Coupled Atmosphere-Fire Modelling of Wildland Fire and Low Level Jets with WRF-Fire

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Never Stand Still

School of Physical, Environmental and Mathematical Sciences

Source: Reuters
Region: Colorado Springs, USA

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Dynamic Fire Spread

- Fire is a complex physical and chemical process
- Interacts with the surrounding weather, fuel and topography
- Interactions can lead to dynamic fire spread

  i.e. rate of spread varies with no change in fire environment
- Can lead to eruptive or blowup fire behaviour
- Dynamic fire spread is difficult to predict
- Not included directly in many operational tools and knowledge

  e.g. operational wildland fire spread models

  Commonly assumed that rate of spread will remain constant unless there is a change in the underlying fire environment

Examples of Dynamic Fire Spread

- Flow attachment on steep slopes
- Fire whirls e.g. dynamic fingering, VLS
- Continually increasing rate of spread in closed canyon
- Fire lines intersecting at an oblique angle
- Mid to long-range spotting (e.g. firebrands in plume)

- Trench effect in structure fires e.g. Kings Cross 1987

Fire Whirl in Action

Vorticity-Driven Lateral Fire Spread

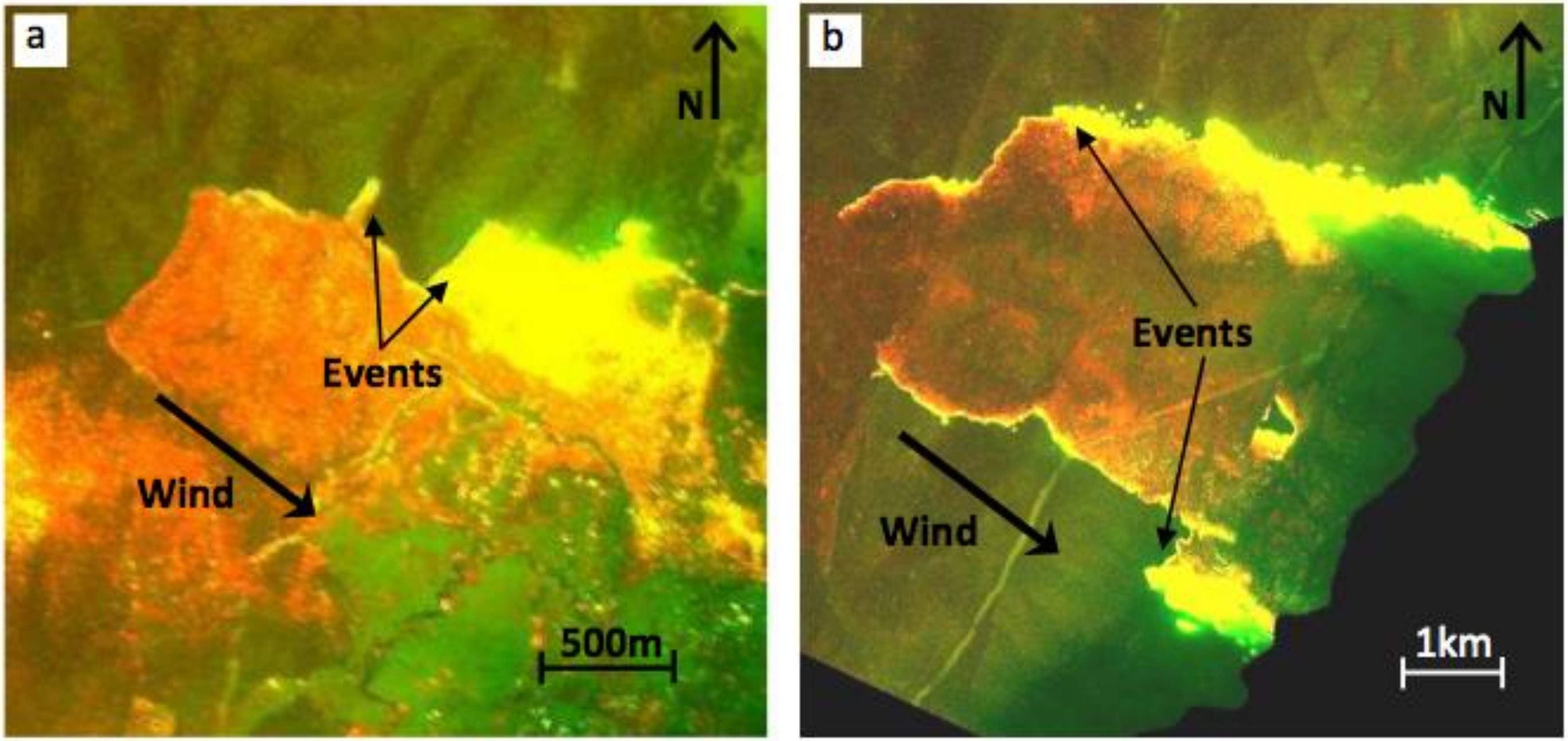

Figure 1. Multispectral line-scan imagery of the Canberra fires 18 January 2003 showing events at: (a) 'Pig Hill', and (b) 'Broken Cart'. Source: New South Wales Rural Fire Service.

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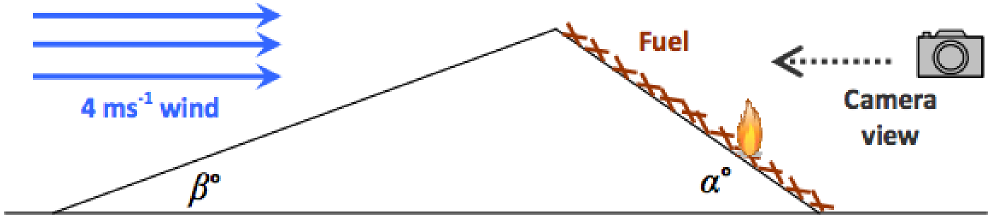
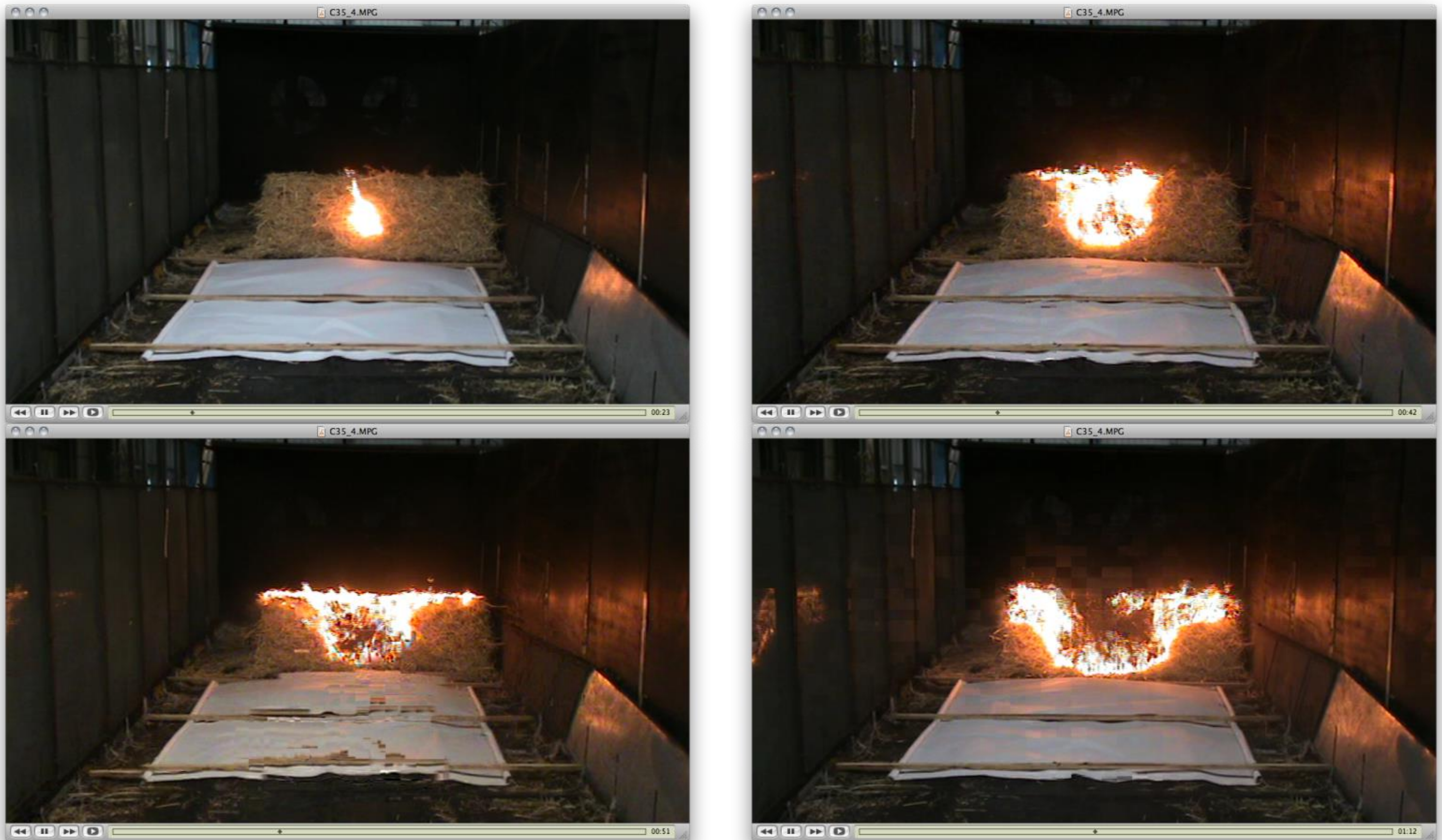


Figure 2. Schematic diagram (cross section) of the experimental ridge configuration and the approximate ignition point.



Prediction of Dynamic Fire Spread

- Violates the common assumption in operational tools that the rate of spread is quasi-steady state unless there is a change in the underlying fire environment.

- Therefore, highly subjective prediction
- Limited understanding of environmental thresholds
- Limited understanding of physical processes
- Poses a serious risk to firefighters
- Can contribute to blowup fire behaviour

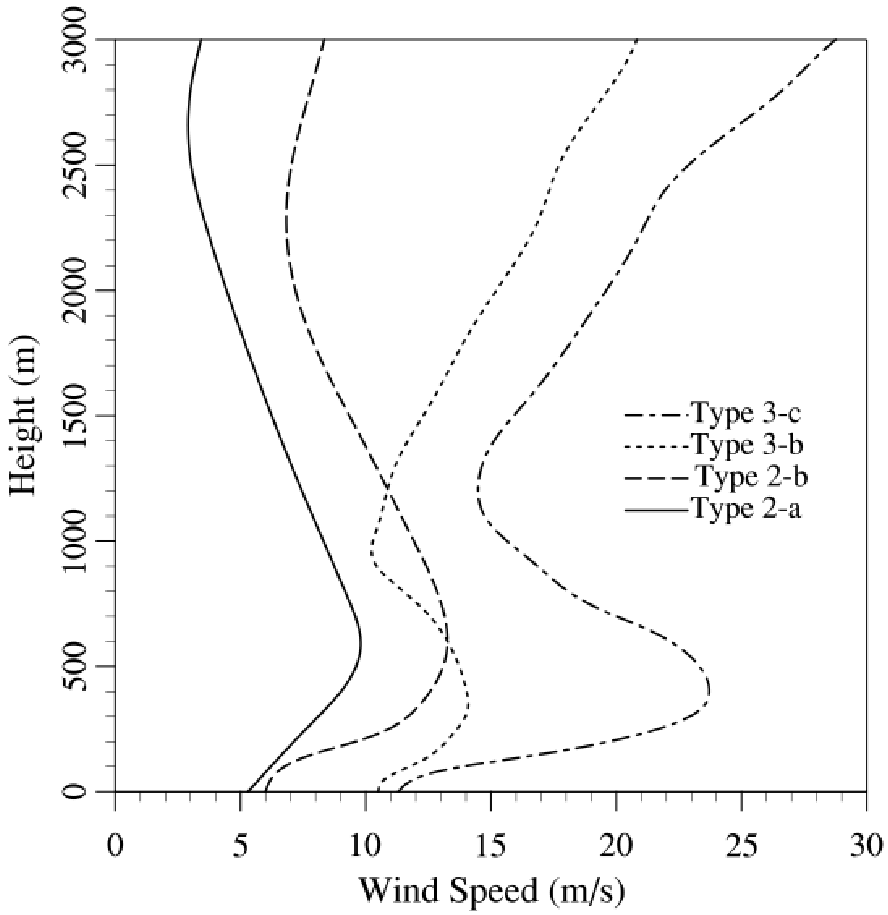
Blowup Fire Behaviour

- Blowup: a sudden increase in fire intensity or rate of spread that precludes direct control
- Can happen on any size of fire. Factors include:
  - Instability, spotting, fire whirls, dry and heavy fuels, strong winds
- Often accompanied by extreme pyro-convection e.g. 2003 Canberra and 2009 Victoria bushfires
- Ongoing efforts to improve operational prediction (see McRae and Sharples, in press)

Low Level Jet (LLJ)

- Wind speed maxima, narrow current of fast moving air:
  - Nocturnal LLJ e.g. Great Plains of USA, thermally forced
  - Valley exit LLJ
  - Barrier LLJ, due to orographic blocking
  - Lower portion of jet stream dynamics
- Distinct from the jet stream (i.e. higher aloft)
- Characterised by strong wind shear and turbulence
- Common in many regions e.g. Great Plains of USA

Byram's Low Level Jet Profiles



- "Adverse" wind profiles at 17 blowups in southern US
- LLJ a common feature in Byram's wind profile types
- Possible physical connection with blowups
- Wind profiles discussed relative to fire behaviour
- Difficult to reconcile observed profiles with Byram's generalised types

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Current State of Knowledge

- Fairly common knowledge of Byram's wind profiles, but subjective/limited operational implementation
- Brotak (1977): 1/3rd of 62 blowups had a LLJ
- Considerable fire whirl formation at LLJ blowups
- No well tested causal theory
- Potter 2012: considerable scope for further study
- Limited knowledge of interaction between LLJ, plume updraft and descending rear inflow

Why the LLJ?

- Blowups often considered in terms of relative influence of the “power of the wind and fire”
- Several theories proposed that blowups can occur due to relative balance of advective and buoyant forces
- Vertical atmosphere-fire interaction likely to play a role
- LLJs may be linked to blowups through their effect on pyro-convective plume dynamics?
- Or perhaps through their role in spotting and fire whirls?

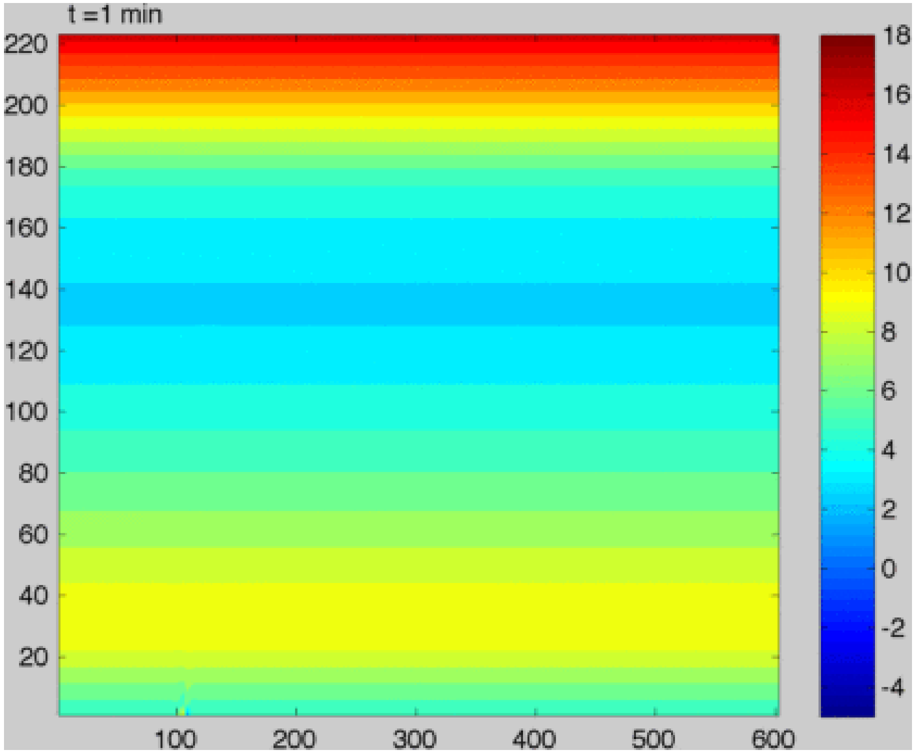
Fire to Atmosphere Numerical Modelling

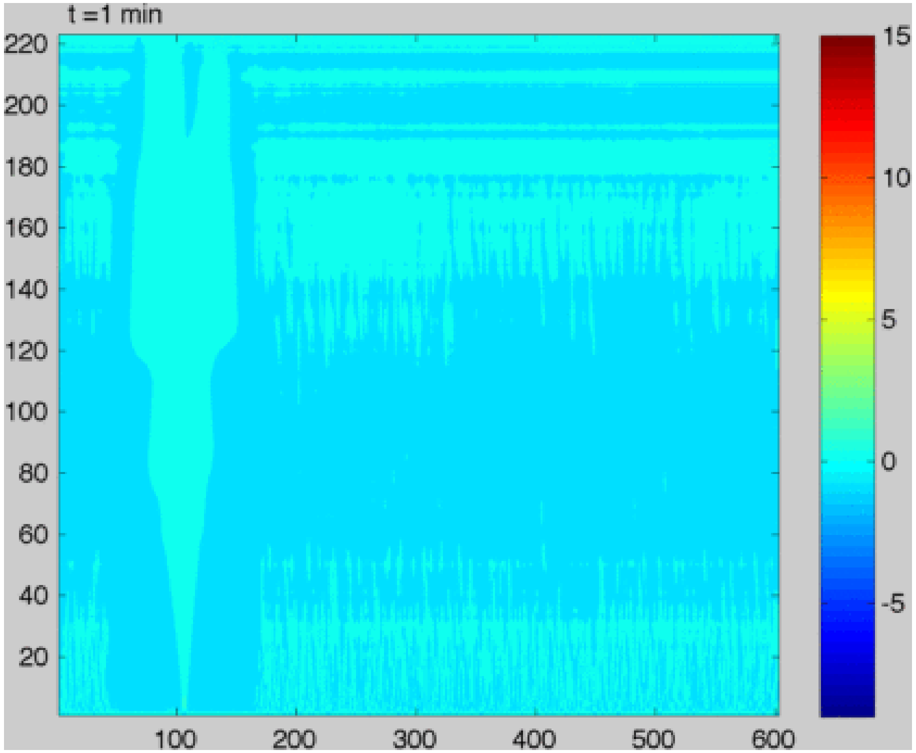
- Wide range of numerical models exist for:
  - Wildland fire spread (empirical, physical, 1-D, 2-D, etc…)
  - Numerical weather prediction (NWP)
- A number of researchers have incorporated fire to atmosphere coupling in an NWP model:
  - "Fire" often represented as a steady state source of heat
  - Allows for investigation of impact on atmosphere
  - Fairly easy to implement in an NWP model
  - e.g. modification of the potential temperature, water vapour
  - However, limited to one-way coupling, no dynamic feedback onto the fire spread and therefore distribution of heating

Modification of ARPS

- Advanced Regional Prediction System (ARPS)
- Kiefer et al. 2008, 2009:
  - Modified ARPS to include a steady state heat source
  - Investigated convective modes based on critical level analysis
- Simpson et al. 2013 used ARPS to investigate fixed heat source and four of Byram's wind profiles (2a, 2b, 3b and 3c)
- Found possible mechanisms for LLJ to affect fire behaviour:
  - High turbulent kinetic energy
  - Pre-heating of fuels ahead of fire front
  - Strong inflow at edges of fire line, convergence ahead of fire front
- Sensitive to jet properties i.e. height, intensity, shear above

ARPS Simulations with Type 2a Profile





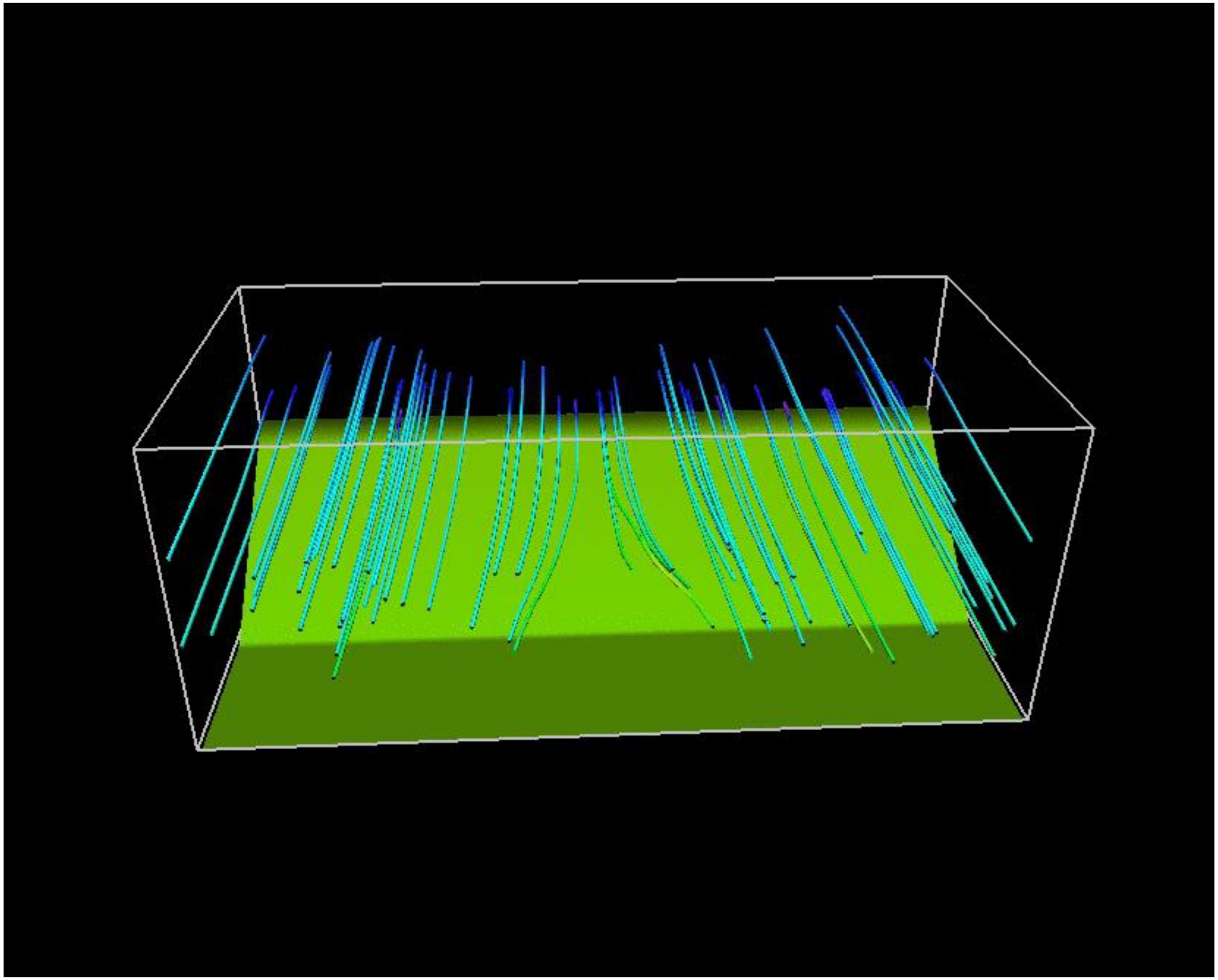
Two-way Coupled Atmosphere-Fire Modelling

- Combine wildland fire spread and NWP models
- Used to study multi-scale dynamic feedbacks between wildland fire and atmosphere:
  - Limited number of such models exist
  - FIRETEC, MesoNH-ForeFire, CAWFE
  - Differ in their model formulation, intended scale and use
- Can directly model micro-scale feedbacks between LLJ, plume updraft and descending rear inflow
- Systematic numerical study under controlled conditions
- These are research tools, **not** yet operational

CAWFE and WRF-Fire

- CAWFE (Clark 1996a, 1996b): predecessor of WRF-Fire
  - Used to study dynamic fingering and convective feedbacks
  - Used to simulate the Big Elk fire (Coen et al. 2005)
- Weather Research and Forecasting (WRF) NWP model
- Version 3.6 (released April 2014) includes WRF-Fire
- WRF-Fire has been used to study coupled atmosphere-fire interactions like VLS (Simpson et al. 2013b)
  - Including resolving fire whirls responsible for lateral fire spread
  - A number of validation studies by Kochanski, Peace, …

Modelling VLS With WRF-Fire



WRF and SFIRE

- Mandel, Kochanski and co. maintain a more regularly updated version of WRF-Fire i.e. WRF and SFIRE
- They are adding new modelling components:
  - Fuel moisture
  - Chemistry with WRF-Chem
- Their intention is more to operational deployment
- WRF-Fire has not been updated since WRF v3.3:
  - Simpson et al. are now planning their own modifications
  - May need to release our own code version in future

Ideal… Not Real. WRF-LES

- WRF can be run in either Ideal or Real mode
- Real: weather forecasting and detailed simulation of many aspects of land, atmosphere, etc…
- Ideal: high controlled study of limited aspects of environment, useful for sensitivity studies
- Large Eddy Simulation implementation i.e. WRF-LES
  - Large scale eddies explicitly resolved
  - Subgrid-scale motions modelled using a subfilter-scale stress
  - 1.5 order prognostic turbulence closure scheme and diffusion in physical coordinates is calculated using eddy viscosities

Overview of SFIRE

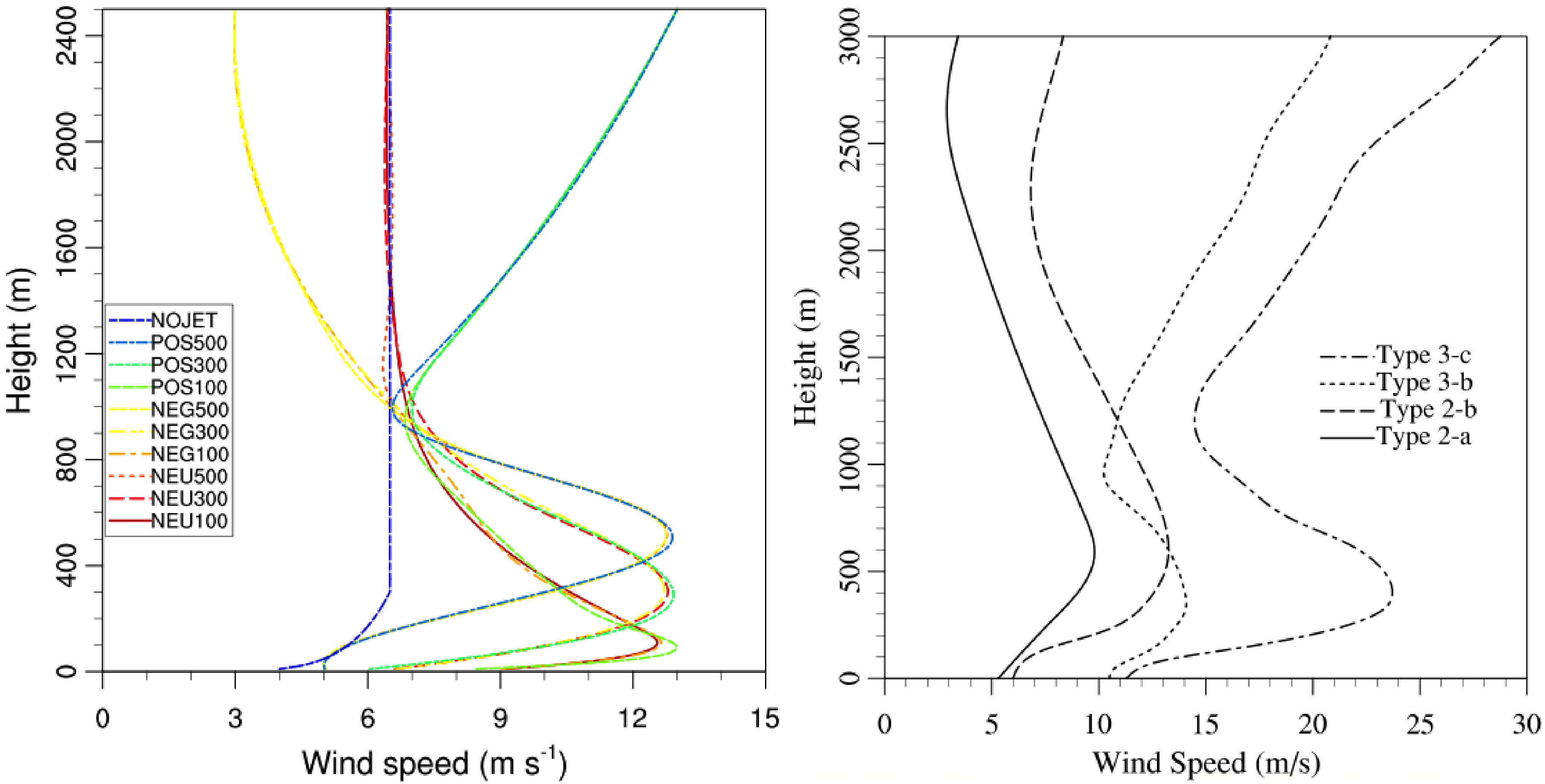
- Fire spread model used in WRF-Fire
- Level set method implementation of Rothermel:

  $R = R_0 (1 + W + S)$
- Level set provides a good 2-D method for computing the time-evolving fire perimeter
- R is calculated at each point along the fire perimeter, take components of local wind and slope along outward normal direction

WRF-Fire Model Grid

- Domain size is 8 x 4 x 5 km
- WRF-LES defined on a 3-D model grid: 20 m horizontal grid spacing, non-stretched terrain-following sigma vertical levels
- SFIRE is defined on a 2-D model grid: 5 m grid spacing
- Background wind profile (LLJ) prescribed as westerly wind
- LES often use periodic x and y boundary conditions:
  - Intense pyro-convection advected can distort upstream wind profile
  - Periodic x boundary condition replaced with open radiative
  - However, open radiative boundary raises numerical stability issues
- Limited to a short 30 min simulation, 20 min with fire

Prescribed Background Wind Profiles



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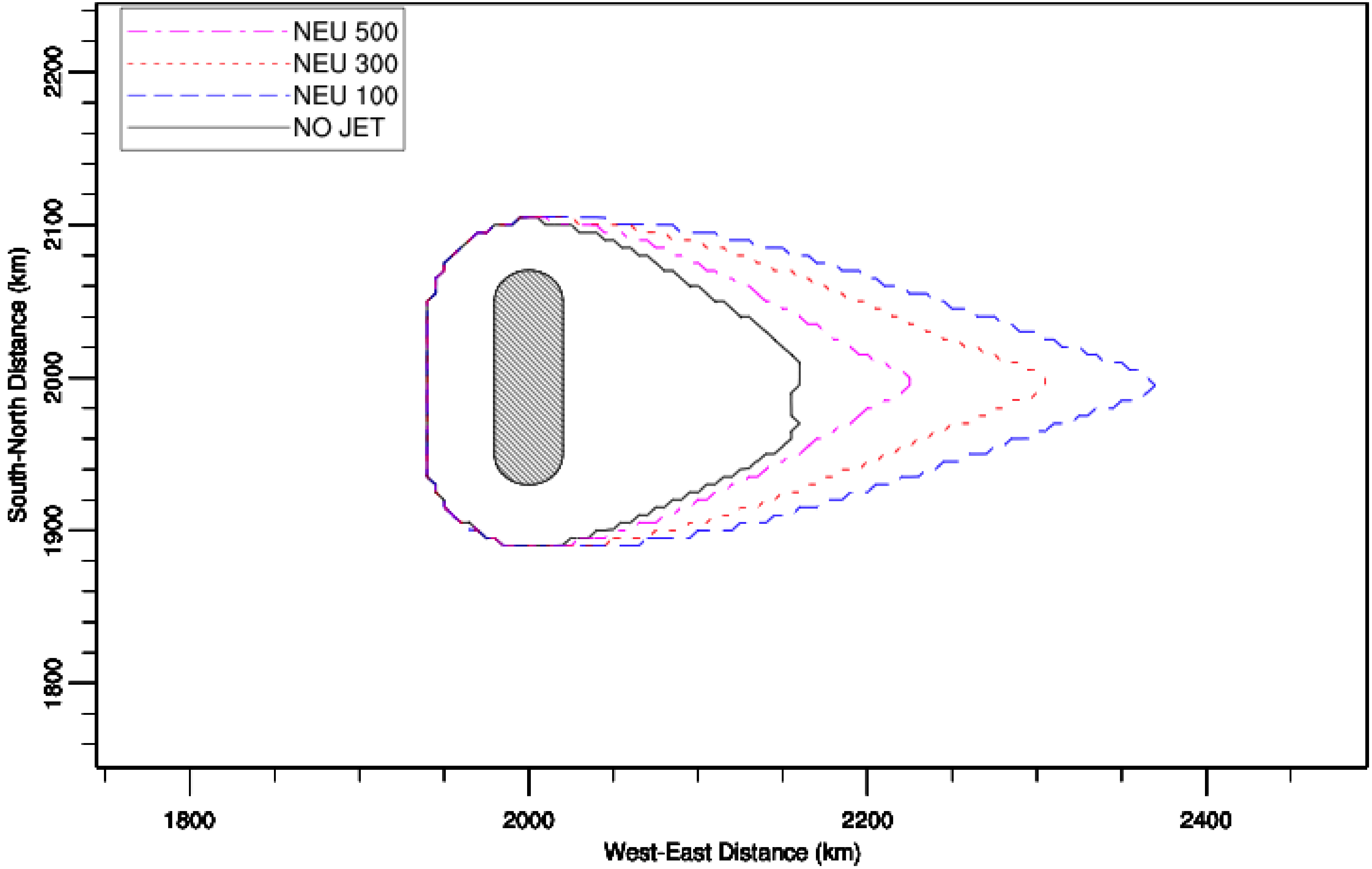

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From Clark et al. 1996

Exhibits "convergence zone" ahead of fire front

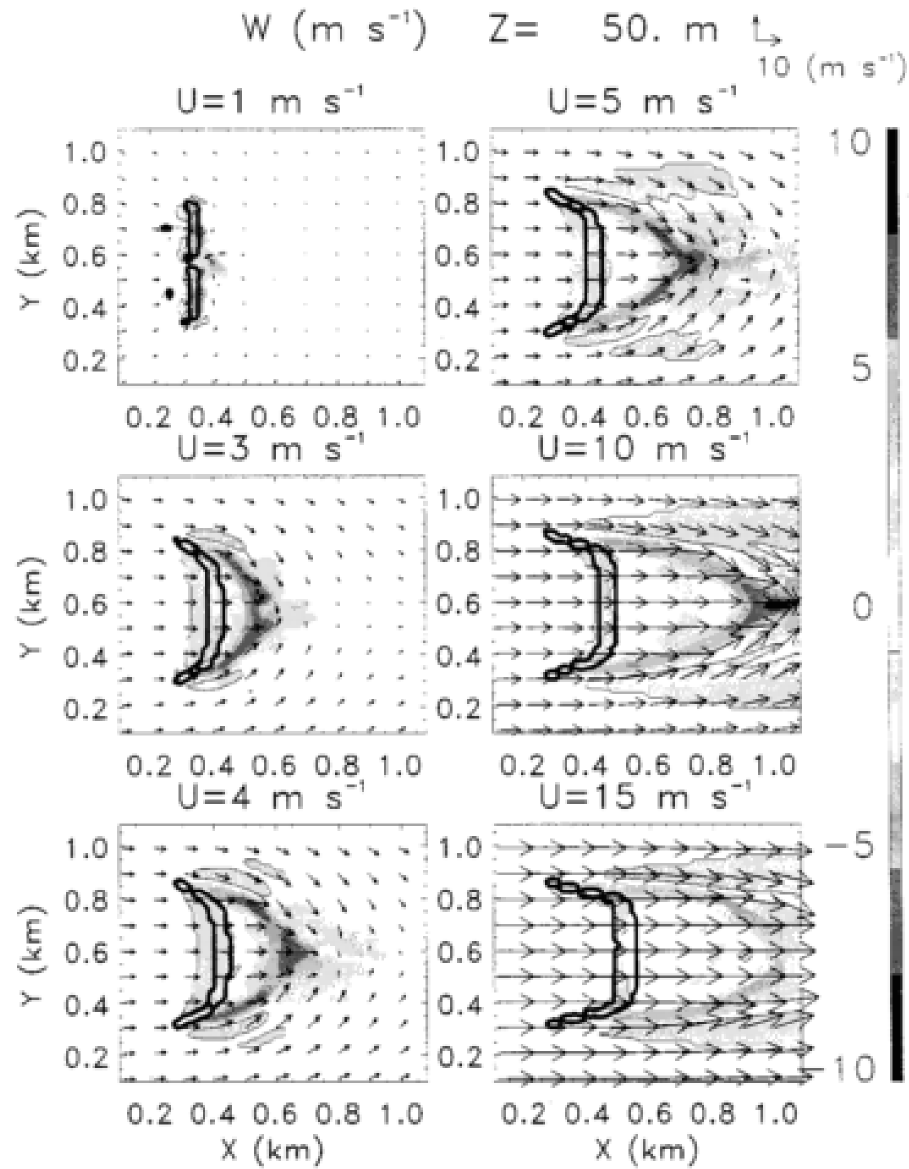

Figure 7. Horizontal cross sections of vertical velocity $w(x,y)$ for $U_0 = 1, 3, 4, 5, 10$, and $15\ m\ s^{-1}$ at $t = 6$ min corresponding to experiments FIR7AR, FIR7CR, FIRE7Z, FIR7DR, FIRE7E, and FIRE7F, respectively. The cross sections are taken at $z = 50$ m AGL and arrows represent wind vectors taken at 15 m AGL.

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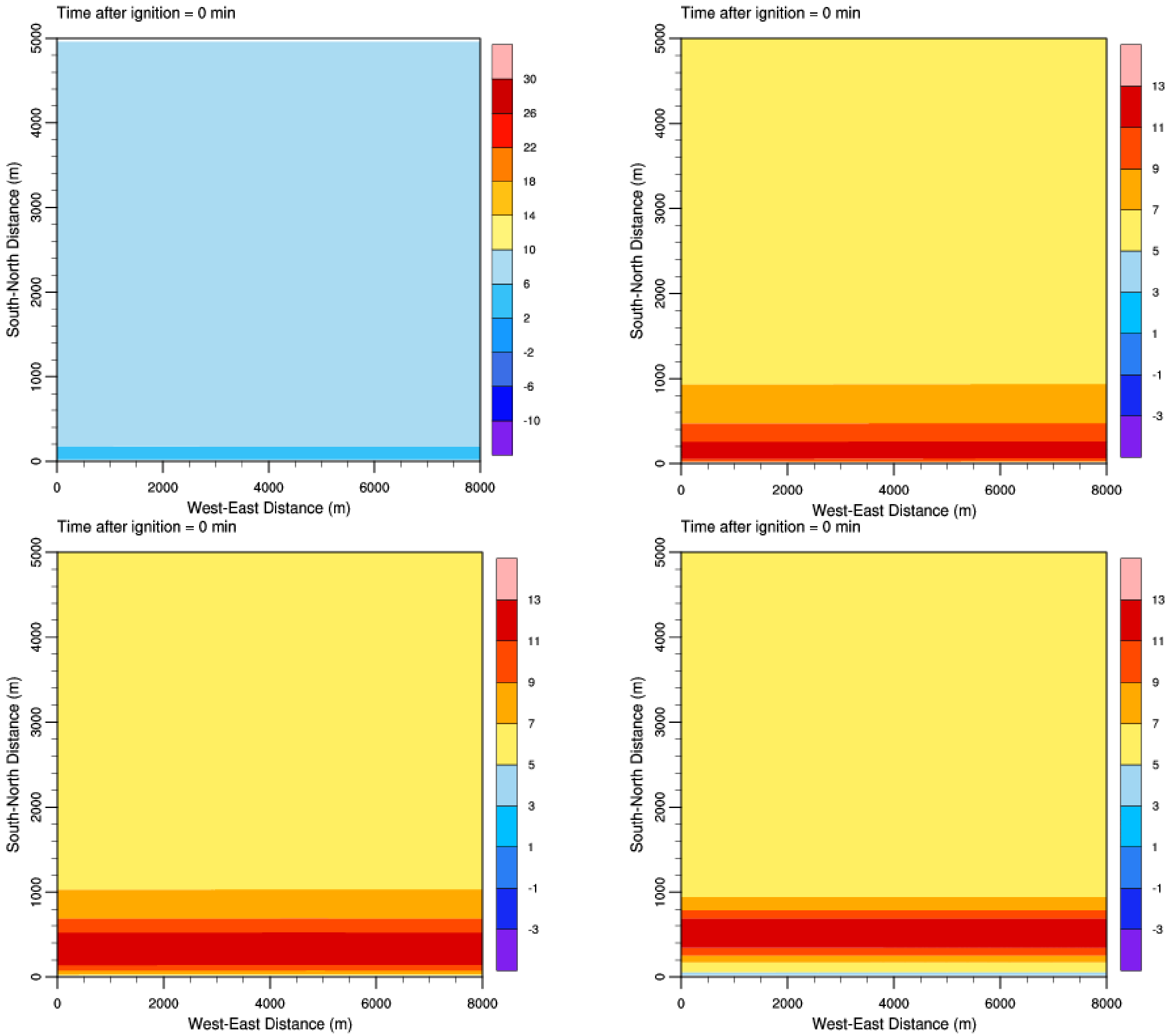

Horizontal Velocity (m/s)

No jet, and with varying jet height

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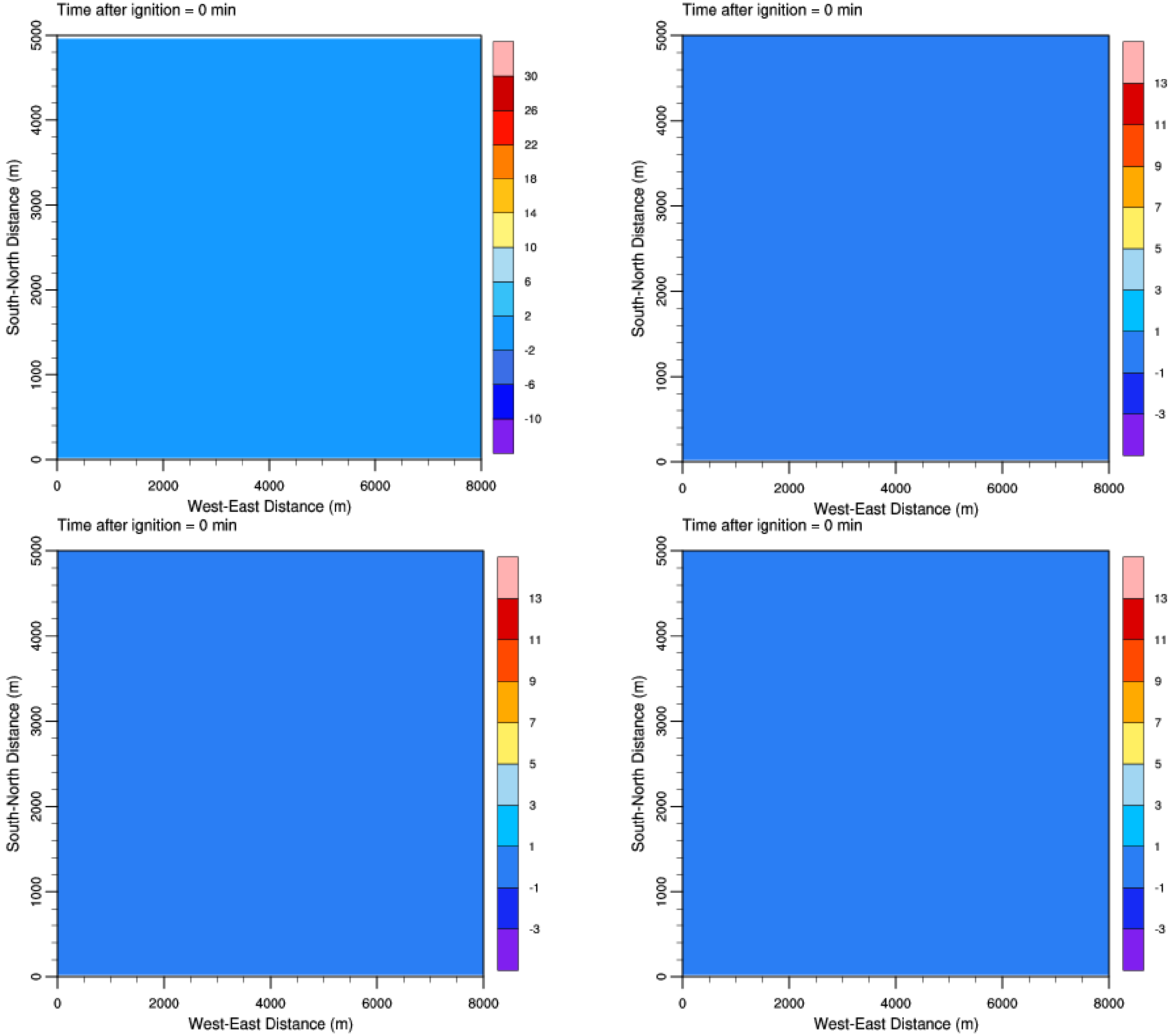

Vertical Velocity (m/s)

No jet, and with varying jet height

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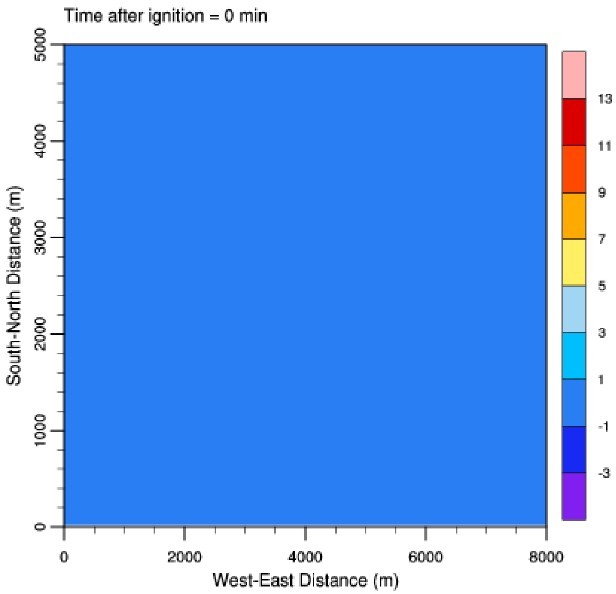
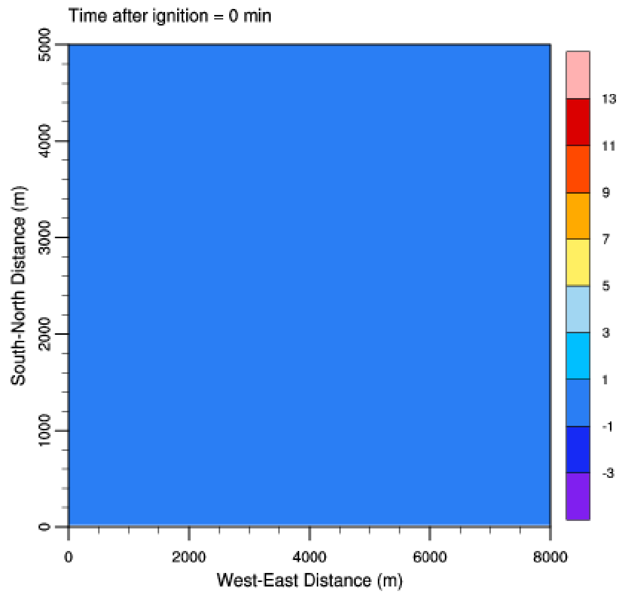
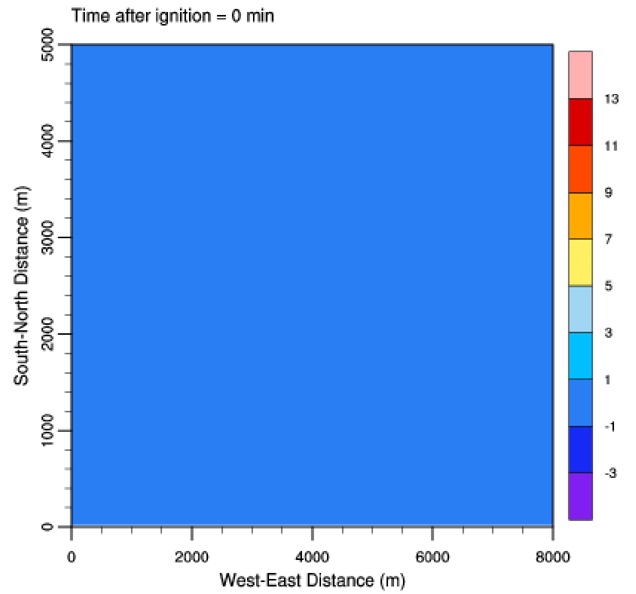
Limited Sensitivity to Wind Shear Above Jet

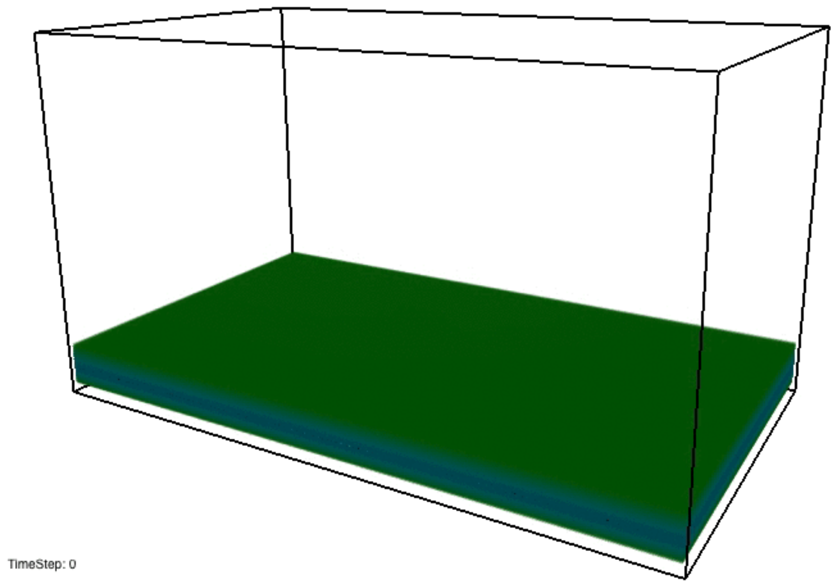




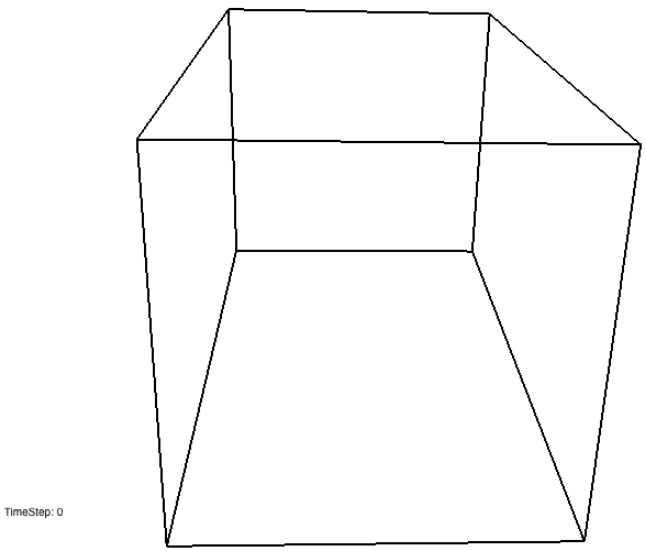


Isosurfaces of Horizontal Velocity

LLJ

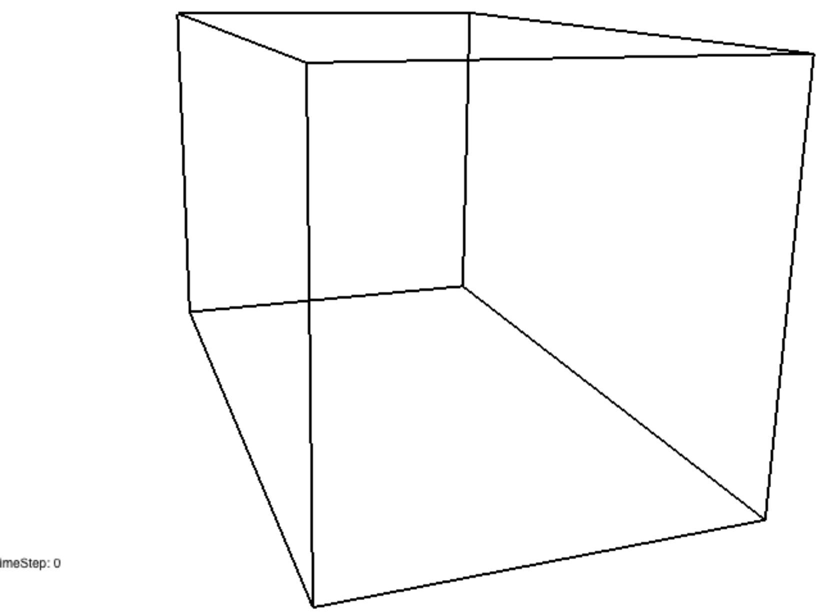


No LLJ

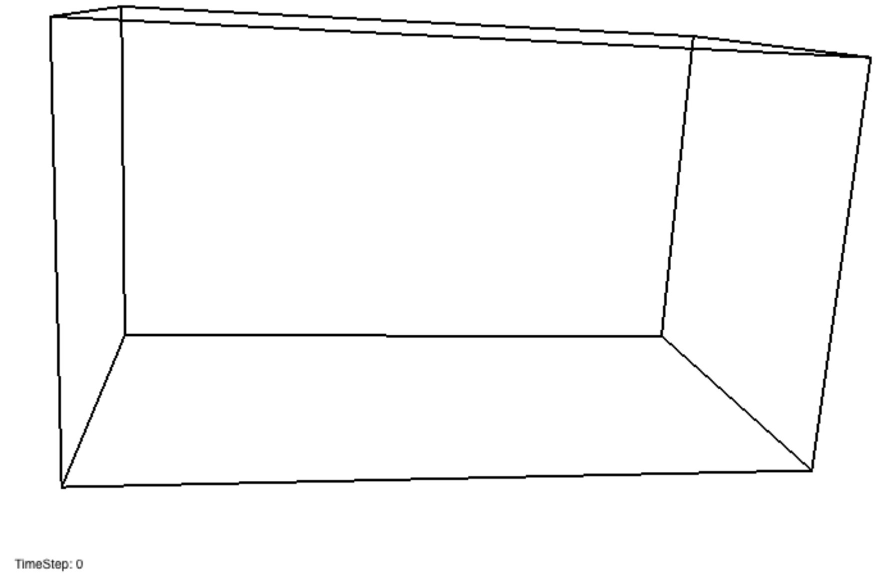


3-D Shaded Updrafts and Downdrafts

LLJ



No LLJ



Summary and Conclusions

- Limited sensitivity of pyro-convective plume structure to LLJ properties such as height and wind shear aloft
- Limited dynamic, and no blowup, fire spread
- Significant downwind tilting of pyro-convective plume
- LLJ likely to be conducive to mid to long range spotting
- Highly idealised environment – high degree of uniformity and symmetry not conducive to fire whirl formation
- Rothermel model is semi-empirical, uncertainties over its validity in representing dynamic modes of fire spread
- No spotting. Since LLJs may play a pivotal role in enhanced spotting, need to include this in WRF-Fire

Future Research and Outcomes

- Simulations, simulations and more simulations…
- A large parameter space to explore
- Other coupled models to compare and contrast against e.g. more direct comparison of ARPS and WRF-Fire
- Critical level analysis as suggested Potter is a good start
- Eventually, move towards a more quantitative understanding of blowup fire behaviour
- This will improve operational prediction of blowups