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Incorporation of spotting and fire dynamics in a coupled atmosphere - fire modelling framework

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INTRODUCTION

This project focuses on searching for ways to improve operational fire-spread modelling by looking for computationally cheap techniques to model dynamic fire spread, and by the incorporation of spotting. In this part of the project we model the transport of embers. The goal is to find the appropriate methodology for modelling ember transport using modern computational techniques.

EMBER TRANSPORT: THE TERMINAL VELOCITY ASSUMPTION

Under some simplifying assumptions, the equations of motion of an ember moving with velocity $\vec{u}$ in a wind field $\vec{w}$ are

$$\frac{d\vec{u}}{dt} = \frac{C_d \rho A}{2m} |\vec{w} - \vec{u}|(\vec{w} - \vec{u}) - g\vec{k} \qquad (1)$$

where C_d is the drag coefficient, ρ is the atmospheric density, A is the cross-sectional area of the ember in the direction of $\vec{w} - \vec{u}$, and m is the ember's mass. If $\vec{w}$ and $\frac{C_d \rho A}{2m}$ are constant, one can show analytically that an ember rapidly approaches its terminal velocity

$$\vec{u}_\infty \equiv \vec{w} - \sqrt{\frac{2mg}{C_d \rho A}}\vec{k} \qquad (2)$$

where $\sqrt{\frac{2mg}{C_d \rho A}}$ is the terminal fall speed of the ember. The *terminal velocity assumption* (TVA) posits that for slowly varying $\vec{w}$ there is little error in assuming that the ember always travels at its terminal velocity, ie according to (2). This greatly simplifies ember transport calculations and early researchers, using a combination of analytical and experimental techniques, made extensive use of the TVA. With the advent of high speed computers, numerical simulations are able to explicitly resolve at least the larger of the eddies in a simulated turbulent wind field, and it is not clear that the TVA is valid in such cases. In very high resolution simulations of grass fires using a coupled-physical model, Koo et al. (2012) found that modelled ember travel distances were significantly shorter under the TVA. However, these were short-range simulations and Thurston et al. (2017) used the TVA to model long-range ember transport in turbulent plumes. In this study we used techniques similar to those of Thurston et al. but modelled the transport of the embers both with and without making the TVA, and compared the results.

THE MODEL

The methodology largely follows that of Thurston et al.:

- A turbulent boundary layer is simulated with a large eddy model (LEM)
- A static heat source is introduced to simulate a fire
- Wind field data from the resulting plume are used to simulate ember transport
- Ember combustion is not considered

TURBULENT BOUNDARY LAYER

- WRF atmospheric model (LEM mode)
- Domain 40 x 16 x 12 km (L x W x H)
- dx = dy = 50 m, 256 vertical levels
- 3 km deep dry-adiabatic layer capped by a stable layer to the top
- Initial 15 ms^{-1} wind in x-direction

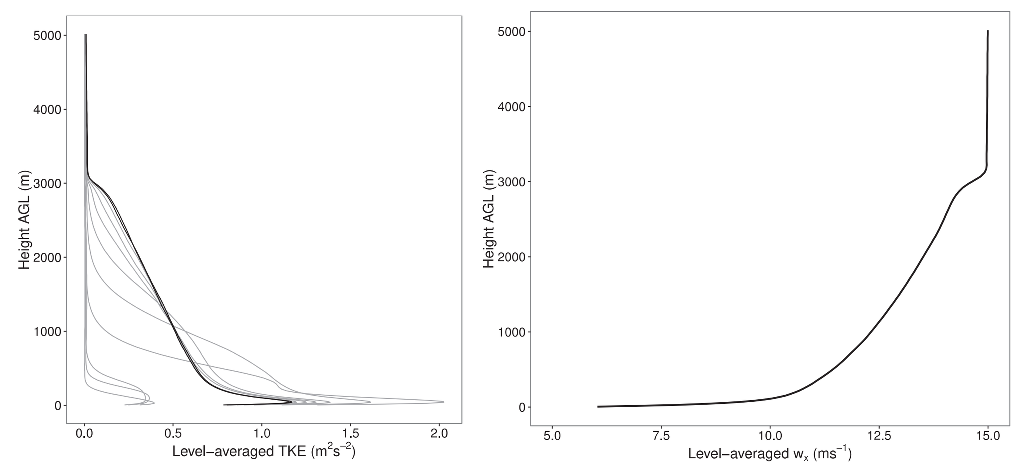

Fig1: Evolution of turbulence kinetic energy (TKE) and final velocity profile of turbulent boundary layer.

STATIC HEAT SOURCE AND SIMULATED PLUME

- Circular surface sensible heat flux anomaly radius 250 m, 2 km inside upwind boundary, intensity 10^5 W/m^2
- Continue LEM simulation for 1 hour to allow plume to develop, then for another hour to collect data at dt = 5 s

EMBER TRANSPORT

u_∞ = fall speed at reference density ρ_0 = 1.16

$$u_\infty = \sqrt{\frac{2mg}{C_d \rho_0 A}}$$

Thurston et al. (2017):

$$\vec{u} = \vec{w} - u_\infty \vec{k} \qquad \textbf{(Constant TVA)}$$

From (2):

$$\vec{u} = \vec{w} - \sqrt{\frac{\rho_0}{\rho}} u_\infty \vec{k} \qquad \textbf{(Variable TVA)}$$

From (1):

$$\frac{d\vec{u}}{dt} = g \frac{\rho}{\rho_0} \frac{1}{{u_\infty}^2} |\vec{w} - \vec{u}|(\vec{w} - \vec{u}) - g\vec{k} \qquad \textbf{(no TVA)}$$

- We compare ember transport using these three equations.
- Embers released for 30 minutes at locations where $w_x > 5$ ms^{-1}
- 3,280,660 ember in total
- u_∞ = 3, 6, 8 ms^{-1}
- Runge-Kutta numerical scheme

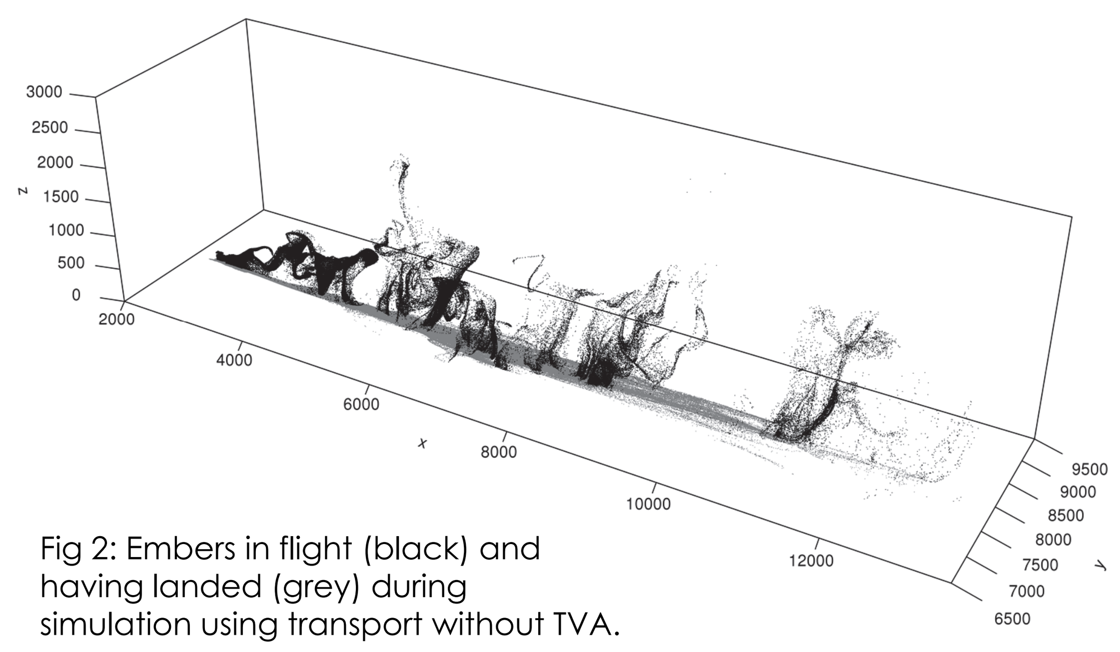

Fig 2: Embers in flight (black) and having landed (grey) during simulation using transport without TVA.

RESULTS

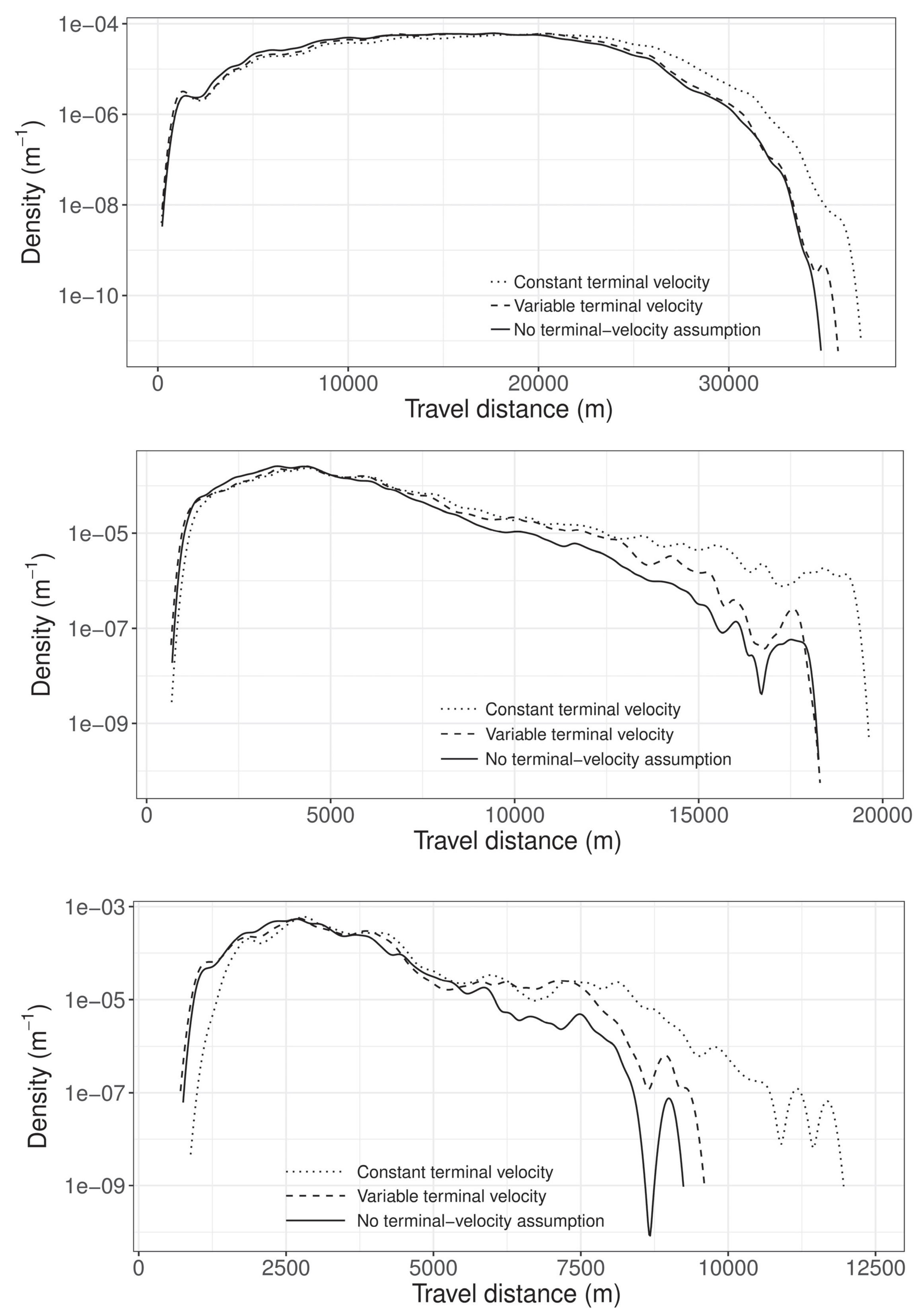

Fig 3: Distributions of travel distance for u_∞ = 3 ms^{-1} (top panel), u_∞ = 6 ms^{-1} (centre panel) and u_∞ = 8 ms^{-1} (bottom panel).

CONCLUSION

The constant TVA overestimates travel distance for all values of u_∞, because it does not take into account increased terminal fall speeds due to variation in ρ at higher altitude and within the plume. The variable TVA overestimates travel distances compared with no TVA because, when modelled with momentum (ie no TVA), embers tend to exit the plume earlier, and therefore do not travel as far. This effect is significant: for example in Fig 3 (centre panel) the density of embers travelling 15 km is 14 times higher under the constant TVA, and 5 times higher under the variable TVA, than it is if no TVA is used. This has important implications for the stochastic modelling of spot-fire development. The difference between the variable TVA and no TVA cases is less for small values of u_∞ because terminal velocity is achieved more rapidly in this case; see Fig. 3, top panel.

END USER COMMENT

Spotting is a challenging aspect of bushfire operations. We currently have poor capacity to estimate exactly how far ahead of a fire a spot fire could form. This research is providing insight into this problem by helping us understand the dynamic effects that can influence ember transport. This will help emergency response during major bushfires. - Brad Davies, NSW RFS

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SPOTFIRE PROJECT