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Fire-spotting modelling and parametrisation for wild-land fires

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Abstract: This article describes a mathematical formulation for simulating the effects of firebrands on the propagation of the wild-land fires. Among the different approaches available in literature, this formulation is defined in a way to provide a versatile approach for application to operational wildfire models. Most of the operational wildfire models like WRF-SFIRE and ForeFire model only the evolution of the fire-line according to the definition of the rate of spread, fuel characterisation and the average fire properties and concurrent atmospheric conditions. But this information is not enough to simulate the effects of turbulence and fire-spotting. The formulation presented here can perform as a crucial addition: (1) on the physical aspect by including random fluctuations and (2) on the operational aspect by serving as a post processing application at each time step. The post-processing updates at each time step modify the fire-perimeter obtained from the operational model through a probability density function corresponding to the physical properties of the turbulence and fire-spotting behaviour. A lognormal distribution in convolution with a Gaussian distribution is utilised to emulate the landing distributions of the firebrands. The main aim of this study is to provide a physical parametrisation to the behaviour of the model with respect to the lognormal distribution. The sensitivity of the landing distribution of the firebrands corresponding to the changes in factors like wind speed, fire intensity, radius of firebrand is highlighted through simple and idealized test cases. The results presented in this study provide a tentative outlook towards both qualitative and quantitative assessment of the firebrand landing.

Keywords: *wild-land fire, fire-spotting, lognormal distribution*

1 INTRODUCTION

Fire-spotting is a important phenomenon associated with the wildfires. Spot fires occur when parts of the fuel such as barks and twigs from trees and shrubs or building material from urban surroundings get detached from the source and are transported by the convective plume away from the main source of fire. These burning embers cause new secondary ignition spots which can create potentially dangerous situations. Accounts of various historical fires mention the contribution of firebrands in the rampant propagation of the wildfire causing widespread destruction. The fire-fighting community recognises firebrands impact as a huge risk factor both in wild-land fires and wild-land urban-interface fires. To understand the phenomenology of fire-spotting and to mitigate the effects, different experimental and theoretical aspects have been explored by the researchers. Experimental approaches are useful in characterising the shape and size of the firebrands, but unfortunately with the localised set-up, a detailed study of the impact and the landing distribution is difficult. On the other hand, the fire-brand transport models try to formulate the physical processes and dynamics involved during the generation, lofting and propagation of the firebrands and provide a analysis of the maximum spotting distance and landing distribution involved. A better forecast of fire spread involves improving the deterministic fire spread by inclusion of different random phenomenon related to the fire spread. These well-performing models not only help the forest management to face fire propagation but also help the policy makers with the improved monitoring and protection.

The initial experimental combustion tests by Tarifa (1965) for the determination of firebrand lifetimes and flight trajectories and the conceptual formulations developed by Albini (1979,1981,1983) to provide a basic estimation of the potential fire-spotting distance, have contributed towards a paradigm shift in the development of the firebrand transport models. Woycheese et al. (1999) in a number of their works model the plume rise using the Baum-McCaffrey model (Baum and McCaffrey, 1989) and estimate the maximum propagation distance for firebrands in terms of the fire intensity, atmospheric wind and fuel characteristics. A numerical study by Sardoy et al. (2007) estimates the effect of atmospheric conditions, fire properties and fuel properties on the firebrand behaviour, while in an another numerical study (Sardoy et al. 2008) they provide a statistical estimate of the ground level distributions of the disk shaped firebrands. The results highlight that firebrands landing at short distances (up to 1000 m from source) follow a lognormal function. Among other models related to firebrand dispersal, Porterie et al. (2007) use small world network model to include the long range effect of firebrands. Wang (2011) also applies an analytical approach to model the mass and distribution of the firebrands generated during a wildfire. He suggests a Rayleigh function to depict the landing distributions and utilize the results by Tarifa (1965) to provide an estimation of the maximum landing distance. Koo et al. (2007) employ a physics based multiphase transport model for wildfires (FIRETEC) to study the firebrand transport. Even with the presence of multiple studies focusing on the detailed aspects of the firebrand transport, none of the them is able to provide a comprehensive yet versatile approach for application to operational models. To assess the threat of a potential spot fires, a quick and efficient approach is needed which can provide a basic feedback to the fire-fighters for a timely action. In past, only the approach developed by Albini (1979, 1981, 1983) has been included to operational wildfire models like FARSITE (Finney 1998) and BEHAVEPLUS (Andrew and Chase 1989) but this formulation does not include any functional model for the ignition probability. The new operational models like WRF-SFIRE (Mandel et al. 2011) and FOREFIRE (Filippi et al. 2009) are fast and allow coupling with the atmospheric models for a better representation of the initial and concurrent atmospheric conditions; but they provide the fire perimeter resulting only through the definition of the rate of spread (ROS) based on fuel characterisation and averaged fire properties. These models include various approximations and exclude out many variables which cannot be measured through conventional techniques, hence the aleatory and epistemic uncertainties associated with this simplified framework limit an exact representation of the phenomenon.

In this paper, a new statistical formulation within the physical parametrisation of the fire-spotting phenomenon is proposed to estimate the firebrand landing distribution in terms of the fire intensity, wind conditions and fuel characteristics. This formulation is independent of the method for the fire-line propagation and the definition of the ROS, and is versatile enough to be utilised with any of the existing operational wildfire models. In this proposed approach, the effect of the firebrands is encompassed within the fire-line by addition of a noise pertaining to the statistical description of the firebrands transport. Since, the ignition of the fuel by the firebrands involves heat exchange over a sufficient period of time, this model also includes a delay effect. The design of the formulation allows for a direct application to existing wildfire models as a probabilistic sub-model to include the transport of firebrands. In a number of their previous works (Pagnini and Mentrelli 2014, Kaur et al. 2016) the authors have highlighted the utilisation of the different aspects of the model in combination with the two different approaches of the fire-line propagation methods. Another potential application of this probabilistic sub-model, though not trivial, is towards data assimilation techniques. The statistical information of the firebrand landing profiles can be used to define a simple model error covariance matrix to be integrated with ensemble Kalman filter techniques.

The article is organised as follows: The section 2 discusses the model development, section 3 discusses the simulation set-up, section 4 provides a brief discussion about the results and conclusions are provided in section 5.

2 MODEL DEVELOPMENT

2.1 Mathematical Formulation

The proposed approach defines the motion of the fire-line as a sum of the drifting part and a fluctuating part. The fluctuating part is independent of the drifting part and represents a comprehensive description of the random effects in correspondence to the physical properties of the system. On the other hand, the drifting part is obtained from any of the existing wildfire propagation models. The formulation presented here can perform as a crucial addition to such operational models by serving as a post processing application at each time step. The post-processing update at each time step modifies the fire-perimeter obtained from the operational model through a fluctuating component which is independent of the drifting component.

A very short description of the mathematical formulation is provided here, for a detailed description the interested readers are referred to Pagnini and Mentrelli (2014) and Kaur et al. (2016).

Let $\mathbf{X}^{\omega}$ be the trajectory of each burning particle. The motion of the propagating fire-front is randomised with respect to the fire-line motion provided by an existing wildfire simulator through the addition of the probability density function (PDF) corresponding to the turbulent transport and fire-spotting. Let $\Omega \subseteq S$, where S is the domain of the simulation, be the burnt region provided by an existing wildfire simulator, and marked by an indicator function $I_{\Omega}(\mathbf{x},t)=1$ over the burnt region and zero otherwise. Using the Dirac Delta function, the time evolution of the position of each burning point can be randomised through

$$I_{\Omega}^{\omega} = \int_{\Omega(t)} \delta(\mathbf{x} - \mathbf{X}^{\omega}(t,\overline{\mathbf{x}}))d\overline{\mathbf{x}} . \tag{1}$$

An ensemble average of the motion of all active burning points is used to define an effective indicator $\phi_e(\mathbf{x},t)$ function :

$$\phi_e(\mathbf{x},t) = \int_S I_{\Omega}(\overline{\mathbf{x}},t) f(\mathbf{x};t|\overline{\mathbf{x}})d\overline{\mathbf{x}} \ , \tag{2}$$

where, $f(\mathbf{x};t|\overline{\mathbf{x}})$ is the PDF which accounts for the fluctuations of the random effects. Assuming the fire-spotting to be a downwind phenomena, the shape of the PDF is defined as follows:

$$f(\mathbf{x};t|\overline{\mathbf{x}}) = \begin{cases} \int_0^{\infty} G(\mathbf{x} - \overline{\mathbf{x}} - l\hat{\mathbf{n}}_u;t)q(l)dl, & \hat{\mathbf{n}} \cdot \hat{\mathbf{n}}_u \geq 0 \\ G(\mathbf{x} - \overline{\mathbf{x}};t), & \text{otherwise} \end{cases} . \tag{3}$$

The function $G(\mathbf{x} - \overline{\mathbf{x}};t)$ includes the parametrisation of the turbulent heat fluxes and the form is assumed to be isotropic bi-variate Gaussian. The effect of the turbulent heat fluxes over varying scales is parametrised through a turbulent diffusion coefficient D. A short description of the characterisation of D is provided in the next section. The selection of the shape of $q(l)$, the PDF for the downwind landing distribution of the firebrands has been studied though the numerical solution of the energy balance equations (Sardoy et al. 2008, Kortas et al. 2009). Experimental analysis of the firebrand flights have shown that in positive direction from the source, the frequency of the landing increases with distance to a maximum value and then gradually decays to zero (Hage 1961). In past, this pattern of the landing distribution has been described through the lognormal distribution (Sardoy et al. 2008), Rayleigh distribution (Wang 2011) and Weibull distribution (Kortas et al. 2009). it can be noted that the Weibull distribution is a generalisation of the Rayleigh distribution. In this article, the frequency profile of the landing distribution is assumed to follow a lognormal distribution with landing distance l :

$$q(l) = \frac{1}{\sqrt{2\pi}\sigma l} \exp\left(\frac{-(\ln l/\mu)^2}{2\sigma^2} \right) \quad , \tag{4}$$

where, μ is the ratio between the square of the mean of l and its standard deviation, while σ is the standard deviation of $\ln l/\mu$.
The ignition of the fuel under the effect of hot air and firebrands is not an instantaneous process, hence the landing of the firebrands is considered as an accumulative process over time, through another function $\psi(\mathbf{x},t)$ defined as,

$$\psi(\mathbf{x},t) = \int_0^t \phi_e(\mathbf{x},\eta)\frac{d\eta}{\tau} \quad , \tag{5}$$

where, the τ is the ignition delay.

2.2 Physical Parametrisation

The diffusion coefficient D gives a measure of the turbulent heat transfer generated by the fire. It can be parametrised in terms of the Nusselt number Nu. Nusselt number defines the ratio between the convective and conductive heat transfer in fluids and is defined as $Nu = (D+\chi)/\chi$, where χ is the thermal diffusivity of air at ambient temperature. Experimentally, Nusselt number has been related to Rayleigh number Ra as $Nu \approx 0.1 Ra^{1/3}$ and $Ra = \gamma \Delta T g h^3 / \nu\chi$. Where, γ is the thermal expansion coefficient, h is the dimension of the convective cell, ν is the kinematic viscosity and ΔT is the temperature difference between the top and the bottom of the convective cell. Assuming the size of the convective column to be 100 m and the temperature difference as 100 K, and using values of the constants from literature, the scale of the turbulent diffusion coefficient turns out to be approximately 10^4 times the thermal diffusivity of air at ambient temperature.
For a characterisation of the jump length of the firebrands, the 90th percentile of the lognormal distribution is used as a measure of the maximum landing distance travelled by the firebrands:

$$L = \mu \exp(z_p \sigma) \tag{6}$$

where, z_p is the value corresponding to the 90th percentile. From the experimental results of Tarifa (1965), and the numerical analysis of Wang (2011), the maximum landing distance of the firebrands can be approximated through the maximum loftable height $H_{\max}$, the mean wind U and the size of the firebrands r:

$$L = H_{\max} \left(\beta \tan \theta_f + U \left(\frac{3\rho_a C_d}{2\rho_f r g} \right)^{1/2} \right). \tag{7}$$

Here, θ_f represents the inclination angle of the convective column with the vertical plane. The variables ρ_a and ρ_f represent the density of the ambient air and wild-land fuels respectively, while C_d is the drag coefficient. This simplified landing distance models assumes that the ejection of the firebrands from the convective column is a random process affected by the turbulence in the environment around the fire. Once the firebrands are expelled from the column, they are steered by the constant horizontal wind velocity and they fly at their terminal velocity of fall.
In the framework developed here, the maximum loftable height of the firebrands is assumed to be equivalent to the maximum height of the convective column. An estimate of the maximum height attained by a convective column can made through a measure of the smoke injection height from wildfires. It is remarked that the physical processes governing the plume rise from stacks and wildfires are inherently different, hence, an analytical function for plume heights for wildfires provided by Sofiev et al. (2012) is utilised. This function provides an adaptation of the smoke injection heights for wildfires in terms of the fire radiative power FRP and the Brunt Väisälä Frequency N, and height of atmospheric boundary layer H_{abl}:

$$H_{\max} = \alpha H_{abl} + \beta \left(\frac{FRP}{P_{f0}} \right)^{\gamma} \exp\left(\frac{-\delta N_{FT}^2}{N_0^2} \right), \tag{8}$$

where, $\alpha = 0.24$ represents the part of the atmospheric boundary layer which passes freely, $\beta = 170 m$ denotes the weight of the fire intensity in building up the plume, $\gamma = 0.35$ describes the power law contribution of the FRP and $\delta = 0.6$ defines the dependence of the stability in free troposphere. $P_{f0} = 10^6 W$ is the reference fire power and $N_0^2 = 2.5 \times 10^{-4} s^{-2}$ is the reference Brunt Väisälä frequency.

Finally, for fire-spotting, the landing distributions can be assumed to be governed by the parameter μ and σ through the following functional dependence:

$$\mu \propto H_{\max} \tag{9}$$

$$\sigma \propto \ln\left(\frac{\rho_a U^2}{\rho_f r g}\right) \quad . \tag{10}$$

3.1 NUMERICAL SET-UP AND SOFTWARE

3.1 Simulation set-up

A few idealised test cases are selected for the numerical simulation to highlight the potential applicability of the formulation. It should be noted that the parametrisation is simplified and does not reproduce any realistic fire but the values of different parameters are chosen to represent a valid range. For all the simulations, a flat domain with a homogeneous coverage of a hypothetical fuel is selected. The simulations have been run using a basic set-up of wildfire model which involves the Level set method (LSM) as the moving interface method (Pagnini and Mentrelli, 2014). In this model, the ROS of the fire-line is estimated by the means of the Byram Formulation (Byram 1959, Alexander 1982)

$$V(x,t) = \frac{I(1+f_w)}{H\alpha\omega_0} \quad , \tag{11}$$

where, I is the fire intensity, $H = 22000 KJkg^{-1}$ is the fuel low heat of combustion, $\omega_0 = 2.243 Kgm^{-2}$ is the oven-dry mass of the fuel and the variable f_w describes the functional dependence over wind.
With reference to the lognormal, the numerical simulations are performed to with different values of parameters μ and σ to analyse the main features of the model, while depicting the firebrand landing behaviour. Two sets of test cases have been discussed to describe the sensitivity of the process to different values of μ and σ: when one is varied and the other is constant.

3.2 Software

The mathematical formulation for the fire-spotting is developed in C. For the simulations presented in this article, a Level Set Method (LSM) code utilised to plug in the fire-spotting formulation as a post processing at each time step. The LSM also forms the basis of the operational wildfire simulator WRF-SFIRE. Here, we make use of a general-purpose library which aims at providing a robust and efficient tool for studying the evolution of co-dimensional fronts propagating in one-, two- and three-dimensional system. The library is written in Fortran2008/OpenMP, along with standard algorithms useful for the calculation of the front evolution by means of the classical LSM, includes Fast Marching Method algorithms. The results presented in this paper are visualised using the python 2-D plotting library: Matplotlib. The complete code for the formulation is freely available at https://github.com/ikaur17/firefronts .

4 RESULTS AND DISCUSSION

Figure 1 shows the evolution of the fire-line when μ increases, but σ is constant. As evident from the figures, the present formulation works well in generating secondary fires associated with the firebrands but an increase in μ points towards a declining trend in the long range probability of the fire-spotting. This can be explained from the behaviour of the lognormal distribution with an increasing value of μ. For a lognormal distribution, an increasing value of μ corresponds to a decrease in the maximum value and a very slow decay of the right tail with small values of probability. This behaviour of the lognormal tends to replicate the situations when firebrands can travel to large distances but have insufficient temperature to cause the ignition. Ignition of the fuel is not an instantaneous process, but rather an accumulative process. Sufficient number of firebrands with enough energy are required

to ignite the fuel. According to (8) and (9), an increase in μ physically corresponds to the increase in the fire intensity and the height of the plume. As height of the plume increases, the firebrand is ejected from the plume at a higher height, the travel time for the firebrand to reach ground also increases. Since, for the simulations in Figure 1, the wind conditions and the firebrand size remain unchanged, hence a larger travel time corresponds to a increased combustion and the firebrands reach the ground with a lower value of temperature and have a lesser probability of ignition.
On the other hand, Figure 2 shows the evolution of the fire-line when σ increases but μ is constant. The increasing value of σ points towards an increase in the fire-spotting distance. For first two cases, the increase in the wind velocity causes an increase in the landing distance of the firebrands but the characteristic length of landing is still not large enough to delineate the effective contribution to fire due to the action of fire-spotting. But a further increase in the value of σ causes a new secondary fire to develop and progress. The primary and the secondary fire progress independently with the increase in time and eventually merge with each other. In the model, the secondary fire is assumed to be of the same intensity as the primary fire and it is further effective in generating a tertiary fire (Figure 1 a, Figure 2 c). For a lognormal function an increasing value of σ corresponds to a very sharp rise of the maxima but with a gradual decay. A left shift in the maxima and corresponding sharp rise causes the tails to decay slowly and have a high probability value. This behaviour of the lognormal can be compared to the phenomenon when a strong wind pushes the firebrands away from the main source. Historically it has been reported that strong winds coupled with extremely dry conditions form the perfect recipe for long range fire-spotting. In physical terms increasing value of σ can be attributed to both increasing wind velocity and decreasing fire-brand size. Smaller firebrands can travel larger distances but have a higher chance of combusting completely before landing. In fact, it has been experimentally shown that the firebrands with size greater than the “collapse diameter” (Woycheese et al.1999) have the same propagation distance under identical initial conditions. The size of the fire-brand in the formulation of σ in these test cases can be assumed to be equal to the “collapse diameter”.

5 CONCLUSION

This article provides a versatile approach to include the effects of fire-spotting into operational wildfire models. The mathematical formulation is devised to be used as a post processing technique with the output of most of the operational wildfire models. The results from the basic numerical simulations highlight the fact that the mathematical formulations reproduces the effects of fire-spotting in agreement with the physical behaviour of the firebrand transport. The lognormal distribution within the proposed formulation performs well and is also able to emulate the generation of the secondary fires . Though this study provides a brief insight into the qualitative assessment of the firebrand landing distribution within the describes physical parametrisation, in future, an attempt to use the formulation to replicate real-life situations with operational models like WRF-SFIRE or Forefire will be made.

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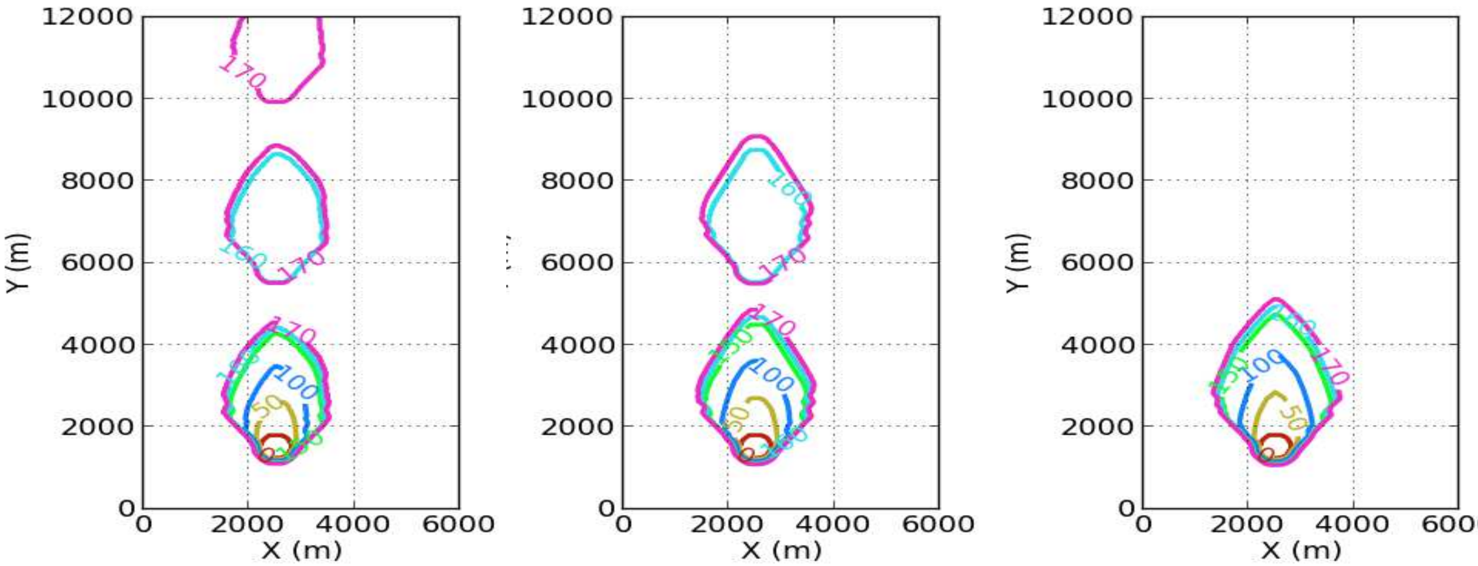
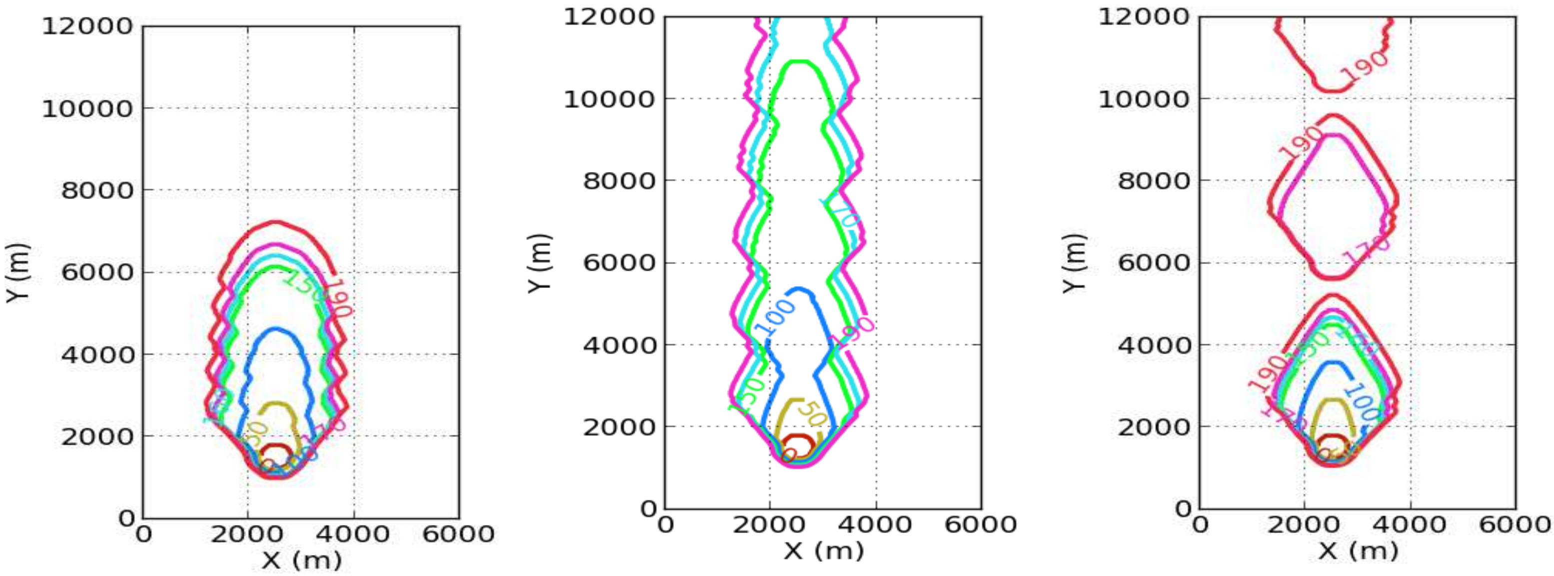


(a) μ = 13, σ = 5.5, I = 20 MW/m

(b) μ = 15, σ = 5.5, I = 30 MW/m

(c) μ = 17, σ = 5.5, I = 40 MW/m

Figure 1 : Figures showing the evolution of the fire-line with increase in μ but constant σ.



(a) μ = 16, σ = 4.5, U = 3 m/s

(b) μ = 16, σ = 5.0, U = 4 m/s

(c) μ = 16, σ = 5.5, U = 5 m/s

Figure 2 : Figures showing the evolution of the fire-line with increase in σ but constant μ.