FINAL REPORT

Title: **Evaluating thunderstorm outflow boundaries in WRF-Fire**

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Abstract

Strong and variable winds in thunderstorm outflow boundaries interact with wildland fires, often spreading flames faster to threaten firefighter safety and amplify economical destruction. These boundaries are difficult to detect in complex terrain with operational observing networks, so reliable forecasting is required to protect life and property. One such forecast model, the Weather and Research Forecasting model coupled with a wildland fire-behavior module (WRF-Fire), has exhibited some skill in accurately predicting thunderstorm outflow boundaries in complex terrain, but rigorous validation still needs to be established before WRF-Fire can be relied upon in wildland fires. The overarching goal of the proposed research is the validation of the WRF-Fire model's capability to accurately predict the development, movement, and magnitude of thunderstorm outflow boundaries in complex and flat terrain and during wildland fire conditions. The objectives of the proposed research are to: (Obj. 1) Evaluate the ability of WRF-Fire in non-fire conditions to accurately predict the timing, location, and characteristics of thunderstorms and their outflow boundaries and their interactions with the local terrain using state-of-the-art research instruments and operational networks; (Obj. 2) Evaluate forecast skills of WRF-Fire in terms of timing, location, and strength of thunderstorms and resulting outflow boundaries for past wildland fire events in complex terrain; and (Obj. 3) Develop and test ideas and approaches on how to evaluate forecast skills in real-time and how to best communicate outflow boundary characteristics and model uncertainties to the operational fire weather community. The research combines state-of-the-art numerical modeling using WRF-Fire, currently used by the fire weather community, with operational and state-of-the art observational tools. It quantifies model skills and uncertainties as a function of atmospheric conditions and terrain. The research outcome advances our knowledge and understanding of outflow boundary characteristics and their interaction with terrain and ambient atmospheric conditions and quantifies the forecasting skills of WRF-Fire for thunderstorms and their outflow boundaries. The proposed research evaluates the utility of research instruments such as microwave radiometers, profiling lidars, profiling sodars, profiling and scanning radars, and radar wind profilers for quantifying outflow boundary characteristics in complex terrain and will develop methods that can be used operationally for real-time model assessment and model uncertainties that can be communicated to the fire weather community.

1. Objectives

Objectives: The objectives of the proposed research are to: (

Obj. 1) Evaluate the ability of WRF-Fire in non-fire conditions to accurately predict the timing, location, and characteristics of thunderstorms and their outflow boundaries and their interactions with the local terrain by using state-of-the-art research instruments and operational networks;

Obj. 2) Evaluate forecast skills of WRF-Fire in terms of timing, location, and strength of thunderstorms and resulting outflow boundaries for past wildland fire events in complex terrain; and

Obj. 3) Develop and test ideas and approaches on how to evaluate forecast skills in real-time and how to best communicate outflow boundary characteristics and model uncertainties to the fire weather community.

The research will synthesize state-of-the-art numerical modeling using WRF-Fire, currently used by the fire weather community, with operational as well as state-of-the art observational tools. As part of this study, we will address specific questions under the objectives above:

- *Questions related to Obj. 1*: How do outflow boundary characteristics (depth, length, propagation speed and direction, temperature/pressure chance, turbulence and maximum velocity at the surface) depend on the thunderstorm type, terrain, and ambient atmospheric conditions? Is WRF-Fire capable of correctly representing thunderstorm initiation (timing, placement) and evolution of gust fronts in a range of terrain types?
- *Questions related to Obj. 2*: What is the role of topography and fire behavior on thunderstorm initiation and evolution? How do fire and topography alter boundary characteristics, and are those changes represented in WRF-Fire? Are changes in fire behavior from outflow boundaries correctly represented in WRF-Fire? How can operational weather and fire information be used to verify thunderstorm and outflow boundary lifecycles in WRF-Fire?
- *Questions related to Obj. 3*: How can probabilities of outflow boundary occurrence and characteristics and model uncertainties be best communicated to fire weather community?

A summary of the objectives and outcomes of this project are listed in Table 1.

Table 1: Project milestones associated with the objectives and how they were met.

Project Mileston e	**Description**	**Outcomes**
1A	Characterize outflow boundaries at different study areas using operational and research instruments; quantify added benefit of research-grade instruments	Completed; results are published in Luchetti et al. (2020a, 2020b); were able to use research and operational instrumentation to characterize outflow boundaries in complex terrain.
1B	Simulate selected cases including sensitivity studies; compare observed and	Completed; Conducted sensitivity studies for different canyon types and thunderstorm types;

	modeled outflow boundary and parent thunderstorm characteristics	results are submitted to Monthly Weather Review (Luchetti et al. 2021)
2A	Characterize thunderstorm and outflow boundary characteristics for selected wildland fire events using operational instruments (related to Obj. 1A).	Completed; Analyzed radar and surface observations ~100 km around Albuquerque, NM, and Flagstaff, AZ (Luchetti et al. 2020b)
2B	Simulated selected wildland fire events including sensitivity studies; compare to observations	Partially completed for Yarnell Hill fire; conducted WRF-Fire simulations and compared those to radar observations. We were unable to conduct more simulations due to COVID restrictions (18 months of the project was under COVID).
3A	Develop methods to communicate outflow boundary characteristics and model uncertainties to fire weather community; evaluate methods; develop training material	Partially completed; developed methods to i) analyze general propagation pattern of outflow boundaries using operational data (Luchetti et al. 2020b) and ii) general behavior of outflow boundaries in canyons using WRF (Luchetti et al. 2021). Were unable to work with forecast meteorologist to develop adequate training material due to COVID restrictions (18 months of the project was under COVID).

Task Statement Relevancy: The project objectives correspond to the task statement needs which are i) quantifying the effects of terrain, vegetation, and ambient atmospheric conditions on outflow boundary behavior, ii) analyzing the added benefit of state-of-the-art research instruments for characterizing outflow boundary behavior, iii) evaluating the forecast skills of WRF-Fire in terms of reproducing the observed outflow boundary behavior, and iv) communicating outflow boundary conditions and model uncertainties to the fire weather community. The project will combine data analysis from research and operational instruments with sensitivity studies using numerical modeling to study outflow boundary behavior in different terrain, vegetation, and atmospheric conditions with and without wildland fire interaction. In addition, the project uses data analysis and sensitivity studies to quantify the forecasting skills of WRF-Fire in terms of accurately reproducing outflow boundary behavior.

2. Background

Thunderstorms are often associated with dangerous downdrafts also referred to as microbursts. Dry microbursts, mainly found in arid and semi-arid regions like the United States intermountain west, develop by evaporation, melting, and sublimation of precipitation causing strong and turbulent ground-level winds that propagate as outflow boundaries radially away from the microburst (Fujita and Wakimoto 1983; Wilson et al. 1984; Fujita 1985). Dry microbursts are often short-lived (< 10 min) with typical diameters of < 4 km and occur with very little rain reaching the surface. As such, they are almost impossible to detect with operational observing networks (Haines 1988; Wakimoto et al. 1994), particularly in mountainous terrain where observational density is sparse and measurements are obscured by the mountains. Microbursts and outflow boundaries in mountain terrain pose a major threat to firefighters' safety as microbursts and outflow boundaries can spread the fire rapidly towards locations that were previously considered safe. Furthermore, terrain itself can enhance and modify microburst and outflow-boundary winds adding complexity and tactical challenges faced by emergency management teams during wildfire events (Goens and Andrews 1998; Sharples et al. 2017). Given the potential threat and the lack of observations, this study quantifies changes in wind speed and turbulence from microbursts and outflow boundaries interacting with canyons and ridges through idealized simulations using the community numerical Weather Research and Forecasting (WRF) model.

Outflow boundaries associated with intense dry microbursts are difficult to predict and observe, given that they are typically associated with high cloud bases and precipitation that evaporates before reaching the ground (Monastersky 1987; Haines 1988; Wakimoto et al. 1994; Potter and Hernandez 2017). Observations of dry microbursts across the intermountain west reveal that many of these events are associated with low radar reflectivity signatures compared to those less complex terrain (Wakimoto et al. 1994), making them difficult to observe by radar (Haines 1988). A deadly example of a dry microburst interaction with a wildfire occurred on 26 June 1990, as hundreds of firefighters fought the Arizona Dude Fire in the hills of the Tonto National Forest northeast of Phoenix, AZ. Surface winds, associated with several dry microbursts developing in the vicinity of the fire, caused the fire to spread in all directions. On the southern side of the fire, these surface winds were enhanced by the local terrain and channeled into a canyon, where six firefighters were killed (Goens and Andrews 1998). Strong surface microburst gusts in combination with complex terrain and wildfires have caused fatalities in other wildfires such as the 1949 Mann Gulch Fire (Rothermel 1993), the 1976 Battlement Fire (USDI 1976), the 1994 South Canyon Fire (USDI/USDA 1994), the 2012 Waldo Canyon Fire (Johnson et al. 2014), the 2013 Arizona Yarnell Hill Fire (Karels and Dudley 2013; Hardy and Comfort 2015; Paez et al. 2015), and the 2015 California Frog Fire (Draeger 2016). Considering the potential safety hazards associated with outflow boundary-induced fire spread in mountainous areas and the lack of observations, the use of high-resolution numerical weather models to accurately simulate thunderstorm outflow boundaries in complex terrain is a research priority for the fire weather community.

Most numerical studies of microburst outflow interactions with terrain have focused on bell-shaped 2-D hills or mountains, and escarpment-like features (Letchford and Illidge 1999; Wood et al. 2001; Mason et al. 2007, 2010). While wildfires can surely be influenced by these types of terrain features (e.g., Hawley 1926; Sullivan 2009; Sullivan et al. 2014), a dangerous situation can also develop when wildfires are terrain-channeled into and within canyons (Goens and Andrews 1998; Brown 2002; Esperanza Investigation Team 2006; Coen and Riggan 2010; Sharples et al. 2010). For example, during the 2006 Esperanza Fire in California, Santa Ana winds aligned with channeled creek drainage flow in a nearby canyon, producing enhanced surface winds and fire behavior which led to the loss of five firefighters (Esperanza Investigation Team 2006; Coen and Riggan 2010). A key finding from the investigation report (Esperanza Investigation Team 2006) was that none of the fire shelters for the deceased firefighters were deployed, suggesting that the head fire must have accelerated as it came through the canyon and caught the firefighters off guard. Another canyon-induced fatality event occurred during the 2001 Thirtymile Fire in Washington where fire-induced winds were channeled up the canyon sidewall killing four firefighters who deployed at a site located 30 m upslope from the valley floor (Brown 2002). An analysis of tree needle heatset observations made at the incident site indicates that fire-induced winds were in the up-canyon and upslope direction, suggesting that the fire's convective column was channeled up the canyon, rather than rising vertically from the surface (Brown 2002). Further analysis suggests that the increased fire spread rate which caught the firefighters off guard likely resulted from a combination of up-canyon winds and downward mixing of stronger upper-level winds which were oriented along the canyon's axis. Explosive fire blow-up and acceleration such as in the events outlined above (1990 Dude Fire; 2001 Thirtymile Fire; 2006 Esperanza Fire) are not rare, especially for wildfires that occur within canyons (Viegas 2005; Viegas and Simeoni 2010). Thus, the combination of hard-to-predict surging microbursts, along with terrain channeling, presents an especially challenging situation for firefighters and emergency managers when responding to wildfires in canyons.

Given the dangers to firefighters by these difficult-to-predict and difficult-to-observe microbursts and outflow boundaries in areas of complex terrain, along with a lack of focus on microburst interactions with canyons in the literature, the aim of this research is to quantify outflow boundaries in complex terrain and the canyon-enhancement of wind and turbulence from microburst outflow boundaries.

3. Data and Methods

3.1 Data

This study utilizes three types of data: i) data from operational networks, ii) data from research instruments, and ii) numerical model output from the Weather and Research Forecasting model coupled with a wildland fire-behavior module (WRF-Fire).

Operational networks: Reflectivity and Doppler velocity from the WDR-88D radar, satellite information, lightning information from the Colorado Lightning Mapping Array (CoLMA) and national lightning network, and surface observations of wind, temperature, and relative humidity from operational networks are used to identify parent thunderstorms and track the movement, characteristics, and lifecycle of outflow boundaries. Outflow boundaries can be identified as a thin line of enhanced reflectivity and/or line of apparent convergent flow in Doppler velocity traveling away from the parent thunderstorms. Radar observations allow for continuous tracking of gust front characteristics such as depth, length propagation speed, maximum radial velocity, and changes in radial velocity. Since most radars provide insufficient coverage over the mountains, we also used lightning data from the national lightning network to determine location and lifecycle of thunderstorms in complex terrain. In addition to radar and lightning observations, changes in wind speed and direction, temperature, pressure, and moisture observed by surface stations were used to determine on propagation speed and strength of gust fronts.

Research instruments. State-of-the-art vertically-profiling remote sensing instruments were used to derive information of the vertical structure of outflow boundaries, with emphasis on shear instabilities, turbulence, depth, velocity and directional changes. We used a 449 MHz wind-profiling radar with Radio Acoustic Sounding System, meteorological tower, wind-profiling sodar, wind-profiling lidar, and microwave radiometer. Vertical profiles of horizontal winds and turbulence were derived from the sodars, lidars, radars, and tower observations; temperature profiles from radiometer, tower observations, and RASS; humidity profiles from radiometer and tower observations; reflectivity profiles from radar and lidar. The instruments were deployed) at the Boulder Atmospheric Observatory at the Colorado Front Range located

~25 km east of the eastern slopes of the Rocky Mountains and ~25 km north of downtown Denver, CO, and the National Wind Technology Centre located ~4 km east of the eastern slopes of the Rocky Mountains and ~20 km northwest of Denver.

WRF-Fire: The WRF model is a popular community-driven, fully compressible, nonhydrostatic, Reynolds-averaged Navier–Stokes system widely used for weather forecasting. WRF-Fire is a synthesis of WRF with a code that represents a surface fire behavior model (Coen et al. 2013). The semi-empirical surface fire behavior model calculates the rate of spread of the fire line based on WRF's predictions of wind speed and direction as well as terrain slope and fuel properties. As run operationally at NCAR, the WRF simulations consist of two domains, downscaled from NOAA's High Resolution Rapid Refresh model. The coarser domain, at 1 km resolution, is a mesoscale simulation centered over the state of Colorado or Arizona with a 100-km boundary, using the MYNN planetary boundary layer scheme, Thompson microphysics, and RTM-G shortwave and longwave radiation. The inner nest (LES) is centered on the study site, at 111 m resolution. Terrain elevation is based on the USGS 30-m resolution database. For fire aspects, the fuel catalog comes from the LANDFIRE data (http://landfire.cr.usgs.gov/viewer/), and currently considers the thirteen Anderson (1982) fuel models but will be expanded in early 2017 to forty models (Scott and Burgan 2005). The fire spread model is based on Rothermel (1972).

3.2 Methods

Observational and research instruments: The research and operational data described above were used to characterize parent thunderstorms and outflow boundaries (Luchetti et al. 2020a, 2020b). Research instruments were used to determine outflow boundary characteristics, which also depend on the distance from the parent thunderstorm and include depth, speed and directional changes along the boundary, maximum velocity, and shear instability. In Luchetti et al. (2020a) we analyzed observations from the XPIA[1] campaign conducted in March-July 2015 at the BAO foothills site. We identified 10 thunderstorms events, where outflow boundaries passed over the research instruments. Operational weather radar at Denver was used to track the boundaries and determine propagation speed, length, and wind speed and direction. For more details on the analysis method, we refer to Luchetti et al. (2020a).

In Luchetti et al. (2020b), using operational WSR-88D data and in-situ observations from Automated Surface Observing System (ASOS) stations, 122 gust fronts in the Mogollon Rim region in Arizona and the Rio Grande Valley in New Mexico are assessed to quantify changes in temperature, wind, relative humidity, and propagation speed as they pass over the weather stations. We quantified the change in wind speed and direction, temperature, and relative humidity when a gust front, identified by the radar, passed the ASOS station. In situ 1-min ASOS data are analyzed 30 min prior to and 30 min after the radar-indicated gust front passage time. During this timeframe we identify the time when the largest gradient in each atmospheric variable occurs. We then quantified the magnitude change in each atmospheric variable by taking the difference between the 5-min mean of the variable prior to and after the gust front passage. The magnitude change is analyzed for each atmospheric variable across all gust front events in each of the two study areas. We also tracked the radar fine lines observed by the radars to determine the role of the underlying terrain on gust front characteristics (propagation direction,

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[1] XPIA - eXperimental Planetary boundary layer Instrumentation Assessment

speed, number of gust fronts per month). More information can be found in Luchetti et al. (2020b).

4. Results and Discussion

Luchetti, N. T., K. Friedrich, C. E. Rodell, J. K. Lundquist, 2020a: Characterizing Thunderstorm Gust Fronts Near Complex Terrain. Mon. Wea. Rev., 148, 3267–3286: This study focuses on gust fronts (GFs) from mainly single and multicell thunderstorms in and near complex terrain in the Colorado Front Range, east of the Rocky Mountains. In this study, in-situ and remote sensing observations are combined to quantify the magnitude and rate change of atmospheric variables that occur in 24 GF events. Horizontal wind, turbulence (TI and TKE), vertical velocity, temperature, and humidity are analyzed in the lowest 300 m AGL using a remote sensing microwave radiometer, wind-profiling lidars, and in situ data from three meteorological towers. The main findings from this analysis are:

- The median radar-derived propagation speed was 7.6 m s^{-1} with a maximum of 16.6 m s^{-1}, and the influence of the prefrontal cross-front ambient wind component on propagation speed was found to be negligible (Figs. 1-2). However, GFs that encountered higher variability in terrain and slope (from the northerly directions) were on average slower (6.6 ± 3.3 m s^{-1}) when compared with the other propagation directions (10.1 ± 3.8 m s^{-1}). Variability in terrain slope and elevation influenced the propagation speed of GFs in this study.
- Magnitude changes in temperature (0.28–3 °C), maximum vertical velocities (2–3.6 m s^{-1}), and maximum wind gusts (mean = 7.9 m s^{-1}) observed here are generally weaker than in studies of GFs initiating from organized, severe thunderstorms in flatter terrain. The average cold-air depth is about 360 m, shallower than in other studies, which may explain the weaker magnitude changes observed in this study.
- While most wind energy GF studies focus on quantifying turbulence using 2D TI, this is one of the first studies that also evaluates the 3D TKE associated with GFs. Short-duration spikes in TKE (0.4 m^2 s^2) occur in 14 (58%) of the 24 GF events, exceeding TKE values often associated with unstable boundary layer conditions.

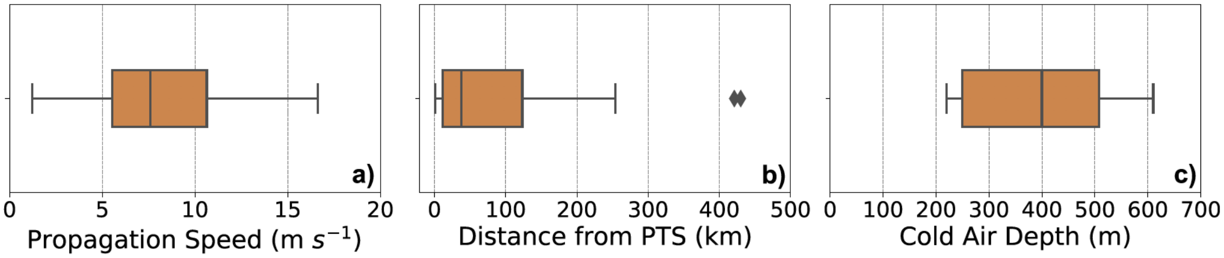

Fig. 1: Box-and-whisker plots of radar-derived thunderstorm and GF characteristics. Variables analyzed include (a) radar-derived propagation speed (m s21), (b) distance from parent thunderstorm (PTS) (km), and (c) cold-air depth (m). The filled box represents the interquartile range. The whiskers extend to data points that fall within 1.5 times the interquartile range of the lower and upper quantiles. Outliers that fall beyond this range are independently represented by diamond symbols.

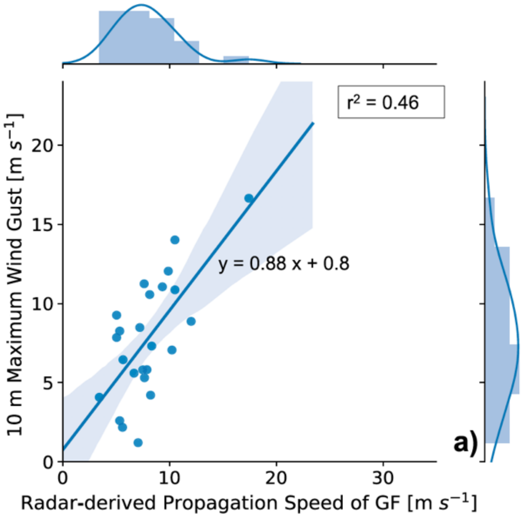

Fig. 2: (a) Comparison of maximum wind gusts as the GFs passed over the instrument (m s-1) as a function of propagation speed derived from the radar (m s-1) for 24 events. The variance explained is listed in the upper-right corners. In addition, linearly regressed fits are plotted as the solid blue lines. The light-blue-shaded regions surrounding the regressed fits represent the 95% confidence intervals of the regressions. In addition, the fitted distribution for each axis is displayed as histograms.

Luchetti, N. T., K. Friedrich, C. E. Rodell, 2020b: Evaluating Thunderstorm Gust Fronts in New Mexico and Arizona. Mon. Wea. Rev., 141, 4943–4956: This study quantifies the variability in propagation speed and atmospheric characteristics across 122 gust fronts that occur in the complex terrain of NM and AZ during the 2010–18 monsoon seasons (June–August). Using radar and ASOS station data, gust fronts that were pushed uphill and propagated atop the crest of the Mogollon Rim in AZ were compared to those that propagated down into or along the Rio Grande Valley in NM (Fig. 3) to assess how variability in terrain may influence gust front characteristics. The main findings from this analysis are as follows:

- Gust fronts that propagated downhill into and along the Rio Grande Valley in NM were generally associated with faster propagation speeds (pspd = 8.6 m s^{-1}), slightly larger decreases in temperature (dT = -2.2°C), larger increases in horizontal wind speeds (wsp = 7:5 m s^{-1}), and changes in wind direction (wdir = 76.5°) compared to gust fronts that reached the crest of the Mogollon Rim in AZ (pspd = 5.2 m s^{-1}; dT = -1.5°C; wsp = 3.5 m s^{-1}; wdir = 53.1°; Fig. 4).
- The prefrontal ambient wind was not a strong determining factor for gust front propagation speed (r = 0.26; R^2 = 0.07) for those that propagated downhill into and along the Rio Grande Valley in NM. However, faster (slower) AZ gust fronts often did have stronger tailwinds (headwinds) (r = 0.57; R^2 = 0.32), and thus the prefrontal ambient wind did moderately influence propagation speed for the cases studied atop the Mogollon Rim in AZ.
- Gust fronts that propagated downhill into the Rio Grande Valley in NM behaved more in accordance with traditional density current theory than those that were pushed uphill and propagated atop the Mogollon Rim in AZ. In the theory, the stronger the difference in temperature between the boundary and the ambient air, the stronger the wind speeds behind the two air masses. Here, the relationship between the magnitude decrease in

temperature and magnitude increase in wind speed was stronger for gust fronts that propagated down into and along the Rio Grande Valley in NM (r = 0.57; $R^2 = 0.33$) compared to those atop the Mogollon Rim in AZ (r = 0.28, $R^2 = 0.08$).

- For gust fronts that propagated downhill and within the Rio Grande Valley in NM, larger magnitude decreases in temperature were weakly associated with those that encountered less negative mean terrain slopes (r = 0.24; $R^2 = 0.06$). Similarly, larger magnitude changes in wind speed were also associated with less negative mean terrain slopes (r = 0.36; $R^2 = 0.13$). For gust fronts that propagated uphill and atop the Mogollon Rim in AZ, no discernable relationships between upslope or downslope adiabatic processes and gust front wind speed and temperature drop was found.

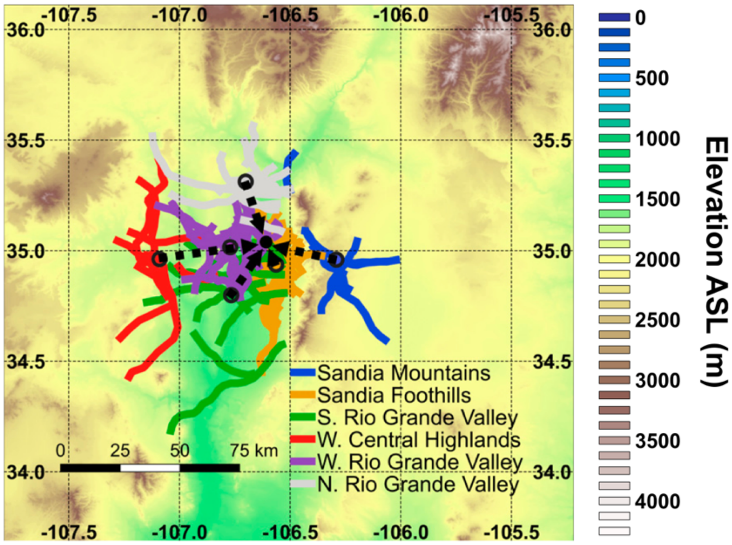

Fig. 3: Topographic map with radar fine lines for the 79 New Mexico gust fronts at the moment they first appear on the KABX operational radar at Albuquerque, New Mexico. Gust fronts are grouped into six groups depending on the location of first detection and the direction they propagate toward the KABQ New Mexico ASOS station (black dot). The open-colored circles represent the centroid of each gust front group. The black dashed arrows represent the path between the centroid and the ASOS station used to calculate the ap- proximate terrain profile.

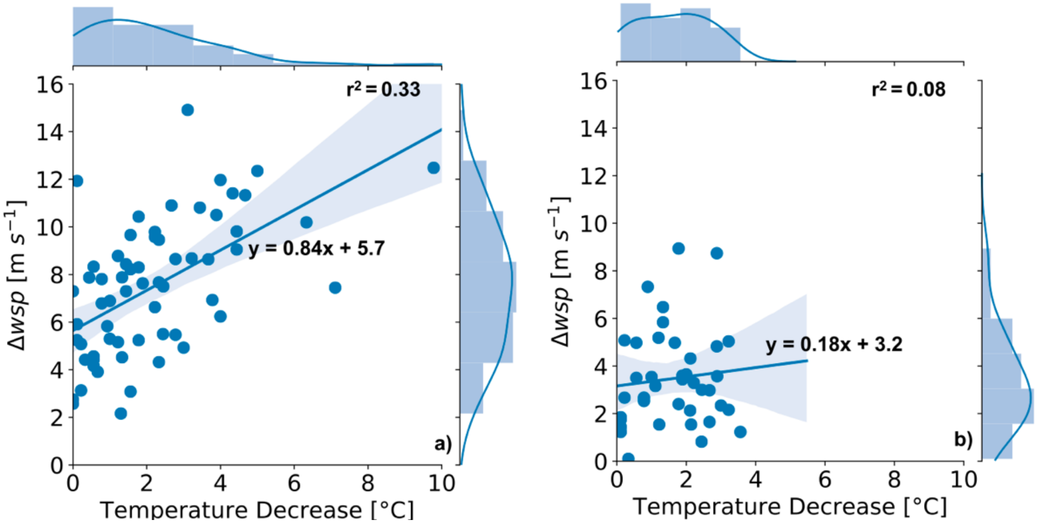

Fig. 4: Scatterplot of magnitude change in wind speed (m s-1) as a function of the decrease in temperature (8°C) measured by the ASOS stations in (a) New Mexico and (b) Arizona. The prefrontal cross-front ambient wind is derived by wind anemometers deployed at the ASOS stations. Linear regression fit is plotted as the solid blue line with coefficient of determination (r^2) shown in the top right. The blue shaded region surrounding the regressed fit is the 95% confidence intervals of the regression. The fitted distribution for each axis is displayed as histograms.

Luchetti, N. T., K. Friedrich, B. Kosovic, 2021: Quantifying microburst wind and turbulence enhancement in canyons. Mon. Wea. Rev. (under review)

This study quantifies the enhancement of microburst outflow boundary winds and turbulence within canyons using the WRF-LES simulation capability. Simulated microburst outflow boundaries propagate through short- (~1.5 to 4.5 km) and long-distance canyons (~3 to 6 km) where canyon walls have slopes of 10° and 30°. These canyon simulations are compared to microburst outflow boundary characteristics in flat terrain. Microbursts were placed close to the canyon, so that the maximum in outflow boundary wind speed occurs at the canyon entrance, and farther away to study the influence of topography on outflow boundaries with weaker wind speeds. The main findings from this analysis are:

- Compared to flat terrain, an increase in *wsp*, w_{up}, and TKE are observed within the canyon (Table 1)
- Short-distance microbursts (SDM; ~3 km upwind of the canyon) produce stronger canyon-induced enhancements in *wsp* (3 m s^{-1}), w_{up} (3 m s^{-1}), *TKE* (4.7 m^2 s^{-2}), and M_t (28 %) in the canyons and along the canyon walls compared to long-distance microbursts (LDM; ~6 km upwind of the canyon) – Table 2; Fig. 5.
- For canyons located closer to the microburst, the increase in *wsp* (3.2 m s^{-1}), w_{up} (0.8-4.6 m s^{-1}), *TKE* (1.4 m^2 s^{-2}) and M_t (29%) is generally stronger in the canyon and along the walls of the 30°-sloped compared to the 10°-sloped canyons. When the canyons are farther from the microburst, steeper slopes do not enhance wind and turbulence in the canyon in either short- or long-distance canyons.

- For both SD and LD canyons, the maximum increase in *wsp* is mostly observed near the canyon floors and towards the exit region of the canyons regardless of the proximity to the microburst. Conversely, the maximum increase in w_{up} and *TKE* is mostly observed at higher elevations on the walls and along the canyon crests in both SDC and LDC.

	Short-distance microburst (SDM)			**Long-distance microburst (LDM)**		
	wsp (m s^{-1})	w_{up} (m s^{-1})	*TKE* (m^2 s^{-2})	*wsp* (m s^{-1})	w_{up} (m s^{-1})	*TKE* (m^2 s^{-2})
10° CANYON SLOPE – SHORT CANYON (10°SC)						
	SDM10°SC - SDM0°BL			LDM10°SC - LDM0°BL		
0 m	5.2	2.1	1.4	3.7	1.8	0.9
50 m	5.6	2.8	1.2	3.5	2.7	0.7
150 m	4.1	4.0	3.7	3.3	2.8	0.8
250 m	3.1	3.7	5.1	4.7	3.1	0.5
30° CANYON SLOPE – SHORT CANYON (30°SC)						
	SDM30°SC - SDM0°BL			LDM30°SC - LDM0°BL		
0 m	6.6	1.9	1.4	4.0	1.7	0.9
50 m	5.7	3.4	1.4	4.0	3.1	0.7
150 m	4.5	5.1	5.6	3.0	4.9	0.8
250 m	6.5	8.4	6.6	4.2	5.3	4.3

Table 2. Maximum differences between baseline (0°BL) and short-distance canyon (SC) simulations (10° and 30° slopes) for short and long-distance microbursts: horizontal wind speed (wsp) (m s^{-1}*) at z = 10 m, upward vertical velocity (*w_{up}*) (m* s^{-1}*) at z = 50 m, and turbulence kinetic energy (TKE) (*m^2 s^{-2}*) at z = 10 m.*

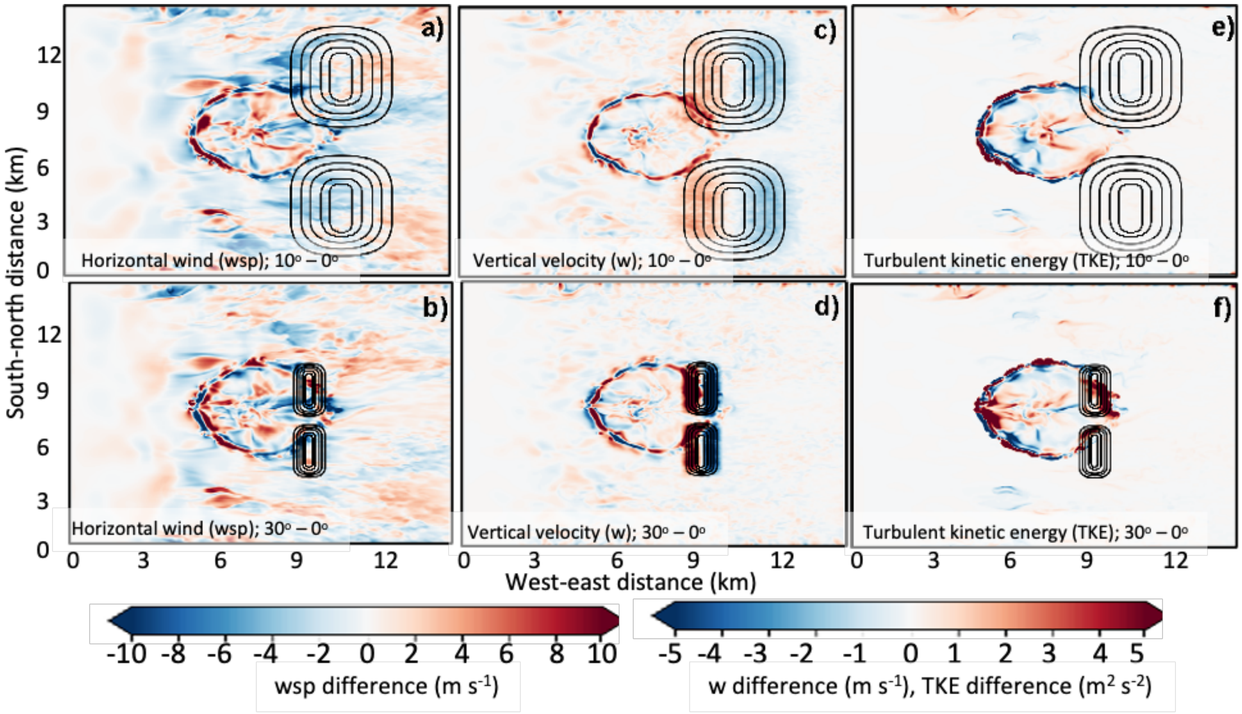

Fig. 5. Differences between a, c, e) SDM10°SC-SDM0°BL and b, d, f) SDM30°SC-SDM0°BL for a-b) wind speed at 10 m (wsp; m s^{-1}), c-d) vertical velocity at 50 m (w; m s^{-1}), and e-f) turbulent kinetic energy at 10 m (TKE; m^2 s^{-2}) at 06h:03min:00s. Terrain is indicated by black lines with 50 m terrain contours.

Friedrich, K., Sarah, L., A. Winters, 2021: The Effects of Thunderstorms on Complex Terrain Wildfires in the Southern Rocky Mountains (in preparation): One of those few studies is Johnson et al. (2014), who focused on the role of a thunderstorm outflow during the early stage of the Waldo Canyon Fire (23 June – 10 July) on 26 June 2012. Using satellite, radar, and surface observations and results from numerical simulations, they linked the rapid spread and further intensification of the fire to the passage of a strong gust front. Gust front-induced wind direction change has also been identified as the main catalyst for rapid fire intensification and re-direct fire spread (Surveys and Investigation Staff 1981; Haines 1988; Goens and Andrews 1998; Kern et al. 2004; Sharples et al. 2017). While these studies are fundamental in understanding the interactions and the potential threat of thunderstorms on wildfires, the question remains about how often thunderstorms interact with wildfires, which is addressed in this paper. In this study, we use daily lightning data from the U.S. National Lightning Detection Network to identify the location of thunderstorms and then relate the thunderstorm location to daily burn area boundaries that occurred between 2000-2018 in the western U.S. (Figs. 6-7). The analysis focuses on the wildfire season between May-September during which 94% of fires occur resulting in 98% of area burned (Westerling et al. 2003).

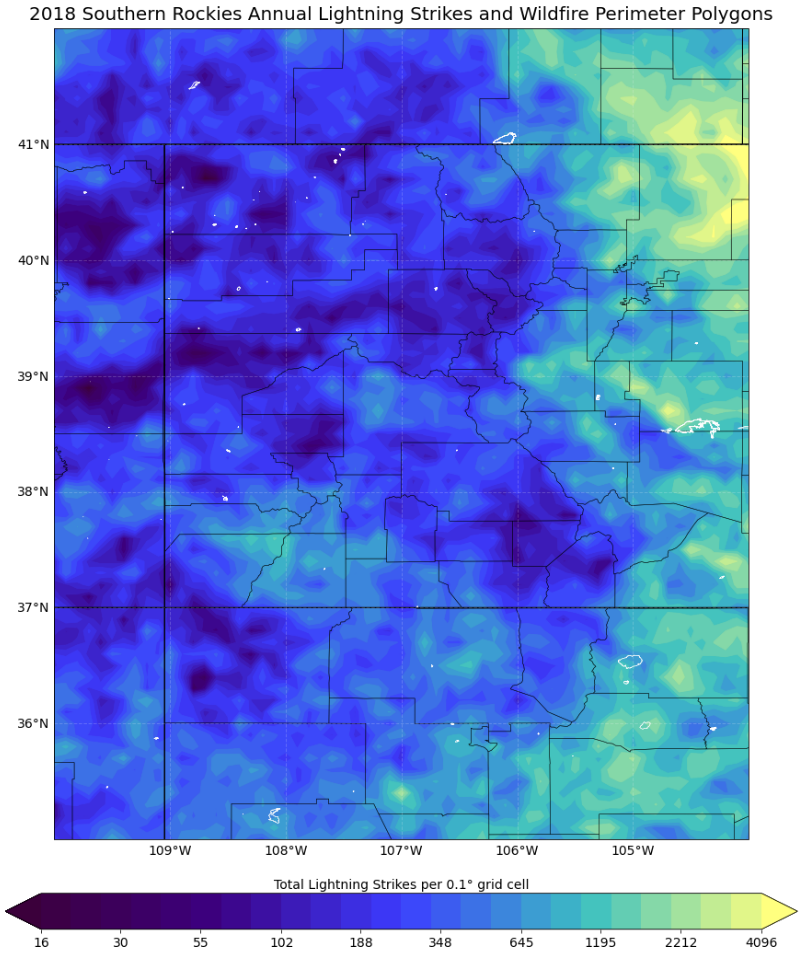

Fig. 6: Map of the Southern Rockies with 2018 Accumulated Lighting Strikes (Vaisala, 2018) and 2018 Wildfire Shapefiles (white) (National Interagency Fire Center, 2018).

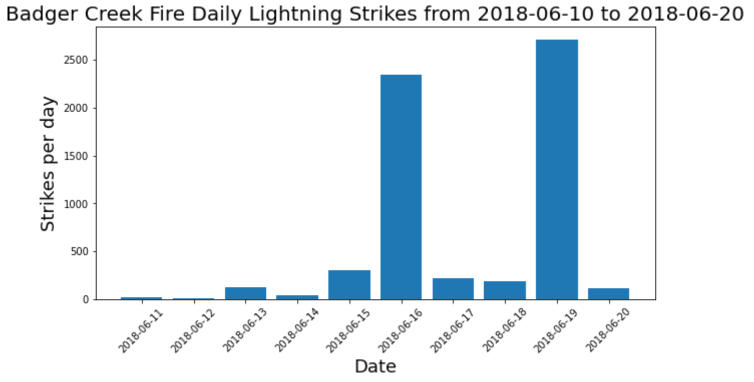

Fig. 7: 2018 Badger Creek Lightning Strike daily accumulation time series (Vaisala, 2018).

5. Conclusion and Implication for Management/Policy

Luchetti, N. T., K. Friedrich, C. E. Rodell, J. K. Lundquist, 2020a: Characterizing Thunderstorm Gust Fronts Near Complex Terrain. Mon. Wea. Rev., 148, 3267–3286: Comparing GF characteristics among different types of thunderstorms and in different terrain is often challenging considering that methods and instruments used in GF studies are not always uniform. In particular, calculating the change in GF atmospheric characteristics is highly dependent on the interpretation of when the boundary passed over the instruments. A more uniform understanding of how to quantify the GF passage time would help to better facilitate regional comparisons. A future observational study could, therefore, address the influence of terrain on propagating GFs by comparing the magnitude change in GF boundary variables in this study to the magnitude change in GF boundary variables from single- or multicell thunderstorms in flatter terrain using similar methods and instruments. A future study should also expand this analysis to surface stations scattered across the Intermountain West. Statistically examining many more GF events in the complex terrain of this region would ideally further our understanding of how the underlying terrain may influence propagating GFs. The additional statistics could also help to validate numerical weather prediction models, which in the past have shown promise in their ability to accurately model GFs and other high-impact wind events in mountainous terrain (Coen and Riggan 2011; Coen et al. 2013; Johnson et al. 2014; Coen and Schroeder 2017; Coen et al.

Luchetti, N. T., K. Friedrich, C. E. Rodell, 2020b: Evaluating Thunderstorm Gust Fronts in New Mexico and Arizona. Mon. Wea. Rev., 141, 4943–4956: Results from this study provide an initial step in understanding the influence of common terrain features on propagating thunderstorm gust fronts. A future study should compare the results here to other terrain regions where gust fronts either propagate down into valleys or get pushed up and over ridgelines, or to those that interact with other terrain features such as plateaus or depressions. Additional observations could benefit numerical models that must be able to accurately incorporate the influence of terrain features on the strength and modification of thunderstorm gust fronts. This is particularly true for operational turbulence-resolving fire models, where their accuracy is highly dependent on the model's ability to simulate realistic turbulent boundaries in the vicinity of wildfires in areas of complex terrain. One potential limitation here, however, is that we are trying to link gust front characteristics observed at a fixed location in time and space to the mean slope across the entire terrain profile. While the mean slope may suggest a primarily downhill path, for example, the actual profile likely includes alternating uphill and downhill sections. Therefore, a future study could utilize a Lagrangian modeling approach to quantify the changes in gust front characteristics at every uphill and downhill stretch of the profile. This type of approach would likely yield a better under- standing of whether or not downslope or upslope adiabatic processes influence gust front characteristics.

*Luchetti, N. T., K. Friedrich, B. Kosovic, 2021: Quantifying microburst wind and turbulence enhancement in canyons. Mon. Wea. Rev. (under review)***:** Results from this study provide an initial quantification of canyon-enhancement of microburst outflow winds and turbulence using idealized numerical simulations. A future study could expand upon these experiments and investigate the influence of other important parameters such as the magnitude and horizontal extent of the cold bubble perturbation, altering the background atmospheric stability and shear profile, changing the surface roughness length, or altering the height of the mountains. Additional analysis of these parameters could benefit fire weather forecasters and emergency responders who assess the potential dangers of outflow boundaries in and around ongoing canyon wildfires.

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Appendix A: Contact Information of Key Project Personnel

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

1. Articles in peer-reviewed journals

Luchetti, N. T., K. Friedrich, C. E. Rodell, J. K. Lundquist, 2020a: Characterizing Thunderstorm Gust Fronts Near Complex Terrain. *Mon. Wea. Rev.,* **148**, 3267–3286.

Luchetti, N. T., K. Friedrich, C. E. Rodell, 2020b: Evaluating Thunderstorm Gust Fronts in New Mexico and Arizona. *Mon. Wea. Rev*., **141**, 4943–4956.

Luchetti, N. T., K. Friedrich, B. Kosovic, 2021: Quantifying microburst wind and turbulence enhancement in canyons. *Mon. Wea. Rev*. (under review)

Friedrich, K., Sarah, L., A. Winters, 2021: The Effects of Thunderstorms on Complex Terrain Wildfires in the Southern Rocky Mountains. (in preparation)

2. Graduation thesis

Luchetti, N. T. 2020: Evaluating thunderstorm outflow boundaries in complex terrain. U. of Colorado, Department of Atmospheric and Oceanic Sciences. Defense date: 18 December 2020.

3. Conference or symposium & posters

Sarah, L., K. Friedrich, A. Winters, 2021: The Effects of Thunderstorms on Complex Terrain Wildfires in the Southern Rocky Mountains. 2021 REU Poster Conference, Boulder, CO.

Luchetti, N. T., K. Friedrich, C. Rodell, J. Lundquist., 2019: Evaluating Gust Front Characteristics in Complex Terrain. *2019 Earth System and Space Science Poster Conference, Boulder, CO.*

Luchetti, N. T., K. Friedrich, C. Rodell, J. Lundquist., 2018: Evaluating Gust Front Interactions with Idealized Terrain in WRF-Fire. *2018 Earth System and Space Science Poster Conference, Boulder, CO.*

Luchetti, N. T., K. Friedrich, C. Rodell, J. Lundquist., 2018: Evaluating Outflow Boundary Characteristics in Areas of Complex Terrain. *2018 Earth System and Space Science Poster Conference, Boulder, CO.*

Luchetti, N**. T.**, K. Friedrich, C. Rodell, J. Lundquist., 2018: Evaluating Outflow Boundary Characteristics in Areas of Complex Terrain. *29th Conference on Severe Local Storms, October 2018, Stowe, VT.*

Luchetti, N. T., K. Friedrich, J. K. Lundquist, B. Kosovic, and C. Rodell: Evaluating thunderstorm outflow boundaries in WRF-Fire. 11th Annual Earth System and Space Science Poster Conference, 30 Nov 2018. Boulder, CO.

4. Website development

- Project website: http://clouds.colorado.edu/fire/
- Outflow boundary characteristics (cases discussed in Luchetti et al. 2020a): http://clouds.colorado.edu/jointfire_outflow_overview/

5. Presentations/webinars/other outreach/science delivery material

Luchetti, N. T., K. Friedrich, C. Rodell, J. K. Lundquist, 2019: Evaluating Gust Front Characteristics in Complex Terrain. *18th AMS Conference on Mesoscale Processes, Savannah, GA.*

Appendix C: Metadata

Luchetti, N. T., K. Friedrich, C. E. Rodell, 2020: Evaluating Thunderstorm Gust Fronts in New Mexico and Arizona. Mon. Wea. Rev., 141, 4943–4956:
All radar and ASOS data used for this analysis are openly available from the NOAA National Centers for Environmental Information (NCEI) data archives. Radar data are available at https://www.ncdc.noaa.gov/ nexradinv/. All ASOS station data are available at https:// www.ncdc.noaa.gov/data-access/land-based-station-data/land- based-datasets/automated-surface-observing-system-asos.

*Luchetti, N. T., K. Friedrich, B. Kosovic, 2021: Quantifying microburst wind and turbulence enhancement in canyons. Mon. Wea. Rev. (under review)**:***
The WRF model code (https://doi.org/10.5065/D6MK6B4K, Skamarock et al., 2008) is publicly available at http://www2.mmm.ucar.edu/wrf/users/ (last access: 11 June 2020). Model output data for hours 6-7 h and analysis code including namelist.input, input soundings, and auxiliary terrain netcdf files needed to run the simulations and create the figures are located at
https://github.com/nluchett/wrf_canyon_experiment.