A Coupled Atmosphere–Fire Model: Convective Feedback on Fire-Line Dynamics

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ABSTRACT

The object of this paper is to describe and demonstrate the necessity and utility of a coupled atmosphere–fire model: a three-dimensional, time-dependent wildfire simulation model, based on the primitive equations of motion and thermodynamics, that can represent the finescale dynamics of convective processes and capture ambient meteorological conditions.

In constructing this coupled model, model resolution for both the atmosphere and the fuel was found to be important in avoiding solutions that are physically unrealistic, and this aspect is discussed. The anelastic approximation is made in the equations of motion, and whether this dynamical framework is appropriate in its usual form for simulating wildfire behavior is also considered.

Two simple experiments—the first two in a series of numerical simulations using the coupled atmosphere–fire model—are presented here, showing the effect of wind speed on fire-line evolution in idealized and controlled conditions. The first experiment considers a 420-m-long fire line, and the second considers a 1500-m-long fire line, where wind speeds normal to the initial fire lines vary from 1 to 5 m s$^{-1}$. In agreement with some general observations, the short fire line remains stable and eventually develops a single conical shape, providing the wind speed is greater than about 1–2 m s$^{-1}$, while under similar conditions, the longer fire line breaks up into multiple conical shapes. In both cases, the conical shapes are attributed to a feedback between the hot convective plumes and the near-surface convergence at the fire front. The experimental results reveal a dynamical explanation for fire-line breakup and geometry, demonstrating that the model is a valuable tool with which to investigate fire dynamics, and eventually it may be able to provide a credible scientific basis for policy decisions made by the meteorological and fire-management communities.

1. Introduction

At present, fire services can forecast the danger rating of, or the specific weather elements relating to, a wildfire. There is a need not only to rate fire danger and weather, but also to understand and predict fire behavior and spread. In this regard, numerical models are a promising tool for assimilating the observational data, for understanding the connections between different components of the fire–atmosphere system, and above all for predicting fire behavior. This paper’s purpose is to demonstrate the necessity and the utility of a coupled atmosphere–fire model. The only other coupled atmosphere–fire model of which the authors are aware is that of Grishin (1992).

Forest fires are very complex phenomena. They have extremely complicated chemistry; interactions between forest fires and airflow are highly nonlinear, and radiation and combustion properties are not fully understood. Discussions with the fire-modeling community suggest that fire modeling is still at the stage of defining a viable model framework to represent a developing

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fire. For example, the fire spread rate in the two main fire models (Noble et al. 1980; Rothermel 1972, 1991) assumes an empirical relationship between the rate of spread and the ambient wind speed measured away from the fire. In many applications a single value of this wind speed is applied over a large area and long time period. Microscale processes that affect the fire spread rate and involve the variable winds within the fire and adjacent fuel have not been treated.

The empirical formulas currently used to link the fire spread rate to the ambient winds ignore any feedback between the small-scale air motions and the fire. However, the heat and moisture supplied through the burning of ground and canopy fuel during a forest fire generate extreme levels of buoyancy. The horizontal buoyancy gradients produce vortices of toroidal strength (Banta et al. 1992), which in turn affect the nature of the fire spread through advection of hot gases and burning material. Winds at the fire scale can either be strongly modified or even solely produced by the fire, depending on the level of atmosphere–fire coupling. This coupling, or feedback, occurs over spatial scales from tens of meters at the flame front to kilometers on the scale of the total burn area.

We have developed a dry eucalyptus forest fire model, which we coupled to an existing mesoscale model (Clark 1977, 1979; Smolarkiewicz 1983, 1984; Clark and Farley 1984; Clark and Hall 1991; Clark and Hall 1996, submitted to J. Appl. Meteor.) with the goal of developing a coupled atmosphere–fire model that reproduces reasonable fire behavior. The meteorological model is a three-dimensional, nonhydrostatic numerical model based on the Navier–Stokes momentum, thermodynamic, and conservation of mass equations using the anelastic approximation (Batchelor 1953; Ogura and Phillips 1962; Schaefer 1975). It has a two-way interactive grid-nesting capability that provides the high resolution (∼10 m) needed in the fire, while capturing the outer (or forcing) domain scale of the environmental mesoscale winds. It also has vertically stretched and terrain-following coordinates that allow solutions in regions of rough terrain.

For these preliminary studies, the dry eucalyptus forest fire model specifies the ground and canopy fuel’s initial mass, moist/dry ratio, heat liberation, and burn rates. The fire model has a contact ignition parameterization to trace fire movement, a simple formulation for canopy ignition, and a simple radiation treatment. Coupling between the fire and atmosphere occurs through the sensible (radiation and conduction effects) and latent heat fluxes supplied by the fire model to the atmospheric thermodynamic equation. Coupling between the fire and the atmosphere associated with forest canopy drag is not active at present.

We discuss several important features of coupled atmosphere–fire numerical modeling. The effect of model resolution on the balance between convective heat transport and heat flux from the fire as well as the effect of fire fuel resolution on fire behavior are two important aspects of the coupled model. The validity of the anelastic approximation in the governing equations as applied to fire modeling is another aspect that is considered. We also discuss the question of whether or not the solenoidal effect in the pressure gradient term can be ignored, as is usual in the anelastic equations of motion.

We use the coupled model to test some fire behavior characteristics in which mesoscale and fire-induced wind–convection interactions are important. In this study, we report the first of these experiments: a simple demonstration of fire-line stability and shape in different but constant ambient winds for neutral atmospheric conditions, no topography, weak surface friction only, no Coriolis forcing, and homogeneous fuel.

The physical justification for a coupled atmosphere–fire model is demonstrated by the convective Froude number, a measure of the larger-scale ambient flow response to the convective heating by the fire and, thus, a measure of the degree of coupling between the fire and the wind. Based on the convective Froude number, it is shown that even for typical fire conditions—where the local winds are only slightly modified or are modified in a rather stable or nonexplosive sense by the fire—the degree of coupling is significant.

Often a fire line does not remain linear. It can take a parabolic or conical shape, or it may experience "fingering." We consider two general types of fingering in our fire modeling. The first is "convective fingering," a result of convective-scale motions. The second is "dynamics fingering," occurring on the scale of the width of the fire front and as a result of vertical vorticity generation along the fire front. We discuss convective fingering in this paper. Dynamic fingering is a topic of future works.

An example of convective fingering of a fire line is the 1985 Onion sagebrush fire in Owens Valley, California (Fig. 1): a fire line with multiple protrusions, or "fingers," spaced about 1 km apart and appearing only when an ambient wind was present (C. George, personal communication). When the mean wind subsided, the fuel between the fingers burned out, forming a stalled and more linear smoldering fire line. When the wind returned, fire spread resumed, and fingers formed again pointing in the direction of the wind. Inhomogeneous surface fuel distribution or type have been suggested as possible causes for this phenomenon. This study shows, using the coupled atmosphere–fire model, that a physical explanation for this type of fingering lies instead in how the convection draws air from the surface. Model simulations show clearly that the stability or breakup of the fire line and its geometry result from the atmosphere–fire dynamics, demonstrating the value of a coupled model for a comprehensive description of fire-research problems.
An important issue is how crucial to our results the level of sophistication of the fire model is. The feature in the current fire model that directly impacts fire-line behavior is the fire-spread-rate formula. Accordingly, fire spread rate increases monotonically with the development of near-surface convectively driven winds. Although atmospheric heating due to the fire is variable, the basic (first-order) process of convective feedback to the fire dynamics remains the same. A simple heuristic argument is that although a fire model's heating rate to the atmosphere affects the level of forcing on the winds, the corresponding monotonic increase or decrease in the fire spread rate should not influence the first-order effect of convective feedback on fire-line dynamics described in the paper. This means that for different fuel characteristics or fire spread rates we expect our results to differ in detail, not in kind.

The paper is organized as follows. In section 2, we show that the degree of atmosphere–fire coupling, even in ordinary fires, is significant. The coupled meteorological model and the dry eucalyptus forest fire model are described in section 3. The meteorological model's two-way interactive grid-nesting capability and vertically stretched, terrain-following coordinates, along with the effects of model resolution, are discussed in section 4. We outline the first of our numerical experiments performed with the coupled model in section 4, and in sections 5 and 6 we report the results of two simple demonstrations of fire-line behavior under idealized wind conditions. The validity of the anelastic approximation in the governing equations of motion as applied to fire modeling is discussed in section 7. We present our conclusions in section 8.

2. The convective Froude number: A measure of the degree of coupling

Thorpe et al. (1980) discussed the relationship between the heating rate and the momentum of the mean flow. Although this problem was examined in the context of downdrafts (response of a flow to cooling), it can be easily reinterpreted as the response of a flow to heating by inverting the vertical coordinate and reversing the direction of the schematic trajectories in their Fig. 12. If air is heated enough to rapidly rise, it can draw air in from the rear. If air is heated less intensely, it then flows over the heat source with a light upward inclination to the direction of the flow. A nondimensional number used to distinguish between these flow regimes is the convective Froude number $F_z$, a measure of the relative importance of buoyancy and inertial accelerations; the smaller the $F_z$, the larger the buoyancy forcing's effect on the acceleration of the flow.

Appropriate ratios of the kinetic energy of the air and potential energy provided by the fire can be used to gauge when coupling between the fire and atmosphere are important. The measure of kinetic energy is the relative speed of the air passing over the fire, $U$
\[ F^e = \frac{U^2}{g(\langle \Delta \theta \rangle / \theta) W_f}, \]  

which is similar to the formulations proposed by Byram (1973) and Grishin (1992). Here \( \theta \) is potential temperature, and \( g \) is the acceleration due to gravity. The angle brackets represent the average or mean value of the temperature anomaly \( \Delta \theta \) over the region of intense heating (about 30 m in these simulations) and through \( W_f \), the width of this region. When \( F^e > 1 \), the flow does not respond strongly to the heating supplied by the fire. When \( F^e \approx 1 \), the flow enters a regime where both fire and dynamics are important. When \( F^e < 1 \), the flow responds strongly to the heating supplied by the fire—so much so that the fire can force its own firescale circulations, possibly resulting in blowup fire conditions. If the fire is to control the larger-scale dynamics, values of \( F^e \) should be small. In our simulated fires, for typical values of \( U = U_0 - S_p = 5 \text{ m s}^{-1}, \theta = 300 \text{ K}, \Delta \theta = 50 \text{ K}, \text{ and } W_f = 50 \text{ m}, \) the \( F^e \approx 0.3 \).

3. The coupled model

a. The continuity and momentum equations of the mesoscale model

The Navier–Stokes equations of the atmospheric model are approximated using the momentum equation

\[ \rho \frac{dV}{dt} + 2\Omega \times V = -(1 + \gamma) \nabla p' + g\rho B + \frac{\partial \tau_{ij}}{\partial x_i} \]  

(in mixed vector and tensor notation) and the anelastic continuity, or conservation of mass, equation

\[ \nabla \cdot \rho \mathbf{V} = 0. \]  

Here \( \mathbf{V} = (u, v, w) \) is the air’s velocity in the \( x, y, \) and \( z \) Cartesian coordinate system, \( \rho = \rho(z) \) is the base-state air density, \( \Omega \) is the earth’s rotational vector, \( p' \) and \( B \) are the respective perturbation pressure and buoyancy, and \( \tau_{ij} \) is the stress tensor. The \( \frac{dl}{dt} \) is the Lagrangian time derivative, and \( \nabla \) is the three-dimensional gradient operator. The \( \tau_{ij} \) stress terms are treated using a first-order subgrid closure of Smagorinsky (1963) and Lilly (1962), where the value of the mixing coefficient is set equal to the square of a mixing length times the amplitude of the deformation. Above the surface layer, the mixing coefficient is multiplied by a Richardson number term, which turns off mixing in regions that are statically stable. In the surface layer, a Blackadar (1962) mixing length is used with a \( z_0 \) surface drag formulation. Dropping the partial derivative of \( \rho \) with respect to time in the mass continuity equation leads to the anelastic form (3), where sound waves are filtered (e.g., Batchelor 1953; Ogura and Phillips 1962). This naturally leads to density \( \rho \) being only a function of height. Equations (2) and (3) are numerically approximated using the conservative Arakawa (1966) scheme.

The \( (1 + \gamma) \) factor on the right-hand side of (2) approximates the solenoidal effect in the anelastic framework. The value \( \gamma = 0 \) is used for all simulations presented in this paper. The formulation of the equations with \( \gamma = B \) is used in a postanalysis mode in section 7 to assess the effect of the solenoidal term on the small-scale dynamics in forest fire modeling. The effect of forest canopy drag on the momentum field is left for future consideration, when canopy drag may be added to (2) as a separate term or as a modification of \( \tau_{ij} \).

<table>
<thead>
<tr>
<th>Table 1. Description of experiments, where ( U_0 ) is the constant ambient wind perpendicular to the fire line, ( \Delta t ) is the time step, ( \Delta x ) and ( \Delta y ) are the horizontal resolutions, and ( \Delta z ) is the near-surface vertical resolution. The lowest level of both domains is the ground surface, that is, ( z = 0 ).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment</strong></td>
</tr>
<tr>
<td>( U_0 ) (m s(^{-1}))</td>
</tr>
<tr>
<td>Fire-line length (m)</td>
</tr>
<tr>
<td>Outer domain</td>
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<tr>
<td>( \Delta t ) (s)</td>
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<tr>
<td>( \Delta x, \Delta y ) (m)</td>
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<tr>
<td>( \Delta z ) (m)</td>
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<tr>
<td>Inner domain</td>
</tr>
<tr>
<td>( \Delta ) (s)</td>
</tr>
<tr>
<td>( \Delta x, \Delta y ) (m)</td>
</tr>
<tr>
<td>( \Delta x_{final}, \Delta y_{final} ) (m)</td>
</tr>
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</table>
The usual procedure for treating thermodynamic field variables in the anelastic framework is to expand about a reference environment. This leads to

\[ \phi(x, t) = \bar{\phi}(z) + \phi'(x, t) = \bar{\phi}(1 + \phi^e), \]  

where \( \phi \) represents \( \rho, \theta, \) absolute temperature \( T, \) pressure \( p, \) or water vapor mixing ratio \( q_v. \) An overbar denotes the mean state, and a prime denotes the local deviation of the field from the basic state. Field variables such as cloud condensate mixing ratio \( q_c, \) rain water mixing ratio \( q_r, \) and any other water species or particle concentrations are treated without expansion about a reference state. The bulk warm rain parameterization scheme of Kessler (1969) is used in the model. The reference-state variables are in hydrostatic balance where

\[ \frac{\partial \bar{\rho}}{\partial z} = -g \bar{\rho}, \]  

and they obey the ideal gas law

\[ p = \rho R_d T. \]

Here \( R_d \) is the dry-air gas constant. Using the definition of potential temperature

\[ \theta = T \left( \frac{p}{p_0} \right)^{-\kappa}, \]

where \( \kappa = R_d / C_p, C_p \) is the heat capacity of dry air at constant pressure, and \( p_0 \) is the standard pressure (taken as 1000 mb), the buoyancy is approximated as

\[ B = \left[ \frac{\theta'}{\theta} (1 + \epsilon q_v) + \epsilon q_v - q_c - q_r \right]. \]

Here \( \epsilon = R_v / R_d - 1 \) where \( R_v \) is the water vapor gas constant. This approximation of buoyancy uses the nonlinear biconstituent term (Schaefer 1975), which can be important in fire modeling due to the large concentrations of \( q_v \) released through the burning of hydrocarbons.

b. The thermodynamic equation of the mesoscale model

The conservation equation for the thermodynamic variable \( \psi \) is

\[ \frac{\partial}{\partial t} \bar{\rho} \psi + \nabla \cdot (\bar{\rho} \nabla \psi) = S_\psi + F_{\psi}. \]
where $S_\psi$ is the local grid scale and $F_\psi$ is the subgrid-scale source and sink of $\psi$. The field variable $\psi$ represents $\theta$, $q_v$, $q_e$, or $q_r$. The $\partial / \partial \tau$ operator is the local time change. Sensible heat and moisture fluxes associated with the fire are introduced into the atmospheric model through $F_\psi$, where

$$F_\psi = \frac{\partial}{\partial x_i} H_i^\psi,$$  \hspace{1cm} (10)

and the flux terms $H_i^\psi$ are represented by

$$H_i^\psi = \bar{\rho} K_H \frac{\partial \psi}{\partial x_i},$$  \hspace{1cm} (11)

where $K_H$ is the coefficient of eddy thermal diffusion. An eddy Prandtl number of unity is used so that $K_H$ is set equal to the eddy mixing coefficient for momentum $K_H$.

The coupling between the fire and the mesoscale model occurs mainly through the sensible heat flux $F_s$ and latent heat flux $F_l$ terms, where

$$H_s^\theta = \bar{\rho} K_H \frac{\partial \theta}{\partial z} + F_s(x, t)$$  \hspace{1cm} (12)

and

$$H_l^\psi = \bar{\rho} K_H \frac{\partial q_v}{\partial z} + F_l(x, t).$$  \hspace{1cm} (13)

A description of $F_s$ and $F_l$ follows.
Since the forward-in-time Smolarkiewicz (1983, 1984) scheme is used to approximate (9), the inclusion of $F_r$ and $F_i$ as described in (12) and (13) results in a second-order numerical treatment of sensible and latent heating. It is necessary to use the nonoscillatory option of the Smolarkiewicz advection scheme, as otherwise, numerical truncation errors result in the formation of clouds within the fire.

c. The fire model

The fire model is very crude, especially the radiation treatment (below), and is presently only a test bed with which to evaluate the potential utility of a coupled mesoscale atmosphere-fire model. The fire’s fuel characteristics are treated as a homogeneous dry eucalyptus forest with both ground and canopy fuel.

1) State of the fuel

Ground, $FG(x, y)$, and canopy, $FC(x, y)$, fuels are specified in units of kilograms per square meter. The initial mass of the ground fuel is

$$FG(x, y) = FG_i(x, y) + FG_t(x, y) + FG_s(x, y),$$

where $FG_i$ is ground litter, $FG_t$ is trash, and $FG_s$ is scrub. The initial masses of $FG_i$, $FG_t$, and $FG_s$ are set equal to 2.0, 0.5, and 0.2 kg m$^{-2}$, respectively. The initial mass of the forest canopy is
FC(x, y) = [1 + FMCC(x, y)]FCI_d(x, y), \hspace{1cm} (15)

where FCI_d is the initial dry mass and FMCC is the initial moist/dry ratio of the canopy fuel. The respective initial dry mass and moist/dry ratio of the canopy fuel are FGI_d = 1.2 kg m^{-2} and FMCC = 1.25.

Fuel burn rates for ground litter, trash, scrub, and forest canopy are FGBR_{li}, FGBR_{tr}, and FGBR, equal 0.040, 0.005, and 0.004 kg m^{-2} s^{-1}, respectively, and FCBR = 0.020 kg m^{-2} s^{-1} with a combustion coefficient of 1.7 \times 10^7 J kg^{-1} applied to each dry fuel type (Walker 1981). Of the sensible heat released, 3% is used to dry the ground fuel, where it is assumed that 56% of the dry fuel’s mass is converted to water vapor.

To emulate smoldering, the burn rates are premultiplied by B_{ratio}, which both limits the rate for slow fire velocities and adds a random component. The formula for B_{ratio} is

\[ B_{ratio} = \left( \frac{S_p + 1}{S_p + 4} \right)^{1/2} r_f, \hspace{1cm} (16) \]

where the units for each term under the square root are meters per second, S_p is the fire spread rate, and r_f is a random factor that varies between 0.95 and 1.05.

2) CONTACT IGNITION PARAMETERIZATION

Fuel is divided into rectangular grids. To drive the ground and canopy fire spread, four tracers are assigned to a grid cell once the ground fuel for that particular cell is ignited. Based on the following empirical
exists with a ground fire. However, a low intensity ground fire can exist without igniting a crown fire.

3) Radiation parameterization

The calculated heat fluxes from the ground and canopy burns are absorbed by the air using a simple extinction depth $\alpha$ such that

$$F_r(x, t) = F_s(x, y, h, t) \exp\left(-\frac{z-h}{\alpha}\right),$$

$$F_t(x, t) = F_l(x, y, h, t) \exp\left(-\frac{z-h}{\alpha}\right),$$

(18)

where $F_r$ and $F_t$ are the sensible and latent heat produced by the burns and $h = h(x, y)$ is the height of the topography. The $\alpha$ may range from 50 to 100 m; the current value of $\alpha$ is taken as 50 m.

In summary, this formulation treats the effects of blackbody radiation, convection, and turbulent mixing occurring on scales not resolved by the model very crudely. It is intended only for use in initial feasibility tests of the coupled mesoscale atmosphere–fire model and will be upgraded in the future.

4. Experimental design

a. The vertically stretched grid

The atmospheric model’s two-way interactive grid nesting and coordinate transformation are useful facilities that allow resolution to vary from, say, 10 km to 20 m in the horizontal and provide solutions to the equations of motion in regions of rough terrain with highly variable horizontal and vertical resolutions. The model uses the following vertically stretched and terrain-following coordinate transformation:

$$z = F(\zeta) \left[ 1 - \frac{h(x, y)}{H} \right] + h(x, y),$$

(19)

where $z$ is the vertical Cartesian coordinate, $\zeta$ is the transformed vertical coordinate, $F(\zeta)$ is a monotonically increasing function of $\zeta$, and $H$ is the height of the model lid. The boundary conditions for $F(\zeta)$ are

$$F(\zeta) = \begin{cases} 0, & \zeta = 0 \\ H, & \zeta = H, \end{cases}$$

(20)

where $\zeta = 0$ when $z = h$ so that the model’s surface follows the terrain, and $\zeta = H$ when $z = H$ so that the model lid is at a constant mean sea level height of $H$. The Jacobian of the transformation is

$$\frac{\Delta z}{\Delta \zeta} = F_r \left[ 1 - \frac{h(x, y)}{H} \right].$$

(21)
In the outer (or forcing) domain, \( F_\zeta = 40 \) m for the first two levels, and

\[
F(\zeta) = a_0 + b_0 \left( \frac{\zeta}{\Delta \zeta} \right) + c_0 \left( \frac{\zeta}{\Delta \zeta} \right)^2
+ d_0 \left( \frac{\zeta}{\Delta \zeta} \right)^3 + e_0 \left( \frac{\zeta}{\Delta \zeta} \right)^4
\] (22)

for \( \zeta/\Delta \zeta > 2 \), where the values of the coefficients in (22) are derived as \((a_0, b_0, c_0, d_0, e_0)\) equal \((-8.1565781, 52.526173, -6.5543919, 1.2380518, -0.036413290)\), respectively. Equation (22) allows a smooth transition from \( F_\zeta = 40 \) to 200 m over 16 levels. A tanh transition in \( F(\zeta) \) centered at 10 km using a 1-km half-width increases the grid size from 200 to 500 m. For further details on the transformed equations and numerical considerations see Clark (1977), Clark and Farley (1984), Clark and Hall (1991), and in particular Clark and Hall (1996, submitted to J. Appl. Meteor.), where the importance of designing a smooth vertical grid in the context of vertical refinement with stretching is discussed.

b. **Effect of resolution on heat flux**

When the fire begins, there is initially no convection to remove heat efficiently, causing very high air temperatures to build near the surface. Once the convection...
is well established, the temperature equilibrates to significantly lower values as the convective heat transport balances the heat flux from the fire. The time the fire takes to establish this balance varies from case to case, and in our experiments so far, this timescale for convective adjustment, $t_{\text{adj}}$, was between approximately 1 and 2 min, as determined from the plot of the maximum temperature anomaly versus time.

After convective adjustment, the atmosphere transports heat away from the fire such that the convection is in balance with its heat source. The sensible heat flux is calculated as

$$ F_i = c_p \langle \rho w' \theta' \rangle \approx F_s, \quad (23) $$

where $c_p$ is the specific heat capacity at constant pressure $p$, and $w'$ and $\theta'$ are the respective vertical velocity and temperature perturbations from the mean. Consequently, it is crucial that the convection responds to the atmospheric variables in a realistic way, pointing to the significance of a dynamical atmospheric model. The maximum vertical velocity anomaly $\Delta w \approx 20–30 \text{ m s}^{-1}$, and the maximum temperature anomaly $\Delta \theta \approx 40–80 \text{ K}$ over the region of intense heating for a typical numerical simulation. A rough estimate of $F_i$ supplied by these perturbations is therefore

$$ F_i \approx c_p \langle \rho \Delta w \Delta \theta \rangle \approx 0.8–2.4 \text{ MW m}^{-2}, \quad (24) $$
which easily accounts for the 0.8 MW m$^{-2}$ of sensible heat flux emitted by the fire. Due to the efficient heat transport by convection, it seems fairly clear that $\Delta \theta$ is limited to values as low as 40–80 K, even though the fire may have radiant temperatures of approximately 1000–1200 K.

Model resolution has an extremely important influence on the heat transport away from the fire; if horizontal and vertical resolutions are substantially reduced, then the model fluid becomes much less efficient at transporting heat and the heat balance changes dramatically. For example, in initial test runs a 200-m horizontal resolution was used for the dynamics. The results were much higher perturbation temperatures, a much smaller convective Froude number, and an almost immediate blowup fire. The fire spread rates went out of control and reached values in excess of 50 m s$^{-1}$.

The importance of model resolution for the dynamics cannot be over emphasized: to realistically investigate the coupling between fire and atmospheric dynamics, model resolution must not dictate the values of $F_z$ and $F_q^2$ and, thereby, the overall fire behavior.

The horizontal resolution of the fuel is another important issue. A reasonable guideline is to consider the time it takes the fire to burn the small fuel $\tau$ and the fire-line advance speed $S_p$ to establish a horizontal fire resolution: $\Delta x_{\text{fuel}} \leq S_p \tau$. A fire line typically moves 10–25 m in time $\tau$, where $\tau$ is the same order as the
convective adjustment timescale $t_{\text{adj}}$. For $S_p \approx 0.5 \text{ m s}^{-1}$ and $\tau \approx 50 \text{ s}$, $\Delta x_{\text{fuel}} \leq 25 \text{ m}$ should provide a continuous fire behavior. If $\Delta x_{\text{fuel}}$ is too large, a discontinuous heat flux from the fire forces air to always readjust to the fire. Since $t_{\text{adj}}$ is comparable to the time required for the small fuel to burn, namely about 100 s, the effects of the heat flux from a model with coarse fuel resolution are not expected to average out with time. A $\Delta x_{\text{fuel}} = 10 \text{ m}$ horizontal resolution for the fire was generally sufficient to avoid discontinuities in the model solutions. One of our experiments, FIRE7A, which had weak ambient wind forcing, did result in detectable discontinuities in the ambient maximum heat flux versus time, which most likely affected the details of the results. But, as discussed in section 5b, this was due to the limitations of (17) and was not related to resolution.

c. Outline of experiments

A series of numerical experiments with idealized initial conditions is used to examine the temporal evolution of fire lines and demonstrate the role of feedback of convection on the fire-line dynamics. Experiments FIRE7A, FIRE7C, and FIRE7D represent three coupled atmosphere–fire simulations of short fire lines (420 m). Experiments FIRE8D and FIRE8E are two simulations of long fire lines (1500 m) in various constant ambient wind conditions. Table 1 shows the different ambient winds $U_o$ and fire-line lengths used in these experiments.
One level of mesh refinement with two-way interactive grid nesting is used in the simulations. The horizontal and near-surface vertical resolutions, and the time steps for outer and inner domains are given in Table 1. The local wind used to determine fire speed $S_f$ is taken at a height $\Delta z/2 = 10$ m, and the resolution of the fuel is $\Delta x_{fuel} = \Delta y_{fuel} = 10$ m.

A well-mixed, 1-km-deep boundary layer with a constant potential temperature $\theta = 300$ K, and therefore neutral static stability, and a water vapor mixing ratio of $q_v = 12$ g kg$^{-1}$ is chosen. Above the boundary layer to a tropopause at 10 km, water vapor $q_v$ decays exponentially to a minimum of 0.1 g kg$^{-1}$, and the buoyancy frequency is $N_f = 0.01$ s$^{-1}$. Above the tropopause to 13 km, the top of the outer domain, the buoyancy frequency is $N_f = 0.02$ s$^{-1}$. The surface roughness length is $z_o = 0.5$ cm. Each simulation is integrated out to 12 min.

The fuel is homogeneous, so that any scale selection in either the air motions or shape of the fire line is due to the dynamic and thermodynamic interactions between the fire and the meteorology. Topography, Coriolis force, or diurnal effects are not considered.

All results shown are for the fire's developed convective stage—that is, for times much larger than $t_{adj}$, where $t_{adj}$ is determined from the plots of maximum temperature anomaly versus time, as shown in Fig. 2. Figure 2b indicates that maximum temperature anom-
aly occurs near $t = 0$ and then drops off to a steady value by about $t = 2$ min for experiments FIRE7A, FIRE7C, and FIRE7D. The fully developed convection transports heat away, resulting in a significantly reduced temperature anomaly maximum for $t > t_{\text{adj}}$.

5. Effects of ambient wind on short fire-line evolution

Figures 3, 4, and 5 each show the surface fuel ignition at four times for FIRE7A, FIRE7C, and FIRE7D, respectively. These figures display the effect of the feedback by the atmospheric dynamics on fire-line shape. With $U_0 = 1$ m s$^{-1}$ in FIRE7A (Fig. 3), the position of the fire front remains fairly stationary and linear, and the fire line eventually breaks up. With $U_0 = 3$ m s$^{-1}$ in FIRE7C (Fig. 4), the fire front moves forward, forming a continuous parabolic shape. Similarly in FIRE7D (Fig. 5) with $U_0 = 5$ m s$^{-1}$, the fire front first takes on a continuous parabolic and then later a conical shape. The following section explains how the variations in the ambient wind feed back on the fire to produce these basic fire-line patterns.

a. Projection of the low-level convergence pattern onto the fire line

The parabolic (or conical) shape of the fire line for the higher winds can be explained by considering the projection of the low-level convergence pattern produced by hot convective columns onto the fire line. In the absence of an ambient wind, a vertically oriented convective cell positioned at $(x, y) = (x_0, y_0)$ draws low-level air equally from all sides, and the structure
of $u(y)$ at a fixed $x$ position horizontally displaced from the cell has a bell-like shape with a maximum amplitude at $y = y_0$. Figure 6 shows the simplest example of this geometry. Here, for the sake of argument, the low-level convergence field feeding the hot column is ideally represented by $V_r = \beta/r$, where $V_r$ is the radial velocity, $\beta$ is a constant, and $r = [(x - x_0)^2 + (y - y_0)^2]^{1/2}$ is the radial distance from the center of the hot air column. At a point $x = x_f$ in the fire,

$$u(x_f, y) = V_r \cos \theta = \frac{\beta(x_f - x_0)^{-1}}{1 + (y - y_0)^2(x_f - x_0)^{-2}},$$

(25) and for $x_f = \text{constant}$, the $u$ component normal to the initial fire line has a bell-shaped structure. It is assumed that in a mean ambient wind, the convective column is tied to the fire at the surface and tilts downstream with height. The effect of downstream tilting is to shift the center of the low-level convergence pattern ahead of the fire front, and the faster the ambient wind, the stronger the tilt and the farther forward the center of the convergence zone. If the fire-induced convective column advects quickly enough so that it remains in front of the fire line, but slowly enough so that it never totally decouples from the fire, then its near-surface convergence pattern can induce a smoothly and contin-
Fig. 14. Four time levels of vertical vorticity $\eta(x, y)$ at $z = 30.0$ m AGL for experiment FIRE7C. The wind vectors represent the horizontal winds at 10 m AGL, and the heavy solid line represents the 0.1 MW m$^{-2}$ sensible heat flux contour. The thin solid line represents $\eta = -0.01$ s$^{-1}$ to outline the negative regions. The initial fire length is 420 m, and $U_0 = 3$ m s$^{-1}$.

ually evolving parabolic shape to the fire line. In other words, for $0 < S_f < U_0$, the tilted convection column projects a surface convergence zone slightly forward of the fire line, drawing air (at the 10-m height) from different azimuthal angles along the fire line, forming a curved inflow region at the fire front. Although the degree of tilt affects the near-surface shape of the wind component $u (x = x_r, y = y_f, z = 10$ m) over the fire due to variations in exactly how air is drawn into the updraft, the basic curved shape remains. If the advecting wind is large enough, the hot convective columns may continually break away and reform over the fire front, complicating these interactions.

Keeping these basically linear arguments in mind, we now consider the simulations of experiments FIRE7C and FIRE7D. Plots of $B$ (Figs. 7 and 8) and $w$ (Fig. 9) show that for FIRE7C, where $U_0 = 3$ m s$^{-1}$, the convection is at all times tilted slightly downstream of the fire line (Fig. 7) and remains slightly in front of the fire (Figs. 8 and 9), drawing air in at an increasing azimuthal angle to the fire line from the farthest points of the fire, as shown by the wind vectors in Figs. 8 and 9. The result is the formation of a parabolic-like shape to the fire line, seen previously in Fig. 4. For FIRE7D ($U_0 = 5$ m s$^{-1}$) (not shown) the convective column is more sharply tilted and remains well in front of, but
still with, the fire, drawing air from sharp azimuthal angles at the fire-line extremities. As a result, there is the formation of a much more pronounced parabolic or arrowhead shape to the fire line, seen previously in Fig. 5.

Figure 2a shows that there is a dependence between the ambient wind speed $U_0$ and the maximum fire spread rate $S_{\text{max}}$: increasing $U_0$ from 1 to 3 m s$^{-1}$ results in $S_{\text{max}}$ increasing from about 0.3 to 0.4 m s$^{-1}$; increasing $U_0$ from 3 to 5 m s$^{-1}$ results in $S_{\text{max}}$ increasing from approximately 0.4 to 0.5 m s$^{-1}$. The $S_{\text{max}}$ values in Fig. 2a are quite different from the initial values of $S_f$ at $t = 0$. Initial values of $S_f$ are 0.20, 0.23, and 0.27 m s$^{-1}$ and are obtained by simply substituting $U_0 = 1, 3$, and 5 m s$^{-1}$, respectively, for $|V_h|$ in (17). There are some notable transitions in the structure of $S_{\text{max}}(t)$ as $U_0$ increases. Figure 2a shows that for $U_0 = 1$ m s$^{-1}$ in FIRE7A, $S_{\text{max}}$ pulses a lot; for $U_0 = 3$ m s$^{-1}$ in FIRE7C, $S_{\text{max}}$ pulses a little around 4 min; and for $U_0 = 5$ m s$^{-1}$ in FIRE7D, $S_{\text{max}}$ does not really pulse at all, but goes into a regular cyclic variation with a period of about 1 min. The pulses in FIRE7A and FIRE7C are most likely a result of small-scale vorticity dynamics at the fire front, where vortex tilting locally amplifies $S_f$. A second contributing effect is the preheating of the air caused by the backfire in these experiments. This subject is discussed further in section 5b. We have not yet analyzed the results to determine
the cause of the regular oscillations in $S_f$ that occur in FIRE7D.

Figure 2c shows that the relative humidity never reaches saturation within the second domain, which extends to $z = 1.2$ km or 200 m above the top of the boundary layer. However, cumulus clouds do develop as a result of the forced updrafts in all of the present simulations. The cloud bases were high enough above the boundary layer that they had no significant effect on the fire dynamics presented. This is partly because the duration of the simulations was too short for precipitation to reach the boundary layer and induce evaporatively cooled downdrafts. Until the effects of evaporation can be realized, clouds basically suck air from the boundary layer. Before clouds can affect the fire dynamics, they must first develop gust fronts through evaporative cooling, which can then blow air on the fire. There is a fundamental difference between gust fronts and suck fronts. As any smoker knows, it is very difficult to suck out a match from any safe distance whereas it is a simple matter to blow it out from the same distance. An interesting phenomenon to investigate in the future is the possible effect of precipitation from pyroconclus on the fire dynamics.

b. Nonlinear dynamics: Fire-line breakup in weak ambient winds

The weak ambient wind speed of $U_0 = 1$ m s$^{-1}$ in FIRE7A results in a small $P_c$ value, meaning that the air is coming from both sides of the main fire line and feeding the hot convection column almost directly from
below. Note how there is little tilt to the convection column (Fig. 10) and little horizontal displacement between the fire and the hottest air aloft (Fig. 11). The convective mechanism of forming a parabola does not exist, as shown by the wind vector pattern in Fig. 11, and the convergence pattern feeding the initial rising hot air does not affect the shape of the fire as in FIRE7C and FIRE7D. Also note the significant temperature anomalies and vertical velocity gradients along the fire front (Figs. 11 and 12).

In this simulation the circulation on the scale of the width of the fire front, about tens of meters or less, dominates the fire dynamics. The fire line’s speed is slow enough that fire-generated winds basically break up the fire line. Eventually the convection and local dynamics become nonlinear, producing rather erratic shapes to both the fire line and convection. The very large horizontal buoyancy gradients at the fire front produce strong horizontal vortices, and the vertical motions within the fire eventually lead to vortex tilting, producing vertical vorticity. In some cases vorticity is further amplified by stretching, and the results indicate that some of these vertical vortices cause the breakup of the fire line shown in Fig. 3. In the future, we plan to investigate the production and effect of horizontal and vertical vorticity in the vicinity of fires and to compare our results to the various types of fire vortices that are observed (Church et al. 1980).
Figures 13–16 are plots of FIRE7C and FIRE7A vertical z-vorticity \( \eta \), where \( \eta = \mathbf{k} \cdot \nabla \times \mathbf{V} \). Plots of FIRE7C \( \eta \) (Figs. 13 and 14) and FIRE7D \( \eta \) (not shown) indicate that, although nonlinear dynamics occurred, z vorticity was well ahead of, not embedded in, the fire line. Plots of FIRE7A \( \eta \) (Figs. 15 and 16) show that in this case the vertical vortices embedded within the fire line resulted in its breakup.

In the case of FIRE7A the mean wind speed was small enough that the local fire convection changed the sense of the wind. As a result, a fire-line tracer that had been moving with the wind would suddenly find itself in an opposing wind condition. The logic of the fire-tracer code was not general enough to deal with this complexity, and consequently the gridpoint fuel frequently burned out faster than a forward-moving tracer (moving with the wind) could pass through a fuel grid point before the wind conditions reversed. Figure 2d shows that the heat flux \( F_h(r) \) maximum was often well below the possible 0.8 MW m\(^{-2}\) maximum, indicating that during these times there was no single dynamical grid point (at 20-m horizontal resolution) with all four fuel grid points (at 10-m horizontal resolution) burning. This defect in the treatment of the logic for the fire-line tracers will be corrected in the future.

6. Effects of convection on long fire lines: Convective fingering

Figures 17 and 18 show the fire-line evolution at four times for experiments FIRE8E \( (U_0 = 2 \text{ m s}^{-1}) \) and
Fig. 19. Full inner domain view of $w(x, y)$ for $z = 110$ m AGL at (a) $t = 6$ min and (b) $t = 12$ min for experiment FIREBE. The initial fire length is 1500 m, and $U_0 = 2$ m s$^{-1}$. The heavy solid line represents the 0.1 MW m$^{-2}$ sensible heat flux contour. The thin solid line represents $w = -1$ m s$^{-1}$ to outline the negative regions.

FIRE8D ($U_0 = 3$ m s$^{-1}$), respectively. The $x$–$y$ vertical velocity $w$ and heat flux $F_t$ contours of 0.1 MW m$^{-2}$ are shown in each plate. Only the lower 1 km $\times$ 1 km portion of the domain, a little over one-half of the full extent of the 1500-m-long fire lines, is displayed in these figures to focus on the details of the fire-line structure. To display departures from symmetry, Figs. 19a and 19b show the full domain extent of $w(x, y)$ with overlaid fire-line ignition at $t = 6$ and 12 min. In these two cases, as the longer fire line evolves, it first takes on a slight parabolic shape, which by $t = 6$ min shows signs of breaking up; by about $t = 8$ min the fire line has broken and each part has taken on a conical shape.

This longer fire-line behavior in a relatively weak ambient wind can be described as a two-step process. Our explanation for the shapes of the fire lines shown in Figs. 17 and 18 and the Onion fire shown in Fig. 1 is a simple extension of our explanation for the cause of the parabolic shape of the short line fire. The added complexity here is that once the fire line is long enough, it cannot sustain a single convective updraft column and develops multiple columns due to along-line instabilities within the convection. For a long fire line in a relatively weak ambient wind, the convection attempts to form a long, vertically deep, nearly two-dimensional structure. Such two-dimensional structures are typically dynamically unstable due to either convective or shearing instabilities and result in so-called cross-roll

Fig. 20. The maximum fire spread rate $S_{f\max}$ (m s$^{-1}$) versus $t$ for experiment FIREBE.
instabilities. Similarly, the long single column in experiments FIRE8E and FIRE8D displayed a cross-roll instability and broke into the two parts shown in Figs. 17–19. After the breakup of the convection column, the formation of fingers is identified with the modification in the low-level convergence pattern in the vicinity of the fire. In weak ambient winds, the convection remained just downstream of the long fire line, forming two protrusions, or convective fingers.

The depth of the convection is a dominant scale of this problem, and it seems likely that the horizontal spacing between the convective updrafts should choose a similar scale. In the present problem the convection is approximately 1000 m deep suggesting that the 1500-m fire-line length in these experiments is marginally short. A much longer fire line of about 3–4 km would have allowed a much more unambiguous choice of horizontal scale for the cross-roll breakup of the atmospheric convection and resulting choice of scale for the convective fingers of the fire line. However, this was considered too expensive an experiment, as the short fire-line experiments already take about 4 h of Cray YMP processor time for 12 min of simulated time.

Due to the limitations of the present experiment, a detailed analysis of the actual breakup of the convection along the fire line for these cases was not considered. However, strong vorticity production with tilting during this transition resulted in an intense vertical vor-
Fig. 22. Same as Fig. 21 except for $\eta_{blk}$, the solenoidal source of vertical vorticity. The contours range between $\pm 0.006$ s$^{-1}$. The thin solid line represents $\eta_{blk} = -0.0001$ s$^{-2}$ to outline the negative regions.

In the next section, this vortex is used to present what might be considered a worst case scenario on the effect of neglecting the solenoidal term by setting $\gamma = 0$ in (2). This vortex also demonstrates the potential for lofting of burning material in future fire simulations.

7. Effect of the solenoidal term

Figures 17–19 show that an intense vertical rotor developed in experiment FIRE8E. The impact of the vorticity dynamics associated with this rotor on the fire spread rate is shown in Fig. 20. Here $S_{\text{max}}$ develops a pronounced spike near $t = 5.8$ min, when it jumps from about 0.5 to almost 1.5 m s$^{-1}$ over a period of about 1 min, as the rotor advects along the fire line. This dynamical interaction between the fine-scale vorticity at the fire front and the fire-spread rate highlights the importance of accurately modeling the vorticity budget.

As discussed in sections 1 and 3, it is important to consider the effect of excluding the solenoidal term in the pressure gradient force—that is, whether the anelastic approximation where $\gamma = 0$ is adequate for fire modeling. To address this question, the two source–sink terms for vertical vorticity $\eta$ are compared in a post analysis mode by putting $\gamma = B$ in (2). The two vorticity source–sink terms are the vortex tilting term $\eta_{\text{tilt}}$, defined as

$$
\eta_{\text{tilt}} = -\frac{\partial w}{\partial x} \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \frac{\partial u}{\partial z},
$$

(26)
and the solenoidal production $\eta_{sol}$, defined as

$$
\eta_{sol} = \frac{\partial B}{\partial y} \frac{\partial \phi}{\partial x} - \frac{\partial B}{\partial x} \frac{\partial \phi}{\partial y},
$$

(27)

where $\phi = p'/\rho$. Here $\eta_{lin}$ represents the generation of vertical vorticity by the tilting of the x and y vorticity components into the vertical in a nonuniform vertical motion field. The $\eta_{sol}$ is a result of

$$
- \nabla \times (B \nabla \phi) \cdot \mathbf{k} = \nabla_n B \times \nabla_n \phi
$$

(28)

and represents the generation of vertical vorticity when the flow field is displaced from a state in which $\nabla_n \phi$ and $\nabla_n B$ are parallel.

An analysis of $\eta_{lin}$ and $\eta_{sol}$ for the conditions shown in Figs. 17 to 19 is considered a severe test of $\gamma = 0$. In this situation, the horizontal gradients of $B$ and $\phi$ are strongly misaligned due to centripetal acceleration shifting the pressure minimum to the rotor's center. Figures 21 and 22 show $\eta_{lin}$ and $\eta_{sol}$, respectively, at four time levels spaced 5 s apart during the period of significant vortex spinup. The contour interval in these two figures differs by a factor of 10, indicating vortex tilting by far dominates the solenoidal vorticity source in this experiment. This suggests that even for these nonhydrostatic scales, the horizontal gradients of $\phi$ and $B$ are aligned sufficiently that the forcing is dominated by the usual anelastic baroclinic terms.

8. Conclusions

This paper describes how a mesoscale model, which has been used successfully on a wide variety of meteorological phenomena such as downslope windstorms, severe cumulus convection, frontal dynamics, and tropical convection, is coupled with a simple dry eucalyptus forest fire model to construct a three-dimensional, time-dependent wildfire simulation model. Even the recent modeling attempts by Heilman and Fast (1992) and Heilman (1992) at studying the intense heating effects in wildfires used a two-dimensional, nonhydrostatic model with terrain-following coordinates that did not include coupling between fire and dynamics. An exception is the recent work of Grishin (1992), in which he also presents examples of coupled atmosphere–fire modeling. These studies demonstrate how physically based and verifiable coupled models can simulate the interaction between the fire and the atmosphere to successfully study forest fire behavior and structure.

The coupled atmosphere–fire model simulations of short fire lines with single convection columns show how ambient wind strength, not fuel distribution or type, can affect fire-line stability and geometry. In weak constant ambient winds, air feeding the hot convection column comes directly from below, resulting in nonlinear dynamics, vertical vortices embedded in the fire line that cause erratic fire scale, fire-generated winds to break up the fire line. Although the fire line remains linear, it is unstable and experiences breakup. Breakup is therefore not simply due to increased fire-line length or inhomogeneous surface fuel distribution or type. Stronger constant ambient winds result in linear dynamics, where the fire line takes on a parabolic or curved shape; if the convective cell aloft remains just downstream—and is not decoupled—from the fire line, it draws the fire with it, and its near-surface convergence pattern induces a smoothly, continually evolving parabolic shape to the fire line.

This argument is extended to explain the multiple protrusions of fire, or convective fingers, that occur in the coupled atmosphere–fire model simulations of longer fire lines. The formation of fire fingers is the result of a long fire line and relatively weak ambient winds. Under light winds, the long fire line is dynamically unstable and experiences breakup of the nearly two-dimensional column of hot air into multiple columns. A feedback between the near-surface convergence pattern and the winds in the vicinity of each column’s fire front pulls the fire line into a parabolic shape.

The demonstration for the necessity of using a coupled atmosphere–fire model is based on the convective Froude number. As a measure of how strongly the flow responds to the convective heating by the fire, estimates of $F^2_c$ show that even for nonblowup fire conditions the wind and fire are essential parts of the same system and cannot be separated.

For a physical interpretation of fire conditions without a detailed description of the fire–atmosphere dynamics, the convective Froude number is a ratio of fundamental importance. Practical problems in the dynamics of fire–atmosphere flow may be reduced to a formulation of relevant functions of $F^2_c$ over a certain range of values of $F^2_c$. The initial step is to discover, either experimentally or theoretically, the $F^2_c$ values that relate the dynamic state of one flow field to another. The scale parameters regarded as critical to fireflow regimes are the potential temperature anomaly, width of the anomalous heating, and fire airflow strength.

It has been found that $F^2_c$ can be an important parameter for fire-tunnel experiments to match real fires, and one example of a laboratory test possible in a fire tunnel is the convective fingering hypothesis. Assuming that the horizontal spacing of the hot air column is determined by the depth of the convection, then the most obvious scale in the free atmosphere is the depth of the well-mixed boundary layer; for aspect ratios of about 1, the expected spacing between convective updrafts is then about 1 km for a 1-km-deep boundary layer. A vertical scale to the convection could be imposed in a fire tunnel by installing a shield some distance above the fire where this height could be varied. By tuning both the shield height and the airflow rate,
it might be possible to induce fire-line fingering with variable horizontal spacings.

Our long term goal is to develop a comprehensive coupled atmosphere–fire model with forecast potential in the operational mode. However, this is impractical at the present time and for the foreseeable future. The reason is partly because many physical processes in the fire–atmosphere system, especially those involving flame physics and combustion chemistry, remain poorly understood and partly because the computational demands of such a model exceed the capability of present-day computer technology, despite the remarkable recent advances in this field. A real-time workstation model may be available in a few years. On the other hand, recent computational advances are sufficiently significant that it is possible to model subcomponents of the fire–atmosphere system with a considerable degree of sophistication, as this study shows. We see this current coupled atmosphere–fire model as a sensible forerunner to a completely coupled atmosphere–fire model.

In the meantime, there are many model refinements to be attempted. The fire model is very crude, presently only a test bed with which to evaluate the potential utility of a coupled atmosphere–fire model.

Hopefully, the current empirical McArthur or Rothemel formulas for fire spread rates can be replaced with a more accurate model treatment of microscale processes involving variable winds within the fire and adjacent fuel. The effects of blackbody radiation, convection, and turbulent mixing occurring on scales not resolved by the model are also treated very crudely and will be upgraded in the future. As mentioned, no drag parameterization was included in any of the coupled model simulations. Available canopy drag formulations will be tested to determine drag effect and eventually incorporated into the coupled model. Possible sources for appropriate formulations are Wilson and Shaw (1977), Shaw and Segner (1985, 1987), Wilson (1987), and Wang and Takle (1995a,b; 1996a,b).

A vorticity budget analysis shows that the solenoidal source term for vertical vorticity is at least an order of magnitude smaller than the tilting term. This analysis was performed when an intense vertical rotor occurred, a situation where the solenoidal term may develop its largest amplitudes. The relatively small magnitude of the solenoidal source of vertical vorticity compared to the vortex tilting indicates that the usual anelastic formulation for the equations of motion, where the pressure gradient does not produce vertical vorticity, is acceptable for fire modeling. Nonetheless, including modifications to the pressure gradient will be considered in future simulations.

The simulations demonstrate that intense vertical rotors can develop and significantly affect the fire spread rate. From these experiments, it is easy to see how other physical effects, such as the lofting of burning material, also rely on the sources and sinks of vertical vorticity. Vertically oriented rotors can be so intense as to loft burning material and eject it ahead of the fire, possibly creating spotting conditions that can result in jump fires. High-amplitude vertical rotors are frequently noted by fire observers and have been observed by lidar in the Battersby fire in northern Ontario (Banta et al. 1992).

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