19th International Congress on Modelling and Simulation, Perth, Australia, 12–16 December 2011
http://mssanz.org.au/modsim2011

Lateral bushfire propagation driven by the interaction of wind, terrain and fire

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Abstract: The interaction of rugged terrain and extreme fire weather can have a variety of influences on bushfire propagation. These influences can sometimes result in highly atypical modes of fire propagation that can cause rapid escalation of bushfires to their most catastrophic state, thereby subjecting communities and assets to the highest levels of risk. In one such example, referred to as *fire channelling*, the interaction results in rapid lateral development of a fire (in a direction transverse to the synoptic winds) in addition to enhanced downwind fire development and the production of expansive flaming zones, which may occur as a precursor to the formation of pyrocumulus, or even pyrocumulonimbi. In this paper, we give an overview of the fire channelling phenomenon and report on some of the recent modelling and simulation efforts directed at providing a more formal understanding of it.

The fire channelling phenomenon was first noted in connection with the extreme bushfires that burnt into Canberra on the afternoon of 18 January 2003. In this instance, fires were observed spreading laterally at a number of locations within the rugged terrain in the Brindabella Ranges to the west of Canberra. Subsequent observations of the 2003 Thredbo fires revealed additional examples. Moreover, in the time since studying the 2003 fires a number of other likely instances of fire channelling have been noted in the Blue Mountains, California, Sardinia and Portugal.

The fire channelling phenomenon has been attributed to the (hypothetical) interaction of a horizontal vortex that forms due to separation of the ambient winds over a sufficiently steep lee slope with an active lee slope fire. The interaction causes the fire to spread laterally within the vortex as a turbulent finger of flame. The increased turbulence enhances ember production and some of these embers are incorporated into the synoptic flow above the vortex and deposited downwind. Over all the process results in a type of 'bidirectional' fire propagation. This hypothetical mechanism has been tested and supported by a series of combustion tunnel experiments which are reported briefly in the paper.

The existence of the atypical lateral fire propagation across a lee slope is now firmly established and so our concerns in this paper turn to the question of how best to model the effect. We report on a number of preliminary modelling efforts using a two-dimensional numerical model that describes the interaction of the horizontal vortex with a surface heat source through coupled fluid and heat conduction equations. The model results are by no means authoritative, however, and we discuss some possible ways to progress the modelling of the fire channelling phenomenon.

Keywords: *Dynamic fire spread, wind-terrain interaction, atypical fire spread, bushfire, topography*

1. INTRODUCTION

The use of models (e.g. Noble et al. (1980)) to predict the propagation of bushfires and associated fire behaviour characteristics has traditionally invoked the assumption of a quasi-steady rate of spread. Under this assumption the rate of spread, and other fire behaviour attributes such as flame height and intensity, are taken to be uniquely defined by each distinct set of environmental input conditions. In particular, if conditions of fuel, weather and topography are unchanging then it is assumed that an approximately constant rate of fire spread will result. However, there are a number of examples from around the globe which indicate that such an assumption is only of limited validity. These examples, in which fires spread in a distinctly dynamic fashion, even when environmental conditions are unchanging, often involve steep or rugged terrain, extreme fire weather conditions and the apparent interaction of these factors with an active fire (e.g. Viegas 2009). Sharples et al (2011) describe one such example, where the interaction of wind, terrain and fire result in the propensity for the fire to propagate laterally along certain terrain elements: namely, steep, lee-facing slopes. This lateral propagation occurs in a direction transverse to the prevailing winds; the rate of lateral propagation is distinctly unsteady and is far more rapid than what would be expected based on the assumption of a quasi-steady rate of spread; and the process is often accompanied by multiple spot fires and the production of extensive flaming zones.

Sharples et al (2011) determined that the phenomenon, which they dubbed *fire channelling*, most likely resulted from the interaction between a lee-slope fire and the horizontal vortex (separation eddy) that can form over steep, lee slopes when winds are strong (> 20 km $h^{-1} \approx 5.5$ ms^{-1}). Small-scale combustion tunnel experiments discussed in Sharples et al (2010) provided experimental confirmation of the existence of the fire channelling phenomenon and supported the hypothetical mechanism espoused by Sharples et al. (2011).

In this paper we provide an overview of the fire channelling phenomenon and summarize the modelling and simulation work that has already been done. We also discuss some of the implications of dynamic processes such as fire channelling for fire spread prediction modelling and outline future plans aimed at better understanding and modelling these dynamic effects.

2. FIRE CHANNELLING – A BRIEF HISTORY

The presence of atypical modes of fire spread was first noted by McRae (2004) after analysing multispectral line-scan data collected during the Canberra fires of January 2003. The distinguishing features of the atypical spread may be summarized as follows:

- Rapid lateral propagation of the flank (i.e. in a direction transverse to the synoptic winds) along a valley or lee slope, including instances of lateral spot fire development;
- Downwind extension of the flaming zone with uniform spectral signature for 2-5 km;
- The upwind edge of the flaming zone constrained by a major break in topographic slope.

Some examples of multispectral line-scan imagery showing the fire channelling phenomenon can be seen in Figure 1. The imagery near point 1 in Figure 1a indicates lateral propagation of the fire in a northeasterly direction, while near point 2 the fire has propagated in a southwesterly direction. In both instances the direction of fire spread is nearly perpendicular to the west-northwesterly wind direction and the upwind edge of the fire coincides with a ridge-line. The large areas of uniform (yellow) spectral signature near points 1 and 2 indicate large regions of active flame downwind from the where the lateral spread occurred. Similar features can also be seen near points 3 and 4 in Figure 1b. Photographs of some fire channeling events can be seen in Figure 2.

McRae (2004) postulated that the atypical spread was caused by what he called *lee-slope channelling* or by forced channelling of winds in incised valleys (Kossmann et al. 2001). Paraphrasing McRae (2004), lee-slope channelling involves recirculation of a significant quantity of embers within a lee rotor, which burns out the lee slope. The recurrent part of the eddy also sheds some embers into the bulk wind flows, and causes rapid and intense progression of the fire immediately downwind. It is notable that McRae (2004) does not postulate a cause for the lateral component of the fire progression during an instance of lee-slope channelling. Forced channelling, on the other hand, does provide a rationale for lateral fire progression, as it involves the diversion of synoptic winds along incised valleys in a direction dictated by the component of the wind vector in the direction of the valley axis.

The two hypothetical mechanisms proposed by McRae (2004) were further scrutinized by Sharples et al (2011). While Sharples et al (2011) could not completely rule out forced channelling as a driving mechanism, their findings tended to favour lee-slope channelling, subsequently dubbed *fire channelling*, as the key

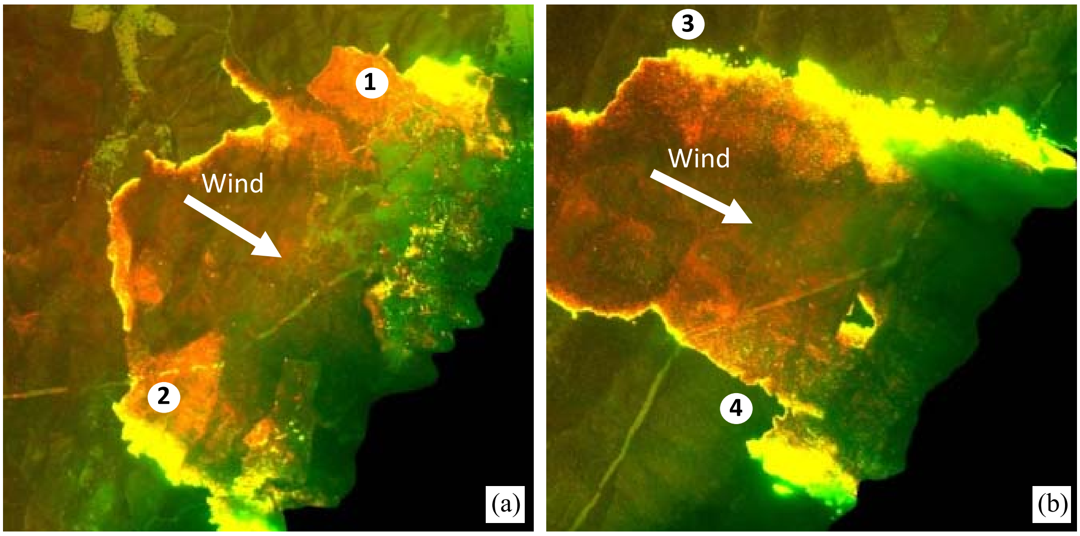

Figure 1. Multispectral line-scan imagery obtained to the west of Canberra on the afternoon of 18 January 2003. (a) Two instances of fire channelling within the McIntyres Hut fire complex at Pig Hill (point 1) and near the Blue Range (point 2), (b) Two instances of fire channelling within the Broken Cart fire complex at Browns Creek (point 3) and Log Hut Creek (point 4). In each panel the wind direction is indicated by the arrow.

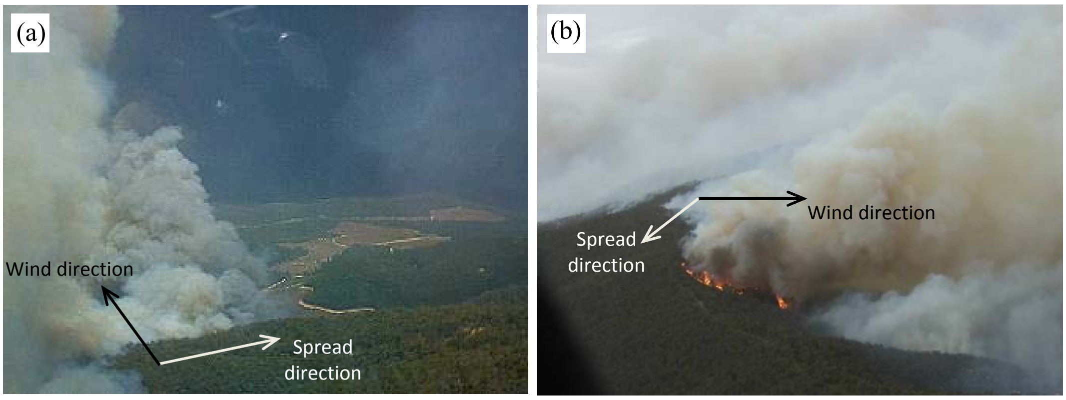

Figure 2. Photographs of fire channelling events during (a) the Canberra Fires, January 2003; (b) the Tinderry Fires, January 2010. Note the darker smoke and turbulent convection on the advancing flank in each case.

mechanism. Indeed, Sharples et al (2011) indicated that strong winds (> 20 km $h^{-1} \approx 5.5$ ms^{-1}) and a slope greater than approximately 25°, with an aspect within about 30° of the direction the wind is heading, were necessary conditions for the phenomenon to occur.

Overall, research into the atypical lateral spread first noted by McRae (2004), suggested the existence of a previously unknown mechanism for fire propagation that becomes highly significant in rugged terrain under dry and very windy conditions. While the exact physical processes driving the lateral component of the fire propagation are still uncertain, analysis of the available evidence provides a strong indication that the lee rotor has a significant effect on the way the heat from a lee-slope fire is distributed. In particular, it seems that the strong wind shear and turbulence associated with flow separation at a ridge line causes heat, flames and embers to be directed preferentially in an across-slope direction.

3. COMBUSTION TUNNEL EXPERIMENTS

To test the hypothetical mechanism outlined by Sharples et al. (2011) a number of combustion tunnel experiments were conducted using the facilities at the Center for the Study of Forest Fires in Lousã, Portugal. Sharples et al (2010) reported on the results of some preliminary combustion tunnel experiments, which demonstrated that the atypical lateral spread readily occurred under conditions that excluded the possibility of forced channelling. The experimental set-up (illustrated in Figure 3) involved a triangular hill that was

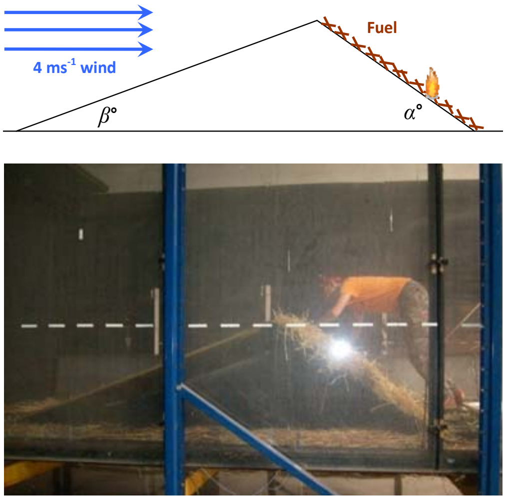

Figure 3. Schematic diagram (cross section) of the experimental ridge configuration and the approximate ignition point (top), and actual combustion tunnel set-up (bottom).

subject to wind (speed = 4 ms^{-1}) flowing in a direction perpendicular to the ridge-line. Referring to Figure 3, the slope parameters $\alpha = 35°$ and $\beta = 20°$ were chosen to ensure the formation of a lee rotor. Combustible fuel (straw) was placed on the lee slope and ignited in a series of ignition patterns. In all cases the fire was observed to spread up the lee slope against the main wind direction until it reached a position near the break in slope. At this point the fires exhibited a distinct acceleration in the across-slope direction in the form of a narrow finger of flame. Some lateral and downwind spotting was observed, as was the presence of distinctive darker smoke on the advancing flank (cf. Figure 2).

Following these preliminary investigations, additional combustion tunnel experiments have recently been conducted. These experiments were carried out using the same facilities at the Forest Fire Research Laboratory of the University of Coimbra, this time using a triangular section hill with variable configurations. The model of the hill was placed in the work section of the combustion tunnel with its ridge line perpendicular to the wind flow (Figure 3). The length of the model was 2.0 m and it was placed close to the lateral vertical wall of the combustion tunnel. The inclination angles α and β respectively of the leeward and the windward faces of the model could be adjusted. The following three configurations were tested: 1. α=15º, β=8º; 2. α=30º, β=20º; 3. α=40º, β=25º.

The leeward face that was used to perform the fire spread tests was covered with a uniform layer of fuel that consisted of straw particles with a load of 0.6 kg m^{-2} or 0.8 kg m^{-2} (dry basis). The flow velocity in the combustion tunnel could be adjusted continuously from 0 to 6 ms^{-1}. The following values of the reference wind velocity were used: 0 ms^{-1}, 1.5 ms^{-1}, 3 ms^{-1} and 4 ms^{-1}.

In each test a point ignition was made on the leeward face 0.15 m from the bottom of the hill and 0.5 m from the vertical wall. Shortly after ignition the combustion fans were turned on and set to produce the desired flow velocity. Video and infra-red (IR) cameras were placed at the exit of the combustion tunnel to record the evolution of the fire. More details on the experimental methodology can be found in Farinha (2011).

A series of 24 tests under varying conditions were performed. A sequence of photos of Test 4 is shown in Figure 4. This test was performed with a fuel load of 0.8 kg m^{-2} and a flow velocity of 3 ms^{-1} using configuration 2 of the hill. In the photos the fire near the top of the hill can be clearly seen spreading along the ridge in a direction transverse to the main flow much faster than the lateral spread of the fire near the bottom of the hill.

The lateral spread R_{YT} at the ridge top was evaluated from the analysis of IR camera frames at predefined time steps. The lateral spread R_{YB} near the bottom of the leeward face, along a horizontal line a third of the distance from the bottom to the top of the slope, was also measured to assess the differences in fire behaviour at the top and at the bottom of the hill. Rate-of-spread (ROS) values were evaluated by determining the slope of a linear regression between the average distances travelled by the fire versus time along three closely spaced horizontal lines near the top of the slope (Farinha 2011). ROS values were normalized as $R'=R/R_o$ where R_o is the basic rate of spread of a linear fire front in the same fuel bed in the absence of wind or slope. Average values of R'_{YT} and R'_{YB} for a series of tests are shown in Figure 5 as a function of wind velocity. These results correspond to a fuel load of 0.6 kg m^{-2} but the results with a higher fuel load did not show a dependence on fuel load in this range. As can be seen in Figure 5, the average ROS at the top of the slope increases with wind velocity and can reach values of $4R_o$ for configurations 2 and 3. The ROS at the bottom remains close to R_o and shows less dependence on the wind velocity and hill configuration.

4. BUSHFIRE SPREAD MODELLING IMPLICATIONS AND FUTURE DIRECTIONS

It is important to note the contrast between the atypical spread driven by the fire channelling phenomenon and the predictions of traditional quasi-steady fire spread models. Considering a lee-slope fire driven by synoptic winds blowing in a direction perpendicular to a sufficiently long and straight ridge-line, a traditional

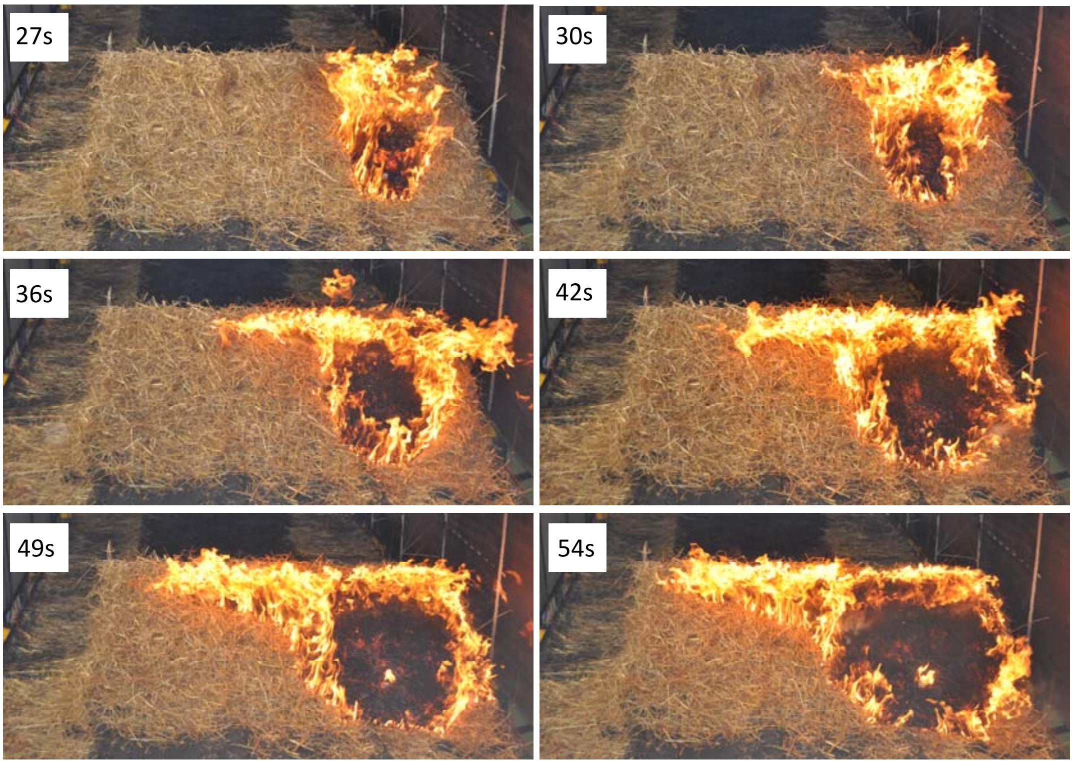

Figure 4. Fire spread on the leeward slope of the hill during Test 4 looking upwind. The time since fire ignition is indicated in each frame. This test was carried out with configuration 2 of the hill and with a wind velocity of 3 m/s.

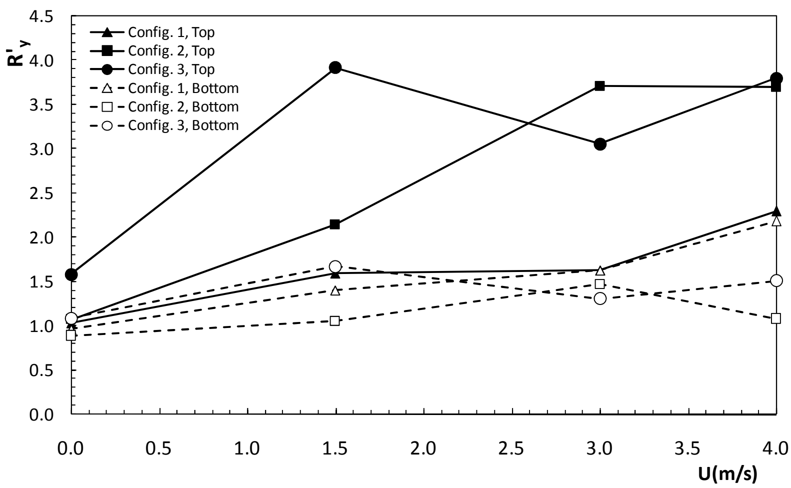

Figure 5. Nondimensional average values of the rate of lateral spread of the fire front at the top and at the bottom of the hill as a function of wind velocity for the three configurations that were studied.

fire spread modelling approach would first estimate the wind speed and direction over the lee-slope. Depending on the sophistication of the methods used to estimate terrain-forced winds (in the absence of a fire) the predicted wind direction would be either upslope (if the wind-terrain model accounted for turbulent eddies) or downslope (if turbulent effects were discounted). In each case the across-slope direction is orthogonal to the wind direction over the lee-slope and so any across-slope spread of the fire flanks would be taken to occur at a quasi-steady rate that is independent of the wind (Sharples 2008). However, as noted above, the across-slope rate of spread observed in fire channelling cases is neither quasi-steady, nor independent of the wind strength. The fire channelling phenomenon thus provides a significant counter-example to the universal validity of the assumption of quasi-steady fire spread. Given the reliance on the assumption of quasi-steady fire spread in-built into current operational fire spread models (Noble et al. 1980;

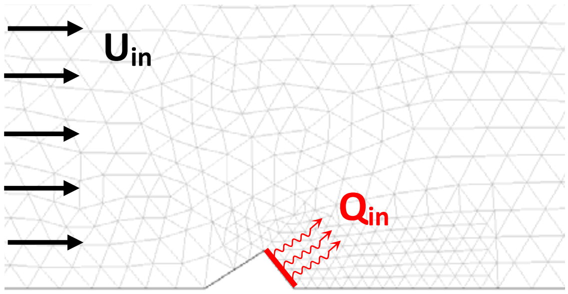

Figure 6. Geometry considered in the two-dimensional numerical simulation of the interaction between a lee-surface heat source and a lee-rotor. Significant boundary conditions are indicated: Q_{in} is the lee-surface input heat flux and U_{in} is the (constant) input air flow. The triangular mesh used to numerically solve the coupled fluid-heat conduction equations is also shown.

Tolhurst and Chong 2011), the atypical spread associated with fire channelling poses a significant challenge to the operational prediction of fire spread over rugged terrain during times of extreme fire weather. Devising methods for incorporating fire channelling effects into operational fire spread models is very much an open problem that requires further research.

Before fire spread models can be amended to include the effects of fire channelling it is necessary to better understand the underlying dynamics of the phenomenon. This can be accomplished in several ways, for example:

- Better documentation of wildfires burning in rugged terrain;
- Further small-scale experimentation using combustion tunnels;
- Numerical simulation of the interaction between a fire and a horizontal vortex.

Indeed, given that conducting landscape-scale experimental investigation into fire channelling is not feasible for reasons of community safety the only way to study the phenomenon in a controlled environment is through small-scale experiments or through landscape-scale numerical simulation. One of the authors (JJS) conducted some preliminary two-dimensional numerical simulations in collaboration with Prof. Dold at the University of Manchester. These simulations used a finite-element multiphysics package (COMSOL™) to investigate the interaction between a lee-rotor and a surface heat source on the lee-slope. An illustration of the geometry considered and the important boundary conditions can be seen in Figure 6. The simulations focused on an idealized triangular hill (similar to the one used in the combustion tunnel experiments) subject to a constant wind entering from the left of the model domain. All surface boundaries were considered isothermal except for the lee slope, from which an input heat flux emanated.

An example of the simulation results can be seen in Figure 7. The results indicated two key features: firstly that much of the heat emanating from the surface was re-circulated within the lee eddy, and secondly that a strong maximum in the turbulent kinetic energy occurred at the point of flow separation. While this is perhaps not surprising, it is worth noting as this region of maximum kinetic energy appears to accord well with the location where the atypical lateral spread was observed in the combustion tunnel experiments (Sharples et al. 2010). Interestingly, in these two-dimensional simulations the lee-rotor was observed to warm and grow in size, presumably as more heat was re-circulated within it. While three-dimensional simulations are yet to be performed we can speculate that the lee-rotor would not grow in size if air movement in an across-slope direction was also possible. This will be investigated more thoroughly in future work.

It is also important to note that a number of problems with the convergence and stability of the solutions delivered by the COMSOL™ package were encountered. This meant that it was only possible to apply parametric continuation (for example, of viscosity, heat conductance and the input fluxes) over a limited and

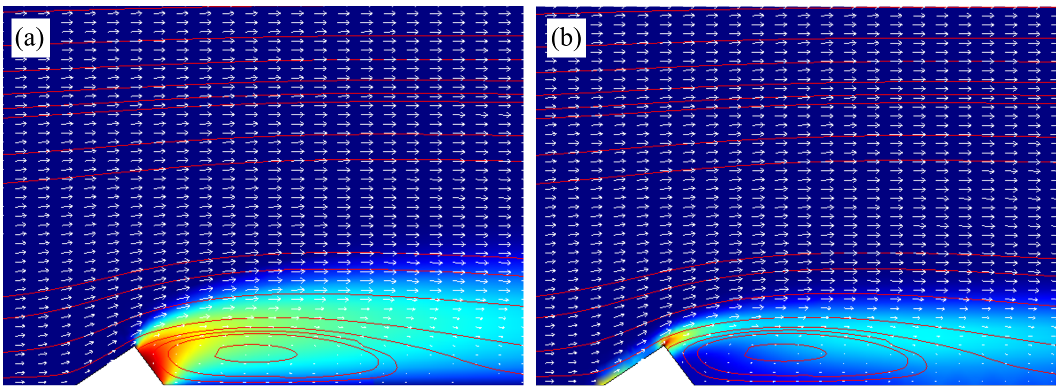

Figure 7. Results from the two-dimensional simulations: (a) logarithmically-transformed temperature field, (b) turbulent kinetic energy. White arrows indicate wind vector and red contours are streamlines.

physically unrealistic range. As such the results obtained should be taken as indicative only – they are by no means authoritative. The issues of numerical convergence and stability are being addressed in ongoing work.

Ultimately, comprehensive modelling of the phenomenon will require a full three-dimensional consideration of the problem with more representative topography and the inclusion of environmental effects such as temperature stratification of the atmosphere and vertical variation in the input wind profile. To be realistic, this will require the use of a meso-scale numerical weather prediction model. The WRF (Weather Research and Forecasting) model (Michalakes et al. 2001) is currently being considered in this respect.

5. DISCUSSION AND CONCLUSIONS

Complex bushfire propagation mechanisms, like those underlying the fire channelling phenomenon, pose a significant challenge to landscape-scale fire spread modelling. The assumption of quasi-steady spread that forms the basis of current operational bushfire spread simulators does not appear to be valid in the case of fire channelling. Rather the phenomenon is a consequence of the interaction between a turbulent eddy and the fire, the type of which is not accommodated by traditional quasi-steady, point-functional fire spread modelling frameworks. As such, current operational fire spread simulators are not able to account for such effects and so are not able to provide any direct guidance on any atypical fire development that may consequently arise. Given the apparent effects that fire channelling can have on a fire: for example, significant widening of the 'head fire', initiation of extensive flaming zones, and intense lateral and downwind spot fire development; not being able to accommodate such effects should be viewed as a significant shortcoming in current best bushfire risk management practice.

While significant progress has been made in incorporating effects such as mass-ignition by spot fires into fire spread simulators (Tolhurst and Chong 2010), their distinctly stochastic nature does not seem to faithfully represent the underlying processes, as exemplified by the experimental observations reported above. Indeed, by all indications the fire channelling phenomenon, while prone to some random fluctuation, is distinctly deterministic in nature and thus should be describable in terms of an appropriate deterministic model. In our opinion, development of such a model will be an important step in providing a comprehensive understanding of bushfire risk in rugged landscapes.

REFERENCES

Farinha, H.A.S. (2011) – *Formação de Vórtices num Incêndio Florestal – Estudo Laboratorial de um Vórtice de Eixo Horizontal e de um Tornado de Fogo*. Ms.Sc. Thesis (in Portuguese), Department of Mechanical Engineering, University of Coimbra, Portugal, July 2011 (63 pp.).

Kossmann, R., Sturman, A. and Zawar-Reza, P. (2001) Atmospheric influences on bush fire propagation and smoke dispersion over complex terrain. In: *Proceedings, 2001 Australasian Bushfire Conference*, Christchurch NZ.

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

Michalakes, J.G., Chen, S., Dudhia, J., Hart, L., Klemp, J.B., Middlecoff, J., Skamarock, W.C. (2001) Development of a next generation regional Weather and Research Forecast model. In: Zweithofer, W., Kreitz, N. *Developments in Teracomputing: Proceedings of the 9th ECMWF Workshop on the Use of High Performance Computing in Meteorology*, pp 269-276.

Noble, I.R., Bary, G.A.V. and Gill, A.M. (1980) McArthur's fire-danger meters expressed as equations. *Australian Journal of Ecology*, **5**: 201-203.

Sharples, J.J. **(**2008) Review of formal methodologies for wind-slope correction of wildfire rate of spread. *International Journal of Wildland Fire*, **17**: 179-193.

Sharples, J.J.**,** Viegas, D.X., Rossa, C.G. and McRae, R.H.D. (2010) Small-scale observations of atypical fire spread caused by the interaction of wind, terrain and fire. In: D.X. Viegas (ed.) *Proceedings of the VI International Conference on Forest Fire Research*, November 2010, Coimbra, Portugal.

Sharples, J.J., McRae, R.H.D. and Wilkes, S.R. (2011) Wind-terrain effects on the propagation of wildfires in rugged terrain: fire channelling. *International Journal of Wildland Fire*. In press, accepted for publication 25 May 2011.

Tolhurst, K.G. and Chong, D.M.O. (2010) The importance of mass-ignition by spotting on wildfire behaviour – examples from the 2009 Black Saturday bushfires in Victoria Australia. In: D.X. Viegas (ed.) *Proceedings of the VI International Conference on Forest Fire Research*, November 2010, Coimbra, Portugal.

Viegas, D.X. (2009) *Recent Forest Fire Related Accidents in Europe*. European Commission, Joint Research Centre, Institute for Environment and Sustainability.