burns, but the patterns usually are not as distinct as pictured in Fig. 11.

The crown streets with the accompanying charless understory strongly suggest downward air motion. The film of the helical circulations suggests HRV action (Figs. 12 and 13). Other investigators have found downward air motion in large fires, although the pattern of vertical flow was not well organized (Countryman, 1968). Also, several observations have been recorded of wind blowing outward from large fires (Chandler *et al.*, 1963).

Although there has been no documentation in the literature of straight crown streets, and, to the best of my knowledge, no previous notice of uncharred understory, Wade and Ward have summarized speculation about what causes concentric bands of unburned tree crowns outlining the perimeters of some fires. Possible causes suggested have centered on changes in ambient wind speed and/or direction or

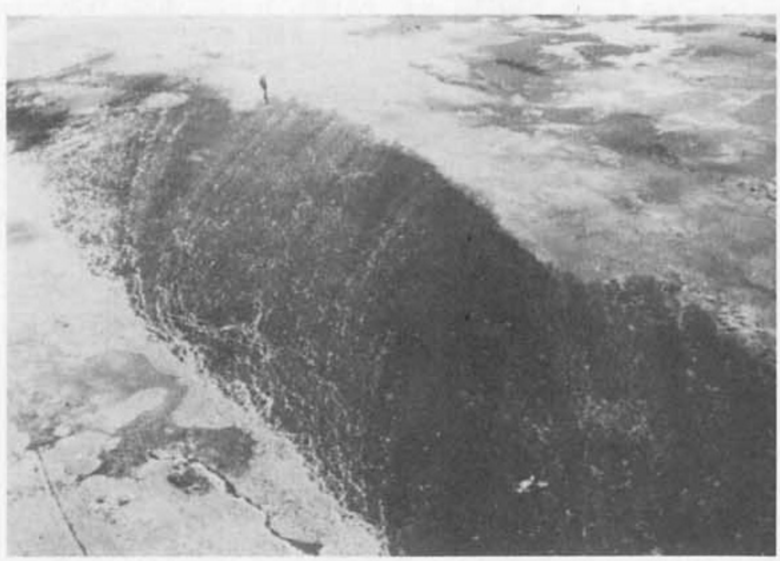

FIG. 11. Bands of 2–3 m tall, unburned sawgrass resulting from a controlled burn in Everglades National Park. Forward fire spread was from the lower to the upper portion of the photograph. Photograph courtesy of Richard W. Klukas, Everglades National Park, Florida.

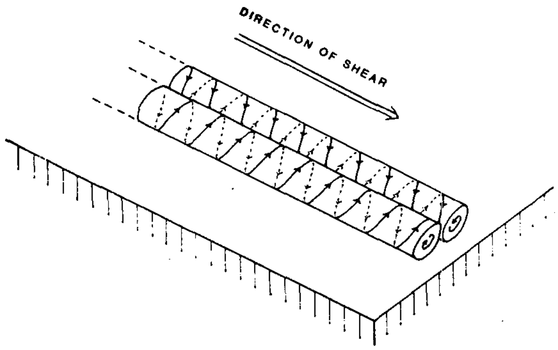

FIG. 12. A three-dimensional view of HRV's or helical circulations. Manifestations are referred to as "streets", "lines", "bands", "strips", "dunes", and "streaks".

on changes in fire-brand spotting frequency in conjunction with fire pulsation.

The observational evidence presented in this paper suggests that concentric banding on the fire's forward perimeter results from the action of the same helical circulations that cause the straight crown streets. As an example of possible action, a HRV with counterclockwise rotation forms along the northern perimeter of an eastward-moving crown fire. A HRV with clockwise rotation forms along the southern perimeter. In this scenario the shape of the fire is symmetrical. If the forward rate of fire spread slows or stops, the vortices on either flank encircle the forward perimeter and join. Repeated action of this sort results in relatively smooth concentric banding on the forward perimeter, as seen in the early stages of the Exotic Dancer fire (Fig. 9). But if the fire burns unevenly because of some factor such as nonuniform fuel distribution, then when the forward movement slows, the vortices' attempt to encircle the forward perimeter will result in disjointed banding, as seen on the Fletcher Road fire (Fig. 6). We could not verify this hypothesis conclusively on the Mack Lake fire, because all three curved streets there ended abruptly, apparently destroyed by the head fire. The trees in the curved streets on the Fletcher Road fire did not survive the 12 years between the fire and our attempt at ground verification.

We might also hypothesize that what happens along the forward perimeter is synchronized with fire pulsations described by Wade and Ward, and that both are largely controlled by the ambient wind. When the ambient wind is low the smoke column is upright, and the forward rate of fire spread slows or even stops for a period. This could allow time for the helical circulations on the fire's flanks to completely encircle the fire head. When the wind increases the smoke column again leans forward, and the head fire continues on, but the HRV has fixed the previous position of the perimeter with a curved crown street. If the continuing head fire is strong, much of the curved street may burn as the fire moves forward, as on the Mack Lake fire. If the head fire is not strong, the curved crown street survives as on the North Carolina fires. This hypothesis will be supported or refuted by searches for uncharred understory on future burns having curved crown streets.

4. Evidence of HRV's in nature, in the laboratory and in theoretical studies

Since at least the early 1930's, investigators have explored the link between cloud forms and Bénard cells. For example, Mal (1930) observed cloud streets occurring with a spacing of 4 km and believed they resulted from rising air between every other HRV. Kuettner (1959, 1971) summarized the work accomplished by the pioneers in this study area. The consensus is that cloud streets of different scales and types are a common atmospheric feature. They occur at all latitudes and in some areas represent the prominent convective cloud pattern.

In addition, Keuttner expanded upon the theory of HRV's as the preferred convective mode of flow in which buoyancy forces are counteracted by vorticity forces arising from a vertical shear gradient. His observations indicated that parallel cloud streets originate in convective layers with higher than normal winds and a curved vertical velocity profile of rather uniform direction. These findings were attributed to the thermal wind connected with large-scale advection of cold air in the boundary layer moving over warm surfaces.

Cloud streets form along the intersection of two counterrotating HRV's having sustained upward motion. Bagnold (1952) suggested that long parallel systems of sand dunes, covering more than half of the world's deserts, are aligned and spaced by this atmospheric mechanism. Hanna (1969) offered further observational evidence and outlined a model in support of this hypothesis.

Ocean and lake observations by Scott *et al.* (1969) and others show at least two types of water mechanisms referred to as Langmuir circulations. Type 1 produces well-defined and well-spaced water-debris

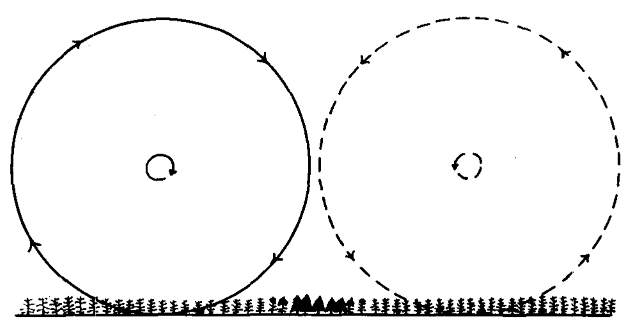

FIG. 13. A cross-sectional view of possible counterrotational HRV activity in a crown fire.

streets that maintain their form over long periods with winds greater than some critical value, perhaps 3 m s^{-1}. Type 2 is transitory, appearing briefly as streaks during wind gusts. Several dynamicists have proposed hypotheses to explain Langmuir circulations. Scott *et al.* tested six of these hypotheses with field data gathered when the two mechanisms occurred. Their conclusions suggest that only one hypothesis, that involving shearing instability dependent upon development of Ekman flow, could explain the action of Type 1 water vortices. This hypothesis may parallel the mechanism of the HRV in the atmosphere.

Laboratory observations show that buoyancy-generated convection begins when the vertical temperature gradient of a fluid heated from below exceeds a critical value. Both laboratory and numerical investigators have studied the onset of such flow called the Rayleigh stability problem, after Rayleigh (1920) who first attempted its mathematical expression. Many studies of the simpler flow aspects followed until Chandrasekhar (1961) virtually completed solution of the linear theory of the problem.

Some laboratory containers use a sheet-glass top moved horizontally to induce shear in enclosed fluids. Experimentation shows that the magnitude of the shear in unstable layers of fluid is critical. Vertical-axis polygonal cells form with no induced shear. When the shear is small, roll vortices form with vorticity transverse to the fluid flow. When the shear is large, vortices appear orientated nearly parallel to fluid flow (Low, 1925; Mal, 1930; Brunt, 1951). Adjacent rolls rotate in opposite directions in either horizontal case (Fig. 12).

The Rayleigh stability problem applies to crown fires in the sense that a critical Rayleigh number (Ra_c) exists which must be exceeded for buoyant forces to produce cellular (or vortical) fluid motion. It appears that the large-scale motion and high temperatures produced in wildland crown fire always cause the Rayleigh number to exceed the minimum value necessary for instability. Linearized stability theory can predict both a critical Rayleigh number ($Ra_c = 1708$) as well as the size of unstable disturbances for low Rayleigh numbers.

The Rayleigh number may be expressed as

$$\mathrm{Ra} = \mathrm{Pr} \cdot \mathrm{Gr},$$

where Pr is the Prandtl number and Gr the Grashof number. Because the values of the kinematic viscosity and the thermometric conductivity are roughly the same in this situation, we assume a Prandtl number ≈ 1.0. Therefore,

$$\mathrm{Ra} = \mathrm{Gr} = \frac{g\beta\Delta T L^3}{\nu^2}.$$

Here, g is the acceleration of gravity, β is the expansion coefficient, ΔT is the temperature difference, L is the scale length, and ν is the kinematic viscosity. For the Mack Lake fire, a HRV radius of 200 m (from Fig. 5) and a T surface of 1273 K yield Ra $\approx 10^{15}$.

Kuo's (1979) derivations show that transition from laminar to turbulent convection occurs around Ra $= 3.1 \times 10^4$. Fully turbulent flow is recognized for PrGr $> 10^9$ (Parket *et al.*, 1969). Obviously crown-fire production of HRV's takes place in turbulent extremes. This raises the question of the applicability of most previous laboratory and theoretical work, done at low Ra numbers, to the crown fire problem. For example, in turbulent flow an eddy viscosity K can be defined which is several orders of magnitude larger than ν. $\nu = 0.6$ cm^2 s^{-1} in the case of the Mack Lake fire. Average atmospheric turbulence produces values of $K = 5 \times 10^4$ cm^2 s^{-1} and crown fires generate still higher values.

Buoyancy/stratification models are defined in terms of the bulk Richardson number

$$\mathrm{Ri}_b = \frac{g(d\bar{\theta}/dz)}{\bar{T}(d\bar{u}/dz)^2},$$

where $d\bar{\theta}/dz$ is the average vertical temperature gradient, $\bar{T}$ is the average temperature, and $d\bar{u}/dz$ is the average velocity gradient. Low Ri_b numbers indicate roll convection while large numbers indicate cellular convection. Using representative values from the Mack Lake Fire, $\mathrm{Ri}_b = -0.022$. This result is in the low number range where roll vortices are favored in the planetary boundary layer, and it is in the same value range LeMone (1973) found using empirical data.

Derivations by Asai and Nakasuji (1973) show that the Rayleigh number, Prandtl number, Richardson number, and Reynolds number (Re) are related by the expression

$$\mathrm{Ra} = \mathrm{Pr}\mathrm{Re}^2\mathrm{Ri}\left(\frac{H}{D}\right)^4,$$

where H is the thickness of the fluid and D is the characteristic depth of the boundary layer. Because of the close association among these dimensionless parameters, calculation of Re does not appear to contribute additional insight into the structure and/or process of HRV formation. We might note, however, that $\mathrm{Gr} \gg \mathrm{Re}^2$ implies free convection, which certainly occurs in these fires. The results of this discussion show that crown fires should be treated as fully turbulent with the flow favorable for HRV development rather than cellular convection.

Koschmieder's (1966) and Krishnamurti's (1973) laboratory studies may have direct application to the curved perimeter streets seen in Figs. 6, 8, and 9. They found that circular rolls could be forced by using circular boundaries. Countryman (1968) stated that in the cumbustion zone, stationary fires appeared to block ambient air movement and, conse-

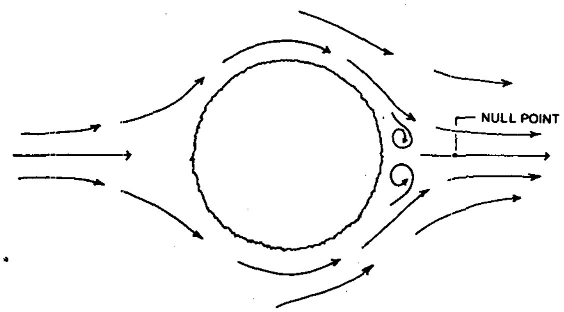

FIG. 14. Schematic of air flow around a stationary fire, from Countryman (1969).

quently, air flow was similar to fluid flow around a solid object (Fig. 14). Air photographs from the Mack Lake fire show that a sustained crown fire moving rapidly at 3 km h^{-1} may form a relatively stationary boundary when subjected to an ambient wind of 30 km h^{-1}.

LeMone's (1973) numerical derivations suggest that atmospheric HRV's can obtain energy to drive their circulations by:

1) Buoyancy;
2) A Coriolis effect allowing shear along the roll axis through a parallel instability mechanism;
3) Shear from the cross-roll component of the mean planetary boundary layer (inflectional instability in the Ekman spiral).

Energy can also be gained or lost from interactions with roll-scale or lesser scale turbulence. These categorizations depend upon many assumptions. In the case of crown fire one of the more important assumptions may be that the rolls can be treated two-dimensionally, i.e., the flow pattern in a certain plane is the same as that in all other parallel planes within the fluid. This is sometimes assumed to be true when the roll is very much longer than wide.

A summary of previous atmospheric modeling efforts shows that rolls may be simulated in dynamic models in conformity to these energy sources:

1) Buoyancy models produce rolls aligned nearly parallel to the wind as a result of suppression of transverse waves by the mean wind shear. Models conforming to this criterion were developed by Kuo (1963) and Asai (1970).

2) Rolls can also be produced by the above and/or the shear gradient as shown by Kuettner (1959, 1971).

3) Inflection instability models require only the existence of an inflection point in the wind profile. Models based upon this criterion were developed by Faller (1961), Lilly (1966), Faller and Kaylor (1966), and Brown (1970, 1972).

LeMone's observational data suggest that the inflectional instability models most closely predict the detailed structure of the HRV in the planetary boundary layer. Hanna (1969) believes that Kuettner's methods are the most applicable to the boundary layer of the hot desert surface.

5. Discussion

Because of fully turbulent flow in crown fires, it appears that physical realism may best be served by employing the k–ϵ models of turbulence (Launder and Spalding, 1974). Here the magnitudes of two turbulence quantities, the turbulence kinetic energy k and its dissipation rate ϵ, result from transport equations solved simultaneously with those governing the mean flow behavior. These models require modification to account for such factors as buoyancy and curvature with potentially major problems usually confined to the ϵ equation. Recently Luti (1980, 1981) attempted simulation of a two-dimensional mass fire using these modified models and produced encouraging results. Both upstream and downstream HRV's appeared as a feature of his streamlines.

The ambient wind certainly plays a key role in HRV action. It causes shear and shapes the perimeter of the fire, determining possible curvature of the resulting HRV. It may be hypothesized that low winds in a passive or active crown fire allow HRV's created on the flanks to completely encircle the head of a fire, as seen in the Exotic Dancer fire (Fig. 9). Higher ambient winds in an active or independent crown fire could produce HRV's causing quasi-straight crown streets. It appears that in these more typical cases the vortices alternately form and dissipate so that the downdrafts acting on the fire serve to explain the char pattern pictured in Fig. 3. Very strong ambient winds occurring with an independent crown fire may create one HRV that widens its diameter and dominates much of the fire, as happened at Dudley Lake (Fig. 7). In this more atypical situation, the flow structure apparently persists at the edge of the fire causing the whole pattern to simply expand over the horizontal plane.

Perhaps well-established peripheral roll vortices inhibit the propagation of the crown fire. If so, the vertical velocities (buoyancy-driven) needed to sustain the roll vortex will diminish, allowing foliar drag and other frictional effects to dissipate the vortex. By the time the crowns are again involved and spreading the fire, the edge will move outward, leaving behind crown streets and char-patterned understory marking the previous activity. As the crown fire propagates and intensifies, vortices will again intensify to the point that they obstruct the crown-fire spread and in a lull of the ambient wind the cycle begins again.

Another interesting unknown concerns the possibility of single vs. multiple HRV's at a given time. Do multiple vortices occur simultaneously in crown fires as indicated in Fig. 13? Or, will a single HRV usually dominate on the perimeter, dissipate, and then be replaced with another HRV on the first vortex's outer flank? Photographs appear to show single vortices outlined by smoke on the north and south flanks of the Mack Lake fire (Fig. 5). A single HRV dominated the Dudley Lake fire (Schaefer, 1957).

Nonuniform heating is one of the major differences between HRV development in crown fire and HRV occurrence in most other natural or laboratory situations. Previous laboratory studies of the Rayleigh stability problem have stressed uniform heating. In crown fires as at Mack Lake, fire is concentrated at the perimeter. At Mack Lake, residence time (the time required for the flaming zone of a fire to pass a stationary point) was $\sim$1–2 min. After that period, the fine and flash fuels, which made the major fire contribution, were completely burned, although some smoldering and burning still occurred in scattered larger fuels. This situation appears to favor a minimal number of adjoining vortices at any given time.

We will consider four scenarios of HRV development:

1) Given an eastward moving crown fire, a counterclockwise HRV develops along the northern perimeter (dashed outline, Fig. 13) driven by the buoyancy in the fire plumes. An induced clockwise HRV (solid outline) then develops to the left of the first HRV. This combination produces the flow necessary to create tree-crown streets and the understory char pattern. The fire is spread northward by fire brands entrained in the counterclockwise flow of the perimeter HRV. Problem: This proposal requires the transfer of energy to the second HRV, either from the mean wind or from the buoyantly driven initial HRV.

2) A second scenario resulting in two HRV's would necessitate enough fire-brand spotting ahead and on the flanks of the perimeter to essentially create a second perimeter with an unburned zone between. Two buoyancy-generated vortices, originating in the two perimeters, could create the situation shown in Fig. 13. Problem: This proposal requires rather uniform spotting to create the second perimeter. Even if this might be possible on the forward perimeter, experience indicates that it would be unlikely to occur on the flanks.

3) A third possibility would utilize atmospheric vortices of various scales, the type that occur in any natural boundary-layer flow. These vortices are enhanced by heating of the boundary layer from below, and the observed tree crown streets and char pattern result. Problem: The scales of these natural vortices would have to fit the perimeter, perhaps too conveniently.

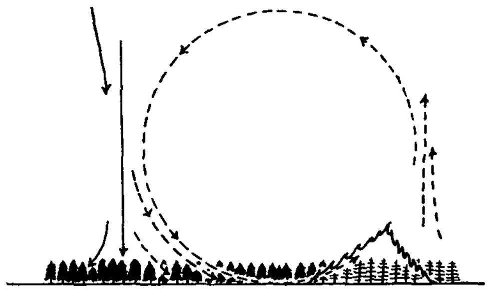

FIG. 15. A cross-sectional view of possible early activity when only one HRV exists. Events begin with HRV development in buoyancy produced along the fire perimeter (extreme right). Cooler ambient air entrains to the left (solid lines). Firebrands from the perimeter entrained in the HRV eventually begin new fire activity and burn all trees not in the crown streets.

4) A fourth possibility utilizes only one HRV, generated in the buoyant perimeter (dashed outline, Fig. 15). Entrainment of cooler ambient air (solid outline) does not induce a second HRV, but is strong enough to cause the results pictured in Figs. 3 and 4. Problem: Proposed induced ambient air motion may not be sufficient to counteract the buoyant fire forces on its side of the street.

Luti's (1980, 1981) findings tend to favor the fourth possibility. Although he simulated mass fires, not running crown fires, the gross features in these cases may be comparable. Luti found that the outstanding simulation feature was the domination of the flow field by a single upstream HRV. Downstream activity showed variation, with creation and shedding of HRV's over time. There would not be postburn field evidence for the upstream HRV, but his downstream simulation results may indicate the flow field that creates crown streets. There is one major difference: Luti's streamline region is too large to account for the width of the observed tree crown streets in most instances. A region of narrower extent is necessary to support this paper's central hypothesis, but, again, Luti's study did not model a moving crown fire.

Further questions concern the minimum fire size critical to HRV formation. This size should be a function of fire intensity and ambient wind. Crown streets 1 km long formed on both the north and south flanks of the Mack Lake fire when the fire was $\sim$30 hm^2. At this time, according to observers on the fire's north side, "An eastward moving crown fire suddenly switched to the north," trapping and killing a fire fighter who was working on the north flank. The evidence suggests that the newly formed HRV on this flank began spreading the fire laterally to the north. Air photographs also show that vortices may have formed earlier, perhaps at an area of 2 hm^2. This minimum area would be similar to the Fletcher Road and Exotic Dancer fires that displayed banded perimeters when their enclosed areas were less than 4 hm^2. On the other hand, air photographs of the Air Force Bomb Range fire show the smallest area of perimeter banding at 85 hm^2. Of course, subsequent burning could have destroyed evidence of early banding.

Finally, there is the question of optimum vertical fuel arrangement, type, and bulk density as well as foliar moisture content. To some extent Van Wagner (1977) has investigated this for conifer forests, but there is little information available for other fuels. An examination of post burns shows that banding patterns appear in the grass at Everglades National Park in much the same way as in the conifer-burned areas. Perhaps grass banding is caused by the same mechanism that causes conifer crown streets. On the other hand, the mechanism may be quite different in the same way that long-term water-debris streets and quickly formed wind streaks are caused by different mechanical and thermal forces.

6. Summary and recommendations

This paper presents observational evidence suggesting that HRV's are a mechanism of spread in many crown fires. It also briefly surveys other evidence of HRV's in nature along with existing laboratory and numerical studies that may apply to crown fires.

Additional field observations and modeling efforts are necessary to support or refute the paper's major hypotheses. Needed observational data include:

1) Film of the perimeter, especially the flanks of an ongoing crown fire. This should involve reference to ground features so that analysis can determine vortex size and angular velocity. In addition, an onsite vertical wind profile and a continuous surface wind record would also be useful.

2) Air photographs of the entire burned area soon after crown fire and well before the scorched conifers in tree-crown streets lose their needles.

3) Additional documentation of uncharred tree-trunk understory. This is especially important for fires with well-established tree-crown banding on the forward perimeter.

4) Topographic information to determine if there is a critical point at which topographic influence can overcome the energy of the vortex.

Modeling strategy might concentrate on modifying existing turbulence flow models in an attempt to simulate a moving crown fire. Laboratory experimentation should explore the results of nonuniform surface heating on HRV formation. In particular, instrument design could employ independently heated elements in transient modes to simulate the shapes of the crown fire perimeter. A wind tunnel experiment might also resolve such questions as parallel perimeters resulting or not resulting in a pair of counterrotational vortices.

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