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WRF-Fire simulation of pyro-convection under the influence of low-level jet wind profiles

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Abstract: Blowup wildland fire behaviour is characterised by a sudden increase in the fire intensity or forward rate of spread that precludes direct control. It is often accompanied by extreme pyro-convection and can pose a serious risk to firefighters. Blowups are difficult to predict due to our limited understanding of their environmental thresholds and the underlying driving physical processes. Low-level jets, a fairly common feature of the atmospheric boundary layer, have previously been observed at a number of blowups. However, there is currently no well-tested causal theory to explain this apparent connection between low-level jets and blowup fire behaviour.

In this study, a two-way coupled atmosphere-fire model is used to conduct a series of idealised simulations that examine the sensitivity of modelled pyro-convective plume dynamics to variations in the low-level jet height and wind shear above the jet. The Weather Research and Forecast (WRF) numerical weather prediction model is used here in a large-eddy simulation configuration, and coupled to the WRF-Fire wildland fire physics module. Sensible and latent heat fluxes are calculated in WRF-Fire and can directly modify the potential temperature and water vapour mixing ratio in WRF, allowing the modelled fire to modify the local atmospheric dynamics. This dynamic feedback allows WRF and WRF-Fire to directly model the development of a pyro-convective plume under the influence of a low-level jet.

The model simulations show only a limited sensitivity of the pyro-convective plume dynamics to the presence of a low-level jet and the variation in jet properties. In particular, the level of tilting and total vertical development of the plume, in addition to the resolved turbulent kinetic energy within the core of the plume, display some differences due to variations in the wind shear above the jet. It seems likely that the fire intensity is too high to allow for more pronounced variations in the plume properties, and future work will focus on fuel types with a lower fuel mass per unit area.

Keywords: *Coupled atmosphere-fire modelling, large eddy simulation, pyro-convection, low-level jet*

1 INTRODUCTION

Although there is no standard definition of blowup fire behaviour in the fire science literature (Potter, 2012), it can be broadly described as an event in which either the fire intensity or forward rate of spread suddenly increases to such an extent that direct control of the fire is precluded. Blowups are often accompanied by extreme pyro-convection, such as that observed in the 2003 Canberra bushfires in Australia (Fromm et al., 2006). A number of factors are widely believed to contribute towards blowups, including an unstable atmosphere, high relief terrain, dry and heavy fuels, strong winds, and spotting. Blowups are difficult to predict using existing operational fire management tools and knowledge, as there is only limited understanding of the physical processes involved (Byram, 1959). However, efforts are underway to continue improving the operational forecasting of blowup fire behaviour (McRae and Sharples, 2013).

Byram (1954) presented wind speed profiles associated with 17 blowups that occurred in the southeastern United States between 1936 and 1953. Byram categorised these wind profiles into a number of different types, and discussed the fire behaviour characteristics associated with each one. He noted that low-level jets (LLJs) were a common feature in the wind profile types, suggesting a link with blowup fire behaviour. LLJs are common in the central and eastern United States (Sjostedt et al., 1990), amongst other regions in the world, and can develop either as a surface-forced feature of the atmospheric boundary layer (Whiteman et al., 1997), or as an element of tropospheric jet stream dynamics (Uccellini, 1980). Since the study by Byram (1954), LLJs have been observed at a number of additional wildland fires that exhibited extreme or blowup behaviour (Brotak and Reifsnyder, 1977). Kiil and Grigel (1969) found that blowups associated with LLJs are often accompanied by fire whirls, and Steiner (1976) presented a qualitative explanation for the relationship between blowup fire behaviour and certain wind profiles.

As noted in a review of atmospheric interactions with wildland fire by Potter (2012), there are considerable gaps in our understanding of the interactions between fire behaviour and wind profiles. This extends to the consideration of LLJs and blowup fire behaviour, and there is currently no well-tested causal explanation for the apparent link between LLJs and blowups. As such, the current operational implementation of Byram's wind profiles in fire management is through the subjective assessment of observed wind profiles, and there is considerable scope for further study and the development of new quantitative fire weather indices to aid fire management agencies. Given the recent advances in the development of coupled atmosphere-fire models, such as CAWFE (Clark et al., 1996) and FIRETEC (Linn et al., 2002), it is sensible to apply numerical modelling techniques to improve our understanding of the physical processes involved in blowup fire behaviour and its interaction with wind profile features like LLJs.

Simpson et al. (2013) examined the sensitivity of pyro-convective plume dynamics to four of Byram's wind profiles types that featured a LLJ using a fire to atmosphere only coupled version of the Advanced Regional Prediction System (ARPS) (Kiefer et al., 2009). The aim of this study is to use a numerical weather prediction (NWP) model, coupled dynamically to a wildland fire spread model, to expand on the study by Simpson et al. (2013) and further investigate the sensitivity of the atmosphere-fire interactions to varying LLJ properties. At present there is little understanding of how these wind profiles affect potential temperatures, vertical velocities, turbulent kinetic energy and downstream fire plume structure and smoke dispersion. It is expected that idealised numerical simulations will provide new insights into the feedback processes and their role in blowup fires. The next section describes the numerical model configuration and is followed by a discussion of the results and a number of conclusions.

2 NUMERICAL MODEL AND CONFIGURATION

The simulations presented in this study were performed using version 3.6 of the Advanced Research Weather Research and Forecasting (WRF) model (Skamarock et al., 2008), which includes a version of the WRF-Fire wildland fire physics module (Coen et al., 2013). WRF is used in a three-dimensional large-eddy simulation (LES) configuration (Moeng et al., 2007), and coupled dynamically to WRF-Fire. WRF in an LES configuration explicitly resolves the large-scale atmospheric eddies that typically dominate the atmospheric boundary layer, whereas subgrid-scale motions are modelled using a subfilter-scale stress model. WRF-Fire is a two-dimensional level set method implementation of Rothermel's semi-empirical fire spread model (Rothermel, 1972):

$$R = R_0 \left(1 + \Phi_W + \Phi_S\right) \tag{1}$$

where R is the rate of spread and R_0 is the base rate of spread without wind or slope. The slope and wind correction factors, Φ_S and Φ_W, are calculated using the outside normal component, relative to the fire region,

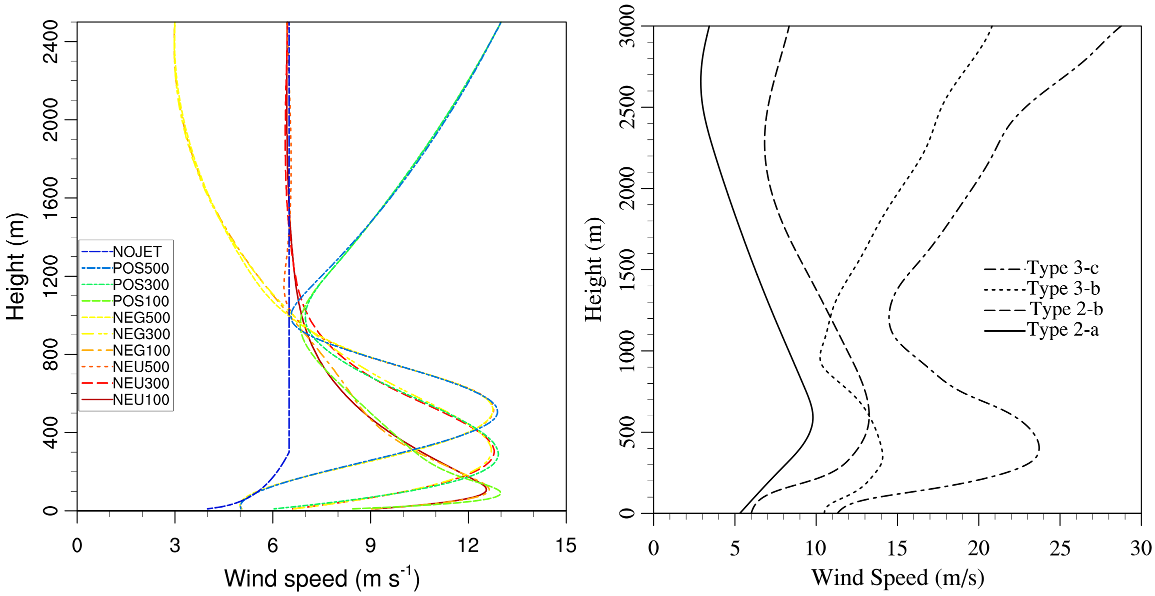

Figure 1. (left) The wind speed profile used in the ten WRF-Fire simulations, alongside (right) the four Byram wind profiles tested by (Simpson et al., 2013). Note that the *x* and *y* axis are different for the two individual plots.

of the local slope and mid-flame height winds at each point along the fire perimeter. The mid-flame height winds are calculated by interpolating the WRF winds to an estimated mid-flame height of 1 m above ground level. The fire spread model incorporates physical processes that facilitate fire spread, including radiative and convective heating, fuel drying, contact ignition and short-range spotting.

In this study, the WRF-Fire model grid is defined on a 4:1 refinement of the WRF horizontal model grid. The model domain extends approximately 20×4×5 km (E-W, S-N and vertical, respectively), with a horizontal grid spacing of 40 and 10 m in WRF and WRF-Fire, respectively. There are 125 sigma vertical levels extending from approximately 10 m to 5 km above ground level. The vertical level grid spacing is stretched following a hyperbolic tangent function, and due to the use of hydrostatic-pressure vertical levels, there is some variation in the model top height throughout each simulation. The simulations are highly idealised, and no microphysics or radiation physics parameterizations are used. Eddy viscosities are calculated using a prognostic 1.5 order turbulent kinetic energy closure scheme, and diffusion is calculated using the velocity stress tensor. The lower boundary condition is free slip, the lateral boundaries are periodic, and an open radiative upper boundary is combined with a 1 km deep Rayleigh damping layer (Klemp et al., 2008).

The background horizontal winds are prescribed as a westerly wind using one of the ten vertical wind profiles shown in Figure 1. Each one of the ten numerical simulations presented in this study is subsequently referred to by the label given to the corresponding wind profile. The potential temperature is initially set to 300 K up to a height of 4 km, and increases linearly to 310 K at the model top. This upper stable layer prevents the model top from descending throughout the simulation, as WRF uses hydrostatic pressure vertical levels. The atmosphere is initially dry, although moisture is later included as a product of the combustion process. A single fuel type, based on the heavy logging slash Anderson fuel category (Anderson, 1982), is initialized homogeneously across the WRF-Fire model grid. The fire is ignited, following a 10 min initialisation period, out to a distance of 80 m from a 240 m long south-north line located 2 km in from the western lateral boundary. The primary model time step is 1/25 s and the total simulated time in each simulation is 40 min, corresponding to 30 min of modelled fire spread. This time period was chosen as the fire-modified, or pyrogenic, winds subsequently affected the upstream wind profile over the fire after 40 min due to the periodic lateral boundary conditions.

The fire to atmosphere coupling is modelled through the injection of sensible and latent heat from WRF-Fire into WRF for each model time step. For each kilogram of fuel combusted in WRF-Fire, 17.43 MJ of sensible heat and a smaller quantity of latent heat is injected into WRF. Following the ignition of a WRF-Fire model grid cell, the fuel mass within that cell decreases exponentially according to a weighting factor. An exponential decay function is used to determine how the sum total of the sensible and latent heat for each

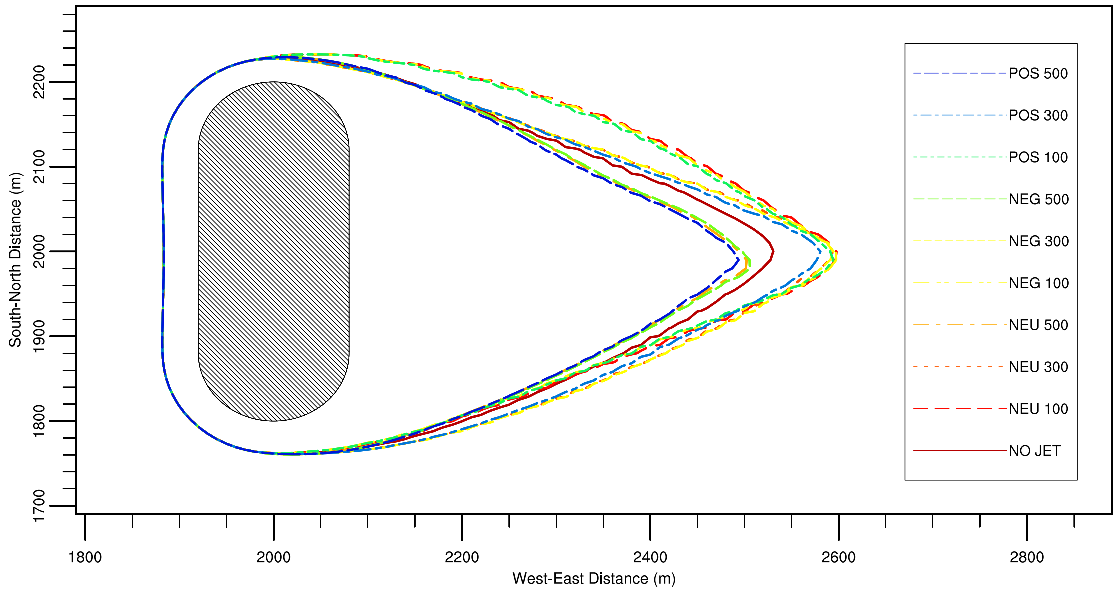

Figure 2. Modelled fire perimeter at a time of 30 min in four of the WRF-Fire simulations. The dash filled region indicates the region ignited instantaneously at a time of 10 min.

model grid column is distributed between the vertical levels. The sensible and latent heat flux separately affect the potential temperature and water vapour mixing ratio, thereby facilitating modification of the local atmospheric dynamics by the fire. The fire-modified winds then subsequently affect the modelled fire spread, allowing for direct modelling of two-way coupled atmosphere-fire interactions.

3 RESULTS AND DISCUSSION

Following the prescribed ignition described above, the fire spread is modelled for a period of 30 min. In each case, the fire front develops into a parabolic shape due to the convergence of the mid-flame height winds ahead of the fire front at the base of the pyro-convective plume, similarly to that noted by Clark et al. (1996) in their numerical simulations. The resulting fire perimeter relative to the fire ignition region is shown for four of the simulations in Figure 2. The slight variation in the fire perimeter between the simulations is predominantly accounted for by differences in the mid-flame height wind speed, as seen in Figure 2. The eastward rate of spread is around 0.28 m s^{-1}, compared with the base rate of spread of around 0.12 m s^{-1} for this fuel type.

The absence of any blowup fire behaviour in these simulations can be explained due to numerous factors. First, the fire has an initial width of 400 m, which is sufficiently narrow for a single pyro-convective updraft plume to develop. As a result, the modification of the near-fire wind is dominated by convergence ahead of the fire front at the base of the pyro-convective plume. Clark et al. (1996) found that for a fire line twice as wide, around 800 m, fire whirls began to develop that interacted with the fire front, resulting in non-steady state fire spread. There is no such interaction in the simulations presented here. Second, the fire line and background winds are initially symmetric about the x axis, which limits the development of fire whirls and other turbulent atmospheric features that can directly interact with the fire front. Third, WRF-Fire does not include a mid to long-range spotting model, so there is no ignition of secondary fires due to the transport of firebrands downwind by the pyro-convective plume and atmospheric eddies. Fourth, the background atmosphere has neutral stability, whereas an unstable atmosphere is typically observed at blowup events (Byram, 1954). The inclusion of an unstable background atmosphere would impact on the vertical development of the modelled pyro-convective plume and would therefore also likely affect the modelled fire spread.

Included in the analysis of these numerical simulations is the calculation of the turbulent kinetic energy (TKE) in the atmospheric flow above and downwind of the fire region. Given that the analysis of LES typically requires consideration of the statistical properties of the flow, we do not focus on specific flow features, but rather time-averaged characteristics of the flow, including the TKE. The TKE for a model grid cell is calculated

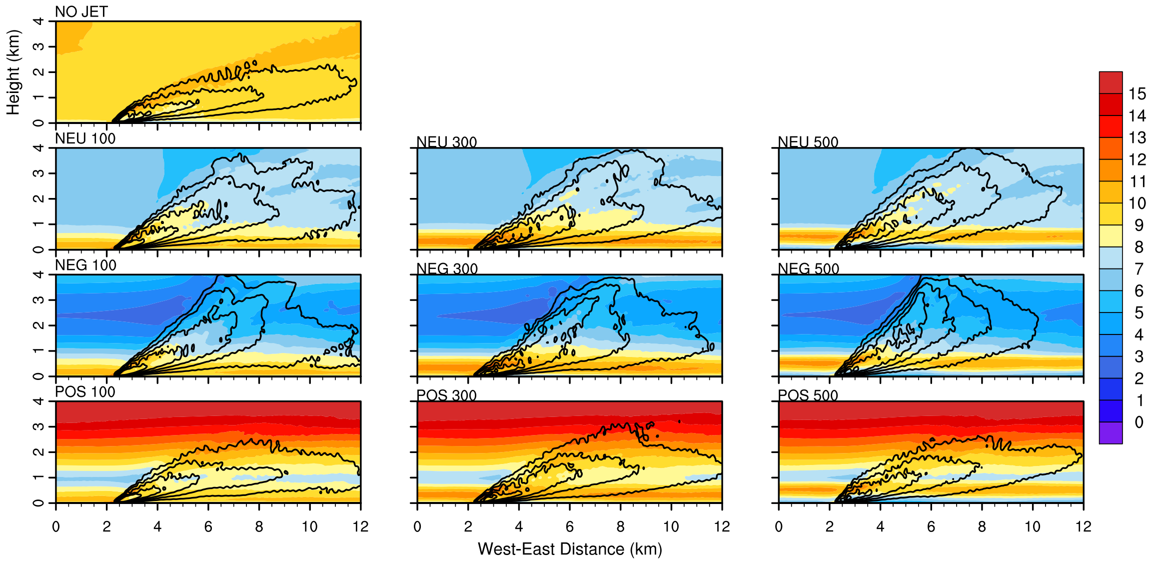

Figure 3. Horizontal wind velocity (m s^{-1}) along an *xz* cross-section through the centre of the *y* at a time of 30 min. Overlaid is the average vertical wind velocity (m s^{-1}) at 1 m s^{-1} intervals in solid black lines.

from the 1 min interval winds over the 30 min fire spread period using:

$$\text{TKE}\,(x,z) = \frac{1}{2}\left(\overline{(u')}^2 + \overline{(v')}^2 + \overline{(w')}^2\right) \tag{2}$$

$$\overline{(u')}^2 = \frac{1}{n}\sum_{i=1}^{n}(u_i - \overline{u})^2 \tag{3}$$

$$\overline{u} = \frac{1}{n}\sum_{i=1}^{n} u_i \tag{4}$$

where $\overline{u}$, $\overline{v}$ and $\overline{w}$ are the individual time-averaged wind components, and n is the number of data points (i.e. time steps). Although taken over only a fairly short time period, this period seems to be sufficient to capture the bulk of the plume variability.

Relative to the modelled fire spread, there are much more pronounced differences in the pyro-convective plume structure and TKE between the simulations, as seen in Figures 3 and 4. In each case, the pyro-convective plume has a central core with average updrafts exceeding 5 m s^{-1} up to around 2 km downwind of the fire, and updrafts exceeding 1 m s^{-1} up to a maximum of around 10 km downwind. Not shown is the development of a counter-rotating vortex pair within the pyro-convective plume that constrains the development of the plume along the *y* axis, and the downdrafts on both flanks of the plume.

The large-scale characteristics of the plume, such as the tilt angle relative to the ground and the internal vertical velocity and TKE, are fairly insensitive to the LLJ height, with more notable variations due to changes in the wind shear above the jet. Similarly to the ARPS simulations presented by Simpson et al. (2013), the pyro-convective plume extends above the jet height, although the vertical development of plume is affected by the wind shear, as expected. The positive wind shear above the jet limits the vertical development of the plume, such that the leading and trailing edges of the plume are tilted further over towards the ground, particularly for a jet height of 100 m. In contrast, the negative wind shear encourages the plume's vertical development, tilting the plume away from the ground, particularly for a jet height of 500 m.

The TKE shows a considerable sensitivity to the presence of a LLJ and the wind shear above the jet. As could be expected, the TKE has its highest peak value for negative wind shear above the jet, and has a larger area of high TKE (greater than around 10 m^2 s^{-2}) than for the no LLJ case or positive wind shear above the jet. The results suggest that there is more pronounced atmospheric turbulence immediately downwind of the fire when a LLJ is present, which would be conducive to mid to long-range spotting, although this can not be explicitly modelled with WRF-Fire.

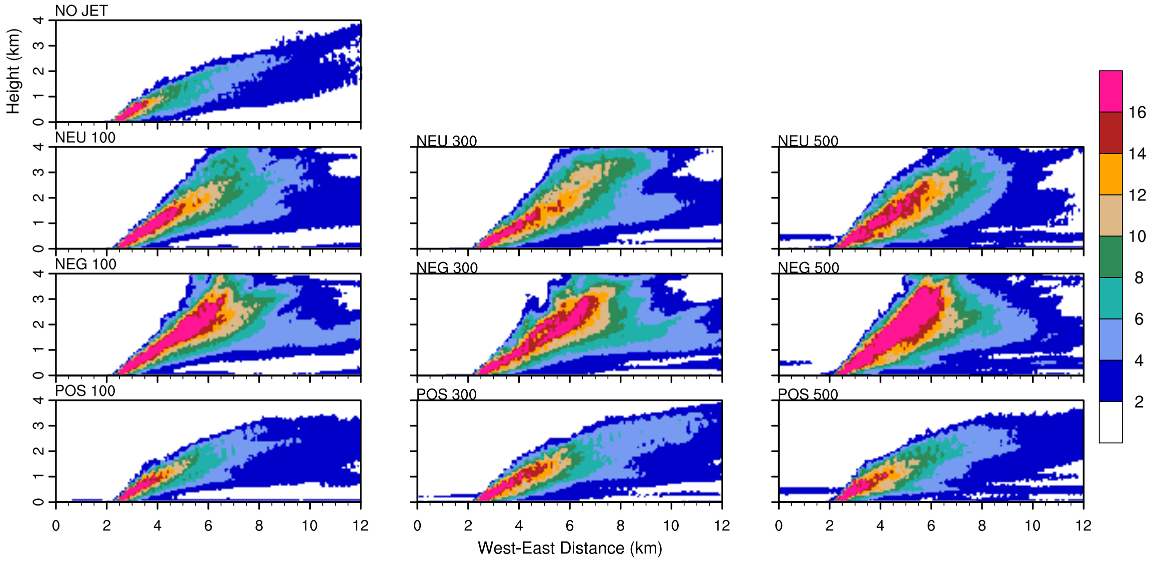

Figure 4. TKE ($m^2\ s^{-2}$) along an *xy* cross-section through the centre of the *y* axis. The TKE is calculated using 1 min winds from WRF in the 30 min period of fire spread. The winds were initially interpolated to a rectilinear grid with 40 and 20 m grid spacing in the horizontal and vertical directions, respectively.

4 SUMMARY AND CONCLUSIONS

This study has presented a number of WRF and WRF-Fire coupled atmosphere-fire numerical simulations of the pyro-convective plume dynamics associated with vertical wind profiles containing a low-level jet. The plume characteristics were only slightly sensitive to the jet height, and were relatively much more sensitive to the wind shear above the jet. It is worth noting that the fuel type used in these simulations has the highest sensible heat output per unit area of the 13 default fuel types available in WRF-Fire. It therefore seems likely that the atmospheric dynamics are being dominated by the heat release close to the fire, which can explain the limited variation in fire spread between the no jet and LLJ cases. The considerable turbulent kinetic energy and updraft velocities within the plume suggest that the presence of a LLJ could be conducive to mid to long range spotting downwind of the fire, which is known to have been a factor in some blowup fires. The development of counter-rotating horizontal vortices within the plume results in little lateral expansion as it propagates downwind. Although this study did not look in any detail at the near-fire atmospheric dynamics, it was noted that due to the high degree of symmetry in the prescribed fire ignition and uniformity of the background wind profile, that there was little expectation of dynamic fire spread.

Although this study provides only a brief investigation of the sensitivity of the dynamic feedbacks between wildland fires and LLJs, it provides a useful numerical modelling framework for use in future research. We intend to further extend this study to consider a much wider range of LLJ properties and numerical model configurations. In particular, there is considerable scope for varying the background atmospheric stability, as unstable conditions are often observed at blowups and would likely affect the pyro-convective plume development considerably. In addition, we aim to test the effect of varying the fuel type, and consequently the heat release per unit area and large-scale plume properties. Future analysis will also focus more on the fire-modified atmospheric dynamics that can directly influence the rate of spread or fire intensity, such as spotting or pyrogenic vortices, particularly in close proximity to the fire. Although WRF-Fire does not currently include a spotting model, which would be of great use in such an analysis, there is active development on such a feature.

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