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Title: USE OF TRANSPORT MODELS FOR WILDFIRE BEHAVIOR SIMULATIONS

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Use of Transport Models for Wildfire Behavior Simulations

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INTRODUCTION

Recently catastrophic wildfires have been a threat to human life and property around the world. In many cases these catastrophic fires have resulted from long histories of fire suppression. People are starting to realize that continuous fire suppression does not work indefinitely and that fires are an unavoidable part of nature. They are necessary for the natural maintenance and evolution of forests. Some of the goals of our wildfire research are to provide guidance for planning of controlled burns, understanding of conditions under which wildfires can be allowed to burn, and real time exploration of ways to best respond to catastrophic fires in order to save life and property. Investigators have attempted to describe the behavior (speed, direction, modes of spread) of wildfires for over fifty years. Current models for numerical description are mainly algebraic and based on statistical or empirical ideas. We have developed a transport model called FIRETEC (Linn , 1997). The use of transport formulations connects the propagation rates to the full conservation equations for energy, momentum, species concentrations, mass, and turbulence. In this paper, highlights of the model formulation and results are described, whereas the details of this work are described in other papers (Linn , 1997), (Linn and Harlow , 1997).

The goal of the FIRETEC model is to describe most probable average behavior of wildfires in a wide variety of conditions. FIRETEC represents the essence of the combination of many small-scale processes without resolving each process in complete detail.

The FIRETEC model is implemented into a two computer codes, a two-dimensional code that examines line-fire propagation in a vertical spatial cut parallel to the direction of advancement and a three-dimensional code. With this code we are able to examine wind effects, slope effects, and the effects of nonhomogeneous fuel distribution. Selected results of some of the two dimensional calculations are shown in this paper.

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FORMULATION

We envision three different relevant size scales for the representation of the physics involved in the wildfire. The largest of the relevant size scales, A scales, is the size of the largest fuel structures. The next largest scales are the B scales, which are associated with the distance between branches. C scales are the smallest and are associated with scales at the size of the small structures of the fuel, such as leaves or pine needles.

The mixing processes that occur at the smallest of scales, C scales, control the rates of the chemical reactions. We treat the binary reactions as if they were mixing limited and the chemical kinetics is instantaneous when reactants are brought together at high enough temperatures. A critical temperature is associated with each reaction (pyrolysis of wood, evaporation of pitch or water, oxidation of carbon, combustion of hydrocarbons, etc.). It signifies the point at which there is enough heat in the reactants for the reaction to commence.

The average temperature in a resolved volume is related to the extremes of temperature by means of a probability distribution function that enables an estimation of the fraction of a given volume that is over the critical temperature for ignition.

There is much complex chemistry involved in the combustion of wood, of which we represent with a few simplified reaction models, including descriptions of pyrolysis, char burning, and the combustion of hydrocarbons and soot in the presence of transported oxygen and inert gases.

In order to describe the presence of reactants we use a separate transport equation for each species that we are interested in and for the combined gas. Individual gaseous species are transported with the following transport equation for species d.

$$\begin{aligned}\frac{\partial \rho_d}{\partial t} + \frac{\partial \rho_d u_i}{\partial x_i} &= \frac{\partial}{\partial x_i}\left[\left(\sigma_{b,ij} + \sigma_{c,ij} + \delta_{ij}\sigma_m\right)\frac{\partial \frac{\rho_d}{\rho}}{\partial x_j}\right] \\ &\quad + (\text{net species sources}_d) \end{aligned} \tag{1}$$

In this equation the densities and velocities are appropriate averages and the σs are diffusion coefficients associated with the turbulent structures at the B and C scales.

The conservation of momentum equation is of the form

$$\frac{\partial u_i \rho}{\partial t} + \frac{\partial\left(\rho u_i u_j + R_{ij}\right)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \rho g_i - D\rho u_i \,. \tag{2}$$

where we have introduced R_{ij} and $D\rho u_i$ to represent the Reynolds-stress tensor and the drag term respectively.

The internal energy of the gas is also computed with a transport equation, including the effects of radiation heat loss, convective heat exchange, and the heat lost or gained from chemical reactions.

One of the most complicated facets of a wildfire to simulate is the radiation heat transfer that occurs as a result of the radiating soot (what we normally call the flame). This source of the radiation is not

well known since the production rate of soot is not well characterized for wildfire conditions. For this reason we formulate a model that estimates the average soot content at a location based on the oxygen concentration and temperature. Using a probability distribution function for the temperature to the fourth power, we can estimate the energy lost from the soot in the form of thermal radiation. We use a diffusive virtual energy technique for radiation transport to represent the radiation process, because ray tracing techniques are too computationally expensive for this model under the current computational constraints.

We use a virtual energy diffusion model (VEDM) to represent primarily the radiative heat transfer from the vegetation, hot gases, and airborne particulates (soot) to the solid fuel. This approach represents the transfer of thermal radiation energy from the flame and solids with a diffusional model. This approach is developed for radiation emitted from a volume of point sources rather than a solid emitting surface of comparable size to the distances over which the radiation is tracked. The VEDM model is linear with respect to the transported variables. This feature makes it possible to sum up the radiative effects of a number of point sources in order to get a combined solution. Our approach treats flame and radiating solids as if they were made up of many point sources (each of which can emit and absorb). It is noted that this treatment does not produce the same emission pattern as the representations in which the flame and emitting solids are assumed to form diffuse grey body surfaces.

Turbulence is described at the three separate scales, A, B, and C. For simplicity we use transport equations for the Reynolds-stress trace at A and B scales, with a Boussinesq approximation to extract the full Reynolds stress components.

For the turbulence energy density at the A scale we write

$$\begin{aligned}\frac{\partial \rho K_A}{\partial t} &+ \frac{\partial u_i \rho K_A}{\partial x_i} = -R_{il_A}\frac{\partial u_i}{\partial x_l} \\ &+ \frac{2}{3}C_{DR}\frac{\partial}{\partial x_l}\left[s_A\frac{R_{lk}}{\sqrt{K}}\frac{\partial K_A}{\partial x_k}\right] - \frac{\rho_g}{T_o}g_i\overline{u_i'T'} \\ &- \frac{\sqrt{K}}{s_A}K_A - \frac{3}{8}C_D\frac{\rho\, K_A\sqrt{K}\alpha_s}{s_B} \end{aligned} \tag{3}$$

The second term on the left side of the equation represents the mean-flow advective transport of turbulence kinetic energy while the second term on the right side represents the random walk advection of the turbulence caused by turbulent velocity fluctuations (self diffusion). The first term on the right side of the equation represents the creation of turbulence in the presence of a mean flow shear gradient. This term is especially important at the locations where the mean flow shears across the canopy. The third term on the right represents the creation of turbulence in the presence of temperature-driven buoyancy. The fourth term represents the cascade of turbulence energy to fine scales. The last term describes the removal of turbulence energy from the A scales due to the drag in the forest.

For the transport of K_B there are two additional drivers that describe the creation of turbulence at the B scale, due to the break up of turbulence at the A scale and to the mean flow in the vegetation.

These source terms are

$$\frac{\partial \rho K_B}{\partial t} = \ldots + \frac{3}{8} C_D \frac{\overline{\hat{\rho}}_g \sqrt{K} K_A \alpha_s}{s_B} + \frac{3}{8} C_D \frac{\overline{\hat{\rho}}_g |\tilde{u}|^3 \alpha_s}{s_B} \tag{4}$$

We could also write a transport equation for the turbulence energy at the C scales, but for our present model we approximate the C-scale Reynolds stress by setting it proportional to that of the B-scale Reynolds stress.

The overall chemistry is extremely complicated. At this stage, we have examined three idealized limiting cases for guidance in the formulation of our burn model. These are

1. gas-gas, with two reactants forming a single final product, with no intermediate species,
2. gas-solid, representing the burning of char in the presence of oxygen,
3. single reactant, for pyrolysis of wood.

The essential features of the three results are remarkably similar, leading us to propose a simplified burn model that contains much of the essential physics and test its adequacy for representing the essence of fire propagation. Our principal postulate is contained by the "universal" reaction rate

$$F = c_F \frac{\rho_f \rho_o \sigma_{cm} \Psi}{\rho_{ref} s^2} \lambda \tag{5}$$

in which s is the scale of the smallest fuel elements and Ψ is the volume fraction of the region that is above critical ignition temperature as described by the temperature probability distribution function. Numerical experiments show that $c_F = .07$ is consistent with the expectation that a fire in a 1 m/s wind can barely sustain itself.

The form of λ is

$$\lambda = \frac{\rho_f \rho_o}{\left(\frac{1}{N_f}\rho_f + \frac{1}{N_o}\rho_o\right)^2} \tag{6}$$

RESULTS

This burn description has been inserted into the FIRETEC model for testing with a variety of configurations. Simulations were run out to 250 seconds after ignition. Figures 1 through 6 depict the gas temperatures for these simulations at 250 seconds after ignition.

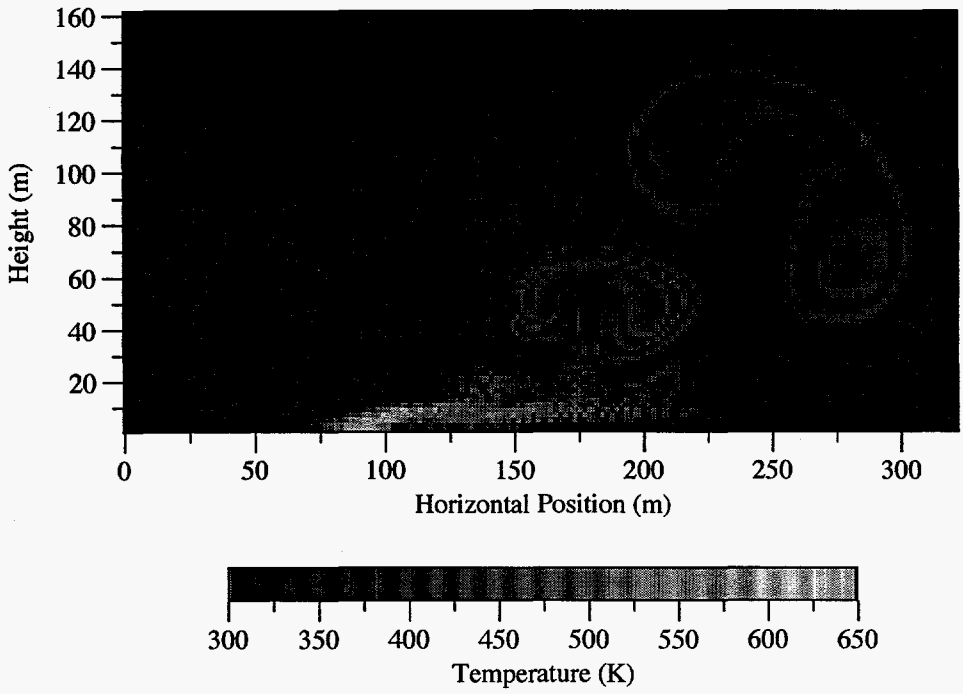

Figure 1: Temperature contour images with 2 m/s crosswind 250 s after ignition

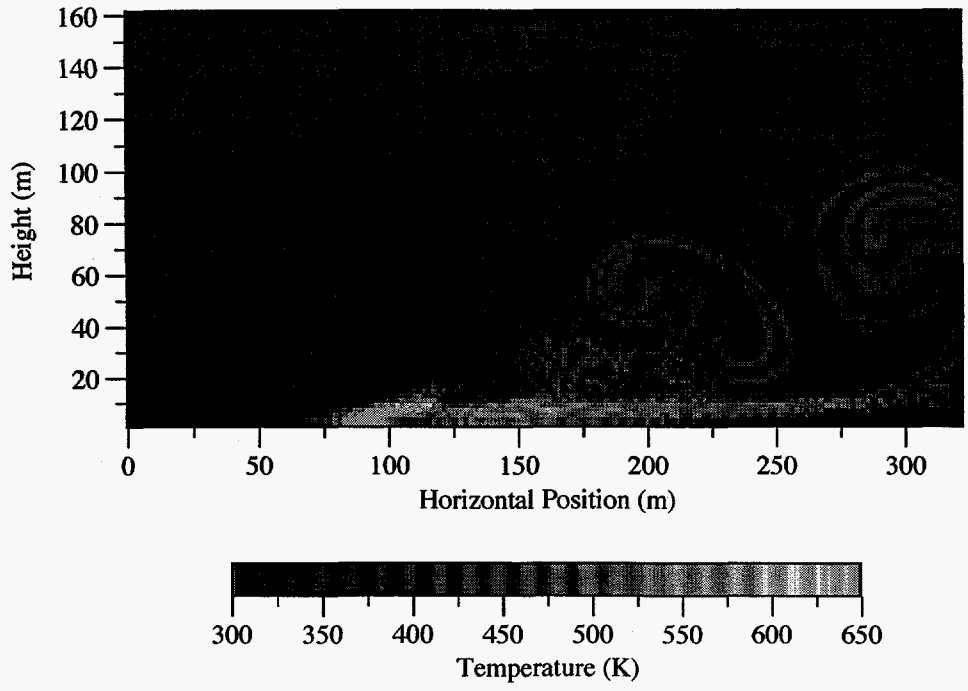

Figure 2: Temperature contour images with 3 m/s crosswind 250 s after ignition

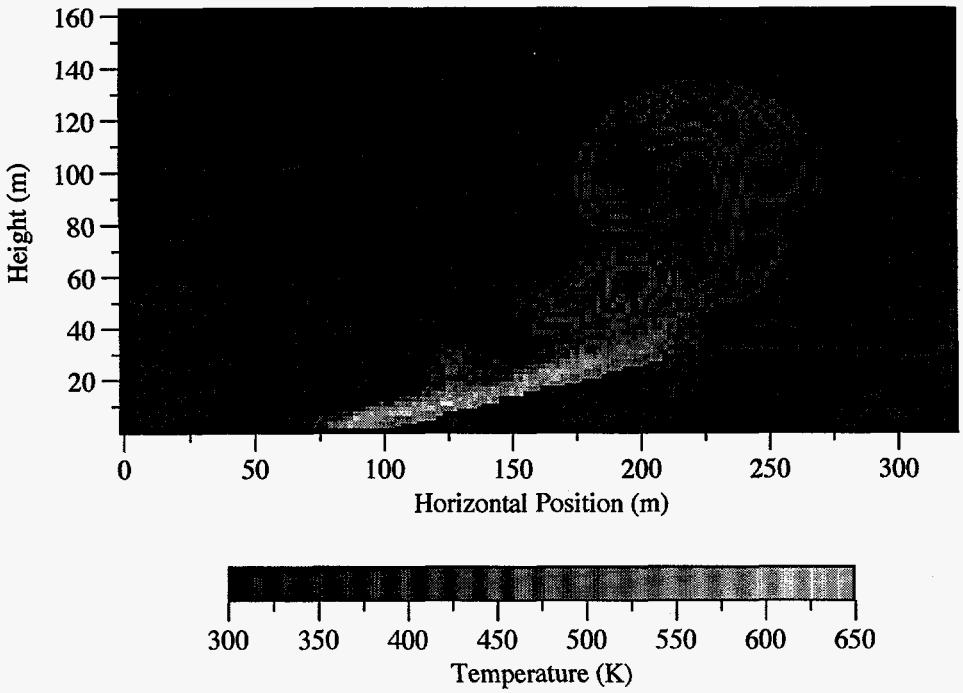

Figure 3: Temperature contour images for upslope terrain 250 s after ignition

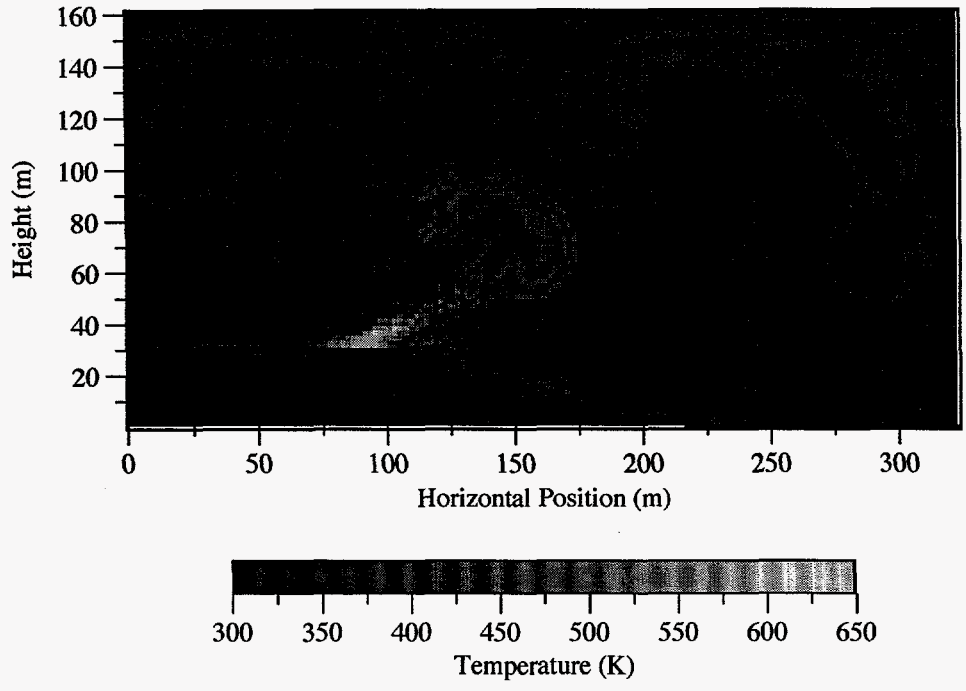

Figure 4: Temperature contour images for downslope terrain 250 s after ignition

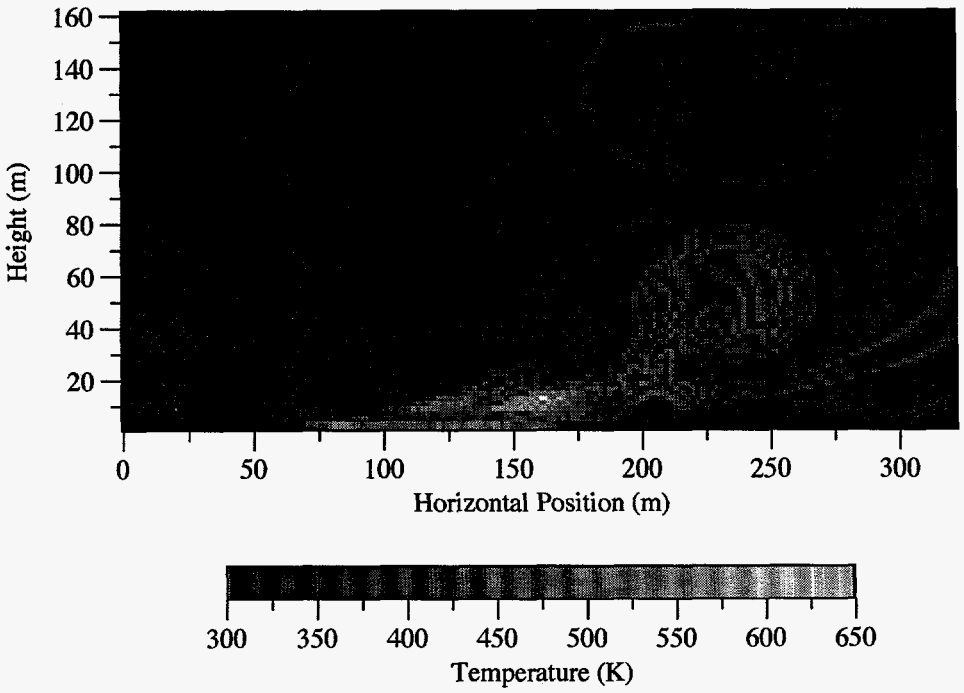

Figure 5: Temperature contour images for simulation with separated canopy and understory

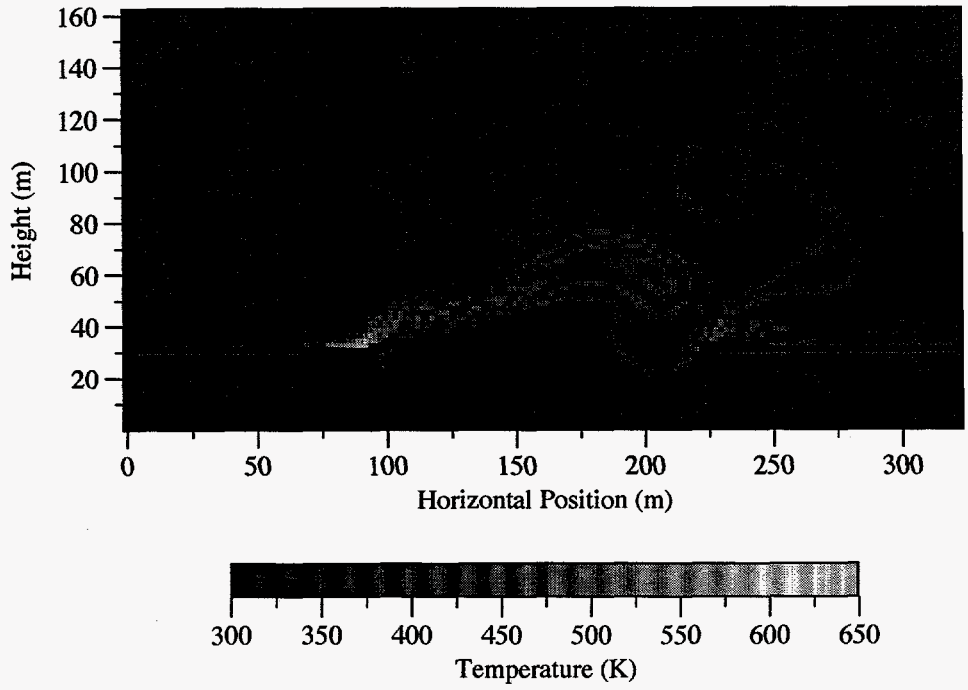

Figure 6: Temperature contour images for canyon simulation

Figure 1 shows the temperature contours with ambient wind of 2 m/s and Fig. 2 is for a wind speed of 3 m/s from the left, each with a fuel bed that is distributed to a height of 10 m from the ground. Figure 1 shows the temperature contours with ambient wind of 2 m/s and Fig. 2 is for a wind speed of 3 m/s from the left, each with a fuel bed that is distributed to a height of 10 m from the ground. These two figures show the effects of different windspeeds on the behavior of the fire. Notice the difference in the fire spread rate as well as the difference in plume angle above the fire. The effects of mean wind on plume angle in FIRETEC simulations agrees well with previous observations (Weise, 1993).

Figures 3 4 illustrate fires driven by 2 m/s cross wind in the same conditions except that the terrain has been modified to an upslope in the first picture and a downslope in the second picture, showing, in particular, the accelerated spread rate on the upslope and the decelerated spread on the downslope. Figure 5 depicts a fire that is being driven by a 2 m/s crosswind through a fuel bed that has the same total fuel load as the fuel beds used in previous calculations but the canopy is separated from the understory by a gap that has negligible vegetation in it. This gap allows a different fire behavior because the air can flow in between the two layers of vegetation and feed the fire in the understory.

Figure 6 illustrates especially well the capability of a transport representation to describe history dependent nonlocal processes. A canyon, 120 m wide is approached by a fire burning in a 2 m/s crosswind. The fire was ignited well back from the edge of the canyon. Complex wind patterns result from buoyancy and the induced circulation within the canyon. The plume touches the fuel at the far edge of the canyon resulting in the ignition. This representations is possible because the probability-distribution-function approach for temperatures describes the probable fraction of mass in the debris-laden plume that lies above the critical temperature for ignition. This formulation thus describes the presence of ignited firebrands and therefore makes the simulation of touchdown spotting possible.

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