NUMERICAL MODELING OF HORIZONTAL VORTICES FORCED BY WILDLAND FIRES

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1. INTRODUCTION

Wildland fires interact with the atmosphere in very complex, highly nonlinear ways across a wide range of temporal and spatial scales. A common phenomenon related to fire-atmosphere interactions is the development of rotation within the flow, the most dramatic and most studied example of which is the fire whirl (McRae and Flannigan, 1990; Satoh and Yang, 1997; Battaglia et al., 1999; Farouk et al., 2001; Snegirev et al., 2004). Any whirling mass of air in the form of a column or spiral whether vertically oriented or not, can be described as a vortex, with its intensity measured by the amount of rotation, or vorticity. Haines and Smith (1987) described a variety of horizontal vortices associated with wildland fire.

Three varieties of horizontal vortices were characterized by Haines and Smith (1987, hereafter HS87), a single large longitudinal vortex, a transverse vortex and longitudinal vortex pairs. While only one case of the single longitudinal vortex has been described, it did act as a significant mechanism for lateral fire spread on the Dudley Lake fire in Arizona during June of 1956 (Schaefer, 1957). Through their analysis, HS87 hypothesize that this vortex relied upon the generation of horizontal vorticity from an upstream topographic obstruction rather than vorticity present in the ambient flow or buoyancy driven vorticity produced by the fire.

In contrast the transverse vortex and longitudinal vortex pair rely upon both the vorticity in the ambient flow and that supplied by the fire through buoyancy. The transverse vortex is hypothesized to be a form of a buoyantly forced vortex ring that becomes distorted by the flow. Complete vortex rings were not evident on any of the fires studied in HS87 as turbulence and unsteady eddies broke up the downstream portion of the ring; however the upstream segment of the ring was discernable. While this partial vortex ring resembled the classic horseshoe vortex resulting from flow around an obstacle, the vorticity is of the opposite sign, owing to its buoyant forcing.

The horizontal vortex pair is the best described of the three vortex types listed in HS87. Church et al. (1980) documented a split smoke plume attributed to large counter-rotating rolls and cite three mechanisms for concentrating vorticity in the thermal plumes: tilting and stretching of ambient vorticity, buoyantly generated vorticity and convergence of preexisting background vorticity. Wind tunnel experiments by Haines and Smith (1983) support the theories put forth by Church et al.

In this study we utilize a three-dimensional non-hydrostatic numerical model to investigate the atmospheric response to a region of intense heating that represents an idealized wildland fire. The focus of the study is to simulate both the transverse and counter-rotating vortex pair variants of the horizontal vortices described in HS87, and to more fully describe their forcing mechanisms and assess their possible implications to smoke management and fire behavior.

2. MODEL DESCRIPTION

For this study we utilize the dynamical core of the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2001). For a full description of our implementation of the WRF model for simulating buoyant plumes from wildland fires the reader is referred to Cunningham et al. (2005). The WRF model employs the compressible form of the Navier-Stokes equations. The model domain is a rectangular box with spatial dimensions 1800 m in the streamwise direction (x), 1200 m in the spanwise direction (y), and 1500 m in the vertical (z). 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 in all simulations. The heat source is located at point (x_h, y_h) which is (450 m, 600 m) from the origin.

To represent a fire in the WRF model a volumetric heat source is introduced into the equation governing temperature. An idealized fire can be represented by an ellipse (with major axis in the streamwise direction). The most intense part of the fire would be at the downwind edge of the ellipse (the head), less intense on the sides (the flanks), and weakest along the upwind edge (the back). Such an idealized fire can be represented by the following function:

$$Q(x,y,z,t) = Q_0 \tanh(t/T)\exp(-z/h)\left\{\frac{(\cos[\operatorname{atan}(Y/X)]+1)}{2\left[2-(X/A)^2-(Y/B)^2\right]^4+2}\right\}, \qquad (1)$$

where $X = x - x_h$, $Y = y - y_h$, and we choose A = 200 m and B = 100 m such that the heat source assumes the form of an ellipse with major axis in the streamwise direction. The parameters $h=25$ *m* and $T = 10$ *s* describe the vertical decay of the heat source with height and a short ramp up time scale for the heat source respectively. The base heat source, Q_0, is specified as 1 kW m^{-3} gives a total heat release rate of 1700 MW. Such values for the total heat release rate and the heat release per unit volume are considered representative of those found in typical wildland fires. The ambient atmospheric wind profile, $U(z)$, is initially laminar, in the positive *x*-direction as follows:

$$U(z) = U_0 \tanh(z/z_0), \qquad (2)$$

where U_0 = 4.5 m s^{-1}, and z_0= 100 m, producing a layer of wind shear near the surface.

3. RESULTS

The conceptual model for the horizontal vortex pairs described in HS87 and originally described by Church et al. (1980) is supported in our simulations, with some added complexity. The conceptual model describes the interaction of horizontal vorticity in the ambient flow interacting with the vertical motions induced by a point source of heat (Figure 1). While at a large scale the heat source used in the current simulations could be viewed as a point source, it is obviously more complex at the scale of the simulation. Instead of one large hairpin vortex as in the conceptual model, hairpin vortices develop along each flank of the fire. As these vortices progress toward the head of the fire, the vortices converge and the outer branches combine to form a large hairpin vortex similar to that of the conceptual model, while the inner branches join to form a closed, vertically oriented ring (Figure 2).

This vertically oriented ring is potentially the source for the transverse vortices described by HS87. The mechanism for the transverse vortices described in HS87 relied upon the development/deformation of buoyantly forced horizontal vortex rings with the downwind portion of the ring being eroded by vortex shedding in the wake of the heat source. The presence of a horizontal ring vortex would imply regions of longitudinally enhanced vorticity completing the ring, of which HS87 could find no evidence. The vertically oriented ring vortex provides the observed sense of rotation, the vertical sections of the ring would be difficult to discern in the presence of the counter-rotating vortex pair.

4. SUMMARY

Idealized numerical model results of the atmospheric response to heating from a wildland fire were capable of reproducing two of the horizontal vortices common to wildland fires as described by HS87. For the horizontal vortex pair, the conceptual model originally described by Church et al. (1980) does well to describe the development of the counter-rotating vortex pairs; however, this model applies at the scale of the entire fire, as originally intended, as well as at the scale of the fireline. An alternative conceptual model for the transverse vortices is presented in which the origin of the vorticity is the ambient environment, rather than buoyancy from the fire.

5. REFERENCES

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Scott Goodrick is a Research Meteorologist with the US Forest Service Southern Research Station. Scott's area of research is fire-atmosphere interactions, fire weather and smoke plume dynamics. Prior to joining the Forest Service, Scott served as the Fire Weather Meteorologist for the Florida Division of Forestry. Scott received his masters and PhD in Atmospheric Science from the University of Alabama in Huntsville.

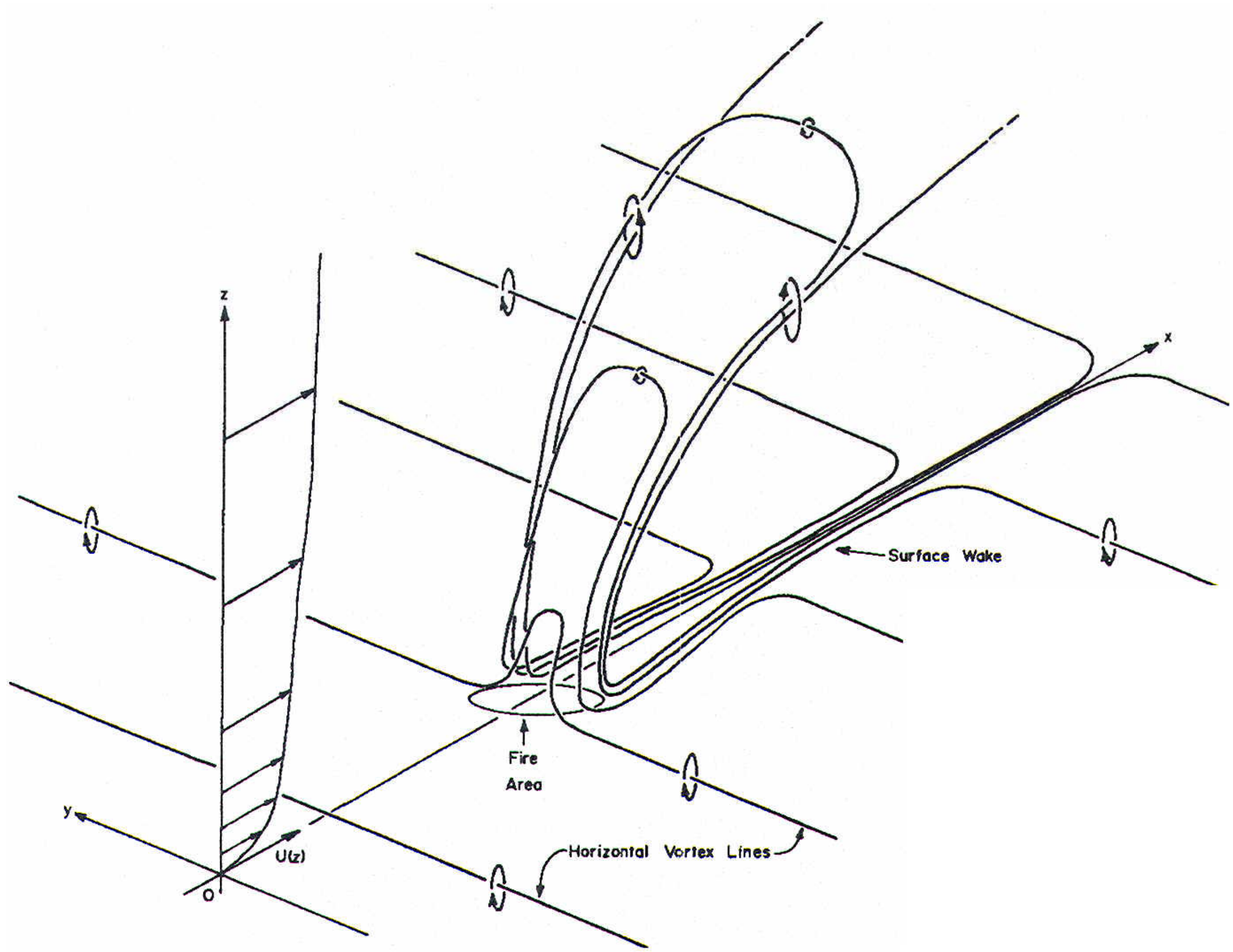

Figure 1. Conceptual model of the modification of horizontal vortex tubes by a heat source to produce counter-rotating vortex pairs (from Church et al., 1980).

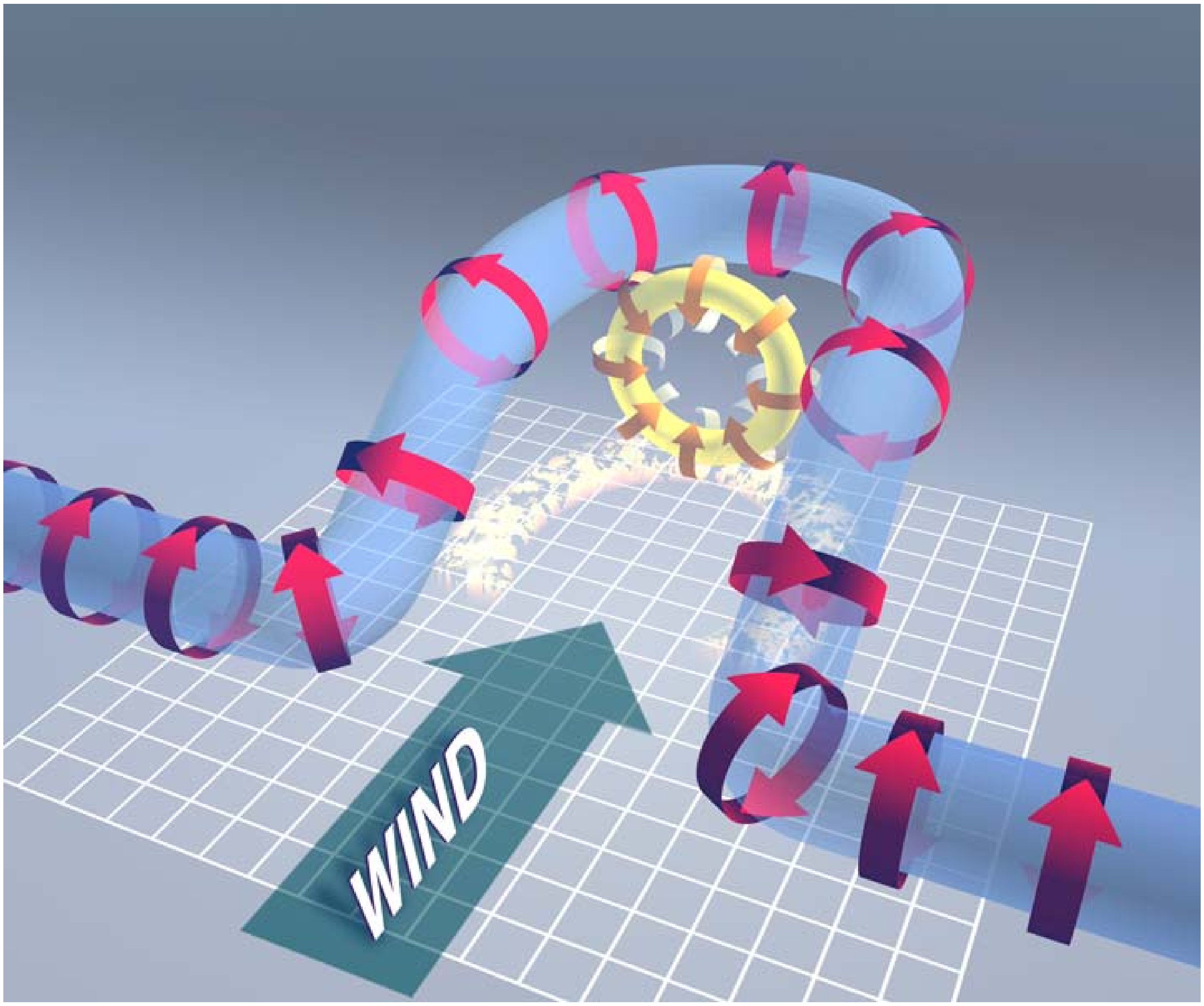

Figure 2. Revised conceptual model illustrating the presence of a vertical vortex ring formed from the merger of the inner branches of hairpin vortices that formed along each flank of the fire.