Introduction

We present model output from two moving grassfire simulations in environments with uni-directional vertical shear in the background flow (Figure 1) from WRF-fire model, the coupled wildfire fire version of Weather Research & Forecasting Model.

Both numerical experiments are of a moving grass fire line of uniform fuel load of 0.628 kg m⁻², roughness height of 0.038 m on level terrain, initialized as a fire line perpendicular to the direction of weakly background flow. Initial fire line width/length is 400/200 m. Atmosphere is neutral to connection below 1 km, weakly stable above. Model grid size Δx = Δy = 20 m and vertically-unstretched starting with smeared Δz = 2.5 m for first grid level. Open boundary conditions used at lateral model boundaries.

Our goal is to explain why, although surface wind speed in both simulations is the same (see Figure 1), fire-spread rates (Figure 2) are not.

A time series of the forward-most (in positive x direction) positions of the modeled fire lines are shown in Figure 3. Solid line is for simulation with constant-with-height ambient wind (solid line Figure 1). Hereafter referred to as 'CONTROL run'. Dashed line is for simulation with tanh vertical wind profile of ambient wind (dashed line Figure 1). Please ignore other lines in Figure 1. Hereafter referred to as 'TANH run'. Figure 2 shows that the fire front in CONTROL moved steadily forward, while fire front in TANH moved forward at first, slowed, and then finally stayed between 800 to 900 seconds into model run.

What are the dynamical reasons for these differences in fire line propagation?

To date the only fluid dynamical explanation for propagation of a fire front (to the authors' knowledge) is by Clark et al 1996 (J. of Applied Meteorology). In the absence of an ambient wind, a vertically-oriented convection column is positioned on level terrain, and that then are advected in the direction of background wind.

The Fluid Dynamical Forces Involved in Grass Fire Propagation

Why did it take approximately 900 s for advection of vertical vorticity in the negative x direction by the upper-level winds in the TANH run to impact the flow dynamics in these ways? The answer is that the advection of z-vorticity by upper-level winds back into the fire line took place only after significant magnitudes of vorticity were established at upper levels. A plot of maximum magnitudes of v-x vorticity as a function of height at different times in TANH (not shown) indicates vorticity, and horizontal advection of v-z vorticity, developing from the bottom up as time increases.

The ideas behind Figure 3 remain valid, but what we can amend Clark et al 1998's 'kinematic' explanation for fire line propagation. A dynamical explanation for fire line propagation is in terms of the perturbation pressure-gradient force. The results suggest the perturbation pressure force responsible for fire front movement is tied to the counter-rotating vertical vortices that develops naturally along the fire line and that then are advected in the direction of background wind.

Surface convergence slightly forward of the fire line, drawing air from different azimuthal angles along the fire line, forms a curved inflow region along the fire line. This is a 'kinematic' explanation for fire line propagation.

The flow that propagates the fire line and convection column in the horizontal is governed (ignoring fluid friction) by the horizontal perturbation (i.e., not hydrostatic) pressure gradient force. Likewise dynamically vertical flow is forced by a vertical perturbation pressure gradient force plus buoyancy force. The horizontal pressure pattern is ultimately responsible for the forward-shifted convergence zone. The key to a dynamical' explanation for fire line propagation is to understand the behaviour in terms of a perturbation pressure gradient force. The horizontal vorticity, of any sense and any direction, is always associated with a region of low dynamic (perturbation) pressure (Markowski & Richardson, Mesoscale Meteorology in Midlatitudes, 2010) in fluid flow.

Therefore we examine both vorticity, a measure of rotation in a fluid, and pressure fields.

Analyses and Results

Note in Figure 4 the co-location of significant vorticity (i.e., pure rotation in the y direction) with low dynamic pressure perturbations. Also associated with these features are significant plus/minus-z vorticity values and downward/upward motion across the plume (e.g., (b)) (between 1 to 1.5 km above ground level). As well as being responsible for dynamic pressure lows in the flow field which may induce/produce vertical motion depending on the sign of -dp/dz, these 'rolls' of y vorticity would entrain and mix cooler, drier ambient air into the fire plume.

Figure 5 shows y-x cross sections at 240 s in CONTROL at 810 m AGL (Above Ground Level) for: (a) z component of vorticity; (b) horizontal divergence; (c) p pressure perturbation, and (d) -pd/dz. The co-location of significant vorticity in (a) is, fluid in pure rotation oriented in the vertical with significant negative divergence (convergence) in (b) into low pressure regions and (c) +/- -dp/dz showing negative forcing in horizontal by y-vorticity slightly forward of fire line. Light brown contour lines indicate fire line superimposed on x-y cross section at 240 s and y = 810 m.

These regions of significant plus/minus z vorticity are the result of two counter-rotating vertical vortices --- or 'vortex couplet' --- that develop in the fire line convection. The weakly flow in CONTROL background wind (Figure 2) advects the vortices slightly forward of fire line. Regions of low pressure associated with the vortices are therefore positioned ahead of the line to provide proper -dp/dz forcing that moves the fire line in direction of ambient wind. Surface convergence is positioned slightly forward of fire line as depicted in Figure 1.

Concluding Remarks

Why did it take approximately 900 s for advection of vertical vorticity in the negative x direction by the upper-level winds in the TANH run to impact the flow dynamics in these ways? The answer is that the advection of v-x vorticity by upper-level winds back into the fire line took place only after significant magnitudes of vorticity were established at upper levels. A plot of maximum magnitudes of v-x vorticity as a function of height at different times in TANH (not shown) indicates z vorticity, and horizontal advection of z vorticity, developing from the bottom up as time increases.

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Surface convergence slightly forward of the fire line exists because of low pressure associated with pure rotation in each of these vertical vortices.

A background wind field interacts with the entire convergence column. It is the advecting wind, not the surface wind, that is responsible for the positioning of the low pressure centre ahead of the fire line.

Notes:
- Figure 4 shows an y-x cross sections at 240 s in CONTROL through middle of and perpendicular to fire line for: (a) component of vorticity, (b) vertical velocity w, (c) p pressure perturbation, and (d) -pd/dz. Bottom frame shows fire position by rate-of-energy release per area. Vectors denote flow in x-z plane. Ambient wind is present; vertical motion and pressure fields in fire plume are displaced downstream of surface heating.
- Figure 5 shows y-x cross sections at 240 s in CONTROL through middle of and perpendicular to fire line for: (a) component of vorticity, (b) horizontal divergence, (c) p pressure perturbation, and (d) -pd/dz. Bottom frame shows fire position by rate-of-energy release per area. Vectors denote flow in x-z plane. Ambient wind is present; vertical motion and pressure fields in fire plume are displaced downstream of surface heating.
- Figure 6 is the same as Figure 4 except for TANH at 900 s. See text for explanation.
- Figure 7 is the same as Figure 5 except for 900 s into the TANH run. At this time Figure 2 shows the TANH fire line skipped, no longer moving in positive x direction. The explanation for this is that well-organized structures seen in z-vorticity, pressure perturbation, divergence, and -dp/dz fields — that combined are responsible for steady forward propagation of the fire line — at previous times near time = 240 s. The fire line appears to have stopped and then moved slightly eastward before starting to move forward. It is in this region (see Figure 4 for TANH, CONTROL, Fig 7) where the fire line was stopped and then moved slightly eastward before starting to move forward. This region is the same as (blue) layer in (a) in the TANH background wind field gives the fire plume an upstream tilt at below 250 m above ground level, and downstream tilt at heights above 250 m. As in Figure 4 except for TANH.
- Figure 8 is the same as Figure 6 except for TANH at 900 s. See text for explanation.
- Figure 9 shows the horizontal cross section at 240 s and y = 810 m.
- Figure 10 shows the vertical cross section at 240 s and z = 18 m.
- Figure 11 shows the horizontal cross section at 240 s and z = 18 m.