3.1 DYNAMICS OF FIRE PLUMES IN VERTICAL SHEAR

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1. INTRODUCTION

Plumes from wildfires and prescribed fires represent a critical aspect of smoke management and air quality assessment, and as such it is important to understand the structure and dynamics of these plumes, both with respect to a basic understanding of the phenomena and with respect to an assessment of the validity of plume-rise parameterizations over a wide variety of fire conditions.

Many models currently in use today for the prediction of plume rise are so-called "integral models", in which profiles (typically Gaussian) of physical quantities are assumed, along with simple laws describing entrainment of ambient air into the plume. Development of these models largely follows the analysis of Morton et al. (1956) [see also Turner (1973) for a summary of early work, and Hunt (1994) for a more recent perspective].

Integral models have been shown to be successful in predicting plume rise from a variety of industrial and environmental sources, and are employed in numerous models for air quality assessment (e.g., Briggs 1975). Indeed, these models may provide accurate predictions of the plumes arising from low-intensity fires. Integral models are frequently inadequate, however, for describing the behavior of plumes originating from high-intensity fires. In such fires, the dynamical interaction between the buoyancy-generated vorticity in the plume and the vorticity in the ambient atmosphere may be significant, and the behavior of the plume may differ substantially from the predictions of the integral models. When this is the case, numerical simulations often provide valuable insight into the fundamental dynamical nature of the interaction and into the structure and evolution of the fire plume, particularly since this interaction may be conceptually complex.

In the present study, a compressible, non-hydrostatic model is employed to examine the effect of vertically sheared winds near the surface on buoyant plumes arising from intense heat sources that are based on the ground. Two basic types of plume are examined:

(i) an initially two-dimensional plume arising from a line heat source; and

(ii) a three-dimensional plume arising from an isolated, axisymmetric heat source.

2. NUMERICAL MODEL

To adequately represent the dynamics of buoyant plumes arising from intense heat sources, it is desirable to employ the governing equations for compressible flow; to this end, we use the dynamical core of the Weather Research and Forecasting (WRF) Model (Michalakes et al. 2001).

The domain used in these simulations is a rectangular box with a uniform grid spacing of 8 m in all three spatial directions. The domain size is 800x400x600 m in the case of the line source, and 960x480x640 m in the case of the axisymmetric source. Boundary conditions in the streamwise (x) direction are open-radiative, and in the spanwise (y) direction are either periodic (in the case of the line source) or open-radiative (in the case of the axisymmetric source). A 5th-order upstream differencing scheme is used for both horizontal and vertical advection, and constant eddy diffusion is employed for subgrid-scale dissipation. Surface stress is imposed via a simple bulk drag law at the lower boundary, while a stress-free rigid lid with a damping layer is employed at the top boundary. The basic-state stratification is neutral.

A heat source is included to provide a crude representation of a wildland fire and is imposed in terms of a constant (after a brief ramp-up time) rate of heat release per unit volume as follows:

$$Q = Q_0 \tanh(t/\tau) \exp(-z/H) \exp(-x^2/L_x^2 - y^2/L_y^2),$$

where $\tau = 30\,\mathrm{s}$, and $H = 25\,\mathrm{m}$. For the line heat source, $L_x = 100\,\mathrm{m}$ and $L_y^{-1} = 0$, and for the axisymmetric heat source $L_x = L_y = 100\,\mathrm{m}$.

The ambient atmospheric wind profile is specified as an initially laminar flow in the x direction as follows:

$$\bar{u}(z) = U_0 \tanh(z/z_0),$$

where $U_0 = 4$ m s^{-1} and $z_0 = 75$ m.

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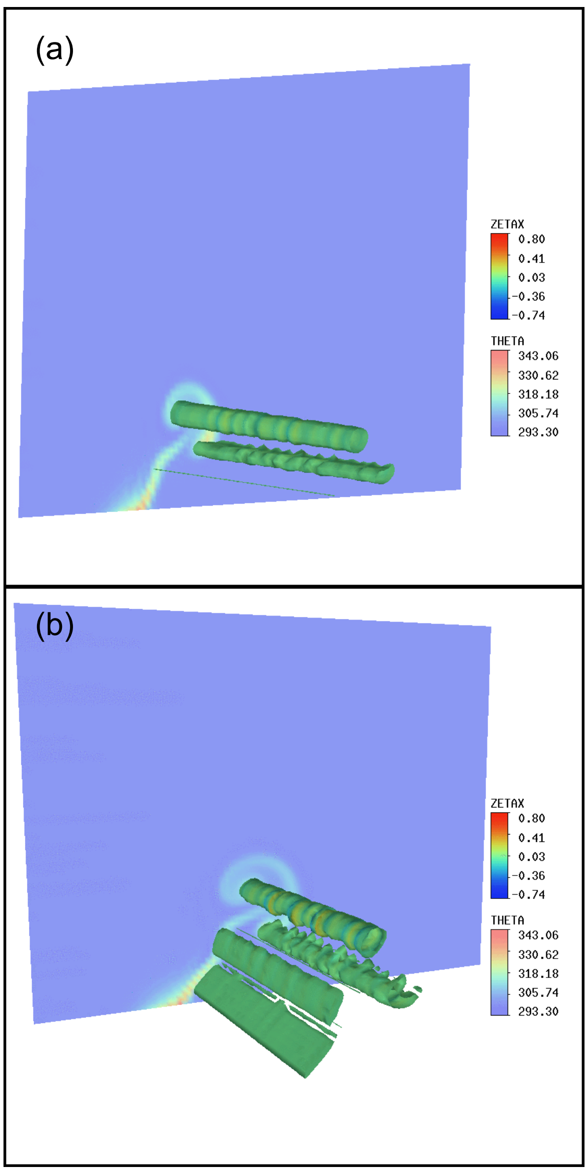
3. RESULTS

3.1 *Plumes from line sources*

Figure 1 illustrates the potential temperature and vorticity fields at several times in the line source simulation. It is evident from this figure that as the plume rises, it is bent downstream and a regular array of perturbations develops in the spanwise (i.e., y) direction along the plume cap. As time progresses, the plume undergoes a transition from its initial two-dimensional structure to a three-dimensional one, and this transition is particularly evident in the region far from the heat source. The vorticity field shows that initially the dominant vortical structure is the spanwise vortex tube associated with the plume cap, while at later times streamwise vortex tubes become dominant.



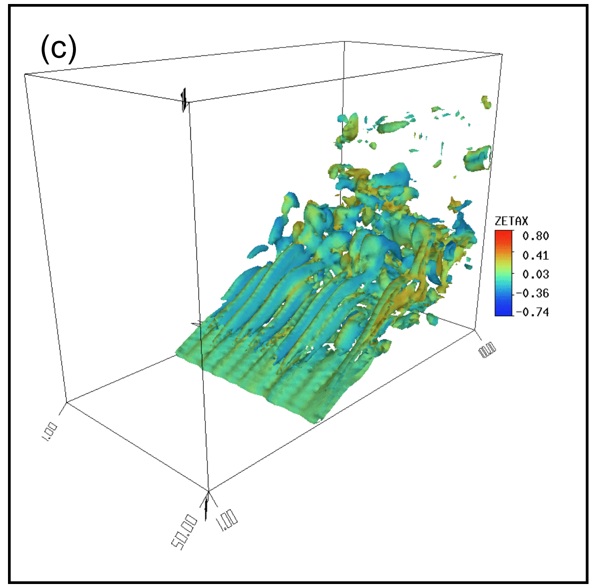


Figure 1. Isosurface of vorticity magnitude, colored with the x-component of vorticity (in s^{-1}) at (a) t = 60 s, (b) t = 100 s, and (c) t = 240 s for the line source simulation. Panels (a) and (b) show potential temperature (in K) in the x-z plane.

3.2 *Plumes from axisymmetric sources*

Jets and plumes arising from isolated sources of momentum or buoyancy have been studied extensively, and a variety of vortical features have been observed in experimental settings (e.g., Fric and Roshko 1994). These vortical features are summarized in the schematic depiction of Fig. 2, which applies to a nonbuoyant jet issuing from a wall into a crossflow. Many of these vortical features are also seen in buoyant plumes; for example, plume bifurcation due to counter-rotating vortex pairs is not uncommon in plumes from intense fires (e.g., Church et al. 1980; McGrattan et al. 1996), and fire whirls are occasionally observed downstream of fire plumes much like the wake vortices seen downstream of the jet in Fig. 2.

The dominant feature of both jets and plumes in crossflows, particularly in the far field, is the counter-rotating vortex pair; however, the details of the generation and evolution of this feature is still under debate [see Morton and Ibbetson (1996) for a discussion of unresolved scientific questions in this regard]. Moreover, although many numerical investigations of nonbuoyant jets in a crossflow have been carried out, there appear to be relatively few investigations focused on the numerical simulation of vortical features associated with isolated, axisymmetric buoyant plumes in a crossflow.

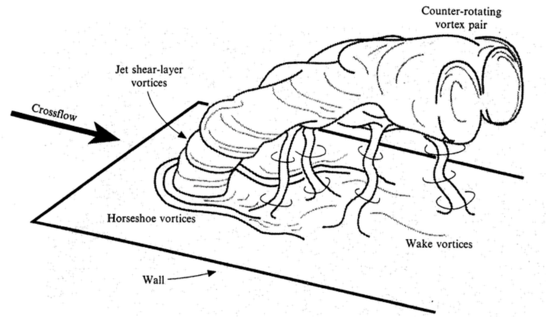


Figure 2. Idealized schematic illustration depicting four types of vortices associated with a nonbuoyant jet in a crossflow (from Fric and Roshko 1994).

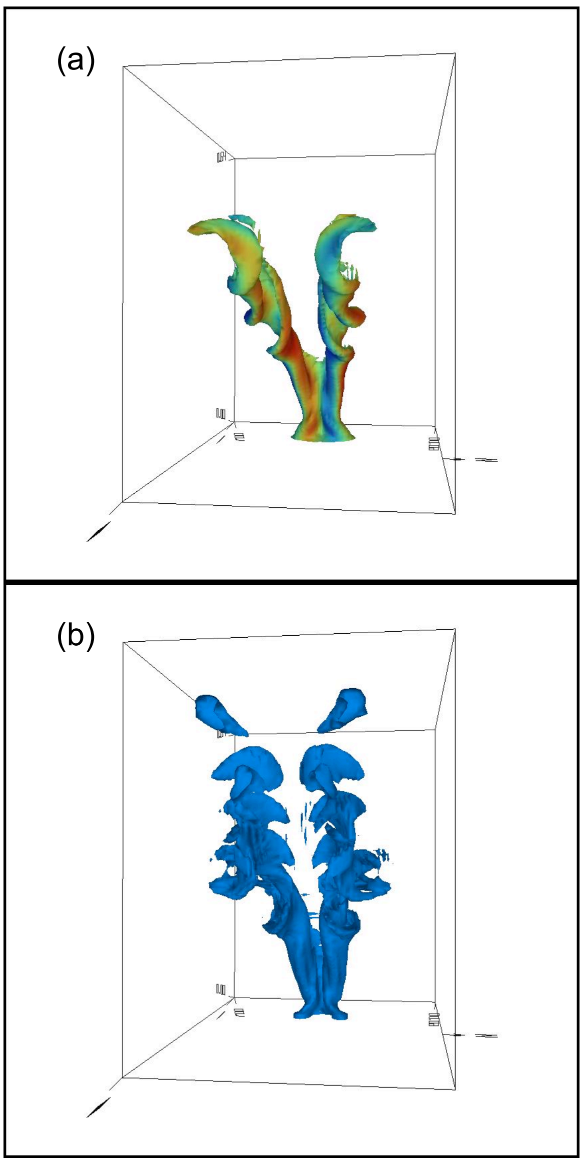


Figure 3. Potential temperature and vorticity at t = 240 s for the axisymmetric source simulation: (a) 303-K isosurface of potential temperature colored with the vertical component of vorticity, and (b) 0.3 s^{-1} isosurface of vorticity magnitude.

Figure 4. Bifurcated smoke plume from a wildfire in Florida (photo uncredited).

The goal of this portion of the investigation is thus to explore the generation and evolution of vortical features of buoyant plumes in a vertically sheared crossflow — particularly the counter-rotating vortex pair — in an effort to determine the dependence of these features on parameters such as the intensity of the heat source, the shear of the ambient atmospheric winds, and the basic-state stratification.

Counter-rotating vortex pairs are indeed ubiquitous in our simulations of axisymmetric heat sources. An example in this regard is provided in Fig. 3, which shows the structure of the potential temperature and vorticity fields at t = 240 s in the simulation. The development of the plume bifurcation is readily apparent, and indeed the vorticity field confirms the presence of the counter-rotating vortices. As noted previously, such plume bifurcation is seen frequently in association with smoke plumes above intense industrial and wildland fires, an illustration of which is shown in Fig. 4.

4. DISCUSSION AND FUTURE RESEARCH

Additional simulations and further analysis of the simulations shown here will be presented at the conference. Specifically, the generation and evolution of the vortical structures seen in these simulations that are associated with the interaction of the plumes with the vertically sheared ambient atmospheric winds will be described for a range of the controlling parameters (i.e., intensity of the heat source and the magnitude of the vertical shear). In addition, the implications of the results of these simulations for the behavior of plumes arising from wildland fires will be discussed.

5. ACKNOWLEDGEMENT

This research was partially supported by the USDA Forest Service, through a cooperative agreement with the Southern Research Station.

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