Regimes of Dry Convection above Wildfires: Sensitivity to Fire Line Details

MICHAEL T. KIEFER* AND MATTHEW D. PARKER
North Carolina State University, Raleigh, North Carolina

JOSEPH J. CHARNEY
Northern Research Station, USDA Forest Service, East Lansing, Michigan

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ABSTRACT

Fire lines are complex phenomena with a broad range of scales of cross-line dimension, undulations, and along-line variation in heating rates. While some earlier studies have examined parcel processes in two-dimensional simulations, the complexity of fire lines in nature motivates a study in which the impact of three-dimensional fire line details on parcel processes is examined systematically. This numerical modeling study aims to understand how fundamental processes identified in 2D simulations operate in 3D simulations where the fire line is neither straight nor uniform in intensity. The first step is to perform simulations in a 3D model, with no fire line undulations or inhomogeneity. In general, convective modes simulated in the 2D model are reproduced in the 3D model. In one particular case with strong vertical wind shear, new convection develops separate from the main line of convection as a result of local changes to parcel speed and heating. However, in general the processes in the 2D and 3D simulations are identical. The second step is to examine 3D experiments wherein fire line shape and along-line inhomogeneity are varied. Parcel heating, as well as convective mode, is shown to exhibit sensitivity to fire line shape and along-line inhomogeneity.

1. Introduction

For scientists studying wildfires, the complex interplay among fire, fuels, and the atmosphere motivates a great number of research questions. This study will investigate two questions pertaining to atmospheric structures that develop above a fire. First, how does convection develop as a result of the heat output from fires? Second, which factors are important in determining organizational mode and intensity? A limited number of studies have considered the gross characteristics of observed plumes (e.g., height, tilt from vertical) under different atmospheric wind regimes (e.g., wind speeds increasing with height from surface, low-level jets) (Byram 1973b; Grishin et al. 1984; Rothermel 1991). However, the processes fundamental to the generation of convection by wildfires have remained largely unexamined. More recently, studies using coupled atmosphere–fire models have examined how convection generated by a fire can feed back on the fire itself. For example, Clark et al. (1996a, hereafter C96) investigated the breakup of initially linear fire lines into perturbed fire lines with rapidly spreading segments and Linn and Cunningham (2005) have examined the role of convective versus turbulent heat transfer to unburned fuels. The studies suggest that investigating the fundamental processes that yield different types and intensities of convection can enhance our ability to anticipate some types of fire behavior.

The interaction of the environmental (i.e., unperturbed, far upstream) wind with buoyant circulations above wildfires can lead to the development of multiple modes of convection of varying intensity and spatio-temporal scale. The fundamental dynamics behind the development of these convective modes are still not well understood. One such convective mode is multicellular convection, which consists of convective cells that periodically develop and propagate away from the fire. A second mode of interest is the fire plume, which consists of one large, generally upright convection column with strong vertical velocities. Plume and multicell phenomena have been observed extensively (e.g., Banta et al.
and have been reproduced in numerical simulations using coupled fire–atmosphere models (see Fig. 9 in Clark et al. 1996b). It should be noted that the focus of Clark et al. (1996b) was on the multiscale processes that control certain aspects of fire behavior such as fire line shape and spread rate. Although different convective modes were apparent in the figures presented by Clark et al. (1996b), the features were not examined in detail. In this study, we are interested in the characteristics and dynamics of these phenomena.

A recent numerical modeling study, Kiefer et al. (2009, hereafter KPC), examined the processes underpinning the organization of dry convection generated by wildfires. They found distinct relationships between a pair of control parameters and the convection’s organizational mode and intensity. The two parameters developed by KPC from the governing equations were an advection parameter,

$$A = \frac{\bar{U}^2L_z}{\left(\frac{\rho_z}{\rho}gL^2\right)}$$  \hspace{1cm} (1)$$

and a surface parcel heating parameter,

$$B = \frac{Q_oL}{U_s\theta'_zL_z\rho_oC_p},$$  \hspace{1cm} (2)$$

where $Q_o$ is the surface heat flux, $\theta'_z$ is a perturbation potential temperature scale, and $\rho_z$ and $\rho$ are scales of total and perturbation air density, respectively; $\bar{U}$ and $U_s$ are the far upstream mixed-layer mean wind speed and surface wind speed, respectively, and $L$ and $L_z$ are horizontal and vertical length scales of the problem, respectively. All other symbols have standard definitions.

When parameter $A$, a measure of the strength of advection by the mean wind, was less (greater) than unity, plume (multicell) types were simulated. In the plume class, a single deep updraft was simulated, while in the multicell class, a series of updrafts were simulated that developed and subsequently moved away from the fire. Within each broad convective classification (i.e., plume, multicell), the intensity of convection was shown by KPC to be a function of parameter $B$, a measure of the amount of heat surface air parcels receive from the fire. Within the low-advection area of the parameter space, the plume class was divided into intense plume and hybrid subclasses based on whether vertical motion in the upright plume was continuous (intense plume) or consisted of discrete cells (hybrid). Multicell cases were divided into strong and weak subclasses based on the depth of convection and the likelihood of feedback on the fire. Additionally, vertical wind shear was found to play an important dynamical role in cases with base state wind reversal profiles. A summary of the relationship between organizational mode and control parameters is presented in Fig. 1 (reproduced from KPC), and wind profiles for the benchmark cases discussed in KPC are presented in

![Fig. 1. Matrix of control parameter experiments, with organizational mode overlaid. Matrix elements are defined as $AaBb$, where the index $a$ refers to the row and index $b$ refers to the column of the matrix. For example, the element $A2B2$ refers to row 2, column 2 of the experiment matrix, where $A = 0.3$ and $B = 0.4$. Multicell cases are shaded dark (strong multicell) and light (weak multicell), with intense plume cases unshaded and hybrid cases outlined with a dashed line. Cases with base state bulk Richardson number less than or equal to 0.25 are indicated by bold text and cases with base state wind reversal profiles are indicated by underlined text; $A = 1$ and $B = 1$ boundaries are indicated by thick solid lines.](http://journals.ametsoc.org/jas/article-pdf/67/3/611/3519233/2009jas3226_1.pdf)
The wind profiles in Fig. 2 were chosen to depict a range of background conditions from well-mixed boundary layers to strong shear profiles that are characteristic of, for example, frontal passages or jets aloft.

The fundamental processes that were shown by KPC to contribute to development of the intense plume, hybrid, and strong multicell modes are summarized in Fig. 3 (reproduced from KPC). The key difference in forcing for the intense plume and strong multicell modes was shown to be the absence of strong flow over the fire in the multicell case. Such relatively weak flow allowed the upward-directed buoyancy force to periodically dominate over the downward-directed pressure gradient force downstream of the fire, yielding new convection (cf. Figs. 3a and 3c). In general, dynamic forcing associated with the base state wind shear was found to play a minor role for the intense plume and strong multicell modes but was noted to be critical for the hybrid mode. The strong mixed layer wind shear in the hybrid cases was shown to contribute to a perturbation pressure minimum centered above the low-level inflow. Also, the base state wind reversal (Fig. 2b) was shown to allow low-level air parcels to move beneath the dynamic pressure minimum prior to reaching the heat source (Fig. 3b). The result of the dynamic forcing in the hybrid mode was the development of vertical velocities of magnitude similar to the intense plume mode, despite the absence of strong buoyant forcing.

The simple two-dimensional simulations of KPC were well suited to a study for which a large number of simulations was required. However, the restriction to a two-dimensional model did not allow KPC to assess potentially important three-dimensional processes, such as vertical vorticity dynamics, that might yield substantial deviations in convective mode or intensity from the 2D simulations. In addition, a great deal of case-to-case variability is known to exist with respect to three-dimensional fire line details, such as fire line shape and local hotspots (Jenkins et al. 2001; C96). A fire line may exhibit numerous undulations (or fingers) ranging in scale from $O(\text{m})$ (Coen et al. 2004) to $O(\text{km})$ (C96), with comparable scales for along-line variations in heating rate. The undulations and along-line variations in heating rate are in fact well correlated since the heat output from the fire is a function of the amount of fuel consumed per unit time. Assuming all other parameters are held steady, a faster-moving fire segment is more intense (i.e., exhibits stronger sensible heat fluxes). In this study, features with scale $O(\text{km})$ are examined, comparable to the convective fingering phenomena C96 investigated (see their Fig. 1 for an example of the phenomenon). Note that the descriptor “convective” refers here to the role that atmospheric convection plays in deforming the fire line. C96 performed simulations of an initially straight fire line (of length 1.5 km) in a low wind speed environment and concluded that the fingering phenomenon...
was the result of air being drawn into plumes and driving locally stronger cross–fire line flow. The development of increased cross–fire line wind speeds led to increased fire spread rates in segments (typically referred to as the “head” of the fire) adjacent to areas of less perturbed spread rates (typically referred to as the “back” of the fire). While complex fire lines have been simulated using coupled atmosphere–fire models, including the Clark Coupled Wildfire model (C96; Clark et al. 1996b) and the FIRETEC model (Linn et al. 2002; Linn and Cunningham 2005), a fundamental question remains unanswered: How do fire line complexities impact the two-dimensional processes identified in KPC?

This study examines the impact of fire line shape and along-line inhomogeneity on the intensity and organization of fire-induced convection. As in KPC, the fire and atmosphere only interact “one-way”—in other words, the fire may induce perturbations in atmospheric variables (e.g., horizontal wind speed, pressure), but the fire is static and cannot respond to such atmospheric changes. The “fire” in the 2D simulations of KPC was a surface heat flux fixed in space and time in the model, meant to represent conditions in the center of an infinitely long fire line moving at some unspecified rate (assumed to be much less than the base state wind speed). All analysis was subsequently done in a fire-relative framework; this simplified framework is adopted again for this study. Thus, it is important to keep in mind that the dynamics addressed in this study, as well as in KPC, are not intended to represent the complete set of atmospheric processes associated with wildfires. This is a study of the fundamental dynamics of wildfire-generated convection. Fully coupled atmosphere–fire models are extremely complex and nonlinear, making the convective dynamics difficult to isolate. The specific goal of the present study is to improve the understanding of how fire line details, such as shape and inhomogeneities, impact the resulting convection. Thus, this study constitutes

FIG. 3. Schematic depiction of fundamental processes involved in development of (a) intense plume, (b) hybrid, and (c) strong multicell modes; adapted from KPC. Note that the schematic in (b) is a mirror image of the hybrid case discussed in KPC (to ensure that surface flow in all panels is from left to right). The active combustion area is shown by a dark shaded rectangle and convective plumes/cells are indicated by light (weak) and dark (strong) shaded ovals. Representative parcel trajectories are indicated by thick curves and areas of buoyancy shown by thin contours (solid: positive, dashed: negative). Inset panels in (a) and (c) indicate buoyancy force (BUOY) and vertical pressure gradient force (VPGF) experienced by typical surface parcels (indicated by □). Dynamic pressure minimum discussed in text is indicated as \( L_D \) in (b). Short dashed line indicates top of mixed layer; long dashed lines outline plume position prior to crossing fire. All figures are in a frame of reference moving with the fire.
an interim step between the very simple 2D study of KPC and the fully coupled 3D atmosphere–fire modeling of, for example, C96 and Linn et al. (2002). It is important to emphasize that the flow in the vicinity of wildfires exhibits a level of complexity the modeling framework adopted here is incapable of addressing. Thus, when evaluating results of this study, the reader should keep in mind that parcel behavior in nature (e.g., Coen et al. 2004; Clements et al. 2007) may deviate substantially from what is presented here.

The primary utility of a noncoupled model is the ability to perform simulations with a more controlled set of parameters. For example, although coupled atmosphere–fire models are essential tools for studying the complex nonlinear behavior of fires, attributing a particular outcome (e.g., stronger updrafts above a fire) to variation of a single input (e.g., increased fire intensity) is hindered by the number of parameters that change simultaneously. In the sense that the problem is pared down to isolate the basic processes, this current work is analogous to idealized studies of moist atmospheric convection such as Rotunno et al. (1988) in examining the role of wind shear in long-lived squall lines and Fovell and Tan (1998) in understanding the regeneration cycle of multicell storms. The guiding philosophy is to omit any details that prior work suggests should be of secondary importance to the problem and to perform a set of controlled experiments to understand the basic dynamics. Once the basic dynamics are understood, additional complexities may be added in a stepwise manner, and the findings of the simple experiments reexamined.

A description of the numerical model used in this study and the experiment design are presented in section 2. Results and discussion of the experiments are presented in section 3, and the paper is concluded in section 4.

2. Model description and experiment design

As in KPC, the numerical model utilized for this study is the Advanced Regional Prediction System (ARPS) version 5.1.0 (Xue et al. 2000, 2003). ARPS is a three-dimensional, compressible, nonhydrostatic cloud model. Open lateral boundaries are utilized in the along-flow direction to allow disturbances to exit the computational domain, with periodic boundary conditions in the crossflow direction specified in the 3D experiments. For all simulations, ARPS has a horizontally homogeneous initial condition. The upper boundary condition for all simulations is a sponge layer beginning at 6.1 km above the surface and extending up to the top boundary at 9 km. A 1.5-order turbulent kinetic energy (TKE) subgrid-scale turbulence closure scheme is utilized; however, surface radiation physics and surface momentum fluxes are omitted. As discussed in KPC, the most applicable values of drag coefficients for wildfires are not known, and the use of surface momentum fluxes is left to future work. While measurements of surface momentum fluxes are available from field observations (Clements et al. 2008), we choose to neglect them here in order to focus analysis on the impact of surface heat fluxes. Additionally, the Coriolis force is neglected in these simulations because it has a negligible impact on the short-lived convection of the type considered in this study. Fourth-order accurate finite differencing of the advection terms is used in both the vertical and horizontal.

In all experiments, uniform horizontal grid spacing of 50 m in the horizontal and average grid spacing of 40 m in the vertical is utilized. Stretching is applied along the vertical axis with finest grid spacing near the surface \([\Delta z_{\text{min}} = 2.5 \text{ m}]\). The model domain extends 40 km in the \(x\) direction, 7.5 km in the \(y\) direction, and 9 km in the \(z\) direction. Several experiments were performed wherein the \(y\)-axis dimension was varied between 5.5 and 12.5 km in order to determine the smallest dimension that did not inadvertently constrain the scale of phenomena. Through spectral analysis (not shown), it was found that the spectral energy component at large wavelengths (wavelengths that could potentially be constrained by a \(y\)-axis dimension that is too small) is similar for dimensions of 7.5 km and greater. As in KPC, a base state environment with a Brunt–Väisälä frequency \(N\) of 0.0012 \(\text{s}^{-1}\) from the surface to \(z = 5.2 \text{ km}\), and 0.013 \(\text{s}^{-1}\) above \(z = 5.2 \text{ km}\), is utilized. The deep, nearly dry adiabatic layer in the ARPS sounding is consistent with an atmosphere conducive to fire development (Werth and Ochoa 1993). However, the 5.2-km-deep mixed layer is large compared to climatological values of maximum mixed layer depth (approximately 1.5–4 km; see Holzworth 1972). Future experiments will examine the impact of mixed layer depth on plume dynamics.

Also as in KPC, the surface heat flux applied in the model is fixed in space and time for all simulations. Analyses are performed in a fire-relative framework, wherein it is assumed that the fire is moving at some unspecified rate. The fundamental assumption that is made here is that the spread rate is assumed to be much less than the base state wind speed. In other words, the fire spread rate is expected to be substantially less than the speed at which convection moves away from the fire. Thus, an examination of parcel processes and atmospheric convection associated with a fire line fixed in space can instead be interpreted as representing conditions in a frame of reference moving with a nonstationary, nonaccelerating fire line. This limiting assumption is most suitable for situations in which fire spread rate is a function of the background wind only; nonlinear processes
that may lead to rapid fire spread are neglected herein, as in KPC, in favor of more linear first-order processes.

The approach adopted for exploring the complexity of 3D fire lines is to add details in a stepwise manner, beginning with a straight fire line with homogeneous intensity (i.e., surface heat fluxes) in the along-line direction. This first set of experiments is intended to verify the results of KPC in a three-dimensional model and to examine any three-dimensional phenomena that develop that have potential relevance to fire behavior. To achieve this goal, benchmark wind profiles from KPC (Fig. 2) are utilized in simulations with a straight fire line (3DLINE; Fig. 4a). Additional experiments consider (i) a sinusoidal fire line with along-line homogeneity (3DSHAP; Fig. 4b), (ii) a linear fire line with along-line sinusoidal intensity (3DHSPT; Fig. 4c), and (iii) a fire line with both sinusoidal shape and intensity (3DFNGR; Fig. 4d). For all experiments, steady random noise with low amplitude ($\sim 70$ W m$^{-2}$) is added to the fire line (28.8 kW m$^{-2}$ surface heat flux) to encourage the development of heterogeneity in the vertical velocity field above the fire. The value of surface heat flux adopted in this study is identical to that used in KPC and was chosen, in coordination with the choice of other scales (e.g., fire width), in an effort to allow an examination of an equal number of cases with nondimensional parameters greater than and less than unity. Although the choice of heat flux was not based on an analysis of observational data, it is important to note that surface heat fluxes of $28.5$ kW m$^{-2}$ were measured above low-intensity, small-scale (400-m length) grass fires during the FireFlux experiment (Clements et al. 2007). Thus, the fire simulated in this study as well as KPC is relatively weak, a point which should be kept in mind when evaluating results. In experiments with shape or intensity represented by a sine function, the wavelength is $ny/2$ (3.75 km). C96 suggests that the spacing of convective fingers should be similar to the mixed layer height ($5200$ m in this study); however, such a scale relationship has yet to be confirmed. Because the convective finger spacing used herein allows for the development of more than one plume and because the aim of this study is not to examine the dominant scales of fire lines, we utilize a 3.75-km wavelength.

The A2B9 wind profile (Fig. 2a) alone is chosen for the 3D shape and inhomogeneity experiments for two reasons. First, numerical simulations by C96 strongly suggest that low wind speeds, such as in the A2B9 wind
profile, are necessary for the convective fingering phenomenon to develop because the convection must remain close to the fire line. Second, the intense plume mode was identified by KPC as having a greater potential for feedback to a fire line than multicell modes because of its closer proximity to the fire and steadier nature. Assessing the impact of fire line details on the potential for feedback is an important objective of this work. For experiments with along-line variation of heat flux, a maximum (minimum) heat flux of 24.8 (2.48) K m s\(^{-1}\) is applied; such variation in surface heat flux is reasonable considering that fire spread rates in nature can easily vary by an order of magnitude along the line (Jenkins et al. 2001) and surface heat flux is a function of spread rate (Byram 1973a).

3. Results and discussion

a. 3D benchmark cases

Before considering three-dimensional complexities such as fire line shape and local hotspots, organizational mode and updraft intensity need to be compared between the benchmark cases outlined in KPC (2D-A2B9–intense plume, 2D-A2B2–hybrid, 2D-A5B9–strong multicell, 2D-A5B2–weak multicell; see Fig. 2) and corresponding 3D experiments with a linear fire line (Fig. 4a). It can be seen from Figs. 5 and 6 that the 2D and 3D simulations produce similar convective types: cases with \(A < 1\) (Fig. 5, top two rows) are plume types, while cases with \(A > 1\) (Fig. 5, bottom two rows) are multicell types. Also, with respect to the multicell type alone, strong multicells are simulated for \(B > 1\) (Figs. 5c,g) and weak multicells are simulated for \(B < 1\) (Figs. 5d,h).

Although broadly similar, some notable differences are apparent between the 2D and 3D simulations. The updrafts and downdrafts in the 2D simulations are generally of similar size and magnitude, whereas in the 3D simulations updrafts are generally stronger and narrower than downdrafts. This is consistent with comparisons of 3D large-eddy simulations of convective boundary layers with corresponding 2D simulations by Moeng et al. (2004). With regard to organizational mode, the dominant mode in the 3D-A2B2 case more closely resembles intense plume than hybrid. First, the streaks of convection in the 2D-A2B2 case, a signature of the hybrid mode, are absent in the corresponding 3D simulation (cf. Figs. 5b,f). Second, animations of vertical velocity cross sections (not shown) indicate that the convection column is more steady in the 3D-A2B2 case and therefore more consistent with the intense plume mode (KPC). However, while there are notable differences between the 2D- and 3D-A2B2 cases, vertical velocities in the A2B2 cases are substantially stronger than the A2B9 cases in both 2D and 3D (cf. Figs. 7a,b). An important result of KPC was that strong updrafts can develop for fires with low \(B\) (as in the A2B2 case) as a result of pressure gradient forcing associated with strong base state shear. Analysis of the perturbation pressure field for the 3D-A2B2 case confirms this is also true in the 3D simulations (cf. Figs. 8a,b). Note that although the pressure perturbations and associated forcing are weaker in the 3D simulation (Fig. 8b), the impact of the upward pressure gradient force on parcels is apparent from the area of upward motion adjacent to the plume, between \(x = 0\) and \(x = -4\) km, in agreement with results from the 2D simulation (Fig. 8a). In both the 2D and 3D simulations, the role of the pressure gradient force is to provide an additional source of upward acceleration to parcels.

Trends in domain maximum vertical velocity \(w_{\text{max}}\) for the four benchmark cases are also similar between the 2D and 3D model runs (Fig. 7). In both the 2D and 3D runs, \(w_{\text{max}}\) is in general directly proportional to parameter \(B\) in the \(A > 1\) portion of the parameter space, and in general inversely proportional to parameter \(B\) in the \(A < 1\) portion of the parameter space (consistent with KPC). It is evident that updrafts in the 3D simulations are stronger overall than their 2D counterparts. Updrafts of the magnitude indicated in Fig. 7, however, are consistent with observed (Banta et al. 1992; Clements et al. 2007) and simulated vertical velocities (Heilman and Fast 1992; C96) associated with fire-induced convection. It should be noted that although updrafts in the vertical cross sections in Fig. 6 are weaker in the 3D cases (right panels), the vertical cross sections were arbitrarily taken along \(y = 3.75\) km and do not necessarily depict the strongest convection. The larger values of \(w_{\text{max}}\) in the 3D cases are consistent with findings from Schlesinger (1984) and Parker and Johnson (2004) and are in part due to a stronger contribution of buoyancy to vertical acceleration compared to the downward-directed buoyant pressure gradient force in a 3D versus a 2D model. This can also be interpreted in terms of growth rates for disturbances of different size (Asai 1970a,b). Perturbations of large horizontal dimension grow slowly because the vertical pressure gradient force approximately offsets the buoyancy force. For a heat source in a 2D model such as in KPC, where the \(y\) dimension of the heated air is essentially infinitely large, growth rates for disturbances (e.g., updrafts) are relatively small. In a 3D model, where the volume of heated air is finite in all dimensions, growth rates are larger because less of the buoyancy force is counteracted by the vertical pressure gradient force. The greater intensity of updrafts in the 3D simulations is also consistent with...
the results of Moeng et al. (2004) in modeling convective boundary layers.

In contrast to the $w_{\text{max}}$ time series, domain average upward mass flux $\overline{M}$ is considerably weaker in the 3D simulations. This is likely a result of both the weaker intensity of the updraft/downdraft couplets moving away from the fire (Figs. 5a,b) and the fact that in 3D simulations, convection is not homogeneous in the $y$ direction and both weak and strong updrafts are involved in the averaging. Overall, however, it appears that the salient features of the 2D simulations are reproduced in the 3D simulations, including (i) a plume to multicell mode transition near $A = 1$, (ii) a consistent relationship between $w_{\text{max}}$ and parameter $B$, and (iii) a dependence on base state shear for updraft development in low-$A$, low-$B$ cases (e.g., A2B2). In general, the two-dimensional processes
outlined in KPC, namely parcel heating and mixed-layer advection, also dominate in the 3D simulations.

b. 3D processes: Deviations from 2D study

With the salient features of the KPC simulations replicated in 3D, it is important to examine potentially important deviations from two-dimensional dynamics found in the 3D simulations. Of the four benchmark simulations, only one differed substantially in convective evolution. A discrete propagation episode during the 3D-A2B2 (hybrid) simulation, in which the line of convection moved discontinuously toward the fire line,

![Figure 6: Vertical cross sections of vertical velocity (positive: shaded, negative: dashed contour; m s⁻¹) and total wind vectors (m s⁻¹), for (a),(e) A2B9, (b),(f) A2B2, (c),(g) A5B9, and (d),(h) A5B2 cases, at t = 80 min, for the (left) 2D and (right) 3D simulations; 3D panels plotted along y = 3.75 km. Contour and shading intervals are 3 m s⁻¹; values less than 3 m s⁻¹ not shaded. All figures are in a frame of reference moving with the fire.](march2010_kieferetal_619.png)
will be examined. Such evolution may be of particular importance since the proximity of convection to the fire line has a direct effect on the potential for feedback from the atmosphere to the fire. It should be noted that the spatiotemporal scale of the phenomena to be discussed here differs from the finescale “dynamic fingering” phenomena of spatial scale $O$(m) and temporal scale $O$(sec) (Clark et al. 1996b; Coen et al. 2004). The spatiotemporal scales considered herein are closer to those of the convective fingering phenomena examined by C96.

Throughout most of the 3D-A2B2 simulation, no convection develops between the fire and the deep convection (Fig. 5f), similar to the corresponding 2D simulation detailed in KPC (Fig. 5b). Strong base state flow over the fire produces a broad, horizontally homogeneous layer of heated air and thus small growth...
rates. An approximately steady-state flow develops over and downstream of the fire with little or no vertical motion until at least 4 km downstream of the fire. At that distance from the fire, the layer of heated air deepens to the point where the pressure gradient and buoyancy forces no longer balance. This change to the buoyancy field, in combination with the perturbation pressure field associated with the plume itself, yields positive vertical acceleration of air parcels. Such parcel evolution is very similar to that of the 2D-A2B9 case discussed in detail in KPC. In both cases, very weak vertical velocities exist immediately downstream of the fire because of the elongated nature of the heated air and associated weak vertical accelerations.

One can see in Fig. 9 that the region between the fire ("0" on the x axis) and 3–4 km downstream of the fire is devoid of convection at \( t = 4200 \) s (Figs. 9a,e). It is also apparent from Fig. 9 that convection takes different forms depending on the height above the surface: rolls are found at \( z = 200 \) m and cells are predominant at \( z = 1000 \) m. From the perspective of an air parcel moving away from the fire, convection takes the form of rolls nearer the surface and transitions to cellular convection as the parcel ascends. The evolution of convection, with respect to air flowing away from the fire, is similar in structure to the phenomena that have been investigated in numerical simulations of squall lines (e.g., James et al. 2005; Bryan et al. 2007). The atmosphere downstream of the fire in the 3D-A2B2 case shares important characteristics with the area of roll development in Bryan et al. (2007): an absolutely unstable layer, vertical wind shear, and horizontally homogeneous, quasi-horizontal inflow. These factors supportive of roll development, as well as the alignment of the rolls (parallel to the shear vector) and spacing between the rolls (6–7\( \Delta \), where \( \Delta \) is horizontal grid spacing), suggest that such phenomena are physically based and not a byproduct of model numerics, such as found in simulations in Bryan (2005) and Takemi and Rotunno (2003).

Interestingly, by \( t = 4500 \) s, the updraft branch of one particular roll aligned roughly along \( y = 4.75 \) km has extended upstream (i.e., fireward) by 1–1.5 km (Fig. 9b). Five minutes later, at \( t = 4800 \) s (Fig. 9c), the convective line at \( z = 200 \) m has jumped fireward of its earlier position to within 1.5 km of the fire line. Convective evolution at \( z = 1000 \) m (Figs. 9e–g) is similar to that of \( z = 200 \) m, although delayed by about 5 min. To understand why the convection extends fireward, it is useful to examine the field of perturbation potential temperature downstream of the fire. In Fig. 10, a strip of enhanced perturbation potential temperature is apparent at all times, extending from \( (x, y) = (0, 5.5) \) km approximately 3 km downstream to \( (x, y) = (-3, 4.75) \) km. Note that the entire region downstream of the fire line is \( \sim 50 \) K warmer than the upstream atmosphere; however, air in the strip is warmest. The deviation of potential temperature is as large as 1.5 K and appears before the development of the band of upward motion at \( z = 200 \) m. This band of higher perturbation potential temperature signals an important deviation from the otherwise horizontally homogeneous flow between the fire and the preexisting convection. The flow transitions from essentially a 2D fluid to one that is more 3D, and growth rates increase as the scale of the heated air contracts. Thus, a band of positive vertical velocity develops within the band of locally warmer surface potential temperature.

To understand why the strip of enhanced perturbation potential temperature (relative to the along-\( y \)-axis
average) exists immediately downstream of the fire line, it is helpful to consider the situation from a parcel perspective. Therefore, a collection of 30 parcels, spaced evenly between $y = 4$ km and $y = 5.5$ km, were released on the upstream edge of the fire at $t = 4200$ s and examined to discern along-line differences in parcel speed and heating. Interestingly, Fig. 11 indicates that prior to leaving the fire line, parcel speed is about 0.1 m s$^{-1}$ slower for the parcel at $y = 4.75$ km compared to the parcel at 5.5 km. This results in parcels near $y = 4.75$ km spending slightly longer in the fire than parcels elsewhere along the line. The impact on parcel perturbation potential temperature is evident downstream of the fire line where differences approach 1 K (comparable to potential temperature perturbations in Fig. 10). It thus appears that small, local changes to surface wind speed can have a potentially important impact downstream of the fire. In turn, these changes to parcel speed are the result of weak updrafts and downdrafts in the inflow near $y = 5.5$ km (not shown) perturbing the horizontal wind field. As seen in Fig. 12, the origin of this weak turbulence is the outflow of the plume; the low Richardson number $R_i$ (i.e., high shear) flow of the 3D-A2B2 case allows such turbulence to descend to the surface quite easily.

In numerical simulations of grass fires in convective boundary layers, Sun et al. (2009) show that turbulent eddies in the boundary layer can interact with fire plumes to yield downdrafts immediately behind a fire front (e.g.,
enhancing fire spread rates. The enhancement in fire spread rates in their study was the result of an increase in wind speed at the ground, itself a result of stronger momentum aloft being transported down. A similar phenomenon was observed behind fire fronts during the FireFlux experiment (Clements et al. 2007, 2008). In the 3D-A2B2 case in this study, the base state wind decreases with height to zero in the center of the mixed layer before changing direction and increasing again toward the top of the mixed layer (Fig. 2b). Thus, turbulence does not act to significantly increase wind speeds at ground level with any degree of spatial or temporal coherence. What the turbulence does do in the 3D-A2B2 case is yield an inhomogeneous inflow to the fire, which ultimately leads to the fingering phenomenon.

The importance of local changes to the convection pattern induced by the fire must be underscored. All other parameters held constant, feedback from the atmosphere to the fire is greatest when convection is in close proximity to the fire (C96; KPC). The changes to the convective line diagnosed herein are local and sensitive to factors difficult to predict in space and time (e.g., turbulence in the inflow generated by a plume). However, the fact that such behavior is limited to cases with strong base state vertical wind shear and a weak mean wind speed suggests that knowledge of the background wind profile may be useful in assessing the risk for nonlinear feedbacks. In other areas of the parameter space, the dynamics of convection for the straight, homogeneous fire line were generally two-dimensional.

c. Fire line shape and along-line inhomogeneity

Discussion now proceeds to the impact of fire line shape and along-line inhomogeneity on convective organization.
and intensity. Figures 13 and 14 (horizontal cross sections and updraft statistics, respectively) indicate substantial differences between the various A2B9 simulations. Along-line organization of convection shows great sensitivity to fire line details (Fig. 13): convection at $z = 3000$ m is more or less continuous in the 3DLINE and 3DFNGR experiments but is focused downstream of the back of the fire in the 3DSHAP experiment and downstream of local hotspots in the 3DHSPT experiment. The intensity of convection also shows great sensitivity to fire line

Fig. 12. Vertical cross sections of instantaneous turbulent kinetic energy (shaded; m$^2$ s$^{-2}$) and total wind vectors (m s$^{-1}$) every 60 s between $t = 4200$ s and $t = 4380$ s, for the 3D-A2B2 case. Shading interval is 3 m$^2$ s$^{-2}$ (values less than 3 m$^2$ s$^{-2}$ are not shaded; values greater than 21 m$^2$ s$^{-2}$ are shaded darkest). All figures are in a frame of reference moving with the fire.
FIG. 13. Horizontal cross sections of vertical velocity (contoured every 3 m s$^{-1}$, positive: solid, negative: dashed; m s$^{-1}$), perturbation potential temperature (shaded, K) and total wind vectors (m s$^{-1}$) for (a),(e) 3DLINE, (b),(f) 3DSHAP, (c),(g) 3DHSPT, and (d),(h) 3DFNGR runs; $z =$ (left) 200 and (right) 3000 m. Shading interval for $z =$ 200 m ($z =$ 3000 m) level is 2 K (0.5 K), with values less than 2 K (0.5 K) not shaded. Unfilled boxes in (b) indicate positions of lines of parcels discussed in text and displayed in Fig. 15. Centerline of fire indicated by thick contour in each panel. Symbols along the $y$ axis denote latitudes of head (H) and back (B) areas of fire line, except for (c) and (g) where H refers to position of hotspots. Note: for sinusoidal-shaped fire lines, distance from center refers to center of back of fire; for other cases, the $x$ axis label is as in previous figures. All figures are in a frame of reference moving with the fire.
details (Fig. 14; Table 1). Most notably, the $w_{\text{max}}$ time series for the 3DSHAP case is generally 5 m s$^{-1}$ stronger than the 3DLINE case, while the $w_{\text{max}}$ time series for the 3DFNGR case is consistently the weakest of the four cases examined. It is also evident in Fig. 14 that substantial differences in $\bar{M}$ exist between cases: $\bar{M}$ is substantially smaller in the cases with local hotspots along the fire line (3DHSPT and 3DFNGR) than the other cases because the net surface heating is smaller than that of the homogeneous fire line cases. The strategy, as outlined earlier, was to maintain the same maximum surface heat flux for all experiments, with an order of magnitude reduction between hotspots in the 3DHSPT and 3DFNGR experiments.

Several aspects of Figs. 13 and 14 require closer attention. First, the along-line organization of convection in the 3DLINE and 3DHSPT experiments is rather intuitive: a continuous line of convection downstream of a straight, uniform fire line in 3DLINE and convection focused downstream of the hotspots in 3DHSPT. However, the organization in the 3DSHAP and 3DFNGR experiments is not as straightforward to explain. In the 3DSHAP experiment, upward motion is strongest downstream of the back of the fire through a large depth (cf. $z = 200$ and $z = 3000$ m in Fig. 13). In the 3DFNGR experiment, convection exhibits no preference for either the head or back of the fire (Figs. 13d,h). To assess any differences in parcel heating between the head and back of the fire line in the 3DSHAP experiment, parcel trajectory analysis is utilized. Groups of parcels are released upstream of the head and back of the fire, and relevant fields are interpolated to parcel positions to examine the parcel heating process. Figure 15 presents trajectories of parcels released upstream of the head and back of the fire line (Fig. 15a) and back (Fig. 15b) of the fire. Two aspects of parcel behavior are most notable. First, parcels diverge as they approach the head of the fire and converge as they approach the back of the fire. Second, the hottest parcels are located at the back of the fire where they consolidate into a heated region about 250 m in radius.

The convergent flow has an important implication: parcels at the back of the fire are less susceptible to entrainment of lower buoyant ambient air since “outer” parcels tend to insulate “inner” parcels. While a broader heated region is closer to hydrostatic balance (such that the downward vertical pressure gradient force nearly offsets the buoyancy force), the reduced entrainment effect dominates, leading to hotter parcels and, as noted in Fig. 13, stronger updrafts. To understand why parcels converge at the back of the fire and diverge at the head of the fire, it is helpful to consider the induced flow field in a quiescent fluid (Fig. 4b): air accelerates inward, everywhere normal to the fire line, as a result of the hydrostatic pressure minimum associated with heating the air near the surface. With a mean wind applied (directed to the right in Fig. 4b), the result is net convergence at the back of the fire line and net divergence at the head (see vectors in Fig. 13b at $z = 200$ m).

Thus, $w_{\text{max}}$ in the case with sinusoidal shape (3DSHAP) is larger than in the case with a straight fire line (3DLINE) because the sinusoidal shape of the fire line

![Fig. 14. Statistics for 3D-A2B9 (intense plume) cases. (top) Time series of domain maximum instantaneous vertical velocity (m s$^{-1}$). (bottom) Domain-averaged upward mass flux (kg m$^{-2}$ s$^{-1}$).](image-url)
promotes stronger parcel heating at the back of the fire. To assess the overall footprint of parcel heating in the two cases, however, it is valuable to examine perturbation (with respect to base state) potential temperature counts for various thresholds (Fig. 16). Parcel count time series are constructed by counting the number of model grid points exceeding a threshold value, every 60 s. Figure 16 indicates that at 50- and 55-K thresholds, much larger counts are found in the 3DLINE experiment. However, at the 60-K threshold the 3DSHAP experiment dominates (although the count is much smaller than for the lower thresholds). In short, although the 3DLINE experiment features a larger number of heated grid points, the 3DSHAP simulation contains a small number of grid points whose potential temperature perturbation exceeds any perturbation in the 3DLINE experiment. To examine the source region of the hottest parcels in the 3DSHAP experiment, the 3DSHAP parcel count time series was subdivided into head, back, and flank regions (Fig. 17). Figure 17 indicates that the peak counts are greater at the back of the fire compared to the other two regions for each of the thresholds (most notably for the 55- and 60-K thresholds) and that the 60+ K grid points are almost entirely found in the back region.

Given the role of shape in parcel heating, the next logical step is to consider the case where surface heat fluxes are strongest at the head of the sinusoidal-shaped fire line (3DFNGR). As previously noted, $w_{\text{max}}$ was comparatively small in the 3DFNGR experiment (Fig. 14). The lower values of $w_{\text{max}}$ in 3DFNGR compared to 3DLINE can be attributed to two factors. First, the footprint of hot parcels is smaller in the 3DFNGR run since the 24.8 K m s$^{-1}$ heat fluxes are limited to a few grid points (at the heads of the fire line). Second, as shown in the 3DSHAP analysis, the shape of the fire line has an amplifying (de-amplifying) effect on parcel heating at the back (head) of the fire line. Therefore, when the surface heat fluxes are concentrated at the head of the fire (as in 3DFNGR), the parcels that traverse the region of strongest heat flux are at a disadvantage compared to corresponding parcels in the homogeneous fire line cases because the shape of the fire promotes weaker parcel heating exactly where the surface heat fluxes are strongest (i.e., the head). Consequently, the hottest parcels in the 3DFNGR case are still cooler than the most strongly heated parcels in either of the homogeneous fire line experiments.

An assessment of parcel counts by region for the 3DSHAP and 3DFNGR experiments is made difficult by the fact that, separate from the effect of shape, counts will be smaller in the 3DFNGR experiment because the net heat flux is smaller (i.e., surface heat flux is maximized at center grid point in the head region). Instead, it is useful to examine parcel heating in the 3DFNGR experiment through parcel trajectories. Figure 18 (as in Fig. 15 but for the 3DFNGR experiment) shows that the hottest parcels in the 3DFNGR experiment are slightly above 50 K (compared to 60+ K for the 3DSHAP experiment). Thus, although concentrating the strongest heat fluxes at the head of
FIG. 16. Time series of $z = 2.5$ m perturbation potential temperature counts for 50-, 55-, and 60-K thresholds, for 3DLINE (solid) and 3DSHAP (dashed) experiments. Parcel counts determined by counting number of pixels exceeding threshold value, every 60 s. Only the period between $t = 40$ and $t = 120$ min is shown. Note that values on the $y$ axis differ for each threshold.

FIG. 17. As in Fig. 16, but for the head (thick dashed line), back (solid line), and flank (thin dashed line) regions in the 3DSHAP experiment. Only the period between $t = 90$ and $t = 100$ min is shown; model output interval is 5 s, compared to 60 s for Fig. 16. Note that values on $y$ axis differ for each threshold.
The fire (as in 3DFNGR) is the most realistic fire line configuration, it is a nonoptimal setup for parcel heating. In other words, compared to the 2D simulations of KPC or the 3D simulations with homogeneous heating, parcels crossing the fire line receive less heat from the fire when the heat fluxes are concentrated at the head of the line (i.e., 3DFNGR). A relevant question to ask is why convection is not focused downstream of the head of the fire (Fig. 13h). This can be answered by considering the divergence of parcels at and downstream of the head of the fire: while the hottest parcels in the 3DSHAP experiment converge at the back and accelerate upward to form the compact updrafts seen in Fig. 13f, the hottest parcels in the 3DFNGR experiment diverge at the head, yielding the broad field of upward motion seen in Fig. 13h.

The last issue to address here is the potential for the atmosphere to feedback on the fire and how such potential deviates from that discussed in KPC. Several feedback mechanisms were discussed in KPC, including horizontal wind perturbations capable of enhancing fire spread and potential temperature perturbations downstream of the fire that can enhance drying and heating of unburned fine fuels (e.g., grasses, pine needles). With respect to particular modes of convection, the hybrid mode was noted by KPC to be most likely to drive feedbacks, with the weak multicell mode the least likely. The most important factor is the distance away from the fire of the convection: the closer convection remains to the fire line, the greater the potential for highly variable conditions at the fire line (hence the strongly advected weak multicell mode would be associated with the least amount of feedback). The inclusion of three-dimensionality to the simulations in this study yields smaller downstream displacement of updrafts compared to 2D simulations (cf. Figs. 5a,b), and inclusion of three-dimensional fire line structure yields even smaller displacement (compare Fig. 13e to Figs. 13f–h). As the flow capable of advecting updrafts becomes less two-dimensional, weaker advection in the cross-fire line (i.e., $U_{\parallel}$) direction occurs and updrafts remain closer to the fire line.

While not directly relevant in the 2D study of KPC, vertical and horizontal vortices of many scales are known to have important effects on fire behavior (Simard et al. 1983; McRae and Flannigan 1990; Cunningham et al. 2005). Several scales of vertical vortices were simulated in this study, including the low-level “bookend” vortices flanking the updrafts in the 3DHSPT simulation (Fig. 13c). Vertical vortices were also present in the 3DSHAP and 3DFNGR experiments, mainly along the flanks of the fire line (not shown). The potential feedback of fire-induced vortices on fire behavior must be considered when applying the findings of KPC to a real-world situation. To summarize, with all other parameters held steady, as the fire line becomes more three-dimensional in nature, the potential for feedback to the fire increases.

4. Summary and conclusions

This study examined the impact of fire line shape and along-line inhomogeneity on the intensity and organization of fire-induced convection. Efforts were also made to verify the salient results of KPC in three-dimensional simulations and determine specific fire line details that might cause results to deviate from KPC. In the first part of the paper, results were presented from
3D simulations of the four benchmark cases of KPC: A2B9 (intense plume), A2B2 (hybrid), A5B9 (strong multicell), and A5B2 (weak multicell). Trends in domain maximum vertical velocity were very similar between the 2D and 3D model runs, with updrafts in the 3D simulations generally more intense than their 2D counterparts. The salient results of KPC were replicated in 3D simulations, including (i) a plume to multicell mode transition near \( A = 1 \), (ii) a consistent relationship between \( w_{\text{max}} \) and parameter \( B \), and (iii) a dependence on base state shear for updraft development in low-\( A \), low-\( B \) cases (e.g., A2B2).

Partly because of the use of a base state wind profile with no \( u \)-wind, as well as a straight, homogeneous fire line, deviations from the 2D dynamics of KPC were few. Convection evolved uniformly along the line; along-line variation of vertical motion was, in general, minimal. One exception to this, the 3D-A2B2 case, featured several episodes in which convection developed in the otherwise horizontally homogeneous near-surface region between the fire line and the main line of convection. It was found that isolated areas of turbulence in the inflow yielded locally weaker parcel speeds and stronger parcel heating (with respect to the fire line as a whole). The resulting streaks of higher potential temperature led to a more three-dimensional structure of the heated air and an upward acceleration of air parcels within the streaks. The appearance of roll convection near the surface was followed approximately one minute later by cellular convection and a discrete propagation episode in which the preexisting line advanced toward the fire. The strongly sheared base state wind profile is important for this process because it allows for turbulence near the top of the plume to descend to the inflow layer and thus alter surface wind speed nonuniformly along the line.

The second part of the paper examined the impact of fire line shape and along-line inhomogeneity on convective organization and intensity for the 3D-A2B9 case. Substantial differences in along-line organization and maximum vertical velocity were noted and are summarized in Fig. 19. For a straight fire line with uniform heat fluxes (3DLINE; Fig. 19a), parcels generally traveled normal to the fire line and received approximately the same amount of heat at each point along the line. The result was a near-continuous line of convection downstream of the fire line. In an experiment with a sinusoidal shape but uniform heat fluxes (3DSHAP; Fig. 19b), however, parcel heating differed depending on where parcels crossed the fire line. Parcels at the back of the fire became hotter than parcels in the head or flank regions of the fire line. The effect of a sinusoidal fire line in nonzero mean flow is the development of convergence at the back of the fire and divergence at the head of the fire. As air parcels approached the back of the fire, they consolidated and in effect insulated themselves from the impact of entrainment. The consolidated areas of strongly heated air yielded strong, isolated cells downstream of the back of the fire, in contrast to the near-continuous line of convection in the 3DLINE experiment.

Another experiment with a straight fire line but along-line variation of heat flux (3DHSPT; Fig. 19c) featured the strongest parcel heating downstream of the local hotspots, with isolated updrafts farther downstream. Also, “bookend” vortices were found to flank the isolated cells in the 3DHSPT simulations. A final experiment in which sinusoidal shape and along-line variation of heat flux were combined (3DFNGR; Fig. 19d) was found to result in weaker updrafts than the other 3D experiments. The reduction in updraft strength was due to the strongest heat flux being constrained to the head of the fire, where air parcels diverged and were more susceptible to entrainment of ambient air. Convection downstream was found to exhibit no preference for the head or back regions. The 3DFNGR experiment, meant to approximate the convective fingering phenomenon found in nature, suggests that such a fire line structure will result in weaker parcel heating and convection than that found in the 2D simulations of KPC or in 3D simulations with straight, uniform fire lines.

To summarize, the following scenarios are most likely to involve processes not addressed by KPC:

- **Environments with strong vertical wind shear.** While KPC noted that strong feedback potential exists for the hybrid cases where vertical wind shear is strong, this study highlights the potential for convection to rapidly extend toward the fire line in such cases. The strong vertical wind shear (and low Richardson number) allows turbulence near the top of the plume to descend to the inflow layer, thus altering parcel speed and heating locally. In contrast to the phenomenon examined in Sun et al. (2009) and observed in Clements et al. (2007, 2008), the turbulence outlined in this study primarily impacts convection by yielding inhomogeneous inflow and encouraging the rapid extension of convection toward the fire.
- **Fire lines with large undulations and/or along-line inhomogeneities.** Sinusoidal shape in a nonquiescent fluid was found to amplify parcel heating at the back of the fire. For a fire exhibiting convective fingering, with strongest heat fluxes at the rapidly moving head of the fire, parcel heating and updraft strength will be weaker than the KPC simulations would suggest. However, for fires with approximately linear shape, the dynamics of dry convection are largely two-dimensional.
Before concluding, it is important to emphasize again that this study represents an intermediate step in the process of understanding the dynamics of wildfire-generated convection. The flow in the vicinity of wildfires is exceedingly complex, such that parcel behavior in nature may differ dramatically from the idealized simulations of convection presented here. The value of such research is in being able to identify the first-order processes that are intrinsic to wildfire-generated convection, processes that subsequently must be examined using models that more fully describe the physics of the fire and atmosphere. Here, as in KPC, the fire in the model was fixed spatially and temporally, with all analyses performed in a fire-relative framework. Future work will modify the fire-relative framework to include nonlinear processes such as local inflow that enhances fire spread and turbulent eddies of scale \( O(m) \) that alter the flux of heat into adjacent fuels. Such work is best achieved through use of a coupled atmosphere–fire model, wherein the fire and atmosphere are capable of two-way interaction (e.g., Clark et al. 2004; Linn et al. 2002). The purpose of transitioning to a coupled atmosphere–fire model is to address the problem introduced in the beginning of this paper: how to better anticipate fire behavior. Additional experiments using the current one-way coupled model, wherein the wavelength and amplitude of the sine function are varied, would also be useful, since a wide range of scales for the fingering phenomena are possible and this study considered only one subset of parameters.
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REFERENCES


—–, —–, —–, and —–, 1996b: A coupled atmosphere–fire model: Role of the convective Froude number and dynamic fingering at the fire line. Int. J. Wildland Fire, 6, 177–190.


