

Coupled influences of topography and wind on wildland fire behaviour

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Abstract. Ten simulations were performed with the HIGRAD/FIRETEC wildfire behaviour model in order to explore its utility in studying wildfire behaviour in inhomogeneous topography. The goal of these simulations is to explore the potential extent of the coupling between the fire, atmosphere, and topography. The ten simulations described in this paper include five different topographies, each run with two different ambient wind speeds of 6 and 12 m s⁻¹. The five topologies explored are: an idealised hill (which serves as the base centerline for the other topographies), two variations of the hill with lateral gradients downwind from the ignition line (one sloping up from the ‘hill’ at the centerline to form an upward sloping canyon parallel to the ambient wind, and the other sloping down from the centerline to form a ridge parallel to the ambient flow), one with a second hill upwind of the ignition line such that the fire is ignited in the bottom of a canyon that runs perpendicular to the ambient wind, and finally a flat terrain. The four non-trivial topographies have the same profile along the centerline downwind of the ignition line to help assess the impacts of topographic gradients that are perpendicular to the ambient wind. It is hoped that analysis of these simulations will help reveal where point-functional models are sufficient, where topographically modified wind fields are needed, and where fully coupled fire and transport models are necessary to properly describe wildfire behaviour.

Additional keywords: fire propagation, FIRETEC, slope effects.

Introduction

People who fight wildfires must constantly balance the safety of their crews with the need to preserve infrastructure. They need information and guidance as to how a wildfire will behave under a variety of conditions. Ideally they need reliable tools that can provide them with this information at a moments notice. Computer models that predict wildfire behaviour as a function of atmospheric conditions, fuel type and configuration, fuel moisture, and topography are a good example of such a tool, and the widely used FARSITE model is a prime example. Unfortunately wildland fires result from the complex coupled interaction between a large number of physical and chemical processes that occur over a wide range of length scales. Therefore, it is very difficult and computationally expensive to model the interaction of all of the processes that combine to produce wildland fires. FARSITE does not attempt to model all of these interactions, but focuses instead on operational expediency. In addition, it is not currently feasible to collect fuel or wind data at sufficient resolution to provide the boundary and initial conditions that would be required to resolve all of the fine-scale processes that occur in a wildfire (e.g., evolving fine-scale turbulent fluctuations at the boundaries of the domain, flow around specific branches or needles or ignition of individual leaves).

Wind speed and direction, fuel type and condition, and topography are some of the environmental factors that affect fire behaviour. Models that use information about these factors at a specific location to calculate the spread rate at that location are known as point-functional models. In some situations these factors can be considered separately and their influence on fire behaviour is adequately captured. In other situations their effects are intimately coupled and their interaction can modify or even amplify their effect on fire behaviour. In these cases the effects of wind, fire, and topography interact to produce fire behaviour that may be impossible to predict without considering this coupling. Unfortunately, computational models that explicitly model this coupling are very complex and far too computationally expensive to be used for operational purposes. It is not yet well understood what errors might be induced by not accounting for the fire/atmosphere/topography coupling or even just the wind/topography interactions.

The impact of topography on fire behaviour has been studied for at least 34 years and is generally viewed as critical to understanding wildland fire behaviour. Topography is believed to have an impact on a variety of aspects of fire behaviour including fireline width, flame length, and direction of spread. Another important aspect of fire behaviour that is affected by topography

is the rate of spread since many fires accelerate dramatically up a hill and place fire fighters, as well as infrastructure, at risk. Historically the relationships between fire-spread rate and topography have been characterised through empirical models and algebraic relationships. As a part of his systematic study of the complexities of fire behaviour, Rothermel (1972) postulated a linear relationship between fire-spread rate, wind and slope:

$$R = R_0(1 + \phi_{\text{wind}} + \phi_{\text{slope}}) \quad (1)$$

Here the effects of wind and slope are considered separately. Many subsequent authors have opined that this simple relationship cannot represent the non-linear interdependencies present in a general wildland fire.

Nelson (2002) derived a non-linear effective wind speed relationship from the up-slope component of the fire's buoyant velocity combined with the ambient wind speed and direction as a correction to the Rothermel model. He tested this approach using experimental data reported by Weise (1993) and observed good agreement with experiments in which both wind and slope influenced the rate of spread.

In a series of fire table experiments, Viegas (2004a) examines the accuracy of the vector version of the Rothermel (1983) model in the case of non-aligned wind and slope vectors. In 2004, Viegas (2004b) also studied the collective nature of fire behaviour including slope, wind, convection, and radiation. His experiments included a flat, an inclined, and a v-shaped canyon table. The data exhibited distinctly non-linear behaviour in some cases, and he postulated that a unique value for the rate of spread for the fire front should not be expected since it is time dependent.

Weise (2005) developed a logistic model to predict the success of fire spread based on wind, slope, fuel loading, and fuel moisture using empirical data from a set of experiments that he performed. These experiments examined the probability that a fire would propagate at all in live fuels, specifically four different species of California chaparral.

Researchers have tried to enhance the point-functional empirical models by feeding them wind fields generated by an atmospheric fluid dynamics model. By adding this step, some of the non-local topography effects on fire can be included through their one-way interaction with the wind (Forthofer *et al.* 2003).

Another approach is to use a coupled fire and atmosphere transport model to simulate wildfire behaviour in complex terrain in order to study the effects of topography on fires. Reisner *et al.* (1998) coupled a point-functional wildfire behaviour model, BEHAVE, to a three-dimensional compressible hydrodynamics code, HIGRAD, and simulated fires in complex topography. The 1994 South Canyon fire was simulated using this coupled atmosphere fire model with qualitatively good results. Coen (2000) developed a two-dimensional non-hydrostatic atmospheric model coupled to a BEHAVE-like fire model using a contour advection scheme described by Clark *et al.* (2004), which was used to simulate a fire moving over a Gaussian hill. The simulation demonstrated a strong initial dependence on the environmental conditions, which altered over a 10–20-min period to a robust interplay between the atmosphere and the fire.

In recent research efforts, self-determining coupled atmosphere/fire models have been used to simulate wildfires in inhomogeneous topography. HIGRAD/FIRETEC is a coupled atmospheric transport/wildfire behaviour model being developed at Los Alamos National Laboratory, and is based on the principals of conservation of mass, momentum, and energy as well as representations of some of the physical processes that drive wildfires. It is fully self-determining. Linn (1997) used a two-dimensional (vertical slice) version of FIRETEC, a physics-based transport model, to simulate fires in idealised uphill, downhill, and canyon topographies. These simulations, which used a horizontally homogenised fuel bed with various vertical distributions, provided evidence that a crude yet self-determining wildfire behaviour model could capture some of the important features of topographically influenced fire spread. A three-dimensional version of FIRETEC coupled with HIGRAD was later used to simulate fires in complex terrain, such as a portion of the Calabasas fire (Bossert *et al.* 2000) and hypothetical fires on real topography (Linn *et al.* 2002). The physical formulations in FIRETEC continue to evolve. Improved formulations are currently being developed (Colman and Linn 2007), but as always there are trade-offs between physical veracity and computational resources.

Dupuy (2005) studied the propagation of crown fires in a series of two-dimensional simulations using a model referred to as the multiphase model. The multiphase model typically ran at a much higher resolution than three-dimensional models such as FIRETEC and focused particular attention on fine scale vertical inhomogeneity in fuels, radiation transport, and the drying and pyrolysis of the fuels. The multiphase model was used to examine slope effects on fire behaviour, and demonstrated that it was possible to capture some of the expected responses of wildfires to slopes with a model that more fully resolves the chemical reactions and radiation processes that drive wildfires.

These self-determining physics-based models have the potential of capturing additional facets of the coupled fire/atmosphere/topography interaction since they strive to represent the physical processes that drive a wildfire and do not rely on point-functional spread-rate correlations. For this purpose, a set of ten simulations are performed using the HIGRAD/FIRETEC model. The goal of this specific set of simulations is to explore the potential extent of the coupling between the fire, atmosphere, and topography. For this initial study the analysis will focus on the rate of spread and spread patterns, however, rate of spread is only one facet of fire behaviour that is affected by topography. Various other fire behaviour characteristics will be studied using these same types of tools in future work. It is expected that in some situations the topography will dominate to such an extent that one needn't couple the wind fields. In other situations it is expected that just using a topography-influenced wind field to drive a point-functional model would be sufficient. In still other situations, the coupling may prove to be so strong that the only way to capture fire behaviour is with a coupled fire/atmosphere/topography model. This study will not be able to identify specific thresholds for where coupled fire/topography/atmosphere interactions become a critical driver, or derive functional expressions for the way that fire behaviour changes with variations in topography. In order to identify these thresholds and functions, a more detailed study

that involves a greater analysis of variations of specific forms such as hills or canyons must be performed.

Simulations

Ten simulations were performed using FIRETEC, a physics-based wildfire model described in detail in Linn (1997), Linn *et al.* (2002, 2005) and Linn and Cunningham (2005). These simulations use two different ambient wind speeds, 6 and 12 m s^{-1} , over five different topographies. The domain of the simulations is $640 \text{ m} \times 320 \text{ m} \times \sim 700 \text{ m}$. The horizontal grid spacing is 2 m, and the vertical grid spacing is $\sim 1.5 \text{ m}$ near the ground. In each of the simulations, the vegetation in the domain is divided into two regions. One region contains 0.7-m tall grass with a fuel load of 0.7 kg m^{-2} , and the other region contains vegetation resembling a Ponderosa pine forest with inhomogeneous grass and litter surface fuels. The interface between the two regions is a line that is 45 degrees from the direction of the ambient wind as seen in Fig. 1. The fuel bed in the forested area consists of representations of over 8000 Ponderosa pine trees, which were generated using the methodology described in Linn *et al.* (2005). As in Linn *et al.* (2005), the discrete fuel elements used to model trees are based on data collected by the USDA Forest Service Rocky Mountain Research Station and Northern Arizona University as part of the Joint Fire Sciences Program, Fire and Fire Surrogate Treatment Project. The canopy bulk density over the forested area is $\sim 0.12 \text{ kg m}^{-3}$, with an average tree height of 13.8 m (minimum of 7.3 m, maximum of 19.9 m) and an average height to live crown of 8.7 m (minimum of 3.9 m, maximum of 13.4 m). The moisture fraction of the grass fuel bed is 0.05 (kg water mass/kg dry fuel mass) and the canopy moisture fraction is 0.80 of the dry fuel mass.

In each simulation, the fire is ignited 300 m from the inlet wind source. As seen in Fig. 1, the 60-m long and 8-m wide fire ignition line intersects the diagonal fuels' transition from grass to forest so that half of the fireline is in the grass area and half is in the forested area. The fires are ignited by raising the temperature of the ignition region from 300 to 1000 K over 4 s. This ignition method is used for simplicity and to ensure that there is sufficient ignition for the fire to spread. The fires are blown by a 6- or 12 m s^{-1} wind towards the forested area as indicated in Fig. 1. These winds are ramped up from zero wind over 12 s before the

time that the ignition is completed. The simulations are allowed to continue until the fire nears the boundary of the mesh. The time step in these simulations is 0.01 s.

In the first simulation, which we will refer to as the 'flat' simulation, there is no change in horizontal elevation. This simulation was run for comparison with the other simulations, which have non-trivial topographies. The remaining simulations use four idealised topographies. While each of the topographies are unique, they all have identical elevations along the centerline downwind of the ignition location. By making the centerline x -direction elevation gradients identical between the simulations, it is possible to compare the effects of the topography in the lateral and upwind directions more easily. The four non-trivial topographies are generated through the definition of idealised analytical functions combining a base function, which defines the topography along the centerline downwind of the ignition location, with additional functions to change the gradients in the lateral or upwind direction. The base function:

$$\text{base} = 55 + 40 \tan^{-1} \left(\frac{(x - 300) - 140}{60} \right)$$

generates the topography labelled hill in Table 1. This base function defines the elevations along the centerline. The change in elevation in the x direction from the point of ignition ($x = 300 \text{ m}$) to the right side of the domain ($x = 640 \text{ m}$) is 106 m. Other topographies shown in Table 1 are defined by combining this base function with additional functions.

A second non-trivial topography, referred to as 'canyon', adds a hill upwind of the ignition location. This topography generates a canyon perpendicular to the incoming wind field with the ignition location just downwind of the bottom of the canyon.

The third case, which we refer to as 'upcan', modifies the original base topography by a term that changes the slope in the y direction upward while leaving the slope in the centre of the grid in the x direction identical to that of the base case. In this upward canyon, 'upcan', the change in elevation in the centre of the grid is once again 106 m, while at the edges of the grid the slope rises to 211 m.

In the final non-trivial topography, the terrain slopes downward from the centerline in the y direction while leaving the slope in the centre of the grid in the x direction identical to that of the base case. This then creates a ridge down the centre of the grid in the x direction, and so we refer to this case as 'ridge'. The term used to modify the edges of the grid in the y direction downward is simply the negative of the term used to modify them upward in the upcan case. The change in elevation in the centre of the grid is once again 106 m, while the elevation at the edges of the grid drops to 1 m.

Throughout the remainder of this text, we will refer to a topography as flat, hill, canyon, upcan, or ridge when we are discussing points relevant to that topography regardless of wind speed. At other times we will refer to a simulation as, for example, hill6 or hill12 to indicate both the topography and the ambient wind speed of 6 or 12 m s^{-1} used for the simulation. Figs 2 and 3 provide images from the four simulations with non-trivial topographies.

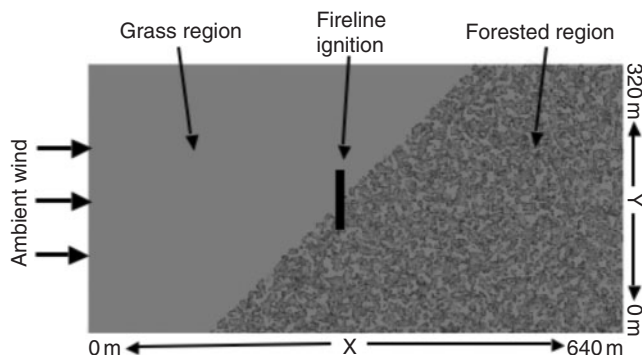
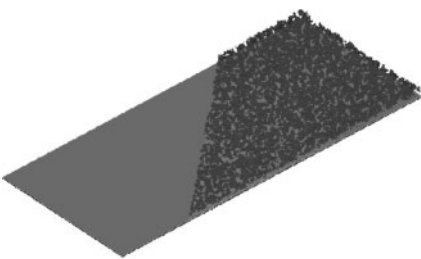
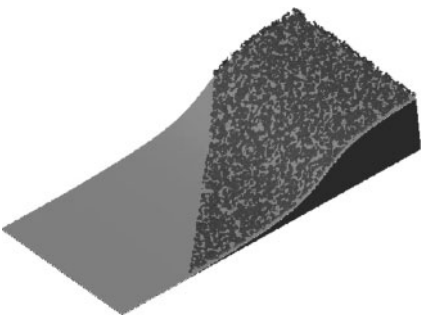
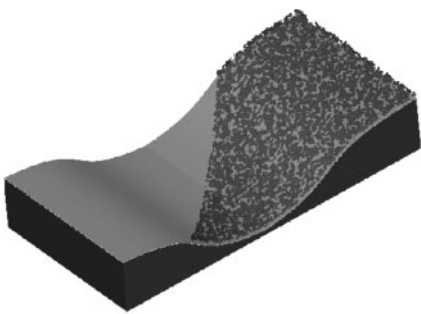
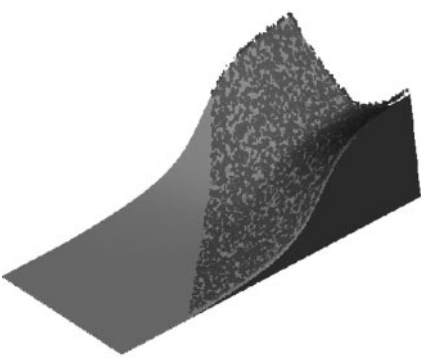
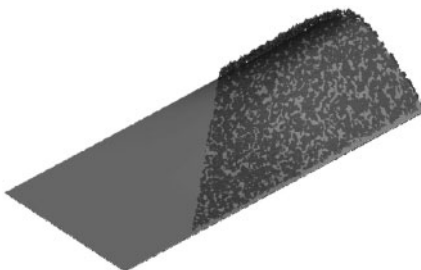


Fig. 1. Diagram showing the grid layout, fuels, fireline ignition location, and ambient wind direction for the simulations.

Table 1. Table describing the five topographies used in the simulations performed

Name	Ground height (zs) function	Topography
Flat	$zs = 0$	
Hill	$zs = base$	
Canyon	$zs = \begin{cases} 55 + 40 \tan^{-1} \left(\frac{ x - 300 - 140}{60} \right) & \text{for } x < 300 \text{ m} \\ base & \text{for } x \geq 300 \text{ m} \end{cases}$ Note: The elevation at the inlet wind (left) end of the topography is 103 m.	
Upcan	$zs = \left(\frac{ y - 160 ^{1.5}}{160^{1.5}} \right) * base + base$ Note: The elevation at the outlet (right) end at the corners is 211 m, or roughly double the base topography elevation of 106 m at the centerline of the outlet.	
Ridge	$zs = - \left(\frac{ y - 160 ^{1.5}}{160^{1.5}} \right) * base + base$ Note: The elevation at the outlet (right) end at the corners is 1 m, or 105 m below the base topography elevation of 106 m at the centerline of the outlet.	

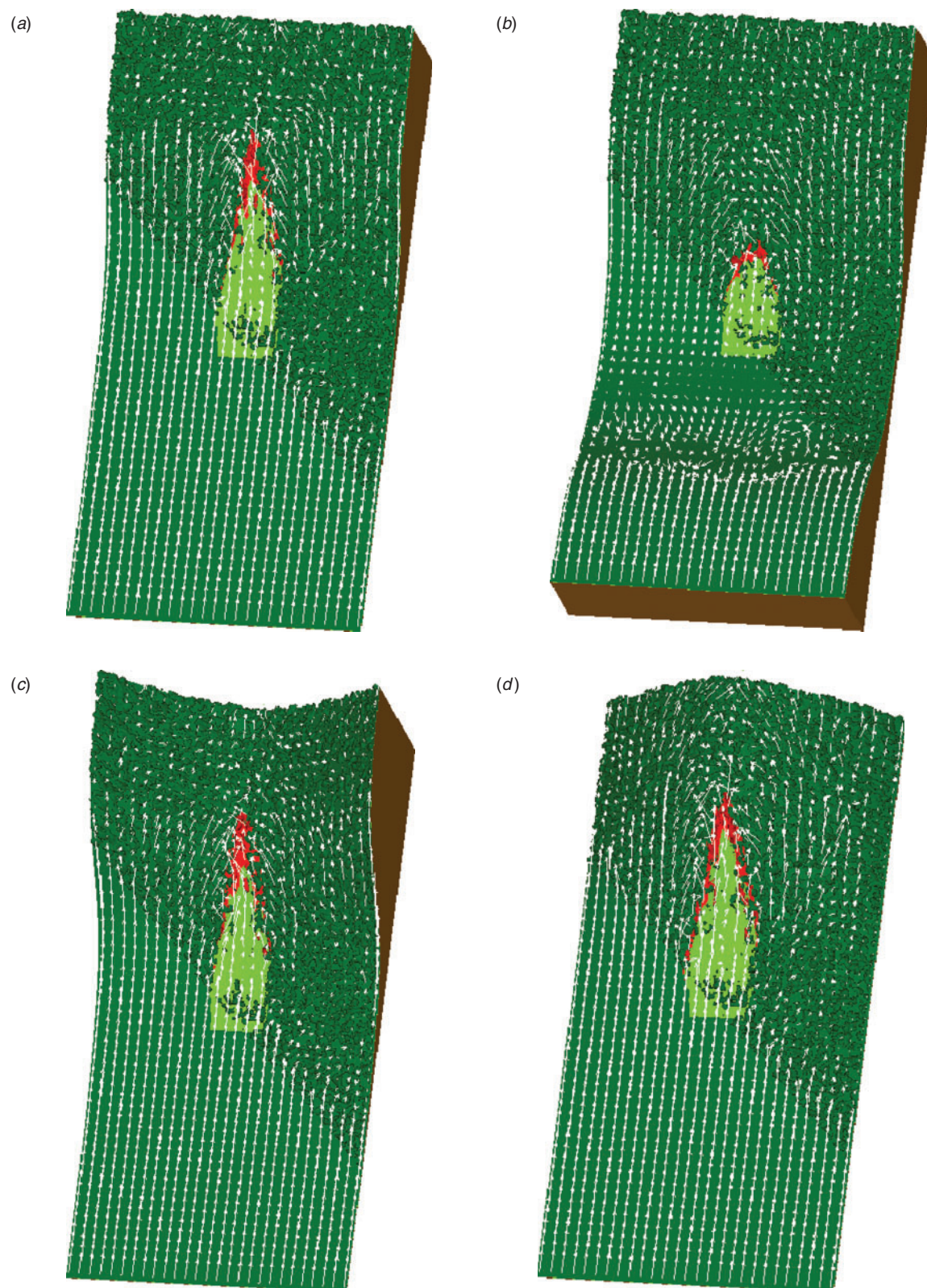


Fig. 2. Isometric images of fires on hill6 (a), canyon6 (b), upcan6 (c), and ridge6 (d) 150 s after ignition with a 6-m s⁻¹ ambient wind. Dark, medium, and light green colours indicate locations of canopy fuels, tall grass, and depleted fuels. Red isosurfaces indicate hot gases, and white vectors show winds at ~15 m above the ground.

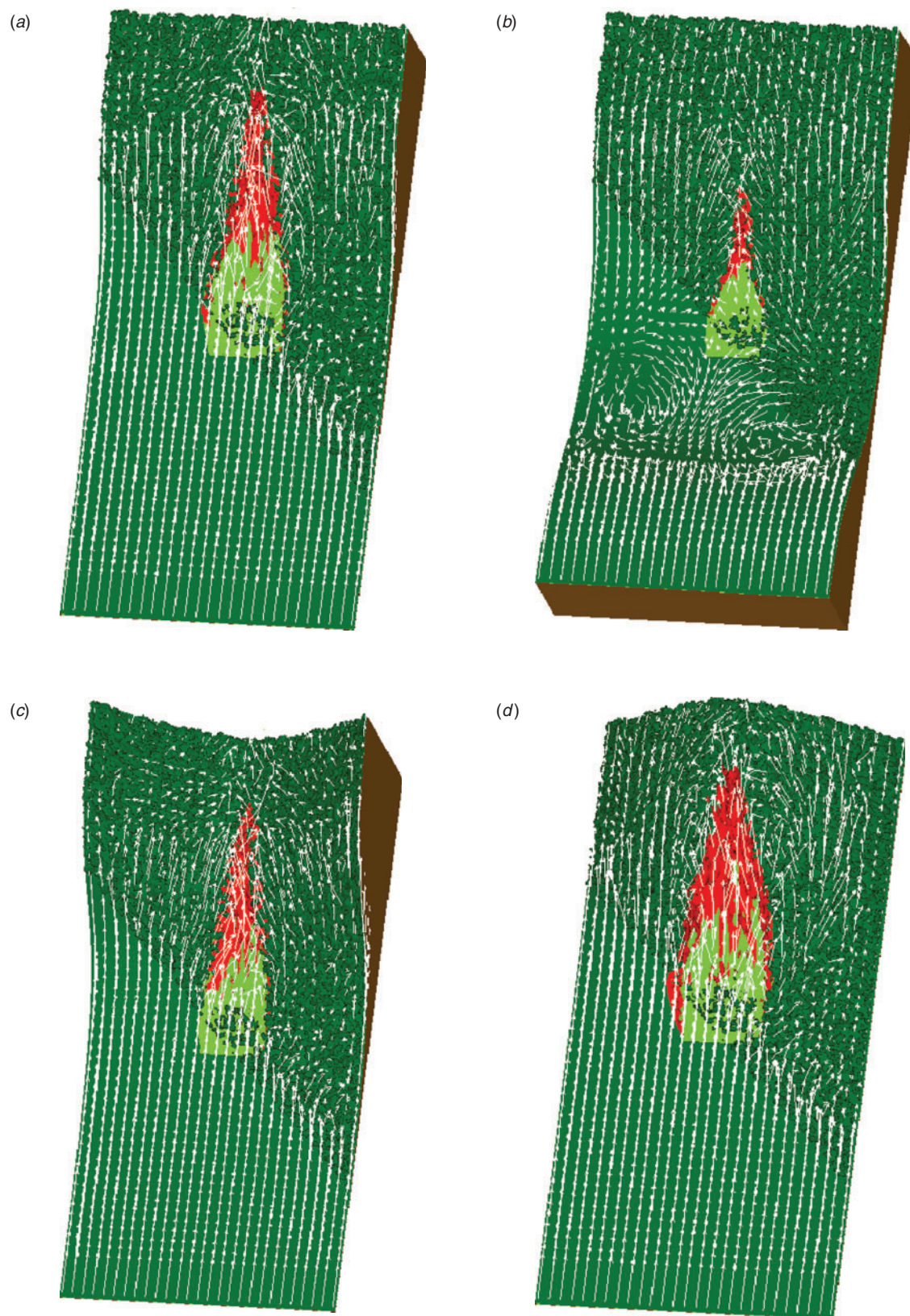


Fig. 3. Isometric images of fires on hill12 (a), canyon12 (b), upcan12 (c), and ridge12 (d) 100 s after ignition with a 12-m s⁻¹ ambient wind. Dark, medium, and light green colours indicate locations of canopy fuels, tall grass, and depleted fuels. Red isosurfaces indicate hot gases, and white vectors show winds at ~15 m above the ground.

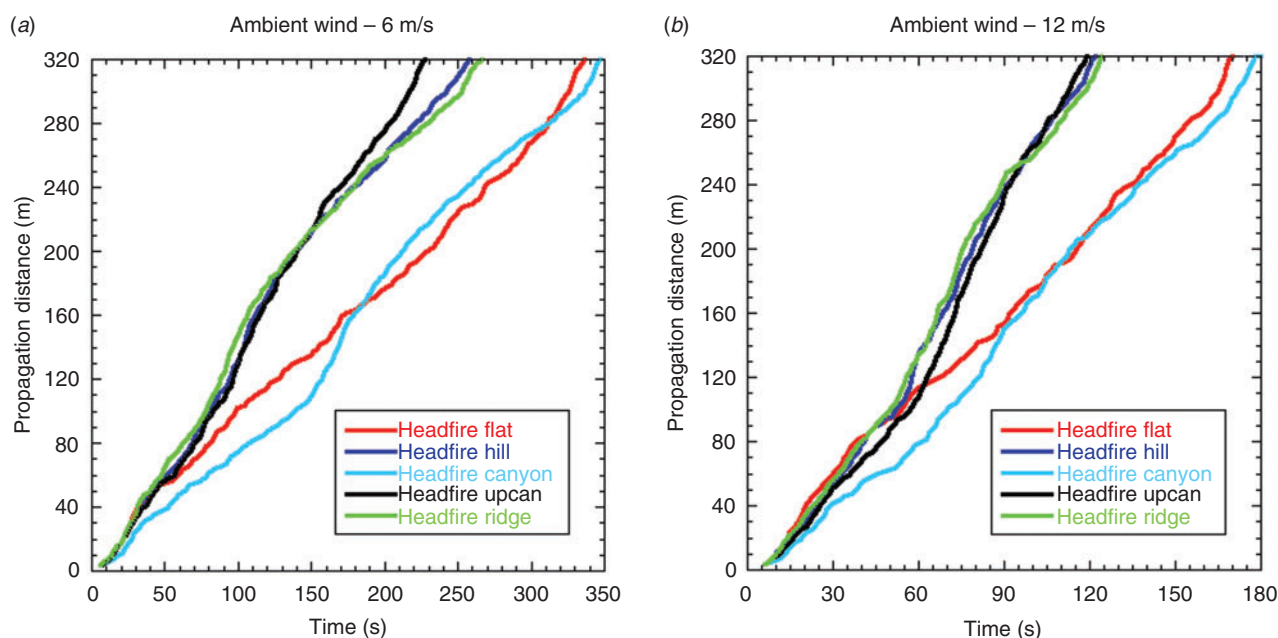


Fig. 4. Propagation distance of the fires in the nominal wind direction as a function of time for the simulations with 6- (a) and 12-m s⁻¹ (b) wind.

Results

Spread rates

The propagation distance of the fires in the x direction (nominal ambient wind direction) as a function of time are shown in Fig. 4a, b for the simulations with 6- and 12-m s⁻¹ wind. It should be noted that spread rate and propagation distance are measured in a horizontal direction in order to ease comparison of the different simulations. If we were to measure the spread rate and propagation distance parallel to the ground, these values would be greater than the horizontal values in cases where the terrain is not flat because of the inclusion of the vertical spread component.

In Fig. 4a, the propagation distances for the five 6-m s⁻¹ wind simulations are shown. The most obvious relationship between the curves is the two groupings that are formed. We have clearly reproduced the well-known result that a fire propagates faster uphill, all other things being equal. The trends in forward propagation distance for the three simulated fires with the same centerline 'base' topography for the entire length of the domain (hill6, upcan6, and ridge6) are nearly the same over 250 s, but are significantly different from the propagation distances of the flat6 and canyon6 runs that have similar net propagation distances to each other. The fires approach the top of the hill after they have travelled around 200 m. The fact that hill6, upcan6, and ridge6 are so similar as they climb the steep part of the hill indicates that the differences in topographic gradients in the y direction do not influence the forward propagation significantly at this point. This can be attributed to two factors: (1) the forward propagation is most significantly influenced by the topographic gradients in the forward (x) direction, and (2) the differences in the lateral topographic gradients (the upward slopes from the centerline in the upcan6 case, and the downward slopes from the centerline in the ridge6 case) are not significant enough until the fires near the top of the hill. After around 220 m the upcan6 fire propagates

faster than the hill6 or ridge6 fires because the upcan6 winds are funneled by the topography and are thus increased at the top of the hill.

The flat6 simulation fire progresses at a fairly constant rate in the direction of the ambient wind. The canyon6 fire initially propagates more slowly than the other simulations, and then accelerates after the fire has travelled ~105 m and slows down after 160 m. Thereafter, it progresses at a rate that is similar to all of the other simulations at the top of the hill except upcan6. The slow motion at the beginning of the canyon6 simulation is a result of the shelter that the upwind hill provides the fire before it escapes the wake of the hill. Similar flow patterns are displayed in Fig. 5, which shows a vertical slice of the vectors that are present in the vicinity of the canyon12 bottom. In Fig. 5, part of the complexity of the vector field is a result of the wake effects of the hill upwind of the canyon and the turbulent flow through the trees.

This complex flow field provides a less coherent push from behind the fire than is present in the other simulations and, in some instances, it also gives rise to a reverse flow that competes with the fire's tendency to move up-slope, and thus the fire initially moves slower. As the fire moves into the region where the ambient wind impinges on the slope of the canyon downwind from the fireline, the fire accelerates because of the combined up-slope effect and the wind pushing the hot gases towards the unburned fuel in front of the fire. The slow rate of spread after ignition and the strong acceleration combine to give a net propagation distance that is similar to that of the flat simulation. This should not be interpreted as being an indication that the impact of the topography is negligible, but that the specific analytically constructed geometry of this canyon and the location of ignition coincidentally produced a net propagation distance that is similar to the flat topography.

Fig. 4b has trends similar to Fig. 4a. The propagation curves for hill12, upcan12, and ridge12 have very similar heading fire

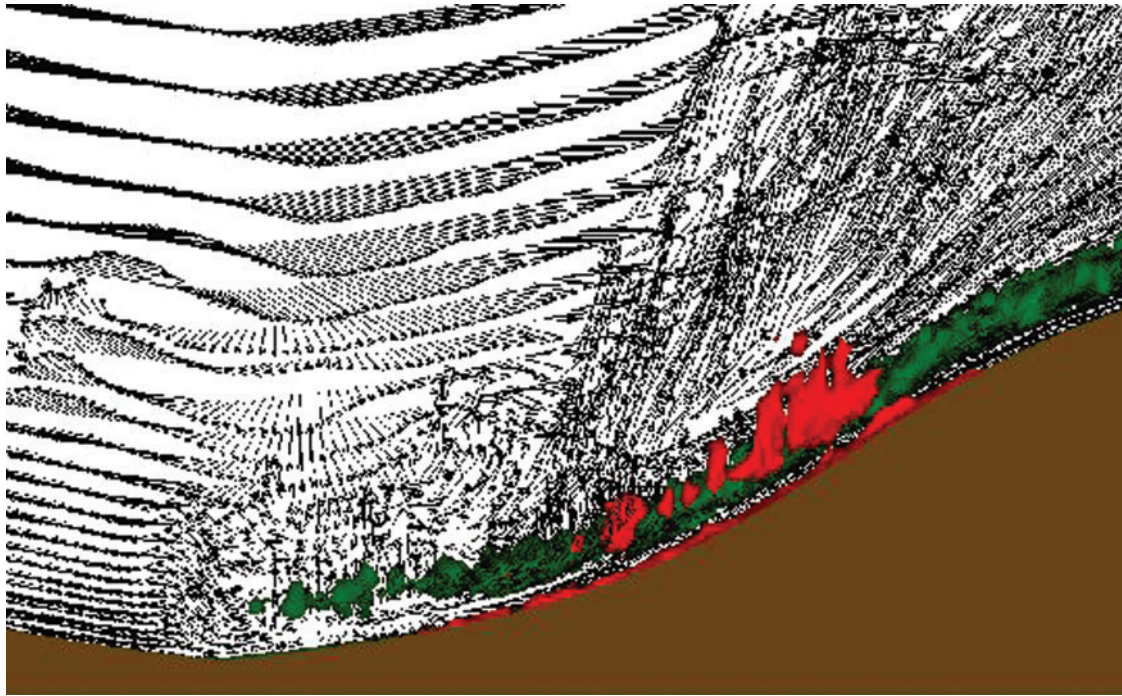
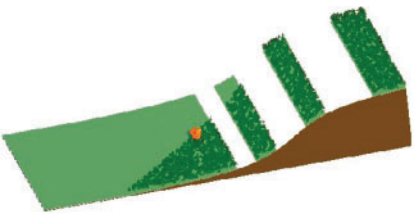


Fig. 5. Cutaway view of the crowning fire 100 s into the canyon12 simulation. The cutaway plane is at the centre of the grid, or at $y = 160$ m.

Table 2. Summary of forward spread rates at various portions of the domain



Simulation	Wind speed (m/s)	Spread rate within selected regions (m/s)		
		Region 1 $40 \leq x \leq 70$ m	Region 2 $110 \leq x \leq 160$ m	Region 3 $200 \leq x \leq 280$ m
Flat6	6	0.742	0.7751	0.9152
Hill6	6	1.079	2.127	0.9586
Canyon6	6	0.672	1.879	0.8131
Upcan6	6	1.038	2.145	1.252
Ridge6	6	1.252	2.295	0.9007
Flat12	12	2.057	1.399	1.910
Hill12	12	2.261	3.813	2.852
Canyon12	12	1.080	2.752	1.573
Upcan12	12	1.800	3.979	3.385
Ridge12	12	2.294	3.360	2.146

propagation rates and the net propagation of the flat12 and canyon12 fires are similar. As in the canyon6 simulation in Fig. 4a, the effects of the upwind hill and the wind impinging on the downwind hill cause an initially slow moving fire and then a period of acceleration. In Fig. 4b, the acceleration of the

canyon12 fire is not as sudden because of the difference in the wind's interaction with the topography.

The local slopes of the curves in Fig. 4 are the spread rates at that time. Table 2 shows a summary of the spread rates for the different simulations over various parts of the domain.

Table 2 provides quantitative values for some of the trends described above, and also allows us to examine location specific details more easily. When examining these local spread rate values it is important to remember that terrain or wind events at other locations (or upwind fire behaviour), as well as local events, affect these values. The most obvious two trends are for the spread rates of the 12-m s^{-1} wind simulations to be larger than the spread rates for the 6-m s^{-1} simulations, and for the spread rates of the flat simulations to be smaller than the upslope simulations at the same wind speed. The other broad difference between the spread rate trends for the 6-m s^{-1} v. 12-m s^{-1} simulations is the former have a wider variation in spread rates.

Region 1

In the 40–70-m range, the hill6, upcan6, and ridge6 have spread rates that are relatively high compared to the canyon6 and flat6 simulations. In hill6, upcan6, and ridge6 the wind has an approach to the fire which is only obstructed by the residual canopy that did not burn near the right side of the fire ignition line. In addition, the spread is aided by the up-slope. The most interesting feature of the spread rates for the 6-m s^{-1} wind simulations in this region is the substantially smaller canyon6 spread rate which is consistent with Fig. 4a and the discussion above.

The canyon12 simulation in the 40–70-m range shows a much slower spread rate than the other simulations for reasons similar to those described for canyon6, but the flat12 simulation has a spread rate similar to the hill12, upcan12, and ridge12 simulations as shown in Fig. 4b. This indicates that in these simulations with higher wind speeds the slope effect is not as significant at this location in the domain.

Region 2

In the 110–160-m range, the spread rates for hill6, upcan6, and ridge6 are similar and the canyon6 is only ~20% lower while the flat6 simulation is significantly lower. This much lower flat6 spread rate can be seen in Fig. 4a along with the nearly parallel curves for the other four simulations as they pass through this range. Within this region, the spread rates for the 6-m s^{-1} simulations seem to be dominated by the local (along the centerline at the location of the fire front) topography and not the terrain upwind or cross wind from the head fire front.

The 12-m s^{-1} wind simulations in region 2 exhibit trends very similar to the 6-m s^{-1} simulations with hill12, upcan12, ridge12, and canyon12 all having significantly faster spread rates than flat12. In the flat simulation, the acceleration as a result of the slope is not present. The spread rate at this location in the canyon12 simulation is nearly double the spread rate of the flat12 simulation because of the effects of the slope.

Region 3

In the 200–280-m range, all of the spread rates in the 6-m s^{-1} simulations are much more tightly grouped as is the slope of the topography at that point. The upcan6 simulation has the largest variation in spread rate for this region because the upward lateral slopes funnel the wind and heat towards the head fire. At this location not only is the local x -direction wind speed growing because of the funnelling effect, but the converging component

of the wind helps move heat along the flanking portions, which helps funnel it to the pointed head of the fire.

The 12-m s^{-1} wind simulations in region 3 show a larger and more complex variation in spread rates. There are several factors that combine to produce this wide range of spread rates including some lateral and upwind slope effects in the four non-trivial simulations, funnelling of wind and heat to the head of the fire in the upcan12 simulation, and the narrow width of the fire front in the canyon12 simulation.

Lateral spread

The plots in Fig. 6 show the maximum lateral spread to the left and right for the 6 and 12-m s^{-1} wind simulations. In Fig. 6a, b the lateral spread to the left is shown with hollow symbols and the lateral spread to the right is shown with solid symbols. The lateral spread is defined relative to the ignition line and a fuel temperature of 500 K, with positive values going to the left. In other words, if the initial 60-m long fireline does not spread to the left or to the right and does not shrink in length, the lateral propagation distance to the left and right will be zero. If the fire spreads to the left the open symbols move in the positive y direction with time, but if the left side of the fireline recedes (moves to the right) the open symbols will move in the negative y direction with time. If the fire spreads to the right the solid symbols will move in the negative y direction with time, and they will move in the positive y direction if the right side of the fireline recedes.

Fig. 6a contains the lateral spread data for the 6-m s^{-1} simulations. This plot shows the difference in lateral spread as a result of the various topographies. By comparing the left and right propagation curves for each of the simulations, the impact of the topography and the fuel load distribution on the movement of the fire to the right or left and the degree of net lateral spread can be examined. The difference between the spread of the flat6 and hill6 simulations shows that, at this wind speed, there is more than twice as much lateral spread on the flat terrain than there is on a simple two-dimensional hill that is oriented orthogonal to the wind. This difference leads to the rounded fire front for flat6 shown in Fig. 7a and the narrower, more pointed fireline shape for hill6 shown in Fig. 2a. The more pointed fire front characteristic associated with fire movement up a hill has been seen in various experiments such as Dupuy (1997).

The difference between the lateral spread of the hill6, upcan6 and ridge6 simulated fires is a result of the influence of the lateral gradients in topography on the wind fields and fires. The fact that the lateral spread is initially smaller in upcan6 than hill6 is attributed to the funnelling of the wind field in the upcan6 simulation, but after ~200 s the lateral spread in the upcan6 simulation begins to increase rapidly. This late spread is a slope effect because of the fire beginning to spread up the hills on either side of the canyon near the end of the simulation. The ridge6 simulation shows significantly more lateral spread than the hill6 or upcan6 simulations, because the ridge forces some of the flow to separate around the hill and thus causes a component of the canopy level winds to be in the direction of lateral spread on either side of the ridge.

The canyon6 simulation shows the most complex lateral spread pattern. Over the first 230 s (during which time the fire front travels ~170 m) there is minimal resolved spread to the left

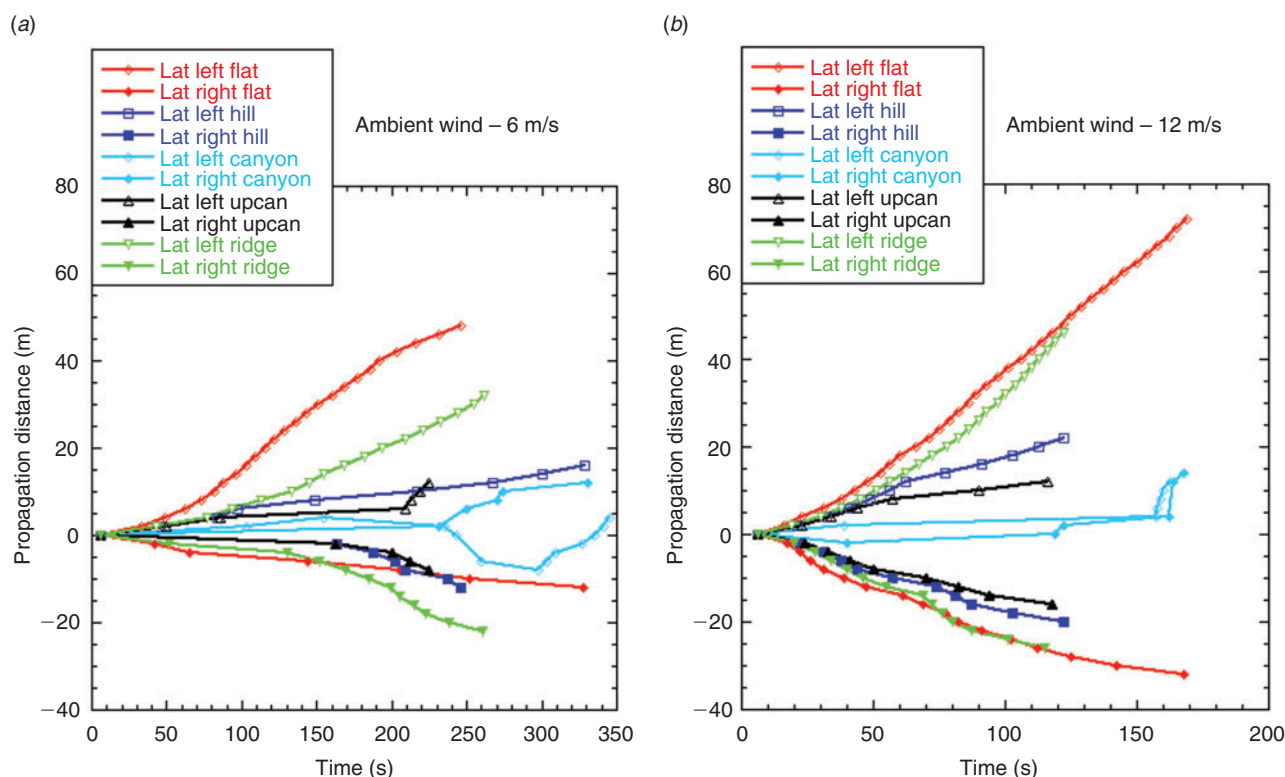


Fig. 6. These images show the change in lateral (y direction) extent of the fire in the 6-m s^{-1} simulations (a) and the 12-m s^{-1} simulations (b). Points for these plots were generated each time the maximum extent of the fire to the left (hollow symbols) or to the right (solid symbols) changed. These curves were terminated when the fire front (headfire) reached the outlet wind boundary.

(4 m) and no resolved spread to the right. The smaller amount of lateral spread could be caused by a variety of physical issues. In the early stages of this fire, it is moving very slowly and has less wind to push it because of the upwind hill. For this reason, canyon6 is less intense than the other simulations during this portion of the simulation, and would cause less lateral radiative heat transfer to occur, in the same way that there is less lateral spread in the flat6 simulation than in the flat12 one.

In the flat6 simulation the left side of the fire spreads much farther, ~ 46 m, than the right side, ~ 12 m. This asymmetry is largely caused by the interaction between the diagonal tree line with the winds that approach it. The forest canopy induces a component of the wind in the positive y direction, which causes additional spread in that direction. This effect can be seen in Fig. 7a.

Initially, the hill6 simulation also shows some asymmetry with the spread to the right not beginning until around 150 s into the simulation, where the spread to the left begins after around 100 s. This effect is also attributed to the diagonal fuel line and is illustrated in Fig. 2a. In this figure, the leading edge of the fire is distinctly to the left of the centerline. Initially, the right side of the fire ignition line is actually behind the leading edge of the canopy and the flow field (as seen in Fig. 1), and trees that remain unburned in this region modify the flow field on the right side of the fireline.

Fig. 6b shows lateral propagation for the 12-m s^{-1} simulations. Some of the same trends between propagation distances of

the different simulations seen in the 6-m s^{-1} simulations are also seen in the 12-m s^{-1} simulations, however, there are also some noticeable differences in the patterns. One difference between the patterns in the 6 and 12-m s^{-1} simulations is that the lateral spread rates of the flat12 and ridge12 simulations are of similar magnitude, whereas the flat6 spread rate is around 30% larger than the ridge6 spread rate. This similarity in the flat12 and ridge12 spread rate is thought to be more coincidence than a result of the same phenomena controlling the lateral spread in both simulations, although the most significant driver in the asymmetry of the spread rates is the angled canopy fuel bed, which is present in both simulations. A major factor that effects the ridge12 spread rate is the splitting of the winds around the ridge and the lateral wind components that are induced. This factor is made most obvious by comparing the ridge12 to the hill12 lateral spread, which is smaller by $\sim 40\%$. The upcan12 simulation and the hill12 simulation are closer to symmetry than the ridge12 or flat12 simulation.

Another potentially significant factor in the canyon12 lateral spread is the interaction between the fire-induced buoyancy and the terrain-influenced flow pattern, which causes stronger inflow at the lateral sides of the fire. The basic flow pattern caused by the canyon topography is for the winds to partially separate from the ground as they come over the leading edge of the canyon and then reattach to the ground part way up the downwind slope. Part of the reattachment includes wind components that are normal to the ground as they approach the downwind hillside. The

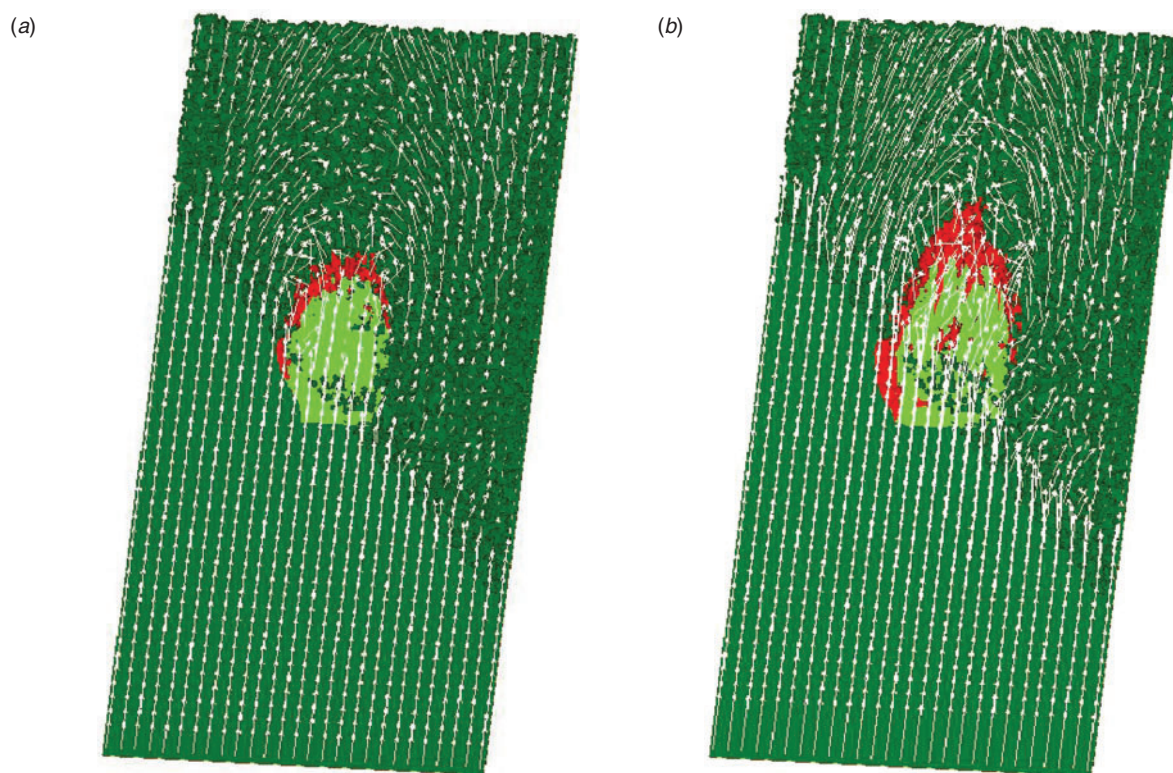


Fig. 7. Isometric images of fires on flat6 (a) 150 s after ignition with a 6-m s^{-1} ambient wind and on flat12 (b) 100 s after ignition with a 12-m s^{-1} ambient wind. Dark, medium, and light green colours indicate locations of canopy fuels, tall grass, and depleted fuels, respectively. Red isosurfaces indicate hot gases, and white vectors show winds at $\sim 15\text{ m}$ above the ground.

intersection of the wind with the sloped ground results in raised pressure perturbations and associated complex and sometimes diverging flows in the planes that are parallel to the ground. The resulting flow on the lower part of the downwind slope of the canyon is something like a set of occasional (non-steady and moving in space) weak jets of air that get close to the slope and are redirected in a wide range of new directions. The redirection of these unsteady air currents results in a region of elevated pressure and some subsequent back flows, forward flows, and lateral flows as the air searches for the paths of negative pressure gradients. For this discussion we will refer to the resulting redirected flows that are parallel to the ground in a lateral direction on the downwind slope as ‘ambient lateral flows.’ The ambient lateral flows are the winds that develop across the downwind slope when there is a pressure gradient in that direction. When the fire exists on the downwind slope, the fire-induced buoyancy causes a low-pressure region that naturally draws an indraft (or a convergence). The combination of the fire-induced low-pressure region and a nearby impinging-flow-induced elevated-pressure region could enhance the negative pressure gradient that would exist near a fire without the topographic influences. The buoyancy-induced indraft at the base of the fire, which often includes winds that are blowing in the direction opposite to the lateral and headwind spread, are accentuated by the enhanced negative pressure gradients and the associated ‘ambient lateral flows’. The result is increased lateral indrafts, which limit the lateral and forward spread of the canyon fire when it is low on the slope.

Following this same logic, as the canyon6 fire moves closer to the region where the air is impinging on the ground, the coupling between the diverging flows and the buoyancy makes the lateral indrafts strong enough that they cause the width of the fireline to shrink. As this happens the left side of the fire actually moves to the right, and the right side of the fire actually moves to the left as seen in Fig. 6a. Eventually, the fire in the canyon simulation reaches a point sufficiently above the location where the winds are impinging on the slope so that the winds that are enhanced by the impinging flows are in the direction of the head fire and the shrinkage of the fireline width stops and the left side of the fire begins to move back to the left. Even though the fireline width begins to grow because the lateral spread to the left is positive, the lateral spread to the right does not recover. This asymmetry is believed to be linked to a combination of asymmetry, wherein the impinging flows are located at various times, and a preferential direction, which is possibly influenced by the diagonal fuel interface. Once the fire is pushed to one side of the depleted fuel area it tends to be more easily pushed in that direction. Once the right flanking fire becomes weaker than the left, the left flanking fire can actually draw air from the right side of the depleted fuel, which further hinders the growth of the right flanking fire, and facilitates lateral spread of the left side of the fire. This positive feedback accentuates the asymmetry that is seen in Fig. 6a.

The canyon12 simulation shows minimal change in the fireline width until around 150 s. After 150 s the right flanking fire loses strength. The fire becomes predominantly one sided on the

Table 3. Summary of average lateral spread rates 150 s after ignition

Simulation	Left extent spread rate (m s^{-1}) (positive: movement to the left)	Right extent spread rate (m s^{-1}) (negative: movement to the right)
Flat6	0.22	-0.036
Hill6	0.058	-0.013
Canyon6	0.026	0.001
Upcan6	0.039	-0.013
Ridge6	0.086	-0.037
Flat12	0.46	-0.29
Hill12	0.23	-0.18
Canyon12	0.024	0.027 ^A
Upcan12	0.14	-0.15
Ridge12	0.047	-0.25

^ARight lateral spread rate for canyon12 is not monotonic over the first 150 s.

left for reasons similar to those described above for the canyon6 simulation.

Table 3 provides a summary of the average lateral spread rates for the initial 150 s of the simulations. This temporal range is used for the lateral spread rates instead of a spatial range, similarly for the forward spread rates, because there is such a wide range in lateral spread distances and there is no single spatial range that is appropriate for the majority of the simulations.

Conclusions

The HIGRAD/FIRETEC wildfire behaviour model is used to perform ten simulations in order to explore the use of a physics-based transport model to study wildfire behaviour in an inhomogeneous topography. The use of a transport formulation to describe wildfire behaviour in terrain that does not have a uniform slope is investigated because non-local elements of topography affect the way a fire burns. In this case, fire behaviour cannot be determined simply based on average ambient winds, nature of the fuel, and local topographic characteristics. In some situations there are certain characteristics of fire behaviour that can be predicted without including the time and space histories of physical quantities and thus can be predicted without a transport model. There are situations in which the inclusion of a transport model for the terrain-influenced air flows can be used to drive a point-functional fire behaviour model with adequate results. There are also situations where the coupling between the fire/wind/topography (and may be even the fuel structure) is important, and in this case a partial differential equation-based fire/atmosphere transport model is a convenient tool to study the phenomena interaction. HIGRAD/FIRETEC is used to survey a variety of topographic situations in order to learn about the coupling that would determine the need for various modelling tools.

The ten simulations that are described in this paper include an idealised hill (which serves as a base for the other topographies), two variations of the hill with differences in the lateral gradients downwind from the ignition line (one sloping up from the 'hill' at the centerline to form an upward sloping canyon parallel to the ambient wind and the other sloping downward from the centerline 'hill' to form a ridge parallel to the ambient flow), and

one with a second hill upwind of the ignition line such that the fire is ignited in the bottom of a canyon that runs perpendicular to the ambient wind. These four topographies have the same profile along the centerline downwind of the fire ignition line and, therefore, can be used to assess some of the impacts of differences in topographic gradients that are perpendicular to the ambient wind and to the central path of the fire, and differences in topographic gradients upwind from the fire. In addition, a simulation of a fire on flat ground is described for comparison. This small set of topographic variations is obviously not extensive and cannot provide fire behaviour characteristics as a function of terrain conditions. Instead, it is meant to invite discussion and insight into how various modelling tools might be used to most efficiently predict wildfire behaviour in inhomogeneous topographies.

For the purposes of this paper, various spread rates including forward spread rates at different locations and lateral spread rates were compared. There were regions of the domain, such as the middle of the hill in the 6-m s^{-1} wind simulations, where the influences of the variations in lateral or upwind topography (not including the flat simulation) had minimal effect on the spread rate. At these locations for this wind condition, the local slope had a more dominant effect on fire spread than the non-local topographic features. It is possible that in these types of locations the smaller variation in spread rate might be linked to the topography through the fire history and its effects on characteristics like fireline length. Point-functional local models probably adequately model this type of fire behaviour.

At other locations, the fire behaviour characteristics are strongly influenced by the coupling between the topography and the ambient wind field, and thus the difference in local winds drive a difference in fire behaviour. This type of topographic influence is exhibited near the bottom of the hill and possibly in the upcan simulations where the winds are being focused by the topography. In these situations the predominant effect of the topography could be captured by characterising the influence of the topography on the local winds and using these winds to drive a local fire model.

There is also evidence that there are some situations where the coupling between the fire, topography, and atmosphere is more critical. This seems to be most important when the topographically influenced winds are not directly complementary to the slope effects on the fire. Examples of these types of situations are the influences of the canyon topography on the lateral and heading fire spread.

In some situations the dominant processes that drive a wildfire might be able to be captured by local topographic characteristics. However, there are time-history influences, such as line length or fire shape, that change fire behaviour. In these cases, even though the dominant driver might be point-functional in time and space, the integrated historical effects could include strong effects of the coupled fire/atmosphere/topography and need to be accounted for.

It is impossible to generalise the impacts of inhomogeneous topography on the forward and lateral spread rate based on these ten simulations. However, the results of these simulations provide significant information that can assist in the understanding of the importance of the coupling between the topography and wind as well as the more complex topography/wind/fire

coupling. Subsequent studies that include detailed analysis of the impact of variations of the particular topographic forms (such as various widths and depths of canyons) will be needed in order to investigate possible thresholds at which coupling between the fire, wind, and topography become important.

In the simulations described in this paper, discrete trees were used to form a heterogeneous fuel bed in the forested region. However, each of the simulations had the same heterogeneous fuel bed, and those fuel beds were statistically homogeneous (except for the transition from grass to trees, which was mentioned in the text) in that a set of measured trees were replicated and randomly arranged on the landscape as described in Linn *et al.* (2005). Because the fuel beds were all the same and this paper focused on the gross aspects of fire spread, it is very difficult to determine the impact of the fuel heterogeneity from this set of simulations. Subsequent studies should be performed to assess the impact of the heterogeneities by altering the fuel bed between simulations while keeping the nature of the heterogeneities statistically similar. This can be done by altering the patchiness and number density of the tree distributions.

Acknowledgements

Critical computing resources for this work were provided by the Los Alamos National Laboratory Institutional Computing Program. Equally important financial support for this work was provided by the USDA Forest Service Rocky Mountain Research Station, USDA Forest Service Pacific Southwest Research Station, Joint Fire Science Program, and the National Fire Plan.

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