Idealized Numerical Simulations of the Interactions between Buoyant Plumes and Density Currents*

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(Manuscript received 9 February 2006, in final form 10 October 2006)

ABSTRACT

Idealized numerical experiments using a large-eddy simulation (LES) model are performed to examine the fundamental dynamical processes associated with the interactions between buoyant plumes and density currents. The aim of these simulations is to provide insight into the rapid changes in the structure of plumes that may be observed during the passage of density current phenomena such as thunderstorm outflows, sea-breeze fronts, or intense cold fronts. The LES model results indicate that when the ambient winds are calm the vertical velocity in the plume decreases with the passage of the density current, but that when the ambient winds oppose the motion of the density current a significant increase in vertical velocity in the plume may occur temporarily. In the latter case, the pressure perturbation and the associated region of horizontal convergence that lead the head of the density current interact with the tilted plume, causing the base of the plume to become vertical and resulting in a dramatic increase in vertical velocity within the plume. This basic dynamical behavior occurs over a relatively broad range of parameters, provided the characteristic velocity in the density current (taken as the densimetric speed) exceeds the ambient wind speed. When this is the case, the interaction is dominated by the effect of the density current on the buoyant plume such that the plume is essentially advected as a passive tracer by the flow due to the density current, and the increase in vertical velocity depends on the inverse of the convective Froude number of the buoyant plume.

1. Introduction

Isolated buoyant plumes occur routinely in the atmosphere and can arise from a wide variety of sources such as wildland or structure fires and industrial stack emissions. Buoyant plumes are a canonical example of turbulent buoyant convection, and in light of their importance in the transport of heat, gases, and particulate matter, they have been studied extensively in widespread contexts (e.g., Morton et al. 1956; Turner 1973; Linden 2000). Density currents are also prevalent in the atmosphere in the form of thunderstorm outflows (e.g., Charba 1974), sea-breeze fronts (e.g., Simpson 1994), and some cold fronts (e.g., Nielsen and Neilley 1990); density currents have also been a topic of extensive investigation because of their role in the initiation of moist convection but play an important role in their own right in the transport of airborne pollutants (e.g., Simpson 1997).

Interactions between buoyant plumes and density currents may have further significance, since the approach and passage of the current may cause substantial changes in the plume that are important for the transport of any pollutants or hazardous materials being carried by the plume. A situation of particular interest in this regard is a density current interacting with a wildfire and its associated plume. Atmospheric conditions exert a strong influence on the behavior of wildland fires in general, and the changes in wind, temperature, and humidity that typically accompany density currents can have a substantial impact on fire behavior as well as on plume structure. Although the arrival of cooler air associated with the passage of a density current often causes a decrease in fire intensity, the period preceding its arrival is typically characterized by gusty winds and strong updrafts and a significant increase in

* Geophysical Fluid Dynamics Institute Contribution Number 450.

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DOI: 10.1175/JAS3947.1

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Fire intensity may occur temporarily. Indeed, although the period of interaction between the fire and the density current may be relatively short, the impact on fire behavior or smoke transport may be significant. Isolated case studies have been presented of wildfires interacting with thunderstorm outflows (Goens and Andrews 1998), sea-breeze fronts (Hanley et al. 2005), and cold fronts (Mills 2005), but few systematic attempts have been made to understand the dynamics of these interactions, primarily because of the difficulty in obtaining detailed spatial and temporal measurements of fire behavior.

Radar observations of smoke plumes associated with fires are often able to provide information regarding the structure of the plume (e.g., Banta et al. 1992; Rogers and Brown 1997). Moreover, since an increase in fire activity typically results in the introduction of more particles into the atmosphere, and hence the potential for an increase in reflectivity, radar observations may also provide a surrogate for fluctuations in fire intensity (e.g., Hufford et al. 1998). Alternatively, an increase in reflectivity may arise simply from a change in plume structure that results in more particles being detected by the radar, without necessarily being accompanied by increased burning. It is also possible that hygroscopic growth of smoke particles may contribute to the increase in reflectivity in combination with these effects.

An example of a fire plume interacting with a density current in the form of a sea-breeze front is shown by Hanley et al. (2005), who describe a wildfire in Florida in which radar reflectivity in the plume increases substantially in the period immediately preceding the passage of the front. Figure 1 shows reflectivity for this case from the Weather Surveillance Radar-1988 Doppler (WSR-88D) site in Tallahassee, Florida, on 5 April 2004 prior to and at the time of the passage of the sea-breeze front. Because of the generally dry conditions prevailing in the southeastern United States during this period, the radar was operating in clear-air mode, and both the fire plume and the sea-breeze front are readily identifiable. As the front approaches the fire, the size of the plume detected by the radar increases dramatically, and reflectivity within the plume increases from about 14 dBZ (Fig. 1a) to values in excess of 30 dBZ (Fig. 1b). The ambient winds in this case are directed offshore, approximately toward the southeast, and thus the plume is carried in this direction both by these winds and by the upper return flow of the sea breeze. Scans at higher elevation angles (not shown) also indicate the presence of a vertical column of high reflectivity directly above the fire. After the passage of the front, reflectivities decrease to levels similar to those in Fig. 1a.

Although it is evident from this case that the passage of a density current can affect fire behavior and plume structure significantly, and there is evidence to suggest that thunderstorm outflows and sharp cold fronts have similar effects (e.g., Goens and Andrews 1998; Mills 2005), the relevant dynamical processes associated with the interaction remain poorly understood, and in this regard, numerical simulations may be able to provide insight. Herein, the dynamics of the interaction between buoyant plumes and density currents are investigated from an idealized modeling perspective, and a series of numerical simulations are described that examine the interactions between a buoyant plume that is representative of a fire plume and a density current that could be representative of a thunderstorm outflow, a sea-breeze front, or an intense cold front. A large-eddy simulation (LES) model is employed that focuses solely on the dynamics of the interaction, with a grid spacing that is fine enough [i.e., O(10 m)] to resolve the detailed turbulent structure of both features. Based on the results of these simulations, general dynamical properties of the interaction are described, along with the dependence of these properties on the magnitude of the ambient wind and on the characteristic parameters of the buoyant plume and the density current.

The simulations described here are intended to provide insight into the fundamental dynamics of the in-

![Fig. 1. Radar reflectivity (dBZ) from the Tallahassee WSR-88D at 0.5° elevation angle for 5 Apr 2004 at (a) 1828 and (b) 2124 UTC.](http://journals.ametsoc.org/jas/article-pdf/64/6/2105/3495463/jas3947_1.pdf)
interactions between buoyant plumes and density currents and are not intended to reproduce any observed case, nor do they allow the determination of the impact of the density current on fire behavior, which requires a coupled atmosphere–fire model (e.g., Linn et al. 2002; Linn and Cunningham 2005). In such a model, the physical processes of combustion, radiation, and convective heat exchange are incorporated such that the dynamics both of the fire and the local atmosphere interact directly to achieve self-determined fire behavior. Nevertheless, it is suggested that the approach employed herein that uses a fixed heat source represents a useful starting point in an investigation of the processes involved in the interaction and provides a potential explanation for the radar observations shown in Fig. 1, as well as direction for future studies using more complex models.

2. Description of the LES model

The LES model solves the nonhydrostatic and compressible equations of motion for a dry atmosphere and employs the dynamical core of the Weather Research and Forecasting (WRF) model in physical height coordinates (Skamarock et al. 2001). Subgrid-scale turbulence is represented in the LES model by a conventional eddy viscosity approach with a prognostic equation for subgrid-scale turbulent kinetic energy (e.g., Deardorff 1973; Moeng and Wyngaard 1988). In addition, a near-ground stress term is incorporated to account for surface drag following an approach similar to Brown et al. (2001). A third-order Runge–Kutta scheme is employed for time integration, and spatial discretization of the advection terms is treated via a fifth-order upwind-biased scheme. Additional details of the model are described by Cunningham et al. (2005).

The computational domain has dimensions of 960 m in the x direction, 3200 m in the y direction, and 1280 m in the vertical (z) direction, and a uniform grid spacing of 10 m is employed in all directions. The ambient potential temperature is taken to be uniform and equal to 300 K. Boundary conditions are periodic in the x direction, and open in the y direction to allow the density current and the plume to exit the domain, and a damping layer is imposed everywhere above z = 1000 m (this layer is not shown in the figures).

The buoyant plume is maintained by a volumetric heat source that is based at the surface and centered at x = 480 m and y = 2720 m. The spatial configuration of the heat source is a smoothed top-hat function, identical to that described by Cunningham et al. (2005), with a diameter of 125 m and a depth of 10 m, and the total heat release rate is taken to be constant in each simulation. The density current is initialized with a slab of cold air at y = 0; this cold slab is uniform in the x direction and extends 750 m in both the y and z directions. At the onset of the simulation, the cold slab adjusts under gravity and initiates a density current that travels in the positive y direction. The size of the domain and the initial locations of the density current and the plume allow both features to establish well-developed turbulent structures before significant interaction occurs.

3. Interactions between buoyant plumes and density currents

In this section, a series of numerical experiments with the LES model are described in an effort to explore the dynamics of the interactions between buoyant plumes and density currents. Initially, the salient dynamical properties of the interaction are described for one set of parameters, both with and without an ambient wind. Subsequently, the dependence of the interaction on the parameters that define the buoyant plume, the density current, and the ambient environment is explored through a larger number of simulations.

a. Dynamics of the interaction

Initially, two sets of three simulations are considered: one set in which the ambient winds are calm (referred to as the “zero wind case”) and one set in which the ambient winds are directed in the negative y-direction, against the propagation of the density current (referred to as the “opposing wind case”). The ambient flow in the opposing wind case thus represents an offshore flow situation similar to that observed in Fig. 1. The ambient wind profile is taken to be horizontally uniform with vertical profile \( \bar{v}(z) = -V_0 \tanh(z/z_0) \), where \( V_0 = 2.5 \text{ m s}^{-1} \) and \( z_0 = 100 \text{ m} \). For each set of simulations, two simulations are performed in which the buoyant plume and the density current are considered in isolation and one in which both are present and they are allowed to interact. In the simulations shown in this section, the volumetric heating that maintains the plume has a constant value of 0.5 kW m\(^{-3}\), corresponding to a total heat release rate of 60 MW for this heat source (which is representative of a wildland fire of mild–moderate intensity), and the maximum potential temperature deficit in the cold slab that initiates the density current is 7.5 K.

The simulated density currents exhibit structures consistent with those seen in laboratory experiments and previous numerical investigations. Kelvin–Helmholtz billows form along the interface with the
ambient environment (e.g., Droegemeier and Wilhelmson 1987; Sha et al. 1991; Simpson 1997), and the ambient flow in the opposing wind case causes a noticeable flattening of the head of the current (Simpson and Britter 1980). The three-dimensional nature of the model allows for instabilities to form in the alongfront ($x$) direction that result in the so-called clefts and lobes that are seen in laboratory experiments (Simpson 1997) and other three-dimensional simulations (Härtel et al. 2000; Özgökmen et al. 2004). After initial transient adjustment periods, the well-developed density currents propagate at steady speeds of $6.5 \text{ m s}^{-1}$ in the zero wind case and $5.4 \text{ m s}^{-1}$ in the opposing wind case. The difference in propagation speeds between the two cases is significantly less than $2.5 \text{ m s}^{-1}$ because of the vertical shear in the ambient wind profile, whereby the ambient velocity over the depth of the density current varies from zero at the ground to $2.4 \text{ m s}^{-1}$ at $z = 200 \text{ m}$. As a result of this vertical shear, which is associated with horizontal vorticity that is in the same sense as that in the head of the density current, the opposing flow has a greater effect with height, leading to the flattening of the head of the current as well as the relatively small difference in propagation speeds between the two cases.

Mean properties of the simulated buoyant plumes in the zero wind case are consistent with the self-similar vertical profiles of vertical velocity and buoyancy described by Morton et al. (1956). Similarly, for the opposing wind case, the mean trajectory of the buoyant plume in isolation is well represented by a standard plume rise equation based on dimensional analysis (e.g., Briggs 1975). Instantaneous fields indicate that turbulence and entrainment are dominated by coherent vortices of several different types, and these vortices are described in more detail for the case with ambient winds by Cunningham et al. (2005). It is noted in this regard, however, that large-eddy simulations of pure thermal plumes are still relatively rare (e.g., Bastiaans et al. 2000; Pham et al. 2006), and the details of the dynamics of the vortices and their role in turbulent entrainment is still a topic of active investigation and hence beyond the scope of the present study.

Three-dimensional depictions of the interaction simulations are shown for the zero wind case (Figs. 2a,b) and the opposing wind case (Figs. 2c,d) at two times in each simulation, one before significant interaction and one during the interaction. It is apparent from Figs. 2a,b that as the density current interacts with the plume in the zero wind case, the plume becomes

![Figure 2](https://example.com/figure2.png)

**Fig. 2.** Three-dimensional depiction of the interaction between the density current and the buoyant plume for the zero wind case at $t = (a) 315$ and (b) 415 s, and the opposing wind case at $t = (c) 250$ and (d) 400 s. The density current is depicted by the 299-K isosurface of potential temperature, and the plume is visualized by volume rendering potential temperatures greater than 300 K.
tilted slightly in the direction of the current propagation, and this tilt increases as the density current passes the heat source (not shown). In the opposing wind case, however, the plume is initially tilted toward the density current in the direction of the ambient flow, but becomes vertical near its base as the head of the current approaches (Figs. 2c,d). These interactions and structural changes have significant implications for the vertical velocity in the plume. For a given heat release rate, the maximum vertical motion will be achieved when the ambient winds are calm and the plume is vertical; turbulent entrainment of ambient air into a plume is greater for a plume in a cross-flow than for a plume in calm conditions, which reduce the buoyancy and thus decrease the vertical velocity in the plume. Consequently, as the plume becomes vertical in the opposing wind case (Fig. 2d), it should be expected that the vertical motion will increase as a result of the interaction.

Figure 3 shows time series of the maximum vertical velocity in each of the simulations. In the zero wind interaction case (Fig. 3a, solid line), the vertical velocity in the plume does not respond significantly until the density current has passed (at $t \approx 425$ s), after which time its magnitude decreases as the plume is tilted by the current and the heat source is overrun by the colder air. In the opposing wind interaction case (Fig. 3b, solid line), however, the maximum vertical velocity begins to increase gradually as the density current approaches, and as the head of the current reaches the heat source ($t \approx 400$ s) it intensifies to a level that is significantly greater than the sum of the maxima for the density current (dotted line) or the buoyant plume (dashed line) alone. The increase in vertical velocity is thus not simply a superposition of the flows associated with the current and the plume but arises from the structural change resulting from the interaction that is seen in Fig. 2d.

Further insight into the structural change that leads to this increase in vertical velocity is provided in Fig. 4, which shows vertical velocity and perturbation pressure in a vertical plane normal to the propagation of the density current for several times in the opposing wind.
interaction simulation. The positive pressure perturbation that leads the head of the density current is readily apparent in Fig. 4a. This pressure perturbation has been discussed in previous investigations (e.g., Droegemeier and Wilhelmson 1987) and is associated with a region of horizontal convergence near the ground ahead of the temperature gradient. In the opposing wind interaction case, the accompanying pressure gradient and associated low-level winds counteract the ambient wind, and so as the density current approaches the plume, the ambient winds in its vicinity decrease and the plume becomes vertical. This results in the gradual increase in vertical velocity in the plume leading up to the arrival of the current head seen in Fig. 3b beginning at \( t \approx 300 \) s and continuing until the arrival of the current at about \( t \approx 400 \) s, after which time the vertical velocity increases substantially as the plume is forced upward by the head of the current.

This progression of events is illustrated further in Fig. 5, which shows a time series of horizontal divergence for the three opposing wind simulations. For the purposes of this figure, the horizontal divergence is averaged over a box with horizontal dimensions of 100 m \( \times \) 100 m centered around the base of the plume and a vertical dimension of 150 m. For the buoyant plume in isolation (dashed line), there is net horizontal convergence in the vicinity of the plume as expected due to low-level entrainment around its base. The convergence ahead of the density current is apparent in the time series for the current alone (dotted line) as a sharp increase as the current passes through the averaging region; the impact of this feature on the intensification of convergence in the base of the plume is seen clearly in the interaction simulation (solid line). The maximum horizontal convergence in the plume occurs at \( t = 405 \) s, just as the head of the current reaches the plume, and precedes the maximum vertical velocity in the plume slightly (Fig. 3b). It is noteworthy that the magnitude of the convergence ahead of the density current is substantially larger than that for the plume alone, suggesting that in this particular case the interaction may be dominated by the effect of the density current on the plume.

The region of horizontal convergence that precedes the head of the current is depicted graphically in Fig. 6, along with the streamlines that illustrate the low-level winds associated with the current that counteract, and are stronger than, the ambient winds (Fig. 6a). The impact of the approach and initial passage of the density current is then to cause the lowest 250 m of the plume to become essentially vertical (Figs. 6b,c), roughly following the streamlines associated with the density current and further suggesting that the interaction may be described essentially in terms of the impact.
of the current on the plume. The horizontal convergence in the base of the plume increases gradually as the density current approaches (Fig. 6b), and then dramatically when the head of the current reaches the plume (Fig. 6c), consistent with the increase in vertical velocity (Fig. 4c).

**b. Dependence of the interaction on the properties of the buoyant plume, density current, and ambient winds**

Since the sources and relative intensities of buoyant plumes and density currents are expected to vary
widely in the atmosphere, it is of particular interest to explore whether the increase in vertical velocity seen in the previous section occurs over a broader range of parameters that define the buoyant plume, the density current, and the ambient wind. To explore the dependence of the interaction on these quantities, a series of 24 simulations were performed for several different values of the volumetric heating that maintains the plume (0.5, 1, 1.5, and 3 kW m\(^{-3}\)), the maximum potential deficit in the cold slab (5, 7.5, and 10 K), and the magnitude of the ambient wind (2.5 and 5 m s\(^{-1}\)). The simulations considered in this section are concerned solely with the opposing wind interaction cases, such that the simulation illustrated in Figs. 2c,d, 4, 6 above is one member of the 24 simulations described below.

In the interests of generality, it is useful to attempt to describe the results of these simulations in terms of the characteristic nondimensional parameters that determine the situation. The approach adopted here is to identify parameters relevant to the buoyant plume and the density current in isolation and to assess subsequently whether these parameters are relevant to the dynamics of the interaction. Following this approach, if the governing equations are nondimensionalized using typical horizontal and vertical length scales for each feature, and the ambient wind speed is used as a velocity scale, it can be shown that the relevant nondimensional parameters that arise are a Froude number for the buoyant plume,

\[
Fr_p = \frac{V_0}{(gQL^2/p_0c_p\theta_0)^{1/3}},
\]

which measures the ratio of the ambient wind speed to a characteristic buoyancy velocity, \(W_p = (gQL^2/p_0c_p\theta_0)^{1/3}\), and a Froude number for the density current,

\[
Fr_d = \frac{V_0}{(gH\Delta\theta_0)^{1/2}},
\]

which measures the ratio of the ambient wind speed to the so-called densimetric speed, \(V_d = (gH\Delta\theta_0)^{1/2}\). In (1) and (2), \(Q\) is the magnitude of the volumetric heating rate in the plume, \(L\) is the horizontal scale of the heated region, \(\Delta\theta\) is the maximum initial potential temperature deficit in the cold slab, \(H\) is the height of the dense flow in the density current behind the head, and \(p_0\) and \(\theta_0\) are characteristic values of density and potential temperature, respectively. It is emphasized at this point, however, that some uncertainty exists in the evaluation of these parameters, and the values chosen for these parameters should be viewed as approximate.

To assess the overall dependence of the interactions on \(Fr_p\) and \(Fr_d\), Fig. 7 illustrates for each simulation the time series of maximum vertical velocity in the plume normalized by the characteristic buoyancy velocity, \(W_p\). Time in these plots has been nondimensionalized by \(L/V_d\), such that the time scale is different for different values of \(Fr_d\). Simulations are thus grouped by \(Fr_p\), whereby every simulation in each group has a different plume Froude number, \(Fr_p\). Each time series is plotted such that the maximum value of the vertical velocity for each case coincides at a common time, which is chosen arbitrarily as that reached by the simulation with the smallest \(Fr_p\).

It is apparent that for small \(Fr_d\) (Figs. 7a,c,e), the interaction between the density current and the plume is substantial for all values of \(Fr_p\), and follows the same general behavior as that of the interaction case shown in the previous section (refer to the solid line in Fig. 3b). As \(Fr_d\) increases, however, the interactions become less well defined. For \(Fr_d = 0.55\) (Fig. 7b), the normalized increase in vertical velocity in the plume increases as \(Fr_p\) decreases but is minimal for large \(Fr_p\), while for \(Fr_d = 0.85\) (Fig. 7d), the normalized increase in vertical velocity in the plume is modest for all \(Fr_p\), and the interactions are erratic. Finally, for the cases in which \(Fr_d = 1.53\) (Fig. 7f), there do not appear to be any organized increases in the vertical velocity in the plume at any \(Fr_p\). In the cases for which \(Fr_d\) approaches and exceeds unity, the ambient wind is similar to, or greater than, the densimetric speed. In these cases, the vertical shear in the ambient wind causes the head of the current to be severely flattened, and the density current propagates slowly as a very shallow wedge of cold air. These density currents exhibit relatively weak convergence and vertical velocity ahead of the current, and as such appear to have almost negligible impact on the plume in advance of the temperature drop.

As was noted in the discussion of Figs. 5, 6, it appears that the interaction is dominated by the effect of the density current on the buoyant plume. Such behavior suggests that, to a first approximation, the plume is advected as a passive tracer by the flow due to the density current. The simulations appear to support this assertion (see Figs. 2–6) and show very little impact on the density current due to the plume. An ad hoc equation for the rate of change of the vertical velocity in the plume, \(w_p\), may thus be written as follows:

\[
\frac{\partial w_p}{\partial t} = v_d \frac{\partial w_p}{\partial y} + w_d \frac{\partial w_p}{\partial z},
\]

where

\[
v_d = \frac{V_0}{(gL^2/p_0c_p\theta_0)^{1/3}}.
\]

It is also possible to write the plume Froude number as \(Fr_p = V_d(D/B)^{1/3}\), where \(D\) is the depth of the heat source, \(B = gQ/\rho_0\theta_0\) is the plume buoyancy flux, and \(Q\) is the total heat release rate.
where it has been assumed that the basic nature of the interaction may be described in a two-dimensional (i.e., y–z) plane that intersects the plume (e.g., the plane illustrated in Fig. 6). An additional underlying assumption in (3) is that the characteristic velocities in the density current must exceed the ambient winds (i.e., $Fr_d < 1$) for a noticeable interaction to occur. If, as above, time is nondimensionalized as $t^* = t V_d / L$, and the change in vertical velocity in the plume is taken to be $\Delta w$, then (3) may be scaled approximately as

$$\frac{\Delta w}{V_0} \approx \frac{1}{Fr_p}.$$  

Figure 8 shows $\Delta w/V_0$ versus $1/Fr_p$ for all simulations except those for which $Fr_d > 1$ [for which $\Delta w \approx 0$ as seen in Fig. 7f, but for which (3) may not be valid anyway]. For each simulation, $\Delta w$ was evaluated as the difference between the maximum vertical velocity in the plume during the interaction and the averaged maximum vertical velocity prior to the interaction. It is apparent from Fig. 8 that the simple dynamical approach embodied by (3) and (4) has some validity in that the results of the simulations appear to be consistent with this ad hoc scale analysis. In particular, as suggested by (4), the magnitude of the increase in the vertical velocity normalized by the ambient wind de-
pends on the inverse of the Froude number of the buoyant plume. It might be anticipated, however, that as Fr$^p$ becomes smaller still (i.e., very strong heating and/or weak ambient winds), the plume will be essentially vertical prior to the interaction, and the flow due to the density current will have little impact. This particular limit of the validity of (3) and (4) as Fr$^p$ → 0 corresponds more closely to the zero wind case described in section 3a and was not explored further in the present study.

Based on the results of this section, it is suggested that knowledge of the Froude numbers for the buoyant plume and density current in isolation, Fr$^p$ and Fr$^d$, respectively, may be useful in assessing the potential for significant interaction; provided that Fr$^d$ is less than unity, an interaction of this form may occur, and the “intensity” of the interaction as measured by the change in vertical velocity prior to the passage of the density current depends on 1/Fr$^p$.

4. Discussion

The idealized large-eddy simulations described here demonstrate that while vertical velocities in buoyant plumes under calm conditions do not undergo noticeable intensification during the interaction with a density current, this is not true of plumes in the presence of ambient winds that are directed opposite to the advancing current. In the latter case, the vertical velocity in the plume increases dramatically as the plume becomes vertical in response to the pressure perturbation and the associated convergent winds that precede the head of the current and that oppose the ambient winds. The basic dynamics of this interaction occur for a broad range of parameters as long as the Froude number of the density current is significantly less than unity (i.e., the densimetric speed of the current exceeds the ambient wind speed), in which case the strength of the interaction as measured by the change in vertical velocity normalized by the ambient wind depends upon the inverse of the Froude number of the buoyant plume.

It is emphasized that the heat source is fixed in these simulations, and hence they are only capable of representing the interaction between the buoyant plume and the density current. To examine the response of fire behavior to the passage of a density current, a coupled atmosphere–fire model is required (e.g., Linn et al. 2002; Linn and Cunningham 2005). Indeed, the response of the fire to this interaction is not immediately obvious. The decrease in horizontal ambient winds would allow the flames and the associated plume to become vertically oriented, which would act to increase flame heights. Nevertheless, this increase in flame height would not necessarily be manifested in an increase in fire intensity as measured by, say, the reaction rates for fuel depletion, and the spread rate of the fire will likely decrease in such a situation. With respect to interpreting the radar observations seen in Fig. 1, however, an increase in vertical velocity may result in the increased vertical transport of a higher concentration of larger particles that are potentially detectable by the radar. At the same time, the return flow above the density current may enhance the streamwise flow in the plume. Consequently, it is suggested that the simulations shown here provide a plausible explanation for the increase in reflectivity without appealing to an increase in fire intensity. Even so, it is important to quantify the actual impact of the passage of a density current on fire behavior, and coupled atmosphere–fire simulations are planned as part of future research.

Acknowledgments. Discussions with Scott Goodrick, Deborah Hanley, Rodman Linn, Michael Reeder, Jon Reisner, and James Brenner are gratefully acknowledged. Numerous insightful comments from the reviewers improved the quality of this paper and are appreciated greatly. This research was partially supported by the USDA Forest Service, Southern Research Station, through Agreement SRS 06-CA-11330136-029, and by the FSU School of Computational Science through a grant of resources on the IBM SP Series 690 Power4-based supercomputer “Eclipse.”

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