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WRF-Fire Simulation of Lateral Fire Spread in the Bendora Fire on 18 January 2003

C. Simpson [a], **J. Sharples** [a] **and J. Evans** [b]

[a]*School of Physical, Environmental and Mathematical Sciences, University of New South Wales, Canberra*
[b]*Climate Change Research Centre, University of New South Wales, Sydney*
Email: c.simpson@adfa.edu.au

Abstract: On the afternoon of 18 January 2003, a number of separate fires located to the west of Canberra, Australia, began major runs under extreme fire weather conditions, and impacted upon the city. These events were well documented by a range of instruments, including a multispectral line-scanning instrument attached to an aircraft. Analysis of the data collected revealed that a number of the fires had exhibited atypical lateral fire spread, in a direction transverse to the background wind, on steep leeward slopes. These lateral fire spread events often contributed considerably to the size and impact of the fire.

In one particular instance, a fire burning to the west of Bendora Dam (35° 28' S, 148° 50 E), which had been burning for the previous ten days subject to control efforts, breached control lines and rapidly developed into a large conflagration. The Bendora fire then ran into the edge of urban areas, where it combined with other fires that had escalated significantly on that day. The fact that the Bendora fire developed so rapidly, from a relatively small breach of the control line, attests to the abrupt transitions that bushfires can exhibit under extreme weather conditions.

In this study, the WRF numerical weather prediction model was coupled to the WRF-Fire wildland fire physics module at high resolution and used to simulate the early development of the Bendora fire on 18 January. The modelled fire spread was compared to the multispectral line-scan data with the fire to atmosphere coupling enabled and disabled. With the coupling enabled, the fire advanced around 1 km further laterally to the south, and this lateral fire spread occurred predominantly in the lee of a ridge. The lateral fire spread was partly driven by pyrogenic vorticity that formed in the lee of the ridge due to the interaction between the opposing pyrogenic and background winds. Additionally, differences between the modelled and actual fire spread on the windward side of ridges suggest that more careful consideration of the combined effects of wind and slope on the rate of spread is required in future versions of WRF-Fire.

A large number of near-surface vortices, with a large component of vertical vorticity, were identified over the leeward slopes and downwind of the fire when the fire to atmosphere coupling was enabled. Additionally, a region of high turbulent kinetic energy extending to the southeast of the fire supports the notion that the fire was carried across the Bendora Reservoir by mid to long-range spotting. As there is no spotting model in WRF and WRF-Fire, the fire was unable to cross the Bendora Reservoir in the numerical simulations, as was observed in the multispectral line-scan data.

The results demonstrate that WRF and WRF-Fire can model atypical lateral fire spread across steep leeward slopes in more realistic terrain than has previously been considered. It may therefore be possible to investigate other known atypical lateral spread events, such as the 2003 Broken Cart fire in Canberra, the 2009 Jesusita fire in Santa Barbara and the 2013 Wambelong fire near Coonabarabran, using this or a similar model configuration. However, we caution that these results were obtained using a single coupled atmosphere-fire model for a highly idealised configuration, and further work is required to replicate this fire behaviour in other coupled models.

Keywords: *Coupled atmosphere-fire modelling, WRF-Fire, fire whirls, atypical lateral fire spread, VLS*

1 INTRODUCTION

The Bendora fire was ignited by dry lightning on 8 January 2003 in rugged terrain close to Bendora Dam, located approximately 32 km southwest of Canberra, Australia. Over the following ten days, the fire burned in an area to the northwest of the dam. During this period, back burning operations were conducted to establish control lines aimed at preventing the fire from developing eastwards, in the direction of Canberra. As part of these operations, a road along the ridge line to the northwest of Bendora Dam was used to form an eastern anchor point. This road and the back burning operation can be seen in Figure 1a. Despite these back burning efforts, the fire made a small breach of the eastern control line on 18 January as unfavourable fire weather conditions developed, likely by a tree falling over the control line. The Bendora fire then flared up in this previously unburned fuel to the east. Multispectral line-scan images (e.g. Figure 1a), indicate that the fire spread rapidly to the south of its initial location on the western side of the Bendora Reservoir, at a rate of up to around 5.5 km h^{-1} (McRae, 2004; Sharples et al., 2012). Interestingly, local weather stations recorded a west-northwest wind direction, suggesting that the rapid fire spread to the south occurred in a direction approximately transverse to the background wind. In addition, there was a rapid downwind extension of the fire approximately to the southeast across the reservoir, presumably aided by intense spotting (Sharples et al., 2012). This concurrent southerly and southeasterly rapid fire spread resulted in a large region of active flame, as shown in Figure 1a, that triggered intense pyro-convective activity (McRae, 2004; McRae et al., 2015).

In addition to the Bendora fire, a number of other wildland fires have now been observed to advance rapidly across steep lee-facing slopes in a direction that is approximately transverse to the background wind. Intense spotting is also often observed downwind of the leeward slope that experienced the atypical lateral fire spread (Sharples et al., 2012). The atypical lateral fire spread can occur on leeward slopes regardless of whether the fire crosses onto the leeward slope from the windward slope (Raposo et al., 2015), or when the fire is initially located on the leeward slope (Sharples et al., 2012). Subsequent laboratory and numerical studies have reproduced qualitatively similar lateral fire spread on steep lee slopes for idealised terrain (Farinha, 2011; Simpson et al., 2013; Sharples et al., 2013; Raposo et al., 2015). The numerical modelling studies were performed using a coupled atmosphere-fire model, and suggest that the lateral fire spread is predominantly driven by pyrogenic vorticity (i.e. fire whirls) that develop in the lee of the ridge due to an interaction between the fire and the terrain-modified winds. This modelled process qualitatively matches the description of lee fire whirls provided by (Countryman, 1971), who noted that non-stationary fire whirls can form in the lee of a ridge and are capable of spreading the fire laterally along the ridge or diagonally downslope.

The objective of this study is to use coupled atmosphere-fire modelling to simulate the initial development of the Bendora fire on 18 January 2003, using realistic terrain and an idealised background atmosphere. Of particular interest is determining the ability of the coupled model to reproduce the observed southerly fire spread on the western side of the Bendora Reservoir, and to investigate the physical processes driving the modelled fire spread. Although a similar numerical model configuration to that adopted by Simpson et al. (2013, 2014) is used in this study, this is the first attempt to model vorticity-driven lateral fire spread in realistic terrain.

2 NUMERICAL MODEL AND CONFIGURATION

The numerical simulations presented here were performed using version 3.6 of the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008). Included in WRF v3.6 is the WRF-Fire wildland fire physics module (Coen et al., 2013). WRF is used here in a large eddy simulation (LES) configuration (Moeng et al., 2007), which allows it to directly resolve the large-scale atmospheric eddies that typically dominate the daytime atmospheric boundary layer. WRF-Fire utilises a two-dimensional implementation of the Rothermel semi-empirical fire spread model (Rothermel, 1972), in which the rate of spread at each point along the fire line is determined by the local fuel, wind and slope. A logarithmic vertical wind profile is applied to the WRF winds in order to determine the local mid-flame height winds.

The two-dimensional fire model grid is defined as a refinement of the WRF horizontal grid, with a subgrid ratio of 4:1. The vertical grid levels are stretched to a model top of approximately 6 km following a hyperbolic tangent function, allowing for higher spatial resolution close to the surface. The simulations are highly idealised: no radiation physics, microphysics, cumulus parameterisation or planetary boundary layer scheme are used. A prognostic turbulent kinetic energy closure scheme is used to calculate eddy viscosities. Periodic lateral boundaries are used to allow for the spin-up of atmospheric turbulence within the model domain. An open radiative upper boundary with a 1 km deep Rayleigh damping layer is used.

Each simulation is initialised with an idealised west-northwest background wind of around 15 m s^{-1}, which approximates the observed wind (Sharples et al., 2012). Additionally, the potential temperature is initially set to 300 K up to a height of 4 km, and then increased linearly to 310 K at the model top. After a 30 min spin-up

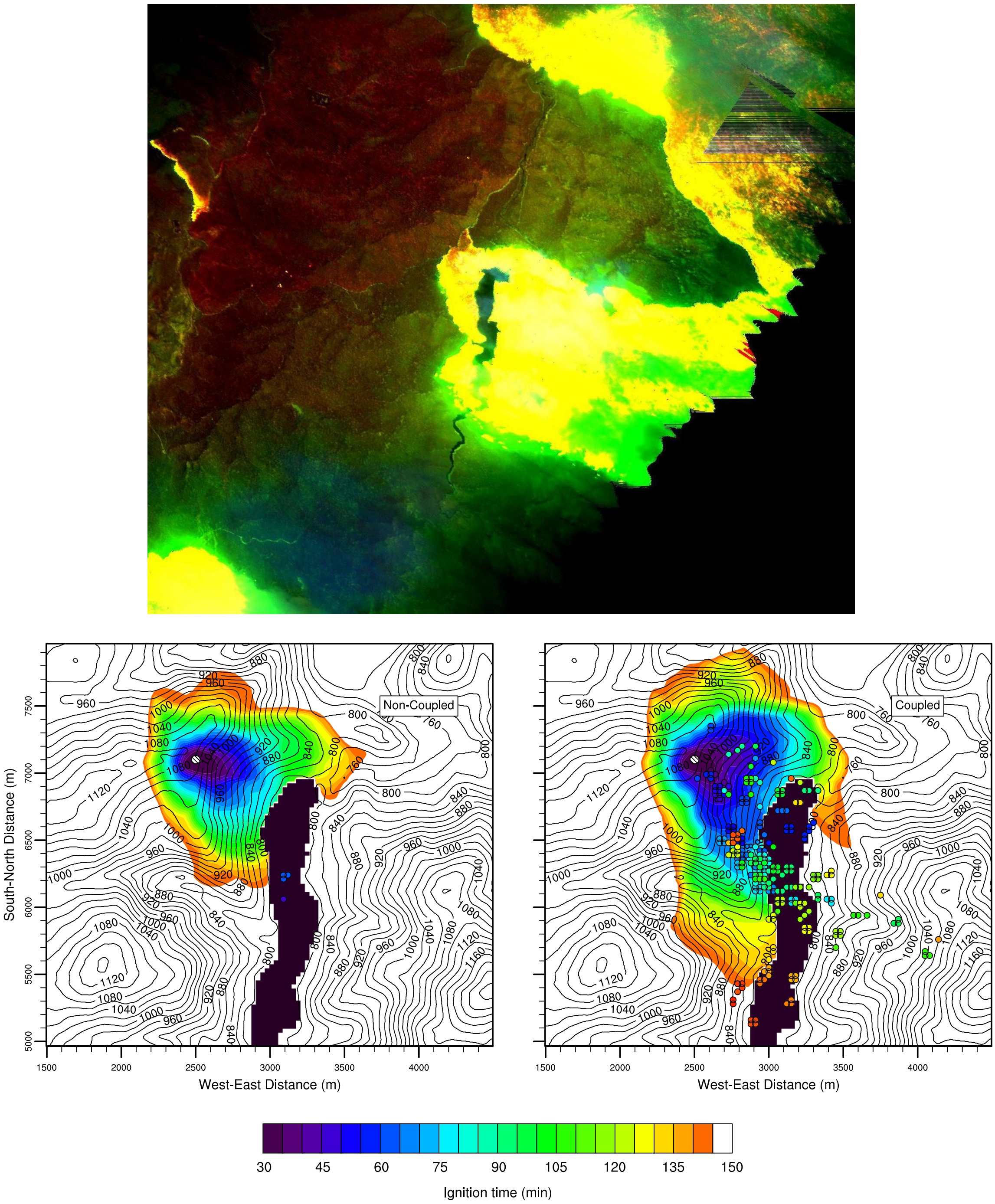

Figure 1. Top (a): multispectral line-scan image of the region surrounding the Bendora fire, taken at 1446 on 18 January 2003. The yellow colour is indicative of active flame (Sharples et al., 2012). Bottom (b,c): time of ignition for the non-coupled (left) and coupled (right) simulations, with terrain height contours at 20 m intervals. The solid black region indicates the spatial extent of the Bendora Reservoir taken from the SRTM Water Body Dataset. The circular markers show the time and location of vortices identified by a fire whirl identification algorithm. The dashed region shows the ignition location, which approximates the location of the control line breach that occurred.

period, the fire is ignited at the approximate starting location of the flare up of the Bendora fire on 18 January, visible as a bright orange region in Figure 1a. The primary model time step is 1/25 s, and 120 min of fire spread is modelled following the ignition at a time of 30 min.

The SRTM digital elevation model (more information available at http://srtm.usgs.gov/index.php) at 1 arcsecond resolution was used to determine the terrain height near Bendora Dam on a 9×9 km model domain, with a WRF model horizontal grid spacing of 30 m. Additionally, Gaussian smoothing was applied to the terrain close to the lateral boundaries, down to a constant minimum terrain height. This smoothing region prevents terrain height discontinuities at the lateral boundaries, and provides a region in which the atmospheric turbulence can partly dissipate prior to being recycled through the periodic lateral boundaries. As shown later, the pyrogenic turbulence can be extreme downwind of the fire, so use of this smoothing region is critical. For consistency with previous numerical studies, we use fuel type 13 in WRF-Fire, which is based on the heavy logging slash Anderson fuel category (Anderson, 1982). However, it is worth noting that the fuel load may be higher in the numerical simulations than in reality (McRae, personal communication). In addition, a no-fuel category is applied to the Bendora Reservoir, whose spatial extent is estimated using the SRTM Water Body Dataset. A visual comparison between Figures 1a and 1b, which show the actual and model reservoir extent, suggests that there is a fairly good similarity. However, there are some notable differences, such as at the north of the reservoir where a region of water extending to the east is not included in the model.

The fire to atmosphere coupling is modelled through the release of sensible and latent heat from WRF-Fire into WRF. In WRF-Fire a parameterised combustion process is used to determine the sensible and latent heat flux at each WRF vertical level in each model grid column. Once a fire model grid cell is ignited, the fuel mass is gradually converted into heat, and the sensible and latent heat flux separately affect the atmospheric potential temperature and water vapour mixing ratio. This facilitates direct modification of the local atmospheric dynamics by the fire, which can then subsequently influence the modelled fire spread. This coupled system allows for WRF and WRF-Fire to directly model the two-way coupled atmosphere-fire interactions.

3 RESULTS AND DISCUSSION

The relative direction of the west-northwest background wind to the terrain near the ignition location, visible in Figure 1, indicates that much of the high-relief terrain to the south and northeast of the ignition is in the lee of a ridge, and therefore susceptible to lateral fire spread (Sharples et al., 2012). Figure 2a shows the modelled mid-flame height winds with the fire to atmosphere coupling disabled i.e. no direct feedback from the modelled fire to the atmosphere. As expected for a neutral atmosphere, the winds accelerate up the windward slope and

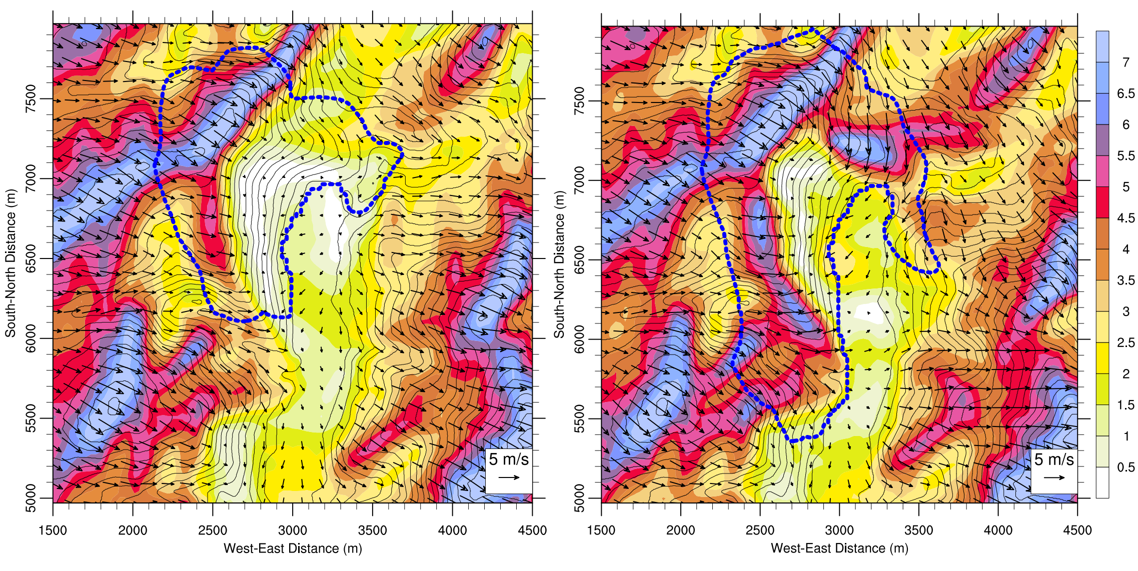

Figure 2. Mean mid-flame height wind speed (colour shown in scale, m s^{-1}) throughout the non-coupled (left, a) and coupled (right, b) simulations. The blue dashed line shows the final fire perimeter in each simulation. A reference westerly wind vector of 5 m s^{-1} is shown in the bottom right corner.

decelerate in the lee of the ridge. The wind direction typically varies between west-northwest and northwest along the ridges close to the ignition location. Importantly, the angle between the ridge orientation and wind direction appears to be less than 40° in these locations, which is the empirical threshold identified by Sharples et al. (2012) for the occurrence of atypical lateral spread.

With the coupling disabled, the background wind and slope allow for limited fire spread to the south and east of the ignition location, as shown in Figure 1b. Further fire spread to the southeast is impeded by the reservoir. In contrast, Figure 1a demonstrates that there was considerable fire spread to the southeast, well beyond the reservoir, in the Bendora fire. Sharples et al. (2012) suggested that extensive spotting played an important role in that downwind extension. For comparison, Figure 1c shows the fire spread with the fire to atmosphere coupling enabled. The modelled fire advances approximately 1 km further south and also advances further to the east and southeast, wrapping partly around the northern edge of the reservoir. The rate of eastward and southward fire spread is particularly high in the initial 40 min of the coupled simulation. During this period, fire whirls develop over the fire region, particularly in the lee of the ridges. This pyrogenic vorticity modifies the local wind speed and direction, acting to increase the southerly lateral rate of spread. However, as in the non-coupled simulation, the fire is again impeded by the reservoir as it advances to the southeast. The fire to atmosphere coupling is also seen to affect the mean local winds, with marked increases in the wind speed to the south and east of the ignition location.

The most likely explanation for the considerable difference in downwind fire spread between the model simulations and the multi-spectral line-scan images of the Bendora fire is that there was extensive mid to long-range spotting across the reservoir. With the Rothermel semi-empirical fire spread model, or indeed any fire spread model that advances the fire perimeter in a continuous manner without spotting, it is not possible to reproduce the observed fire spread without non-realistic wind speeds. However, without a spotting model it is not currently possible to test this explanation directly with WRF-Fire. Although fire spread models that do include mid to long-range spotting may be able to capture that behaviour, a coupled atmosphere-fire modelling system is likely required to capture much of the southerly lateral fire spread, due to its close association with the pyrogenic vorticity.

It is also worth noting that in the coupled simulation, the southerly lateral fire spread occurred on both the leeward and windward sides of the ridge, whereas the multispectral line-scan indicates that it occurred only on the leeward slope in the Bendora fire. This difference can partly be attributed to the numerical method used for combining the wind and slope effects on the rate of spread. At present in WRF-Fire, a fire advancing through uniform fuels under an identical wind will spread downslope at the same rate as along flat terrain, in contrast to empirical evidence that wildland fires typically advance downslope at a slower rate (Weise and Biging, 1997). Therefore, the downslope rate of spread along the windward slope is too high in the numerical simulations presented here, and we suggest that more careful consideration of combining the wind and slope effects is needed in future versions of WRF-Fire.

Fire whirls are identified in the model output through conditional testing for a low local atmospheric pressure, a high vertical vorticity component and wind direction reversal around a central point near the surface. There is no conditional test for heat or temperature, so non-pyrogenic atmospheric eddies can also be identified, as seen over the reservoir in Figure 1b. However, there are many more vortices identified in the coupled simulation, and they are predominantly distributed to the southeast of the ignition location, appearing up to 2 km downwind towards the middle and end of the simulation. The resolved turbulent kinetic energy (TKE) in the bottom 100 m layer of the atmosphere, shown in Figure 3, also reveals the considerable increase in atmospheric turbulence southeast of the ignition location due to pyro-convection. Indeed, the increased TKE and large number of fire whirls identified beyond the fire perimeter support the notion that mid to long-range spotting played an important role in the significant downwind fire spread seen to occur in conjunction with the southerly lateral fire spread.

Similarly to earlier numerical studies in idealised terrain by Simpson et al. (2013, 2014), the fire whirls form due to the interaction between the fire-induced thermal upslope wind and the opposing background wind in the lee of the ridge. The process was described briefly by Countryman (1971) and is qualitatively similar to the process evident in the coupled model. It is clear from Figure 1c that the fire whirls form only in the lee of the ridges, and not over the windward slopes.

4 SUMMARY AND CONCLUSIONS

This study has presented coupled and non-coupled atmosphere-fire model simulations of the early development of the Bendora fire during the 2003 Canberra bushfires. The simulations captured the initial easterly and southerly fire spread, and the southerly fire spread occurs across a lee slope in a direction approximately transverse to the background wind. This southerly lateral fire spread was particularly pronounced in the coupled simulations, and was found to be closely associated with pyrogenic vorticity in the lee of the ridge. This is similar to the process described by Countryman (1971) and that studied previously by Simpson et al. (2013, 2014). However, the rapid and extensive downwind expansion to the southeast of the fire region observed in the multi-spectral linescan was not well reproduced. As noted previously (Sharples et al., 2012), the most likely explanation for this rapid downwind spread is extensive mid to long-range spotting. As evidence in support of this, the simulations showed extremely high values of resolved TKE and large numbers of fire whirls in the approximate region of the downwind fire spread.

The results suggest that WRF-Fire or any other empirically based model that relates rate of spread to fuel properties, wind and slope, but does not include a mid to long range spotting model, will systematically underestimate the downwind extension of these atypical lateral fire spread events. Obtaining a better match to the observational data using the fire spread model in WRF-Fire would require extreme background wind speeds that do not resemble those observed. It is therefore of immediate importance that a spotting model be developed to improve the functionality of WRF-Fire for this research topic.

It is also worth noting the apparently significant effect that small-scale dynamics can have on wildland fire spread in certain situations, such as on steep leeward slopes. Through dynamic feedback with the atmosphere, transient small-scale features such as fire whirls, can develop and interact with the fire, allowing it to spread more rapidly and in varying directions. The current inability to predict the occurrence and impact of these small-scale dynamics in an operational environment could have serious consequences for fire safety, and provides the justification for further research with high-resolution coupled atmosphere-fire modelling. It would therefore be valuable to seek confirmation of this process in additional coupled atmosphere-fire models, in order to reduce the reliance on results from a single model. Nevertheless, it is interesting to note that WRF

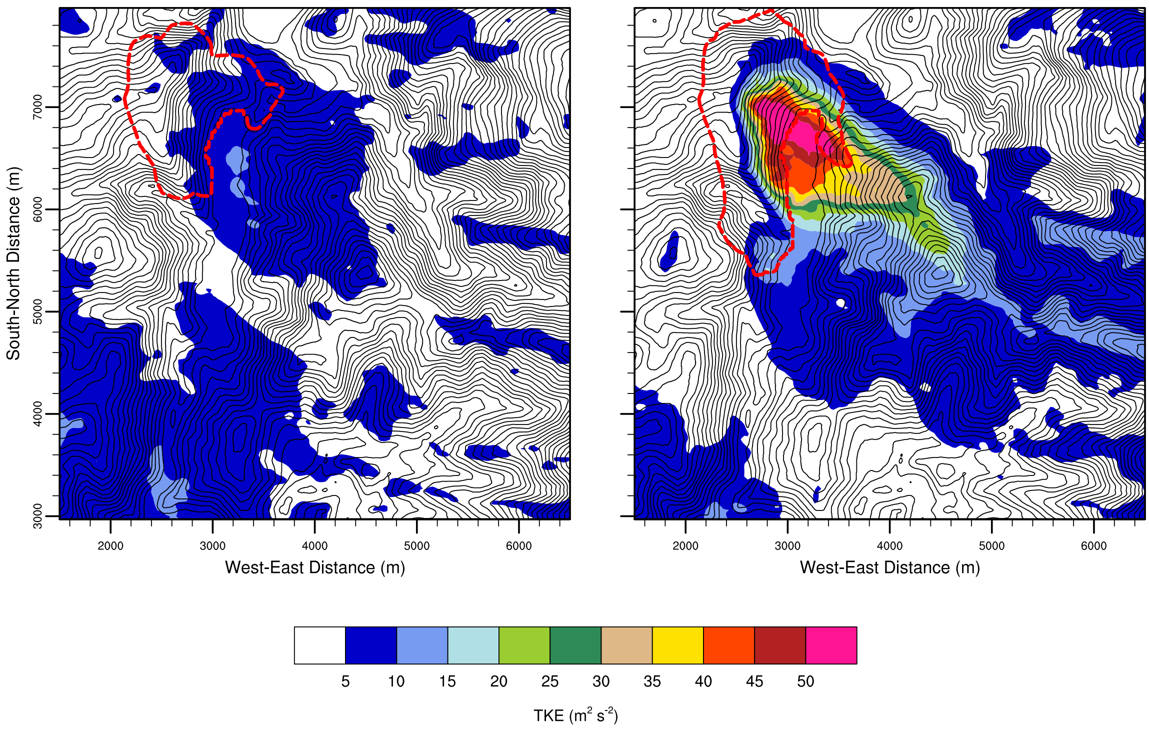

Figure 3. Resolved turbulent kinetic energy (colour shown in scale, m^2 s^{-2}) in the lowest 100 m atmospheric layer for the non-coupled (left, a) and coupled (right, b) simulations. The red dashed line shows the final fire perimeter in each simulation.

and WRF-Fire have now modelled this process in both highly idealised and more realistic terrain.

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