The Fluid Dynamical Forces Involved in Grass Fire Propagation

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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 wildland fire version of Weather Research & Forecasting Model.

Both numerical experiments are of a moving grass fire line of uniform fuel (load of 0.626 kg m^{-2}, roughness height of 0.036 m) on level terrain, initialized as a line perpendicular to direction of westerly background flow. Initial fire line length/width = 400/20 m. Atmosphere is neutral to convection below 1 km, weakly stable above. Model grid sizes $\Delta x = \Delta y = 20$ m and vertically-stretched starting with smallest $\Delta z = 2.9$ m in 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 stalled 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 positioned at x_0 and y_0 draws low-level air equally from all sides, and structure of the x or east-west component of the flow at a fixed x position horizontally displaced from convective column has a bell-like shape with a maximum amplitude at $y = y_0$. **Figure 3** shows this geometry.

In a mean ambient wind, the convective column is tied to the fire at the surface, moving at the fire's surface rate-of-spread and tilting downstream with height. The effect of downstream tilting is to shift the center of low-level convergence ahead of the fire line. The 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.

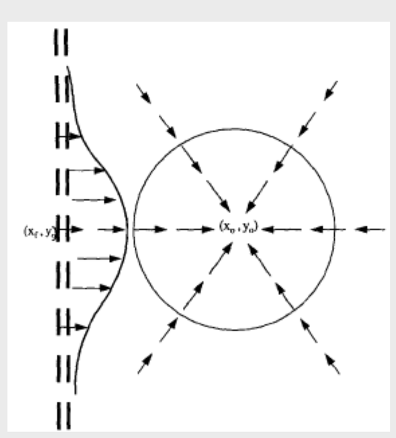

Figure 1 See text for explanation.

The flow that propagates the fire's 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. Pure rotation, 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.

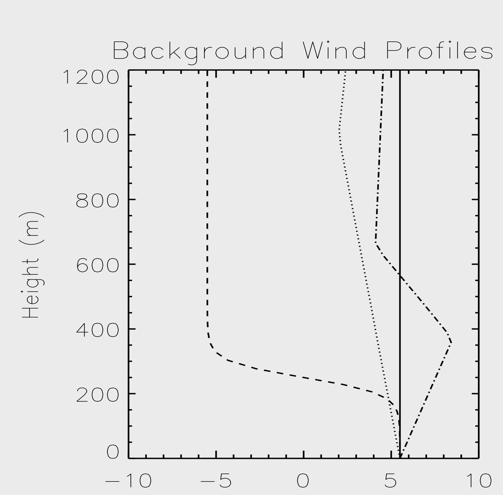

Figure 2 See text for explanation.

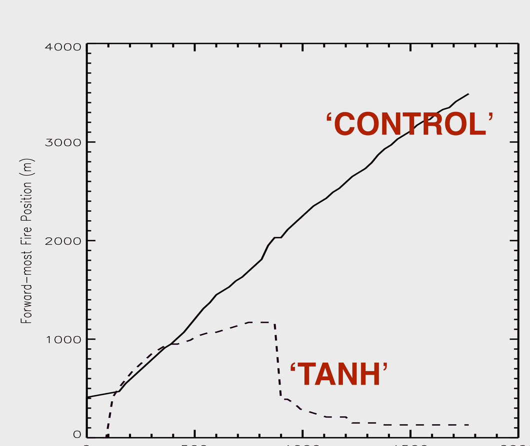

Figure 3 See text for explanation.

Analyses and Results

Figure 4 shows z-x cross sections at 240 s in **CONTROL** through middle of and perpendicular to fire line for: (a) y 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 downwind of surface heating.

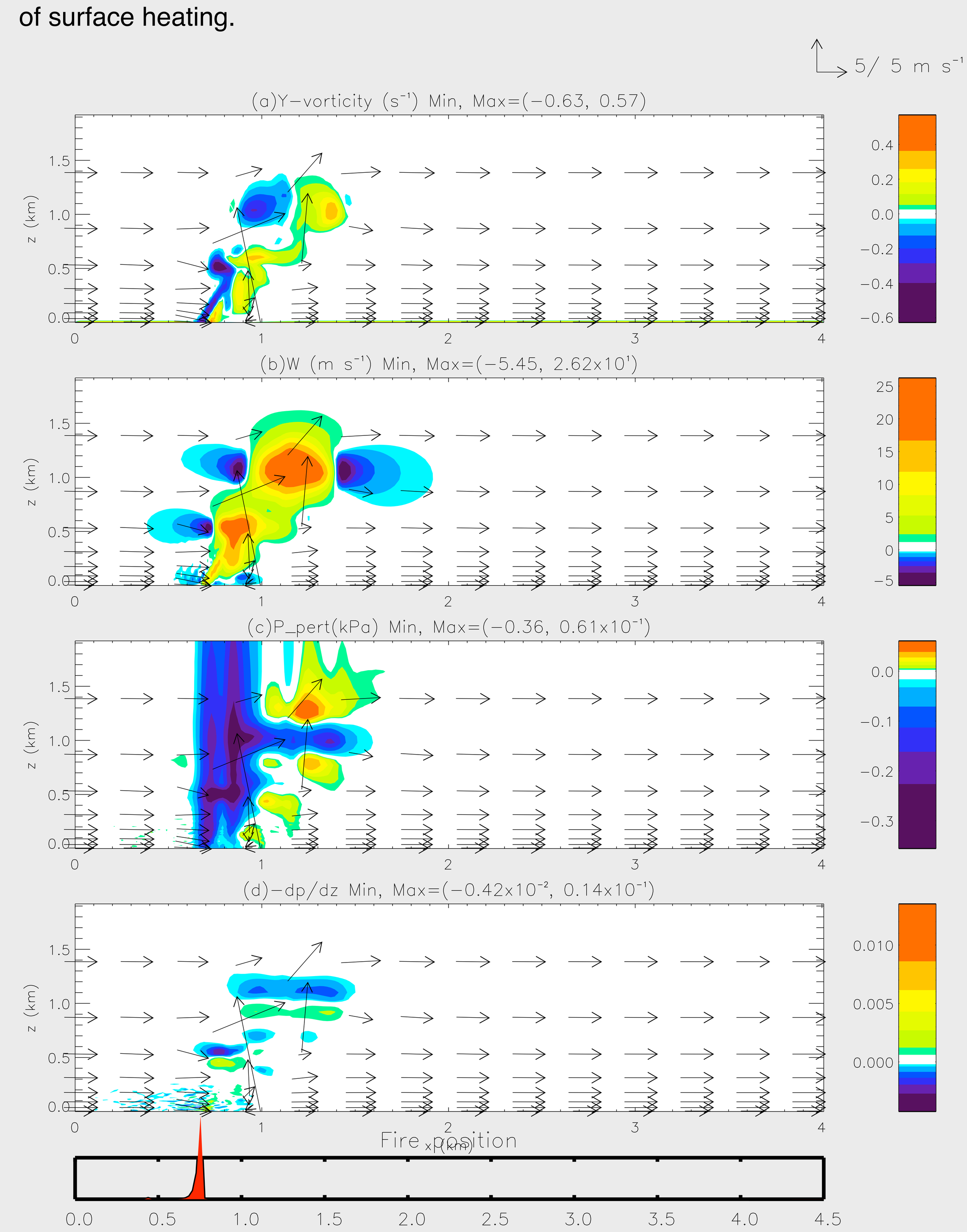

Figure 4 CONTROL z-x cross section at 240 s and y = 810 m.

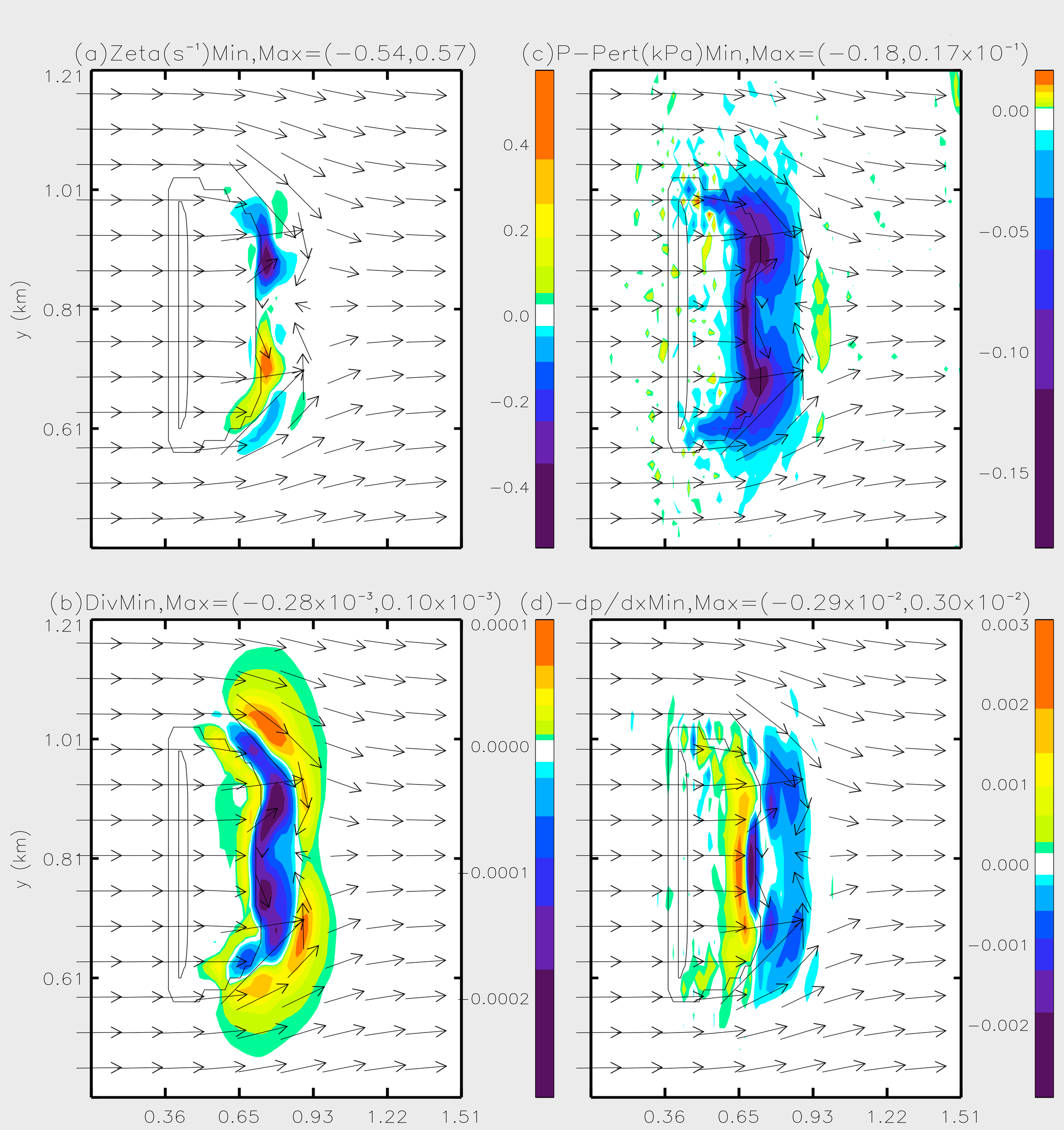

Figure 5 CONTROL x-y cross section at 240 s and z = 18 m.

Analyses and Results

Note in **Figure 4** the co-location of significant y vorticity (i.e., pure rotation in the y direction) with low dynamic pressure perturbations. Also associated with these features are significant plus/minus -pd/dz. values and down/up/down 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/hinder 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 x-y cross sections at 240 s in **CONTROL** at 18 m AGL (Above Ground Level) for: (a) z component of vorticity; (b) horizontal divergence; (c) p perturbation; and (d) -dp/dx. Note co-locations of significant z vorticity in (a) [i.e., fluid in pure rotation oriented in the vertical] with significant negative divergence (convergence) in (b) into low p regions and (c) +/- -dp/dx showing positive/negative forcing in horizontal by x-y p pattern slightly forward of fire line. Light black contour lines indicate fire perimeter. **CONTROL** fire line moves steadily in + x direction (i.e., eastward) at this time [**Figure 3**].

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 westerly 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 fire line to provide proper -dp/dx forcing that moves the fire front in direction of ambient wind. Surface convergence is positioned slightly forward of fire line as depicted in **Figure 1**.

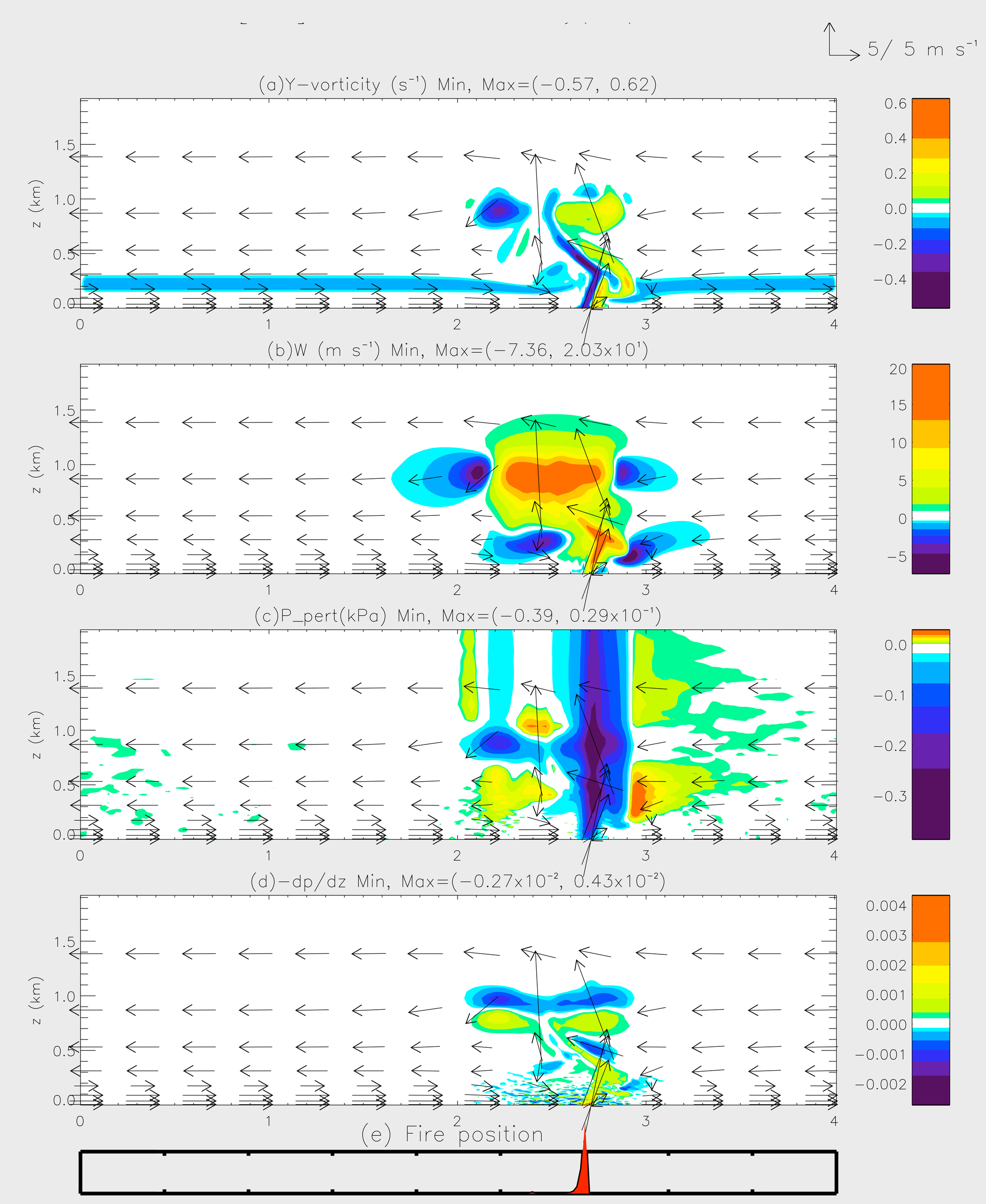

Figure 6. As in Figure 4 except for TANH

Figure 6 is the same as **Figure 4** except for **TANH**. As in **Figure 4** for **CONTROL**, the similar co-location of significant y vorticity (i.e., pure rotation in y direction) with low pressure perturbations, and co-location of significant plus/minus -pd/dz. values and down/up/down motion across plume [e.g., in (b) 250 m and 1 km above ground level]. When ambient wind is present, vertical motion and pressure fields in fire plume are not symmetrical over fire line. Negative vertical shear [see (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.

Analyses and Results

At this time (240 s) **Figure 2** shows **TANH** fire line moving in positive x direction (i.e., eastward). Explanation for this forward fire line propagation is same as that for **CONTROL** (**Figure 5**).

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 stalled, no longer moving in positive x direction. The explanation for this is that well-organized structures seen in z vorticity, pressure perturbation, divergence, and -pd/dx fields --- that combined are responsible for steady forward propagation of the fire line --- at previous times no longer exist. As in Clark et al 1996 (International J. of Wildland Fire), the negative shear in the **TANH** ambient wind profile advects the counter-rotating vortices back into the fire line.

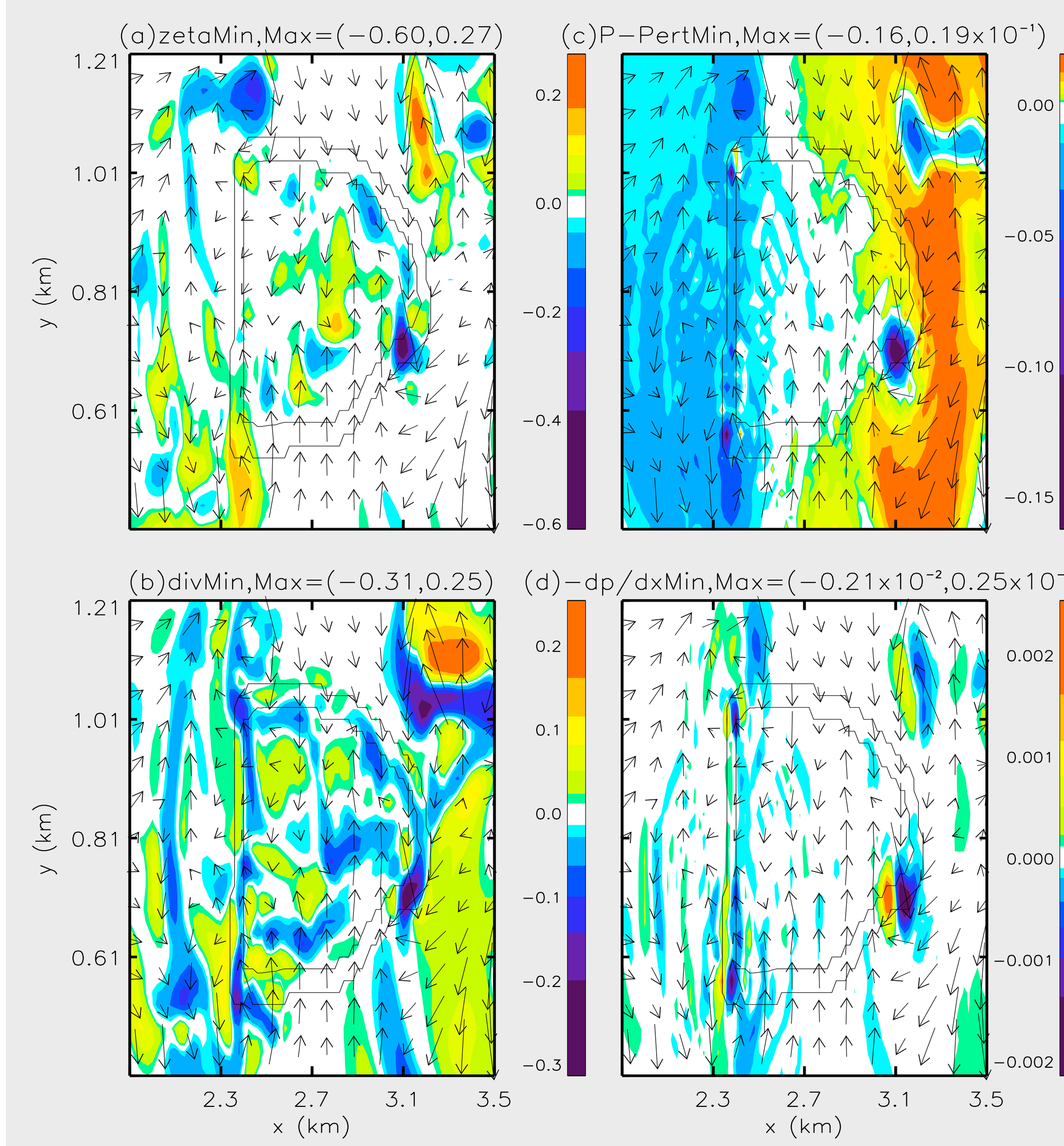

Figure 7 Same as **Figure 3** except for **TANH** at 900 s. See text for explanation.

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 z vorticity by upper-level winds back into the fire line took place only after significant magnitudes of z vorticity were established at upper levels. A plot of maximum magnitudes of +/- z 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.

The ideas behind **Figure 3** remain valid, but what we can amend Clark et al 1996'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 develop naturally along the fire line and that then are advected in the direction of background wind. 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 convection column. It is the advecting wind, not the surface wind, that is responsible for the positioning of the low pressure centres ahead of the fire line.