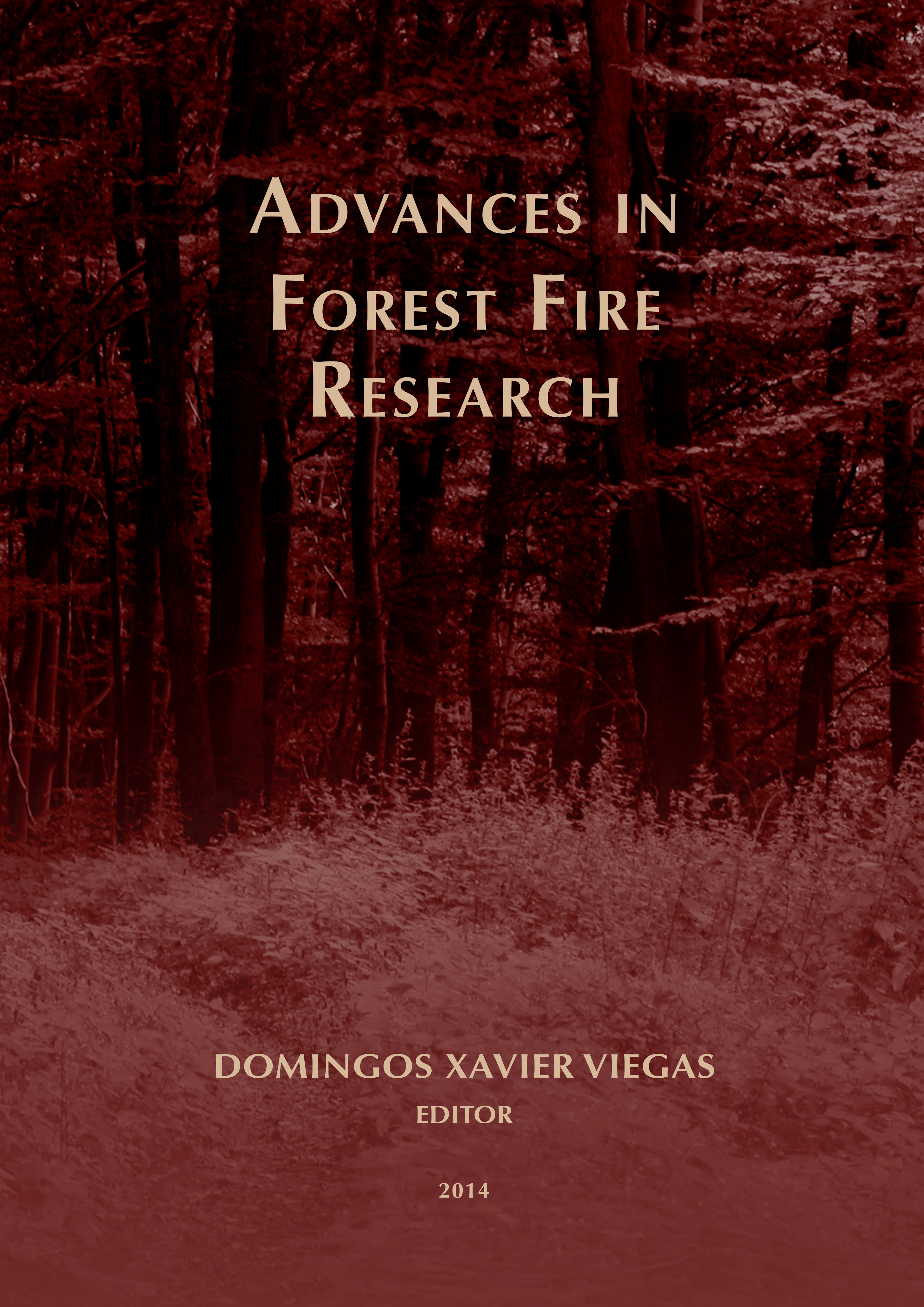

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Environmental thresholds for dynamic fire propagation

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Abstract

Under conditions of extreme fire weather, bushfires burning in rugged terrain can exhibit highly atypical patterns of propagation, which can have dramatic effects on subsequent fire development. In particular, wildfires have been observed to spread laterally across steep, lee-facing slopes in a process that has been termed vorticity-driven lateral spread (VLS; also known as 'fire channelling'). Coupled fire-atmosphere modelling using large eddy simulation has indicated that the fire channelling phenomenon occurs due to a dynamic interaction between terrain modified winds and the fire's convective plume. This interaction creates pyrogenic vorticity that drives a fire laterally across a leeward slope. In this work we extend previous modelling, using the WRF-Fire coupled fire-atmosphere model, to specifically consider the environmental thresholds that define the likely onset of the VLS phenomenon. In particular we investigate the effects of wind speed and topographic slope on the occurrence of atypical lateral spread.

The simulated behaviour of fires on leeward slopes, and the implied transition in fire propagation that can occur when certain environmental thresholds are breached, highlight the inherent dangers associated with firefighting in rugged terrain. The propensity for dynamic interactions to produce erratic and dangerous fire behaviour in such environments has strong implications for firefighter and community safety. At the very least the research findings provide additional support for careful planning prior to prescribed burning operations and the use of well-briefed observers in firefighting operations undertaken in complex topography.

Keywords: *Dynamic fire propagation; environmental thresholds; wind-terrain-fire interaction; VLS*

1. Introduction

Dynamic escalation of wildland fires into large conflagrations represents a significant challenge to the management of fires in the landscape. Multi-scale interactions between a fire and the local environment, which includes fuels, weather and topography, can produce highly complex patterns of fire spread that are currently beyond the capabilities of operational fire spread models. Understanding the physical processes that underpin these complex modes of fire propagation is a key step in improving the way extreme bushfires are managed. Recent research into the behaviour of wildfires has identified a number of dynamic modes of fire propagation. These modes of fire spread are referred to as dynamic because they are manifestly at odds with quasi-steady fire propagation, whereby a fire spreads at an approximately constant rate given uniform environmental conditions.

Viegas (2005) and Dold and Zinoviev (2009) examined the ability of a fire to exhibit exponentially increasing rates of spread up steep slopes and canyons, while Viegas *et al*. (2012) discussed the abrupt increases in rate of spread that can occur when two lines of fires intersect at some oblique angle. Another form of dynamic fire propagation was identified by Sharples *et al*. (2012) in connection with the 2003 Canberra bushfires. This phenomenon, which they referred to as *fire channelling*, involved the rapid lateral propagation of a fire across a lee-facing slope in a direction approximately perpendicular to the prevailing wind direction. Sharples *et al.* (2012) conjectured that the lateral spread was due to an interaction between the wind, the terrain and an active fire.

Simpson *et al*. (2013) found support for this conjecture using the WRF-Fire coupled fire-atmosphere model through simulation of the interaction of the terrain modified flow with the fire's convective plume. It was found that this interaction resulted in the intermittent generation of vertical vorticity, which drove the fire laterally across the top of the slope in the immediate lee of the ridge line. As such, Simpson *et al*. (2013) permitted the characterisation of fire channelling as vorticity-driven lateral spread (VLS). Farinha (2011) conducted a number of combustion tunnel experiments to examine the behaviour of fires burning on the leeward slope of a small triangular ridge. He found that in the absence of wind the fires burnt uniformly across the slope at a distinctly quasi-steady rate of spread. In the presence of combustion tunnel winds of 1.5 m s^{-1}or greater Farinha (2011) found that the fire spread rapidly across the top of the leeward slope at a significantly accelerated rate. The rate of lateral spread varied with the speed of the wind, with the greater rates of lateral spread coinciding with the fastest wind speeds.

In the present paper, the study of Simpson *et al*. (2013) is extended to examine the effect of variation in wind speed and topographic slope on the occurrence of VLS across a lee-facing slope. Fires burning on lee-facing slopes under different wind speed and topographic slope regimes were simulated using WRF-Fire. Two sets of simulations were considered. In the first, the winds were taken as coming from the west with the ambient wind speed characterised in terms of a reference wind speed U_0. The topography was taken to be an idealised triangular mountain with a north-south oriented ridge line, such as was considered by Simpson *et al*. (2013). The windward and leeward slopes were taken to be 20° and 35°, respectively. The reference wind speed U_0 was prescribed values of 0, 2.5, 5, 7.5, 10 and 15 m s^{-1}. The aim of this part of the study was to ascertain if there is a wind speed threshold, below which VLS does not occur.

In the second set of simulations, the reference wind speed was fixed at U_0 = 15 m s^{-1}. The topography was again taken to be an idealised triangular mountain with a windward slope of 20°, but with a leeward slope α° that was varied between 10° and 45°. This part of the study was designed to examine the existence of a threshold topographic slope, below which VLS does not occur. Such environmental thresholds are hypothesised to exist based on the role that flow separation in the lee of the ridge plays in driving the VLS phenomenon (Simpson *et al*. 2013). Flow separation is only expected to occur when wind speeds are sufficiently strong and the leeward slope is sufficiently steep (Wood, 1995).

The 'deep flaming' associated with the VLS phenomenon (Sharples *et al*., 2012) can act as a strong source of pyro-convection, and so systematically establishing the environmental thresholds relating to VLS will provide improved guidance for predicting the onset of extreme pyro-convection and blow-up fire behaviour. As such, the present study has direct implications for firefighter and community safety.

2. Methods

Version 3.5 of the Weather Research and Forecasting (WRF) model (Skamarock *et al*., 2008) is used in a large eddy simulation (LES) configuration (Moeng *et al*., 2007) and coupled to the SFIRE fire spread model (Mandel *et al*., 2011). This coupled atmosphere-fire numerical modelling system, commonly referred to as WRF-Fire, is suited to modelling turbulent atmosphere-fire interactions on length scales of tens of metres to kilometres. The WRF-LES model explicitly resolves grid-scale atmospheric eddies, whereas the effects of subgrid-scale motions are modelled using a subfilter-scale stress model. WRF utilises fully compressible nonhydrostatic equations and has a mass-based terrain-following coordinate system. The WRF-LES model domain has dimensions of 15 km × 5 km × 5 km with open radiative boundaries. The horizontal and vertical grid spacing are both 50 m, although due to the use of mass levels the vertical grid spacing is not constant. A triangular mountain is located within the model domain, as shown in Figure 1, with its ridge line oriented perpendicular to the prevailing wind. The windward and leeward slope angles are 20° and 35°, respectively, and the mountain height is 1 km. The initial and lateral boundary conditions are specified using a 1D sounding with a vapor mixing ratio of zero, a constant potential temperature of 300 K and a wind profile given by U0, which expressed as a function of the Cartesian coordinates (x,y,z), is

$$\mathbf{U}_0(x, y, z) = U_0 P(z)\mathbf{x} \quad (1)$$

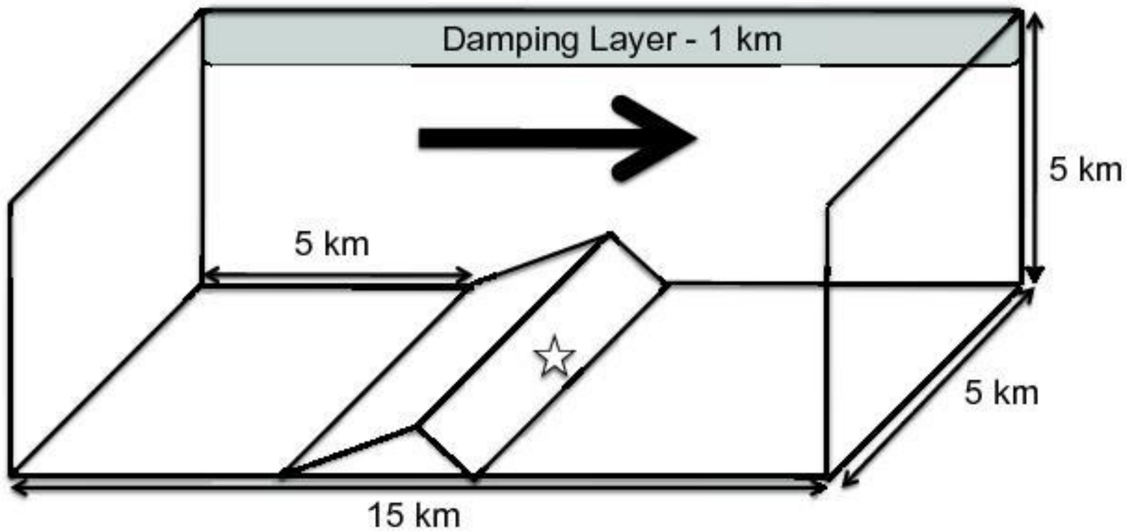

Figure 1. Model domain showing the triangular mountain with its ridge line oriented perpendicular to the input wind field. The windward slope is inclined at 20° and the leeward slope is inclined at an angle of α° (α = 35° in the first set of simulations and is variable in the second set of simulations). The star on the leeward slope indicates the approximate location of the ignition used in the simulations.

Here U0 denotes the reference wind speed – the main variable of interest in this study, and x denotes the unit vector in the x-direction (which coincides with east). The function P(z) in equation (1) prescribes the vertical structure of the initial wind field profile, and is defined as:

$$P(z) = \begin{cases} \left(\frac{z}{200}\right)^2, & z \leq 200, \\ 1, & z > 200. \end{cases} \quad (2)$$

We use a quadratic profile here, rather than the usual logarithmic profile, for the sake of simplicity and, more importantly, so that our results are directly comparable with those of Simpson *et al*. (2013). WRF offers either a physical (not used) or free-slip (used) bottom boundary condition. Since the lowest model level is still above the actual ground level, we don't have a completely zero wind speed on any WRF model level. However, it should be noted that a fuel-dependent roughness length is used in vertically interpolating the wind speeds down to the mid-flame height.

The WRF-LES model is used in an idealised configuration and there is no modelling of the microphysics, radiation physics, cumulus physics and the surface and planetary boundary layers. However, it should be noted that a fuel-dependent roughness length is used in vertically interpolating the wind speeds down to the mid-flame height. Diffusion in physical space is calculated using the velocity stress tensor and the eddy viscosities are calculated using a 3D prognostic 1.5-order turbulence closure scheme. A Rayleigh damping layer in the top 1 km is used to prevent reflection of the pyro-convective plume from the model top. The primary model time integration is performed using a third-order Runge-Kutta scheme and a secondary time step is used to handle acoustic waves. The primary and secondary model time steps are 0.1 s and 0.0125 s, respectively.

A small circular fire is ignited in the SFIRE model near the base of the leeward slope (Figure 1), after a WRF-LES spin-up period of 20 min. The subsequent fire spread is modelled on a 10 m × 10 m horizontal grid as a temporally evolving fire perimeter using a level set method. The spatially and temporally varying fire spread rate, S, is calculated using the Rothermel equation (Rothermel, 1972):

$$S = R_0(1 + \varphi_W + \varphi_S). \qquad (3)$$

The base rate of spread, R_0, is dependent on the parameterised fuel properties. The slope correction factor, φ_S, is calculated using the local terrain in SFIRE. The wind correction factor, φ_W, is calculated from the WRF modelled wind speeds, which are vertically interpolated to an estimated mid-flame height. The "heavy logging slash" Anderson fuel category (Anderson, 1982) is used to initialise the fuel conditions homogeneously across the SFIRE model domain. The parameterised fuel properties include the initial mass loading, fuel depth, surface area to volume ratio, moisture content of extinction and rate of mass loss following ignition.

The two-way atmosphere-fire coupling between SFIRE and WRF-LES is achieved through the release of latent and sensible heat from the modelled fire. For 1 kg of fuel combusted in SFIRE there is 17.43 MJ of sensible heat released into the WRF-LES model, which is about a factor of ten higher than the latent heat released for the fuel type used. These heat fluxes are distributed throughout the WRF-LES vertical levels using an exponential decay function and directly modify the atmospheric conditions surrounding the modelled fire. The two-way coupling in WRF-Fire allows it to directly model atmosphere-terrain-fire interactions down to length scales of tens to hundreds of metres.

3. Results

3.1. Wind speed threshold

Sharples *et al*. (2013) considered the lateral spread characteristics arising for different reference wind speeds. Specifically, they considered reference wind speeds of U_0 = 0.0, 2.5, 5.0, 7.5, 10.0 and 15.0 m s^{-1}. In each case the model output was examined for instances of significant lateral spread (i.e. spread in the north-south direction). Figure 2 summarises the lateral spread rates for each of these cases. For the U_0 = 0.0 m s^{-1} simulation the lateral propagation of the fire occurs at a quasi-steady rate of around 0.2 km h^{-1}. In this case the fire spread predominately towards the west, without any indication of dynamic fire spread. Similarly, Figure 2 shows that the U_0 = 2.5 m s^{-1} case exhibited lateral fire spread consistent with the quasi-steady assumption.

In the U_0 = 5.0 m s^{-1} simulation, the fire spread exhibited a small lateral bulge towards the north (most notably at around 70 minutes after ignition). However, the rate of lateral spread displayed in this case was not significant compared to the other cases for U_0 > 5.0 m s^{-1}. Figure 2 indicates that for all of the cases with U_0 > 5.0 m s^{-1} the fire spread laterally at a significant faster rate. Moreover, this atypical lateral spread occurred immediately after the fire reached the ridge line at about 20-25 minutes after ignition. For the U_0 = 10.0 m s^{-1} and 15.0 m s^{-1} cases the lateral spread rates reach values as a high as 5 km h^{-1}, which is approximately 25 times larger than the quasi-steady lateral spread rates seen in the U_0 = 0.0 m s^{-1} and 2.5 m s^{-1} cases.

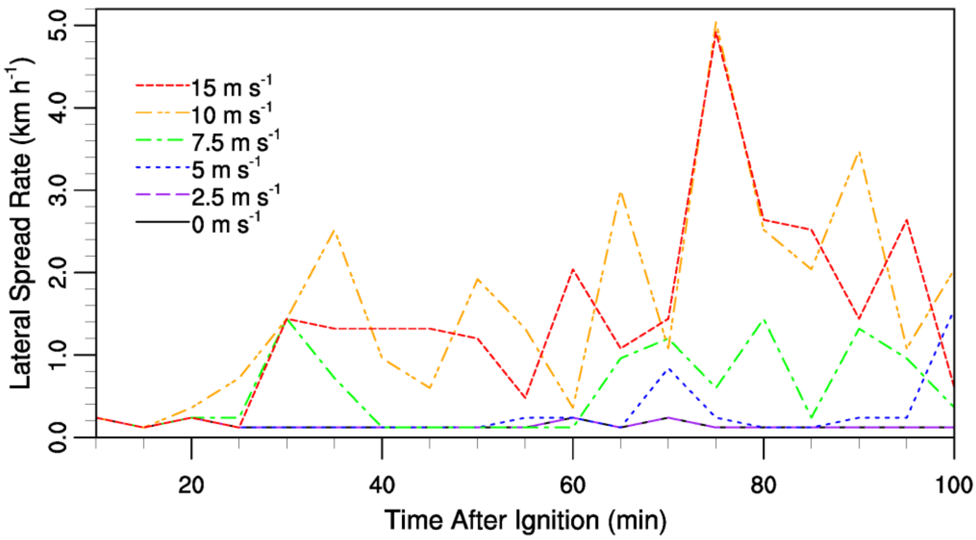

Figure 2. Maximum lateral spread rate for different reference wind speeds.

3.2. Topographic slope threshold

The simulations were conducted using a reference wind speed of U_0 = 15.0 m s^{-1}, but assuming different lee slope angles. Specifically, we considered α = 10°, 15°, 20°, 25°, 30°, 35°, 40° and 45°. The resulting patterns of fire spread can be seen in Figure 3, which shows the time of ignition of various points within the domain of interest. Figure 3 shows that for lee slope angles α < 25°, the pattern of fire spread does not exhibit any significant lateral spread beyond what might be expected from a fire spreading under a quasi-steady regime. The simulated fire spread for the α = 25° case indicates some propensity for lateral fire spread, though the pattern of spread is quite different to that observed in the α > 25° simulations. The α = 25° case may therefore be viewed as marginal with regards to the onset of dynamic fire behaviour. For the remaining cases, for which α > 25°, the pattern of fire spread exhibits a clear tendency for significant lateral spread. Moreover, for larger values of α the lateral spread is more confined near the apex of the idealised ridge.

Interestingly, the threshold slope angle of $\alpha \approx$ 25° identified here is in good agreement with the threshold value determined by Sharples *et al*. (2012) in their empirical analysis of VLS events in the 2003 Canberra fires.

4. Discussion

The propagation of a fire burning on a lee-facing slope was simulated using the WRF-Fire model under a number of different wind speed and topographic slope conditions. In the first set of simulations the fires exhibited two different modes of behaviour. Under the two lowest wind speed regimes the fires did not exhibit any atypical lateral spread, in stark contrast to the two highest wind speed regimes, for which the simulated fires exhibited significantly faster lateral spread. The results suggest the existence of a threshold wind speed, below which the prevailing winds are too weak to drive the vorticity-generating interaction between the wind, the terrain and the fire's plume, so that no atypical lateral spread occurs. The model simulations further suggest that this threshold occurs for wind regimes characterised by $U_0 \approx$ 5 m s^{-1} (approx. 20 km h^{-1}).

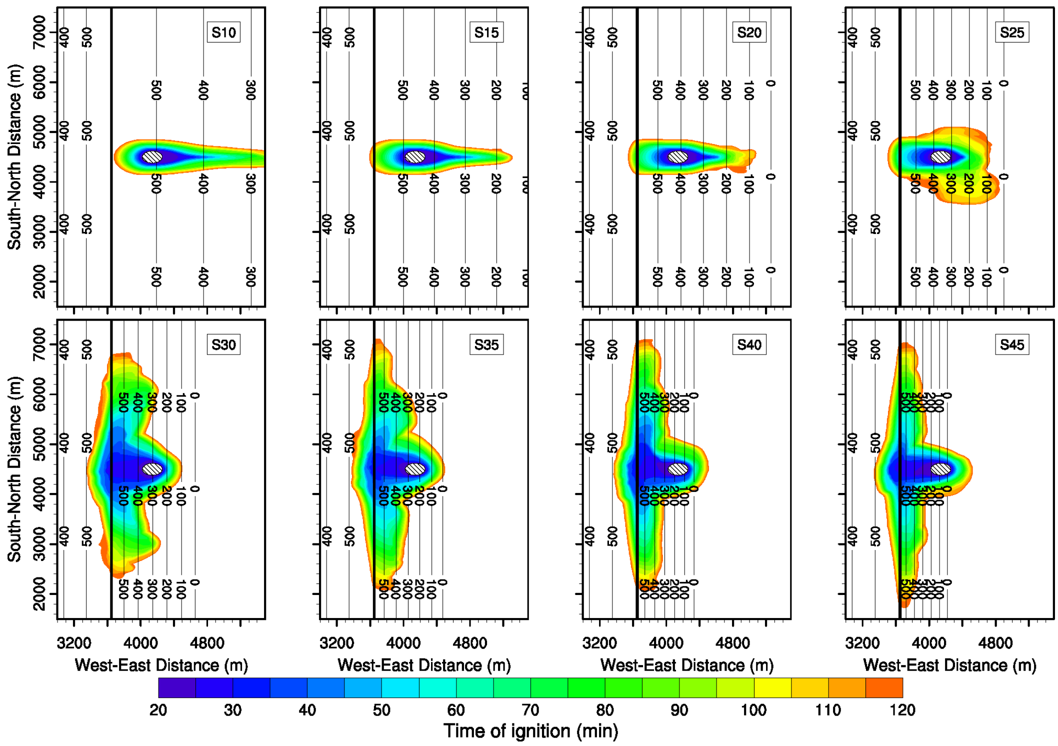

Figure 3. Time of ignition for different lee-facing slope inclinations. The various inclinations are indicated in the top right of each panel; for example, "S15" denotes a lee slope angle of 15°.

In the second set of simulations, in which the wind speed was fixed at U_0 = 15 m s^{-1}, the fires again exhibited two different modes of behaviour. For leeward slope angles less than 25° the fires did not exhibit any significant lateral spread, while for leeward slope angles above 25° the fire spread was dominated by lateral propagation across the leeward slope.

The threshold values determined in this study are in good agreement with the empirically determined values given by Sharples *et al*. (2012). In their study they reported a threshold topographic slope threshold of ~ 26° and a wind speed threshold of 20-25 km h^{-1}. The thresholds determined in the present study are also in general agreement with the values of wind speed and leeward slope angle required for separation of the prevailing winds from the terrain surface (Wood, 1995). As such, the modelling results presented above tend to support the role of flow separation in driving the VLS phenomenon.

Farinha (2011) reported a threshold wind speed of ~ 1.5 m s^{-1} for the occurrence of VLS in their laboratory scale experiments. Although more work is clearly required, comparison of Farinha's value of 1.5 m s^{-1} with the threshold wind speed of ~ 5 m s^{-1} determined above provides preliminary insight into scaling requirements when translating between the laboratory and landscape scales.

The present study has considered the environmental thresholds relating to wind speed and topographic slope. However, this consideration treated the two environmental variables independently, whereas it is quite likely that there is some interdependence of wind speed and topographic slope in defining the threshold to VLS occurrence. For example, for a fixed leeward slope of α = 30°, it is quite possible that the threshold wind speed will be different to that determined for the α = 35° case. These issues will be addressed in ongoing research along with consideration of other environmental variables such as wind direction and topographic aspect.

5. Conclusions

The existence of environmental thresholds relating to the onset of VLS established here has a number of implications for fire operational and firefighter safety. Indeed, the results obtained here imply that significant changes in fire behaviour can result from relatively small changes in the environmental factors that drive wildfires. For example, with a slight increase in wind speed or a small variation in topographic slope, firefighters working on leeward slopes could very rapidly find themselves in great peril, when only a short time before their safety had not been in doubt.

6. Acknowledgements

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