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NUMERICAL SIMULATIONS OF FIRE BEHAVIOR IN THE PRESENCE OF VERTICAL WIND SHEAR

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1. INTRODUCTION

The magnitude and direction of the wind near the ground plays a critical role in wildland fire spread, and significant effort has been devoted to characterizing the dependence of this spread on the wind speed. In this regard, wind speed is generally measured at some nominal height above the ground (e.g., 20 ft or 10 m), and although the vertical wind shear profile generally exhibits significant variability, such variability is not normally taken into account explicitly in predictions of fire behavior.

It is likely, however, that the presence of low-level vertical shear in the ambient atmosphere represents an important component of fire behavior. Vertical wind shear is associated with horizontal vorticity that may be converted into vertical vorticity near the ground via tilting by convection in the vicinity of the fire, possibly leading to highly nonuniform winds near the fire line. Indeed, the presence of low-level negative shear (i.e., winds decreasing with height near the ground) has been shown to be a common feature of so-called blowup fires (Byram 1954). Simulations by Clark et al. (1996) lend support to this observation, and confirm that the presence of low-level wind shear can lead to particularly dynamically active fire behavior. Vertical wind shear can also have an effect on a slightly larger scale, in that it significantly affects plume rise heights (e.g., Trelles et al. 1999).

Given the foregoing discussion, it would appear to be of considerable interest to examine the dependence of fire behavior on the nature and magnitude of the low-level vertical wind shear in the atmosphere. In the present study, we address this issue using a coupled atmosphere–fire model in which the fire behavior is self-determined (i.e., the behavior is controlled by an evolving set of coupled physical processes). Specifically, we employ the HIGRAD/FIRETEC model developed at Los Alamos National Laboratory (Linn 1997; Reisner et al. 2000; Linn et al. 2002) to explore simulated fire behavior for several different idealized wind profiles.

2. NUMERICAL MODEL

The HIGRAD/FIRETEC model has been described in several previous publications (Linn 1997; Reisner et al. 2000; Linn et al. 2002), and the details of its formulation are not reproduced here. The computational domain in all cases is a rectangular box of size 360x240x615 m; horizontal grid spacing is uniform and equal to 2 m, while the vertical grid spacing is nonuniform and approximately 1.5 m near the ground. The fuel distribution is spatially homogeneous, and the fuel properties are identical to those given by Linn et al. (2002) as being representative of tall grass.

Herein we present six simulations as part of a preliminary attempt to understand the dependence of fire behavior on vertical wind shear. We consider two types of ignition region patterns and three different (idealized) profiles for the ambient atmospheric winds. Simulations 1–3 consider ignition over a region of 4x40 m, which we refer to as a “short line”, while simulations 4–6 consider ignition over a region of 4x80 m, which we refer to as a “long line”. The ambient wind is specified to be in the *x*-direction and to be a function of height only as follows:

$$\overline{u}(z) = U_0 \tanh\left(z/z_0\right),$$

where $U_0 = 4$ m s^{-1}; z_0 is either 15 m, 30 m, or 60 m, and these values are taken respectively to correspond to “strong”, “moderate”, and “weak” shear profiles. Table 1 describes the parameters for each simulation.

Simulation	Ignition Pattern	Shear Profile
1	Short line	Strong
2	Short line	Moderate
3	Short line	Weak
4	Long line	Strong
5	Long line	Moderate
6	Long line	Weak

Table 1. Type of ignition pattern and shear profile for all simulations.

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3. RESULTS

The surface temperature and bulk ground fuel density fields are shown in Figs. 1 and 2, respectively, for all six simulations. Short line ignition cases (simulations 1–3) are shown in the left-hand columns, and long line ignition cases (simulations 4–6) are shown in the right-hand columns.

It is immediately apparent from Figs. 1 and 2 that for a given ignition type the rate of spread of the fire increases as the magnitude of the shear increases; however, this result may simply be due to the fact that the near-surface (i.e., 6–10 m) wind speed is increasingly higher as the shear is increased. It is also evident that the fire front is more uniformly parabolic and exhibits less lateral spread in the strong shear cases than in the moderate and weak shear cases.

Convection from the fire line will create vertical vorticity by tilting the horizontal vorticity associated with the vertical shear, resulting in low-level horizontal winds on the downstream side of the fire that are oriented in the opposite direction to the fire spread. Whether these fire-induced winds will slow down the rate of spread of the fire appears to depend on their magnitude relative to the ambient (i.e., upstream) wind speed near the ground; in addition, the stronger the vertical shear, the more the vertical vorticity created by tilting will be converted back into horizontal vorticity by the shear itself. Consequently, in the strong shear cases, the fire spread may not be significantly affected by the fire-induced flow, whereas in the weak shear cases the rate of spread at the center of the fire line may be reduced dramatically; this effect is readily apparent in Figs. 1 and 2.

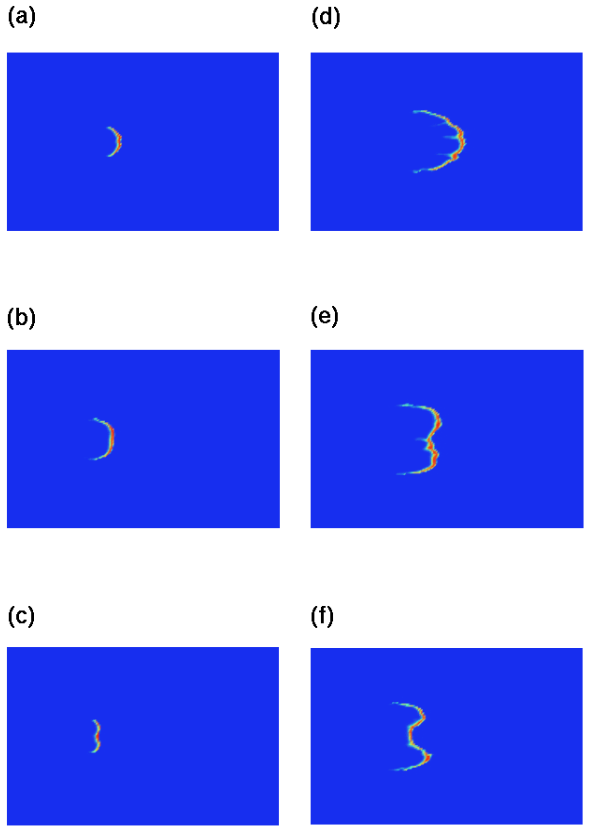

Figure 1. Surface temperature fields at *t* = 240 s for simulations 1–6 shown in (a)–(f), respectively. Short line ignition (left column) and long line ignition (right column) for: (a) and (d) strong shear; (b) and (e) moderate shear; (c) and (f) weak shear. Yellow corresponds to temperatures greater than about 600 K, and red corresponds to temperatures greater than about 1100 K.

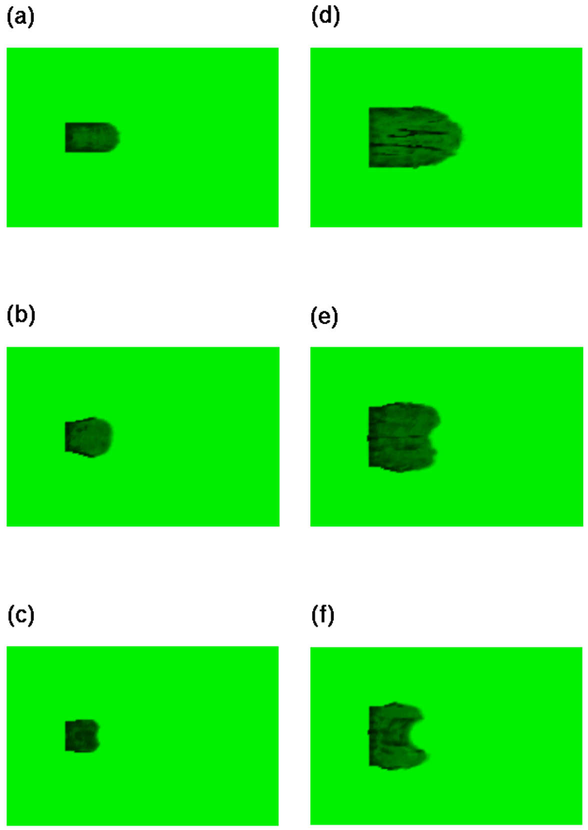

Figure 2. Bulk ground fuel density fields at *t* = 240 s for simulations 1–6 shown in (a)–(f), respectively. Short line ignition (left column) and long line ignition (right column) for: (a) and (d) strong shear; (b) and (e) moderate shear; (c) and (f) weak shear. Bright green corresponds to a bulk density of 1 kg m^{-3} (i.e., undepleted fuel), black corresponds to zero bulk density (i.e., completely depleted fuel).

Figure 3 shows the structure of the fire plumes for two long line cases: strong shear (simulation 4, Fig. 3a), and weak shear (simulation 6, Fig. 3b). Comparison of these figures demonstrates the relatively upright nature of the plume near the fire line at low levels in the weak shear case. It may thus be anticipated that the fire behavior in the strong shear case is primarily wind driven, while the behavior in the weak shear case is primarily buoyancy driven with more erratic fire spread.

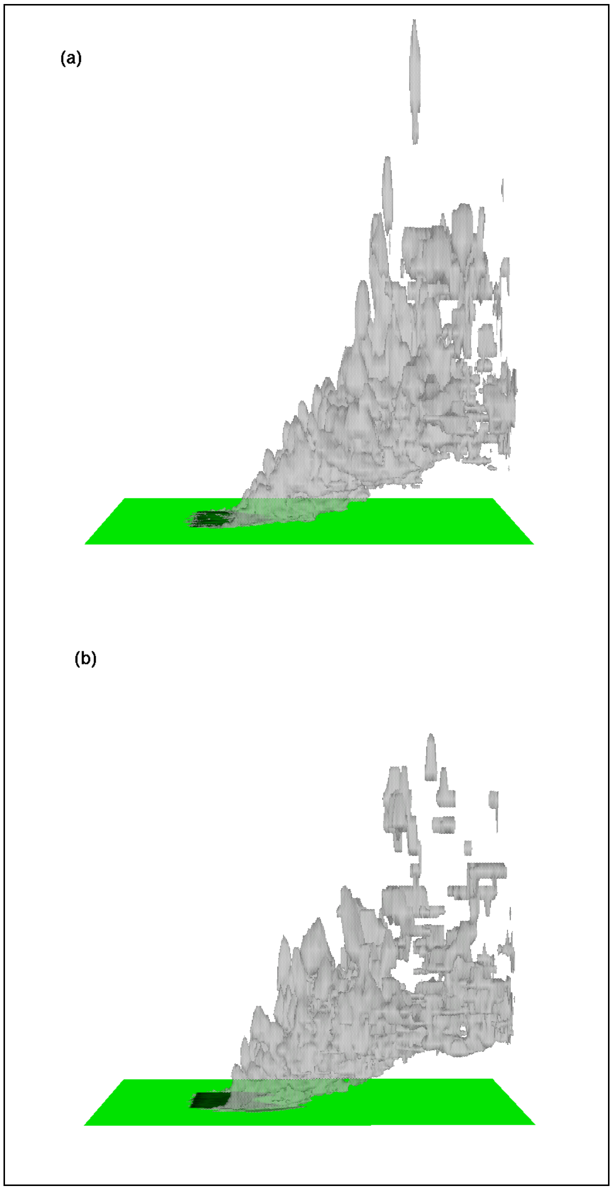

Figure 3. Bulk ground fuel density fields (as in Fig. 2) and 320 K potential temperature isosurface at *t* = 240 s for long line ignition cases: (a) strong shear (simulation 4); (b) weak shear (simulation 6).

It is also noteworthy that the structure of the fire lines exhibit more small-scale variability in the long line cases than in the short line cases. There appears to be greater creation of near-surface vertical vorticity in the former than in the latter. To illustrate this, Fig. 4 shows a comparison of simulations 1 (Fig. 4a) and 4 (Fig. 4b). For the long line case there are several vertically oriented vortex tubes at or near the surface evident in Fig. 4b, and these features correspond to the small-scale variations along the fire line seen in Fig. 1b.

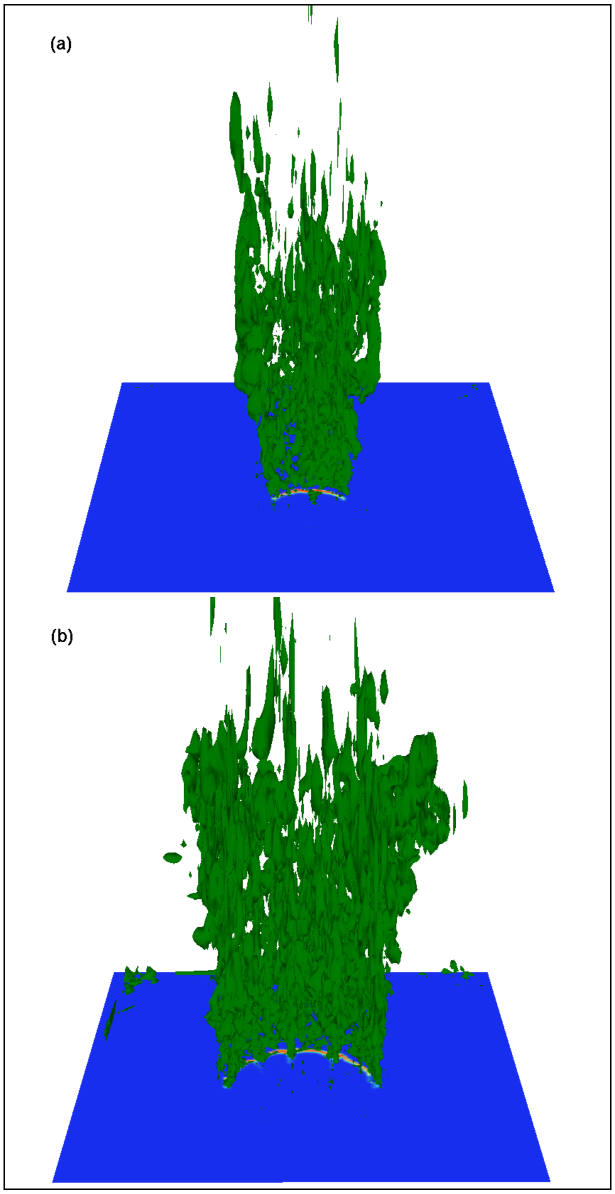

Figure 4. Surface temperature fields (as in Fig. 1) and 0.3 s^{-1} isosurface of vertical vorticity at *t* = 240 s for strong shear cases: (a) short line ignition (simulation 1); (b) long line ignition (simulation 4).

In the short line case, however, there are apparently no corresponding features.

It is unclear at present exactly what processes are causing this difference in vorticity creation between long and short line cases, although the fact that the total heat production is larger in the former is likely to be a critical factor. This question is currently under investigation.

4. DISCUSSION AND FUTURE RESEARCH

This study represents the starting point in a systematic investigation of the effects of vertical wind shear on the behavior of wildland fires. Several simulations of a coupled atmosphere–fire model were presented for different ignition region patterns and different vertical wind profiles. These simulations indicate that the behavior of the fire depends both on the wind shear and on the wind speed near the surface. Specifically, strong vertical shear results in relatively uniform (parabolic) fire spread, because the vertical vorticity created by tilting does not significantly affect the overall progression of the fire line and the ambient wind is strong enough to overcome the fire-induced effects, whereas weak vertical shear results in slightly more erratic fire spread with finger-like features, because the vertical vorticity created by tilting is able to interact more strongly with the fire line.

Additional simulations and further analysis of the simulations shown here will be presented at the conference. The simulations presented herein contain effects due to differences both in the magnitude of the shear and in the magnitude of the near-surface wind. To isolate the effects of the shear, it would be of considerable interest to explore fire behavior for a variety of sheared wind profiles in which the near-surface (e.g., 6–10 m) is similar, but the magnitude of the shear is different. Simulations to address this issue are presently underway.

5. ACKNOWLEDGEMENT

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