Large scale fire whirls: Can their formation be predicted?

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Abstract
Large scale fire whirls have not traditionally been recognized as a frequent phenomenon on wildland fires. However, there are anecdotal data suggesting that they can and do occur with some regularity. This paper presents a brief summary of this information and an analysis of the causal factors leading to their formation.

Additional keywords: Fire behavior, Fire intensity

Introduction

Large fire whirls have not been widely recognized as major contributors to wildland fire risk. However, recent evidence seems to indicate otherwise. An analysis of fire behavior that occurred on the Indians Fire in June of 2008 suggests that such fire behavior is more common than previously believed.

The Indians Fire reportedly started Sunday June 08, 2008 at about 12:35 pm in the Arroyo Seco drainage near the Escondido campground on the Los Padres National Forest. At this time the Arroyo Seco RAWS was reporting a temperature of 89 F with relative humidity (RH) at 11 % and east northeast winds at 5 mph gusting to 10 mph.

On the morning of Monday June 9th, the fire was estimated to be 400 acres. The fire was burning in steep inaccessible terrain. A high temperature of 102 F was recorded with 5% RH during the afternoon. Winds were east northeast at 3 to 5 mph with gusts to 13 mph. Relative humidity in the valley floor reached 40 % during the night with lows around 6 to 10 % during the day.

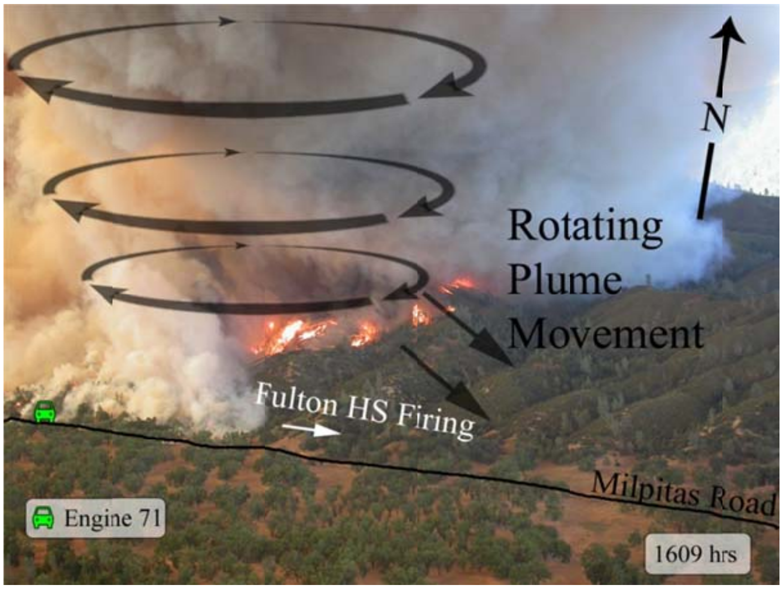
By 0600 hours on June 10th the fire had burned roughly 1100 acres. Fire growth was minimal the previous night. There was not much smoke visible from the fire that morning, and fire behavior was characterized as quiet. Between 2 pm and 5 pm June 10th, the fire activity increased significantly due to the very warm temperatures (95 F) and dry conditions (~5 % RH). A dry cold front was forecast to pass through the region during the night, with strongest winds located north of the fire area. Gusty north winds were to develop behind the cold front with warm and dry conditions forecast to persist for at least another 24 hours. No fire behavior forecast was developed.

By the evening of June 10th, the northern edge of the fire had moved to higher terrain (between 3000 and 4000 feet ASL) and was burning in dense mature chaparral fuels. At 2100 hours on June 10th Red Flag Warnings went into effect across the Bay Area Hills well to the north of the fire for strong north winds and low humidity. There were no Red Flag Warnings in effect over the Indians Fire area, but the conditions were forecast to become drier and windier. The air mass near the ground was very dry and consequently lower elevation relative humidity that night remained near or below 10 % at the Fort Hunter Ligget RAWS. Due to very poor humidity recovery, the fire burned actively all night.

By the morning of June 11th, the day of the entrapment, the fire had burned over 5000 acres. The IAP weather forecast called for north to northeast winds 8 to 18 mph at the ridges becoming north 5 to 10 mph in the afternoon and north 10 mph in the valleys becoming upslope and up canyon at 3 to 7 mph in the afternoon. Forecast fire behavior was also similar with an emphasis on the potential for moderate fire behavior on the south and eastern perimeters that would test containment lines. It was noted in the IAP that firefighters should expect spotting and sustained runs. Temperatures warmed quickly into the 90's at lower elevations (2000 ft. or lower) and RH's dropped to single digits (~5 %) by early afternoon. Ridgetop winds remained from the northeast about 5 to 15 mph, while lower slopes and valleys had lighter, diurnal terrain winds. Fuels along the Milpitas road consisted primarily of light dead grasses in the oak savanna. In the morning, fire behavior in the grass fuels was low, with limited success in a firing operation focused on expanding a safety zone. Around noon another firing operation was attempted. This time fire intensity matched forecast levels, burning actively in the fine grassy fuels driven north by diurnal winds and the ground level winds induced by the main fire further north. By 1400 hours, firefighters observed increased fire intensity as indicated by increased potential for lofting and ignition of new spot fires outside the containment lines.

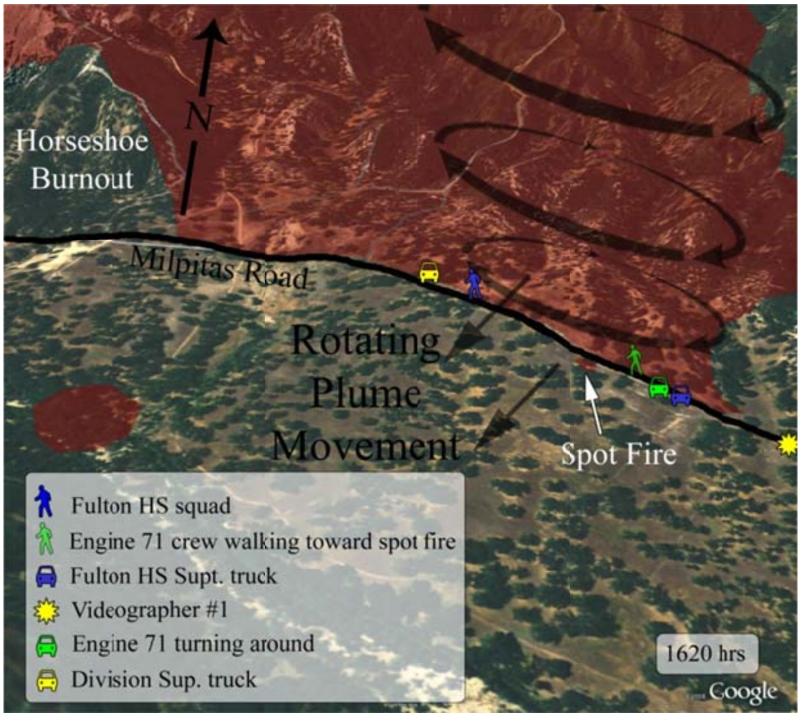
The main fire was now moving east, flanking across the chaparral slopes and making runs up hill to the north of Milpitas Road. The plan was to burn out along the road, heading east and keeping up with the main fire. Photographs of fire behavior in the chaparral on the steep slopes show 20-40 ft tall flames. Post fire inspection indicates intense, nearly complete combustion of all vegetation smaller than ¾ inch in diameter. Large diameter dead fuels were totally burned to white ash. Fire intensity from the burnout near the road in the grass fuels was much lower, with 1-3 ft flame lengths. Although not as intense, the fire spread quickly through the grass fuels toward the main fire.

The firing operation moved from the west to the east and at approximately 1530 hours the smoke plume from the main fire on the slopes north of the road had begun to slowly rotate. By 1557 a large, intense, vertically-oriented, rotating smoke plume was clearly visible above the slopes north of the burnout operation. From video footage, wind speeds in the rotating plume are estimated at 50+ mph (see fig. 1). We speculate that the vertical motion was enhanced by this rotation and was due to



the combination of intense heat released from the chaparral fuels on the slopes and the highly dissected terrain. Photographs indicate that by approximately 1600 the rotating plume was approximately 1000 feet in diameter at its base. The intense rotation would last for over 30 minutes. Video and camera images indicate that this rotating plume was part of the smoke column above the eastern portion of the main fire north of the firing operations being conducted along Milpitas Road (see Fig. 2). Witnesses state that the rotating column appeared to move east, parallel to the firing operation and road. Firefighters at the eastern endpoint of the firing operation had been watching and photographing the large rotating fire plume. Some firefighters stated that they had observed large “fire whirls like that on several occasions”, and did not perceive it to be any real threat to safety.

Also at 1621, the crew of Engine-71 had been assigned to hold the fire along Milpitas Road. At the time they saw a spot fire adjacent to the road only 320 feet west of their location. It was only about 5 ft X 5 ft in size. Three members of the engine crew walked west on the road toward the spot fire while the other two turned the engine around. Once the engine was heading in the correct direction, one of the crew members joined the other three on foot and the driver began to drive the engine toward the spot fire (see fig. 3). Soon after, winds suddenly increased near the crew and engine. The edge of the rotating vertical plume had moved over them and the road. Additional spot fires ignited near the road. The 4 crewmembers on foot were enveloped in strong winds (estimated to be 60-70mph), dense smoke, blowing embers and debris, flames blowing horizontally across the road, and highly variable wind direction and speed. Flame length in the grass is undetermined but flame height was reported to be “knee high” igniting any combustible surface fuels. Firefighters describe a “sheet of flame” over the ground. The spot fire located across the San Antonio River was drawn across the flats toward the main fire. Subsequent photos show active fire underneath the oaks, many of which sustained significant wind damage. After moving onto the flat valley floor the indraft inside the vertical rotating plume scoured any loose material on the ground including pebbles and ash, leaving broad areas of only hard-packed earth. Once the edge crossed the road the rotating plume soon dissipated and fire behavior decreased markedly.



Tornadic events generated by large fires can be extremely dangerous, and apparently occur more often than is generally realized. A brief look into the scientific literature and discussions with veteran firefighters indicate several examples. In 2007 a large fire whirl on the Fletcher Fire in Oregon damaged large trees. Many photos are available clearly showing a tornado-like structure that separates from the main column and moves at least a few hundred yards from the fire. The 2007 Neola Fire in eastern Utah produced similar vegetation damage and also tore the roof off of a nearby structure; three civilians were killed in what appears to have been a tornadic-event similar to that observed on the Indians Fire. The 2002 Missionary Ridge Fire has video documentation of a large rotating vertical plume during which winds were strong enough to overturn vehicles and damage the roof of a building in the area. A 1977 wildland fire in Japan seriously injured firefighters when a rotating plume formed on the lee wind side of a mountain. The 1871 Peshtigo, Wisconsin fire that killed up to 2,500 people was reported to contain a rotating plume that lifted a house off its foundations. In 1926, petroleum tanks near San Luis Obispo, CA ignited and burned intensely for days, generating many large rotating vertical plumes. One whirl was strong enough to lift a cottage located 1,000 yards from the tanks and move it 150 feet. The two occupants of the structure were killed. Evidence exists describing a larger rotating fire plume that occurred during a city fire in downtown Tokyo following an earthquake in 1923 that moved out of the city over a barren area where residents had gone for safety. This event ultimately killed an estimated 38,000 citizens within 20 minutes. Both the Hamburg, Germany and Hiroshima, Japan bombings during World War II also reportedly produced large, intense, damaging rotating plumes that appeared and behaved like tornados.

The main ingredients necessary for rotating vertical plumes of a large scale are a source of vorticity (rotation) and intense heat. Vortices may come from flow channeling from variable terrain/drainage orientation, vorticity induced in the wake of a hill or ridge, or horizontally oriented vorticity present (due to shear near the ground) in the ambient atmosphere that gets tilted to the vertical by the heat source. In all cases of large rotating plumes, an intense heat source is necessary to concentrate the vorticity. In the case of the Indians Fire, the drought had led to extremely dry live fuels and probably a buildup of dead fuels in the chaparral fuel types resulting in a highly flammable condition. The unstable atmospheric conditions promoted vertical transport in the plume. The variable terrain contributed to both enhanced combustion and channeling/blocking of inflow to the plume base. The channeling/blocking of the inflow may have been the initial source of rotation at the plume base. However, once the rotation was initiated the heat source concentrated the vorticity by stretching the plume whirl in the vertical direction, reducing its diameter. This reduction in diameter forced the rotation to increase in speed to conserve angular momentum (just like a figure skater spins faster when her arms are held close to her body). This concentrating mechanism allowed the whirl to obtain high wind speeds and explains the dramatic increase in winds proximal to the plume base. The rotation also significantly reduces the diffusion of energy (both kinetic and thermal) from the rotating plume to its surroundings. The result was a rotating tornado like structure that was able to exist and move across terrain for some distance away from its heat source before dissipating.

Four Types

Four general types of large fire whirls have been identified: 1) plume shedding, 2) L-shaped heat source in cross flow, 3) ambient vertical vorticity, and 4) lee side of hill or mountain.

The Neola fire and possibly the Indians fire fire-whirls are examples of the plume shedding phenomenon. Vortices shed off a main fire front due to shear from the ambient wind. The whirl forms on the lee wind side of the plume. It separates from the plume and advects in the downwind direction. It is very similar to Von Karman vortex shedding behind an obstruction in a flow. Wind in the whirl can be strong enough to cause damage to trees, structures, vehicles, etc. The whirl may stay intact for several minutes and travel for distances of possibly 1 mile. The fire whirls's ability to stay intact even though most of its vortex stretching mechanism (buoyancy) is lost is probably due to the strong reduction in turbulent diffusion of the core. Examples of this type of whirl have been reported by many authors (Church *et al.* 1980; Dessens 1962; Hissong 1926; Pirsko *et al.* 1965; Soma and Saito 1988; Soma and Saito 1991)

The second type or L-shaped heat source in cross flow is easily demonstrated in the laboratory. The whirl is generated by the cross flow interacting with the blocking effect of the corner of an L-shaped heat source. The great Kanto Earthquake fire in Tokyo Japan is an example of this type of fire whirl (Soma and Saito 1991). The whirl forms on the interior of the "L". This is also demonstrated at times from flow over randomly oriented heat sources (see fig. 4). If the orientation of the heat sources is such that a shear is formed then it is possible that a fire whirl will form over some area of the heat sources.

Fig. 4--Image of fire whirl generated by flow over randomly oriented heat sources.

The third type or ambient vertical vorticity is more associated with cold front passage (see fig. 5). It is caused by interaction between the vorticity that is generated by general flow field being rotated to the vertical and then developing into a fire whirl. It is generally associated with flat terrain, or terrain that has features that generate significant shear.

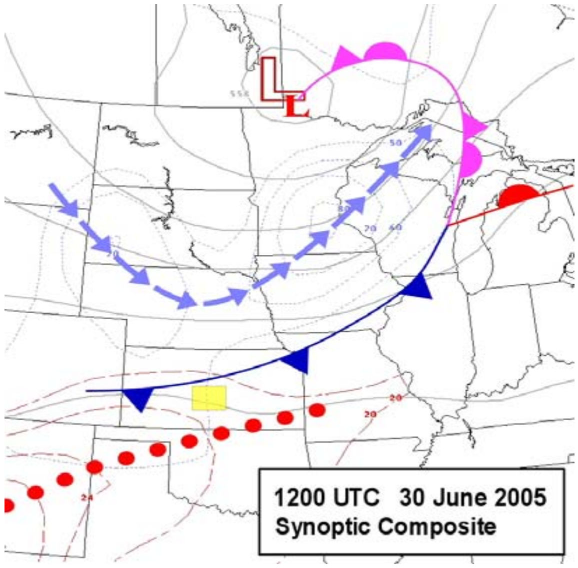


Fig. 5--Vorticity associated with cold front passage has been shown to generate large fire whirls.

The fourth type is generally formed by interactions between a fire located on the lee side of a ridge (see fig. 6). Vorticity generated in the wake of the mountain contributes to the formation of a fire whirl (Countryman 1971).

Common Factors

All four types of large fire whirls can be defined by four common factors: 1) a large heat source. The energy needed to form a fire whirl is significant and requires a large heat source. 2) Unstable atmosphere: For the most part, fire whirls form most easily when the atmosphere is unstable. Instability enhances that opportunity for vortex stretching and fire whirl formation. 3) Strong source of vorticity: all fire whirls require that significant vorticity be present in the flow. However, there are substantial sources of vorticity in most fires such as terrain features or multiple fire locations. 4) Low to moderate ambient wind: while some cases have been documented, in general, large rotating plumes do not develop in strong ambient winds.

Summary

To summarize, the Indians fire demonstrated the scale and danger associated with large rotating fire plumes. A review of the technical literature indicates that such plumes are not unusual given the appropriate set of environmental conditions. When the conditions are present, large rotating plumes can be generated that exhibit many of the characteristics of tornados, including high speed winds. In general it appears that such tornadic flows are very possible in large fires and can persist for 10-40 minutes and in some cases move almost independently of the fire. The added danger is that they can carry burning material with them, spreading the fire outside its normal boundaries. The best defense seems to be having lookouts at both close and long range that can provide up-to-the-minute information for fire crews working in the area. Clearly, when large fire whirls are observed, firefighters should note their presence to others in the area and consider modifying tactics.

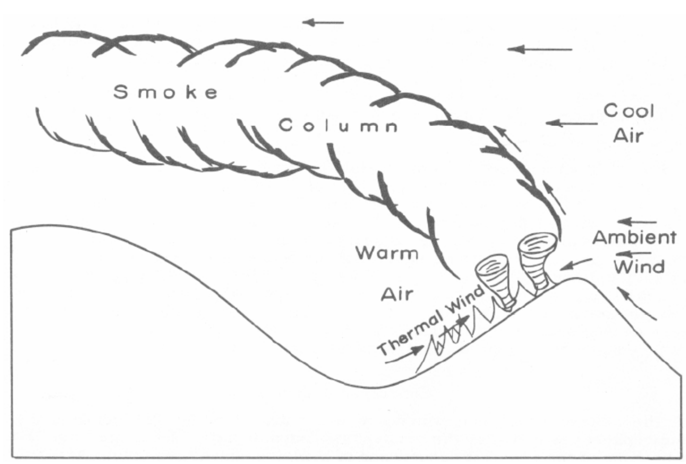


Fig. 6--Flow around and over a terrain obstruction has been shown to generate fire whirls on the lee side (Countryman 1971).

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