Small-scale observations of atypical fire spread caused by the interaction of wind, terrain and fire

Jason J. Sharples
Applied and Industrial Mathematics Research Group,
School of Physical Environmental and Mathematical Sciences,
University of New South Wales at the Australian Defence Force Academy,
Canberra, ACT Australia.
Email: j.sharples@adfa.edu.au

Domingos X. Viegas, Carlos G. Rossa
Departamento de Engenharia Mecânica –Universidade de Coimbra
Centro de Estudos sobre Incêndios Florestais
Associação para o Desenvolvimento da Aerodinâmica Industrial
Coimbra, Portugal.
Email: xavier.viegas@dem.uc.pt; carlos.rossa@dem.uc.pt

Richard H.D. McRae
Risk Management Section
Australian Capital Territory Emergency Services Agency
Canberra, ACT Australia
Email: Rick.McRae@act.gov.au

Abstract
The interaction of wind, terrain and a fire burning in a landscape can produce a variety of unusual yet significant effects on fire propagation. Moreover, there is strong evidence to suggest that such effects played an important role in driving the spread of large wildfires such as the January 2003 alpine fires over southeastern Australia, the February 2009 fires in Victoria and the January 2010 fires in the Tinderry Ranges to the southeast of the Australian Capital Territory. In this paper we investigate the interaction between wind, terrain and a fire burning on a lee slope through a number of small-scale experiments conducted within the combustion tunnel at the Laboroatório de Estudos sobre Incêndios Florestais in Lousã, Portugal. The experiments involved using an idealised ridge configuration, which was aligned perpendicular to a strong wind so as to produce a lee (separation) eddy. Fire was then introduced to the lee slope through a point ignition and the fire spread resulting from the interaction between the fire and the separated flow was observed. The interaction between the fire and separated flow was consistently observed to produce rapid lateral propagation of the fire across the top of the slope. The details of the rapid lateral spread are discussed along with some probable implications of this type of atypical fire spread for wildfire risk management at the landscape scale.

Keywords: wind, terrain and fire interaction; atypical wildfire spread; wildfire experiment; combustion tunnel; wildfire risk management.

1. Introduction

During the last decade a number of serious wildfires have burnt in rugged terrain under the influence of strong winds. Examples include the January 2003 alpine fires over southeastern Australia and the February 2009 Victorian fires. In particular, on 18 January 2003 fires driven by strong winds (averaging 30-40 km h^{-1}) burnt through rugged terrain to the west of Canberra and impacted the city resulting in four fatalities and the destruction of around 500 houses within a few hours (Nairn 2003). Strong winds were also a factor during the fires on Black Saturday (7 February 2009), which caused unprecedented loss of life in rugged terrain in central Victoria (Teague et al. 2010). A number of other examples from around the world (e.g. the 2009 Jesusita fire in California) are also relevant. Given the complex terrain in which these and other large fires have burnt, and the strong winds experienced during their most devastating runs, it is natural to consider the concept of wind-terrain interaction and to investigate what significance interaction between the wind and terrain, and additional interactions with fire, may have on fire development.

As discussed by McRae (2004), multispectral line-scan imagery recorded during the Canberra fires on 18 January 2003 revealed a number of instances of atypical fire spread that appear to be driven by interactions between the wind, the terrain and fire. Examples of such instances can be seen in Fig. 1. The images depict the fires at the locations known as ‘Pig Hill’ (Fig. 1a) and ‘Broken Cart’ (Fig. 1b). The fire behaviour in these instances is characterised by:

1. Rapid lateral propagation of the fire, perpendicular to the wind, across a steep lee slope (including some lateral spotting);
2. Downwind extension of the flaming zone by up to 5 km;
3. The upwind edge of the flaming zone is constrained by a break in topographic slope.

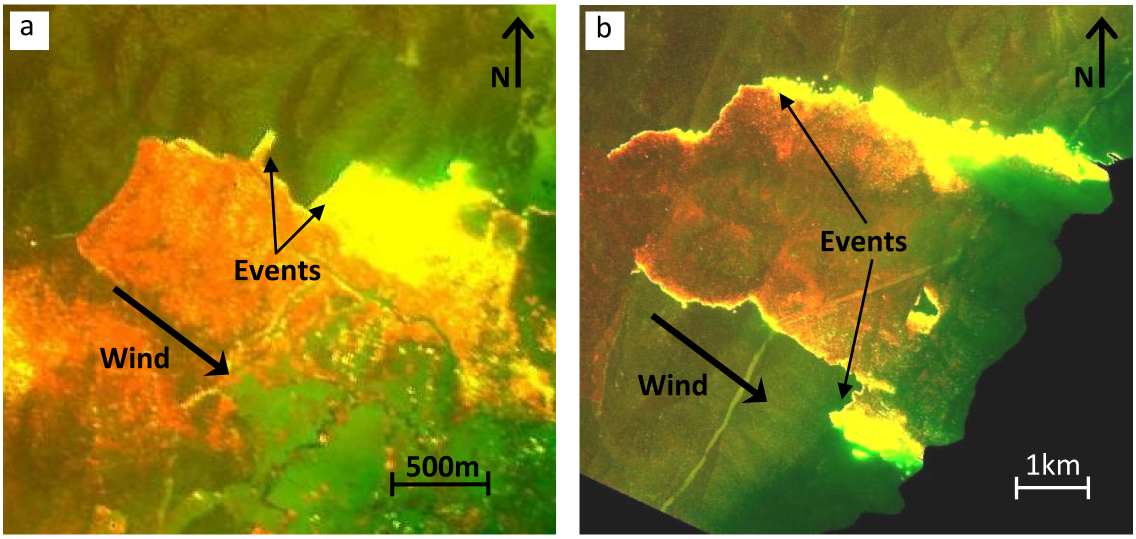

Figure 1. Multispectral line-scan imagery of the Canberra fires 18 January 2003 showing events at: (a) ‘Pig Hill’, and (b) ‘Broken Cart’. Source: New South Wales Rural Fire Service.

Following McRae (2004), a number of cases of this type of atypical fire spread (23 in total) were studied by Sharples et al. (2010). This study considered a number of possible mechanisms that could produce the atypical spread in light of the available evidence. By combining the available evidence with an analysis of terrain characteristics and the results of a previous study of wind regimes over complex terrain, Sharples et al. (2010) were able to discount a number of mechanisms and thereby deduce the most likely (hypothetical) mechanism driving the observed atypical fire spread. It was concluded that the atypical fire spread was most likely driven by the interaction of the fire with a lee (separation) eddy. In this scenario the fire enters a region of separated flow (the lee eddy) and is propagated laterally. Increased turbulence arising from the interaction then results in increased generation of embers, some of which are incorporated into the synoptic winds above the eddy and are deposited downwind.

Conducting fire experiments involving fire behaviour at the scales represented in the line-scan imagery in Fig. 1, is intractable and dangerous. Moreover, the complexities of the physcial environment make investigation and isolation of the key driving processes through field experimentation a difficult task. We therefore sought to further investigate the physical mechanisms driving the atypical fire spread through a number of controlled small-scale experimental fires. The experimental fires were conducted within the combustion tunnel at the Laboratório de Estudos sobre Incêndios Florestais near Lousã in Portugal.

2. Experimental Set-up

To test the hypothetical mechanism discussed in Sharples et al. (2010) a number of experiments were performed in the combustion tunnel at the Centro de Estudos sobre Incêndios Florestais laboratory. The experiments involved the use of an idealised ridge configuration comprised of two adjoining slopes. The windward slope, made of wood, had dimensions of 1.65 m × 2 m and was inclined at an angle of β°. The lee slope, made of a metal plate covered with mesh, had dimensions of 1 m × 2 m and was inclined at an angle of α°. The inclination α was taken sufficiently large to ensure separation of the airflow at the ridge-line and the formation of a lee (separation) eddy. Straw fuel was placed on the lee slope with an areal density of approximately 0.6 kg m^{-2}. The ridge-line was aligned perpendicular to the combustion tunnel wind direction. See Fig. 2 for an illustration of the experimental ridge configuration. The width of the combustion tunnel (2.8 m) was greater than the width of the experimental rig and it was decided to place the rig up against one side of the combustion tunnel, resulting in a gap of around 80 cm between the experimental ridge and the other side of the tunnel. While this resulted in some asymmetry in the flow over the ridge, its effect on the experimental results was minimal.

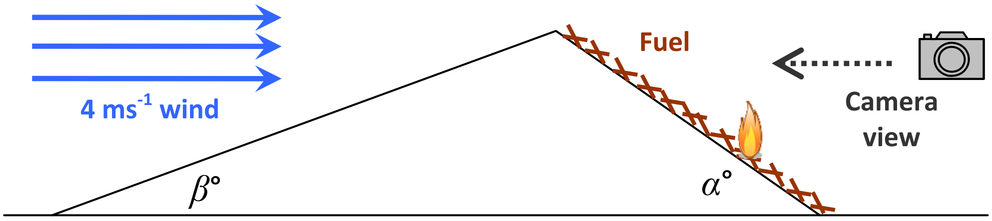

Figure 2. Schematic diagram (cross section) of the experimental ridge configuration and the approximate ignition point.

In a series of experiments, point ignitions were made on the right side of the lee slope (15 cm in from edge), in the centre of the slope and on the left side (also 15 cm in from the edge). All ignitions were made 30 cm from the bottom of the slope. The ignitions were made in the presence of a 4 ms^{-1} wind blowing at a right angle to the ridge. For comparison point ignitions were also made on the right side of the slope and in the centre of the slope in the absence of wind. The defining charateristics of the fire experiments conducted are listed in Table 1.

The spread of the experimental fires was recorded using two video cameras, one in the position indicated in Fig. 2, and one positioned to capture the transverse (oblique) view. Still photography using digital cameras was also used to record the observed fire spread.

Experiment No.	**α°**	**β°**	**Wind Speed (ms^{-1})**	**Ignition**
1	30	18	4	R
2	35	20	4	R
3	35	20	0	R
4	35	20	4	C
5	35	20	0	C
6	35	20	4	L

Table 1. Experimental parameters: R = right side ignition, C = central ignition, L = left side ignition.

3. Results

The observed fire spread was distinctly different in the presence of the 4 ms^{-1} wind, when compared to the no wind cases. In the presence of wind, fire was consistently observed to spread upslope until it reached the region of separated flow near the top of the ridge. At this point the fire accelerated significantly, exhibiting rapid unsteady spread across the top of the ridge in the form of a ‘finger’ of turbulent flame. Figs. 3a and 3b illustrate the difference in lateral spread characteristics for the ‘wind’ and ‘no wind’ cases when the point ignition was made on the right hand side of the lee slope. Figs. 3c and 3d demonstrate that similar atypical spread occurred when the ignition (with wind) was made on the left side and centre of the slope. In fact, for the central ignition the rapid lateral spread was observed to occur in both directions along the top of the slope. This indicates that the rapid lateral spread evident in Fig. 3b cannot simply be due to an asymmetry in the flow.

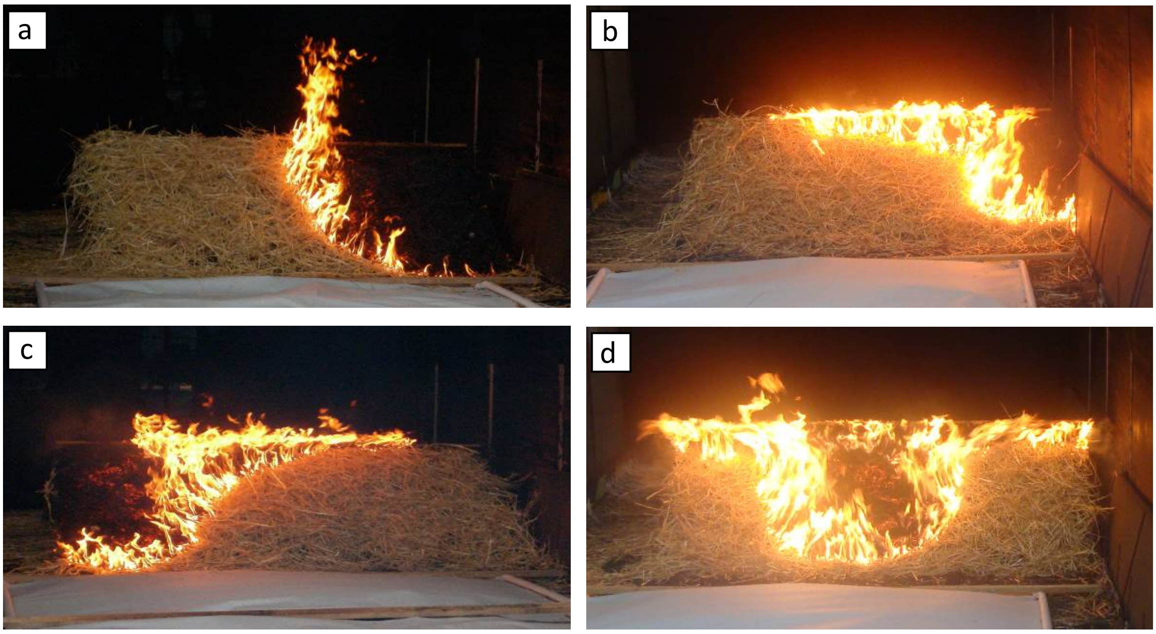

Figure 3. (a) Exp. 3: right side ignition, no wind; (b) Exp. 2: right side ignition with 4 ms^{-1} wind; (c) Exp. 6: left side ignition with 4 ms^{-1} wind; (b) Exp. 4: central ignition with 4 ms^{-1} wind.

Fig. 4 illustrates the rapid lateral spread across the slope in time sequence. Features of interest include the formation of spot fires in Figs. 4f and 4h, and the distinctive pattern of smoke highlighted in Fig. 4e. The turbulent nature of the flames is evident throughout the sequence.

The lateral spread characteristics resulting from the right side ignitions (Exps. 1, 2 and 3) are quantified in Fig. 5. The significant lateral acceleration of the wind-driven fires after reaching the top of the lee slope is evident in Fig. 5a from the change in gradient. Note that the vertical black dashed lines in Figs. 5a and 5b mark the time when the wind-driven fires reached the ridge-line at the top of the lee slope (approximately 20-22 s after ignition

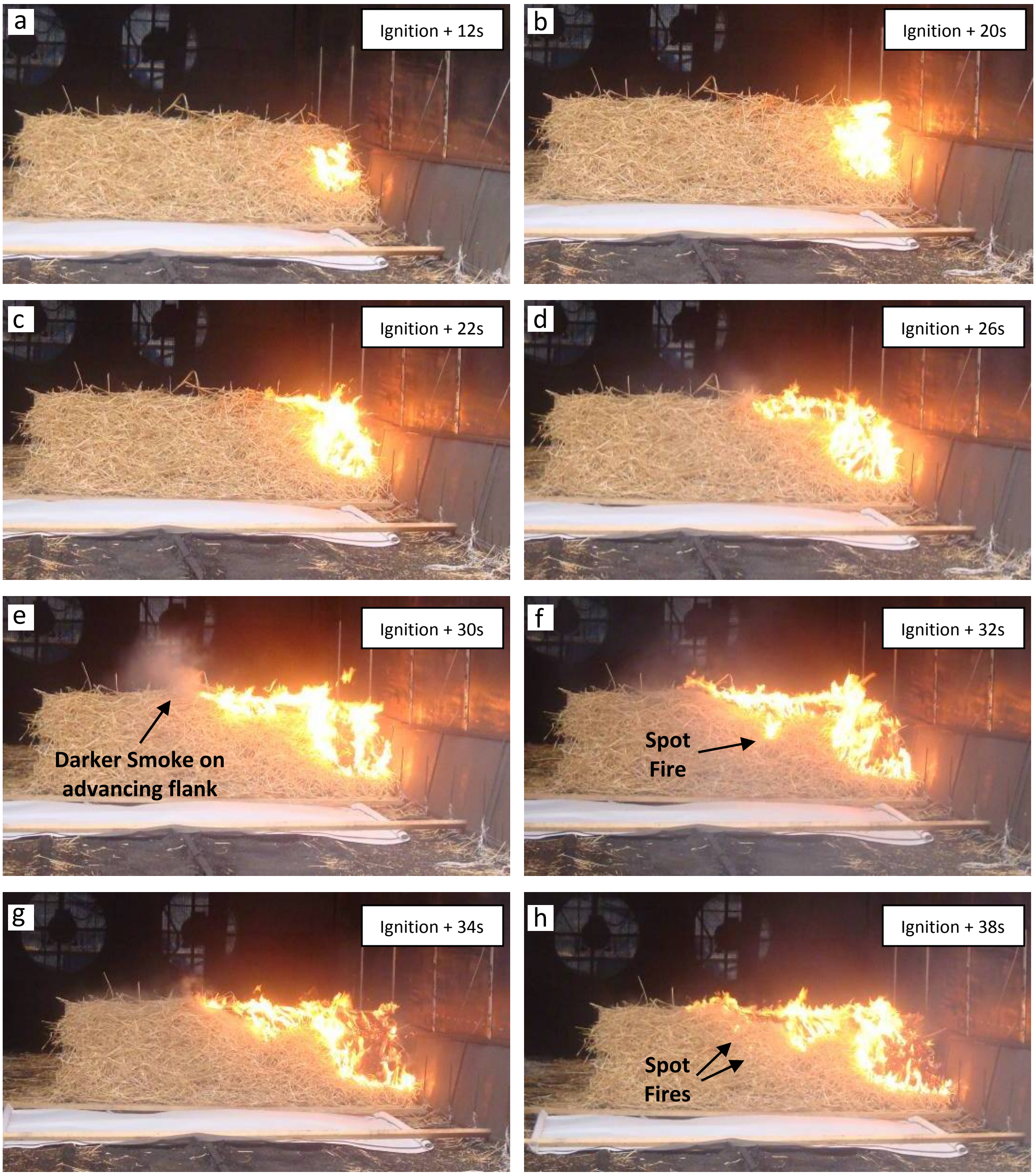

Figure 4. Time sequence of photographs from experiment 1 (right side ignition with 4 ms^{-1} wind). The wind is blowing towards the camera.

in all experiments). Similarly, Fig. 5b shows that after reaching the top of the slope the wind-driven fires exhibited unsteady lateral rates of spread of between 1 m min^{-1} and 6 m min^{-1}, which were between 2 to 12 times faster than the (near constant) lateral spread rate of about 0.5 m min^{-1} observed in the 'no wind' case. Maximum lateral rates of spread occurred immediately after the fires reached the top of the slope. The lateral fire spread in the presence of the 4 ms^{-1} wind exhibited the same qualitative behaviour for both values of the inclination parameter (α = 30° and 35°), though some quantitative differences are apparent.

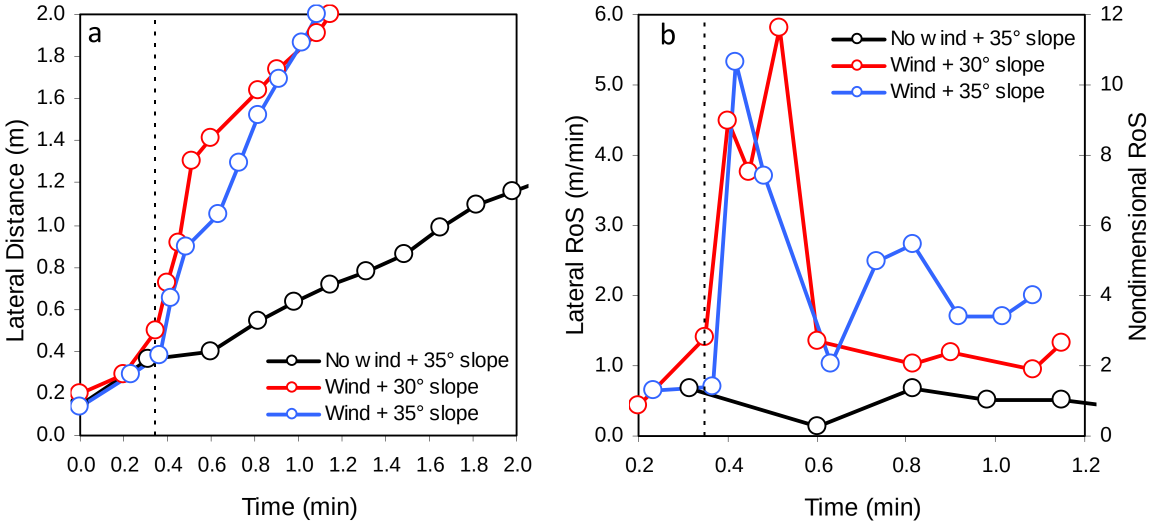

Figure 5. Right side ignitions – experiments 1, 2 and 3: (a) Maximum lateral distance travelled plotted against time since ignition, (b) Dimensional and nondimensional instantaneous rate of spread plotted against time since ignition.

Fig. 6 shows the experimental spread data arising from ignition on the left side of the slope. The wind-driven fire again exhibits a marked increase in lateral spread rate upon reaching the top of the slope, with similar qualitative structure to that seen in the right side ignition cases. The spread rates for the left side ignition were slightly lower (maximum rate of spread of around 4 m min^{-1} as opposed to 6 m min^{-1} in the right side ignition case) but were still up to 8 times greater than the quasi-steady lateral spread rate for the no wind case. The maximum lateral spread rate was again found immediately after the fire reached the top of the slope. The smaller lateral spread rate for the left side ignition case could be due to an assymetry in the flow created by the combustion tunnel wall on the right side of the experimental rig. We note also that the 'no wind' data in Fig. 6 is from the right side ignition case; but due to the symmetry of the experimental configuration in the absence of wind, it was deemed acceptible to compare these data with those from the wind-driven left side ignition case.

The lateral spread characteristics for the central ignition cases (Exps. 3 and 4) are quantified in Fig. 7a. In these cases spread to both the right and left sides of the slope have been accounted for. As expected, in the absence of wind the lateral spread in both directions was approximately constant with a value of about 0.5 m min^{-1}. In the presence of wind, the lateral spread rates were initially approximately the same as that found in the 'no wind' case. However, after reaching a point just below the ridge-line the fire exhibited a significant lateral acceleration, this time in both directions simultaneously. As in the experiments already discussed, the spread towards the right side of the slope was slightly less than that towards the left, probably due to an asymmetry in the flow caused by the wall of the combustion tunnel. Maximum lateral rates of spread were again maximum (in both directions) immediately after the fire reached the top of the slope. Calculation of the gradients of the data curves in Fig. 7a indicates that the wind-driven fires spread laterally with a maximum rate of spread of about 9 m min^{-1}, which is approximately 18 times faster than the spread observed in the 'no wind' case.

Fig. 7b shows that the lateral spread rate characteristics were qualitatively similar for each of the different ignition patterns. This indicates that the physical mechanism driving the rapid lateral spread is independent of the point of ignition.

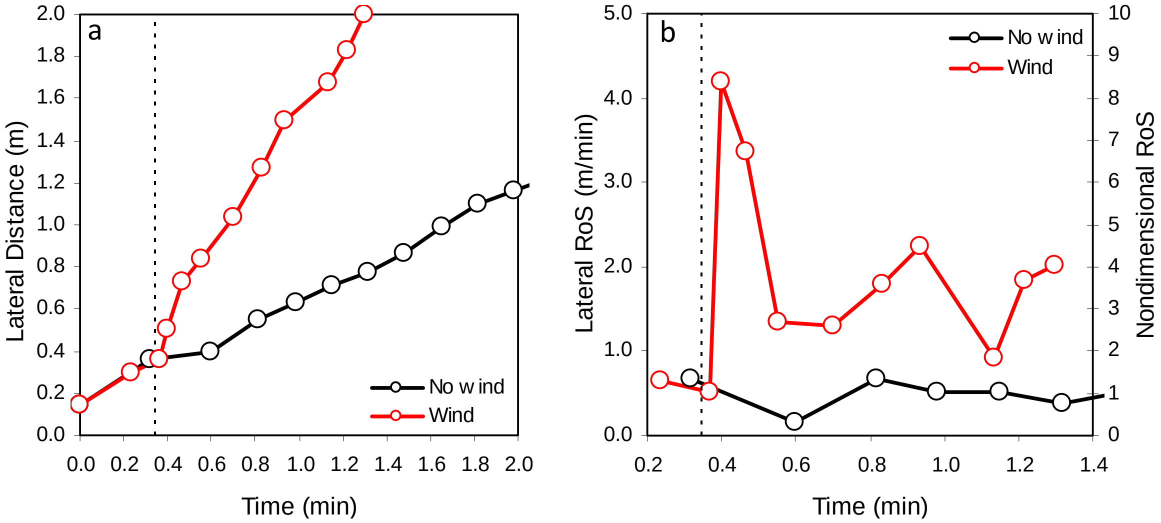

Figure 6. Left side ignition – experiment 6: (a) Maximum lateral distance travelled plotted against time since ignition, (b) Dimensional and nondimensional instantaneous rate of spread plotted against time since ignition.
Note that the 'no wind' data shown is that arising from the right side ignition case.

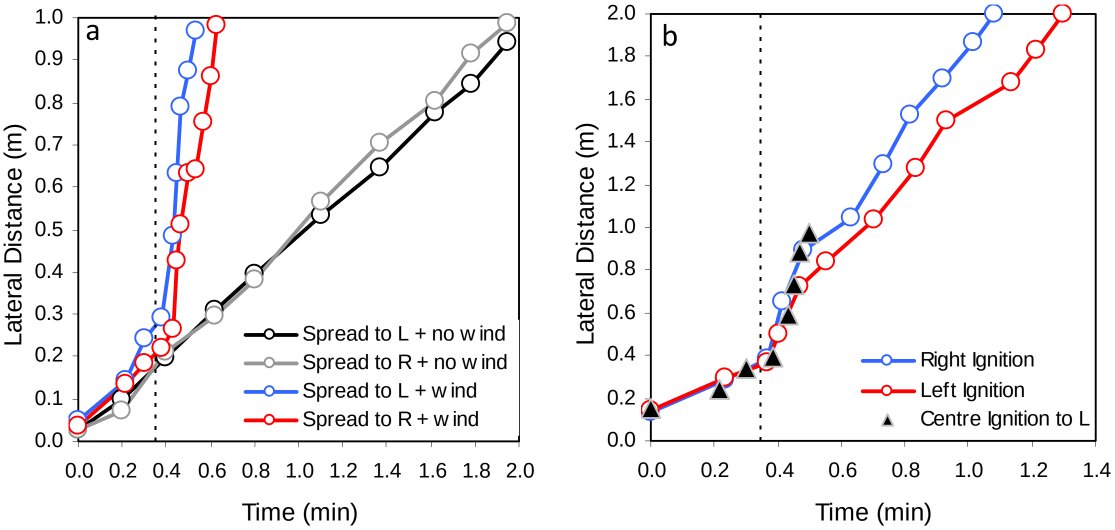

Figure 7. (a) Maximum lateral distance travelled plotted against time since ignition for the central ignition cases - experiments 4 and 5, (b) Comparison of maximum lateral distance travelled versus time since ignition for the different ignition locations.

4. Discussion and Conclusions

A number of small-scale experiments involving fires burning on a lee slope were conducted in a combustion tunnel. The experiments confirmed the existence of a complex interaction between the fire, the wind and the terrain that results in the rapid lateral propagation of the fire across the slope in accordance with the hypothesis advanced in Sharples et al. (2010). The observed behaviour in the small-scale experiments was qualitatively similar to some observations of the Canberra bushfires, which burnt in rugged terrain under the influence of strong winds. For example, the atypical fire spread evident in Fig. 1a bears a remarkable resemblance to the flame structure seen in the initial stages of the lateral spread development observed in the laboratory. Observations resembling the laboratory fire behaviour have also been made in connection with other bushfires burning in rugged terrain under extreme fire weather conditions. For example, Fig. 8 shows two instances of atypical bushfire spread. Of particular note is the distinctive darker smoke on the advancing flanks of the fires in Fig. 8. A similar pattern of smoke can be seen in Fig. 4e.

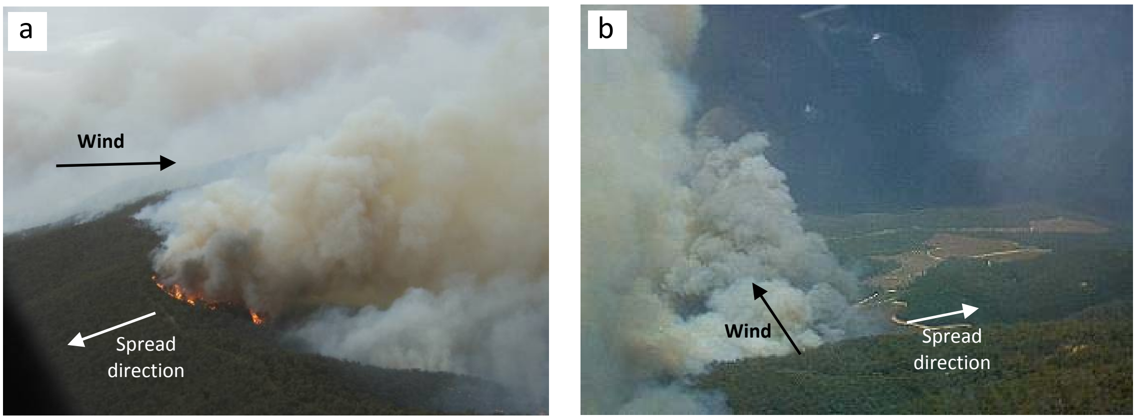

Figure 8. Instances of atypical wildfire spread: (a) fire spreading laterally across a slope during the Tinderry fires southeast of Canberra, January 2010 (Photo by Mr. Steve Forbes, ACT Emergency Services Agency); (b) fire spreading laterally below a ridge-line during the Canberra fires, 18 January 2003 (Photo by Mr. Stephen Wilkes, NSW Rural Fire Service).

The wind-driven experimental fires exhibited maximum lateral rates of spread that were between 6 and 18 times faster than that observed in the absence of wind. These maximum rates of spread were consistently found to occur immediately after the fire reached the top of the lee slope. The physcial mechanism driving the atypical lateral spread was found to be independent of the point of ignition.

The laboratory fires also exhibited some spotting behaviour, though this was limited by the nature of the (straw) fuel. However, it is entirely plausible that in a real bushfire situation (involving fuels that readily produce firebrands such as can be found in eucalypt forests), embers incorporated into the main flow above the separation eddy would result in multiple spot fires downwind of the region of lateral spread and the formation of extensive zones of active flame like that seen in Fig. 1. Such a process could be a trigger for the formation of pyro-cumulonimbus, which are of major concern for bushfire risk management.

The rapid lateral spread indicated in the laboratory fires also poses a significant threat to fire-fighter safety and could seriously compromise fire suppression tactics. In particular, the possibility of rapid lateral spread should cast serious doubts over flank attack options on lee slopes and could lead to a catastrophic decay in the safety of fire-fighters already conducting flank attack operations.

Further collaborative work will involve combustion tunnel studies of lee slope fires under variable wind speeds and directions and burning on slopes of variable inclination. Repeating the experiments with different fuel types (e.g. *pinus pinaster*) will also permit better definition of the lateral spread characteristics and the driving mechansims.

Acknowledgements

This work was supported by an Australian Academy of Science Scientific Visits to Europe Program grant. The authors are indebted to Mr. David Davim, Mr. Ricardo Oliveira and Mr. Jorge Raposo for their invaluable assistance with the combustion tunnel experiments, and to Mr. Antonio Cardoso for design and construction of the experimental rig. Dr. J. Sharples is grateful to Prof. John Dold (University of Manchester, UK) and Dr. Malcolm Gill (ANU, Australia) for their keen interest and illuminating discussions on the topic of this paper. The authors would also like to acknowledge the New South Wales Rural Fire Service, which provided the line-scan imagery.

References

McRae, R. (2004) Breath of the dragon – observations of the January 2003 ACT Bushfires. In: *Proceedings of 2004 Australasian Bushfire Research Conference*, May 2004, Adelaide.

Nairn G (Chair) (2003) *A Nation Charred: Inquiry into the Recent Australian Bushfires*. The Parliament of the Commonwealth of Australia, Canberra.

Sharples, J., McRae, R., Weber, R., Wilkes, S. (2010) Wind-terrain effects on the propagation of wildfires in rugged terrain: fire channelling. *International Journal of Wildland Fire*, under review.

Teague, B., McLeod, R., Pascoe, S., (2010) *2009 Victorian Bushfires Royal Commission Final Report*. Parliament of Victoria. Available from: http://www.royalcommission.vic.gov.au/Commission-Reports/Final-Report