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Modelling wildland fire temperatures

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ABSTRACT

A mathematical model of the maximum temperature as a function of height above the ground, within and above spreading wildland fires, is presented and evaluated. The model is based upon classical work on turbulent plume theory with extensions to include the flaming combustion region above and within the fuel bed itself. This results in a 'three zone' model which gives an appealing qualitative description of wildland fire temperatures. Temperature versus height measurements made in shrubland fuel complexes within Ku-ring-gai Chase National Park, Sydney, New South Wales, are used to calibrate the model. The ability to include the fuel bed and flame temperatures is a significant advantage over previous models which only applied to the plume.

Keywords: Fire temperatures, Models, Australia

INTRODUCTION

Ecological studies of the impact of wildfires need to be concerned with the temperatures to which plants will be subjected. While many measurements of the temperatures obtained within and above wildland fires have been made (e.g. Trabaud 1979), no-one has been able to account for the full variation of temperature with height. Indeed, sampling heights have usually been restricted to less than a few metres. Usually it is only the plume region, above the wildfire, which has been modelled. While this may suffice for studies of crown death, e.g. Van Wagner (1973), it is insufficient for a full understanding of fire effects upon vegetation.

The model presented here is for maximum temperature reached as a function of height as a wildland fire passes. The fuel bed, the flaming region above the fuel bed and the fire plume are all included in a consistent model. Separate temperature-height functions are used in each of the three regions and we demand continuity of temperature and flux (temperature gradient) across the borders of the regions. In this way we are able to match a constant temperature region in the fuel bed with an exponential reaction-diffusion region for flaming and the classical turbulent plume for above the fire.

A knowledge of the temperature above the flames and how this is related to the flame temperature is important in the study of the impact of fire on vegetation above the flames. Issues such as leaf scorch, seed death and stem death are all reliant on a knowledge of the heat exposure of the vegetation.

PLUME STUDIES

Yih (1951) calculated the temperatures reached in a turbulent plume resulting from an idealized line source of heat

$$\Delta T = k\, I^{2/3} / z \qquad (1)$$

where ΔT is the temperature rise above ambient temperature, I is the intensity of the line source per unit length, z is the height above the line source and k is a proportionality constant. Note that equation (1) is applicable directly above the stationary source, $x = 0$. At other points the equation found by Yih (1951) is

$$\Delta T = (k\, I^{2/3} / z) * \exp(- x^2/\beta^2 z^2) \qquad (2)$$

where x is the horizontal distance from the source and β is an entrainment constant
($\beta = 0.16$ according to Lee and Emmons, 1961.)

Although, strictly speaking, Yih's (1951) results apply only for a stationary line source in a quiescent atmosphere, Thomas (1963) and subsequently Van Wagner (1973) have used equation (1) in modelling the temperature rise above wildland fires. As one reaches a height far above a real wildland fire, it can be reasonably approximated as a line source and it appears to move only very slowly. Thus Thomas (1963) and Van Wagner (1973) have had some success; Van Wagner (1973) in particular, with providing a first model for crown death.

A laboratory study of stationary pool fires by Kung and Stavrianidis (1982) provides one of the best experimental tests of the applicability of the similarity analysis of Yih (1951) to fires. The experimental results show impressive agreement in the plume region. However, there is a significant region of measured temperature increases, in and around the flames, where the theoretical results are inadequate.

Our main motivation is to provide a model for the entire temperature profile for wildland fires. The two main benefits of this would be

(i) the ability to predict maximum external temperature rise to which vegetation would be subjected at any height;

(ii) a clarification of the height above a fire at which plume theory can be reliably applied.

Item (i) depends upon the combustion characteristics of fuel types as well as the fluid mechanics of the fire, and we can only provide a partial realization in this paper. Item (ii) depends solely upon the fluid mechanics and we show that our model admits an understanding of the significance of the height at which the classical plume theory becomes applicable.

Other factors which one would like to include are the movement of the fire, fire depth, wind profiles and rough terrain. However, these will not be considered in this paper.

TEMPERATURE MEASUREMENTS

Temperature measurements were made in a series of experiments in Ku-Ring-Gai National Park in NSW, Australia. The measurements involved the use of a single vertical array of sheathed Type K (chromel-alumel) thermocouples to measure temperature rises above ambient in experimental fires in heathy fuels. Fires were lit only on days of very light winds. The depth of the fuel varied greatly, from 0.5 m to 2 m, and the flames ranged in height from 1 m to 10 m. A discussion of the utility of such measurements can be found in Gill and Knight (1991). Typical results are as shown schematically in Figure 1. For clarity, a detailed report of the experiments will not be included here. Readers are referred to the detailed report on the experiments, as opposed to the temperature measurements, that can be found in Bradstock and Auld (1994).

The similarity of form, despite quite different fuel depths, is very encouraging for the development of a universal model. This was the original aim of Thomas (1963) and Van Wagner (1973), founded on the

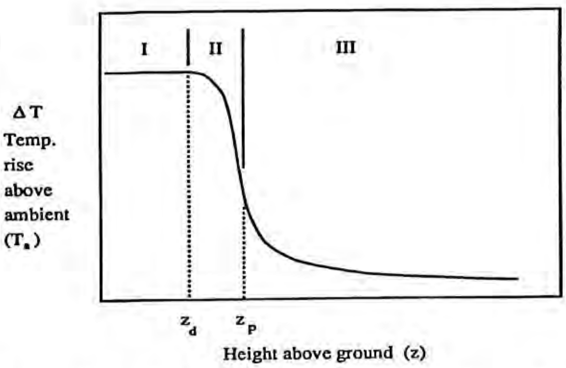

Figure 1. Typical form of curve for temperature rise above ambient vs. height above ground.

expectation that dimensional reasoning provides relationships which are scale invariant. The key problem that arose was the inability to determine a universal value for the plume constant (k in equation (1)). In our analysis, we wish to shift the emphasis away from finding universal constants. Rather, it is our expectation that the full temperature versus height profile can be understood with a 3-region paradigm. This new paradigm is itself a leap in understanding. Furthermore, it allows a comparison of fires and their potential impact upon vegetation. In the next two sections we present our paradigm and relate it to the Ku-Ring-Gai fires.

A 3-REGION MODEL

A typical curve of temperature rise above ambient, ΔT, versus height, z, can be divided into 3 regions, as shown in Figure 1.

$$\begin{array}{lll} \text{I} & \Delta T^{I} = K, & 0 \le z \le zd \\ \text{II} & \Delta T^{II} = K\exp(-\alpha(z - zd)^2), & zd \le z \le zp \\ \text{III} & \Delta T^{III} = C/z, & z \ge zp \end{array} \quad (3)$$

where K, C, α, zd and zp are constants which need to be determined. In Region I it is anticipated that the presence of combusting solid will create a constant high temperature region which extends through a height zd, perhaps comparable to the fuel bed depth. In Region II the flames mix with entrained air and an exponential decrease in temperature rise, following a Gaussian distribution, is assumed. Region III is the plume region, and extends above a height zp.

In order to reduce the number of constants which need to be determined, and to provide a smooth ΔT versus z curve, the temperature rise and the gradient will be matched across the boundaries between regions

$$\Delta T^{I} = \Delta T^{II} \quad \text{at } z=zd \quad (4.1)$$
$$d(\Delta T^{I})/dz = d(\Delta T^{II})/dz \quad \text{at } z=zd \quad (4.2)$$
$$\Delta T^{II} = \Delta T^{III} \quad \text{at } z=zp \quad (4.3)$$
$$d(\Delta T^{II})/dz = d(\Delta T^{III})/dz \quad \text{at } z=zp \quad (4.4)$$

There is a little algebra which needs to be done (see Appendix), but then these conditions determine two of the constants in terms of the other three:

$$C = K\, zp \exp(-\alpha\, (zp - zd)^2) \quad (5.1)$$

$$\alpha = 1/(2\, zp\, (zp-zd)) \quad (5.2)$$

Therefore, the model for ΔT versus z, consists of equations (3) subject to equations (5): and there are three remaining parameters to be found. These are:

(i) K, the maximum temperature reached anywhere. It may be possible to estimate this from a combustion calculation, assuming a certain proportion of total heat generated is lost to the atmosphere.
(ii) zd, perhaps related to fuel bed depth or zone of persistent flame.
(iii) `zp, perhaps related to the height of the flames in the zone of flame flickering.

It is valuable to have these guiding roles for K, zd and zp when one comes to fit wildland fire data. A detailed survey of ΔT versus z data from wildland fires is required to fully justify these guiding roles for K, zd and zp. In this context one should note the extreme paucity of published data which uses thermocouple array, or other temperature measurement means. The most detailed studies known to the authors are Tunstall *et al.* (1976), Van Wagner (1975) and Williamson and Black (1981), none of which, in their current form, can be compared with our three-zone model.

FITTING EXPERIMENTAL DATA

In order to determine the paramters in the 3-Region model, seven of the experimental fires were studied in detail. The 3 model parameters were first determined approximately by simply viewing the T versus z plots of the experimental data.

This instantly provided a smooth curve which gave a good fit to the data. Further refinement using a simple least squares routine in order to minimize the error was then done. This usually provided a small improvement to the original fit. In Figure 2 and Figure 3 we present the results of curve fitting from two of the experimental fires. For the fire presented in Figure 2 the fuel bed was quite deep and the flames quite high, hence we chose K = 700°C, zd = 1.5 m and zp = 2.15 m. For the fire presented in Figure 3 the fuel bed was much shallower, although the flames were of a similar size, hence we chose K =790°C, zd = 0.25 m and zp = 2.00 m.

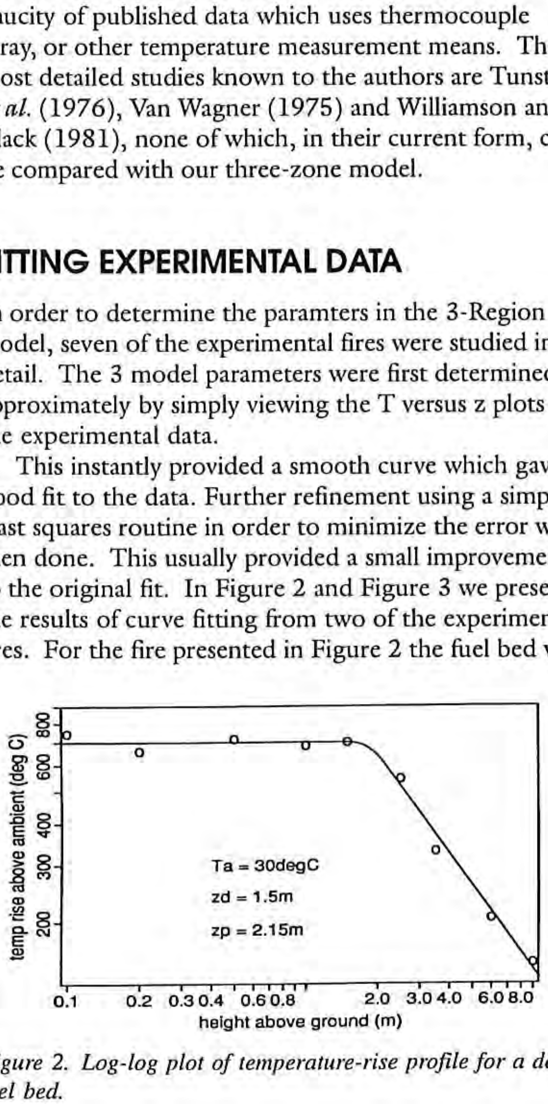

Figure 2. Log-log plot of temperature-rise profile for a deep fuel bed.

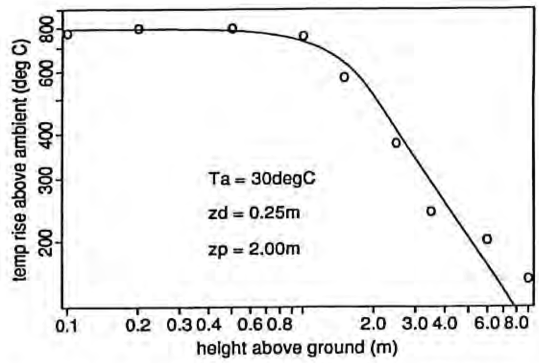

Figure 3. Log-log plot of temperature-rise profile for a shallow fuel bed.

The ability of the curves to fit the experimental data with a minimum of fuss is most impressive. It should be stressed that the model is not yet predictive. Indeed, detailed measurements in a given fuel type would be required to calibrate the model prior to using it in a predictive sense. Environmental factors such as wind, humidity and fuel moisture would also need to be taken into account. Despite this, even prior to any calibration, the results provide an insight into where the fire plume region begins. Namely, for the heath communities in Ku-ring-gai, NSW, it would seem that 2 m is the minimum height at which plume theory can be successfully applied.

DISCUSSION

The three regions identified here could match those identified by McCaffrey (1979) for fires burning natural gas above ceramic plates in the laboratory, *viz.* a continuous-flame region, an intermittent flame region, and a plume region. In wildland fires the fuel is solid - unlike the fuel in McCaffrey's fires - so it is possible that our Regions, especially Region I, may be related to fuel bed characteristics such as depth. Region I is effectively missing in shallow fuels, such as litter (Stott 1986, author's unpublished data), but readily identified in deeper fuels, such as shrublands (present work, Trabaud 1979) and tall grasses (Tunstall *et al.* 1976). Therefore, the situation described in this paper is the more general one.

FURTHER WORK

The main avenue for further work at present is to include the dependence upon horizontal distance from the fire, an analogue of time. For the plume region, this is already taken care of with equation (2). However, in the other two regions the most versatile x-dependence is yet to be determined.

One could pursue laboratory work, to determine how the variables introduced in equation (3) relate to fuel bed depth and heat release rate. This would require a large combustion chamber so that there is negligible interaction between the plume and the walls and ceiling.

Other possible inclusions are fire speed and flame depth which are related to x-dependence, and of course wind profiles. All the present work is for light winds, which is a severe limitation.

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NOMENCLATURE

- C constant
- K constant
- k constant
- I line fire intensity
- ΔT temperature rise above ambient
- x horizontal distance
- z height above ground
- zd height related to the fuel bed depth
- zp height related to the start of the plume
- α constant
- β entrainment constant (0.16)

APPENDIX

Of the matching conditions, equations (4.1) and (4.2) are automatically satisfied by our choice for equations (3.1) and (3.2). This leaves equations (4.3) and (4.4) to be satisfied. Equation (4.3) yields

$$K \exp(-\alpha\,(zp - zd)^2) = C / zp \qquad (A.1)$$

while equation (4.4) yields

$$-2\,\alpha\,(zp\text{-}zd)\,K\,zp\,\exp(-\alpha(zp - zd)^2) = -\,C / zp^2 \qquad (A.2)$$

Equation (A.1) can be immediately rearranged to give equation (5) in the text. Into equation (A.2) we substitute equation (A.1) to give

$$-2\,\alpha\,(zp\text{-}zd)\,C / zp = -\,C / zp^2 \qquad (A.3)$$

which is rearranged and simplified to give equation (5.2) in the text.