The Importance of Wind in the Fire Environment

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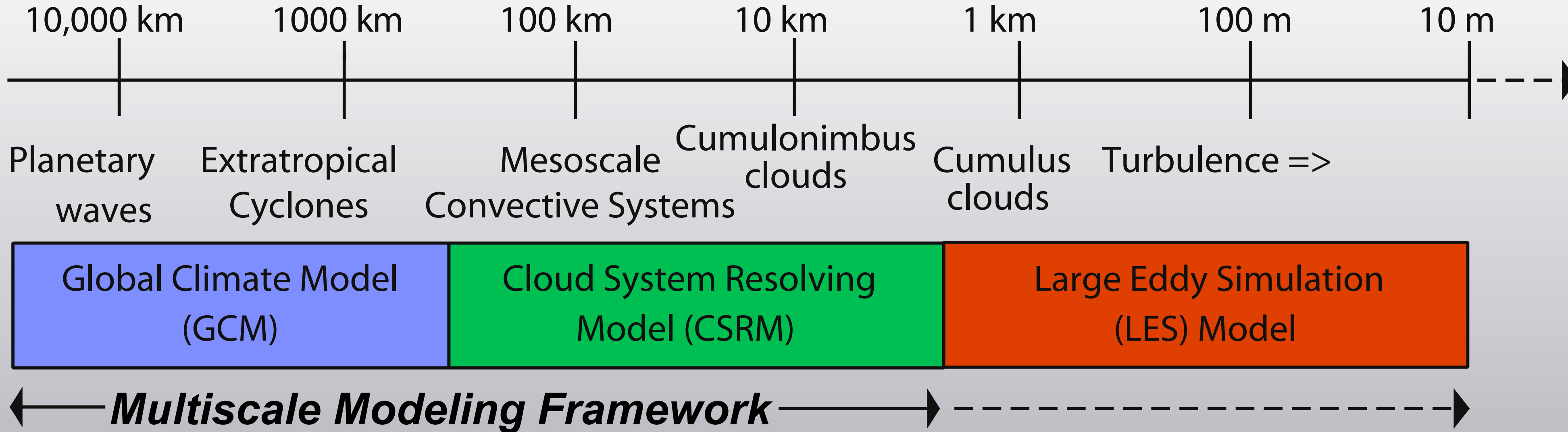
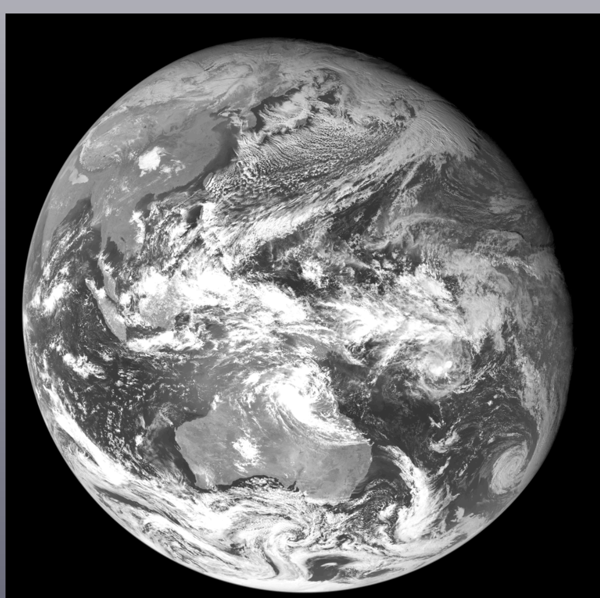
Scales of Atmospheric Motion





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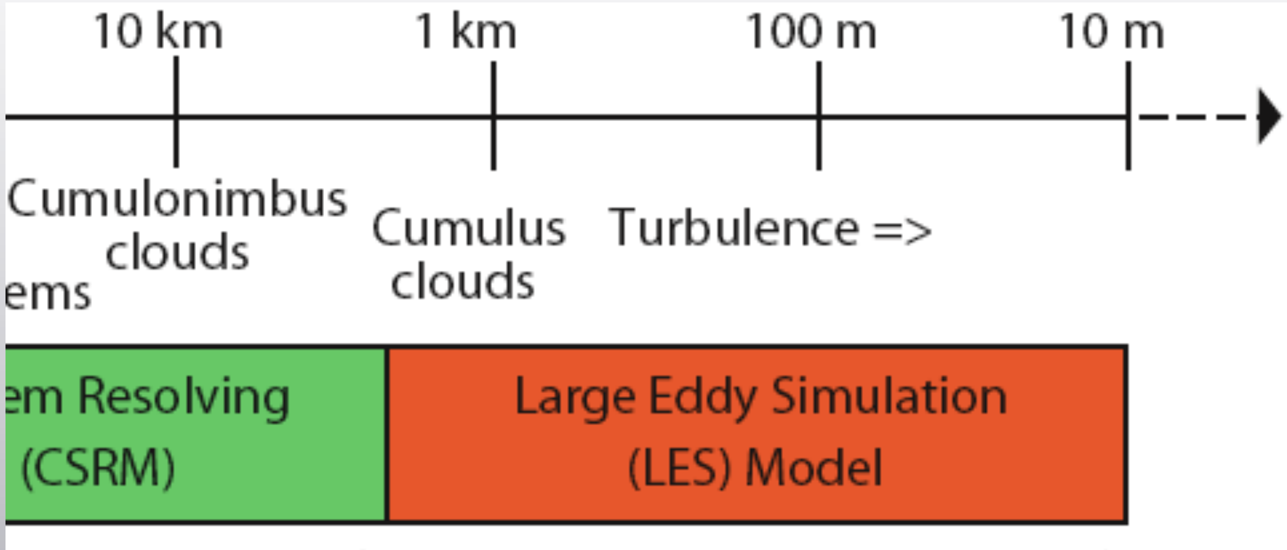
10 km
1 km
100 m
10 m
Cumulonimbus clouds
ems
Cumulus clouds
Turbulence =>
em Resolving (CSRM)
Large Eddy Simulation (LES) Model


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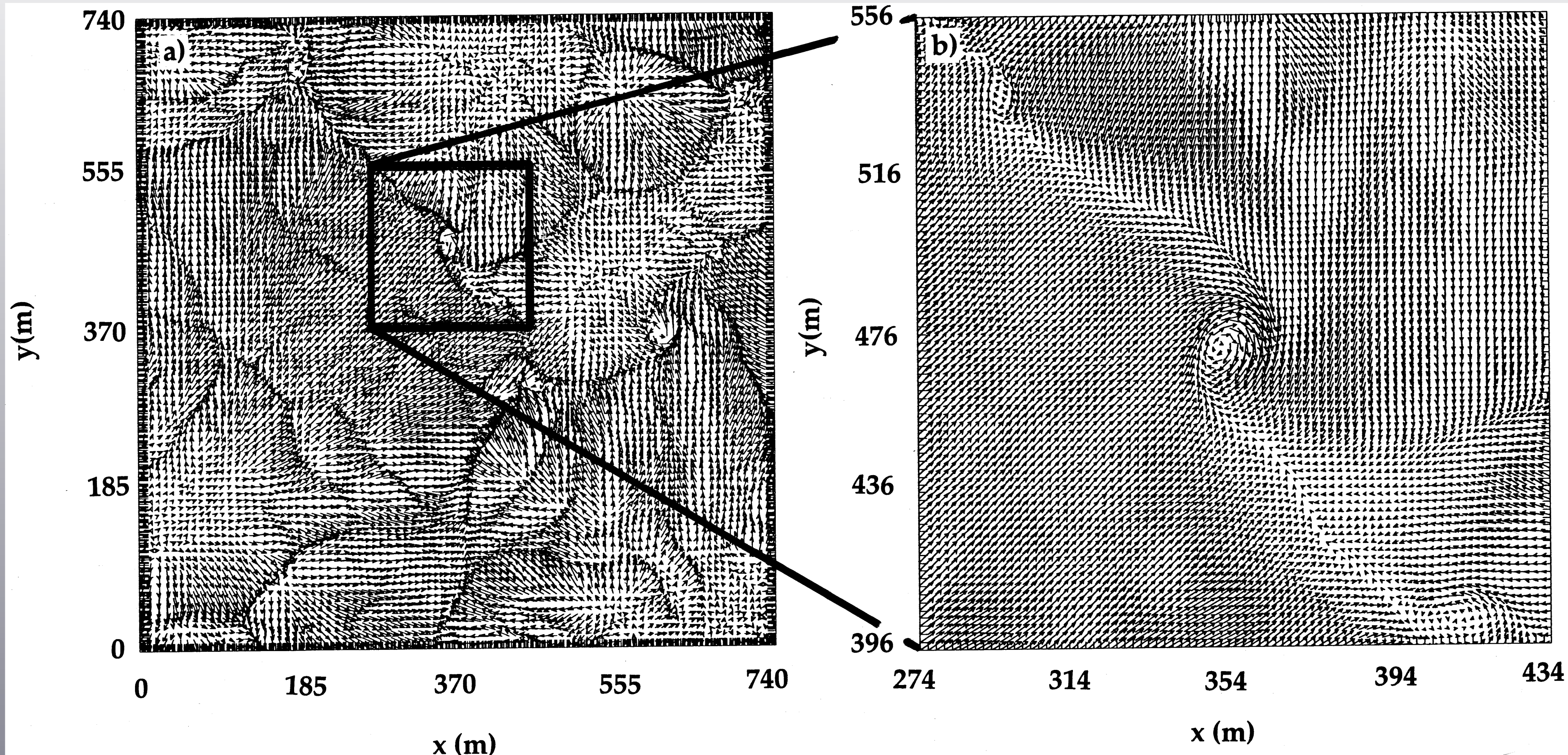

Figure 2. Horizontal cross-sections at height $z = 2.1$ m, of velocity vectors from the 2MLES simulation (see text) for: (a) time $t = 1000$ s, showing vectors at every fourth grid point over the total domain of 740 m × 740 m (370 × 370 grid points), with a maximum vector of 7.9 m s^{-1}; (b) expanded vortex of interest from inside the 'black box' on (a) of size 160 m × 160 m (80 × 80 grid points), with a vector plotted at every grid point and a maximum vector of 6.2 m s^{-1}; (c) and (d) as (a) and (b), respectively, but at $t = 1100$ s, with maximum vectors of 7.7 and 6.3 m s^{-1}; (e) and (f) as (a) and (b), respectively, but at $t = 1800$ s, with maximum vectors of 6.5 and 5.0 m s^{-1}; (g) and (h) as (a) and (b), respectively, but at $t = 2200$ s, with maximum vectors of 7.0 and 5.0 m s^{-1}.

Two factors that spread WUI (Wildland Urban Interface) fires and wildfires and affect their overall behavior are:

- **interaction/coupling between the fire & fire-induced flow;**
- **interaction/coupling between the fire and flow driven by processes in Atmospheric Boundary Layer (ABL).**

Both factors are captured by a coupled ABL-Fire LES approach to WUI/wild fire modeling.

What is LES?

- LES = Large Eddy Simulation
- LES resolves the large, energy-containing eddies of 3D turbulence, and parameterizes the smaller eddies.
- The grid size is 10 to 100 m so it's in the inertial range. This usually allows a simple subgrid-scale (SGS) closure.
- LES provides a flow realization based on the N-S equations; simulations with nearly identical initial conditions can quickly diverge ("butterfly effect").

How does a coupled ABL/WUI-fire LES differ from the other *models?

- Resolves 3D turbulence within the entire atmospheric boundary layer.
- Resolves fire heat flux at fire-line scale (10 m).
- Couples fire spread to fire-line turbulent wind field.

*statistical or empirical (not based on predictive fluid dynamical N-S equations)

What are the generic features of the fire model coupled with LES?

- Fire heat and moisture fluxes are partitioned into turbulent and radiative fluxes and distributed vertically in the LES ABL.

  Magnitude of these fluxes depends on fuel type, load, and heat-release rate.

- Fire surface rate-of-spread at depends on fuel characteristics (dryness, type, load, geometry, etc) and (ideally) surface fire-line winds.

- Roughness height depends on vegetation type and its state (unburned vs burned).

Fire parameterization:

- fireline's rate of spread (ROS) formulation
- surface heat and moisture fluxes from combustion
- roughness height of surface fuel

LES dynamics:

- responds to fire's (sensible and latent) heating
- LES surface winds at fire line determine ROS

ABL flow is conditioned and/or forced by 3D and/or time-varying

- **full-scale topography, surface roughness, surface sensible and latent heat fluxes**
- **wind, humidity, temperature and in the ABL**
- **larger-scale weather systems.**

Wild and WUI fire prediction requires a multi-scale numerical modeling framework capable of providing 3D time-varying high-resolution LES/ABL data.

Comparative numerical simulations with a coupled wildfire-LES model can study the sensitivity of grass fire to different wind environments.

Two examples (time permitting) are simulations of the impact of flow in a convectively-driven ABL (CBL) on

1. **fire spread**
2. **fire brand propagation**

The model fires burn in uniform fuel on level terrain, initialized as straight lines perpendicular to direction of a constant mean background wind, and set in a dry, neutrally-stable atmosphere.

Why study wildfires in the CBL?

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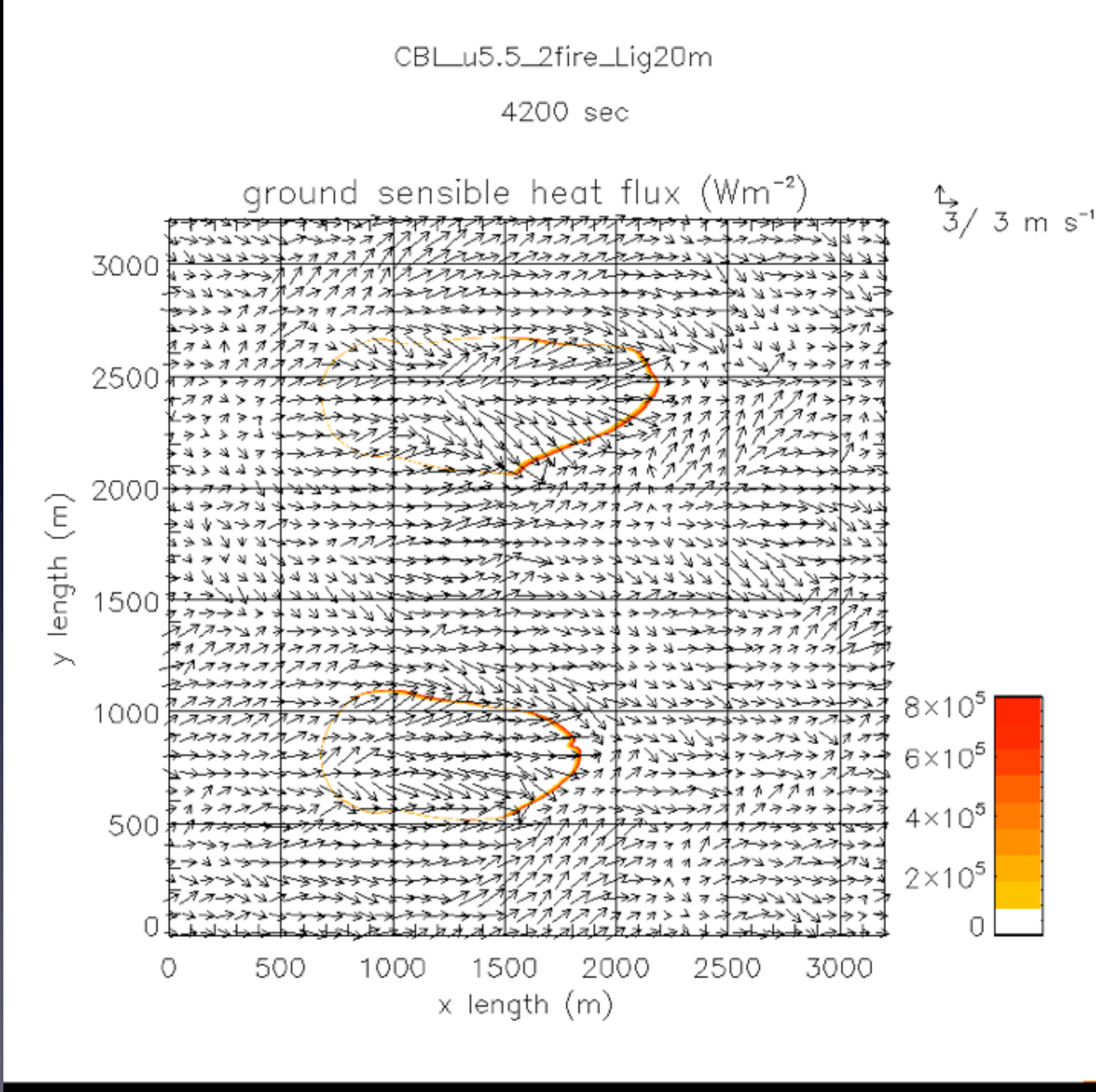
Why study wildfires in the CBL?

- Fires occur in the CBL
- Turbulence/gustiness exists in the CBL
- Gustiness/shear affects fire behavior
- Fire plumes interact with large eddies
- Structure of convection may matter

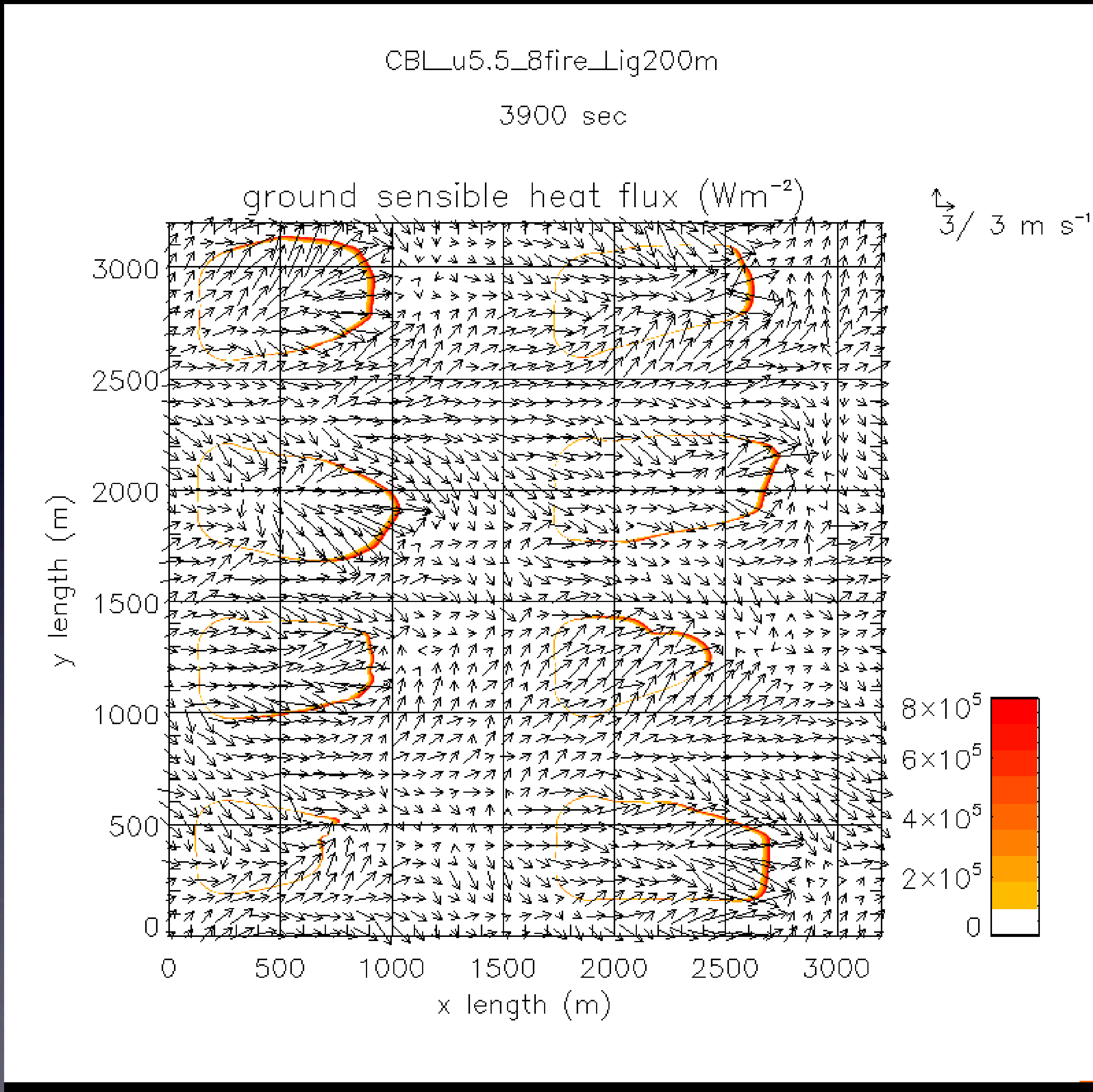
Impact of the CBL/Fire Winds on Fire Spread Rate

Fire parameters for CBL Simulations

fuel type	tall grass
number of fires	up to 8
ignition line length	20 to 200 m
start burn	after 1 hr
burn time	5 to 10 min

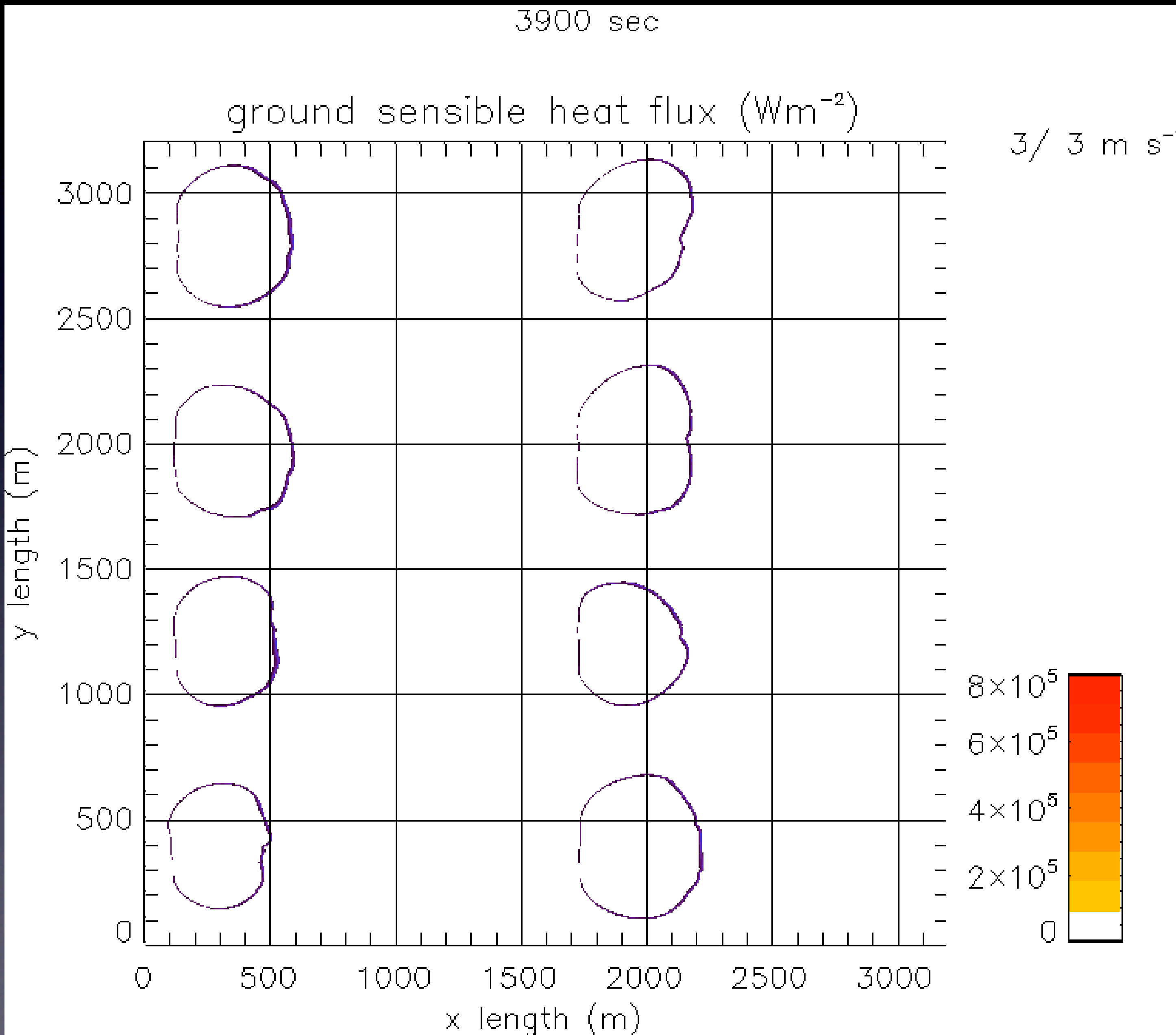


2 fires in buoyancy-dominated CBL



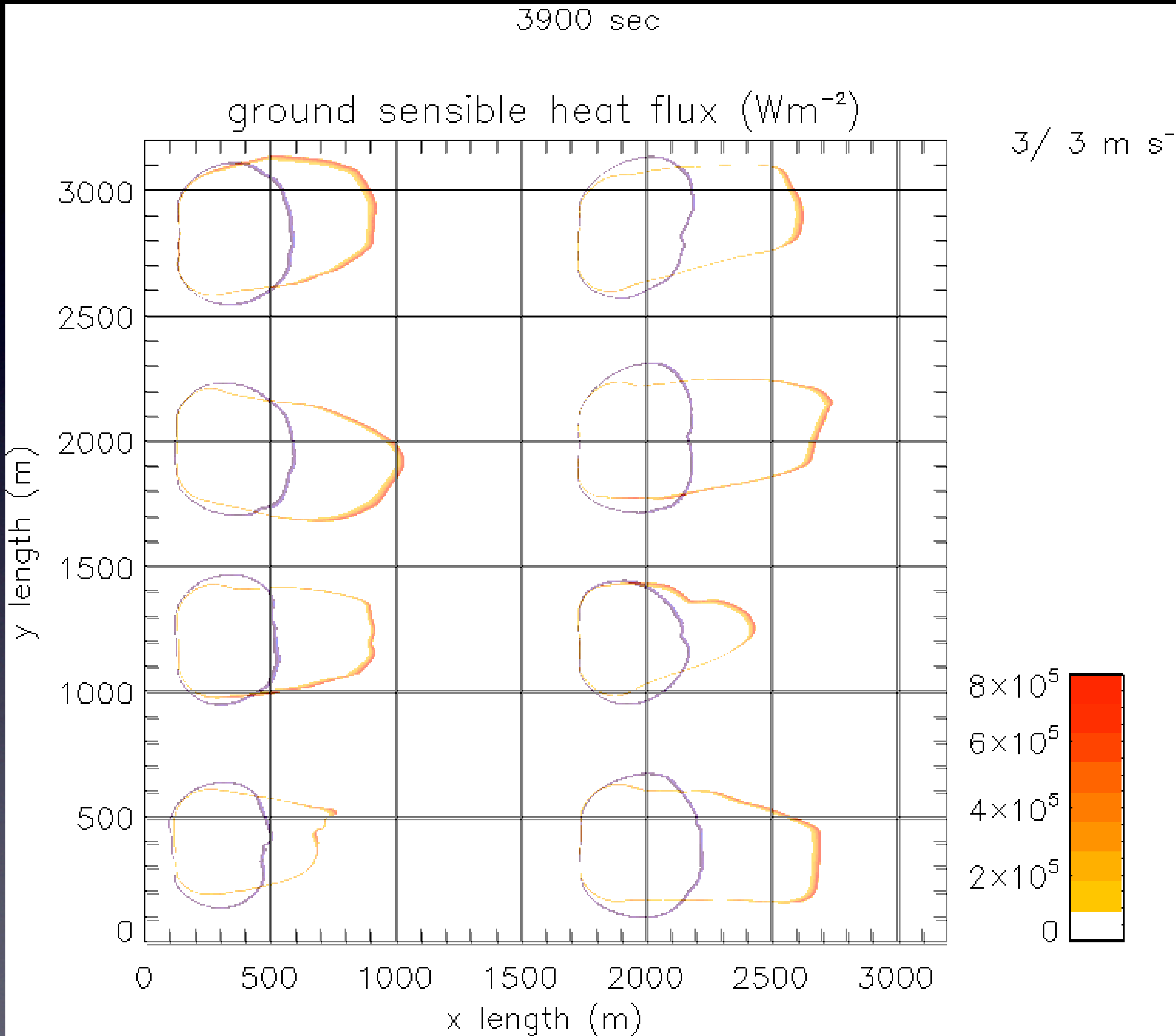
8 fires in buoyancy-dominated CBL

Uncoupled*

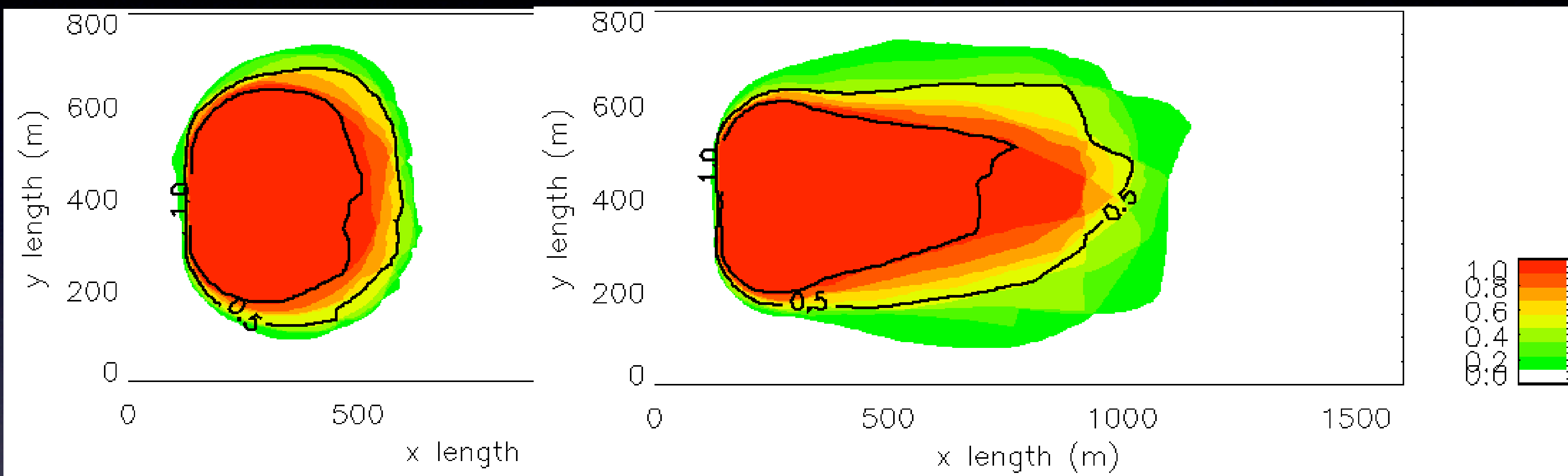


*Sensible & Latent heat fluxes and radiation from fire are not feed into the CBL flow

Coupled vs Uncoupled

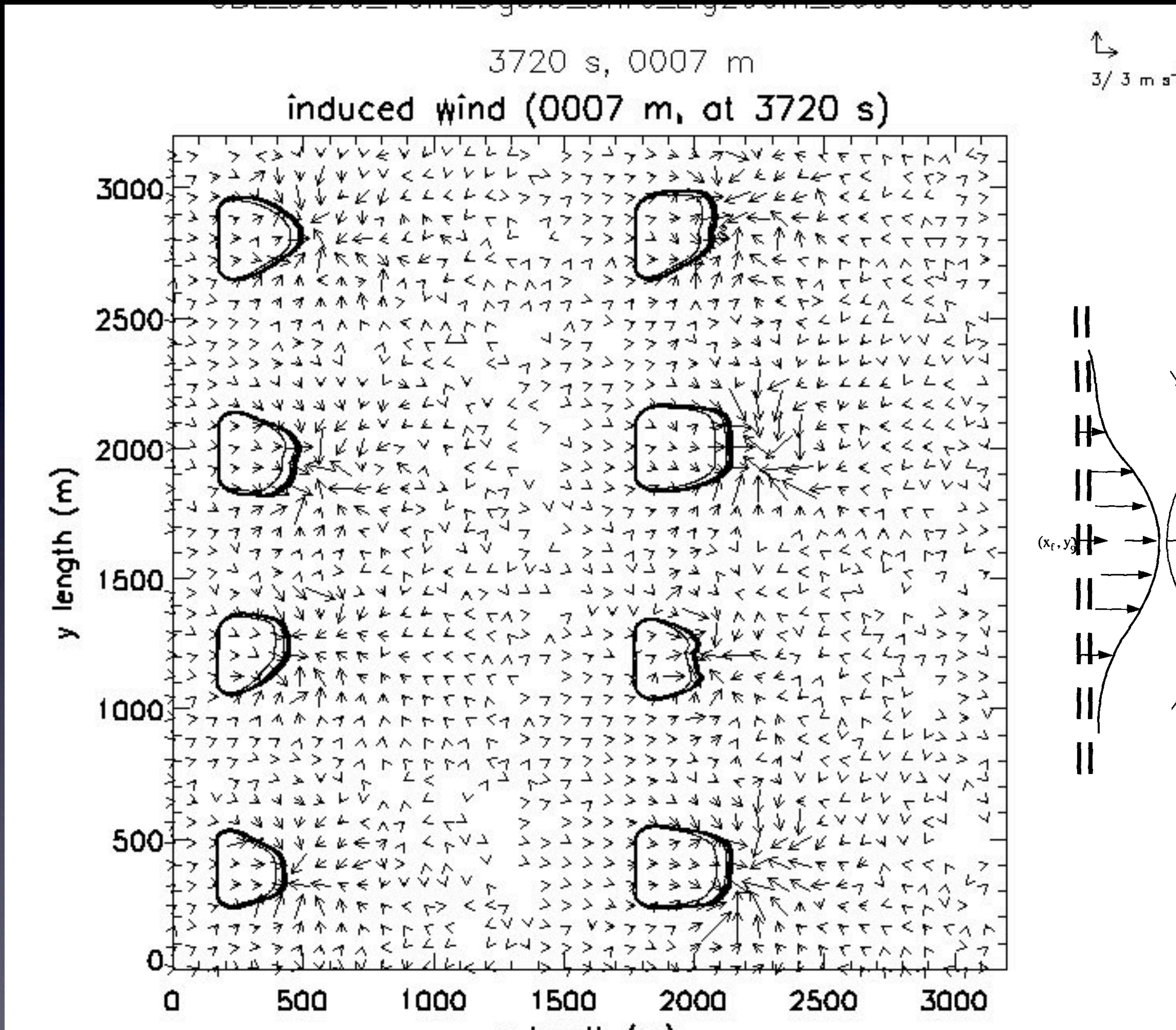


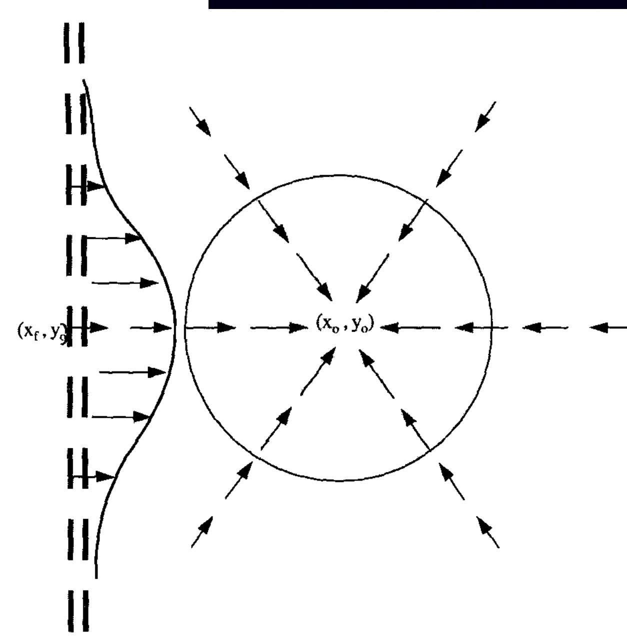
Ensemble fire spread after 5 min from 24 fires



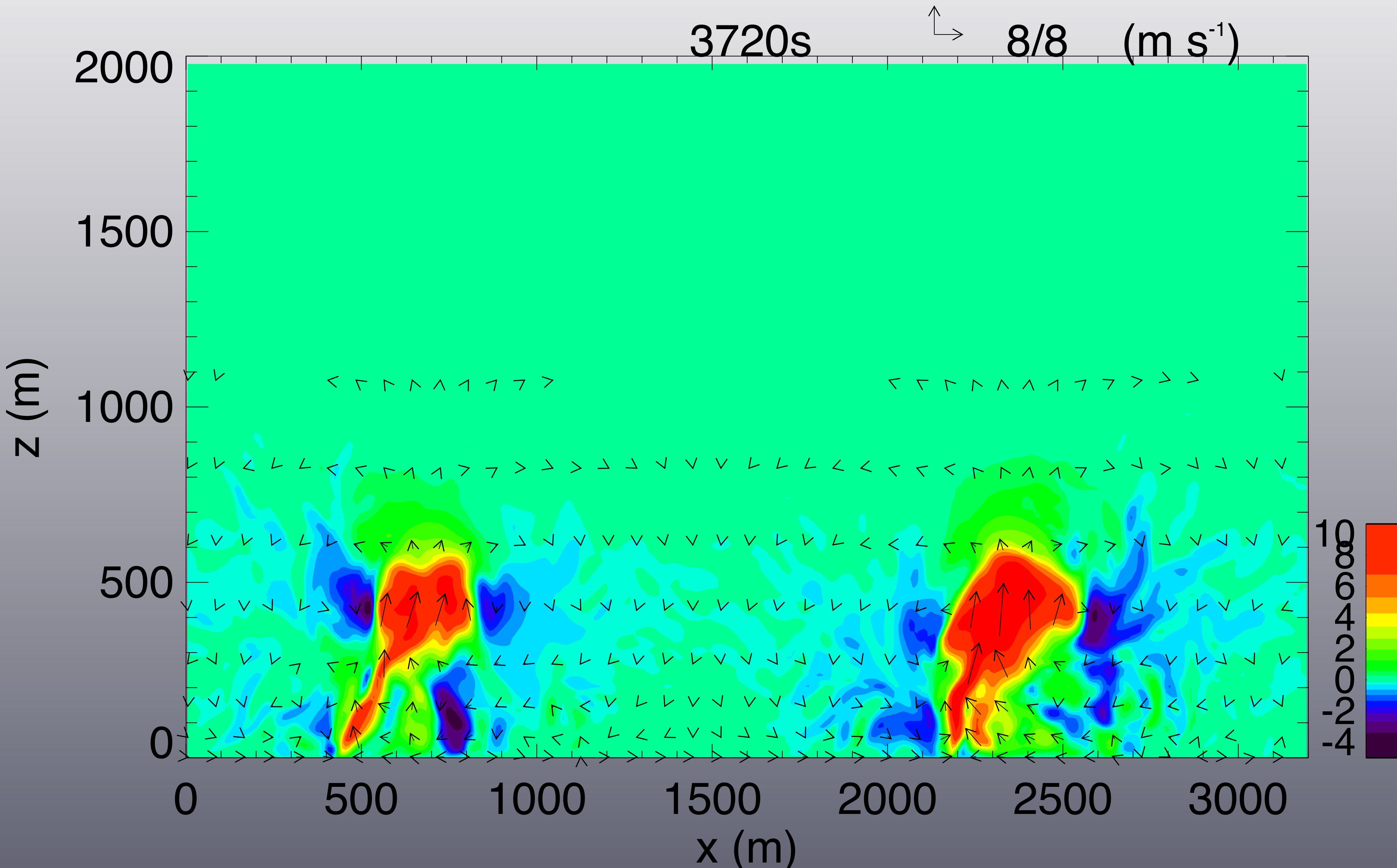
uncoupled **coupled**

Fire-induced flow: updraft





Fire-induced flow: updraft



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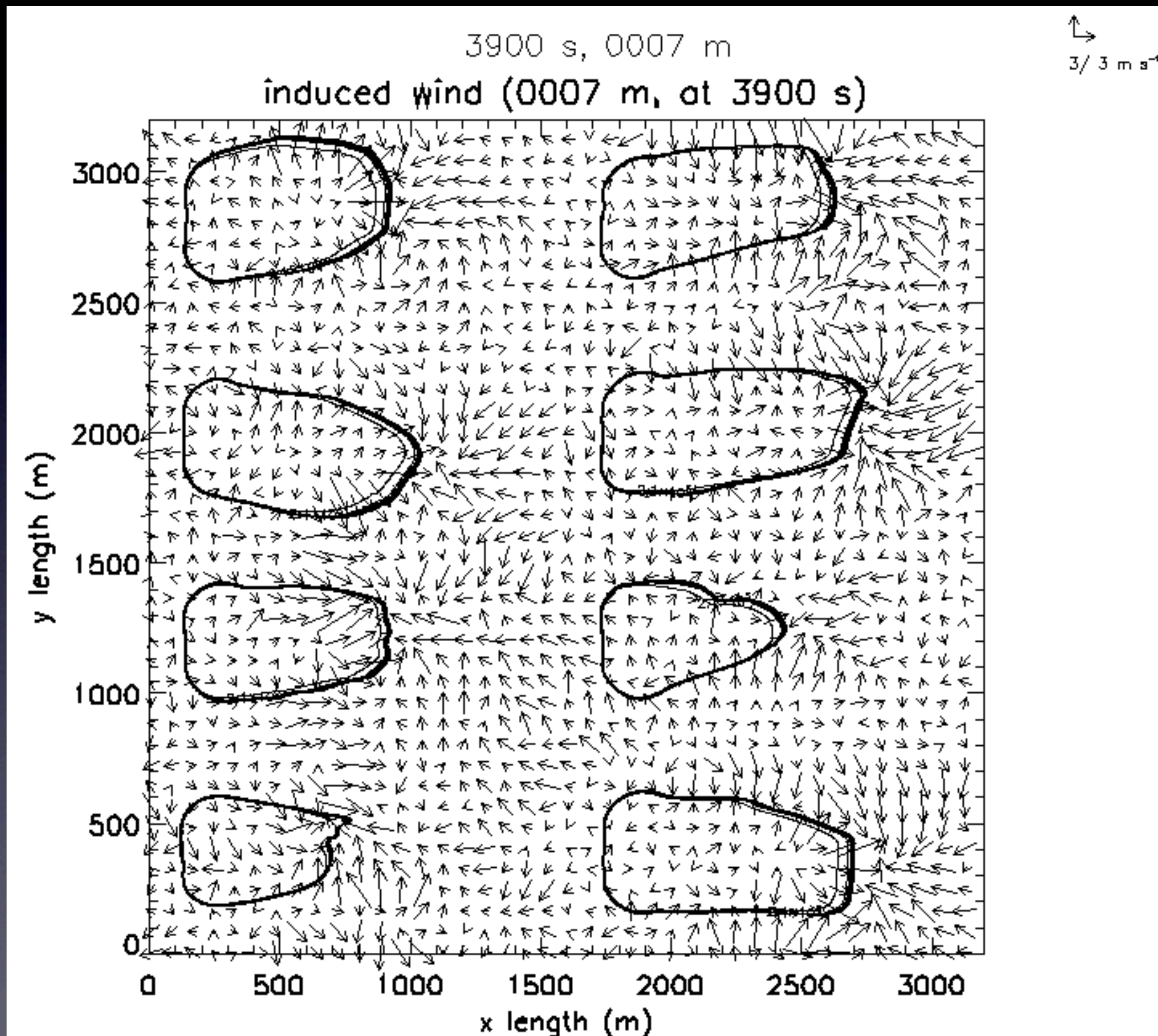
Fire-induced flow: downdraft



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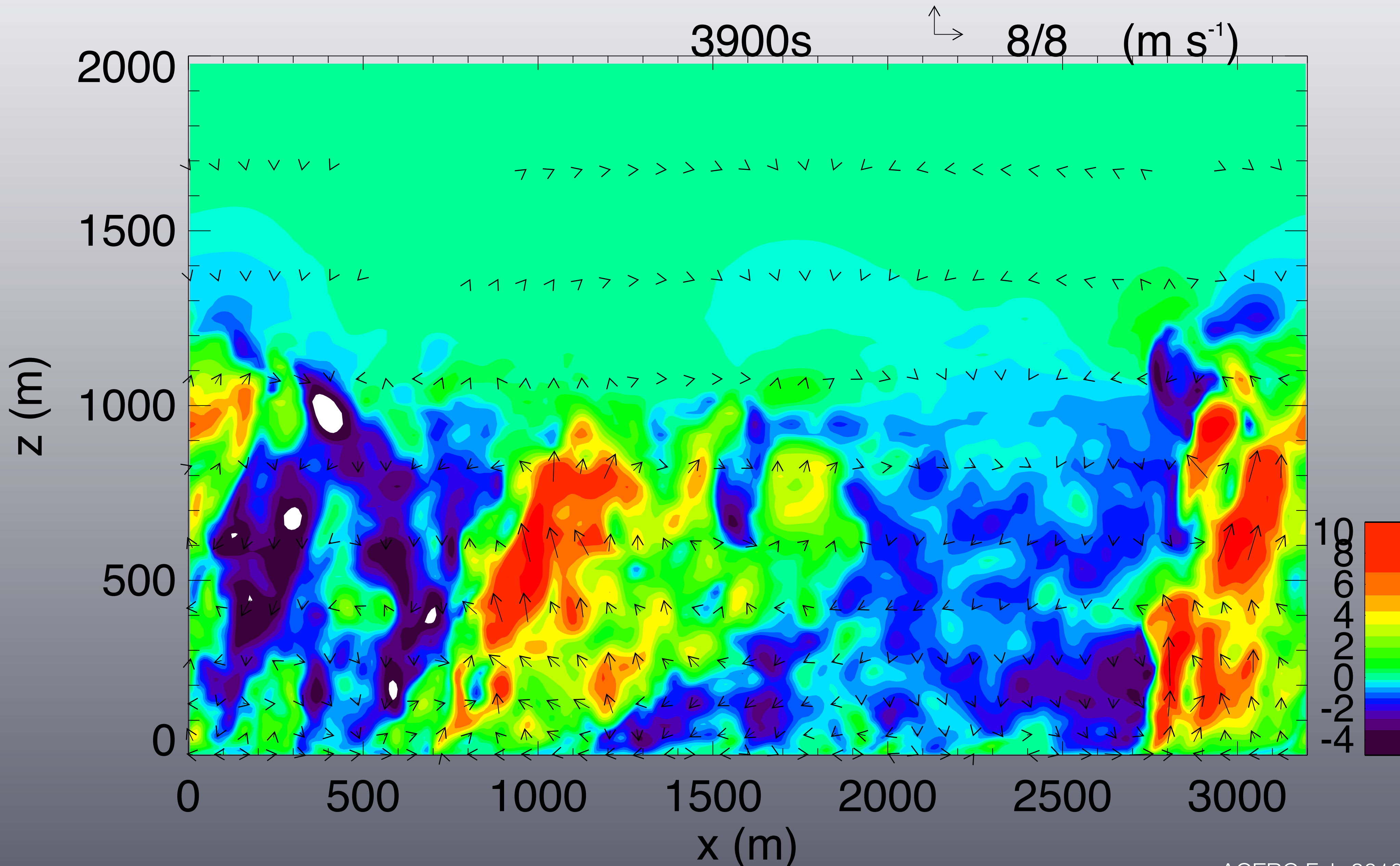
Fire-induced flow: downdraft



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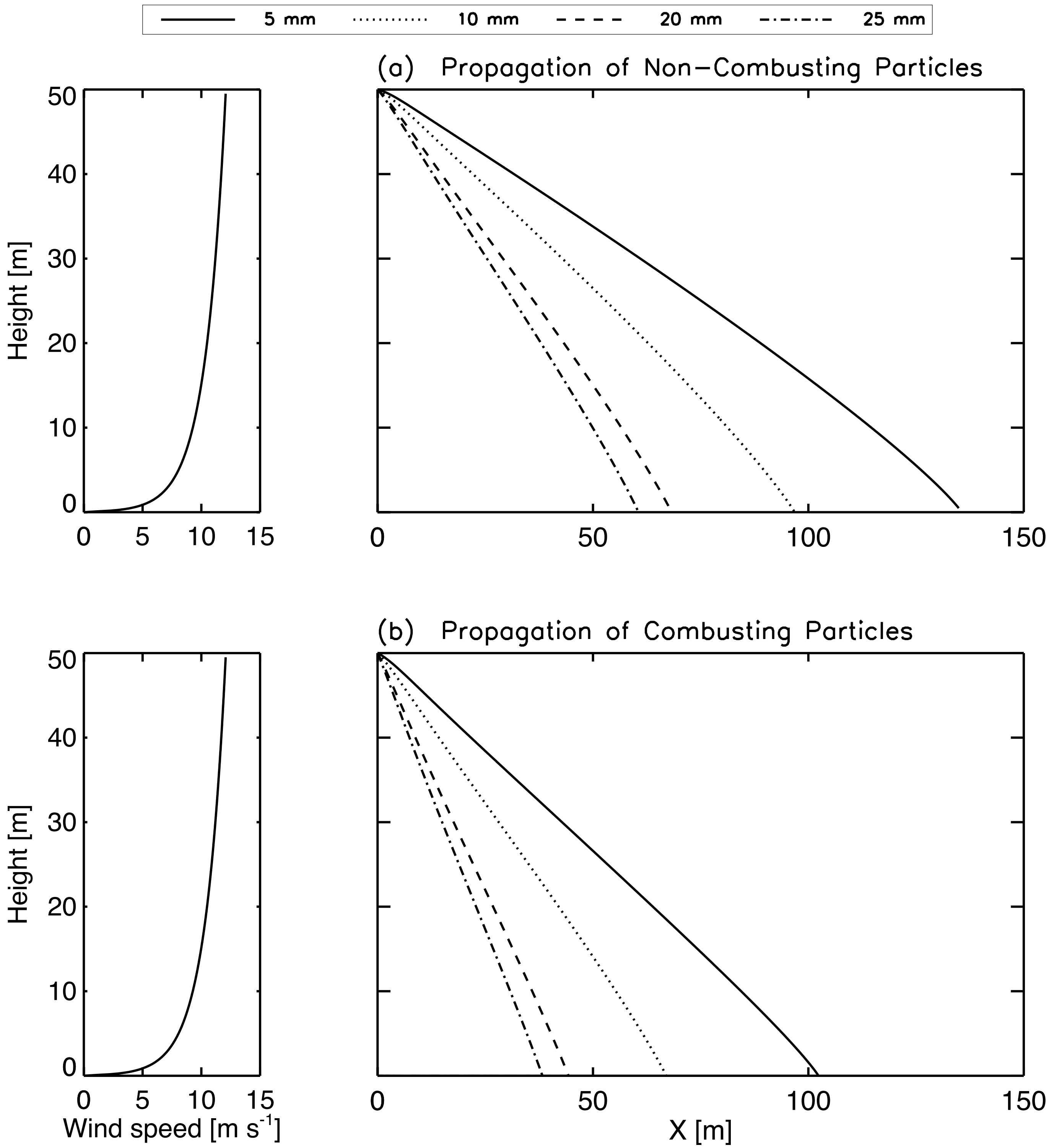
Summary - Fire Spread in the CBL

- Fire spread is not deterministic in CBL.

  A range of possible alignments of CBL and fire-induced circulations produces fire spread variability.

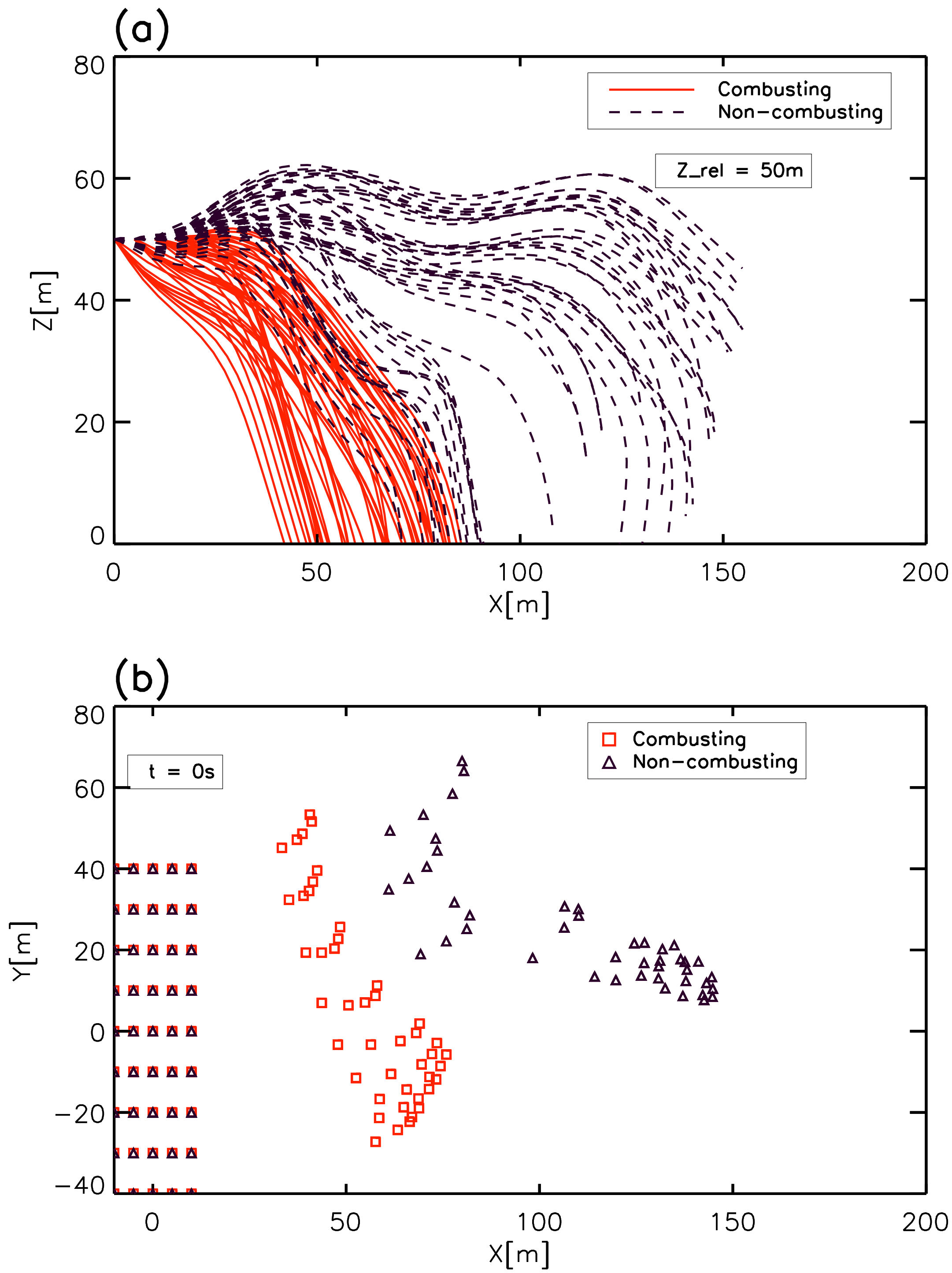
- Fire-induced circulations include:
  - Convergence and updraft ahead of fire line.
  - Divergence and downdraft behind fire line.

Impact of the CBL/Fire Winds on Fire Brand Propagation



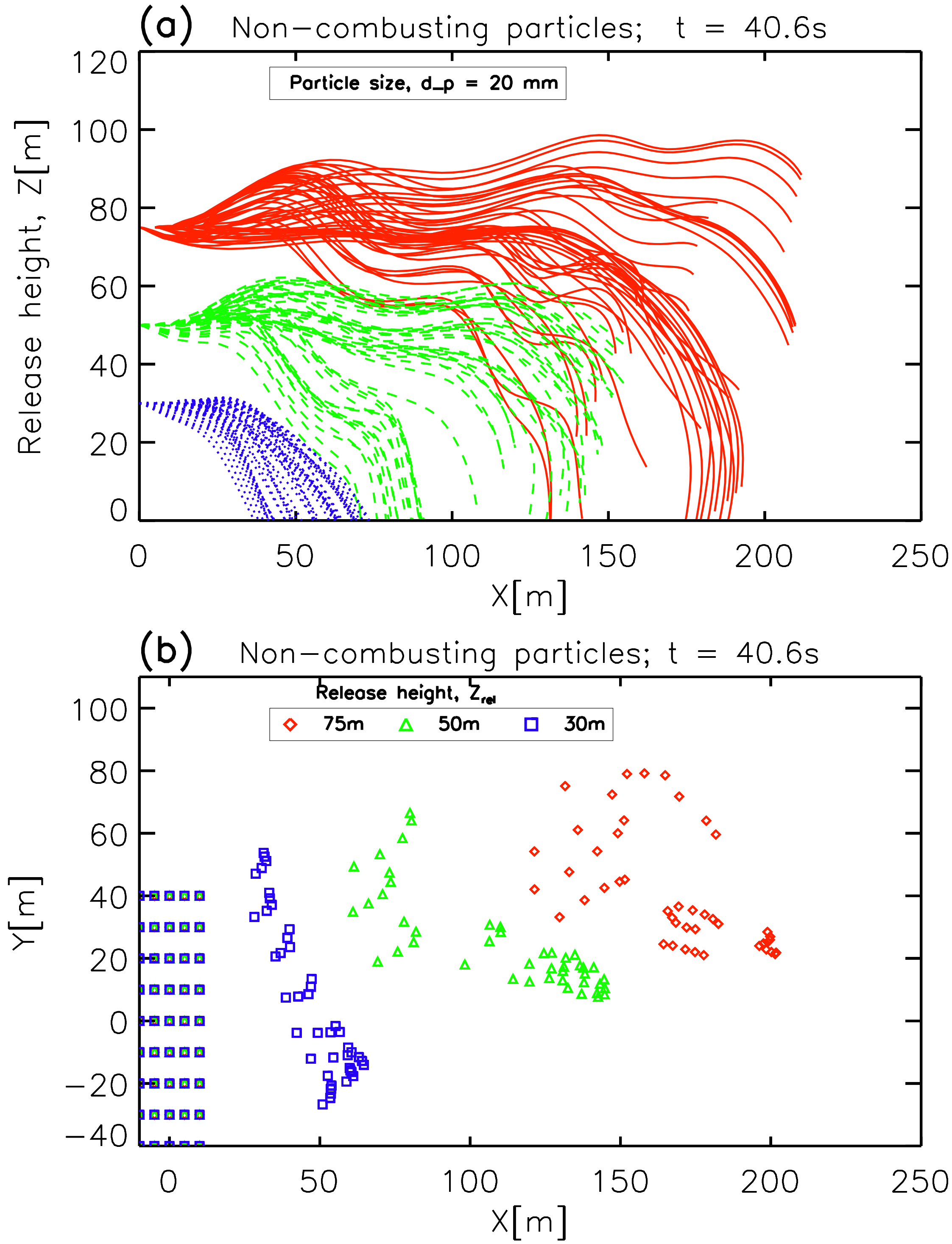
Fire Brand Propagation using a classic plume model to loft non-burning and burning wood particles into a neutral, non-CBL.

Trajectory of the burning particle is affected by ρ_a. The ρ_a around the particle was calculated at an average of air (20 ◦C) and flame (700 ◦C) temperatures, which decreases ρ_a from 1.204 kg m^{-3} for a non-combusting particle to 0.55 kg m^{-3} for a particle at flame temperature. This change is so significant that the burning particles attain a higher initial terminal velocity relative to non–burning particles, as seen in Figure 5d. The impact on V_t of ρ_a for a combusting particle is enough to overcome the impact of the loss of volume and mass on V_t for a combusting particle. Consequently, for the same initial mass, non-combusting (larger) particles propagate farther downwind than combusting (smaller) particles.



Release of 45 particles in 8 CBL fire plumes

Dependence of particle trajectory on combusting versus non-combusting particles



Release of 45 particles in 8 CBL fire plumes

Dependence of particle trajectory on release height

Scatter plot showing particle (x,y) positions at 40 s after release

Importance of fire-induced circulations on firebrand propagation

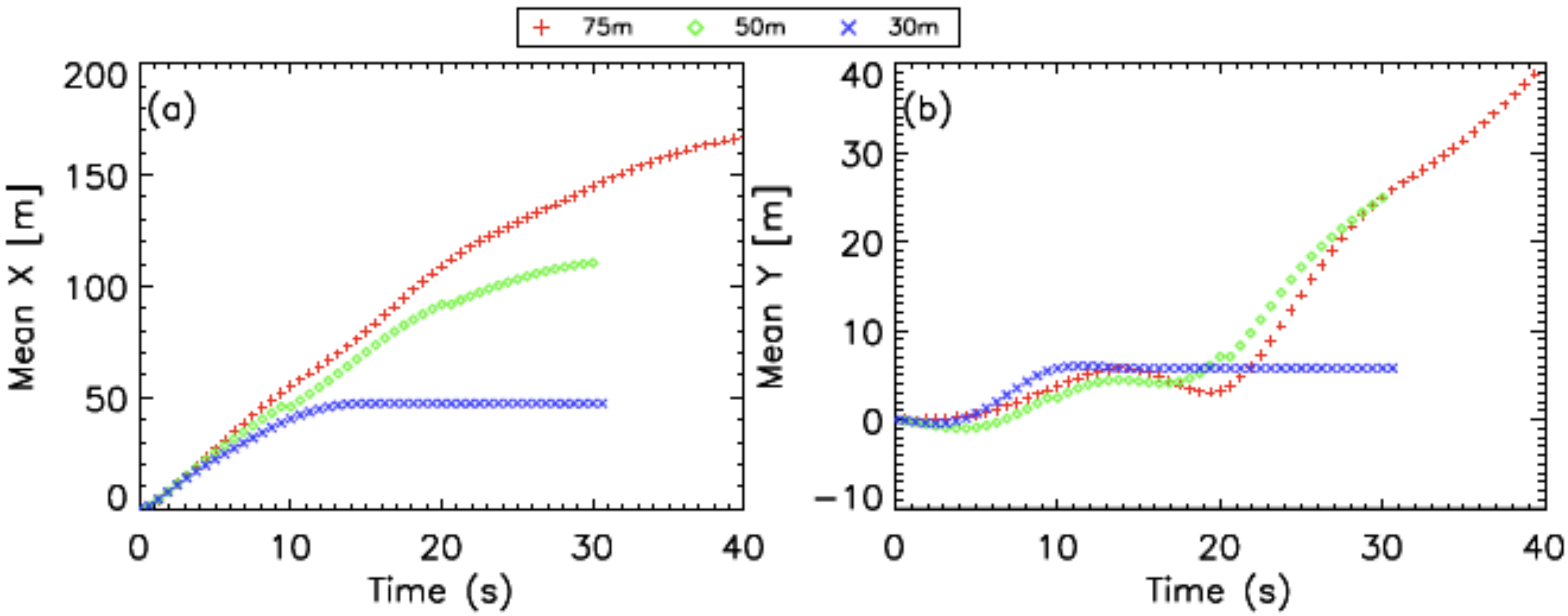
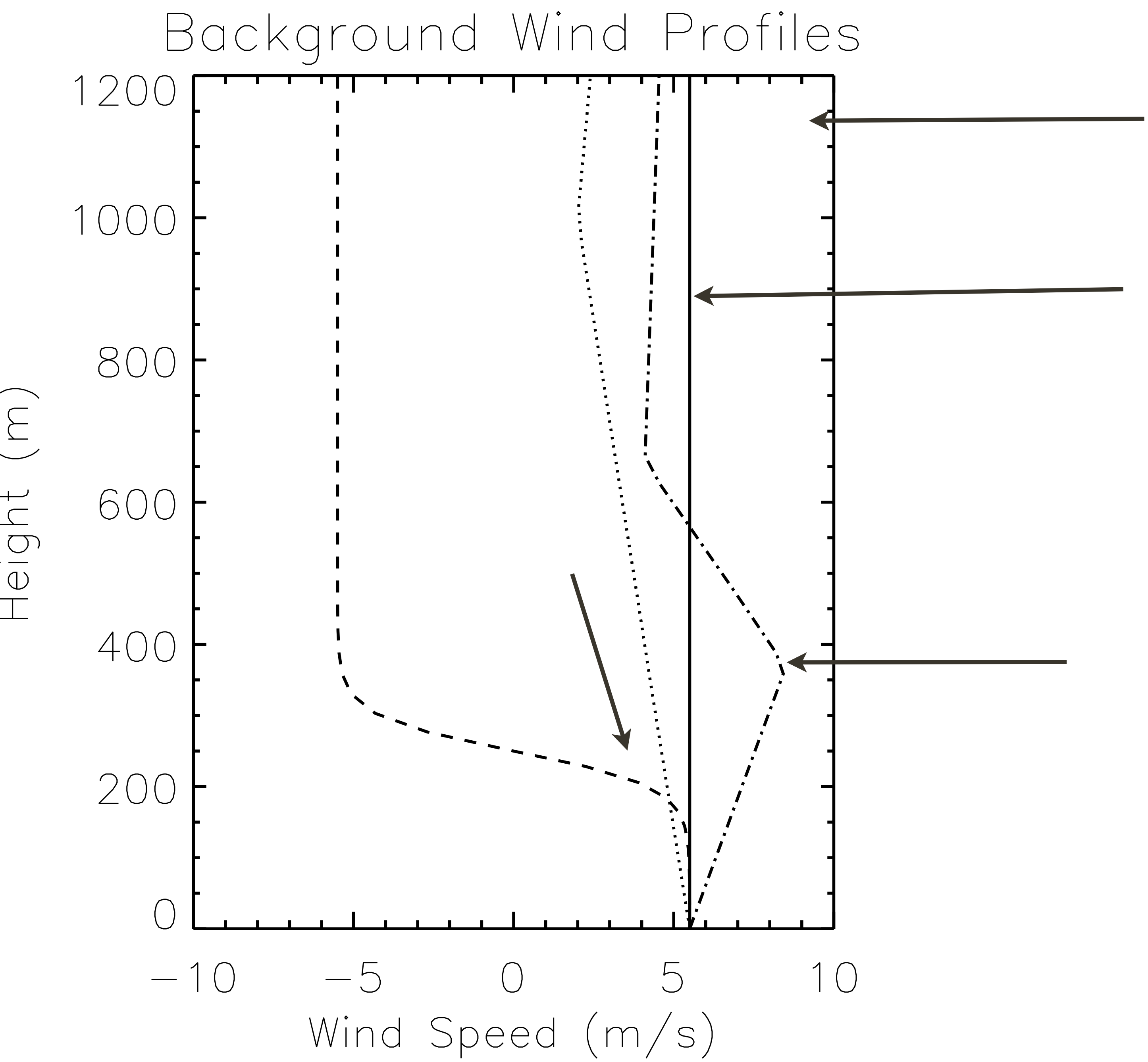


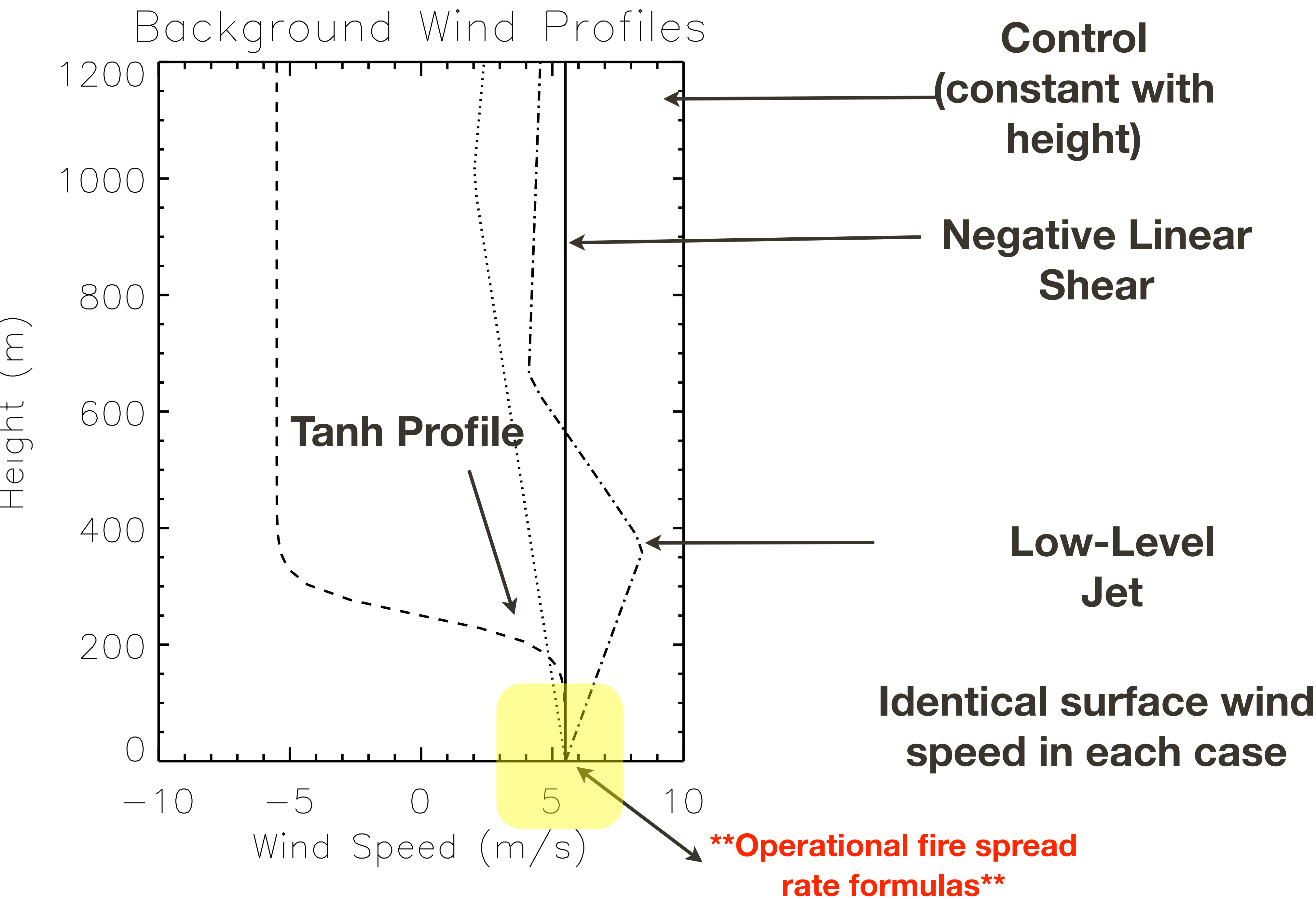
Figure 3.11: Figure showing the average, downwind (Mean X) and lateral (Mean Y), distance traversed by the particles released at various heights.

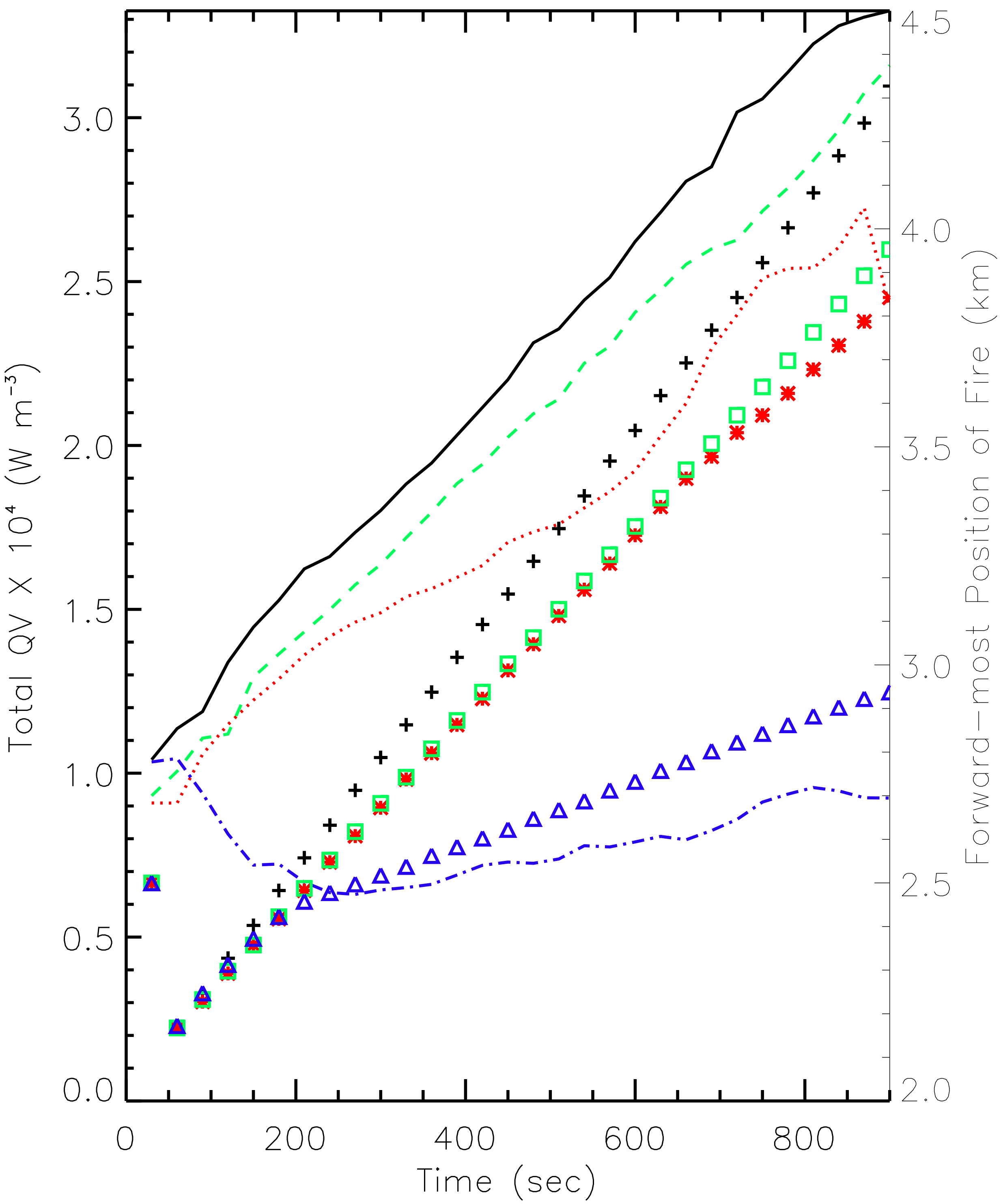
Summary - Fire Brand Propagation in the CBL

- Firebrand propagation is not deterministic in CBL.
- Variability in firebrand propagation depends on
  - CBL turbulence
  - Fire/CBL interactions
  - release height
  - particle size/mass
  - combustion versus non-combustion

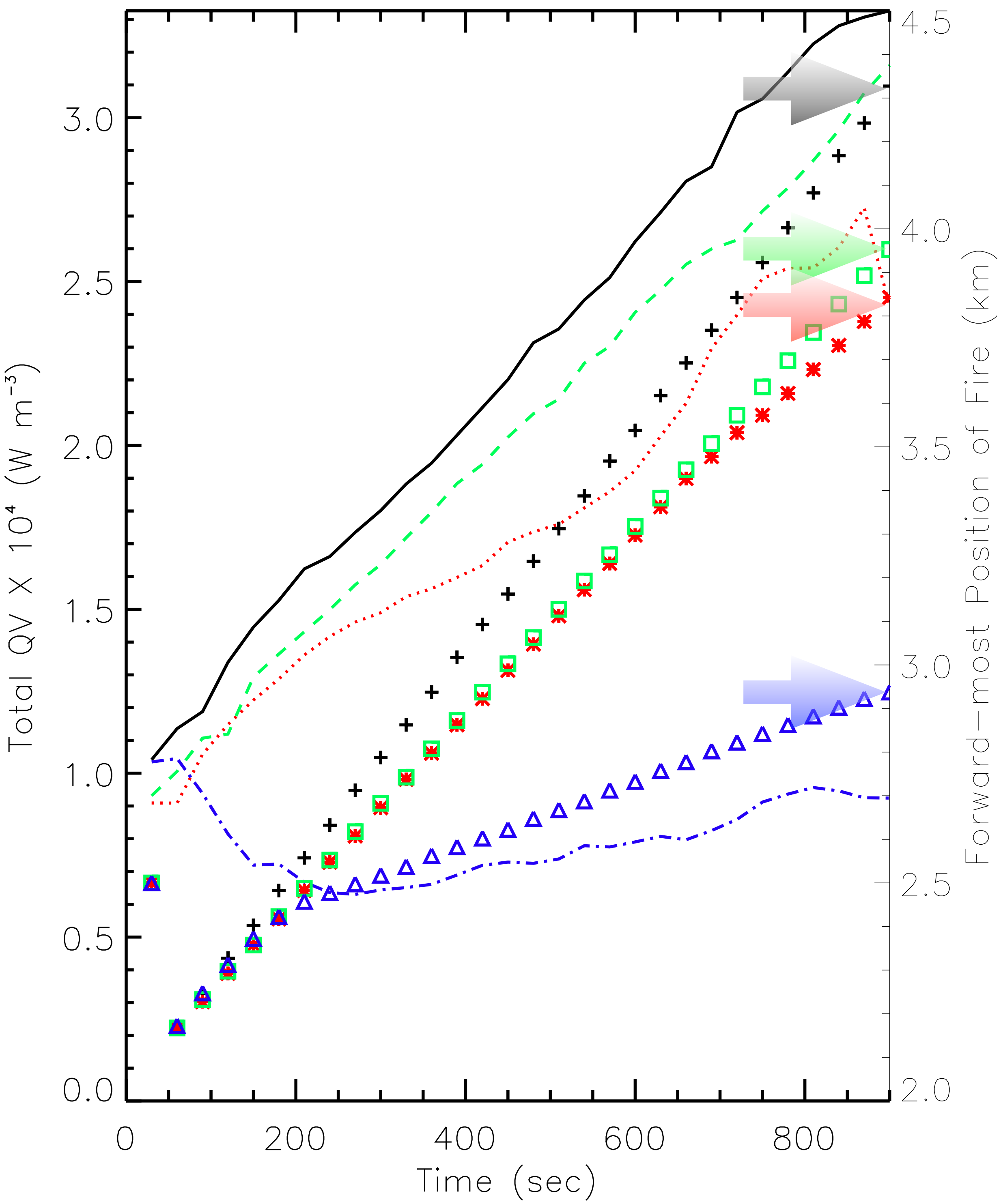
(Time Permitting)
Impact of the Vertical Shear in Background Wind on Fire Brand Propagation


Background Wind Profiles
1200
1000
800
600
400
200
0
Height (m)
−10
−5
0
5
10
Wind Speed (m/s)


Background Wind Profiles
1200
1000
800
600
400
200
0
Height (m)
−10
−5
0
5
10
Wind Speed (m/s)
Tanh Profile
Control (constant with height)
Negative Linear Shear
Low-Level Jet
Identical surface wind speed in each case
Operational fire spread rate formulas



Total QV X 10⁴ (W m⁻³)
Forward-most Position of Fire (km)
Time (sec)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2.0
2.5
3.0
3.5
4.0
4.5
0
200
400
600
800



Control Constant Wind +

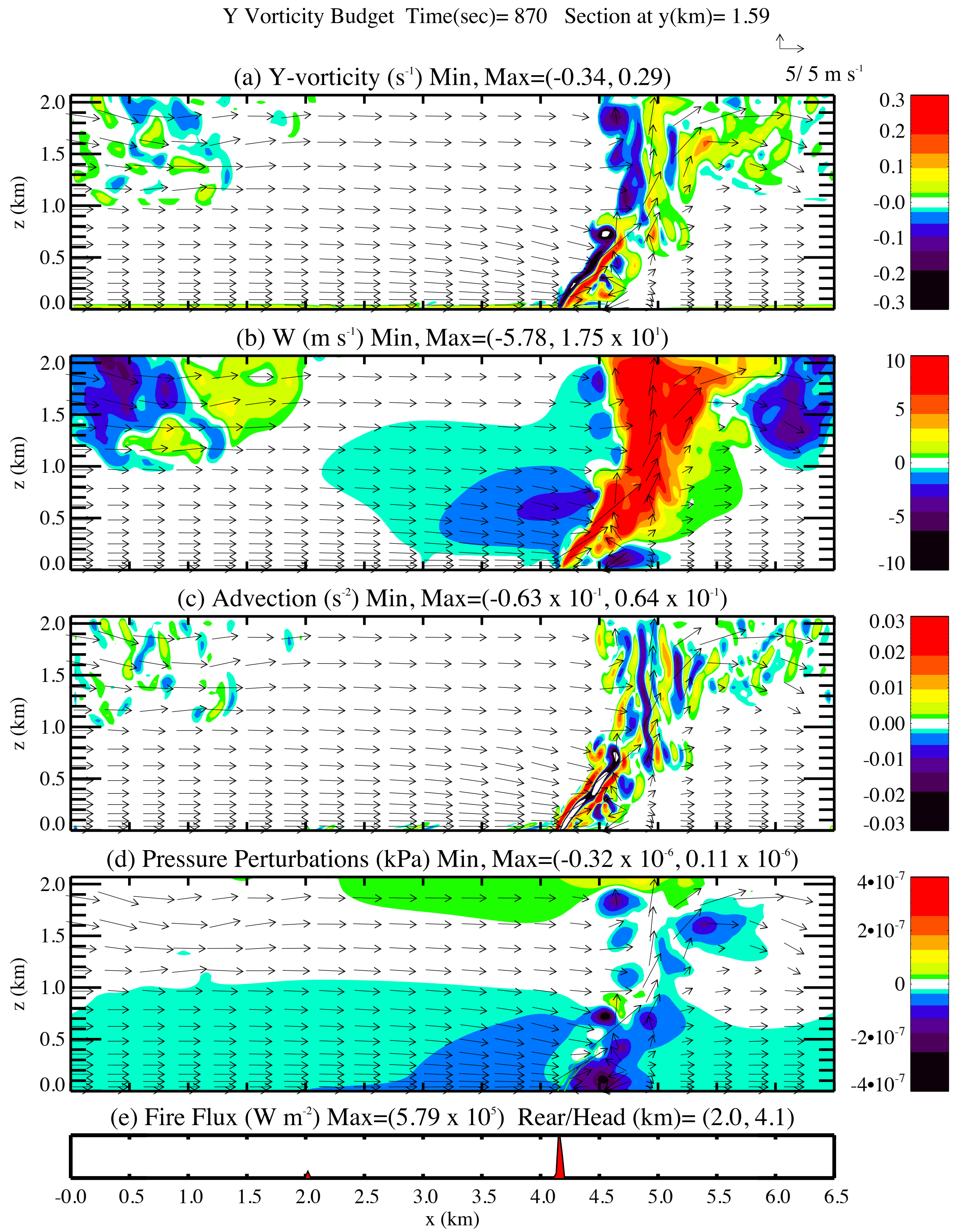
Negative Linear Shear *

Low-Level Jet (box)

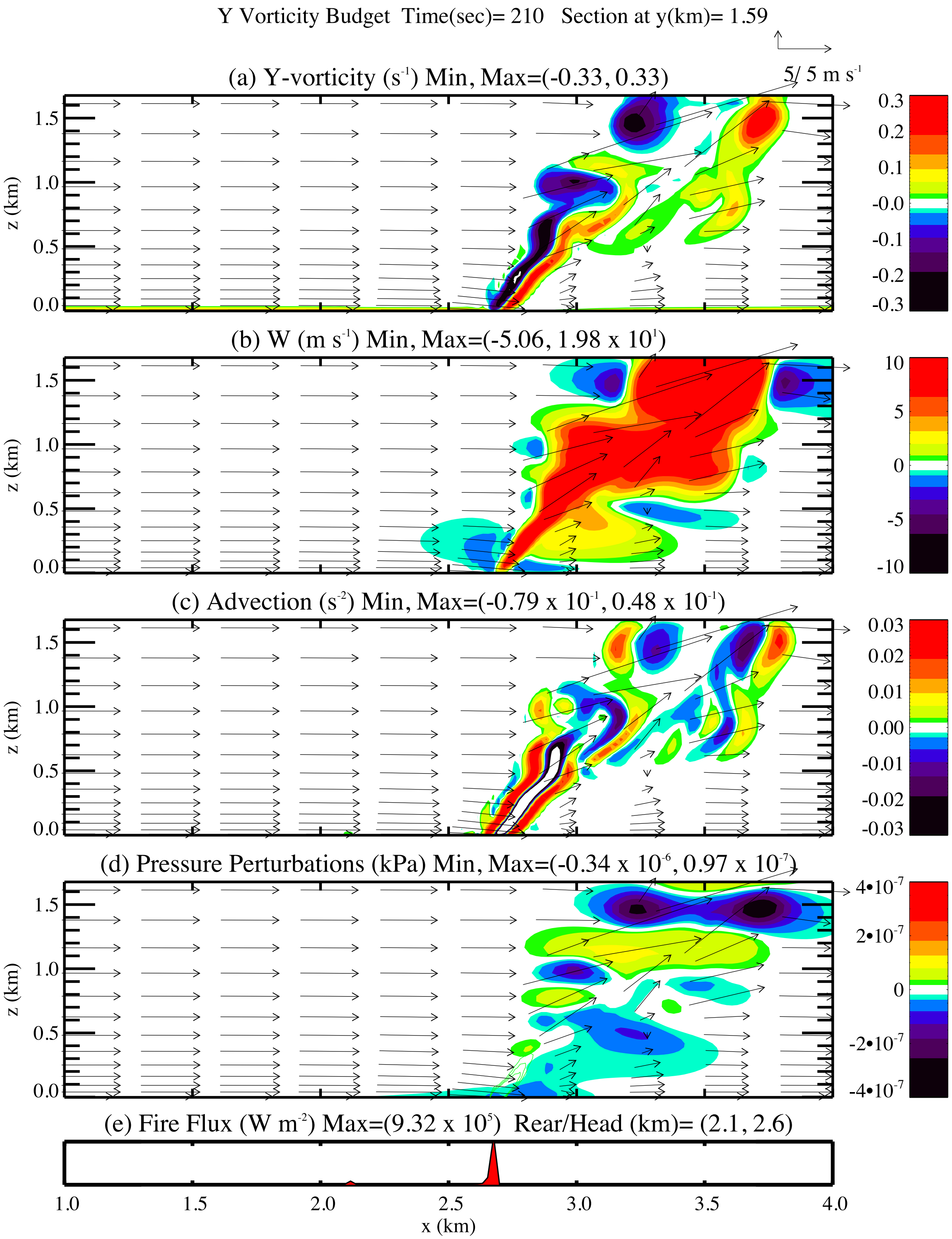
Tanh (Strong Shear) (triangle)

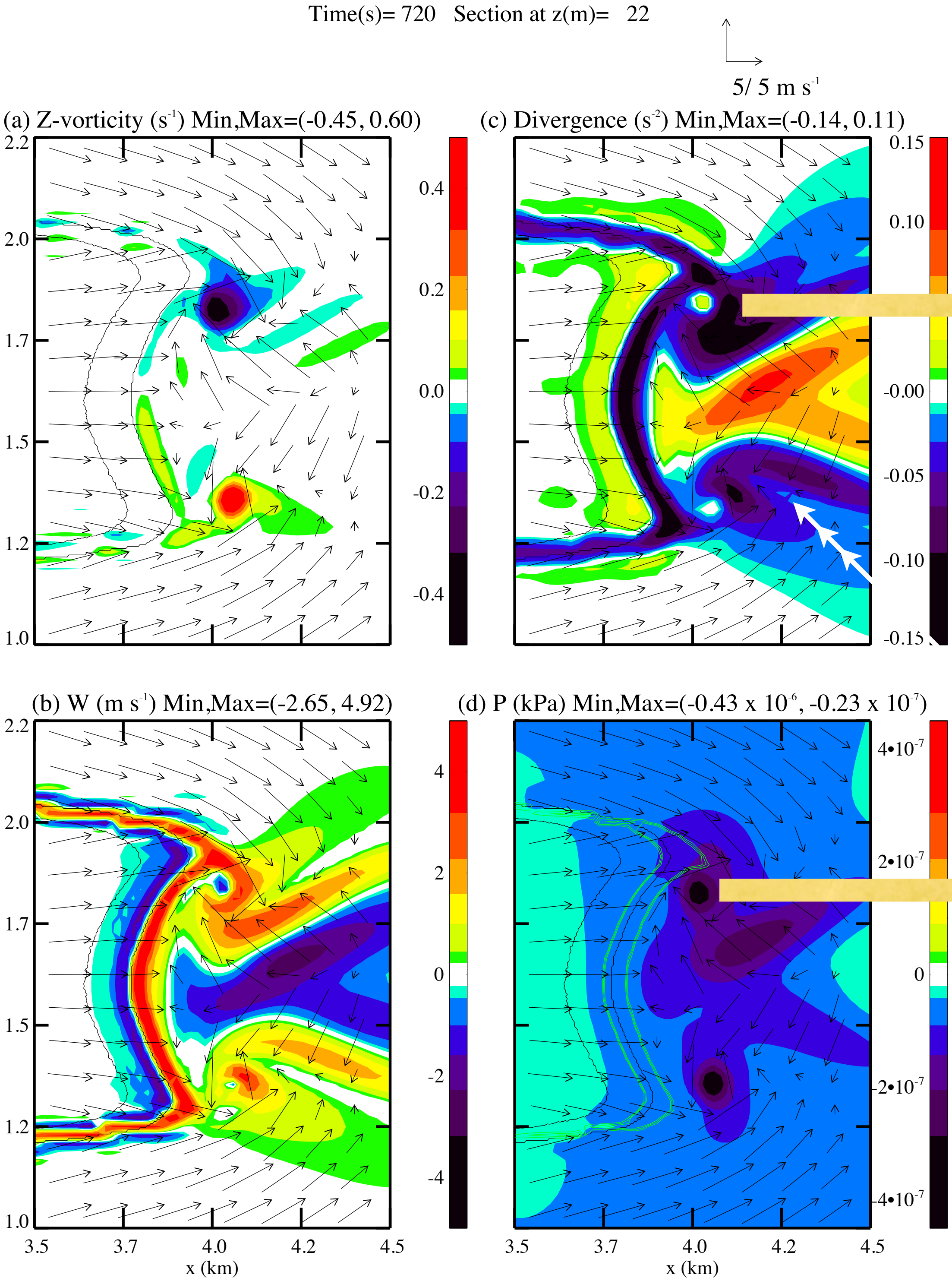
The End

Control Run
No Background Shear



Y Vorticity Budget Time(sec)= 870 Section at y(km)= 1.59
5/ 5 m s-1
(a) Y-vorticity (s-1) Min, Max=(-0.34, 0.29)
(b) W (m s-1) Min, Max=(-5.78, 1.75 x 101)
(c) Advection (s-2) Min, Max=(-0.63 x 10-1, 0.64 x 10-1)
(d) Pressure Perturbations (kPa) Min, Max=(-0.32 x 10-6, 0.11 x 10-6)
(e) Fire Flux (W m-2) Max=(5.79 x 105) Rear/Head (km)= (2.0, 4.1)
z (km)
x (km)


Y Vorticity Budget Time(sec)= 210 Section at y(km)= 1.59
5/ 5 m s-1
(a) Y-vorticity (s-1) Min, Max=(-0.33, 0.33)
(b) W (m s-1) Min, Max=(-5.06, 1.98 x 101)
(c) Advection (s-2) Min, Max=(-0.79 x 10-1, 0.48 x 10-1)
(d) Pressure Perturbations (kPa) Min, Max=(-0.34 x 10-6, 0.97 x 10-7)
(e) Fire Flux (W m-2) Max=(9.32 x 105) Rear/Head (km)= (2.1, 2.6)
z (km)
x (km)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0.0
0.5
0.3
0.2
0.1
-0.0
-0.1
-0.2
-0.3
10
5
0
-5
-10
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
4•10-7
2•10-7
-2•10-7
-4•10-7



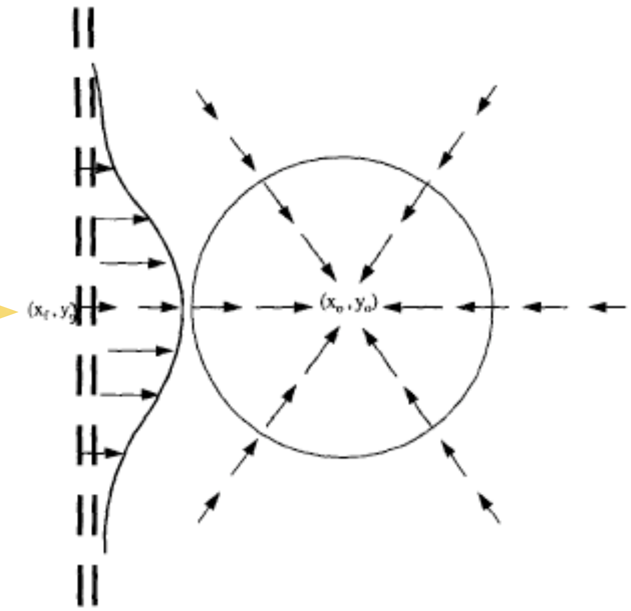
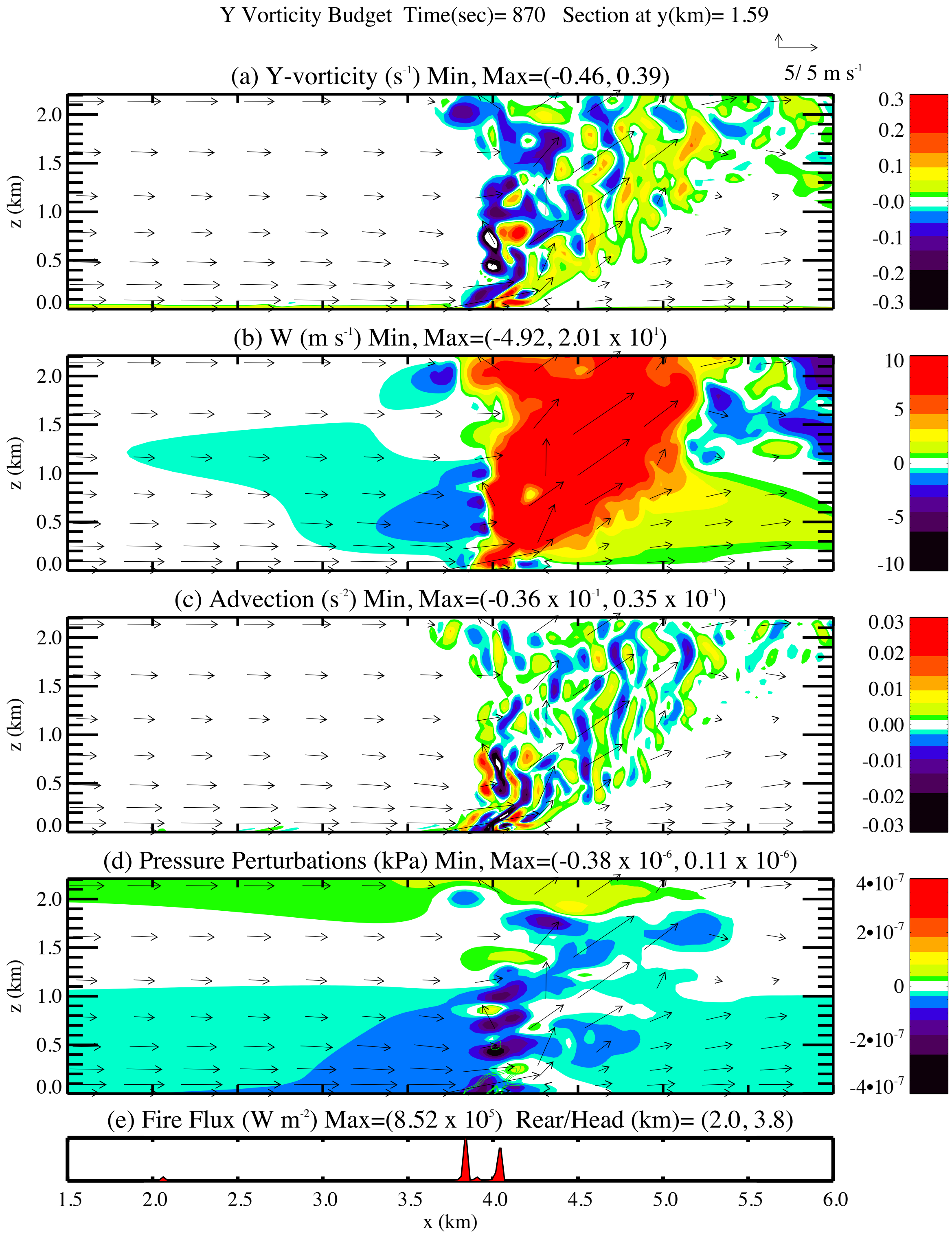
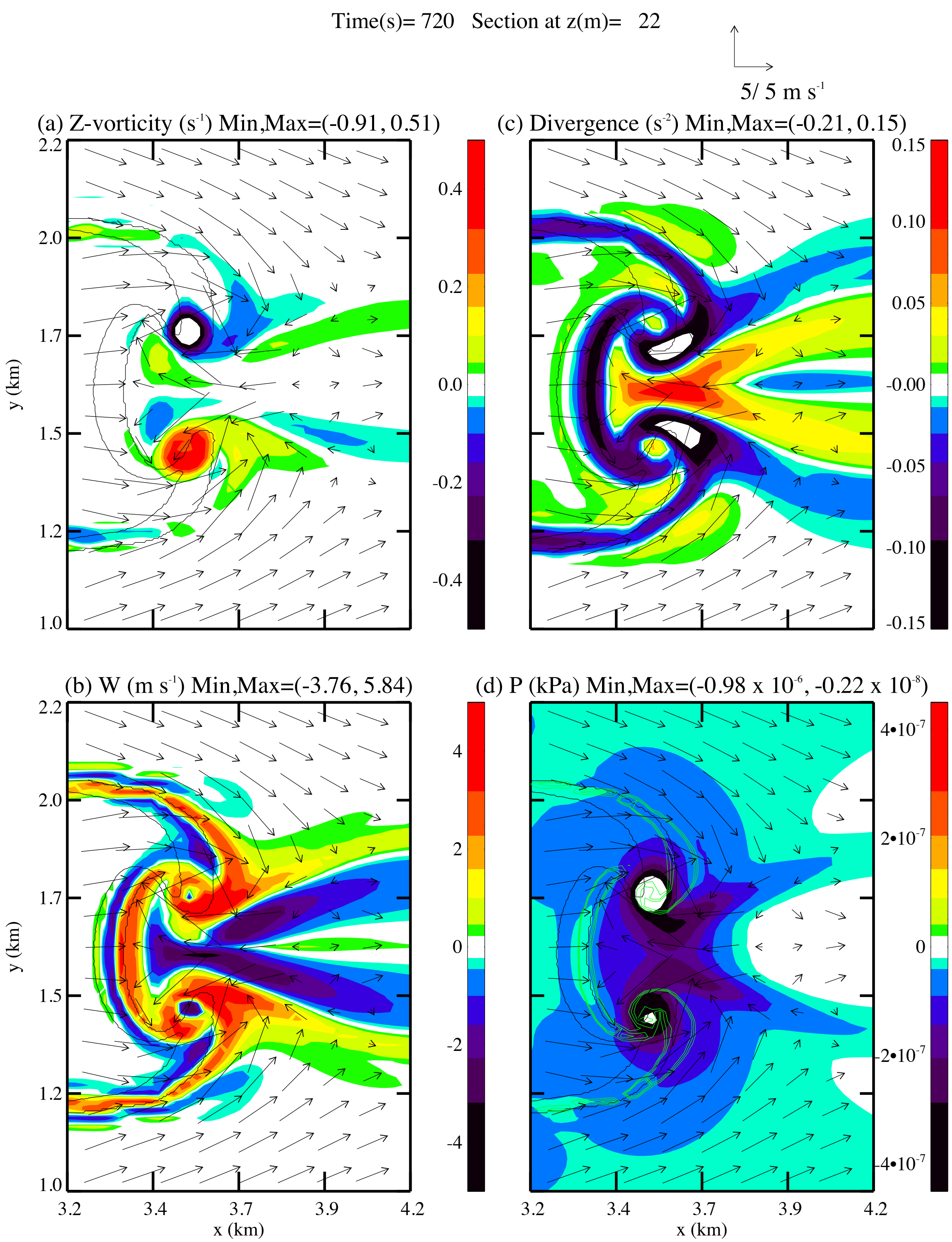


FIG. 6. The idealized structure of the near-surface convergence pattern in the vicinity of the fire as a result of air being drawn into the fire's hot air column. Refer to text for details.

Cyclostrophic Flow, Low Pressure Center

(Weak)
Linear Shear
in Background Wind


Y Vorticity Budget Time(sec)= 870 Section at y(km)= 1.59
5/ 5 m s-1
(a) Y-vorticity (s-1) Min, Max=(-0.46, 0.39)
(b) W (m s-1) Min, Max=(-4.92, 2.01 x 101)
(c) Advection (s-2) Min, Max=(-0.36 x 10-1, 0.35 x 10-1)
(d) Pressure Perturbations (kPa) Min, Max=(-0.38 x 10-6, 0.11 x 10-6)
(e) Fire Flux (W m-2) Max=(8.52 x 105) Rear/Head (km)= (2.0, 3.8)
z (km)
x (km)



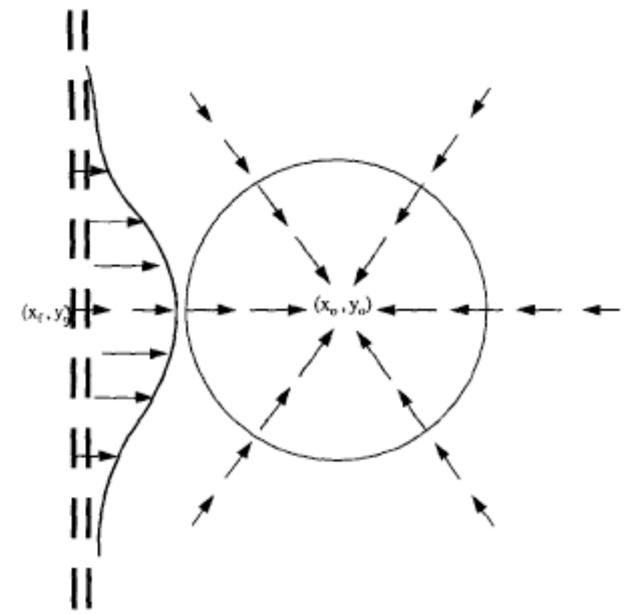
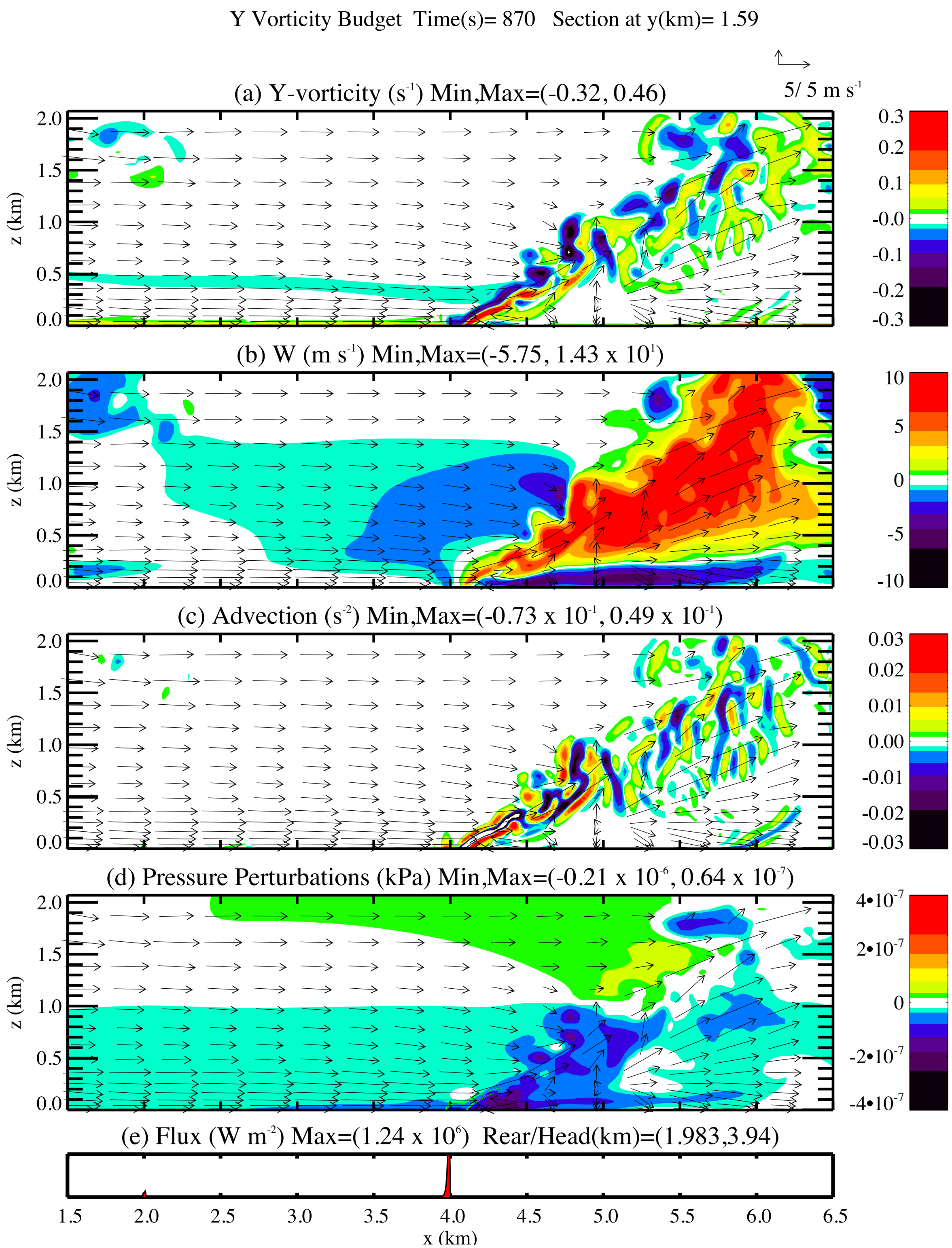


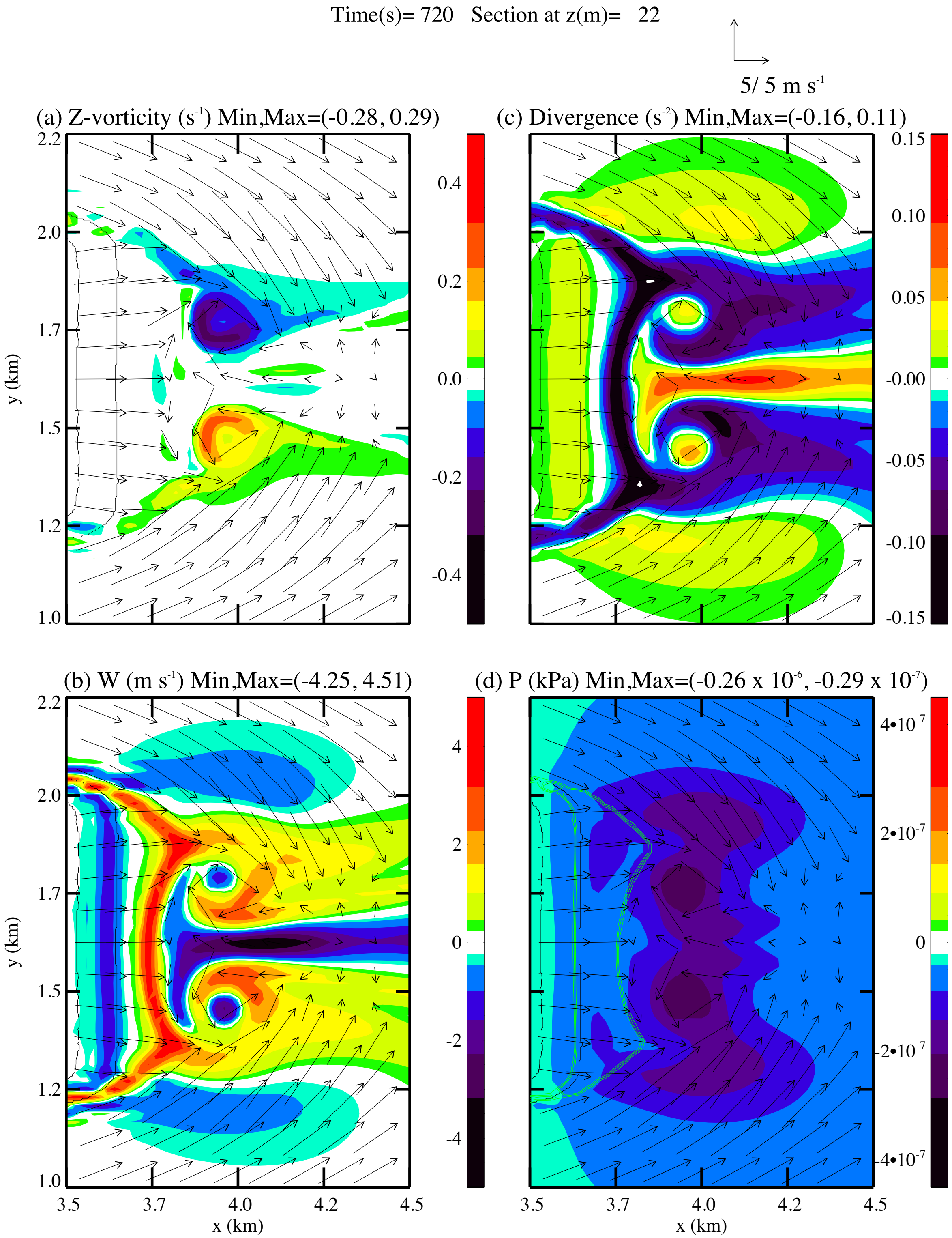
FIG. 6. The idealized structure of the near-surface convergence pattern in the vicinity of the fire as a result of air being drawn into the fire's hot air column. Refer to text for details.

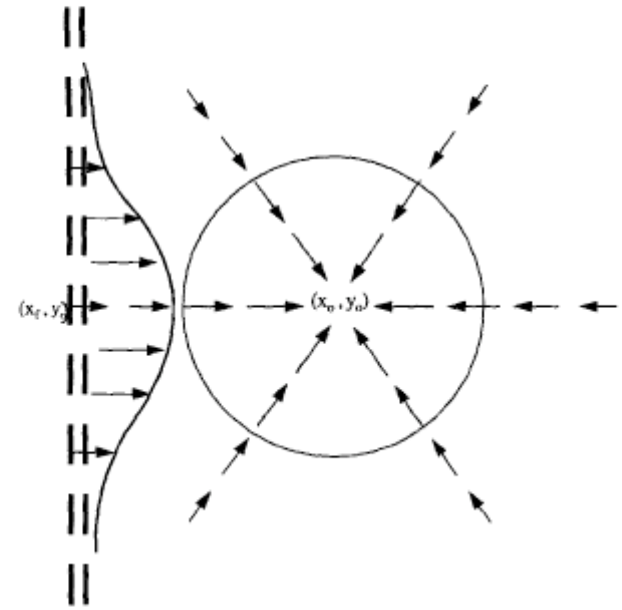
Spread slower than Control Fire.

Low-Level Jet
in Background Flow



Huge winds, but spread is slow. Why?





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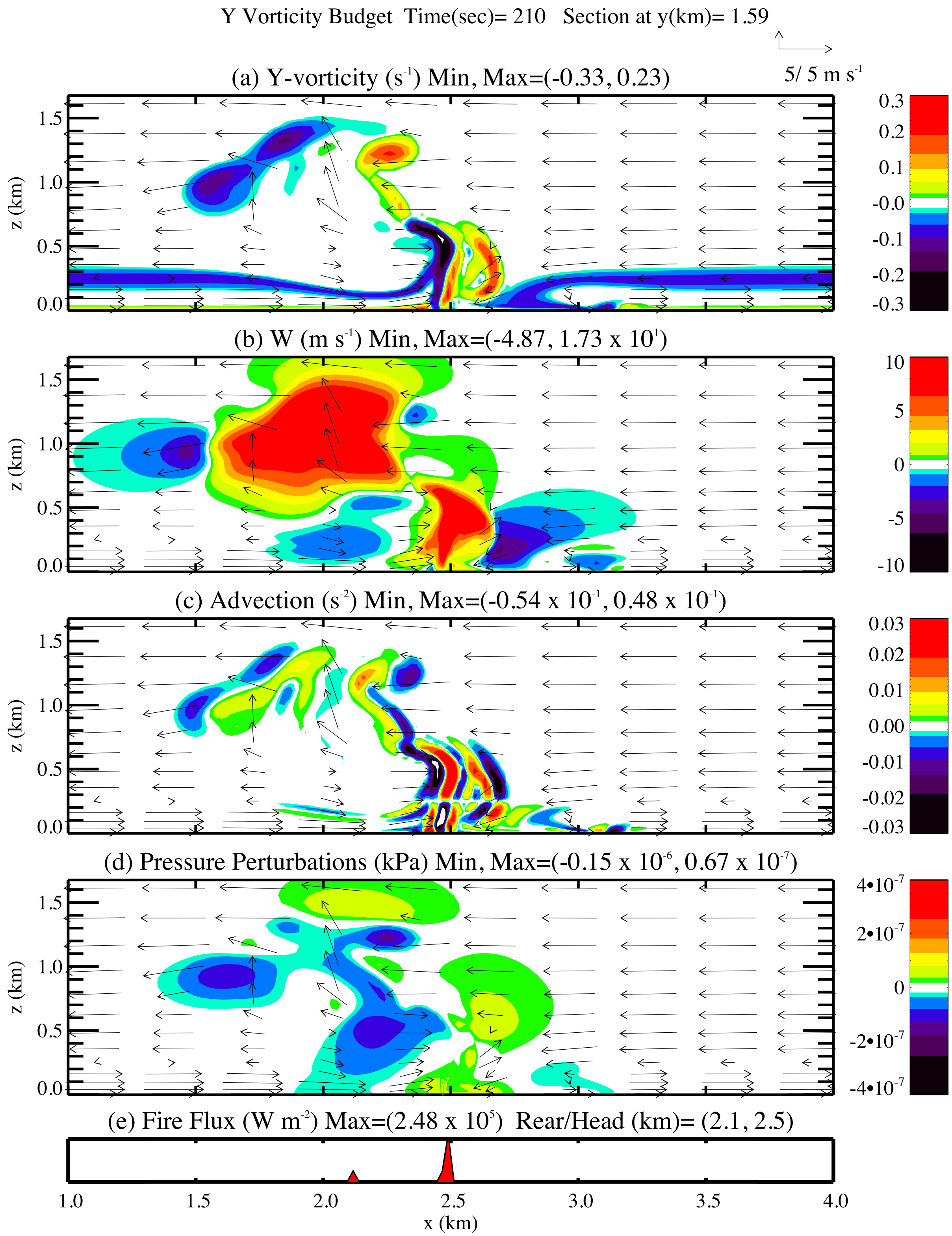
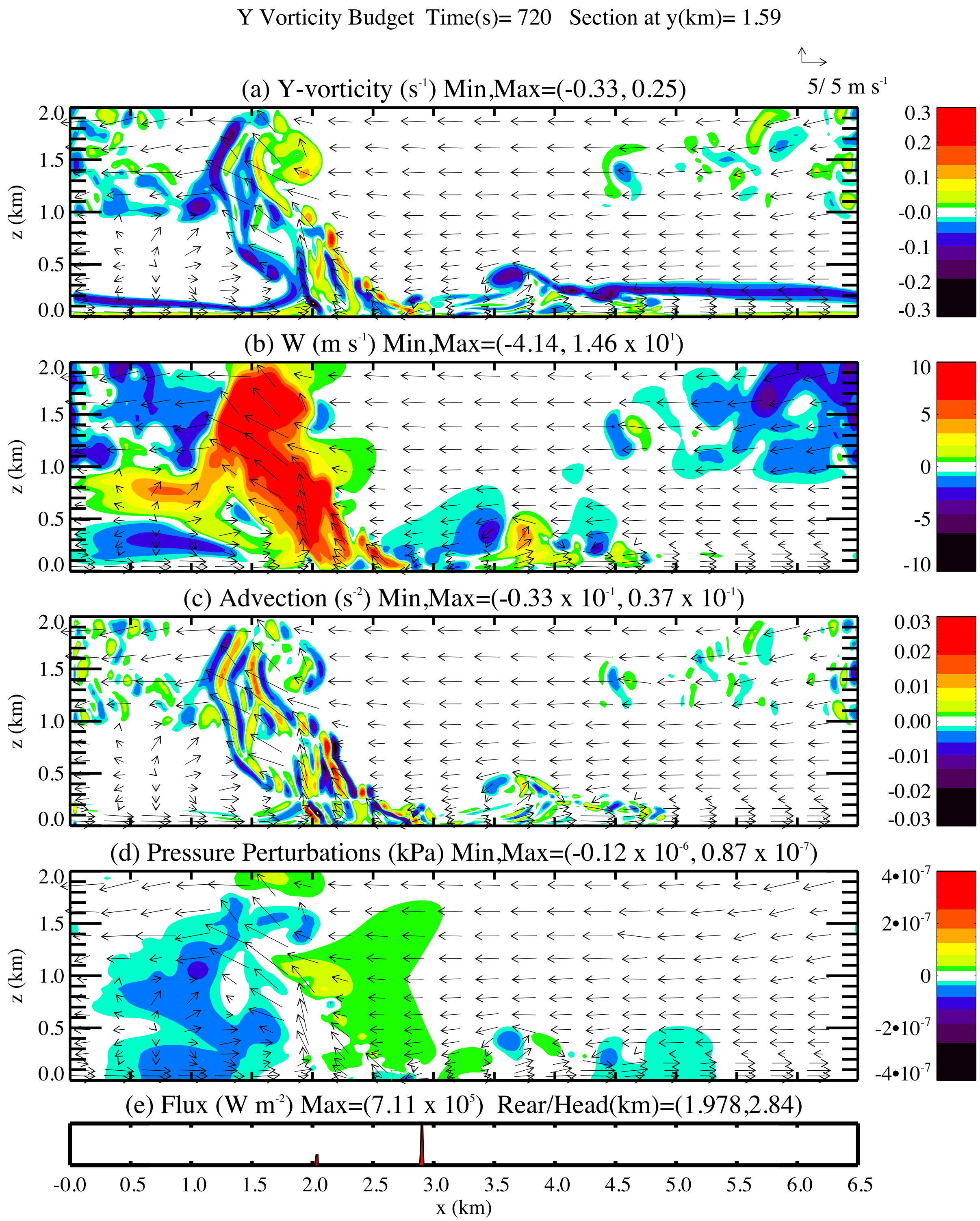
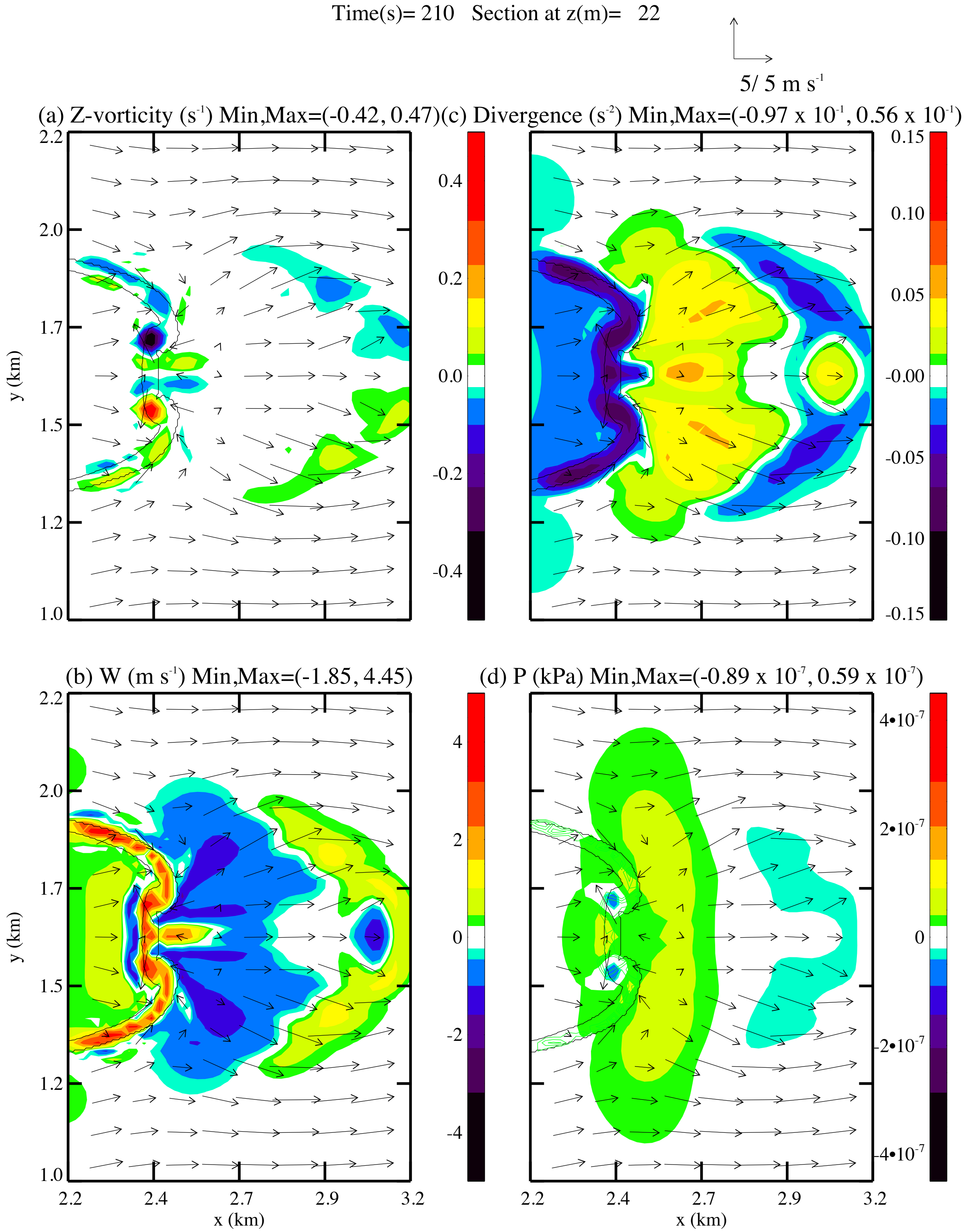
Fire spreads slowly

Strong Tanh
Shear
in
Background Flow


Y Vorticity Budget Time(sec)= 210 Section at y(km)= 1.59
5/ 5 m s-1
(a) Y-vorticity (s-1) Min, Max=(-0.33, 0.23)
(b) W (m s-1) Min, Max=(-4.87, 1.73 x 101)
(c) Advection (s-2) Min, Max=(-0.54 x 10-1, 0.48 x 10-1)
(d) Pressure Perturbations (kPa) Min, Max=(-0.15 x 10-6, 0.67 x 10-7)
(e) Fire Flux (W m-2) Max=(2.48 x 105) Rear/Head (km)= (2.1, 2.5)
z (km)
x (km)



Y Vorticity Budget Time(s)= 720 Section at y(km)= 1.59
5/ 5 m s-1
(a) Y-vorticity (s-1) Min,Max=(-0.33, 0.25)
(b) W (m s-1) Min,Max=(-4.14, 1.46 x 101)
(c) Advection (s-2) Min,Max=(-0.33 x 10-1, 0.37 x 10-1)
(d) Pressure Perturbations (kPa) Min,Max=(-0.12 x 10-6, 0.87 x 10-7)
(e) Flux (W m-2) Max=(7.11 x 105) Rear/Head(km)=(1.978,2.84)
z (km)
x (km)



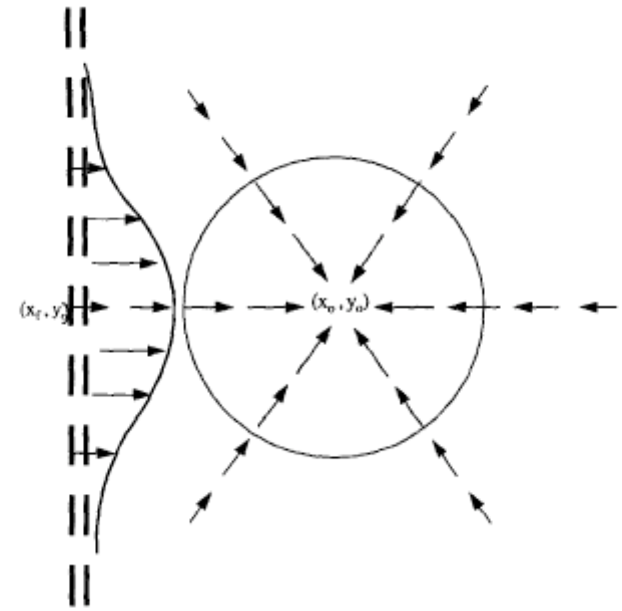


FIG. 6. The idealized structure of the near-surface convergence pattern in the vicinity of the fire as a result of air being drawn into the fire's hot air column. Refer to text for details.

Fire stalled or spreading backwards

Summary - Fire in Vertically-Varying Background Wind Field

- Behavior of fire plume influenced greatly by interaction of fire plume with vertical shear in ambient wind.
- Fire spread determined by upper-air plume dynamics (e.g., advection of plume-generated vorticity).
- Convergence/PGF (due to cyclostrophic vortex development) ahead of fire line drives fire spread.