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IMPROVEMENTS TO WIND FIELD GENERATION IN PHYSICS-BASED MODELS TO REDUCE SPIN-UP TIME AND TO ACCOUNT FOR TERRAIN, HEATED EARTH SURFACE

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Version	Release history	Date
1.0	Initial release of document	12/10/2017

Publisher:
Bushfire and Natural Hazards CRC

October 2018

Cover: (CC BY 3.0)

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ABSTRACT

Wind is one of the most important environmental variables that affects the wildland fire spread and intensity. Previously, fire analysts and managers have relied on local measurements and site-specific forecasts to determine winds influencing a fire. However, advances in computer hardware increased the availability of electronic topographical data, and advances in numerical methods for computing winds have led to the development of new tools capable of simulating wind flow. Several numerical models have been developed for fire prediction. The most widely used physics-based models come with a limitation of computational expenses, because of which these are not suitable for operational use. Our main intention of this study is to reduce this limitation of physics-based models so that fire forecasts can be made faster and easier. Modelling wind in physics-based models such as Fire Dynamics Simulator (FDS) has been shown to reproduce promising results, but at an inordinate cost. So, we will be using FDS as physics-based model to simulate fire. There are various methods available to generate wind field in FDS. The conventional methods of wind field generation are either an unperturbed inlet profile with a roughness-trip or the by embedding artificial turbulence at the inlet. The wind fields generated by these inlet conditions are compared with each other as well as to the wind field generated using a mean-forcing method for neutral atmospheric conditions. We have then used these inlet conditions to study the effects of fire spread in FDS. Currently, we are working on introducing a method in FDS known as penalization method, so that we can use real time wind data from other wind models, such as Windninja into FDS and perform fire simulations. Our hypothesis is that introduction of this method would reduce the simulation time of fire cases to some extent and moreover can include terrain effect in the wind profiles.

INTRODUCTION

Wildland fires occur very frequently in Australian weather conditions, especially during late spring to mid-autumn and impacts people living in the so-called wildland-urban interface. The frequency of these fires has amplified considerably due to further climate changes [1]. These wildland fires are a resultant of many environmental factors, among which wind speed is the predominant one [2]. Therefore, accurate prediction of wind is required for accurate fire behaviour prediction. Several types of models have been developed for predicting fire behaviour, among which physics-based models [3] has been shown to reproduce adequate Atmospheric boundary layer (ABL) flow over flat ground and tree canopies [4]. In the current study, we have used FDS, version 6.6.0, which is a physics based model of fire-driven fluid flow and the detailed description of this model can be found in [5, 6]. The physics-based wildland fire simulations are driven by the inlet and initial boundary conditions which models the ABL. A realistic representation of ABL is required to reproduce a correct manifestation of fire in terms of rate-of-spread, intensity and heat transfer. The inlet and initial conditions prescribed for the simulation preferably leads to a realistic flow over the fire-ground which does not non-physically develop in space and time. For example, Mell [7] used a 1/7-power-law model at the inlet of their simulations. Due to initial perturbations in the simulation, a fully turbulent flow profile will develop in time and space as the simulation progresses. The spatial and temporal development of wind flow comes with the cost of computational intensiveness to reach a steady state profile prior to the start of the fire. Development of techniques for imposing inlet and initial conditions for flow simulations has been a topic of interest in the field of fluid dynamics [8]. Wind data from some other reduced wind models like Windninja can be used as inlet and initial condition for starting fire simulations in FDS. Windninja is a simple diagnostic wind model developed and maintained by the USFS Missoula Fire Sciences Laboratory [9]. It applies the required physics (conservation of mass and momentum or conservation of mass alone) to account for terrain effects on initial flow field obtained from point measurement or a coarse scale weather model. It has much lower computational requirements. Furthermore, this wind model is capable of simulating terrain modified wind at much lesser than 50-m scales, which would significantly benefit fire management. This property of Windninja can be utilized well in our current research paradigm. There are two solvers in Windninja: the conservation of mass solver and the conservation of mass and momentum solver. The conservation of mass solver is the simple and fast-running solver and can generate wind fields in seconds. Therefore, we will be using this solver for our current research. All the technical details of these solvers can be found in [9-11].

MODELLING WIND USING WINDNINJA

Windninja is a computer program that computes spatially varying wind fields. This tool is specifically designed for simulating the terrain effects on the wind flow. This model requires a number of user inputs. These details can be found in the tutorials available with the software. We have run a sample simulation to show the results as obtained from Windninja. We have run the tool for flat terrain type for obtaining the reduced wind. The modelling domain considered is an area of 1.17 km by 1.17km with latitude and longitude of 35^0 45' South and 146^0 6' East near the northern boundary of Melbourne, Australia. We have considered an average speed of 10 m/s as domain average input speed. On running Windninja with required parameters, we get the simulated reduced 3D wind data. The simulation was completed in 4.52 seconds. The 3D wind data obtained is shown in Figure 1(a) and 1(b).

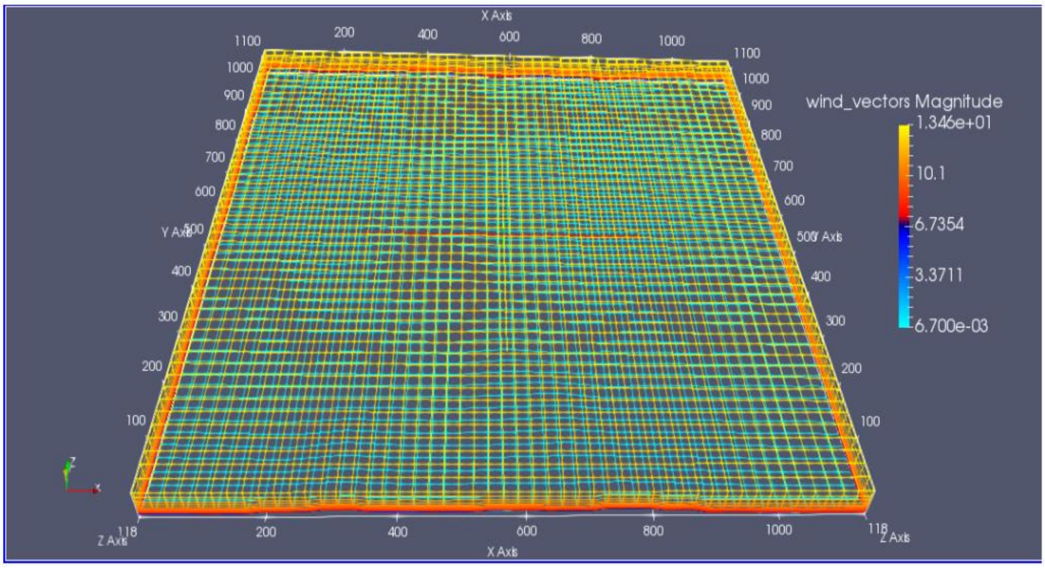

Figure 1(a): The 3D wind field grid representation of Windninja simulation

The simulated wind data provides us with vertically stretched grids. This means, the vertical dimensions of the cells increase as we move higher above the ground. It is due to an idea to capture higher velocity gradient in the ABL near the ground. Since the domain considered is a flat land with minimum terrain perturbation, the wind velocity at a certain height remains almost constant. The wind velocity increases with increase in height vertically until it reaches the maximum domain height where there is a free flow of air with maximum wind speed. The horizontal resolution considered in this scenario is 23 meters. For the current scenario, there is 20 layers of cells generated. The average wind profile obtained by averaging the output wind in each vertical layer with respect to each vertical layer height is found to be logarithmic in nature. This corresponds that a steady state ABL is obtained after the simulation is run in Windninja. The average velocity profile produced from Windninja is shown in Figure (2) in comparison with the theoretical power-law. A good similarity between two velocity profiles is observed which gives us confidence in Windninja. We can be confident to use similar type of data from Windninja as initial and inlet conditions to carry out the fire simulations and test using our physics-based model.

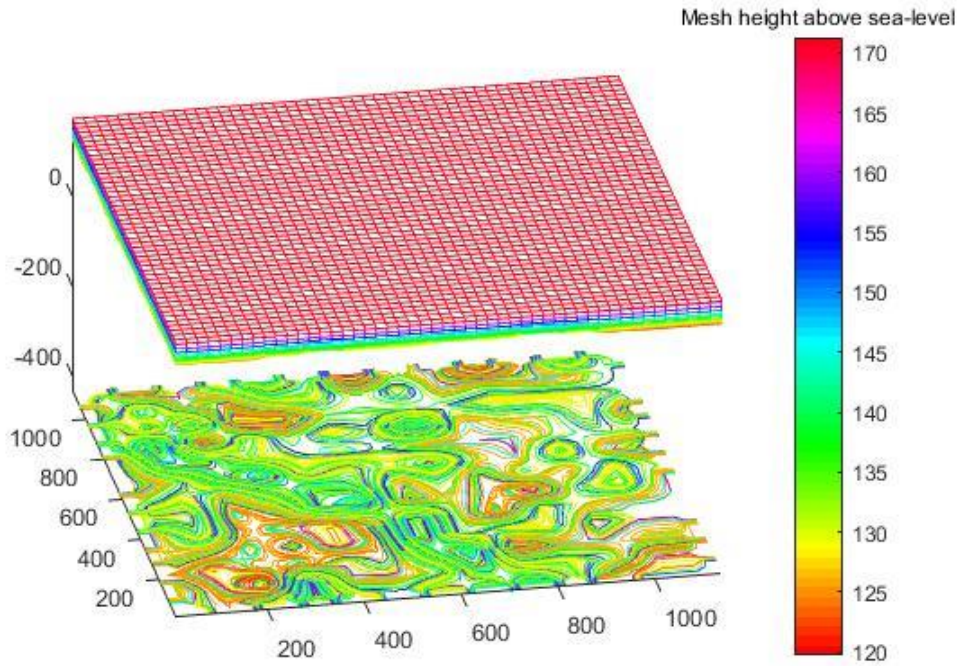

Figure 1(b): The 3D wind field grid representation of Windninja simulation with contour plot of the terrain

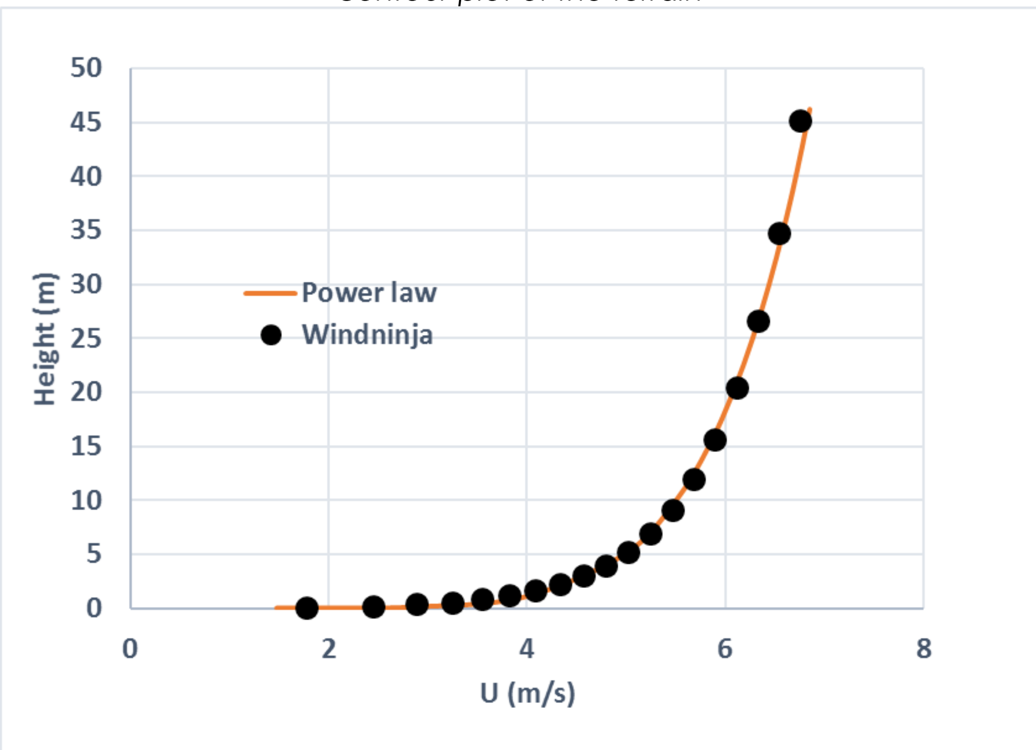

Figure 2: The average wind profiles obtained from Windninja and theoretical power-law

We are currently working towards introducing a new method called penalization method in FDS by code modification so that the terrain modified wind generated by reduced models like Windninja can be used as initial and inlet conditions to start fire simulations in FDS and subsequently reduce the computational intensiveness.

PENALIZATION METHOD

We assume that the initial mean flows for our fire simulation can be generated easily using a mass-conservation terrain perturbed model such as Windninja [9] over a large domain in fraction of seconds. The wind-fields generated by this method can be downscaled by interpolation to give inlet and initial conditions for the fire simulations that we intend to do in the desired domain. To do so, we adopt an immersed boundary method known as the volume penalization method [12, 13] and 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 term numerical boundary conditions will be used to denote the actual boundary conditions at the edge of the domain which close the PDE system. The term physical boundary conditions will be used to denote the desired velocities enforced by the penalisation method. The LES equations are given by Equation (1):

$$\frac{\partial u_i}{\partial t} + u_j\left(\frac{\partial u_i}{\partial y_j} - \frac{\partial u_j}{\partial x_i}\right) = \frac{1}{\rho}\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} + F_i \quad (1)$$

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (2)$$

where u_i is the resolved part of the velocity, ρ is the fluid density, p is (the modified) pressure, and τ_{ij} is the deviatoric part of the stress tensor. The forcing term F_i is the sum of all possible sources of force terms, for example the drag of tree canopies, the drag of fuel beds, or the Coriolis force may be included in F_i. In particular, F_i includes the penalisation term:

$$F_{p,i} = \frac{1}{\eta}\chi(x,y,z)\left(u_i - u_{i,b}\right) \quad (3)$$

where η is the penalisation parameter, taken to be small ($\mathcal{O}(10^{-4})$ at most), $u_{i,b}$ are the boundary values of the i^{th} velocity component, and $\chi(x,y,z)$ is a mask function which specifies the domain boundaries. We consider only rectangular domains with the bottom left-hand coordinate located at (0, 0, 0) and the top right hand coordinate located at $(L_x, L_y, L_z)$and the mask function will be taken to be of the following form:

$$\chi = \begin{cases} 1\,, x \le \delta_x\,, y \le \delta_y\,, x \ge L_x - \delta_x\,, y \ge L_y - \delta_y\,, \forall z \\ 1\,, z \ge L_z - \delta_z\,, \forall x, y \\ 0\,,\text{otherwise} \end{cases} \quad (4)$$

where $\delta_{x,y,z}$ are thicknesses of the penalty region which serve to allow the flow to relax from the physical boundary conditions to the numerical boundary. In practice, the step function is undesirable and the mask function is smoothed by using a moving average filter in the x- and y-directions. The minimum and maximum values of the penalisation filter are kept at zero and one respectively.

The no-slip boundary condition at the ground is applied in the usual manner using wall functions. Similar approach is used for including the precursor wind simulation from downscaled models line Windninja and set as inlet and initial condition for the intended fire simulations. This section is still under progress and we look forward in reducing the domain size and reduce the computational effort significantly conserving all the properties for fire simulations using this approach.

MONIN-OBUKHOV SIMILARITY THEORY (MOST)

Recently, FDS has introduced new atmospheric boundary layer model based on the Monin-Obhukhov similarity theory. According to this theory the wind profile, u, and potential temperature, θ, vary with height, z, by the following equations:

$$u(z) = \frac{u_*}{K}\left[ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)\right] \quad (5)$$

$$\theta(z) = \theta_0 + \frac{\theta_*}{K}\left[ln\left(\frac{z}{z_0}\right) - \psi_h\left(\frac{z}{L}\right)\right] \quad (6)$$

Where u_* is the friction velocity, K=0.41 is the Von Karman constant, z_0 is the aerodynamic roughness, θ_* is the scalling potential temperature, θ_0 is the ground level potential temperature, *L* is the Obukhov length scale, ψ is function of z and *L* that can be determined on the basis of similarities function as proposed by Dyer [14].

MOST describes the non-dimensional mean temperature and mean wind-flow in the surface layer under non-neutral atmospheric conditions is a function of the dimensionless height parameter at *z*=*L*. The Obukhov length, *L*, characterises 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. Accordingly, a neutrally stratified atmosphere will have an infinite Obukhov length. 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 day time. The stable or near-stable atmospheric condition is achieved when the temperature of both the air and surface are same. The atmospheric stability based on the stability parameter z/*L* as given by [6]. Unstable atmospheres are strongly affected by the buoyancy-generated turbulence, resulting in enhanced mixing. Conversely, highly stable atmospheric conditions suppress turbulent mixing.

In this study, we used only mean-forcing technique for the stable cases. Future work will be done by applying MOST theory for the unstable cases. However, one of the major drawbacks of MOST similarity theory is that this it is valid for horizontally, homogeneous and quasi-stationary conditions [15]. This implies that MOST similarity theory cannot be applied to various terrain types like slopes, patchy land, variation in surface roughness, etc. In this context, Windninja has the advantage as the wind obtained is terrain modified spatial data, which is more realistic. Hence, using terrain modified Windninja data to initialize the wind across the domain would be a better choice for different terrain types.

COMPARATIVE STUDY WITH DIFFERENT INLET PARAMETERS

We have subdivided this component of the study into two parts. In the first part, we will deal with the methods of wind generation. The wind can be developed either by introducing an unperturbed log-law or power-law inlet profile with a roughness trip or by superimposing eddies at the inlet with the log law or power-law wind profile. Wind field can also be generated by using a 'mean-forcing' method following usual log-law profile. This study is limited to neutral atmospheric conditions only. The second part of this study will deal with the fire behaviour. Fire simulations will be carried out using these inlet conditions and the rate of fire spread and heat-release-rate will be compared. We will also see the behaviour of fire when the fire is set in a mean-forced and non-steady ABL condition.

We tested the effectiveness of our boundary condition implementation through simulations in channel-flow configuration. The reference simulation used in this study is the wind field generation using the 'mean-forcing' method. In this method, FDS adds a mean-forcing term to the momentum equation to 'nudge' [6] the flow in the direction of specified wind velocity. In this case we need to provide any specific inlet conditions, as log-law is used by default for wind generation. The log-law can be given by Equation (7):

$$u(z) = u_*/\kappa[lnz/z_0] \qquad (7)$$

where $u(z)$is the wind velocity at height z, $u_{(*)}$ is the friction velocity, κ is the $Von\ Karmán'$ constant which is taken to be 0.41, $z_0$is the aerodynamic roughness length and z is the domain height.

The second wind field generation approach deals with the most commonly used method of wind generation; namely allowing the wind to develop naturally with the application of a roughness trip over the surface with a power-law profile enforced at the inlet. In this case, the wind develops over time and space and acquires turbulence eventually and finally reaches to a steady state condition. It takes a reasonable amount of time for the flow to develop a constant and steady ABL. To speed up the process, the Synthetic Eddy Method (SEM), which was originally developed by Jarrin *et al.* [8], can be used in FDS, which accelerates the development of a uniform boundary faster than other methods such as physical trip. This comprises our third method of wind field generation, which is based on log-law method. In this method eddies are injected into the inlet at random positions and advect with the inlet log-law velocity inflow which subsequently gets rescaled to match the desired turbulent characteristics. FDS uses the log-law as presented by [9]. The length, velocity scales and number of eddies are the parameters that the user supplies. Typically the velocity and the length scales of the eddies should be chosen is a way so that some turbulent statistics, usually Reynold's stresses, are reproduced. Jarrin *et al. [16]* say that the total number of eddies can be calculated using Equation (8).

$$N = max(V_B/\sigma^3) \qquad (8)$$

where (σ) is the size of eddies, $V_{(B)}$ is the box volume of the inlet where the eddies are embedded. As discussed in [17], the number of eddies N should be large enough to ensure the Gaussian behaviour of the fluctuating component in each direction. In this study, N is set to 200.

FDS simulates the fire by considering various processes which include Large-eddy simulation for fluid momentum, Mixing-controlled chemistry for combustion and heat transfer by conduction, convection and radiation. LES is a turbulence model which models the effects of small-scale turbulence on large eddies. A detailed discussion about turbulent flows and LES has been given by [18]. FDS uses a mixing controlled combustion model which involves one gaseous fuel where transport equations for only the lumped species, i.e. fuel and products (such as $O_2, CO_2, H_2O, N_2, CO$and soot), are solved (the lumped species air is the default background). In the mixing-controlled method, single fuel species that are composed primarily of C, H, O, and N reacts with oxygen in one mixing controlled step to form H_2O, CO_2, soot and CO. The reaction of fuel and oxygen is considered infinitely fast. Further details about this model can be found in [5]. Thermal degradation of solid fuel to gaseous fuel is modelled with a linear model following [17]. Radiation is accounted for by solving the radiation transfer equation with a discrete ordinates method. Convective heat transfer is modelled using a series of empirical correlations. Conduction is negligible for grassland fuels. References [5] and [6] gives further details about these models. At some critical points in calculations, like the moment of ignition, the limitations in the models or long time steps can lead to large local reaction rates, which can lead to numerical instabilities. An upper bound on the local heat release rate per unit volume needs to be maintained in order to prevent this. Following the scaling analysis of pool fires by [17], FDS 6.2.0 uses an upper bound following Equation (9):

$$q''_{upper} = 200/\partial x + 2500(KW/m^3) \quad (9)$$

FDS 6.6.0 does not use a reaction rate threshold, instead expecting the computation to be sufficiently resolved to avoid such numerical instabilities. The resolution requirement is prohibitive for large-scale wildfire simulations. However, we introduce the threshold Equation (7) to be consistent with previous fire simulations [4] and to avoid restrictive grid resolution requirements. The fire simulations for the current paper has been conducted using this current edited version of FDS 6.6.0. There are two cases of fire simulations that have been performed for the current study. In the first case, the most widely used log-law inlet condition has been used, which is similar to the first wind simulation, and the fire is started after the upstream of the fire reaches a steady-state wind profile obtained from the wind simulations. The second fire simulation uses SEM introduced at the inlet, with conditions similar to the SEM wind simulation mentioned previously

MODEL SET UP

The size of the external domain is chosen such that it ensures to capture the largest relevant structures. The overall domain size for all the simulations is taken to be 130m X 40m X 80m. Inlet velocity of 4.7 m/s is given at a height of 10 m. The mean velocity of ~ 5.5 m/s at steady state is maintained at 2m for all the simulations. 40 m from the inlet in the longitudinal direction, the burnable grass plot (40mX40m) was placed so that there was another 50 m subdomain downstream of the non-burnable grass plot before reaching an open outlet. The spanwise of the flow stream is set to periodic boundary conditions. In case of the fire simulations, a line fire is ignited which covers the width of the domain (along y) as used by [19]. The simulation domain has been divided into multiple meshes with different grid sizes. To avoid any numerical instabilities, the aspect ratio is maintained not more than 2 for any grid cell. The sub-domain with burnable grass plot has 0.25 m grid resolution in all direction throughout the height of the domain. The fuel parameters used in the simulations were replicated as done by Moinuddin *et al.* [4]. Figure (3) represents a generalized domain used for all the simulations.

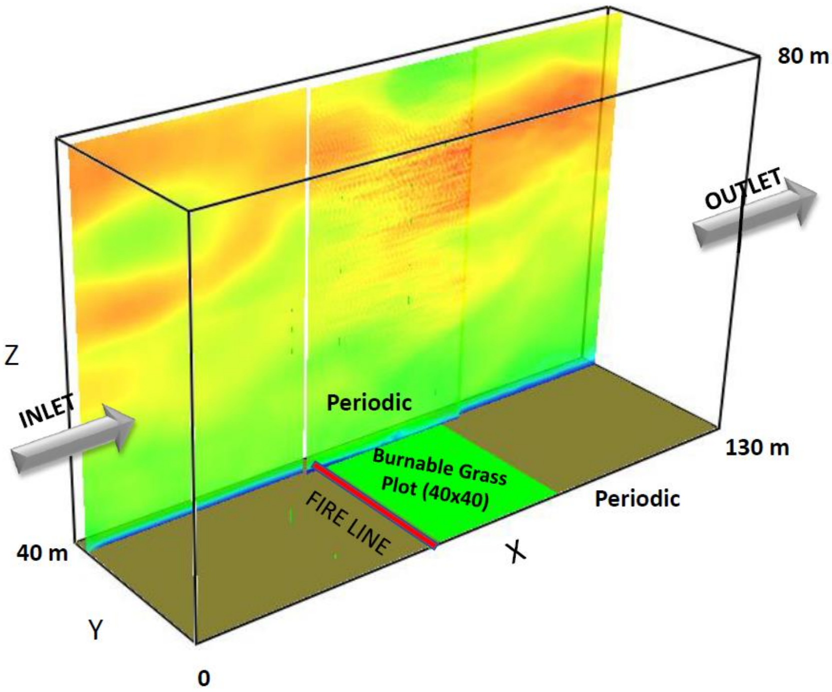

Figure 3: Domain of simulation showing the dimensions, fire plot, fire line and establishment of ABL.

All other relevant information regarding the wind simulations are given in Table 1 and that for fire simulations are given in Table 2. The simulations will be depicted using the case names given in the table hereafter.

Table 1: Wind Simulations

Case Name	Generation Method	Mean Profile	Turbulent profile
wind0	mean-forcing	Log-law	-
wind1	Roughness change-trip	1/7 Power law	-
wind2	Explicit log-law	Log-law	SEM

Table 2: Fire Simulations

Case Name	Generation Method	Mean Profile	Turbulent profile
fire0	mean-forcing	Log -law	-
fire1	Roughness change-trip	1/7 Power law	-
fire2	Explicit log-law	Log-law	SEM

RESULTS AND DISCUSSIONS

Several numerical parameters like inlet conditions, domain size, grid resolution and boundary layer development time are considered for a systematic approach. In our study, we are considering a small domain, and our results are strictly according to the parameters that we have used. The results may vary with different domain size, grid size, inlet conditions or wind velocities. The wind simulations wind0, wind1 and wind2 are run for 5000 seconds of simulation time to find out time for a stable ABL to get established.

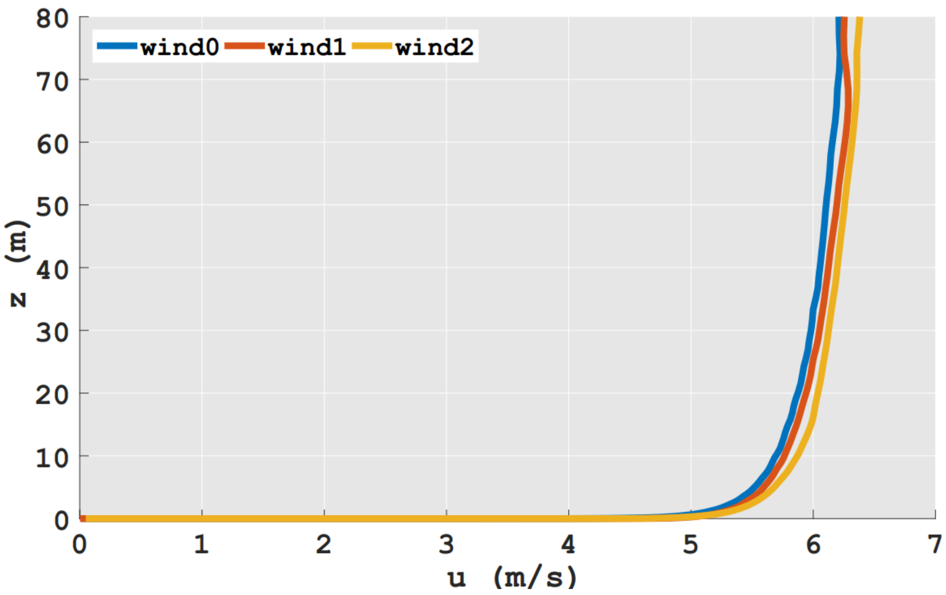

Figure 4: The mean velocity profile over the fire ground.

We observe that wind0 acquires a stable ABL in less than 100 seconds. In case of wind1, the ABL is established in approximately 1000-1200 seconds, whereas for wind2, it takes less than 1000 seconds. Figure (4) depicts the mean wind velocity profile on the fire-plot before the start of the fire. In case of wind1, the flow trips and become turbulent leading to a developing boundary layer. This results in more computational time for wind to get stabilized. On the other hand for wind2, since the turbulence is embedded in the form of synthetic eddies along with the inlet log-law profile, the flow develops faster. We observe that the mean profile pattern for wind0 agrees well with wind1 and wind2.

We have used the stabilized wind-field generated in wind0 simulation as the initial condition for the fire simulations fire0, fire1 and fire2 to reduce the time to reach the steady-state ABL over the fire ground and start the fire. We have started the fire for fire1and fire2 after 300 seconds in order to allow a steady-state ABL to develop prior to starting the fire. For fire0 case, we have located the burnable-grass plot near the inlet with minimum upstream of the fire, so that the wind is not allowed to get stabilized over space and started the fire after 100 seconds. The intention here is to not allow the steady-state ABL establishment prior to the start of the fire. We have done some adjustments over the axes so that fire0 can be plotted against fire1 and fire2 for comparison. The fire ignitor was put off after 11 seconds [7]. The fire took about ~ 25 seconds to burn the burnable grass plot completely for all the three cases. The fire propagated in a straight line across the domain as shown in Figure (5).

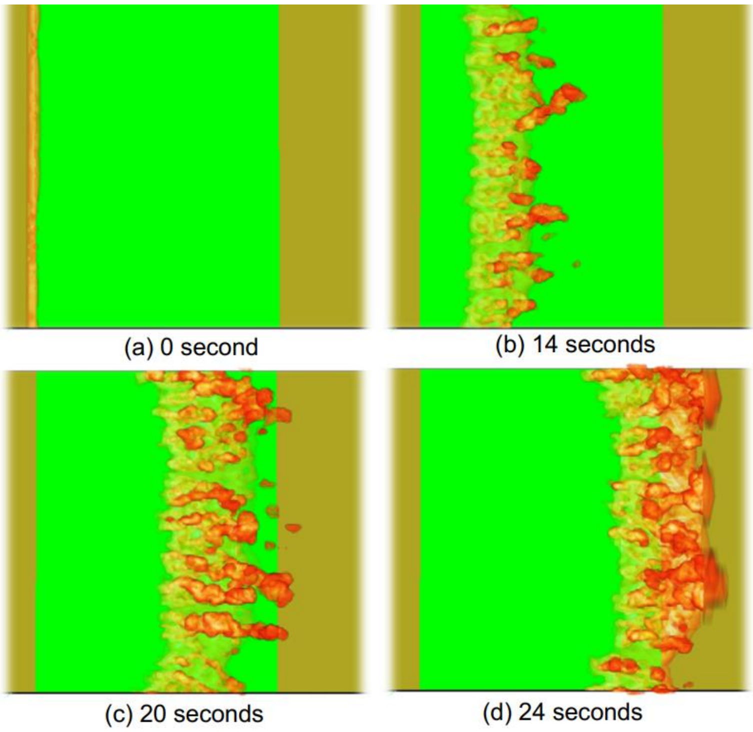

Figure 5: Fire propagation contour for fire1.

There are various parameters for comparing the simulated fire. In the current study, we have compared the Heat Release Rate (HRR) and the Rate of Spread (ROS) to predict the nature of fire propagation. HRR represents the height or intensity of fire whereas ROS depicts fire spread with respect to time.

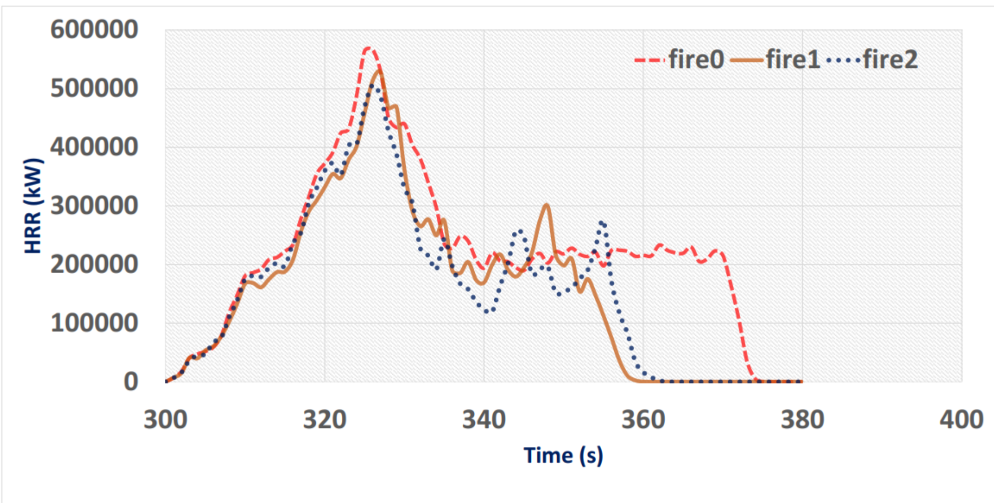

Figure 6: Heat Release Rate (HRR) as functions of time

Figure (6) depicts the HRR for all the three fire simulations to be similar. We observe that the HRR reaches maximum when the fire has consumed the whole burnable fuel over the fire plot (at about 25 seconds) and then drops down to zero as the plume exits the domain. For the fire simulations, the ROS has been calculated at the maximum value of the fire-front on the boundary where the temperature of the vegetation is above 400K-500K (the pyrolysis temperature). From Figure(7), we observe that towards the start of the fire, the ROS is maximum, then it reaches a quasi-steady of about 2m/s state while burning down the whole fire plot and the reaches zero when whole of the burnable fuel has been consumed.

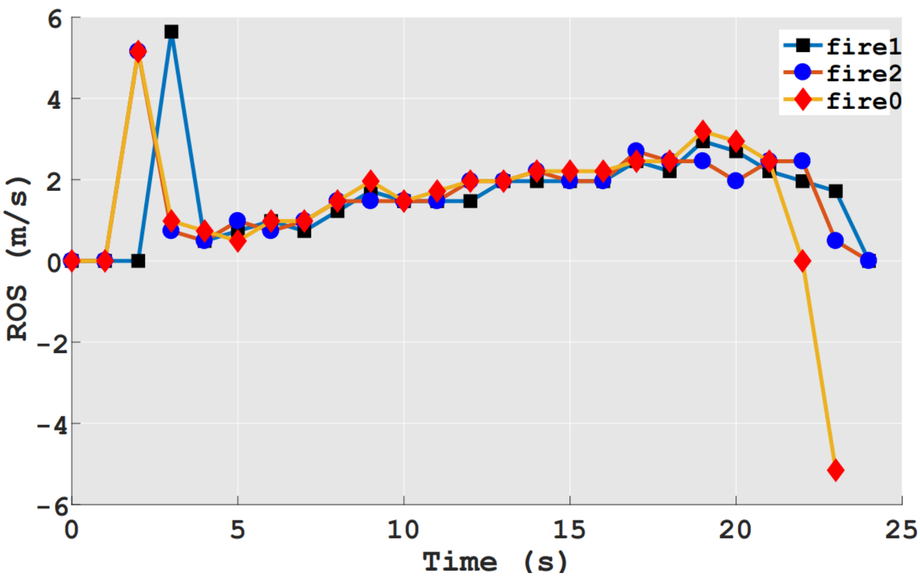

Figure 7: ROS vs time comparison over plot

The fire propagation and its characteristics agree well in both fire1 and fire2. As discussed previously that fire0 simulation was carried out in a naturally developed wind flow situation which means that the fire was started in an unsteady ABL condition. However, the fire propagation is not much affected by this. It can be argued that the domain considered in this study is comparatively smaller, and so the steady-state ABL is getting established in as short as ~ 20m in fire upstream. So, we see a fire propagation pattern similar to the other cases. The simulation results may vary considerably for larger burnable grass domain.

CONCLUSION

Bushfires form an intrinsic part of the Australian environment that results in loss of life and property. The damage caused by such fires increases the need to model them in order to predict and control. The wind simulations performed with existing methods of FDS in this study shows that the SEM and the roughness trip method for wind simulation produce similar steady-state wind profiles to that generated by the mean-forcing method. The mean-forcing method generates a steady-state profile faster than the SEM and roughness trip method and hence uses lesser computational time. The mean-forcing method and roughness-trip method also require fewer input parameters than the SEM. The HRR and ROS profiles shows very little difference between the three fire cases. Therefore, simplicity suggests just taking a 1/7th power-law and a very short upstream distance with a short spin up time is a simple approach which still recovers the RoS results of more complicated methods. The preliminary results obtained from Windninja verifies the fact that it can be used to generate initial wind field for starting fire simulation in FDS. Since Windninja takes just few seconds to generate terrain modified wind fields, the fire simulations in FDS using this as initial condition by using penalization method is expected to reduce the domain size as well as the computation time noteworthy. We are working towards implementing this and validating our hypothesis. In a nutshell, this work will help in carrying out faster simulations for predicting fire behaviours and will help in taking a step forward towards making physics-based models operational in the long run.

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