FIRE SPREAD PREDICTION ACROSS FUEL TYPES

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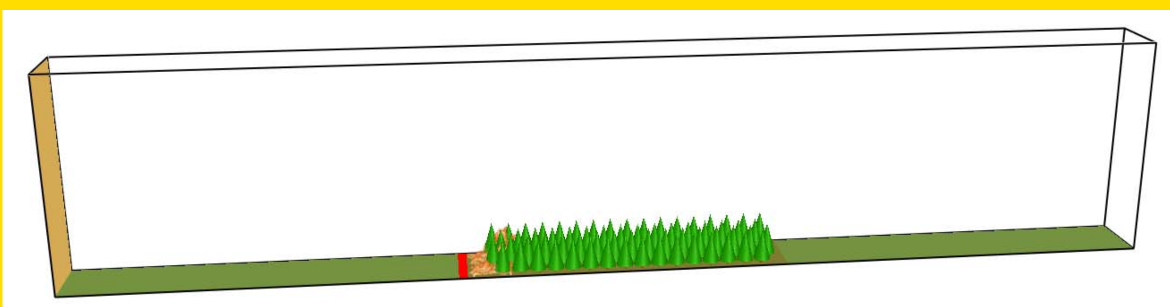

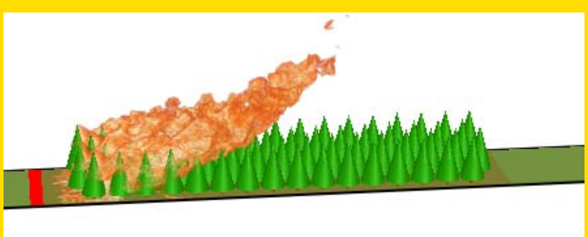

Flame upon impacting the crown

Quasi-steady flame propagation

Transition of a surface fire to a crown fire

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EXECUTIVE SUMMARY

It is essential that emergency and disaster management organisations are able to predict the rate of spread and intensity of bushfires. Currently this is achieved by implementing simplified operational models that have the useful attribute of providing results on time scales commensurate with those required by emergency managers. However, it is essential that these non-physics-based operational tools be refined so that they can predict fire behaviour under a wide range of localised topographic and weather conditions; they also need to be able to account for a range of inhomogeneity, slope, and thermal instability within vegetation and over the terrain. In addition, the operational models need to include a more physically-motivated firebrand model to predict firebrand landing and increased rate of fire spread (RoS).

To help ensure that operational wildfire models are accurate and flexible, we have numerically tested and established a reliable physics-based model that is based on basic fire dynamics theory and corresponding differential equations to simulate bushfire scenarios. Upon this, we investigated the following aspects:

- the effect of a tree canopy on the near surface wind speed with a view to modelling the wind reduction factor (WRF) due to the canopy. The wind reduction factor is used in operational fire prediction models such as the McArthur model, to account for the reduction in wind velocity due to a tree canopy. We modelled surface fire through a homogenous forest canopy and it appears that RoS depends on $\mathbf{U_{10}(0)^{p} / U_2(x)}$ instead of $\mathbf{U_{10}(0) / U_2(x)}$ as currently believed**.** where $U_{10}(0)$ is the velocity at 10m high in the open field and $U_2(x)$ is the velocity at 2m high within the canopy at x m from the leading edge of the canopy. The value of power, P is subject of ongoing research. We have also modelled wind profile within the heterogeneous (both horizontal and vertical, separately) forest canopy. The long-term goal is to develop a map of WRF across Australia.
- semi-quantitatively studied forest floor fire transitioning to a crown fire. Crown fires are often supposed to originate from surface fires spreading either along the bark of the tree trunks or direct flame contact to low branches with leaves and needles. A hypothetical forest of Douglas Fir trees in a grassland, which can be thought of as a model of a plantation, is simulated. We found that the model is capable of modelling a transition from surface fire to crown fire. However, the crown fire is supported by a continuous surface fire. In future, we aim to study threshold conditions for the transition and RoS for crown fire propagation.
- transport of non-burning firebrand (three particle shapes, cubical, cylindrical, and disc shaped particles, representing idealised firebrands) and their landing distribution have been studied. We have extended the experimental work to burning firebrands and simulations are in progress to compare with the experimental results. So far the simulation results are encouraging. In a related study, the thermo-kinetic properties of firebrand materials, such as bark, twigs, and leaves have been measured.

We have conducted two literature reviews:

- on the topic of atmospheric boundary-layer flow over forest canopies. Included in this review are brief discussions of flow over rough surfaces and flow over urban canopies (collections of buildings). The purpose of this review is to inform fire behaviour, analysts of progress in sub-canopy modelling, with an eye to developing simplified models for WRFs. Simulation of canopy flow is also reviewed and discussed. Simulations provide insight into the flow behaviour that is otherwise difficult to obtain from field observations and experiments. The basic principles of Large Eddy Simulation and the validity of the simulation results are discussed. Finally, some open problems are posed.
- on Australian Standard AS3959 which was developed to prescribe necessary structural changes for the structures located at bushfire prone areas (BPA). The AS3959 aims at improving the resilience of buildings against the bushfire attack (radiant heat, direct flame contact, burning ember, or a combination of these three factors) to mitigate the risk of bushfire through better adaptability of structures situated in the wildland-urban interface (WUI). In this review, we have attempted to identify the limitations of AS3959 which can be investigated and improved upon by using a physics-based model. Quantification of firebrand and direct flame attacks, assessing radiative heat load as well as any role of convective heat load, assessing slope correction, accounting for heterogeneous surface fuel have been identified to be studied by a physics-based model.

Two higher degree research students (HDR) are studying the following aspects:

- Reducing the spin-up time for the physics-based model and initialise the wind fields for faster and efficient fire predictions. This is attempted using two different strategies: (a) using Windninja and (b) incorporating Monin-Obukhov similarity theory (MOST). Windninja is a computer program which computes spatially varying wind fields over a complex terrain. Work is progressing towards mapping the terrain modified wind fields generated by Windninja to the physics-based model using the penalization method. The latest version of the model has incorporated the MOST which can provide initial wind and temperature field taking into the consideration of the atmospheric stabilities. Attempts are being made to make efficient use of this new feature.

- A buoyant line plume in a confined region is being studied using Direct Numerical Simulation (DNS). DNS is a numerical technique to faithfully study fluid flows by resolving all the turbulent motions instead of resorting to modelling small-scale turbulence. DNS provides great insight into the physics of flows but are limited to highly idealised and numerically tractable geometries such as channels.

The overall goal of our work is to obtain greater insight into bushfire physics and utilize those insights to parameterize various phenomenon for operational models. The end goal is to improve bushfire modelling so that risks and losses associated with bushfires can be reduced.

END USER STATEMENT

INTRODUCTION

Empirical models of the spread of bushfires are operationally very effective. However they are inherently limited due to the fact that the data on which they are based cover a limited range of conditions, and we may get results that are unrealistic if we extrapolate beyond the ranges of the models. As Sullivan [2] remarked, empirical models are based on observations, and not on theory. These models are developed in the laboratory and under idealised weather condition which are in quasi-steady state. Studies show with empirical models, an estimation error, in the rate of spread, can be around 40-60% [3]. If we are to develop models that accurately predict the rate of spread of bushfires over a wide range of conditions, we must ensure that empiricism contributes to its complement, namely rationalism. For this, we turn to the laws of physics that are the unifying principles that permeate this project.

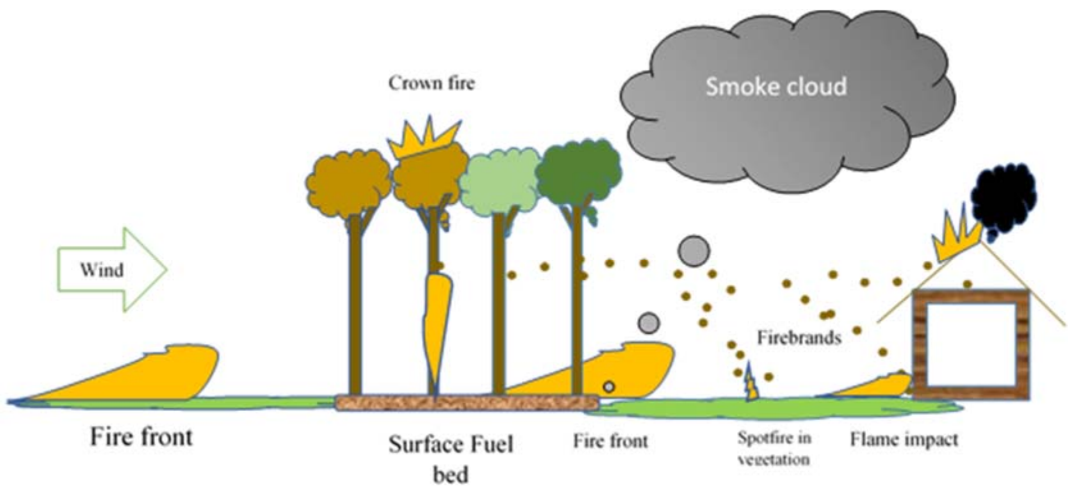


Figure 1: A schematic of fire spread mechanism in the ideal forest causing spotting in vegetation and house fire

Figure 1 represents an ideal scenario that we are attempting to simulate in unprecedented detail and in the process obtain useful application tools for end-users. To address existing gaps in the mathematical/computational modelling of bushfire dynamics, the scenario shown in figure 1 is subdivided into a number of subprojects.

The rate at which fires spread is strongly dependent on the wind speed. This is true for fire over open grassland as well as through and over forests. The velocity profile of the wind within forests is quite different from that over open ground. The dependence of wind speed reduction on forest canopy density is being explored. By comparing wind profiles entering and leaving the canopy we are developing a tool to determine an appropriate Wind Reduction Factor (WRF). We aim to include the variation (heterogeneity) in forest both in the lateral and vertical direction, hence the variation in WRF.

The rate of spread of bushfires is often dominated by firebrands being conveyed ahead of the firefront. We are harnessing our expertise in aerodynamics to design, construct and operate a firebrand generator to accurately quantify how firebrands disperse. This part of the project will generate experimental data to

(a) analyse the dynamics of short-range spotting and (b) improve a physics-based submodel to simulate the transport of firebrands. The latter can be further utilised to study the behaviour of firebrand transport under different weather, vegetation and terrain conditions. We envisage formulating a parameterisation of firebrand transport and landing distribution which can be used with operational models.

Australian standard 3959 [4] was developed to specify necessary structural changes for the structures located at Bushfire Prone Areas (BPA). We are conducting a literature review to identify the limitations of AS3959 which can be investigated and improved upon by using a Physics-based model.

Crown fires often originate from surface fires spreading either along the bark of the tree trunks (see figure 1) or direct flame contact to low branches with leaves. In a previous study, we successfully conducted surface fire (grassfire) spread simulation investigating the effect of wind speed and grass height on the rate of fire spread over flat terrain and uniform distribution of vegetation. Currently, we are investigating the transition from surface fire to the crown and aiming to investigate threshold conditions for such transition as well as crown fire spread rate once transition occurs.

The evolution and dynamics of bushfires are very sensitive to the details of the rugged terrain over which they travel. These details range from leaves measured on a scale of a few centimetres, branches measured on the scale of metres to hills and mountains measured on the scale of kilometres. In a computer simulation, it would be impossible to fully simulate the exact physics on all these length scales. These elements of the terrain also obstruct wind and supply fuel, moisture and heat. Thus, a reliable boundary condition must capture the aggregate effect of the pertinent physics from all the geometrical length scales. We are now using Windninja [5], a software that provides spatially varying wind fields over complex terrain to provide initial and boundary condition to the physics-based model.

The key motivation of our work is to improve wildfire modelling so that risks and losses can be reduced. Results from all these subprojects will be utilised to develop application tools for fire behaviour analysts/regulators.

THE PROJECT - ACHIEVEMENTS

MODELLING WIND FLOW AND SURFACE FIRE THROUGH CANOPIES

Modelling of surface fire through homogenous canopies

The rate-of-spread of a wildfire largely depends on the wind speed. The presence of a tree canopy will act as an aerodynamic drag force and reduce the wind speed. In, for example, the McArthur [6] model, this effect is modelled by using a WRF. The WRF is often defined as the ratio of the wind speed at 10 m height, in the open far from any canopies, to the wind speed at 2 m height within the canopy. The sub-canopy height of 2 m is selected to represent the mid-flame height, which is believed to be the most relevant wind spread to characterize the fire spread.

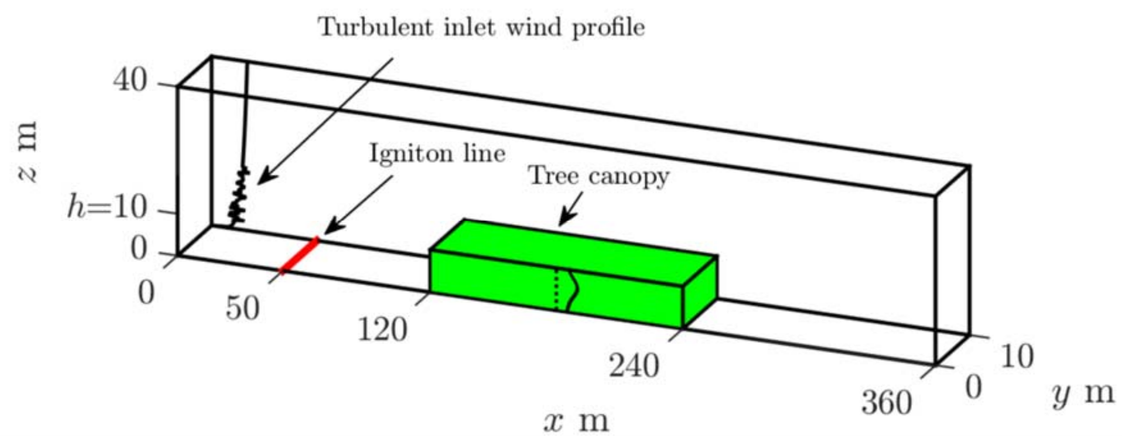


Figure 2. The simulation domain showing the inlet profile, the line ignition source, and the canopy.

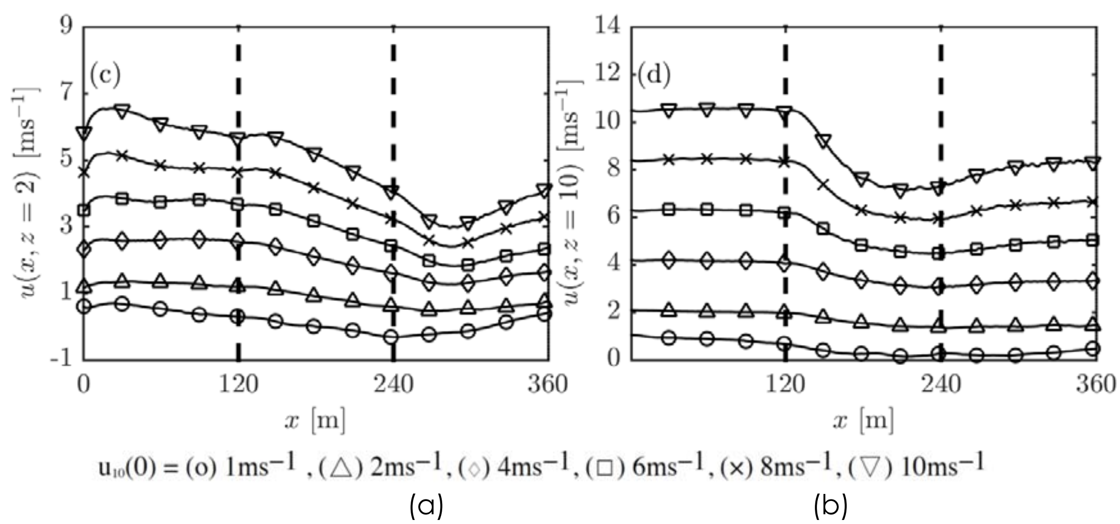
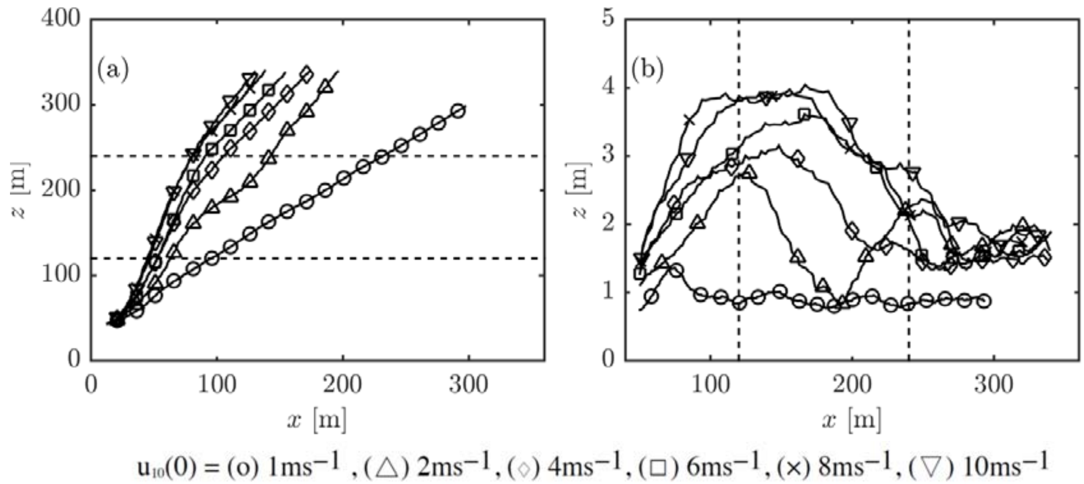


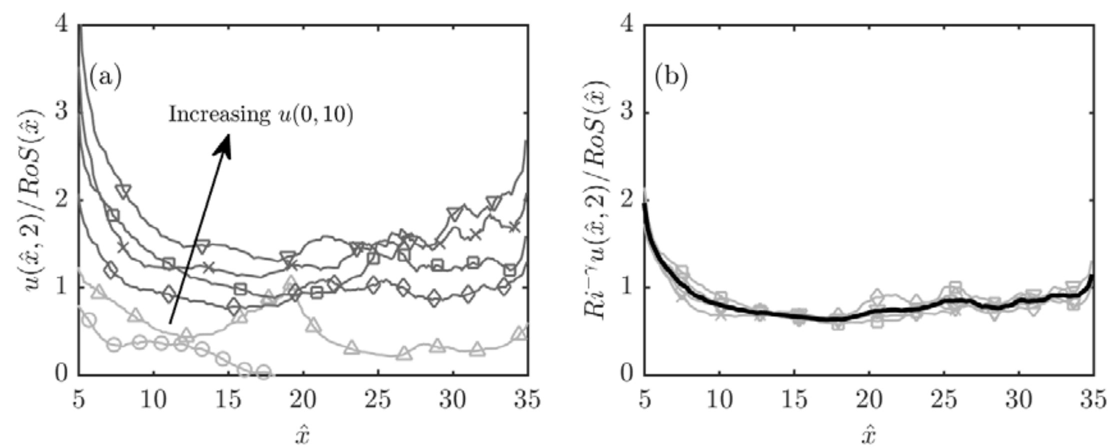
Figure 3. The mean u-velocity (a) u(x; z = 2 m) and (b) u(x; z = 10 m) across the domain for all cases. The canopy and domain edge is represented by the dotted line.

Currently, to model the WRF, fire behaviour analysts use a rule-of-thumb based on the measurements of McArthur [6]. In this subproject, we seek to appraise this rule-of-thumb. We have used a physics-based model, Fire Dynamics Simulator (FDS) developed by National Institute of Standard and Technology (NIST), USA to simulate grassfire propagation through an idealised rectangular-shaped tree canopy as shown in Figure 2. The driving velocities are $U_{10}(0)$=1, 2, 4, 6, 8, 10 m/s. $U_{10}(0)$ represents wind velocity at 10 m height at the inlet of the domain. The height of the canopy is 10 m and the density of the canopy is represented by a Gaussian profile as shown. The grass properties were the same for the cases presented in [7].



(a) (b)

Figure 4. (a) Location of fire fronts as function of time. (b) Calculation of RoS.



(a) (b)

Figure 5 (a) the unscaled ratio of u(x/h; 2/h)/RoS(x/h) suggesting a dependence on $U_{10}(0)$. (b) The scaled ratio and the ensemble average estimate of a correlation. The buoyancy dominated cases are omitted in the ensemble average.

First of all, the wind field is simulated using large eddy simulation (LES) without the presence of a fire. A brief description of LES and canopy implementation in FDS is presented in Appendix A. The sub-canopy wind velocities at 10 m and 2 m height are presented in Figure 3 as a function of longitudinal distance along the centreline of the domain. Then grassfire propagation through the forest canopy is simulated. The flame front locations are presented in Figure 4(a). We can see that in $U_{10}(0)$=1 m/s case, fire front is not affected by the canopy drag. However, it is affected in the rest of the cases. An analysis conducted in terms of Richardson number, Ri, a dimensionless quantity, which measures the relative importance of buoyant (convective) effects and shearing (free-stream) effects. It shows that $U_{10}(0)$=1 and 2 m/s cases are in plume mode (buoyant effect dominates) and the rest are in boundary layer mode (shearing effect dominates). Moinuddin et al [7] found that all cases with $U_{10}(0) \geq 3$ m/s fall in the boundary layer mode. RoS as a function of distance is presented in Figure 4(b).

We have attempted to develop a more realistic WRF correlation based on the simulation data, rather than the ratio of $U_{10}(0)$ to the $U_2(x)$ within the canopy. $U_2(x)$ is the velocity at 2m high within the canopy at x m from the leading edge of the canopy. The motivation is to form a correlation for the dependent variable RoS based on a physically reasonable parameter set that explains the rate-of-spread data in the majority of the cases. The physically relevant properties are the characteristics of the canopy, fuel, combustion, the driving wind speed, and the buoyant plume. The canopy and fuel parameters remained constant throughout these simulations and therefore they are not explicitly considered. However, the canopy properties influence the sub-canopy wind speeds and the fuel properties affect the total amount of heat released, and hence the size of the plume. The buoyancy, the driving wind, and the sub-canopy wind are all coupled. The driving wind speed governs the sub-canopy speed, which in turn affects the fire spread, essentially by supplying oxygen to the fire, transporting heat, affecting the flame angle, and flame dynamics. Based on these considerations, we have proposed a preliminary scaled correlation as presented in Figure 5(b). The unscaled ratio presented in Figure 5(a) shows a relation dependence on $U_{10}(0)$. It appears that RoS depends on $\mathbf{U_{10}(0)^{p} / U_2(x)}$ instead of $\mathbf{U_{10}(0) / U_2(x)}$ as currently believed**.** The value of power, P is subject of ongoing research.

Literature review: Modelling and simulation of flow over tree canopies

Understanding sub-canopy wind profiles are of crucial importance to parameterising the atmospheric boundary layer above a forest canopy and also estimating wind reduction factors for fire spread models. We reviewed recent and operationally relevant scientific literature covering the topics of modelling and simulating sub-canopy wind flow. This review was not intended to be a comprehensive discussion of the topic of canopy flows and turbulence induced by plant canopies. Instead, the aim of this document was to highlight recent research, which is relevant to operationally predicting the mean sub-canopy wind speed under a range of conditions.

For detailed reviews of sub-canopy turbulent flows, from a fluid dynamics perspective please refer to the reviews of Finnigan [8] and Belcher et al. [9].

There are two analytical models (Harman and Finnigan [10] and Belcher et al. [11]) which have potential usefulness in an operational context. The model of Harman and Finnigan [10] is likely to provide useful predictions of sub-canopy flow which could be a basis of a model of the WRF (see Figure 6). However, such a model itself is likely to be of limited use near forest boundaries or over the complicated terrain as it is based on the assumption that the canopy has finite depth. In practical terms, the Inoue model works for the top part of the canopy and progressively makes poor predictions near the ground.

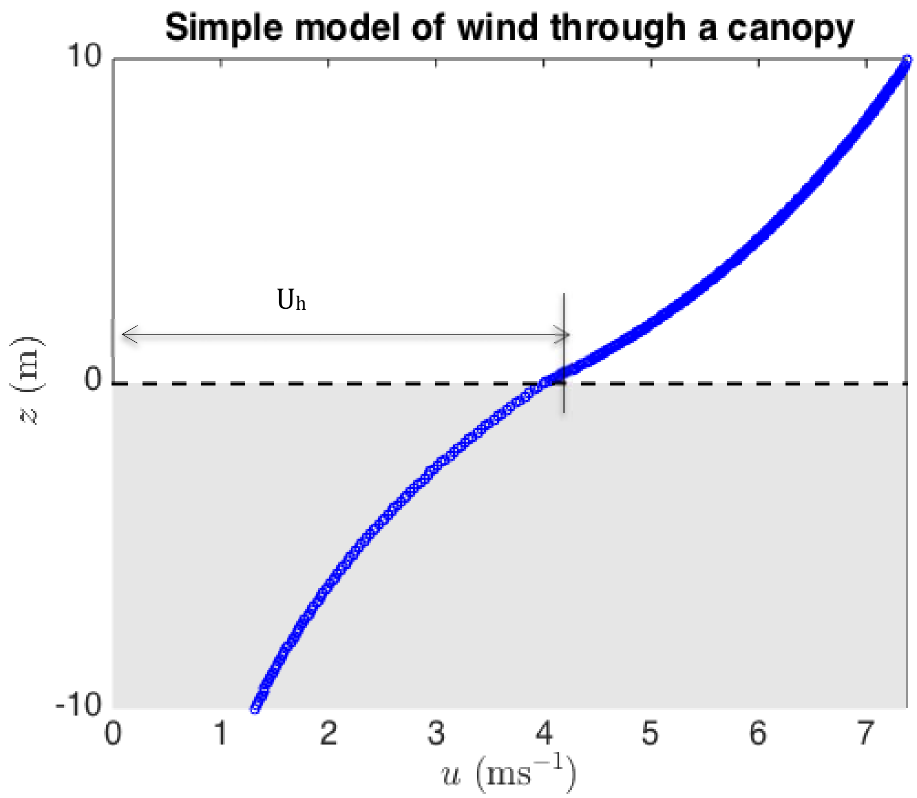


Figure 6: Sample profile of the sub-canopy and above canopy flow predicted by the model of Harmann and Finnigan [6]. The canopy is shaded in grey. Recall that the canopy and the atmosphere above are considered infinite. U_h is the velocity at the canopy top.

LES is the preferred tool for studying sub-canopy wind flows and results of numerous validation studies demonstrate that LES readily provides accurate representations of mean sub-canopy flow and can additionally reliably simulate second-order turbulence statistics. LES also provides a means of investigating flow over rough surfaces and within urban canopies.

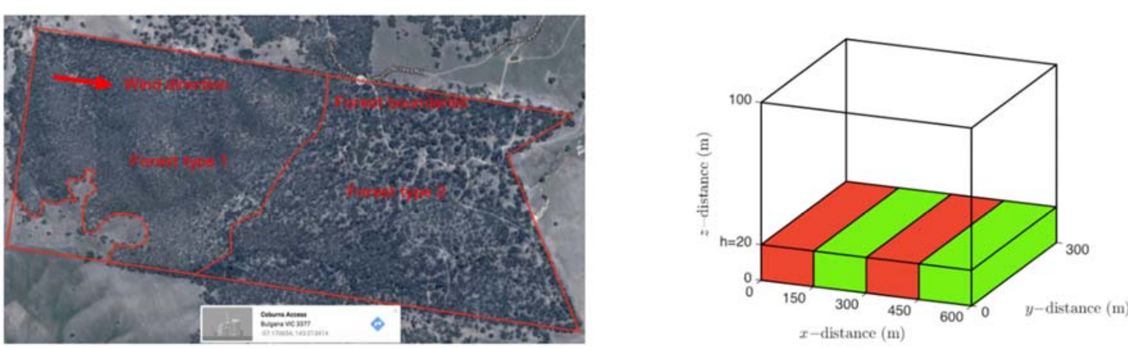
The recurring theme with the LES studies is that mean sub-canopy profiles are fairly easy to obtain with useful accuracy. It may be possible to generate reduced models of these profiles based on extensive simulation datasets.

Most of the studies examined in this review were not motivated by a wildfire application. Nonetheless, the information contained within the reviewed material can serve a valuable purpose in wildfire research and operational modelling. Similarly, there are many areas where fundamental research could reveal knowledge about canopy flows relevant to wildfire behaviour. Thus there are two classes of open problems that we believe are worthy of attention. The first class of open problem will examine if existing knowledge can be applied or implemented in operational wildfire modelling; the second class of problem is the extension simulation studies to novel scenarios.

1. Is it possible to use simplified models such as those due to Harman and Finnigan [10], or Belcher et al. [11] to predict sub-canopy wind fields for use in the McArthur or other empirical fire spread models?
2. How far does a canopy wake persist and what is the effect of the canopy wake on fire spread?
3. What are the dominant physical features of flow over heterogeneous canopies? Can the flow be parameterized similar to flow over rough surfaces?
4. Is it possible to develop reduced, or simplified, models of sub-canopy flow especially in the case of complicated canopies with heterogeneous leaf area density (LAD)? Can these new models be extended like the Harman and Finnigan [10] model to include the effects of atmospheric stability?
5. Can canopy recirculation regions cause the anomalous lateral spread of a fire line? If so, what are the criteria for lateral spread occurring?
6. What is the effect of a canopy recirculation region on firebrand transport? In particular, do firebrands tend to accumulate at a downstream forest boundary?
7. How do flows over rough surfaces, such as terrain, interact with canopy flows? Is there a range of flow conditions where the flow is terrain dominated or where the flow is canopy dominated?

Modelling of wind flow through horizontally heterogeneous canopies-

A good understanding of the effect of heterogeneous canopies will extend our knowledge gained through previous WRF studies in relation to homogenous canopies and eventually improve fire spread prediction. The aerial photograph (Figure 7a) taken near Ararat in Victoria, Australia, shows a canopy region with some heterogeneity in the direction shown. Large-eddy simulation of a neutral atmospheric surface layer (ASL) flow has been performed over a modelled tree canopy with heterogeneous leaf-area density. The canopy is arranged as a series of equally-sized stripes of different leaf-area density, emulating the study of Bou-Zeid et al. [12] over heterogeneous rough surfaces as shown in Figure 7(b).



(a) (b)

Figure 7: (a) Aerial photograph taken near Ararat in Victoria showing a forest canopy with step-like variation in leaf area density between forest type 1 and forest type 2. The wind direction aligned with this step change in forest type is shown by the arrow. (b) Simulation domain for the four-canopy case. Red: $LAD = 0.2$, green: $LAD = 3$. The $x-$ and $y-$boundary conditions are periodic.

Different LAD variations are shown with colour schemes. The size of the exterior domain above the canopy height (h) is chosen so that the largest relevant structures are captured. The overall domain size is $600 \times 300 \times 100$ m ($30h \times 15h \times 5h$). The boundary conditions employed follow Bou-Zeid et al. [12].

This study will allow, in the future, the identification of the equivalent roughness length, displacement length, and blending height which parameterise the flow above the heterogeneous canopy. In the present work, we restrict attention to the characterisation of the four canopy case and the blending height and β parameter, the ratio of shear stress to the velocity at the canopy top. The general characteristics of the four-canopy case are representative of the other cases.

Vertical profiles of averaged (over time and lateral variation) streamwise velocity are shown at a range of locations along the four-canopy case in figure 8(a). When the flow moves from a sparse canopy to a dense canopy the flow slows in the streamwise direction causing regions of strong upward vertical velocity above the dense canopies (figure 8(b)). Correspondingly there is a strong downward vertical velocity above the sparse canopies. It means vertical velocity couplets exist on the vertical interface between two canopies. This implies the presence of sub-canopy recirculation zones at canopy interfaces, which can be confirmed by visualisation of the fluid streamlines.

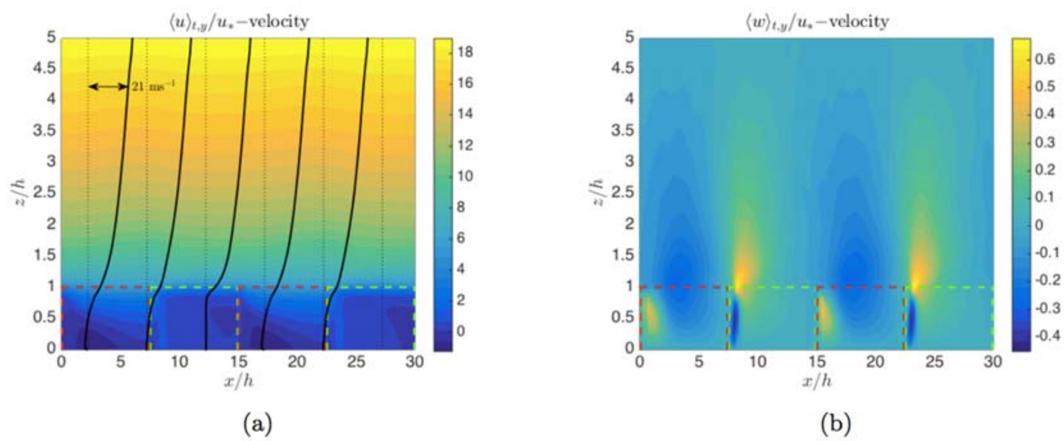


Figure 8: Contours of non-dimensional average u–velocity with superimposed profiles of average u–velocity at a range of locations along the canopy. Note the contours (colours) are non-dimensional but the profiles have an approximate dimensional scale as indicated. (b) Vertical velocity in the whole domain showing the strong up- (yellow) and down-drafts (blue) above and within the canopies. The canopy stripes are shown as dotted outlines.

The recirculation regions are visualised by plotting the streamlines of the mean flow in figure 9(a) over each individual stripe of the canopy which affects the downstream flow. The plumes, mixed layer, and blending height above the canopy can then be visualised as shown in figure 9(b). The critical height where this well-mixed layer commences is called the blending height. In a blended layer, there will be no localised deviations from the mean flow throughout the domain.

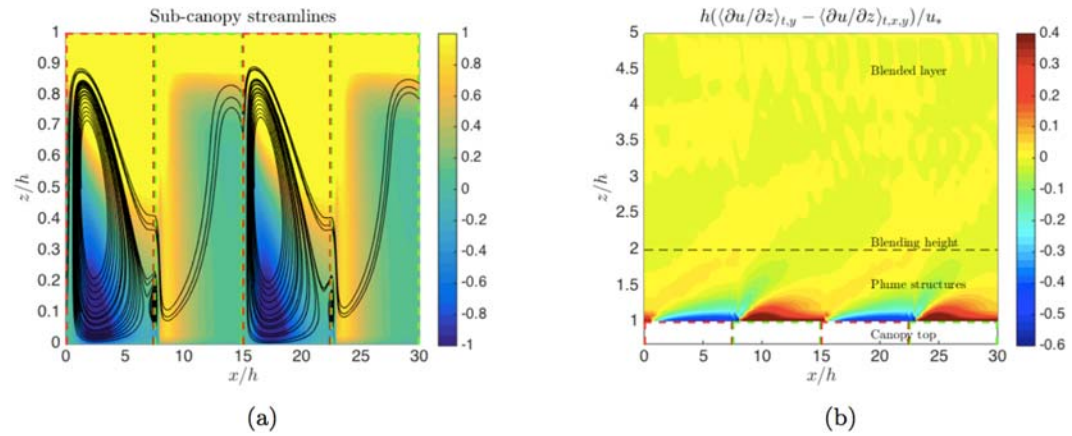


Figure 9: (a) Streamlines highlighting two recirculation vortices within the canopy. Superimposed on the nondimensional average u–velocity. (b) Contours of averaged velocity gradient difference above the canopy, clearly showing the plume structure immediately above the canopy. Above the blending height is a well-mixed boundary layer characterised by neglibible fluctuations in the velocity gradients. Sub-canopy flow is omitted from this figure. The canopy stripes are shown as dotted outlines.

Above the canopy, internal boundary layers form over each canopy stripe and exhibit similar features to the characteristic upstream plumes of flow over a rough surface. The contours of total shear stress, τ and a plot of τ in the plane above the canopy is plotted in figure 10 (a and b). The stress immediately above the canopy varies periodically over the stripes as is expected. However, in contrast to the discontinuous jumps observed over heterogeneous roughness Bou-Zeid et al. [12], the variation over a canopy appears to be somewhat smooth. Over the sparse canopies τ appears to approach a constant value, but over the dense canopies, τ exhibits an inflectional variation. The blending height is identified following Bou-Zeid et al. [12] .

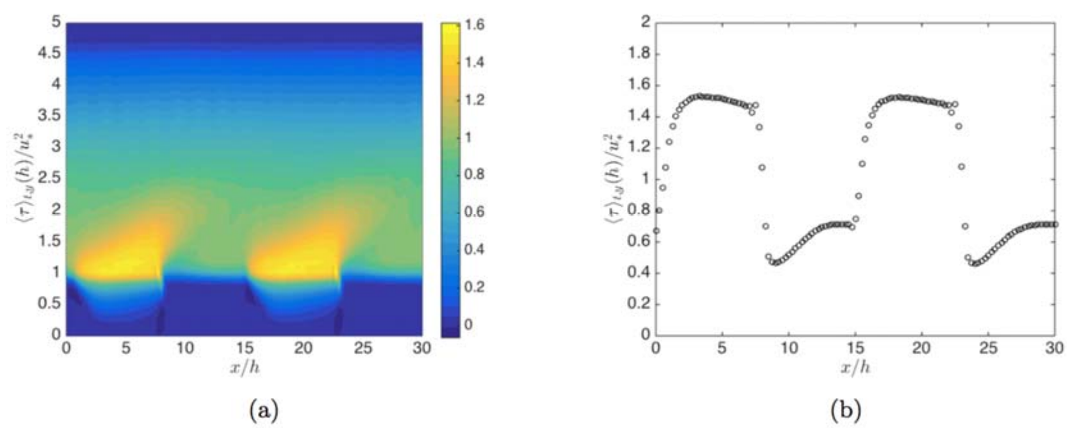


Figure 10: (a) contours of stress over the domain, (b) stress at the canopy top

A homogeneous sub-canopy flow is parameterised by $\beta = u_*/u_h$, the ratio of canopy top friction velocity to canopy top velocity (Harman and Finnigan [10]). In that study β was found to be approximately constant with LAD in neutral atmospheric stability conditions; the value proposed for the neutral conditions $\beta = 0.3$. In figure 11, β as a function of x/h is plotted for all canopy cases. We also find that the mean value of β is approximately constant across the heterogeneous canopies with a value of $\beta \approx 0.2$ as shown in figure 11.

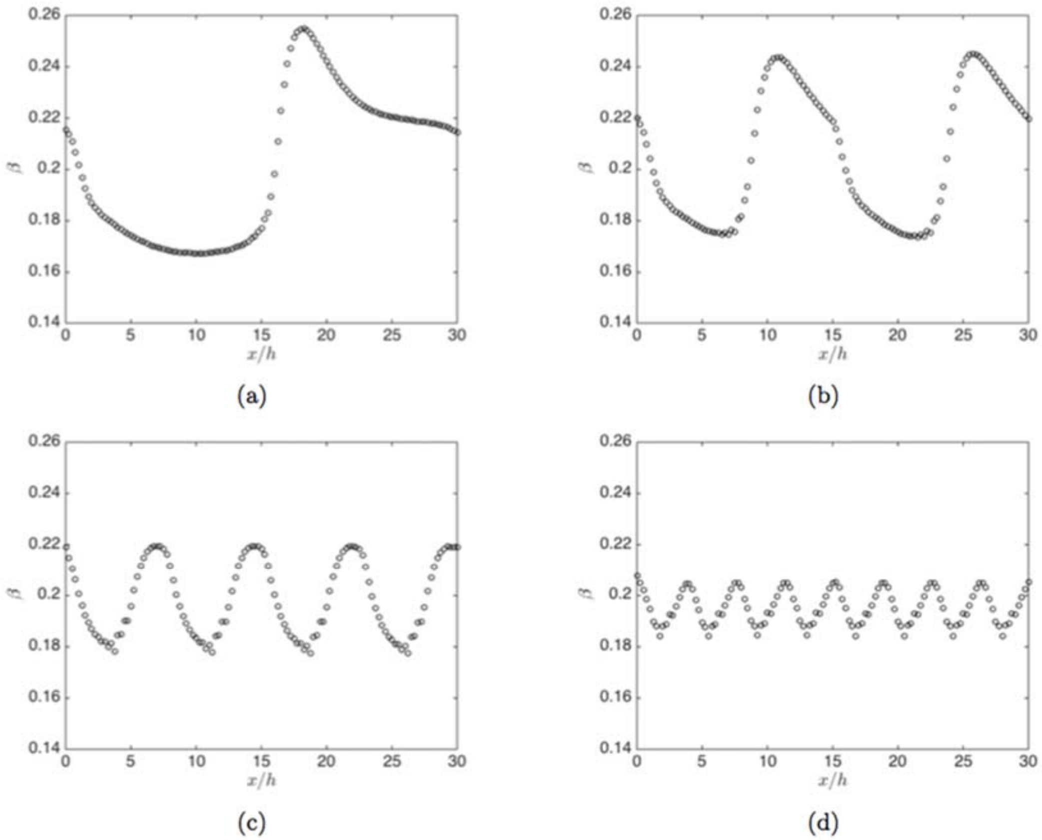


Figure 11: Variation of the β parameter for (a) two, (b) four, (c) eight, and (d) sixteen canopy cases. The mean value is approximately β = 0.2 in all cases.

Further work is required to investigate the dependence of β on the canopy LAD. It is not possible to immediately extend the sub-canopy flow model of (Harman and Finnigan [10]) because the recirculation regions which exist at the canopy interfaces will not be captured. The data set presented here will be used to develop a parameterisation of the boundary layer above a heterogeneous tree canopy and it will also be used to model the sub-canopy flow. The determination of an equivalent blending height, displacement length, and surface roughness length in terms of the canopy parameters can be used in surface schemes of numerical weather prediction models which will improve the overall wind forecast accuracy.

The development of a reduced model of sub-canopy winds in heterogeneous forests will be useful to wildfire management agencies that require estimates of sub-canopy wind speeds for operational fire models such as the McArthur model or the Rothermel [13] model. Extending this work will contribute to understanding the effect of forest heterogeneities on firebrand and smoke transport.

Modelling of wind flow through vertically heterogeneous canopies

In nature, there is strong variation of LAD in all three spatial directions; the variation is most prominent in the vertical direction because trees typically have more vegetation at the top of the canopy than the bottom. As shown in figure 6, an analytic model exists for large, uniform canopy. That is, the occupied volume fraction, or LAD of the canopy is constant over the whole canopy. The model of Inoue [14] is based on a balance between turbulent stresses and the drag force of the canopy. Harman and Finnigan [10] significantly extended the Inoue model to include the above canopy flow and non-neutral atmospheric conditions. Similar to Inoue, their model assumes a very large forest, free of any forest edges or inhomogeneity in the forest canopy. The model has two empirical parameters that are straightforward to measure. The model requires only the canopy top velocity and the leaf area index of the forest to predict the sub-canopy profile in neutral atmospheric conditions. However, no analytical solution exists for canopies where there is a variation LAD in the vertical direction.

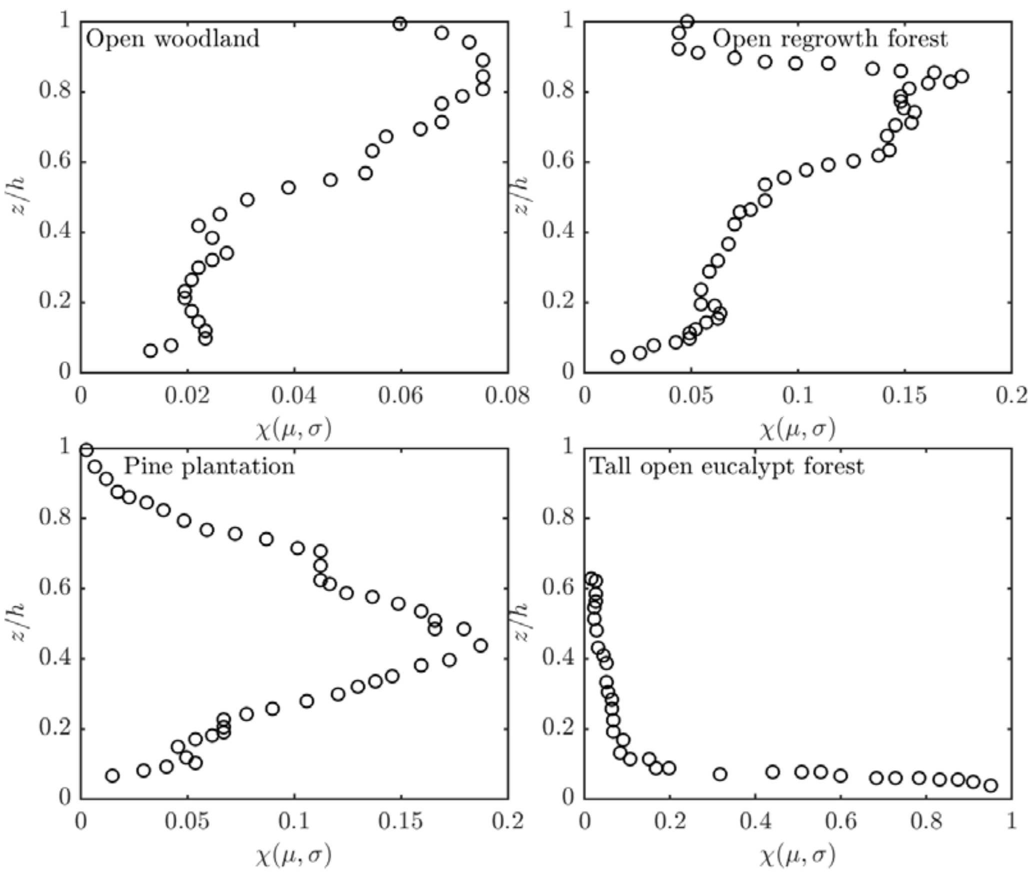


Figure 12: Profiles of LAD measured by Moon et al. [1] for four different forest types.

Recently, Moon et al. [1] performed field measurements of sub-canopy wind speeds in Australian vegetation. The measurements of LAD by Moon et al. and similar measurements made by Amiro [15], show considerable variability in the LAD profiles for different forest types around the world. Some of the measured profiles obtained by Moon are shown in figure 12.

The height of the canopy is taken as $h = 20$ m and h is a natural length scale of the flow.

Some example profiles of LAD are shown in figure 13. The profiles in figure 13(a) were obtained by setting the variance σ^2 to its minimum value and then varying

μ. The profiles in figure 13(b) were obtained by setting μ to its maximum value and varying σ^2 . The black line is the same in both plots.

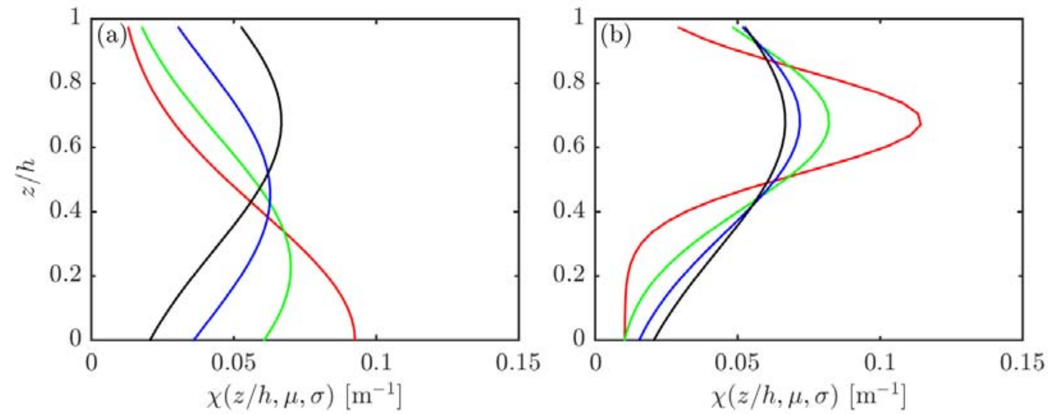


Figure 13: Sample of LAD profiles used in this study. In (a) σ^2=0.325 is held constant and μ= 0.00 (red), 0.233 (green), 0.467 (blue), and 0.700 (black). In (b) μ=0.70 is constant and σ^2=0.325 (black – the same curve as in (a)), 0.233 (blue), 0.142 (green), and 0.050 (red).

The simulated mean wind profiles are shown in figure 14. The profiles are all normalized by the value of the wind speed at the top of the canopy at $z/h = 1$. The pressure gradient and LAI are held constant during these simulations. The variation of the LAD profile leads to variation in the drag force exerted by the canopy upon the fluid. Because the LAD profile is known and the average sub-canopy wind velocity is simulated, the LAD profile, that gives the maximum drag force, can be measured. In these simulations the canopy which exerts the maximum drag force is $\mu = 0.7$, $\sigma^2 = 0.233$. That is the profile with maximum mean and variance.

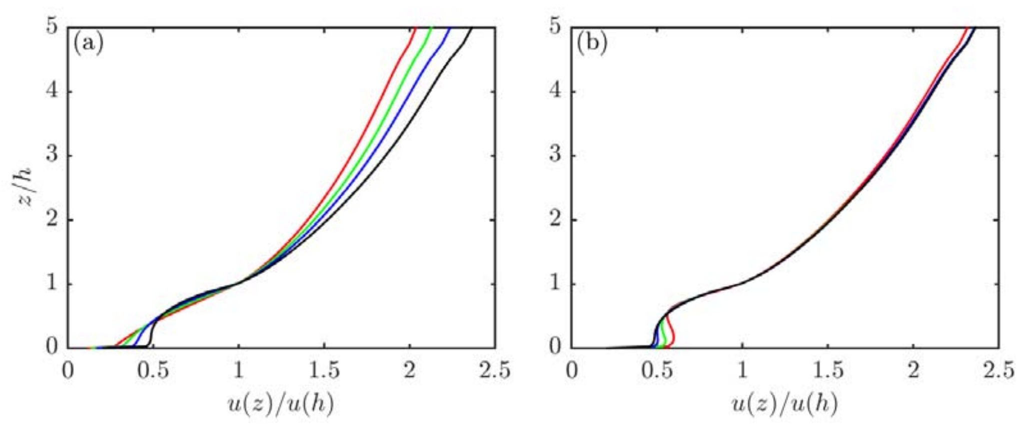


Figure 14: Mean u-velocity profiles normalised by the canopy top value. The canopy LAD profiles are the same as shown in figure 13. That is, in (a) σ^2=0.325 is held constant and μ= 0.00 (red), 0.233 (green), 0.467 (blue), and 0.700 (black). In (b) μ=0.70 is constant and σ^2=0.325 (black – the same curve as in (a)), 0.233 (blue), 0.142 (green), and 0.050 (red).

It is anticipated that a model of sub-canopy flow and a parameterization of above canopy flow will be developed from the results of these simulations.

THE SPREAD AND DISTRIBUTION OF FIREBRANDS AND IGNITION

Firebrands generated by bushfires are the root cause of spotfires which increase the rate of spread of fire. Firebrands comprise a range of components such as species bark, twigs, and leaves. The flow of firebrands in the wind has not been studied in detail previously. The FDS and WFDS (Wildland Urban Interface Fire Dynamics Simulator–a similar model to FDS) do not incorporate the effect shape and size of the firebrand to describe the flow and aerodynamics of firebrand. Their Lagrangian particle model, by which the trajectory of individual particles is tracked in the fluid flow, is applicable only when the particles are small in comparison to the scale of flow. This component of the project is motivated by the need to devise comprehensive models of the dispersion of firebrands, and their propensity to ignite vegetation. This is achieved by characterizing key physical and chemical properties of firebrands generated by a range of Australian flora and determining their aerodynamic properties.

The design and construction of a firebrand generator

To be credible, computational models must be validated against experimental data. Hence a firebrand generator was designed and constructed so that the distribution of firebrands and its associated parameters can be measured. Previously NIST developed a firebrand generator [16], dubbed a 'fire dragon', to study the interaction of firebrands with buildings, but the NIST generator suffers a serious deficiency. The problem was: the outlet from which the fiery firebrands disgorge resembles that of a dragon's mouth set atop of a long vertical neck. As a result, the firebrands are conveyed around a 90° bend immediately before they are projected out horizontally. Hence, the distributions of the firebrands and air velocity at the dragon's mouth are highly non-uniform. We designed a new firebrand generator eliminating the bend and involving two co-axial pipes which produce uniform air velocity at the mouth [17].

Figure 15: Firebrand dragon constructed at our facility to generate repeatable uniform firebrand shower.

Figure 16: One of the firebrand coming from the firebrand dragon. Due to very fast movement of firebrand attempt to capture a still image was very hard

Result and construction of prototype firebrand dragon were discussed in Wadhwani et al. [17]. The observation of the simulation work shows underprediction with the experimental observation. We have made improvements to the Lagrangian sub-model to account for the effect of shape. The improved model is validated with different speed and non-burning firebrand transport. Figure 15 shows the firebrand dragon at our facility. Figure 16 shows a still image of glowing firebrand coming from the firebrand dragon. Due to very fast movement of firebrand particle it is very hard to observe their trajectory. The experimental scenario is currently being used to validate the Lagrangian sub-model for burning particles. Preliminary result of the trajectory with naked eyes and scattering distribution of burning firebrand is shown in figure 17.

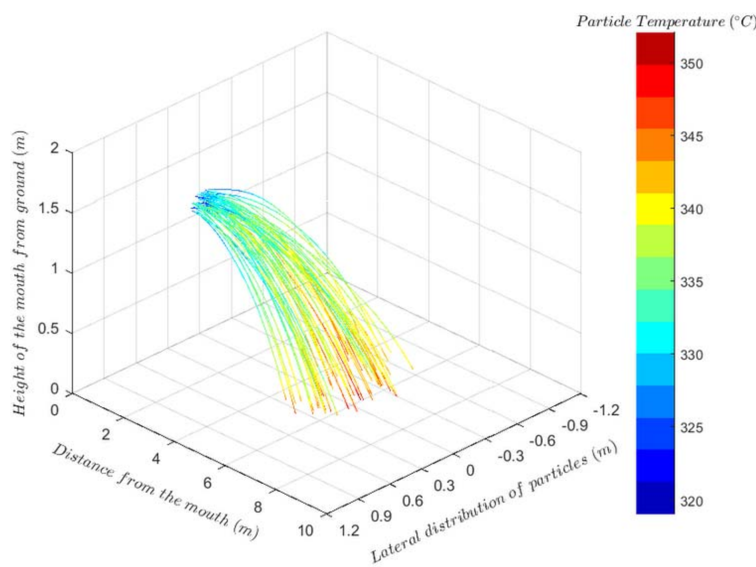


Figure 17: Trajectory of burning cubiform particle from the firebrand generator mouth. The variation in streamline colour denotes the variation in particle temperature.

Thermo-physical, flammability and kinetics properties of fuel bed

To study the ignition of fuel bed from firebrand, it is important to estimate the thermo-physical and kinetic properties of the fuel bed to assess the thermal degradation (gasification when heated prior to taking part in combustion process) sub-model of WFDS/FDS. The kinetic properties of forest litter are significantly different from the timber material of the same species. This has been observed through Fourier transform infra-red spectroscopy (FTIR) and Thermo-gravimetric analyser (TGA). We have estimated kinetic parameters of forest litter fuels i.e. bark, twigs, leaves of pine and eucalyptus and grass in the inert atmosphere of nitrogen. The results are discussed in Wadhwani et al. [18] and Wadhwani et al. [19]. The observation shows a single step linear model is sufficient in predicting the mass loss rate of forest litter at TGA scale. The simulated work at bench-scale such as cone calorimeter is on going. The flammability of forest litter from pine, eucalyptus, and grass is being explored. Figure 18 shows two different type of combustion process occurring in Lucerne hay material in two different ignition scenario.

Auto-ignition scenario

Piloted ignition by firebrand

Figure 18: Ignition of Lucerne hay (a) smouldering combustion during auto-ignition scenario (b) flaming combustion during piloted ignition by firebrand at 30kW/m^2 radiant heat flux

Further work

An improved and validated Lagrangian particle sub-model serve as a stepping stone to develop a statistical model of firebrand transport from different forest canopy, ambient condition, etc. to be used in operational fire model such as Spark, Phoenix. The validation of thermal degradation model also supports the other fire propagation research discussed in this document.

MODELLING OF TRANSITION OF SURFACE FIRE TO CROWN FIRE

Crown fires are often supposed to originate from surface fires spreading either along the bark of the tree trunks or direct flame contact to low branches with leaves and needles. In a previous study, surface fire (grassfire) spread simulation was successfully conducted using WFDS. Previously, we also quantitatively studied a single burning Douglas fir tree experiment conducted at NIST. We found that the grid converged solution agreed well with the experimental result.

In this study, we have semi-quantitatively studied forest floor fire transitioning to a crown fire. A hypothetical forest of Douglas Fir trees sitting on a grassland, which can be thought of as a model of a plantation, is simulated. A sensitivity of the domain height, width and space downstream of the forest is carried out. Final results are obtained with a narrow simulation domain of 124 m long, 8 m wide and 25 m high, which is not sensitive to domain size variation. The domain set up and surface fire-crown interaction is shown in figure 19.

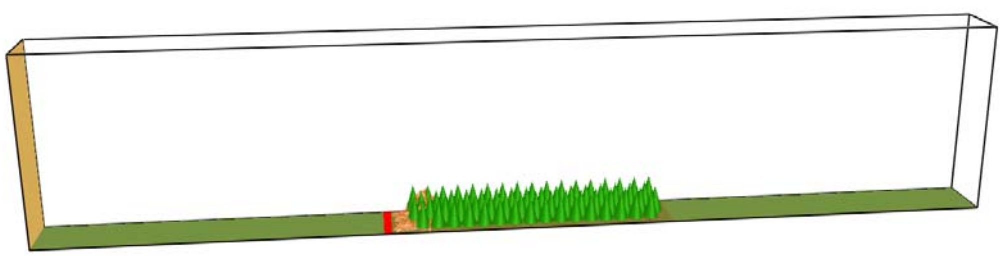
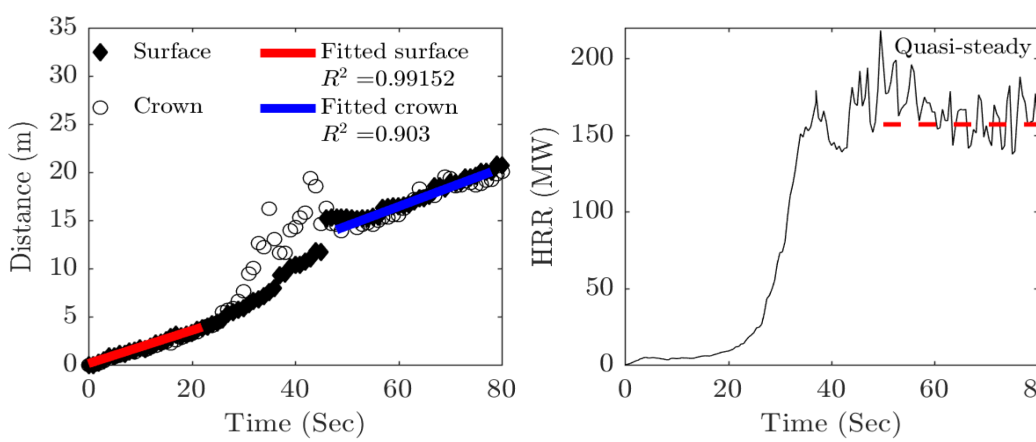


Figure 19: Graphical representation of surface fire-crown interaction simulation.

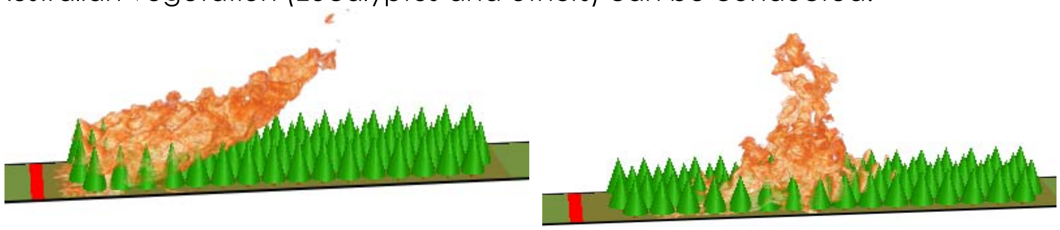


(a) Fire front location (b) HRR

Figure 20: Finding quasi-steady rate of spread of crown fire

In figure 20, fire front location and heat release rate (HRR) as a function of time are presented. A fire front is determined based on the HRR data. The definition of the instantaneous centreline flame front is the xz-location of the point at which 90% of the total HRR is obtained. In Figure 20(a) the red line is a least-squares regression fit to the surface fire behaviour and the blue line is a fit to the crown fire data. Surface fire and transition to crown propagation is clearly visible between 30 to 50 sec. Deciding when the fire has completely reached a crown phase is ambiguous. HRR vs time data in Figure 20(b) shows that roughly 53 sec after the ignition of line fire a quasi-steady period emerges which corresponds well with Figure 20(a).

Visual representation of flames impacting on the crown and during quasi-steady period is shown in figure 21. From the isosurfaces of HRR at 200 kW/m^3 it appears as if the surface fire transitions up to the crown, then transitions back down again at some later time. The surface fire, as measured by large HRR at the surface, appears to propagate fairly uniformly. The isosurfaces of heat release rate associated with surface burning are probably difficult to visually distinguish from the isosurfaces of heat release rate associated with crown material burning. Because the surface fire continues underneath the crown fire, this is a supported crown fire. That is, the surface fire puts energy into the crowns to sustain the burning of the crown material [20]. Overall many features are qualitatively in agreement with other crown fire studies (eg experiments of [21]). We can therefore be confident that crown fire simulations are possible with the physics-based model and the rate of spread of crown fire could be determined. Future work will consider changing the properties of fuels so that simulation of native Australian vegetation (Eucalyptus and others) can be conducted.



(a) Flame upon impacting the crown (b) Quasi-steady flame propagation

Figure 21: Visual representation flame propagation

We stress that these simulation results are for a very particular set of parameters and the numerical results may be sensitive to thermos-physical and combustion parameters which were not varied in this study. Obviously further studies and validation against observed crown fires are required before any operational correlations can be constructed. Such a validation study would need to compare simulations of extreme fire scenarios to field observations of wildland fires. Eventually, it is hoped that this kind of work may lead to the determination of the rate of spread for crown fire as a function of fuel and atmospheric characteristics as well as a threshold condition for the surface to crown fire transition. Threshold conditions for crown fires are difficult to identify because crown fires basically cannot be studied in controlled experimental conditions. Numerically, however, it is possible to discover threshold values of wind speed, fuel moisture content, forest type (their configuration and fire properties) which leads to a sustained crown fire. It is to be noted that in empirical models atmospheric characteristics such as temperature, humidity and drought factor serve as proxies for fuel moisture content.

REDUCING SPIN-UP TIME TO OBTAIN INITIAL AND BOUNDARY CONDITIONS FOR PHYSICS-BASED FIRE MODELLING

The wind is the most influential environmental variable that effects the wildland fire behaviour as explained by [13, 22]. The rate at which fire spread depends strongly on the wind speed. The wind profiles are needed for fire simulation over open grasslands, forests as well as fire over slopes like on mountains and valleys. The evolution and dynamics of the wildland fires are very sensitive to the details of the terrain properties over which they travel. These details may range from leaves measured on a scale of few centimetres, branches measured on a scale of few meters to hills and mountains measured on a scale of kilometres. Prevailing wind conditions serve as initial and boundary conditions for fire propagation modelling. In physics-based modelling, several days of simulation needs to be run to obtain prevailing wind conditions and this is known as the spin-up time.

In this sub-project, we are trying to reduce the spin-up time for FDS/WFDS and initialise the wind fields for faster and efficient fire predictions. We are attempting this using two different strategies: (a) Windninja [5] and (b) Monin-Obukhov similarity theory (MOST) [23].

Windninja

Windninja is a computer program which computes spatially varying windfields over complex terrain. The outputs of Windninja can be used as the initial and boundary conditions for various fire models. Currently, we are working towards mapping the terrain modified wind fields generated by Windninja to FDS using the penalization method. We adopt an immersed boundary method, called the volume penalisation method [24, 25] to enforce the desired mean flow. The volume penalisation method inserts an artificial forcing term in the Navier-Stokes equations to force the velocities to the desired value. The Navier-Stokes equations, with the penalisation term, are then closed with, typically periodic, boundary conditions. That is, the numerical boundary conditions at the edge of the domain are different to the specified velocity boundary conditions that we wish to enforce using the penalisation method. The wind field produced by this reduced model is terrain modified and can be used as initial wind field for the simulations in FDS. This will considerably reduce the simulation time for the fire simulations.

Application of Monin-Obukhov similarity theory

The latest version of FDS 6.6.0 incorporated the MOST which can provide initial wind and temperature field taking into the consideration of the atmospheric stabilities. The MOST [23] depicts that horizontally homogeneous atmospheric surface layer is governed by only four parameters: z, $u*$, $\frac{g}{T0}$ and $Q0$, where z is the vertical distance from the ground, $u*$ is the surface friction velocity, $\frac{g}{T0}$ is the buoyancy parameter and $Q0$ depicts the surface temperature flux. This theory describes that the nondimensionalized mean temperature and mean wind-flow in the surface layer under non-neutral atmospheric conditions is a function of the dimensionless height parameter $z = L$, where L is known as Monin-Obukhov scale length, given by:

$$L = \frac{\{-u_*^3\}}{\left\{\kappa\left(\frac{g}{T_0}\right)Q_0\right\}}$$

where κ is the von Karman constant which is constant and has the value of 0.41. The wind speed profile $u(z)$ and the potential temperature $T(z)$ varies with height z, according to the following equations as given by :

$$u(z) = \frac{u_*}{\kappa}\left[ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)\right]$$

$$T(z) = T_0 + \frac{T_*}{\kappa}\left[ln\left(\frac{z}{z_0}\right) - \psi_h\left(\frac{z}{L}\right)\right]$$

for $z >> z0$, where $z0$ is the aerodynamic roughness, $T*$ is the scaling potential temperature, $T0$ is the ground level potential temperature and ψ is some universal constant.

The Obukhov length, L, characterizes the thermal stability of the atmosphere. When the value of L is negative, the atmosphere is unstable. For atmosphere to be stable, the value of L becomes positive. The atmosphere is said to be stable when the atmospheric temperature is more than the surface temperature and the surface acts as a heat sink, usually during the night time. The atmosphere is said to be unstable when the opposite thing happens, especially during the daytime. The stable or near-stable atmospheric condition is achieved when the temperature of both the air and surface are same.

LITERATURE REVIEW ON AS3959

Australian standard 3959 [4] was developed to prescribe necessary structural changes for the structures located at bushfire prone areas (BPA). The AS 3959 aims at improving the resilience of buildings against the bushfire attack (radiant heat, direct flame contact, burning ember, or a combination of these three factors) to mitigate the risk of bushfire through better adaptability of structures situated in the WUI. In this review, we are attempting to identify the limitations of AS3959 which can be investigated and improved upon by using a Physics-based model.

The bushfire attacks are broadly classified in four main categories (Figure 1):

(1) direct flame contact: The impact of fire front direct impinging on the structure. In Figure 1, a fire front impacts on the structure causing the ignition of the structure
(2) radiant/heat flux attack: is a measure fire intensity or fire size which pre-heats the vegetation ahead of the fire front or the structure to auto-ignite or susceptible for ignition
(3) convective heat flux: similar to item (2), but is a result of heat transported via travelling hot gases. The importance of convective heat transfer as a fire propagation mechanism has been recently been investigated by Finney et al. [26].
(4) ember shower attack: the burning debris from trees blowing along the wind and ahead of the fire front impact on the structure like on the roof tile (shown in figure 1) and ignite the structure .

AS3959 mainly classifies the bushfire attack intensity dependent on different radiant heat attack and abstract ember attack. It suggests the apt design and construction of structure in BPA through a concept of bushfire attack level (BAL). The prescriptive calculation of BAL at a site is dependent mainly on four main features: (a) vegetation type, (b) fire danger index (FDI), (c) distance of the site from the classified vegetation, and (d) topographic slope on which vegetation is located. So far we have identified the following main limitations:

Limitations of FDI

The FDI/FFDI is used on region/site basis as a proxy to flame temperature (fireline intensity), flame width and flame height - all of which determine the radiant heat flux level on a structure. In the present context of the work, FFDI is assigned to Victoria as 100, New South Wales as 80. The current used MK5 FFDI system assign FFDI=100 as 'Catastrophic' fire danger level while FFDI=80 as 'Extreme' fire danger level. A set of tables are provided for various FDIs for various vegetation types for various distances to determine BAL value. There are several drawbacks in this AS3959 approach.

Fire behaviour is not necessarily self-similar with FDI. That is, a different combination of fuel, wind speed, and other parameters which yield FDI 100 may give very different fire behaviours. For example, grassfires have been characterised as wind-driven and buoyancy driven fires [27] and if the (G)FDI is 100 with light fuel and high winds a wind dominated fire may occur. However, if the fuel mass (W) is large and wind velocity (U) is small, then the fire will likely be buoyancy dominated. In a wind-driven fire, the flame is elongated and the flame angle (alpha) is small. In a buoyancy dominated fire the flame is nearly vertical. The difference in flame angle and structure will, therefore, affect the heat flux received by the structure. One can, therefore, ask what set of conditions at FDI 100 is the most dangerous for impact on structures.

Limitations of BAL model

To calculate the BAL, the flame temperature is considered 1090 K. In the Fort McMurray fire 2016 or in Kingslake fire of Black Saturday or in Haifa fire in 2016 the flame temperature reached ~1500 K [28]. Hence, AS3959's radiation model in certain situations and generally in mega-bushfire may severely under predict radiation heat flux load.

View factor

The other aspect that radiant heat flux depends upon is the view factor. The view factor accounts for the exposure of fire on the structure. The dynamic nature of fire front changes the structure of flame hence affecting the view factor. The view factor can change significantly due to different topography, i.e. if the fire is progressing down a slope to the structure would have higher view factor than a fire progressing up the slope to the structure. Obstruction between flame and structure like a dense canopy or building structure like water tank can also reduce the view factor.

Limitations of a single planer source

AS3959, in its classification, assumes a single planar source of fire front approaching to the structure up to a minimum distance of classified vegetation. The approach of curved fire front as well as multiple fire fronts at a site is not accounted for in AS3959. There are numerous bushfire instances in the Black Saturday fire, 2009 and the Haifa fire, 2016 in which fire arrived at a site from multiple planes. In the 2017 Iberian wildfires, Portugal, social media posts showed that many of the structure were exposed to multiple fire front showing a higher heat flux exposure on the structure. This situation plays a major role in the ignition of the material, while in a single plane source of fire the combustible material has an opportunity to cool with the convective current of wind which would not be possible if it is approached from multiple fronts.

Direct flame attack

While the effect of direct flame contact is discussed in AS3959, it is considered through estimating that the flame length is enough to make a contact with the structure. BAL-FZ classification which suggests that flame contact is equivalent to radiant heat flux exposure threshold of 40 kW/m^2. However, the building components, particularly those which have a high surface area to volume ratio can cool down convectively and would not auto-ignite due to only radiant heat flux. Moreover, the direct flame contact involves convective heat flux that would not permit cooling of the material. The presence of direct flame would facilitate in ignition by providing required ignition spark to the volatile gases evolving from the combustible material. The direct flame attack can also occur by the ignition of ornamental vegetation by firebrands. There are several photographic records of firebrands igniting the ornamental vegetation near the house providing a new source of direct flame attack.

Topographical slope

The topographic slope at which the classified vegetation is situated is used to determine the rate of spread accounting the behaviour of fire propagation at a slope. McArthur (REFERENCE leaflet 107) suggests that the rate of fire spread doubles for every 10° of positive slope [6]. The slope correction suggested in AS3959 is restricted for slope <20°. However, there is very little other evidence supporting this restriction. Sullivan et al. [29], studied the effect of negative slope on rate of fire spread correction and observed that the result of fire spread is under-predicted by a factor of 3 for slope of -20°. Sullivan et al. argued that the value of rate of spread for negative slope situation should never be less than 60% that of zero-slope condition.

Heterogeneous (patchy) vegetation

The grassland fire experimental studies by McArthur [6] and the empirical modellings developed from these studies predominantly included continuous or homogeneous fuels. However, there are discontinuity due to eaten out of grasses by cattle or dry/wet spaces. The rate of spread in such heterogeneous (patchy) fuel and the maximum distance between patches that a fire can spread across are not included in AS3959.

No quantification of firebrand attack in AS3959

Apart from the radiation model shortcoming, the current AS3959 lacks an important quantification of firebrand loading on houses or structure. In 'Catastrophic' or 'mega bushfire' conditions firebrands are present and can behave beyond the scientific norms like Black Saturday fire, 2009 where firebrand reached more than 20km ahead of the fire front. In the Canberra 2003 fire or 2017 Californian fire, firestorm or fire whirl were observed making firebrand reached significantly far from the source. The occurrence of fire storm also has an implication for asset protection zone (APZ) requirements. In Duffy (Canberra) houses were separated from the forest by at least 37m. This distance fits with a

BAL 29 classification and thus would have offered significant resistance to bushfire attack. However, that was not the case as 206 houses were destroyed [30].

Approach to Support AS3959

The effect of heterogeneous fuel, slope, atmospheric condition, and firebrand attack on the rate-of-spread of the fire and consequently the radiative heat and firebrand load on structures in the WUI lead to a number of open problems which may be addressed using physics-based modelling. We will also be able to assess the role of convective heat flux and model dynamic aspect of bushfire. It is to be noted that the dynamic behaviour of bushfire accounted to major damage at WUI as observed in various case studies [28].

A suite of simulations could be conducted to compare the simulated heat flux and flame impingement upon a structure with the predictions of radiative heat load in AS3959. The initial simulation would replicate, as close as possible, the fire scenario in AS3959. That is, a 100 m wide straight line fire in (for example) tussock moorland grassland at FDI 50. The driving wind speed and fuel load could be varied to determine if the different modes (wind-driven or buoyancy dominated) fire propagation effects the radiative heat load upon a structure. Additionally, the effect of slope and fuel patchiness upon the radiative and convective heat load may be more rigorously assessed using simulation data.

It is necessary to address the vaguely discussed impact of firebrand on structure in AS3959. The role of firebrand in fire front propagation and damage of houses are dependent of multiple parameters like type of vegetation, fuel loading, atmospheric conditions, etc. The accuracy of firebrand landing estimation through physics-based modelling is limited by imprecise knowledge of what quantity of firebrands is generated from a bushfire. Therefore it is essential that data on the number and physical characteristics of firebrands produced by vegetation be collected and use as input parameters for WFDS/FDS model.

A series of experimental studies have been conducted by various researchers to characterise firebrand generation and flux [31-33]. They characterised vegetation with field and remotely sensed data. To analyse for mass and size distribution, firebrands were collected from different locations in the forest. Fire spread and intensity was also characterised while monitoring meteorological conditions before and during the fire. They tried to relate firebrand flux to the local fire behaviour. In [33] it is shown that 0.82–1.36 pieces per square meter per sec were generated for fire intensities ranging between 7.35 ± 3.48 MW per meter to 12.59 ± 5.87 MW per meter. The particle distribution was also quantified. However, development of an idealised correlation of firebrand generation (in terms of particle number, size, shape and mass as function of fire intensities) is required to use them as input to WFDS/FDS.

Ideal laboratory experiments involving of quantification of firebrand in terms of number, size, shape and mass, and then investigation of firebrand landing and distribution has been successfully conducted by us [3]. The experimental landing and distribution result has been reasonably reproduced by WFDS. In this study, with appropriate input parameters, we will aim at reproduction of firebrand distributions for real life fire using a similar methodology to our previous study [17].

Upon this, we will endeavour to map firebrand and heat flux on structures. It will be used to develop a strategy to include firebrand flux in AS3959. Eventually a risk assessment methodology can be developed against heat and firebrand flux.

DIRECT NUMERICAL SIMULATION OF A TURBULENT LINE PLUME IN A CONFINED REGION

The filling-box model of Baines and Turner [34] of a plume in an enclosed environment is used to understand many important flows, from confined fires to building ventilation. This flow is characterised by a two-way interaction between the plume and its turbulent environment: the behaviour of the plume depends on its environment and conversely the plume modifies its environment. Despite being the basis of predictive models, the filling-box model of this two-way interaction between the plume and its turbulent environment is not well understood.

In this project, we aim to understand this flow through direct numerical simulations (DNS), which has never been attempted for this flow. DNS, which resolves all scales of turbulent motion, will enable us to examine the flow with unprecedented detail. The simulation data will then enable us to test the various assumptions that underlie the filling-box model. This project is timely in light of the recent breakthrough Finney et al. [26] that identifies buoyant convection (as opposed to radiation) in turbulent environments as the critical (limiting) mechanism in the spread of bushfires.

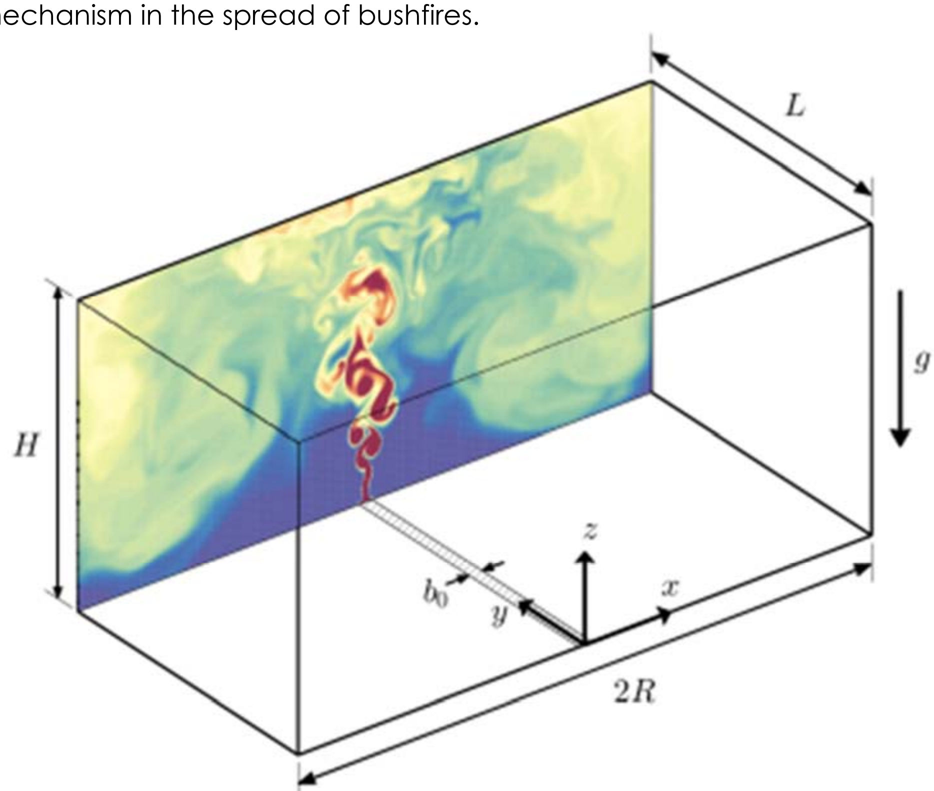


Figure 21: Schematic of a line plume in a confined region. The contours show the instantaneous temperature.

DNS of turbulent line plumes in confined region with adiabatic side, top and bottom walls for aspect ratio, H/R = 1, where H and R are the height and half width of the box, respectively (Figure 21) have been conducted. The plume originates from a local line heat source of length, L, located at the centre of the bottom wall (z/H = 0) and it rises until it hits the top wall (z/H = 1) and spreads laterally to produce a buoyant fluid layer. Since the region is confined, the continuous supply of buoyant fluid forces this layer downwards. After this layer reaches the bottom wall, the flow is said to be the asymptotic state (Baines and Turner [34]). In the present study, two Reynolds numbers, 3840 and 7680, are selected for plume lengths, L/H = 1, 2 and 4, where the Reynolds number of the plume is based on H and the buoyant velocity scale, $F_0^{\frac{1}{3}}$, where F_0 is buoyancy flux per unit length. The current simulations are validated against the analytical model presented by Baines and Turner [34]. The simulations exhibit a slow flapping motion of the confined line plume in the asymptotic state, which precludes a straight forward comparison with the analytical model of Baines and Turners. For the purpose of comparing with the analytical model, we have adapted a shifting method introduced by Hubner [35]. The shifted mean buoyancy profile shows improved agreement with the analytical model.

THE PROJECT - EVENTS

CONTINUING WORKING RELATIONSHIPS WITH RESEARCHERS IN FRANCE

France is subject to bushfires that are often in the vicinity in built infrastructure. This has given rise to the establishments a number of research groups that work on physics-based modelling of fires. During Prof Graham Thorpe 2014 visit, a collaboration was forged with Aix-Marseille University. As continuation Prof Morvan delivered a series of seminars to members of the project team at Victoria University in 2016 and a PhD student of him spent three-months with us in 2017. The PhD student was studying the space needed downstream of a canopy to recover an atmospheric wind profile using their physics-based model in FIRESTAR.

EFFECTIVE ENGAGEMENT

VIII International conference on Forest Fire Research

An extended abstract was accepted for the International Conference on Forest Fire Research to be held in Portugal in November 2018. The presentation will be: 'Simulations of surface fire propagating under a canopy: flame angle and intermittency', Dr. Sutherland, J. Philip, A. Ooi, and K. Moinuddin. We will be presenting results of simulations of a wind-driven surface fire entering, propagating through, and leaving a region of aerodynamic drag. The study is motivated by the need to understand how fires entering forested regions adjust to the lower wind speed inside the forest. We will discuss the transitions in flame angle that occur as the fire propagates under the forest. For lower driving wind speeds the rate-of-spread of the fire is largely unaffected by the canopy, however, for the higher driving wind speeds the fire appears to transition from a wind-driven mode, characterised by a low flame angle to a buoyancy-driven mode, characterised by a nearly vertical flame.

CSIRO collaboration

Duncan Sutherland and Miguel Cruz of the CSIRO met in late March, 2018 and discussed the in-progress simulations of grass fires on slopes and in heterogeneous fuels. Miguel and the CSIRO have an extensive collection of videos of recent grass fires conducted over a range of wind speeds, fuel loads, and grass curing. Some fires are point ignition and other fires are a line ignition. An in-principle agreement was reached where the CSIRO would provide access to their data under license in return for acknowledgement or co-authorship and co-supervision on various projects. The agreement between VU and CSIRO has been formalised and a formal agreement with UNSW is also in progress.

End user discussion

We met our End-users team during RAF, 2017 at RMIT University in October, 2017. Sutherland presented on the results of the study of fire spread under a canopy.

In April 2018, Dr Sutherland met (via Skype) with Andrew Sturgess, Ben Twomey of QLD Fire Service, and Nick McCarthy of the University of Queensland to discuss potential wind reduction factor models. The meeting focused on a potential application of the model of Inoue [14] and the model of Harman and Finnigan (2007). The original model of Inoue is developed from a momentum-balance approach and is used to determine the sub-canopy wind profiles deep within a canopy. The model of Harman and Finnigan [10] extends the original model of Inoue to blend neatly with a roughness sub-layer and logarithmic layer above the canopy. The model was constructed from an established model of sub-canopy and above canopy wind profile due to Harman and Finnigan [10], and from a logarithmic open wind speed model. The models were matched at some assumed blending height, and the wind reduction factor was computed as the ratio of the two models. Contours of wind reduction factor as a function of sub-canopy height and leaf area index were presented.

MODSIM Conference, December 2017

Khalid Moinuddin presented a paper on rigorous modelling of surface fire to crown fire transition and the rate of spread of crown fire at the 22nd International Congress on Modelling and Simulation (MODSIM2017) in Hobart, Tasmania. The paper was shortlisted for publication in *Journal of Mathematics and Computers in Simulation* (Transactions of IMACS) on the theme of good modelling practice and an extended version has been submitted to the journal.

During the conference, a workshop was organised and many researchers from the BNHCRC's Bushfire Predictive Services cluster attended. Duncan Sutherland presented case studies of physics-based modelling of grassfire (a) in open-field with parametric variation of wind speed and grass-height and (b) propagating under a narrow-domain forest canopy. We also had discussions with Dr Mahesh Prakash's DATA61 team at CSIRO for a possible PhD student to develop parameterization for firebrand generation and transport model within the SPARK toolkit.

CURRENT TEAM MEMBERS

Research team

Assoc Prof Khalid Moinuddin, Victoria University
Dr Duncan Sutherland, UNSW, Canberra/ Victoria University
Dr Nazmul Khan, Victoria University
Prof Andrew Ooi, University of Melbourne
Dr Jimmy Philip, University of Melbourne
Prof Graham Thorpe, Victoria University
Prof Vasily Novozhilov, Victoria University

PhD students

Mr Rahul Wadhwani, Victoria University
Mrs Jasmine Innocent, Victoria University
Mr Niteesh George, University of Melbourne
Mr Gavin Maund, Victoria University (to commence soon)
Mr Saeed Mohsenian, (to commence soon)
Dr Mahfuz Sarwar, Victoria University (completed)
Dr Michael MacDonald, University of Melbourne (completed)

Masters by Research students

Ms Sesa Singha Roy, Victoria University

End users

Dr Simon Heemstra, Manager Community Planning, NSW Rural Fire Service
Dr Stuart Matthews, Senior Project Officer, NSW Rural Fire Service
Mr Andrew Stark, Deputy Chief Officer, Country Fire Service South Australia
Mr Lawrence McCoy, Senior Fire Behaviour Analyst, NSW Rural Fire Service
Mr Brad Davies, Senior Fire Behaviour Analyst, NSW Rural Fire Service
Mr Chris Wyborn, Senior Technical Officer, Fire Protection Association of Australia
Mr Mike Wouters, Senior Fire Ecologist, DENS, South Australia
Mr Jackson Parker, Senior Environmental Officer, DEFS, WA
Mr Paul Fletcher, Assistant Chief Fire Officer, SAMFS
Mr Andrew Sturgess, Fire behaviour analyst, Queensland Fire and Emergency Services
Mr Brian Levine, Fire Management Officer, Parks and Conservation Service, ACT
Mr Adam Leavesley, Fire Management Officer, Parks and Conservation Service, ACT

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APPENDIX A: LARGE EDDY SIMULATION OF CANOPY

In large eddy simulation (LES), the continuity and Navier-Stokes equations are spatially filtered to retain the dynamically important large-scale structures of the flow. In FDS, the filtering operation is implicit at the grid scale. The largest eddies contain the most energy and therefore make the largest contribution to momentum transport. The diffusive effect of the unresolved small scales on the resolved large scales is non-negligible. The constant Smagorinsky sub-grid-scale stress model (see, for example, Pope, [36]) is used in this work with the Smagorinsky constant set to $C = 0.1$ (Lesieur et al., [37]). The flow is maintained by a pressure gradient equal to 0.005 Pa/m. The fluid is assumed to be air with density $\rho = 1.225$ kg/m^3 and viscosity $\nu = 1.8 \times 10^{-5}$ m^{2}s^{-1}. Following Dupont et al. [38], the canopy of height h is modelled as an aerodynamic drag term of the form

$$F_{D,i,k}\,(x,z) = \rho c_D \chi(z,h,\mu,\sigma,A,B)\left(u_j u_j\right)^{1/2} u_j.$$

The value of the drag coefficient is taken to be $c_D = 0.25$ roughly consistent with the measurements of Amiro [15] and the study of Cassiani et al. [39]. The function $\chi(z,h,\mu,\sigma,A,B)$, defines the spatial location of the canopy. The canopy is assumed to have a constant height across the whole domain. Below the canopy height there is some LAD profile. In this study the LAD is assumed to be a Gaussian with some specified geometric mean μ and some variance σ. Physically, μ corresponds to the height at which the canopy is most dense; σ roughly measures the width of the leafiest part of the tree crowns.

$A + B$ is the maximum value of the LAD. B is a uniform contribution to LAD; it may be supposed that B represents the contribution to LAD from the tree trunks.

The LAD profile is:

$$\chi(z,h,\mu,\sigma,A,B) = \begin{cases} \mathrm{A}\exp\left(-\dfrac{(z-\mu)^2}{\sigma^2}\right) + B\,, & z \le h \\ 0\,, & z > h \end{cases},$$

The canopy model used here, $\chi(z,h,\mu,\sigma,A,B)$, is a five parameter model. We firstly assume that h is constant which reduces number of parameters to four. The Leaf Area Index (LAI), that is integral of LAD with respect to z over the canopy, is also fixed and for this report we consider only $LAI = 1$. This gives:

$$A = \frac{1 - Bh}{\displaystyle\int_0^h \exp\left(-\frac{(z-\mu)^2}{\sigma^2}\right) dz}.$$

Because A is positive, $B < \frac{1}{h}$, which physically means a canopy of LAI=1 cannot be constructed only from the 'trunks' of trees. We somewhat arbitrarily assumed that the trunks contribute approximately 10% of the LAD and therefore we fixed $\frac{B}{A} = 0.1$. This assumption was partly justified by fitting profiles to the measurements of Moon et al. Therefore the parameter space is $(LAI, \frac{A}{B}, \mu, \sigma)$ where $(LAI, \frac{A}{B})$ were fixed at some physically reasonable value and (μ, σ) were varied in this study. The effects of varying LAI and $\frac{B}{A}$ on the sub-canopy profile are the subjects of ongoing research.