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Photographs and Analysis of an Unusually Large and Long-Lived Firewhirl

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ABSTRACT

On 30 June 2005, a large and long-lived firewhirl was observed and photographed over a field being burned to remove wheat stubble in central Kansas. With a well-defined boundary focusing vertical vorticity in the immediate vicinity, the meteorological setting appeared to have at least some similarity to those associated with many nonmesocyclone tornadoes. This paper photographically documents the firewhirl and its evolution. In addition, an examination of the synoptic and local meteorological environment suggests that a pre-existing frontal boundary contributed to the occurrence and longevity of the firewhirl in this interesting and unusual case. Although they are clearly different phenomena, firewhirls and nonmesocyclone tornadoes appear to share some similarities in formation mechanisms that are illustrated by this case.

1. Introduction

During the late afternoon of 30 June 2005, a long-lived firewhirl (see Fig. 1) occurred over a wheat stubble field prescribed burn in central Kansas. The fire front was approximately 300 m wide at the time of the firewhirl development. The firewhirl, which towered approximately 200 m and lasted around 20 minutes, occurred in the vicinity of a slow moving cold front that we hypothesize played an important role in the evolution, longevity, and strength of this vortex. The unusual duration and size of this fire-spawned vortex, combined with the presence of the frontal boundary, suggest nonmesocyclone tornado processes supplemented local fire vortex generation to support this unique and unusual

Figure 1: A large firewhirl over a burning field of wheat stubble; the view is looking southeast from approximately 800 m away. Photo by Michael Umscheid

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event. The purpose of this paper is to present photographic documentation of the evolution of the firewhirl along with supporting radar, satellite, and surface observation analyses.

2. Firewhirls and Nonmesocyclone Tornadoes

Strong rotation can occur in the convective columns associated with fires. Countryman (1971) shows various configurations of fire, wind, and terrain that are favorable for what are popularly known as "firewhirls" and that these vortices occur across a range of fire sizes and terrain conditions.

Firewhirls also have been observed in association with fires occurring in surface meteorological conditions ranging from quiescent (i.e., light winds, clear skies) (see e.g. Clark et al. 1999) to stormy (i.e., strong winds, thunderstorms). Typically, however, although modeling studies of fire growth and evolution include initial meteorological conditions featuring a range of wind speeds, other aspects of the initial meteorological state are relatively benign.

One of the earliest documentations of firewhirls in the refereed literature appears in Hissong (1926). He describes large firewhirls that developed after lightning struck an oil storage facility near San Luis Obispo, CA. Several firewhirls were observed to develop on the margins of the fire, and significant damage occurred to surrounding structures, with the loss of two lives. Since severe thunderstorms were in the vicinity, and there is anecdotal evidence that tornadoes also occurred in other areas away from the fire, this instance can be thought to represent an extreme example of firewhirl formation in an environment already conducive for tornado formation. This instance also underscores that there may be meteorological ingredients associated with the subsynoptic or mesoscale environment that can augment whatever vertical vorticity generating processes are associated with fires themselves in the development of firewhirls.

Recent analyses of video imagery during a crown fire (i.e., fire restricted to the tops of trees) (Clark et al., 1999) show derived vertical vorticity on the order of 4 to 10 s^{-1} along the fire front, values similar to those observed in weak tornadoes. Observations from the study by Clark et al. (1999) also indicate that vorticity associated with this fire was caused largely by tilting and stretching of horizontal vortices produced by the fire's horizontal thermal gradients on the forward side of the fire line. Vortices occurred near the nose of the fire, with the main vortex tilting occurring at that location. Counter-rotating vortices were also observed on either side of the fire nose, caused by ingestion, convergence, and tilting on the flanks of the fire line. Visible rotation in each of these cases likely would be described as "firewhirls."

Models that simulate wildland fires often depict large firewhirls (Coen 2005) for a range of fire sizes and topographic configurations. The National Center for Atmospheric Research's (NCAR) coupled atmosphere fire model has been used to simulate the large-scale interactions between fire and local winds. Clark et al. (2004) used the model to capture the spread of fires of different sizes and across a range of surface conditions.

Of particular relevance to the present study was the modeled fire on flat terrain with a fire line 140 m long in a light surface wind environment (3 m s^{-1}) (Clark et al. 2004). The fire size and surface conditions are similar to those in the case documented here. Results show that the convective circulation rooted at the head of the fire advected low level air upwind to the back of the fire. Non-linear processes due to terrain or fuel inhomogeneities induced perturbations on the edges of the fire line, affecting the spread rate into unburned areas downwind. Clark et al. (2004) hypothesize that these perturbations augmented horizontal vorticity generation along the fire line through tilting and stretching into the fire updraft, producing firewhirls.

It is also well known that tornadoes can occur along convergent wind shift boundaries with newly developing, multicell storms (e.g., Burgess and Donaldson 1979). On radar, signatures associated with these tornadoes are smaller and typically shallower than those associated with supercell storms and their associated mesocyclones (e.g., Burgess et al. 1993), and are called misocyclones (Fujita 1981). In the 1980s, the term "landspout" (Bluestein 1985) came into use for tornadoes from these circulations because of their similarity to waterspouts. Additional observations and research suggest that these "nonmesocyclone tornadoes" (Brady and Szoke 1989), also called "nonsupercell tornadoes" (Wakimoto and Wilson 1989), develop from pre-existing low-level vertical vorticity circulations along sharp wind shift boundaries that are stretched by expanding updrafts above the circulations. Modeling experiments by Lee and Wilhelmson (1997, 2000) confirm that nonmesocyclone tornadoes occur when horizontal shearing perturbations in vertical vortex sheets along boundaries are stretched by updrafts. Wilczak et al. (1992) also found that tilting of local horizontal vorticity near these boundaries could contribute to nonmesocyclone tornadoes.

Donaldson and Burgess (1982) noted that boundaries associated with nonmesocyclone tornadoes are often detectable as clear air echoes (lines) on radar. Recent studies, such as Pietrycha and Manross (2003) and Caruso and Davies (2005), show the importance of boundary detection and evolution using radar reflectivity and velocity products in nonmesocyclone tornado settings. Brady and Szoke (1989) and Davies (2006) also link nonmesocyclone tornadoes to steep low-level lapse rates (near the dry-adiabatic rate) that could generate rapidly rising low-level parcels and stretching beneath updrafts, similar to boundary-layer thermodynamic profiles associated with dust devils.

There are some evident similarities between fire vortices and nonmesocyclone tornadoes. As in the relationship between nonmesocyclone tornadoes and mesoscale wind shift boundaries, firewhirls occur on the fire line boundary, as described earlier. This boundary serves as a source of vorticity. Vertical stretching in both cases comes from rapidly rising air parcels in steep low-level lapse rate environments above a surface heat source (heated ground from insolation in the case of nonmesocyclone tornadoes, the fire in the case of firewhirls). Because the vorticity and stretching ingredients have similarities, it is conceivable that a mesoscale meteorological feature (e.g., a pre-existing wind shift boundary) could combine with a local fire to help generate a long-lived firewhirl, an issue examined in this paper.

3. Meteorological overview

a. Synoptic setting

The morning synoptic scale environment prior to the afternoon firewhirl in central Kansas is shown in Fig. 2. At 1200 UTC 30 June 2005, the upper air analysis depicted an upper level trough over the northern plains with a surface extra-tropical cyclone centered near the Minnesota-Canada border. The cold front associated with this low moved south through the central plains during the morning.

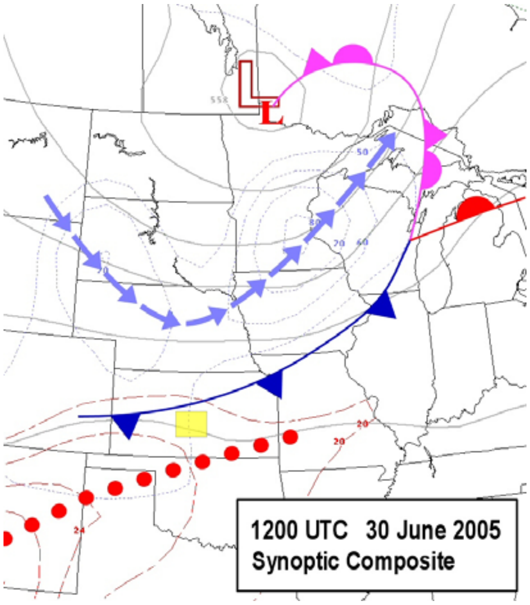


Figure 2: Composite map of synoptic scale meteorological conditions valid 1200 UTC on 30 June 2005. Isotachs at 250mb are dotted blue and the jet core is indicated by blue repeating arrows. Geopotential height at 500 mb is contoured in solid light grey, with the 500 mb low indicated by a hollow red "L". Isotherms at 850mb are dashed red lines with the warm axis shown by repeating large red dots. Surface fronts are shown using standard symbols and colors with the surface low indicated by red filled "L". The yellow box indicates the region of interest in southern Kansas where the firewhirl was observed.

Ahead of the front, a low-level thermal ridge (analyzed at 850 mb in Fig. 2) extended from New Mexico east-northeastward into far southern Kansas and northern Oklahoma. The front moving south into Kansas became increasingly parallel to the middle and upper tropospheric flow, thus slowing its speed. Strong afternoon insolation and surface heating ahead of the front also helped slow the forward frontal motion by late afternoon (Fig. 3).

b. Buoyancy and shear environment

Direct insolation was present for much of the afternoon along the advancing front in the vicinity of the field fire, allowing surface temperatures to reach near 35 °C (mid 90s °F) along and south of the front. Local Analysis and Prediction System (LAPS, Albers et al., 1996) analyses showed that surface dew points approaching 18°C (low to mid 60s°F) were prevalent along the frontal boundary as well (Fig. 4).

An hourly LAPS analysis sounding valid 2100 UTC for a location within 5 miles of the field fire (Fig. 5) showed a well-mixed profile from the surface to about 2 km AGL with a mean lapse rate of around 10 °C km^{-1}. The sounding also showed a moist profile with a mean mixing ratio of around 12 g kg^{-1} through this mixed depth, resulting in nearly 2500 J kg^{-1} convective available potential energy (CAPE) from a surface-based lifted parcel.

Towering cumulus had developed around 2030 UTC (Fig. 3) along the front from Pawnee and Edwards County east into Stafford and Barton County. A plan view LAPS analysis of surface wind and vertical vorticity (Fig. 4) at 2100 UTC showed an axis of maximum vertical vorticity along the front from near Dodge City, KS (KDDC) east-northeastward to around Hutchinson, KS (KHUT). The analysis showed this axis of maximum vertical vorticity positioned very close to the location of the field fire where the firewhirl developed. The LAPS sounding in Fig. 5 showed very weak low-level shear in the local environment, with 0-1 km AGL total shear only around 5 m s^{-1} and storm-relative helicity only 24 m^2 s^{-2} using the ID method (Bunkers et al. 2000) for the same depth.

4. Firewhirl evolution

The lead author photographed the entire evolution of the field firewhirl from its genesis around 2135 UTC to its demise at around 2155 UTC (Fig. 6a-i). Doppler radar analyses from the Wichita, KS WSR-88D at the same time indicate fine-line oriented east-west in the 0.5° base reflectivity data, shown in Fig. 7 from 2115 to 2221 UTC. This fine-line was likely associated with the primary wind shift of the cold front itself, as it was moving south over the field fire. At 2115 UTC, radar showed the fine-line entering northeastern Stafford County (Fig. 7a), approximately 15 miles north of the field fire, which was already underway at the time. By 2137 UTC, the fine-line was within only a couple of miles of the field fire (Fig. 7b), around the time that the large and intense firewhirl was maturing rapidly and taking on the appearances as shown in Fig. 6. The vortex underwent several different stages of appearance during its lifetime, summarized chronologically in the 9-panel of photographs in Fig. 6a-i.

Over approximately the next ten minutes, the vortex remained compact and intense as it meandered slowly south over the field. At various moments during the mature stage of this firewhirl, the circulation at the base of the vortex was exceptionally intense, and significant damage could have occurred had this firewhirl moved over a farm house or other structure. At 2154 UTC, radar showed the fine-line beginning to move south of the location of the field fire and ongoing firewhirl (Fig. 7c). A reflectivity signature of the field fire itself was beginning to show up, indicated by a small ~30 dBZ reflectivity maximum with a northward extending plume of lower reflectivity values near the fire (Fig. 7d). After approximately 2148 UTC the vortex began visually to expand in diameter, taking on the appearance shown in Fig. 6g-i. This wide, yet impressively tall vortex structure remained coherent up until about 2155 UTC when the entire vortex column began to visually collapse as it continued moving slowly south.

At 2221 UTC, almost a half hour after the firewhirl dissipated, radar showed the fine-line associated with the cold front 11 km south of the field fire (Fig. 7d). By this time, the prescribed field fire had diminished, yet the remnant lofted smoke and soot from the fire were still visible on radar as a small reflectivity plume maximum over east-central Stafford County.

5. Summary and Conclusions

This well-photographed and unusual case suggests that the mesoscale meteorological setting can play a significant role regarding development of firewhirls when combined with local fire vortex generation processes as summarized in section 2. We hypothesize two primary sources for the vorticity in the firewhirls: 1) the tilt and vertical stretching of horizontal vorticity generated by the thermal gradients associated with the field fire; and, 2) the stretching of pre-existing vertical vorticity present along the slow-moving synoptic scale front (e.g., Brady and Szoke 1989; Wakimoto and Wilson 1989). Although probably not a primary source given the weak horizontal temperature gradient across the front (Fig. 4), it is also possible that some horizontal vorticity from solenoidal circulations was available along the front, which could be tilted and stretched into the vertical.

The importance of the slow-moving frontal boundary in this case is supported by photo and radar data discussed in section 3 showing that the firewhirl development and intensification corresponded with the southward passage of the front (indicated by a fine-line on radar) over the field fire location. The lead author observed very intense rotation at times with the firewhirl, and the vortex itself was sustained for nearly 20 minutes.

The scale interaction of vorticity from the field fire with the synoptic front appeared to be important, and probably augmented local processes contributing to the firewhirl generation. The firewhirl occurred in the most diurnally favored time of day as a deep mixed-layer developed from direct insolation. As a result, steep lapse rates already present in the low-level environment (e.g., Davies 2006), were further enhanced by the field fire. The combination of local fire vortex generation, a deeply mixed adiabatic environment, and the production of enhanced vertical vorticity associated with a slow-moving front all appeared to contribute to the unusual strength and longevity of this well-documented firewhirl. It may behoove meteorologists and emergency management officials to be aware of mesoscale meteorological features that can interact with local fires regarding production of intense firewhirls like the one documented in this case study.

Acknowledgments. The authors would like to thank the National Weather Service in Wichita, Kansas for providing the 88D radar data used in this study.

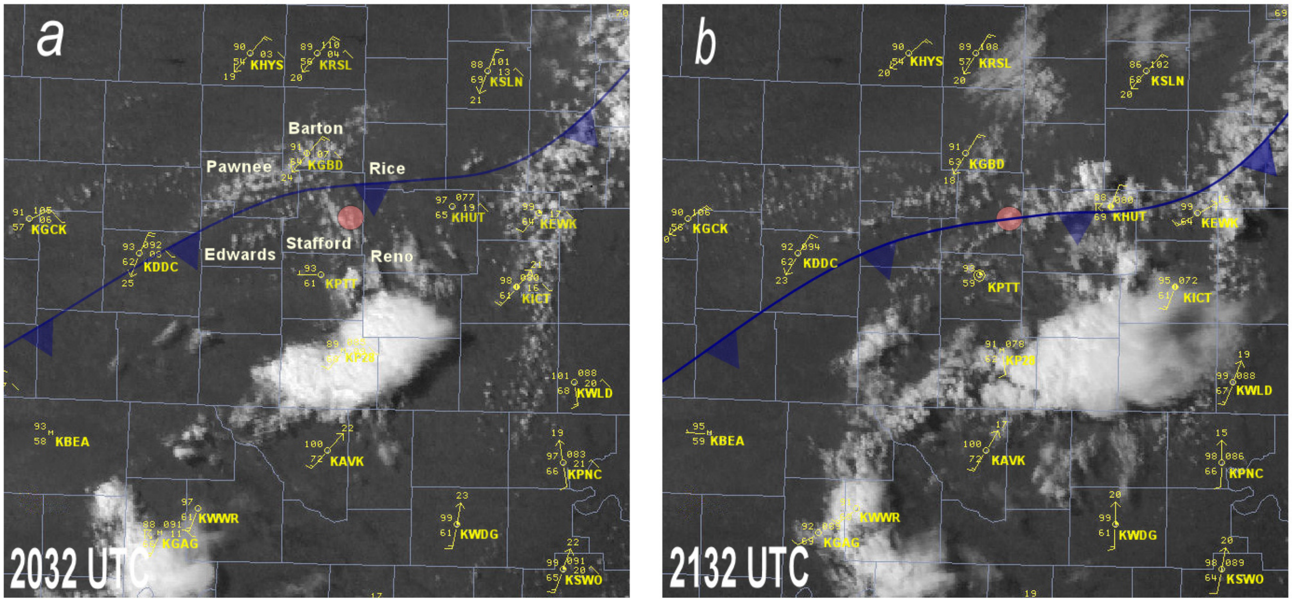


Figure 3: GOES-12 1km visible satellite valid (a) 2032 UTC and (b) 2132 UTC. Surface cold front is analyzed using conventional symbol. Surface METAR station plots are shown in yellow. The red circle indicates the location of the firewhirl. County boundaries are in light grey with county names shown in the area of interest.

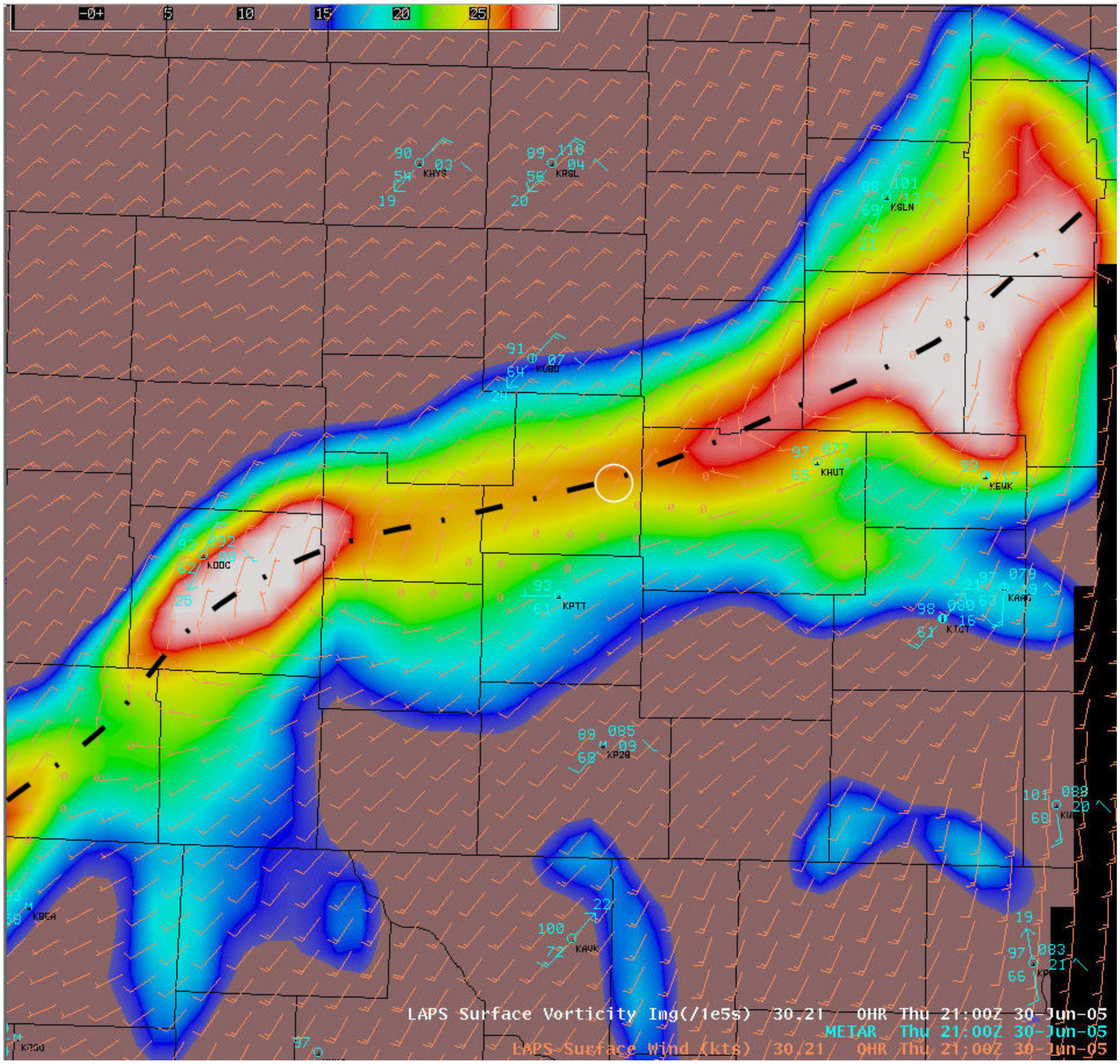
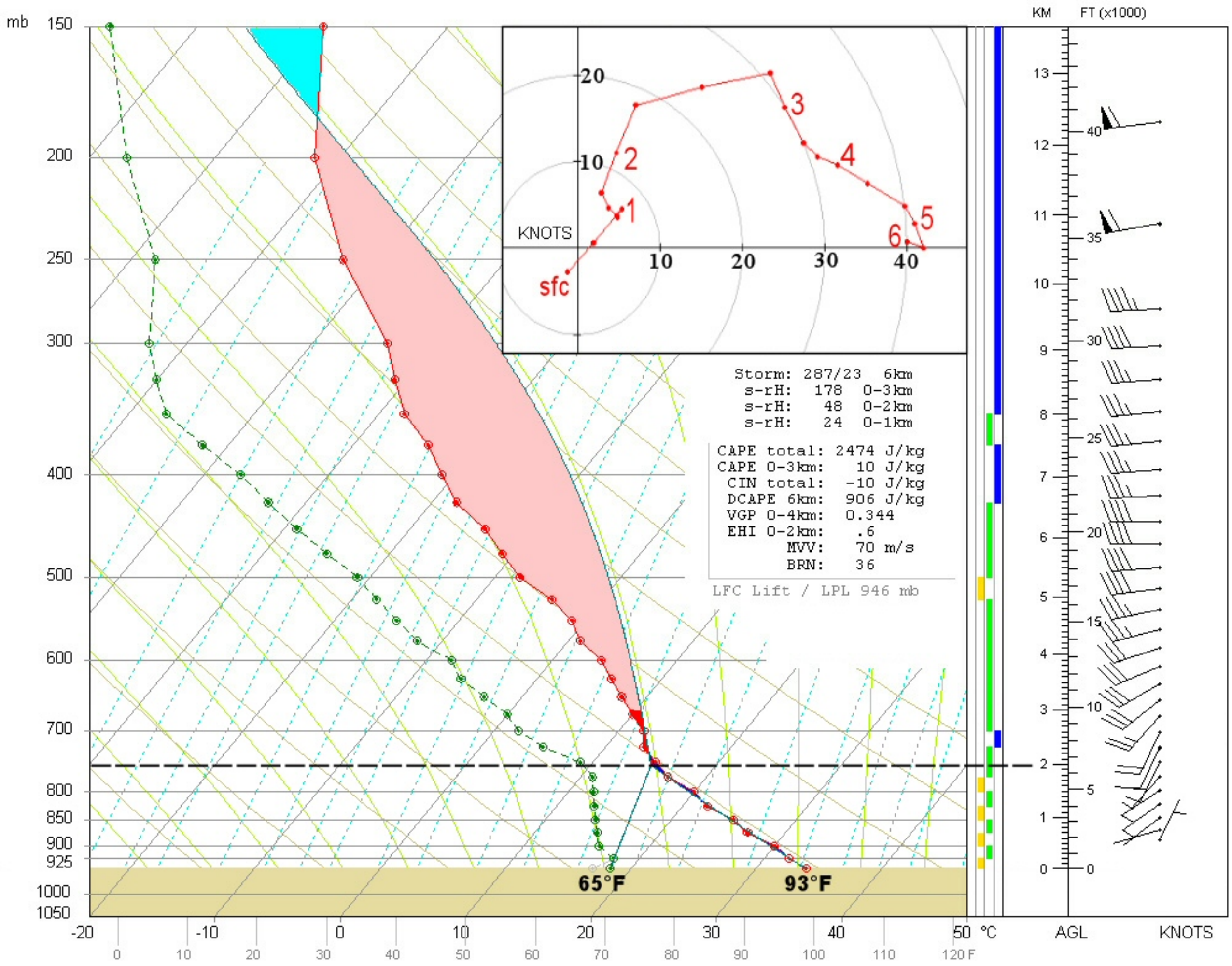


Figure 4: LAPS objective analysis valid 2100 UTC. The color image shows surface vertical vorticity (10^{-5} s^{-1}) where warmer colors indicate larger values. Surface wind flow (knots) is shown in orange. Surface METAR station plots are in cyan. Thick dash-dotted line represents axis of greatest surface vertical vorticity, and the thin white circle denotes the location of the firewhirl. Black lines are county outlines.



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Storm: 287/23   6km
 s-rH:  178  0-3km
 s-rH:   48  0-2km
 s-rH:   24  0-1km

CAPE total: 2474 J/kg
CAPE 0-3km:   10 J/kg
 CIN total:  -10 J/kg
 DCAPE 6km:  906 J/kg
 VGP 0-4km:  0.344
 EHI 0-2km:   .6
       MVV:   70 m/s
       BRN:   36
LFC Lift / LPL 946 mb
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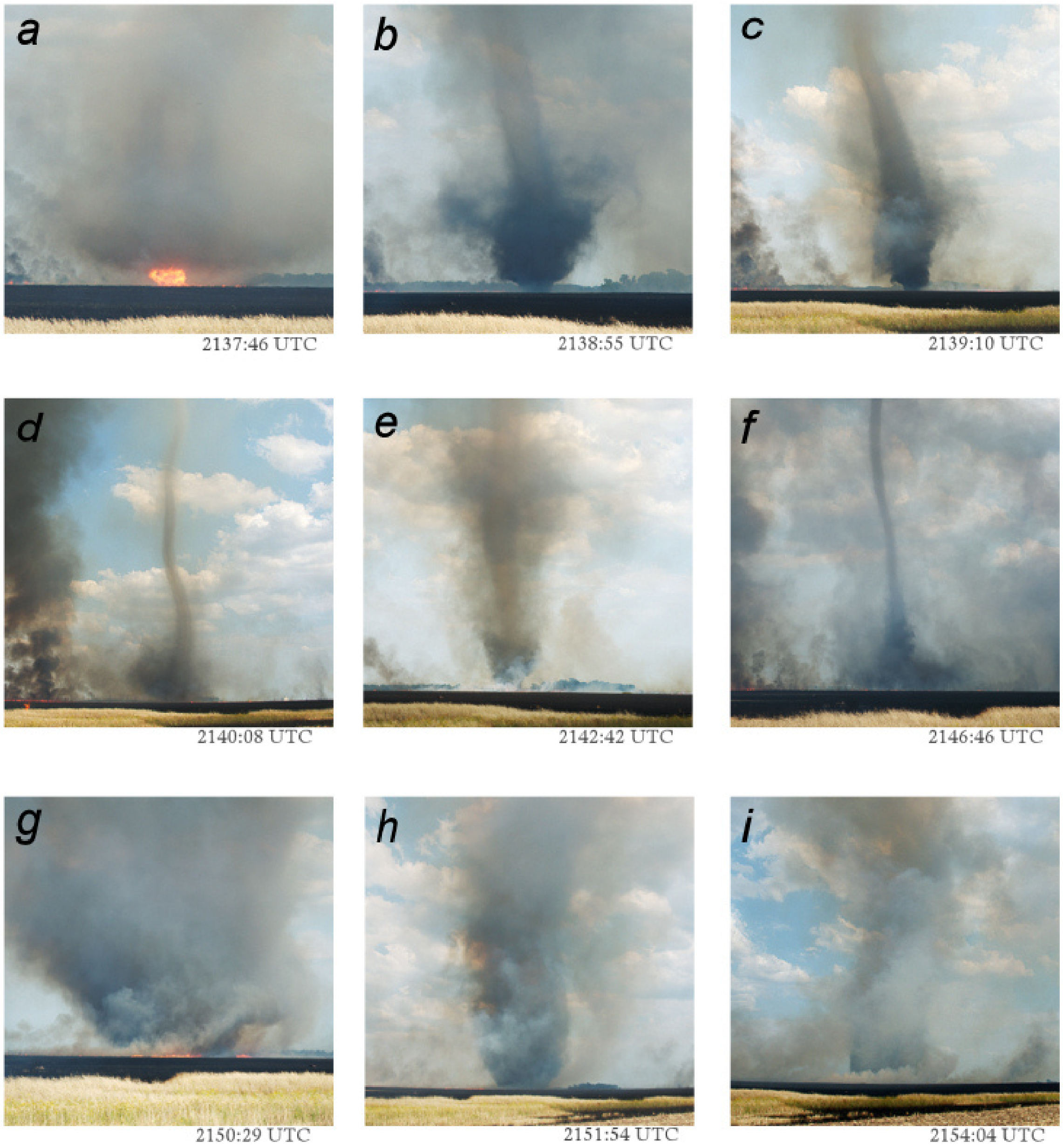
Figure 5: Skew T-log p diagram of LAPS analysis profile with hodograph inset at a location within 8 km of the firewhirl at 2100 UTC. Temperature curve is in red and dew point curve is in green. Dashed black line represents top of the dry adiabatic mixed layer. Light red shading shows CAPE region and cyan shows CIN region from a surface-based lifted parcel. The hodograph inset shows the LAPS wind profile in red with red numbers indicating height in kilometers AGL.



2137:46 UTC
2138:55 UTC
2139:10 UTC
2140:08 UTC
2142:42 UTC
2146:46 UTC
2150:29 UTC
2151:54 UTC
2154:04 UTC

Figure 6: A series of digital photographs of the firewhirl between 2137 and 2154 UTC. Times shown for each image are times taken from each photograph's EXIF data. All images in this series were taken from the same location looking southeast at a distance of approximately one-half mile away from the firewhirl. (Photos by Michael Umscheid)

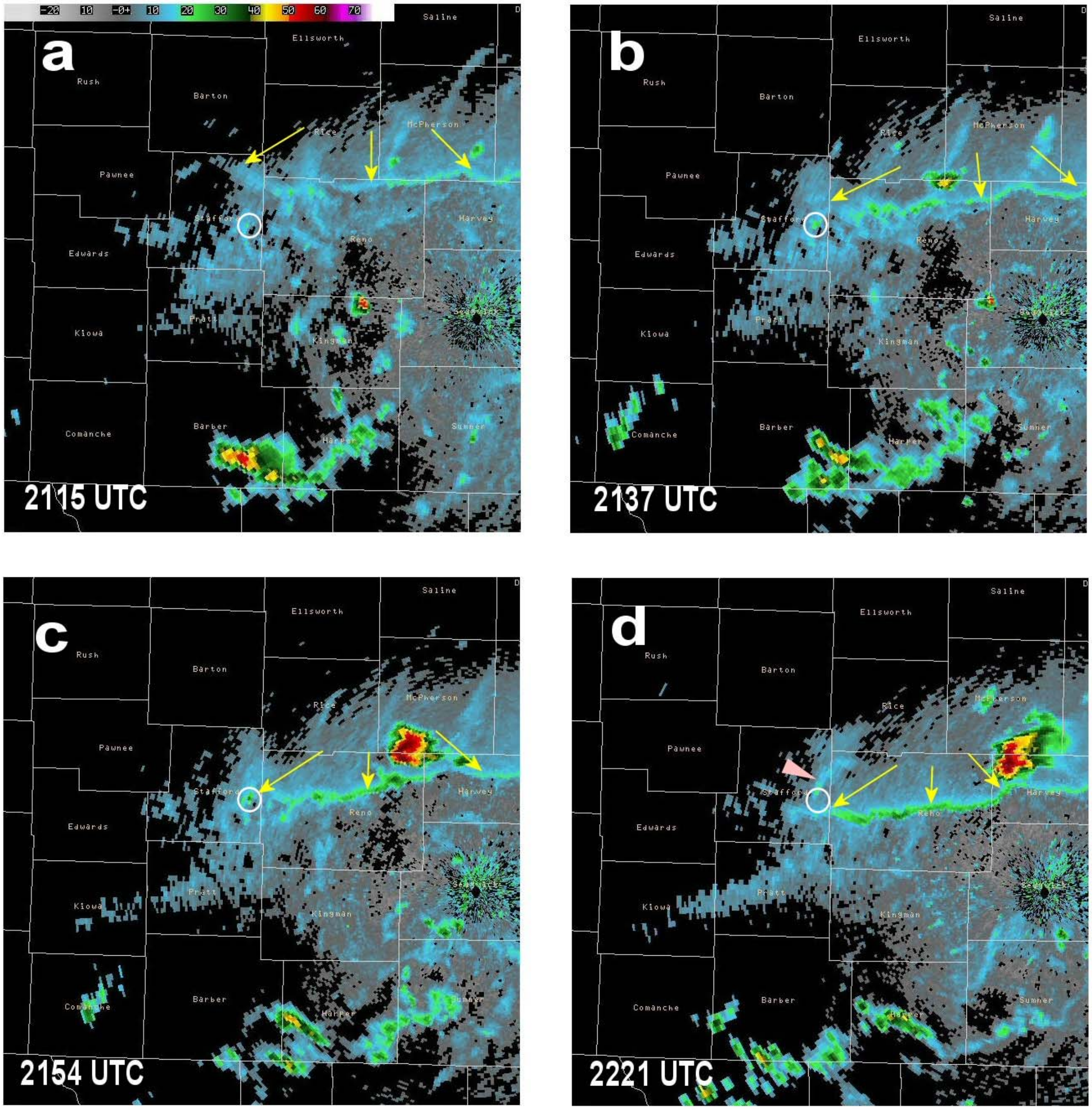


Figure 7: KICT WSR-88D 0.5° reflectivity 4-panel between 2115 and 2221 UTC. Yellow arrows show prominent fine-line associated with frontal boundary. The white circle indicates the location of the firewhirl. In panel (d), a pink carrot points to the reflectivity signature of the smoke plume associated with the field fire. Base reflectivity scale (dBZ) is shown in panel (a).

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REVIEWER COMMENTS

REVIEWER A (Peter C. Banacos):

Initial Review:

Recommendation: Accept with minor revisions

Summary: This paper is well-organized, interesting, and contains carefully constructed analysis work which leaves little question as to the importance of the mesoscale boundary on the development of a "firewhirl" on the central Plains. The paper primarily serves to document a mode of fire behavior that conceivably has relevance to prescribed burns and fire weather aspects of fire fighting and control. The paper also outlines similarities to the "land spout" process, which leaves open some debate as to the how critical the positive low-level buoyancy perturbation over the fire was to the generation of - what otherwise strongly resembles - a classical non-mesocyclone tornado environment. While I hope the authors can shed some additional light on the latter issue, regardless, this paper is quite worthy of publication pending attention to the points listed below. I suspect most of the minor points can be addressed rather easily. Overall, this paper is a fine contribution by Umscheid, Monteverdi, and Davies to the EJSSM.

Major Comments:

1.) The authors spend time in Section 2 discussing similarities between fire vortices and nonmesocyclone tornadoes. There are also possible differences which are not mentioned, one being that a fire in dense fuel loadings – as might exist in a heavily forested area - will exhibit different fire behavior than, say, a grass fire. My major question is the extent to which the spatial and temporal scale of the previously documented firewhirls (e.g. in works by Countryman, Clark et al., etc.) conforms to the firewhirl analyzed here. Video of firewhirls I've been exposed to appear to last on the order of seconds and have heights on the order of 10 m. The central KS firewhirl of 30 June 2005 appears to be much larger, on the order of 100 m while lasting about 20 minutes. Perhaps more important, the diameter of the 30 June 2005 firewhirl appears from the photographs to be on the scale of the fire itself, whereas some firewhirls are clearly small in proportion to the parent fire. The relevant processes responsible for generating a small-scale "whirl" on the front-flank of a fire line (e.g., through horizontal thermal gradients and associated vorticity generation), may be inconsequential to the development of a much larger vortex as is documented here. I'm not convinced that this is much more than a standard nonmesocyclone tornado whose genesis benefited from updraft enhancement due to the positive CAPE perturbation inherent to the turbulent plume rising from the prescribed burn area. That seems plausible based on the data presented.

   The authors do not explicitly mention the spatial and temporal dimensions of the firewhirls in the papers cited, which is of some concern. Since the average meteorologist does not have access to some of these journals, this is particularly problematic. Also, is anything known about the area of the wheat field and how much stubble was burned? In the end, I want to be sure we are comparing "apples to apples" in terms of the spatial dimensions of the Kansas firewhirl and those which have been previously published. Also, it would be fair to mention what the differences are between previously cited firewhirls and this event. The relevance of the previous works to this event is questionable without addressing the dimensionality issues central to dry convection.

2.) As an offshoot of the previous point, the environment in which the central Kansas firewhirl occurs appears predisposed to the nonmesocyclone tornado events which are common in the region under the synoptic and low-level thermodynamic regime present on 30 June 2005. To the extent that the authors are solely trying to demonstrate the effect of the larger-scale environment on behavior of the prescribed fire (e.g., evolution of a firewhirl due to juxtaposition of the frontal boundary, steep lapse rates, deep PBL), this is not a problem. However, it is unclear the extent to which the authors may be implying that the fire was instrumental to the development of a low-level vortex (of any kind) on this particular day. In other words, it's plausible that a nonmesocyclone tornado could

> have occurred in this region absent the fire associated with area towering Cu or thunderstorms. I’m left wondering if the authors believe that the presence of the fire was requisite to low-level vortex generation (through additional buoyancy/vertical stretching), or if a “traditional” nonmesocyclone tornado could have otherwise occurred. Admittedly, there is no way of knowing for sure. However, were there any other reports of “spin-ups” along the boundary other than over the fire? It might be worth saying this was the only observed whirl along the boundary, if that was the case.

Second Review:

The authors have satisfactorily addressed points made in my initial review, and I believe this paper is ready for publication in the *EJSSM*. I thank the authors for their attention to these important details.

REVIEWER B (William Eckrich):

Initial Review:

The paper is acceptable with two minor recommendations.

[Minor comments omitted.]

May I add that the article was well-written and well-presented. I would expect nothing different from the authors involved. Even some of the most intense wildland fires I have witnessed, investigated, or actually help fight have not produced firewhirls of this magnitude. I believe the evidence you presented did a brilliant job of explaining the evolution, intensity and longevity of this particular firewhirl. Having studied Dr. Bruce Lee's work with the modeling of nonsupercell tornadogenesis both through his writings and with him personally, I agree that this situation fits those parameters quite well. The difference here is that a different source (fire vs. thunderstorm) was exploited and rather well.

Second Review:

I do not feel further review of the article will be necessary. My two recommendations were rather minor. One involving aesthetics and readability and the other an additional descriptor that could add to the overall description of the vortex. I would not mind hearing of any responses from the authors, but I certainly believe these recommendations are not critical and they could go forward without implementing them. The science and past studies applied to this event were accurate and appear quite relevant. The article was presented very well.

REVIEWER C (Alan R. Moller):

Initial Review:

The scientific content of the paper is very good. Indeed, I am convinced from the current supporting analysis that the mesoscale meteorological environment can play a significant role regarding the development of firewhirls. Of course, further documentation of this type of event is needed.

However, I think that the authors are lacking, somewhat, in supplying to their projected audience the full relevance and significance of firewhirl events.

For instance, years ago in an old MWR issue, I found a report of a killer firewhirl near San Luis Obispo, CA in 1926. It was the winds, not the fire that killed two people and injured one when a house they were in was destroyed by the firewhirl. The original article was not only in MWR, but much later on p. 801 of Grazulis' Significant Tornadoes, 1680-1001.

The authors need to find the date of the MWR article and reference it. Have injuries or death occurred elsewhere, and/or has anyone been killed by the intense heat of a firewhirl? Are there additional references that have not been cited by the authors?

Do firewhirls add additional dangers, above the wild fire itself, to firemen and/or citizens? Can firemen benefit from the knowledge that certain meteorological conditions make the formation of firewhirls more likely?

The quality of the English in the paper is good, but some improvements are necessary.

[Minor comments omitted]

Additional scientific issues:

Authors should:

> 1) Define "crown fire", LHS, p. 2, 1st para., line 6.
>
> 2) Clarify the discussion about "non-mesocyclone tornadoes" and "non-supercell" tornadoes, on p.2, RHS, para. 1, lines 2-10. Since both mets and fire weather professionals are likely to see this article. It may not be clear to readers that supercells can contain "non-mesocyclone" tornadoes.
>
> *[Minor comments omitted]*

P.S. When the article is completed, the authors should strongly consider another version for fire fighters' journals. This is even more appropriate at this time, because of the intense drought/extreme wild fire threat across the south central and southwest portions of the U.S. this year.

Second Review:

My congratulations to the authors for a very interesting paper.

[Minor comments omitted]