Threshold behaviour in dynamic fire propagation

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Never Stand Still

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The Wambelong Fire, Coonabarabran
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Photo: Andy Green

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Dynamic fire spread and the quasi-steady assumption

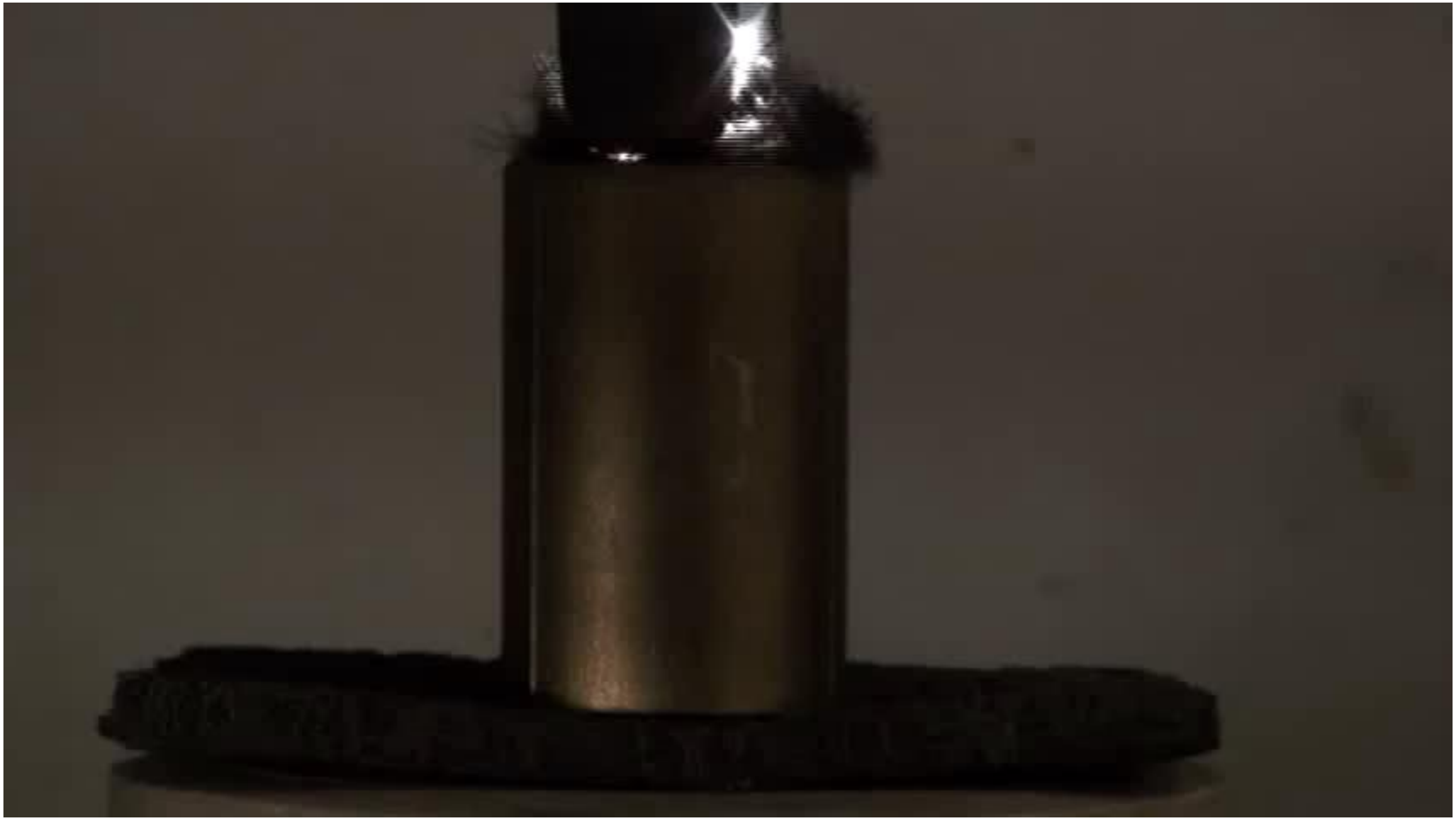
Rate of spread = a function of (W, D, T, H, U, S)

W is Fuel Weight (tonnes ha^{-1})
D is Drought Factor (antecedent rainfall conditions)
T is Temperature (dry-bulb, ° C)
H is Relative Humidity (%)
U is Wind Speed (average at height of 10m, km h^{-1})
S is Topographic Slope (degrees)

The quasi-steady assumption:

Constant “environmental” conditions ⇒ Constant rate of fire spread

Example: Combustion waves



Self-propagating high temperature synthesis

Example: Combustion waves

A combustion wave can be described by the governing (partial differential) equations:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial x^2} + v e^{-1/u}$$

$$\frac{\partial v}{\partial t} = Le^{-1} \frac{\partial^2 v}{\partial x^2} - \beta v e^{-1/u}$$

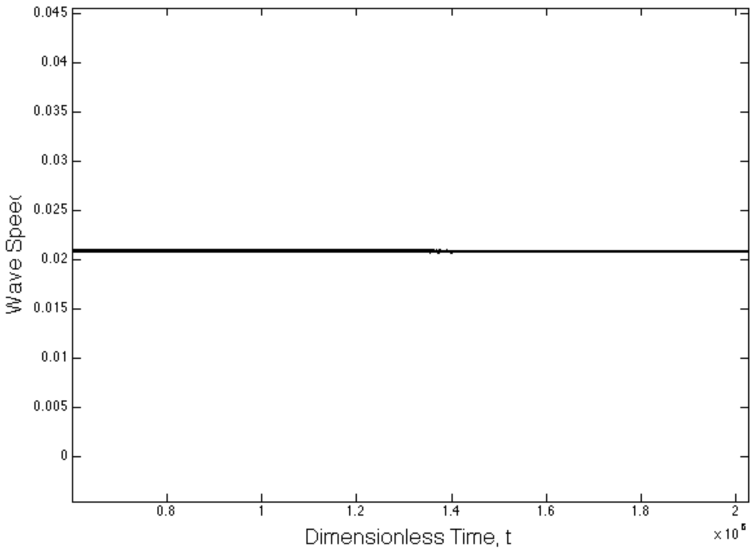
Le is the Lewis number

β is the exothermicity parameter

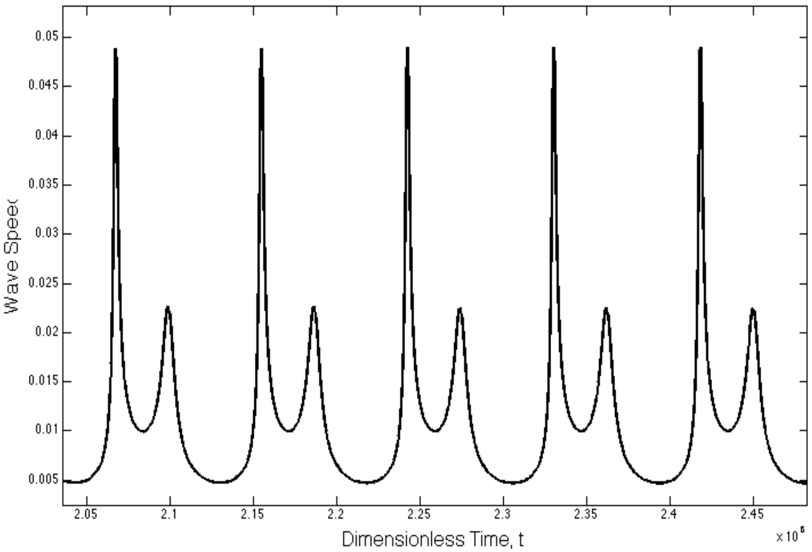
These equations already imply the existence of thresholds, beyond which the propagation of the combustion wave becomes distinctly dynamic...!

Example: Combustion waves

Let's see what happens to the wave speed as we change β

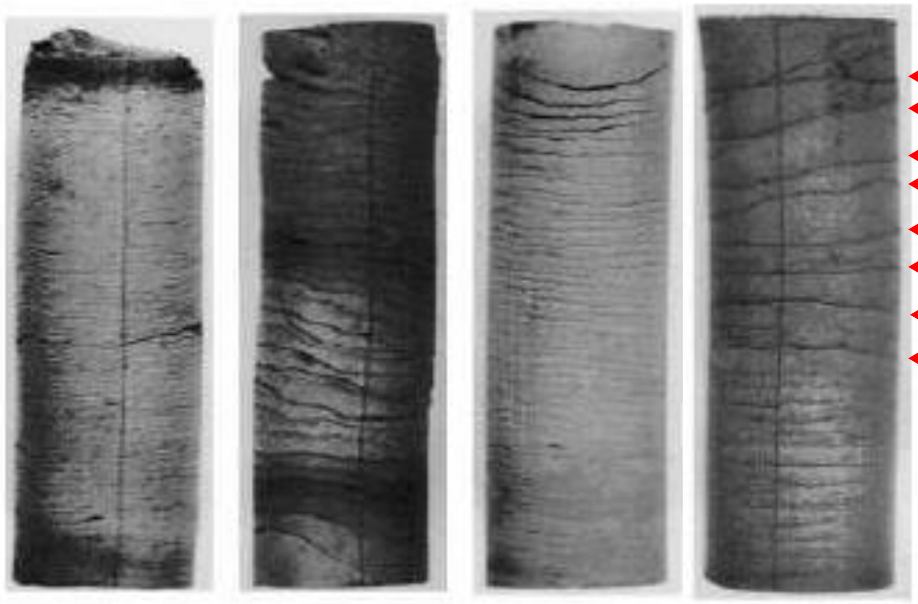


$Le = 8, \beta = 7.5$



$Le = 8, \beta = 7.9$

Example: Combustion waves



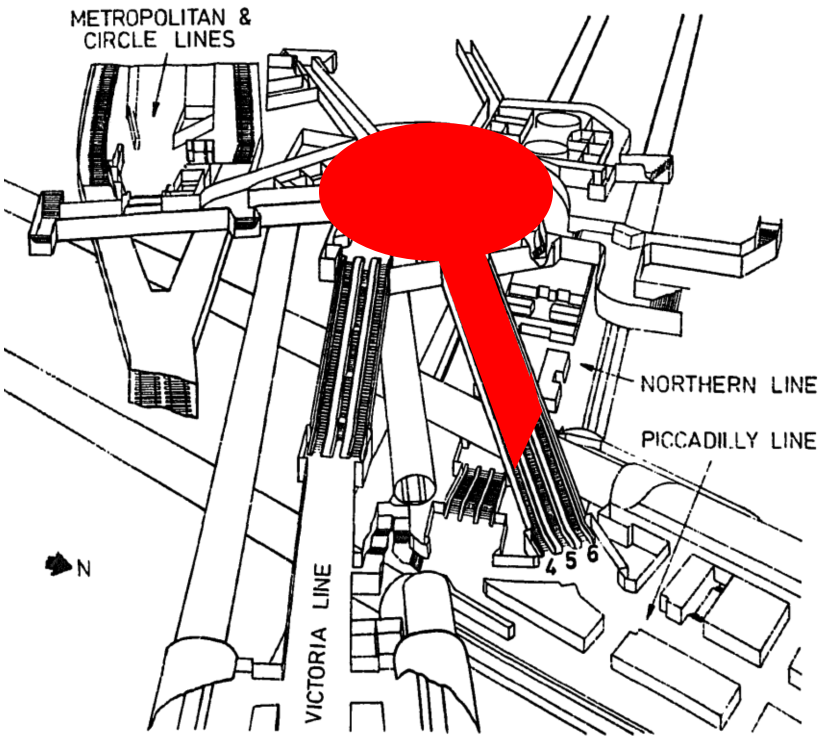
Laminar defects arise as a consequence of a variable wave speed with associated differences in burning characteristics.

The emergence of a dynamic wave speed can result in undesirable consequences...

Other dynamic thresholds:

The King's Cross disaster and flame/plume attachment

- Fatal underground fire in London which broke out at approximately 19:30 on 18 November 1987, and which killed 31 people and injured over 60.



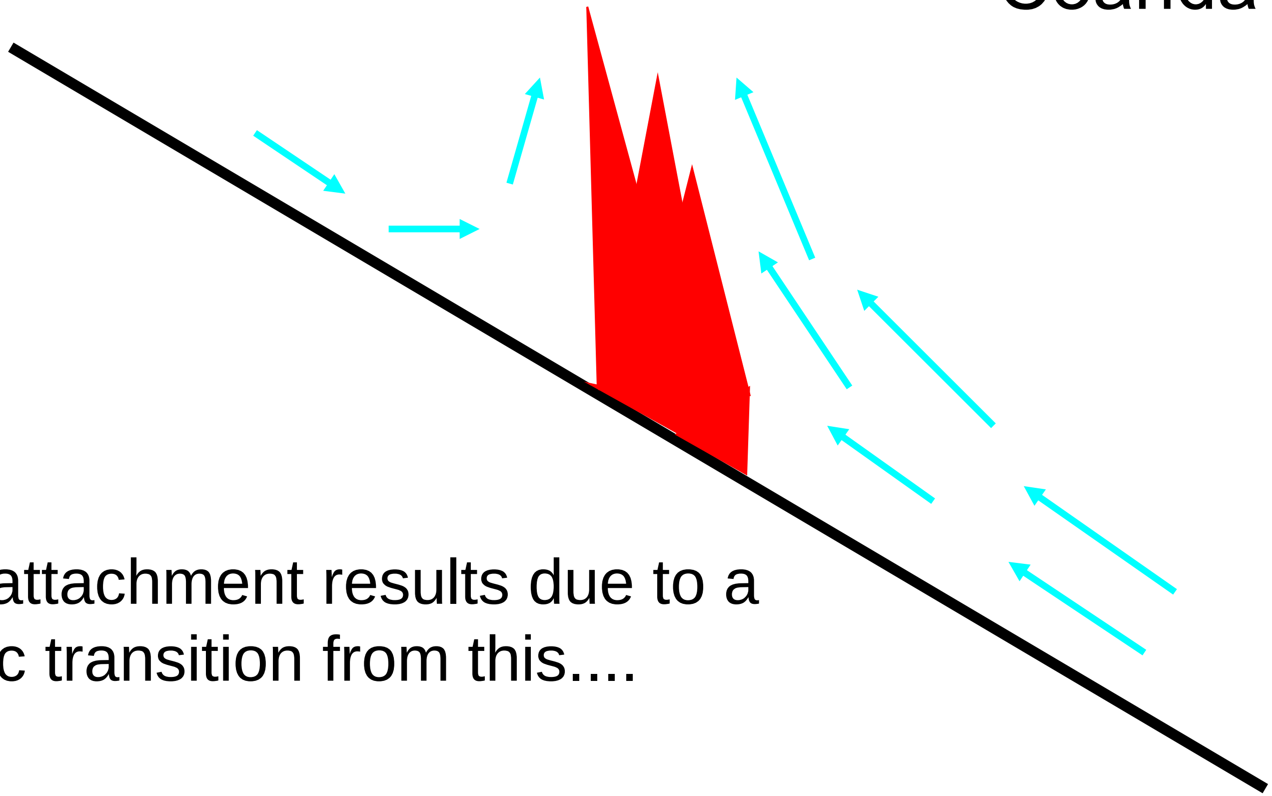
- Fire-fighters who arrived on the scene described the fire as "about the size of a campfire". They were not concerned initially…

- The fire subsequently spread with extreme ferocity up the escalator trench and into the ticket hall and surrounding areas with tragic consequences. It was described as a "blowtorch".

Investigation identified a threshold angle of inclination above which flames attach to the surface of a rectangular trench!

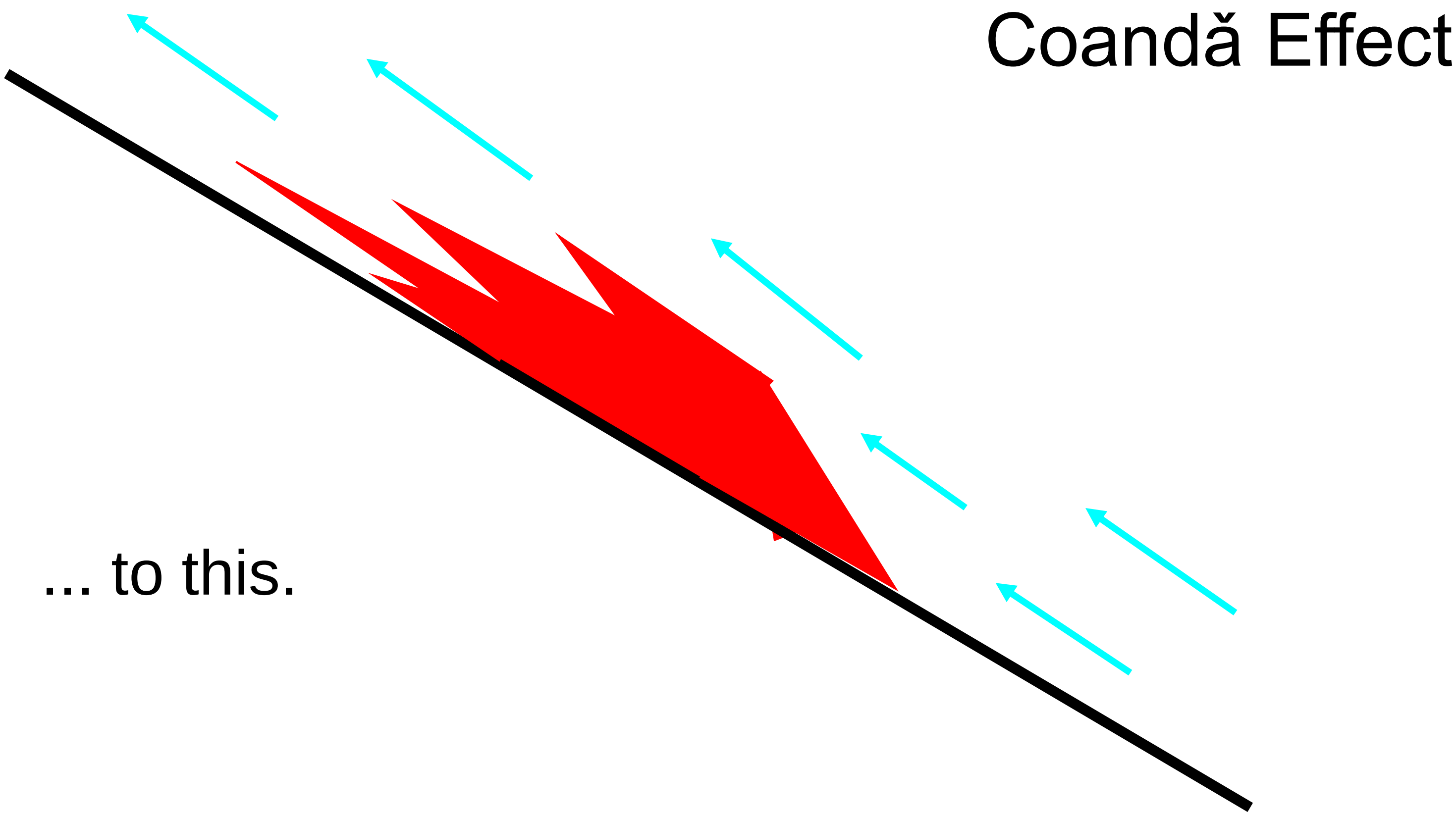
Flame/Plume Attachment

Coandă Effect



Plume attachment results due to a dynamic transition from this....

Flame/Plume Attachment



In trenches with a rectangular profile this will occur when the trench is inclined at an angle of about 26 degrees or greater.

Medium V-shaped Canyon Experiments

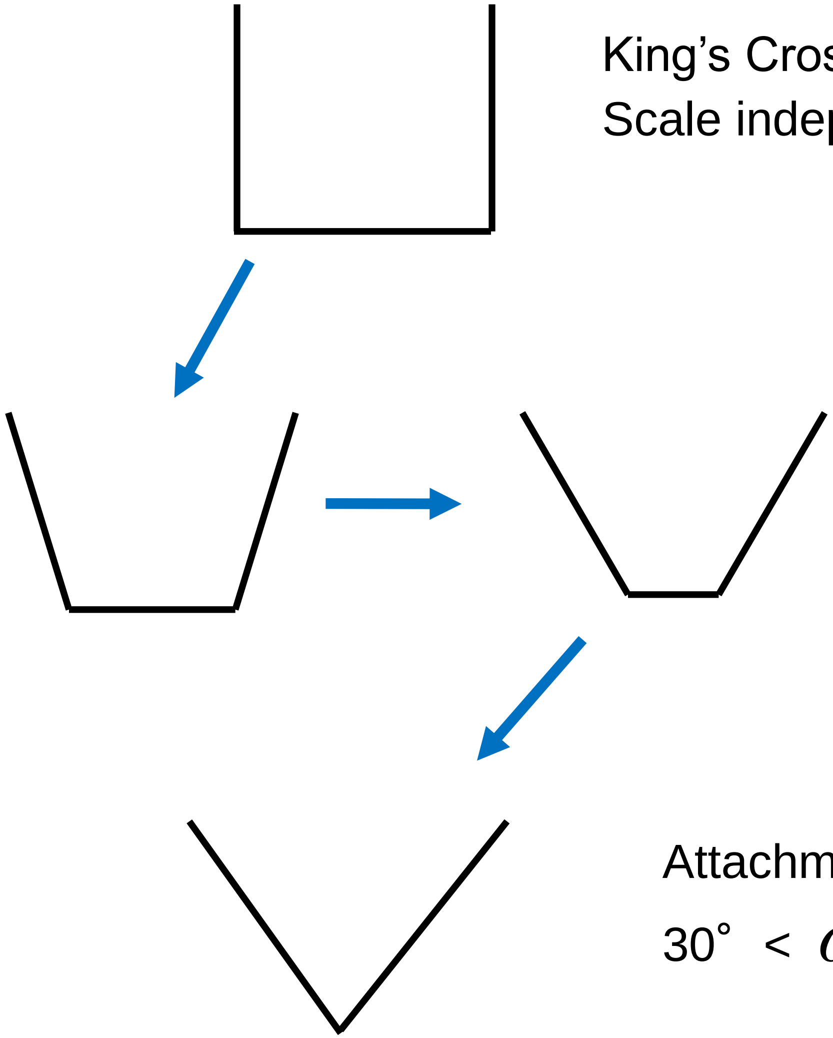
Front-on view

Side-on view

Slope = 30˚
No attachment

Slope = 40˚
Attachment

Flame attachment in different geometries?



King's Cross "Trench effect" $\alpha \approx 26^\circ$
Scale independent

How does the attachment phenomenon change as the geometry is continuously deformed through intermediate configurations???

Attachment in canyons ??

$30^\circ < \alpha < 40^\circ$?? Scale dependence??

We are adressing this through ARC-funded CFD analysis and laboratory experimentation

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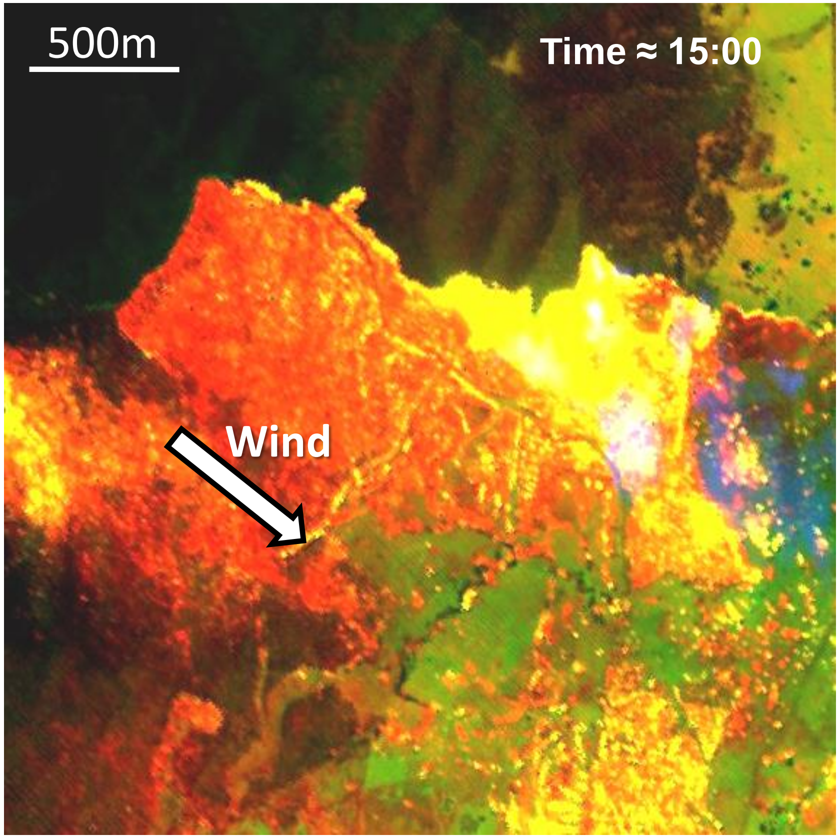
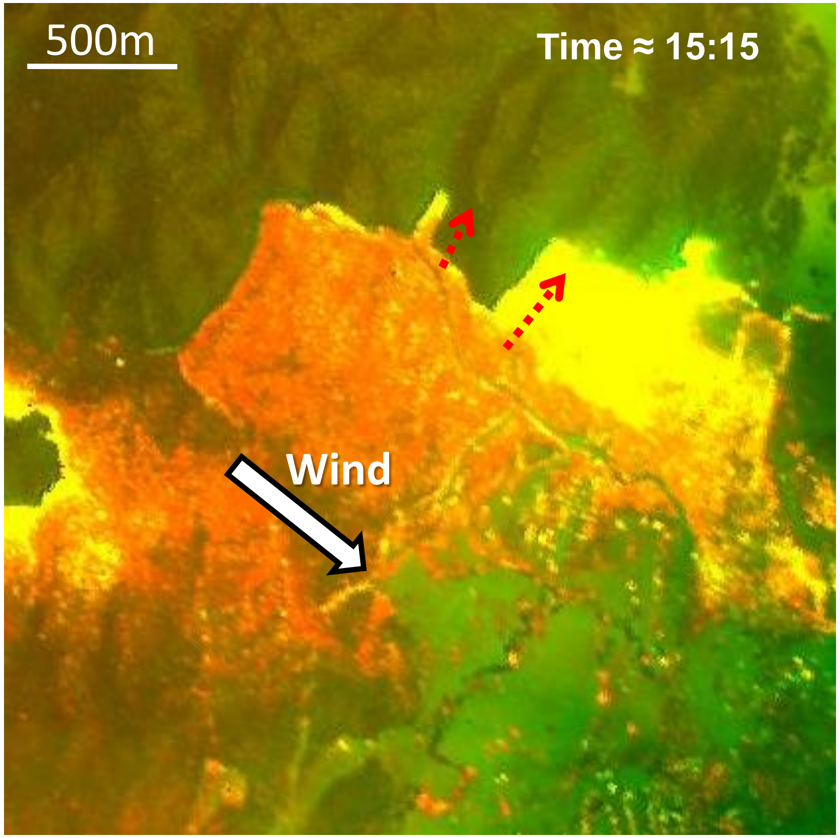
A wildfire example of dynamic spread

McIntyre's Hut fire, west of Canberra 18 January 2003





Lateral rates of spread (across the wind) of about 0.5 – 1.0 km/h

Coupled fire-atmosphere simulations

To better understand the dynamics and physical mechanisms driving the dynamic spread we used an atmospheric model coupled with a model for surface fire spread (WRF-Fire).

Atmospheric model:

- Weather Research and Forecasting model
- Navier-Stokes equations + thermodynamics
- Large eddy simulation is used in idealised mode

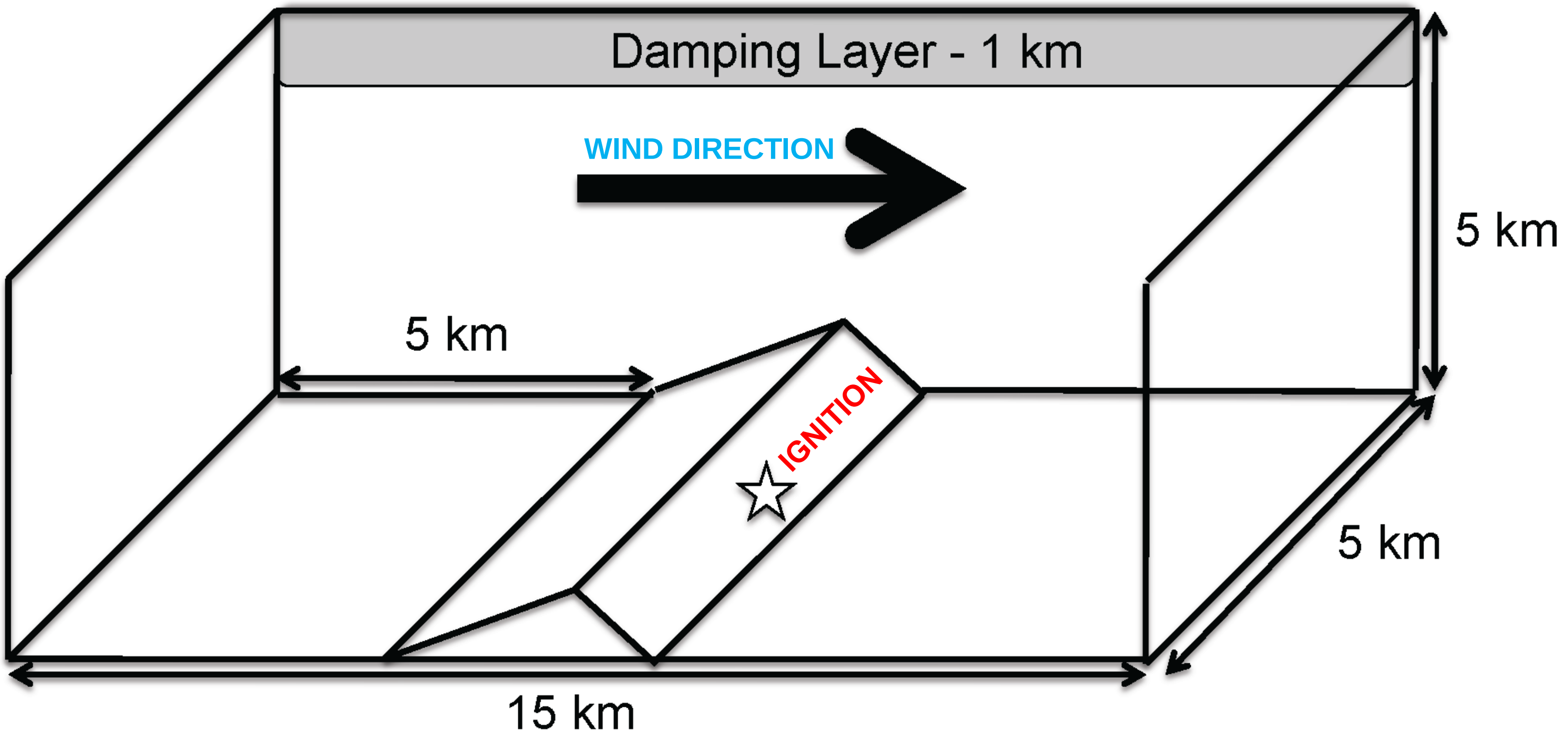
Surface fire model:

- Rothermel:

$$R(w,\gamma_s) = R_0(1+\phi_w+\phi_s)$$

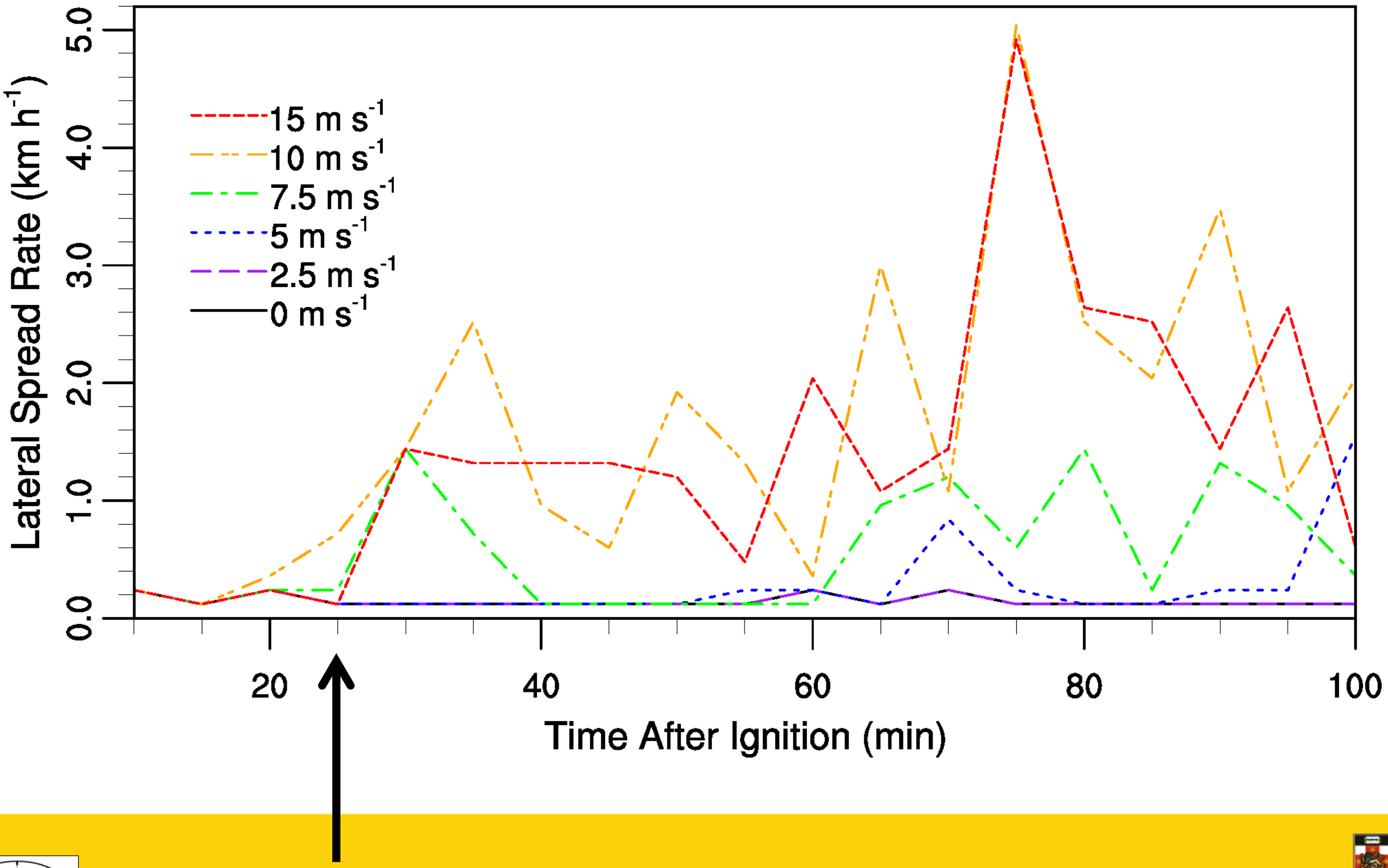
Coupled fire-atmosphere simulations

Modelling domain: Windward slope = 20˚
Leeward slope = 35˚
Mountain height = 1 km



Reference wind speed = U_0

Wind speed threshold: lateral rate of spread

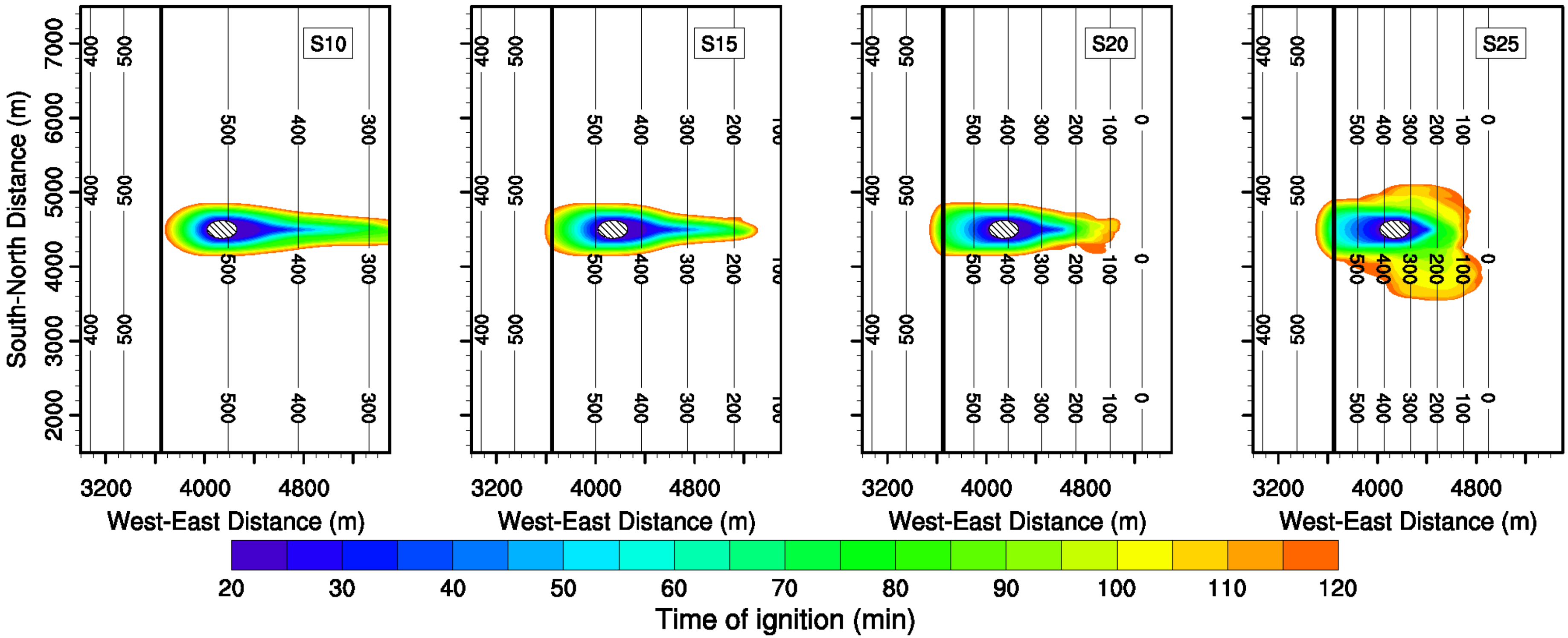


Fire reaches ridge line at top of lee slope!

Topographic slope threshold:

In our previous coupled fire-atmosphere modelling, we assumed a leeward slope angle of 35°

We will now consider other topographic slopes...



No lateral spread!

Topographic slope threshold:

In our previous coupled fire-atmosphere modelling, we assumed a leeward slope angle of 35˚

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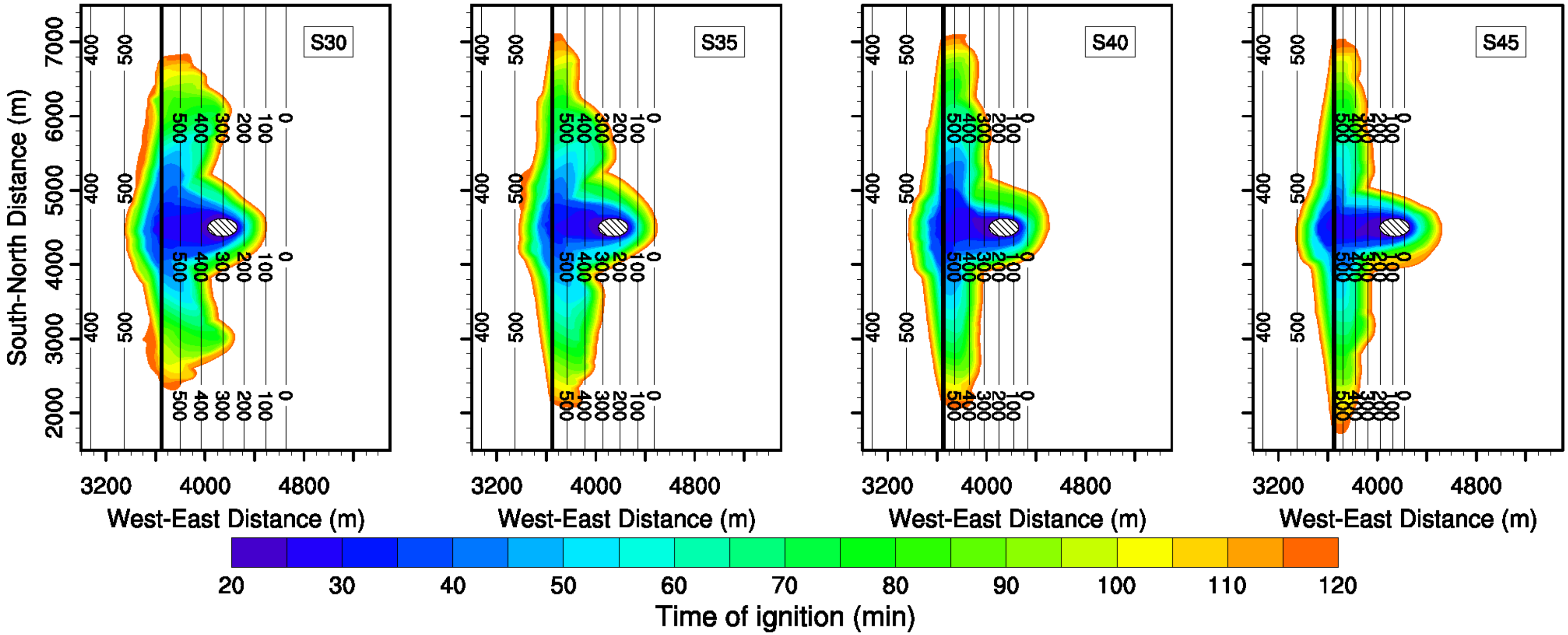

Lateral spread occurs above a threshold topographic slope of 25-30°

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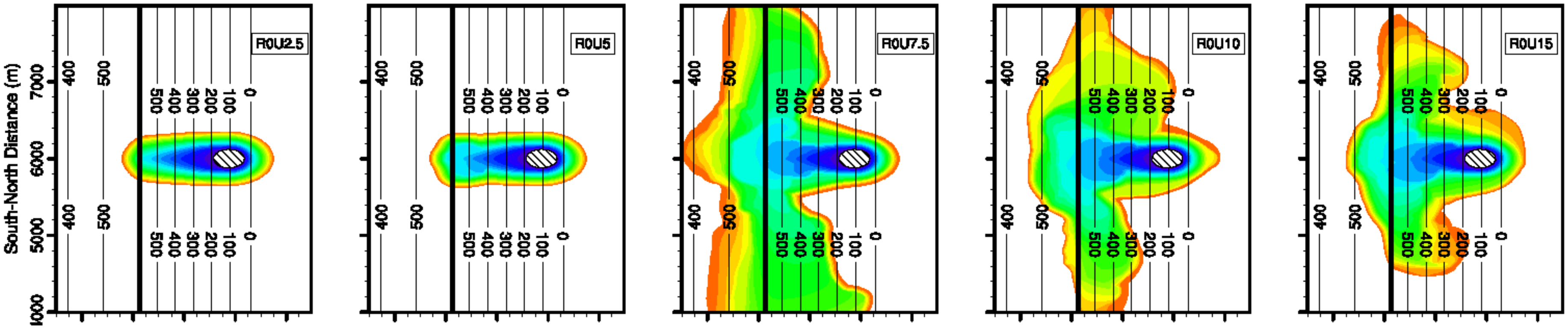
Topographic aspect threshold:

In our previous coupled fire-atmosphere modelling, we assumed that topographic aspect and wind direction were aligned



We will now consider other topographic aspects...

Topographic aspect threshold:

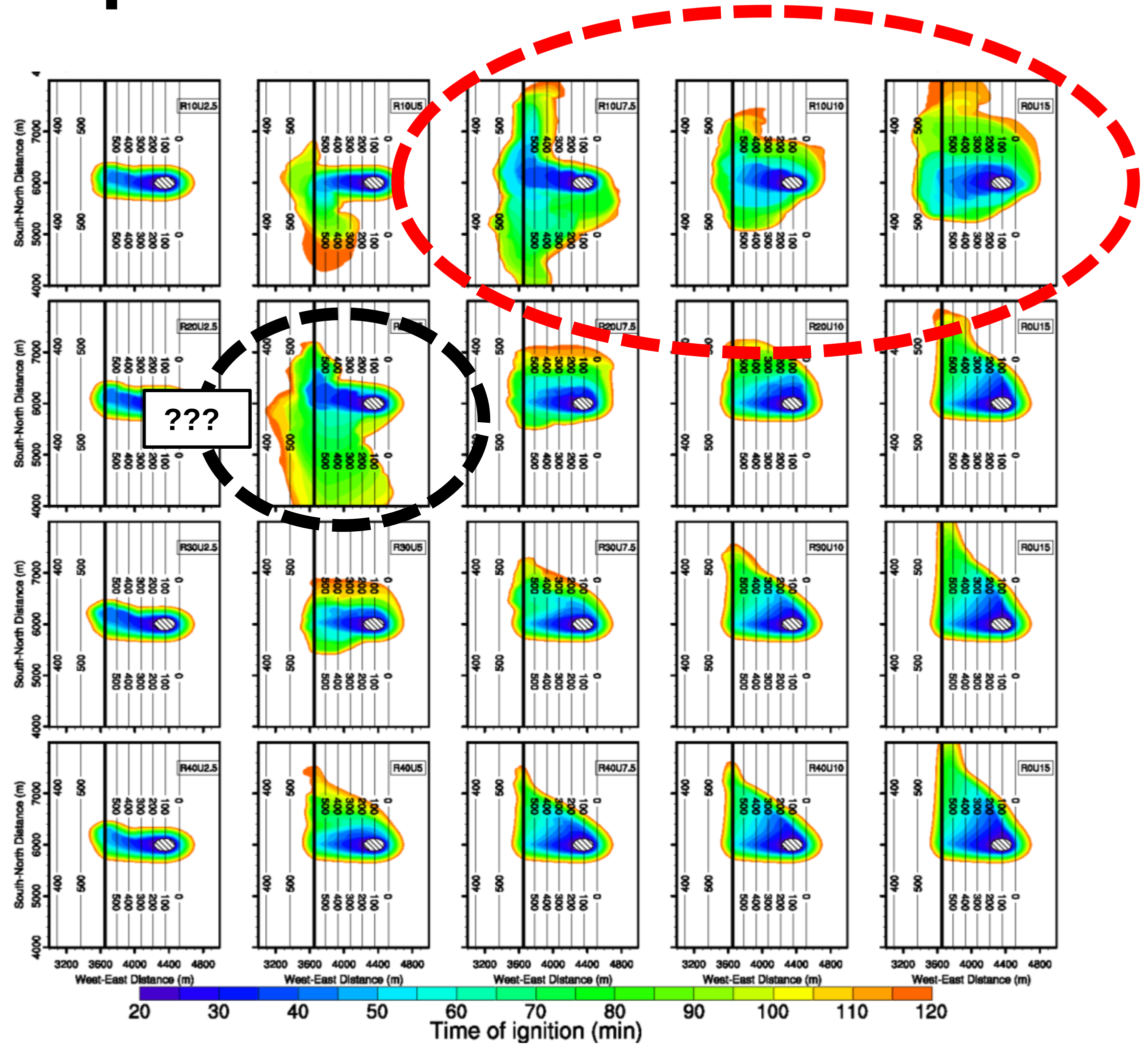
Wind direction (aspect)

10°

20°

30°

40°



2.5 5.0 7.5 10.0 15.0

Wind speed (m/s)

Lateral spread occurs on aspects that are within 10-20°of the wind direction

Fuel properties:

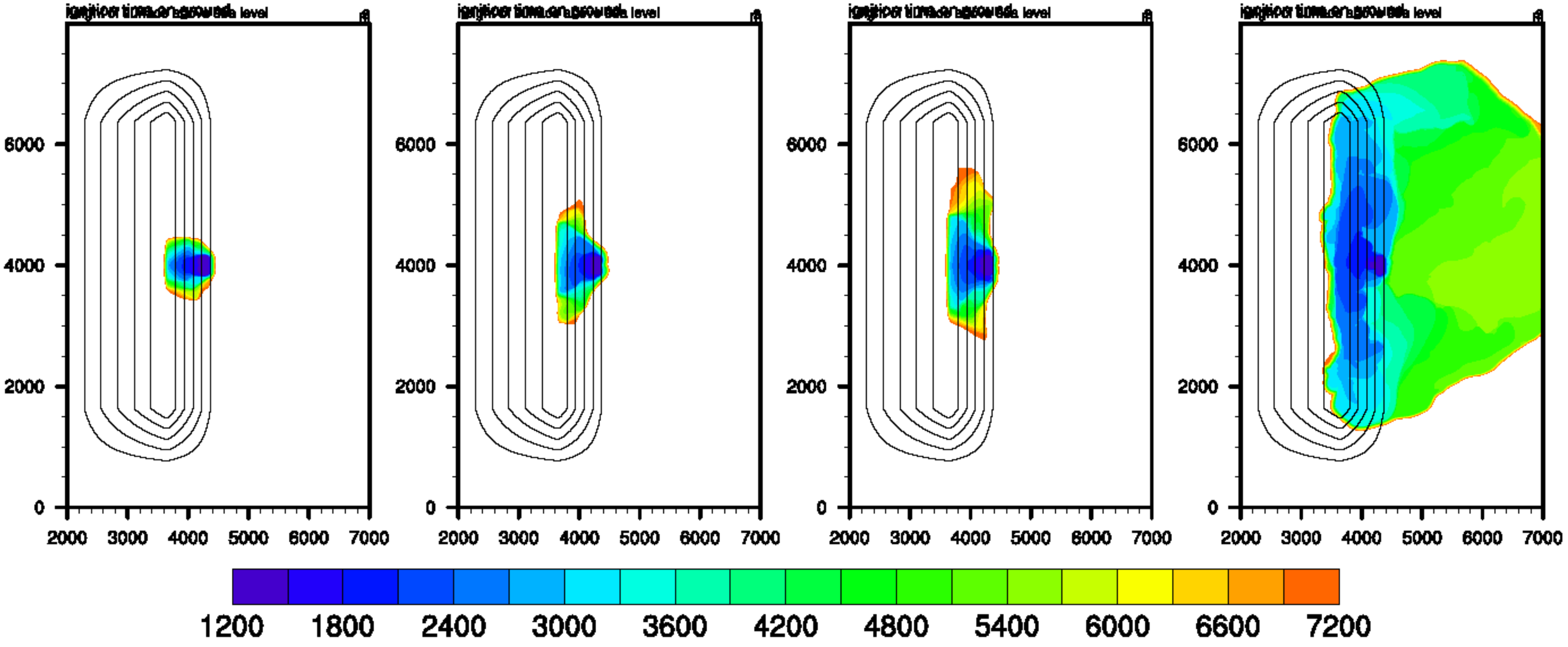
In our previous coupled fire-atmosphere modelling, we considered the following fuel types:

- heavy logging slash
- brush fuel

These correspond to the Anderson fuel categories 13 and 5, resp.

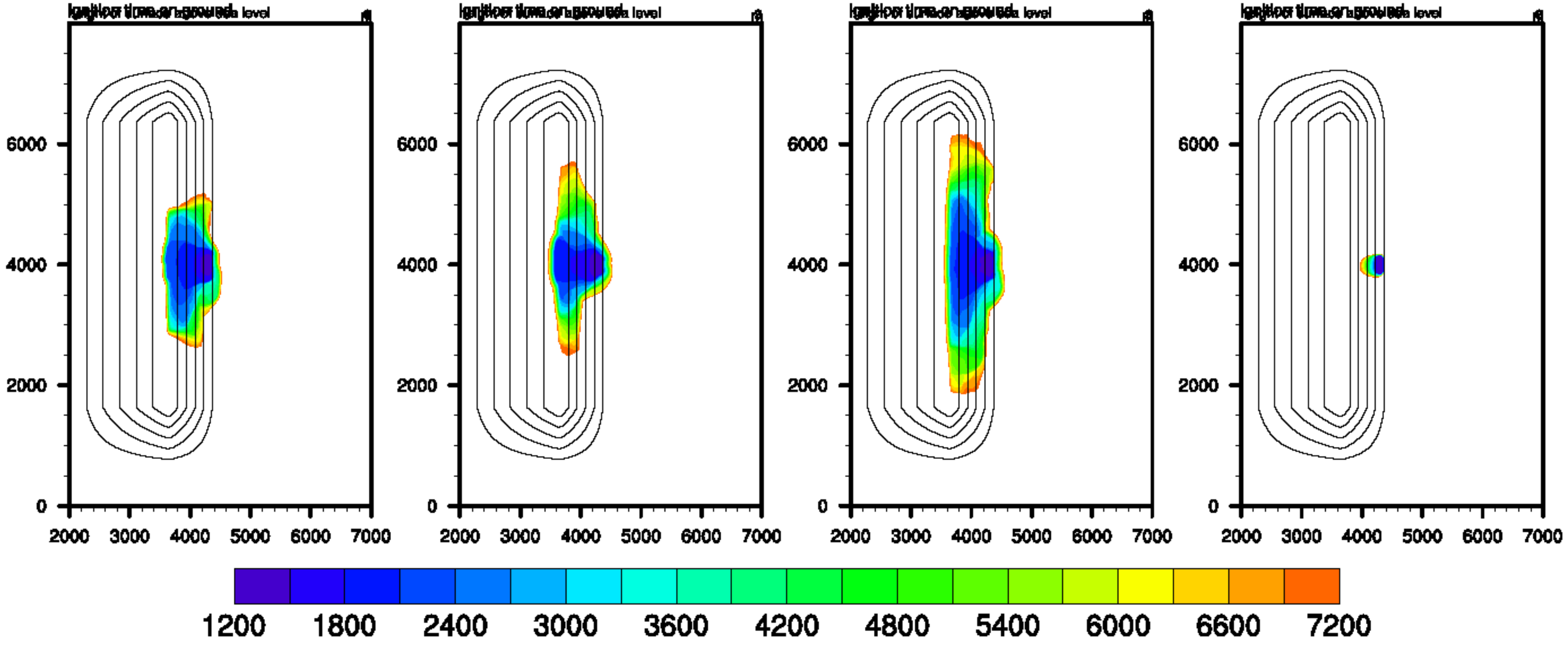
Fuel properties:

Short grass | Timber (grass and understory) | Tall grass | Chaparral



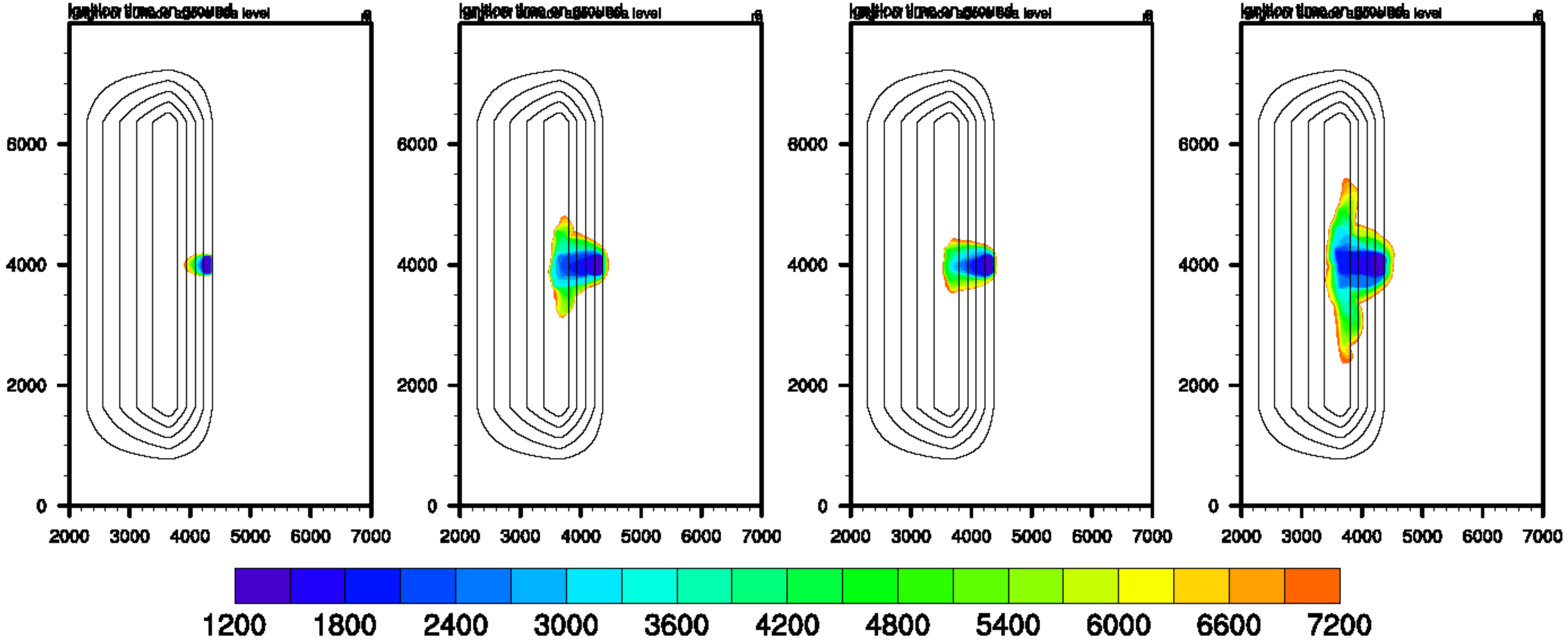
Fuel properties:

Brush	Dormant brush, hardwood slash	Southern rough	Closed timber litter



Fuel properties:

Hardwood litter | Timber (litter and understory) | Light logging slash | Medium logging slash



Conclusions

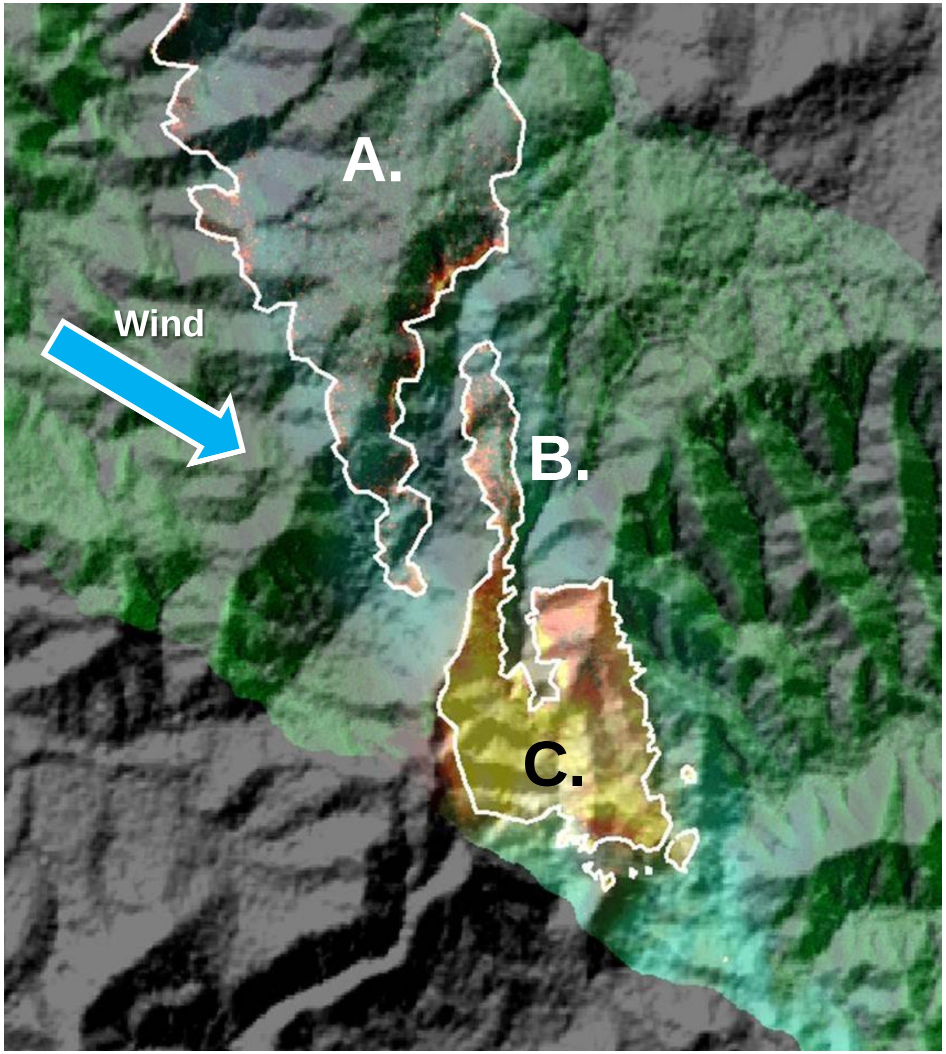
- Thresholds to dynamic behaviour are inherent in combustion systems, even in their most elementary realisations.
- Dynamic fire behaviour in the landscape is also susceptible to a number of environmental thresholds.
- For example, in V-shaped canyons there is a slope threshold, above which flames tend to attach to the surface.
- Don’t really know how wind affects the threshold inclination for flame attachment....???
- Wildfires in rugged terrain can exhibit rapid lateral spread across steep, lee-facing slopes, driven by pyrogenic vorticity on the flanks (VLS).
- VLS is subject to a number of environmental thresholds (wind speed, topographic slope and aspect, fuel properties)

Conclusions

- The wind speed threshold for VLS is approximately 5 ms^{-1}
- The topographic slope threshold for VLS is approximately 25°
- The topographic aspect discrepancy threshold is about 10-20°
- Latest work indicates that there are complicated interdependencies of threshold effects relating to Byram's:

  "*Power of the wind vs Power of the fire*"
- Operational and safety implications: small changes in environment can result in significant changes in fire behaviour.
- For example, with a slight change in topographic aspect, firefighters working on leeward slopes could suddenly encounter an abrupt and distinct change in fire behaviour...

Earlier this year in Victoria…



A. Main fire, which appears to be mostly spreading in a fairly typical way.

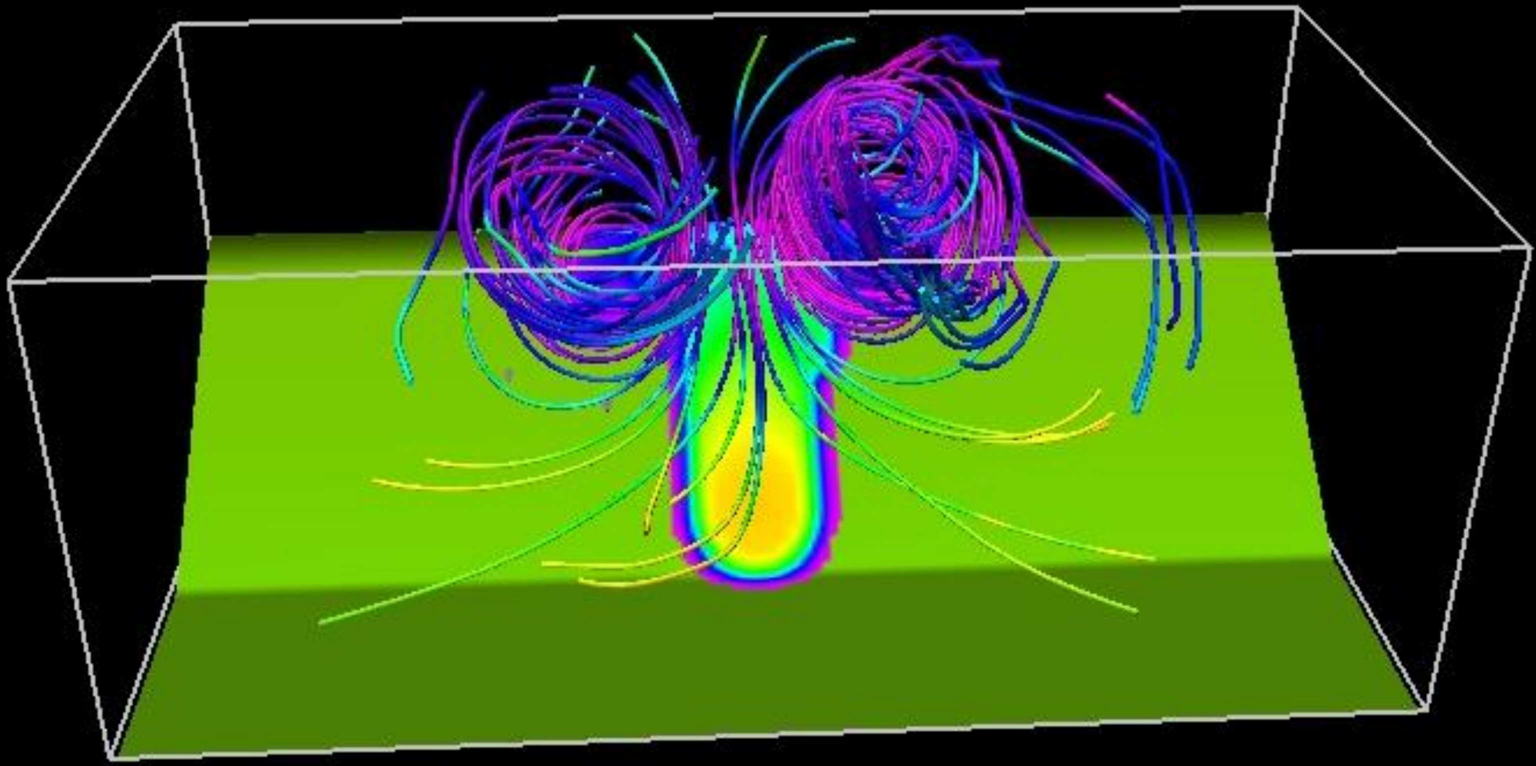
B. Fire progressing downslope towards the west in a typical fashion (eastern edge of fire coincides with a fire trail). Note aspect does not align with wind direction.

C. Fire enters a region where aspect and wind direction aligns. It now exhibits a markedly different and far more alarming pattern of spread.

Acknowledgements

- Research supported by Australian Research Council Discovery Indigenous Award and an Australian Research Council Future Fellowship.
- Prof. Domingos Viegas and his research team at the University of Coimbra, Portugal.
- WRF-Fire runs were performed using the facilities at the National Computing Infrastructure, ANU.
- Insights into the modelling implications were guided by discussions with Rick McRae, ACT Emergency Services Agency and Stephen Wilkes, ACT Territory and Municipal Services.

Thank you for your attention!



Graphic demonstrating the M2V-effect driving the VLS phenomenon.

Questions?