The effects of turbulent plume dynamics on long-range spotting

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Motivation

- The lofting and transport of firebrands ignites spot fires downwind from the primary fire
- Spot fires lead to **accelerated** and **unpredictable** fire spread
  - *Accelerated*: Embers cause the fire to jump ahead. Upper-level winds are often faster than near-surface winds,
  - *Unpredictable*: How far will it spot? Upper-level winds are often in a different direction from the near-surface winds
- A better knowledge of processes involved in spotting will improve our ability to predict fire spread
- There is evidence for very long-range spotting in excess of 30 km, e.g. Kilmore East fire during Black Saturday

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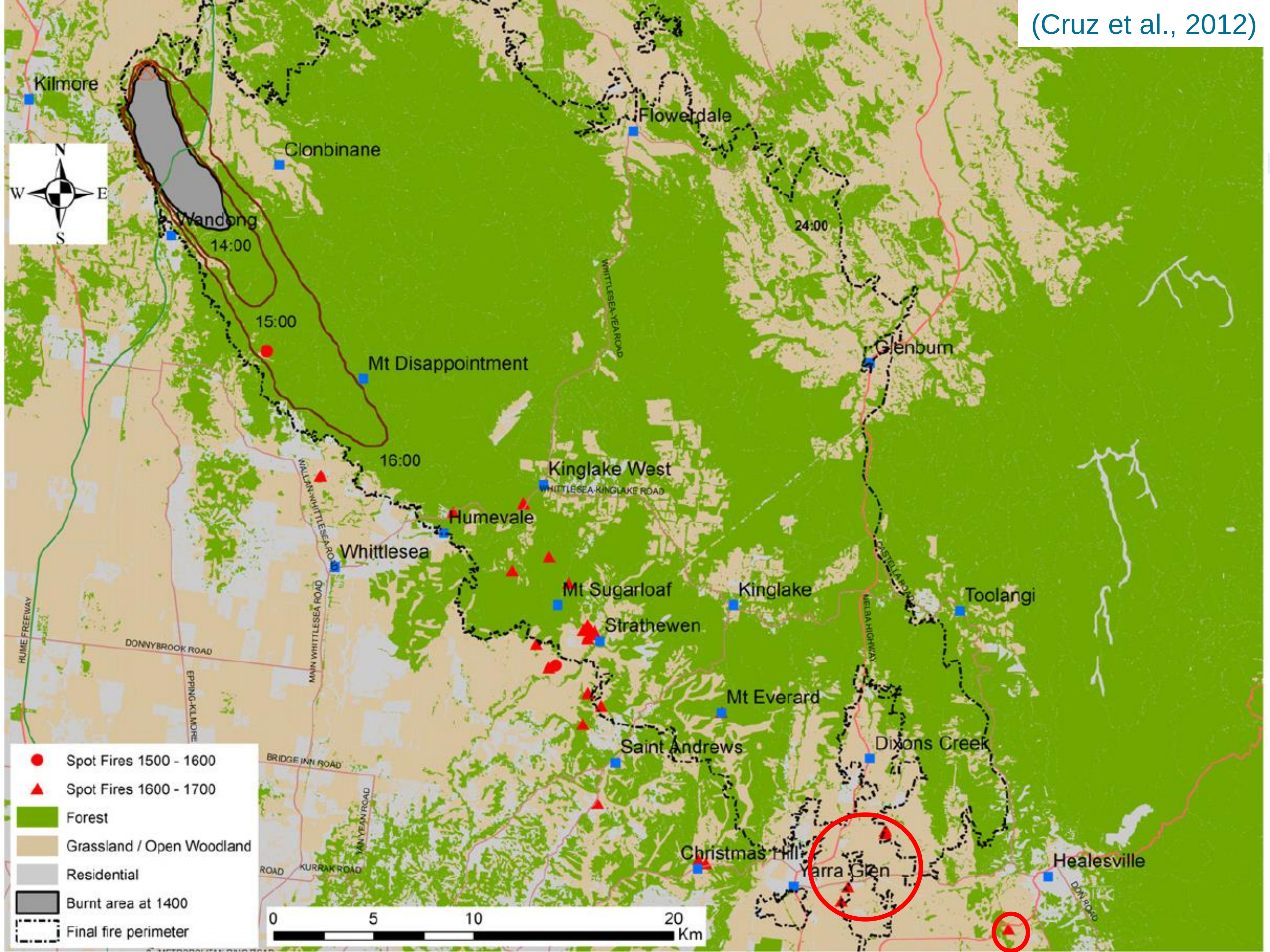
(Cruz et al., 2012)



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FLIR footage – Tomahawk fire

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Credit: Tim Wells, CFA

Modelling methodology

- We use a **two-stage** modelling process to investigate how **turbulent plume dynamics** may affect spotting:

    1. Perform high-resolution simulations of idealised bushfire plumes in different wind conditions using a large-eddy model (LEM)

    2. Use the four-dimensional (3 space, 1 time) velocity fields from the LEM to calculate the trajectories of hundreds of thousands of virtual firebrands assigned a constant fall velocity

- Trajectory calculations are then repeated for a temporal mean "steady-state" plume to asses the effect of in-plume turbulence on transport

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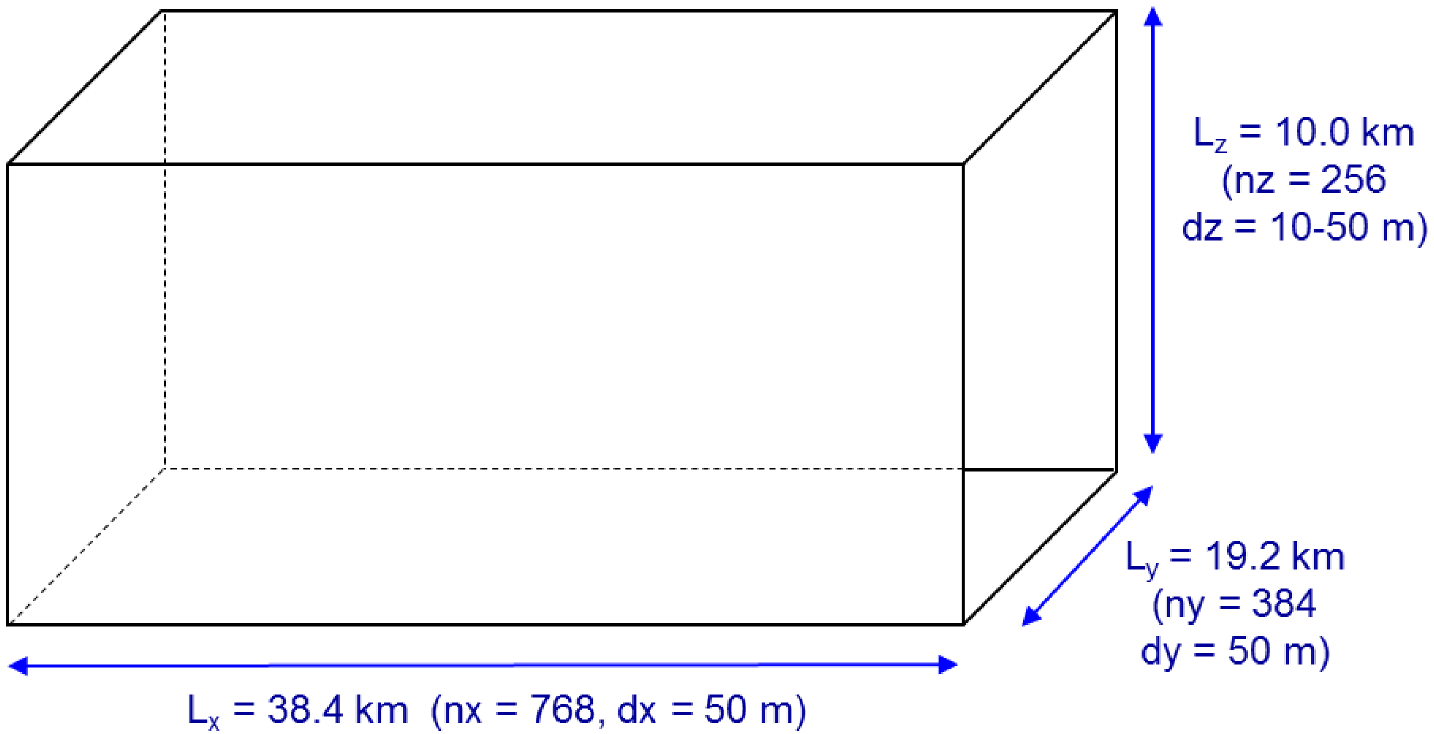
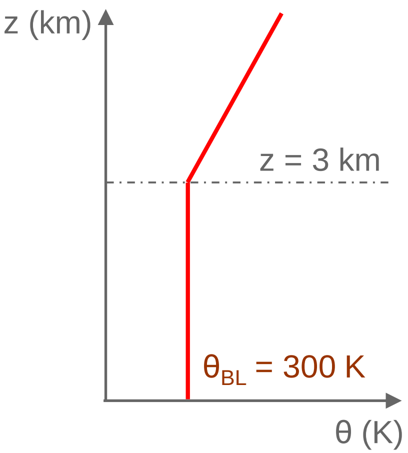
Large-Eddy Model configuration



- Idealised setup (no moisture, radiation, Coriolis, topography)
- Periodic lateral boundary conditions
- No-slip lower boundary
- Free-slip upper boundary (+ Newtonian damping layer in upper 2 km)

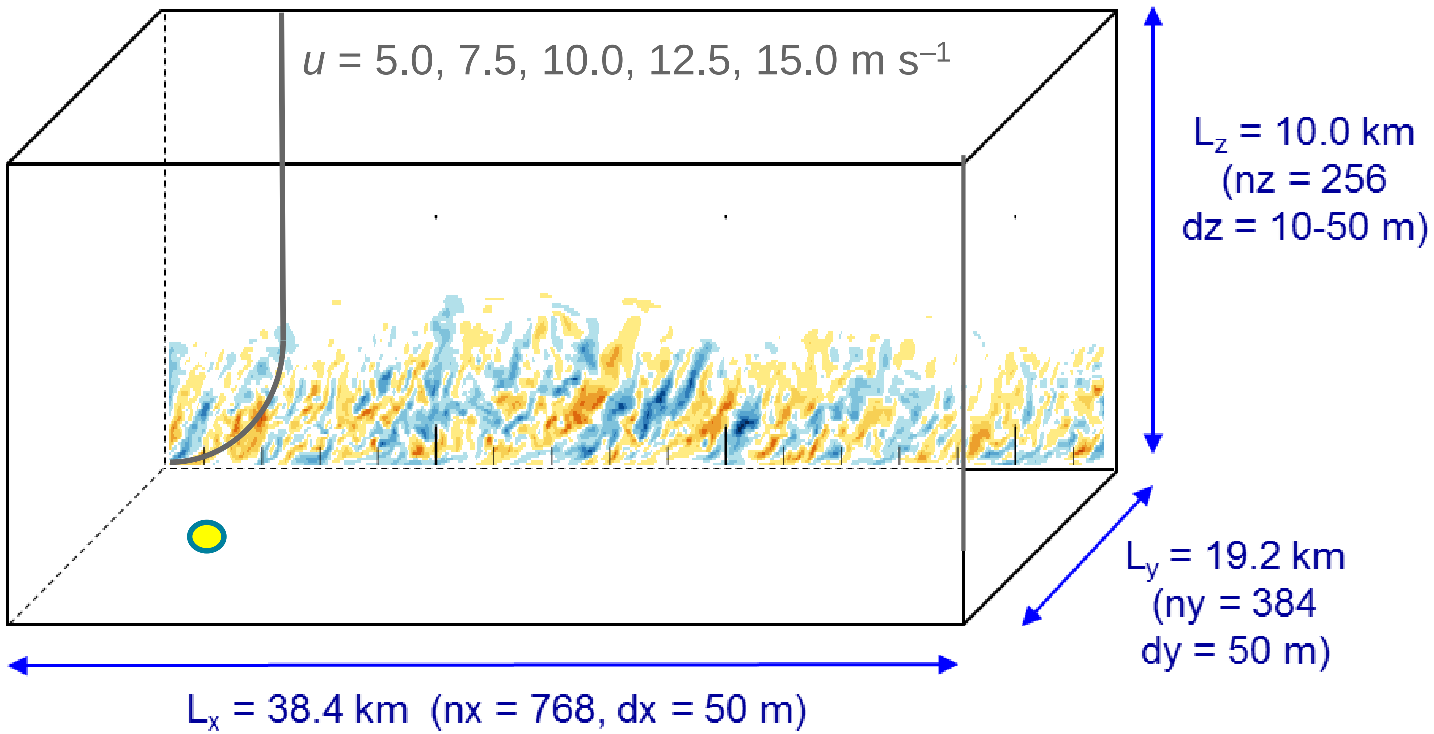
Two-step plume simulation

- Simulate realistic turbulent boundary layers for a range of wind speeds (typically not done in idealised plume studies):
  - Initialise model with horizontally homogeneous potential temperature and wind profiles
  - Apply random perturbations (± 0.2 K) to potential temperature field
  - Run model until turbulence (defined by domain-averaged TKE) has spun up to quasi-steady state



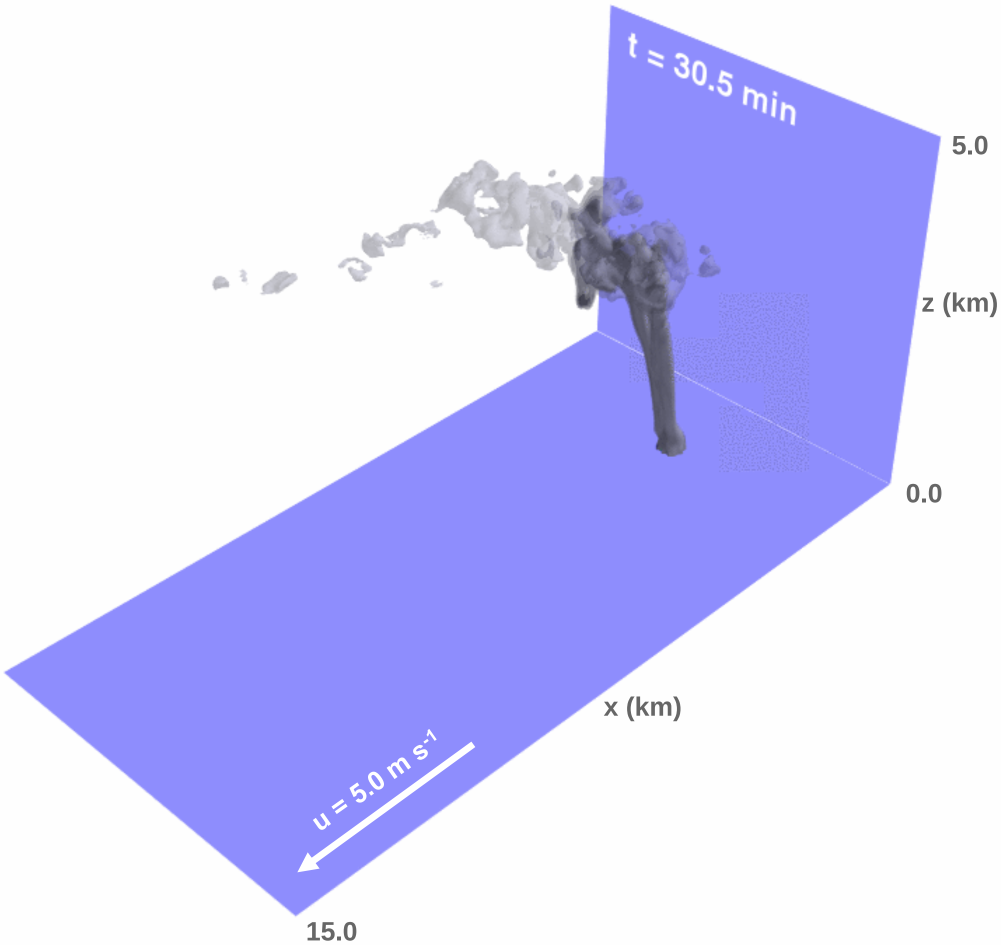
- Generate a “fire” plume by applying an intense circular surface heat flux anomaly (Q = 100,000 W m^{-2}, radius = 250 m)
  - No feedback of atmosphere onto fire behaviour
  - No surface spread
  - Allows us to isolate the way plumes respond to wind

Model “initialisation” – plume generation



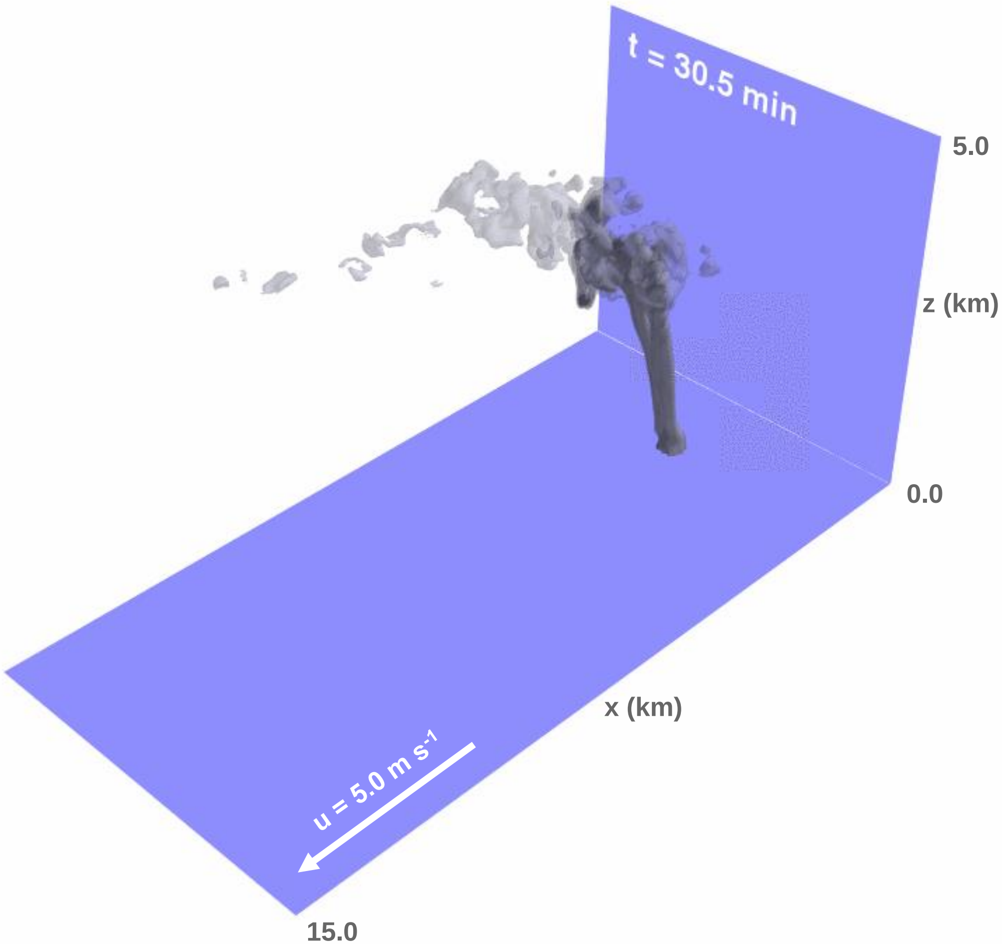
- Generate a “fire” plume by applying an intense circular surface heat flux anomaly (Q = 100,000 W m^{-2}, radius = 250 m) and release passive tracer

Tracer visualisation – 5 m s^{-1} wind



- Lower two-thirds of plume is within boundary layer:
  - Relatively smooth
  - Small instability at top of smooth updraft
  - Consists of a counter-rotating vortex pair
- Upper section of plume above the boundary layer:
  - Plume is much more turbulent

Tracer visualisation – 5 m s^{-1} wind



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  - Relatively smooth
  - Small instability at top of smooth updraft
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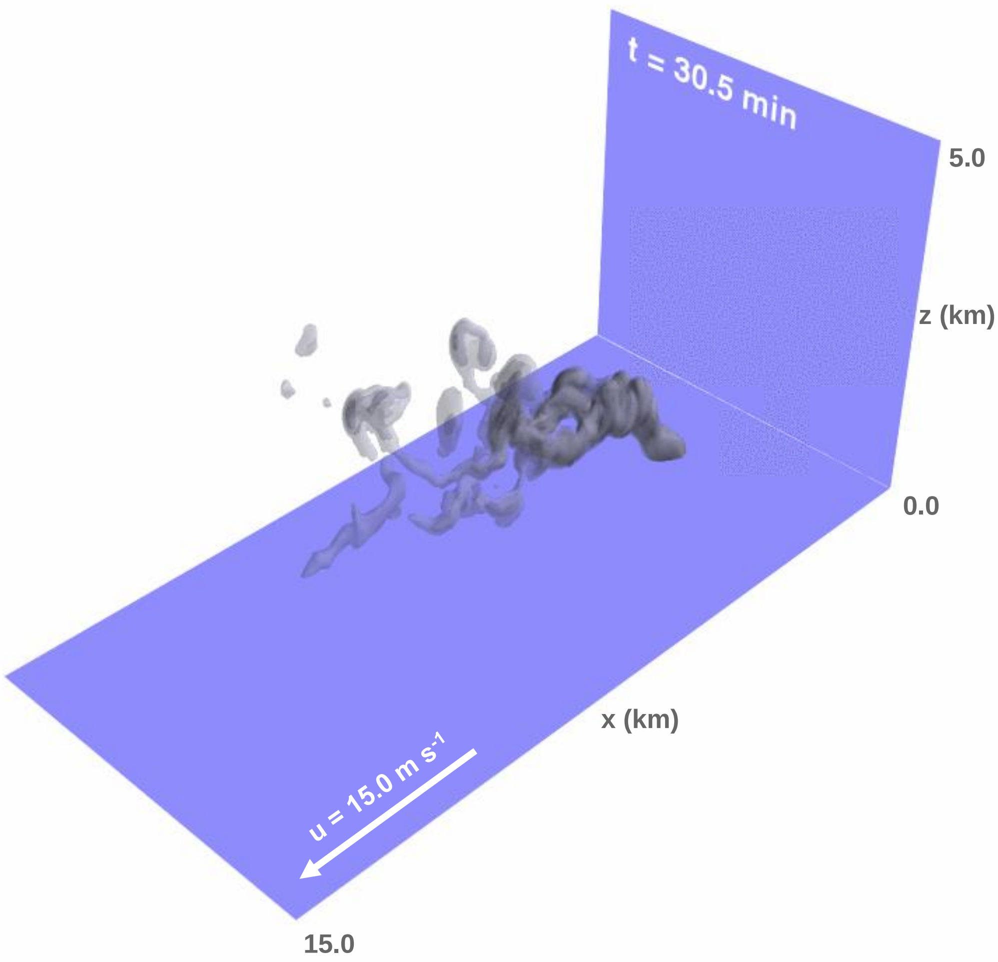
- Upper section of plume above the boundary layer:
  - Plume is much more turbulent
  - Meandering above the boundary layer is more prominent

Tracer visualisation – 15 m s^{-1} wind



- Plume is turbulent from the surface upwards
- Plume is much more bent over
- Plume exhibits pulsing
- Plume is more dispersed
- Plume meanders from near-surface to top

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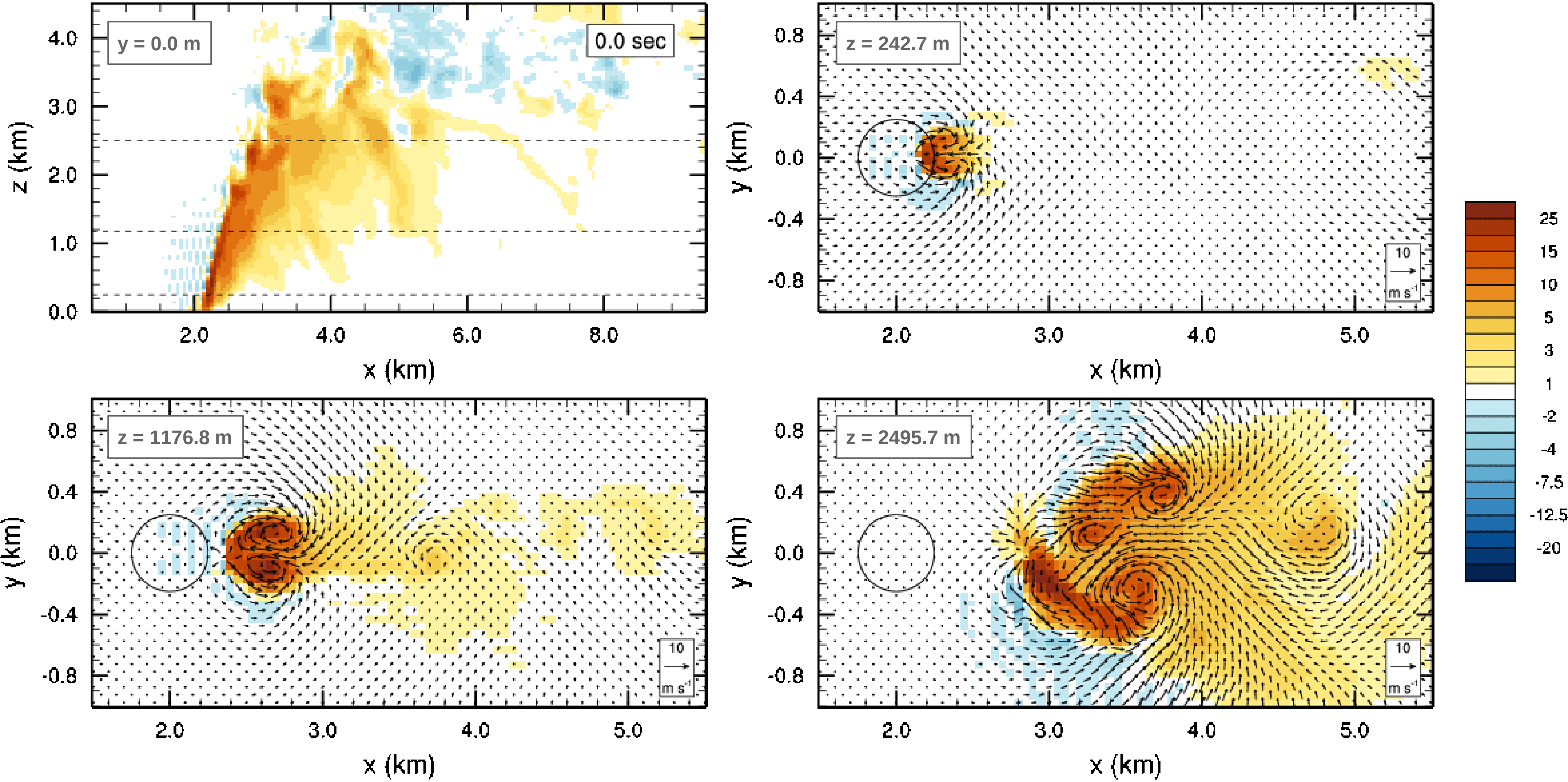
Plume dynamics – 5 m s^{-1} wind



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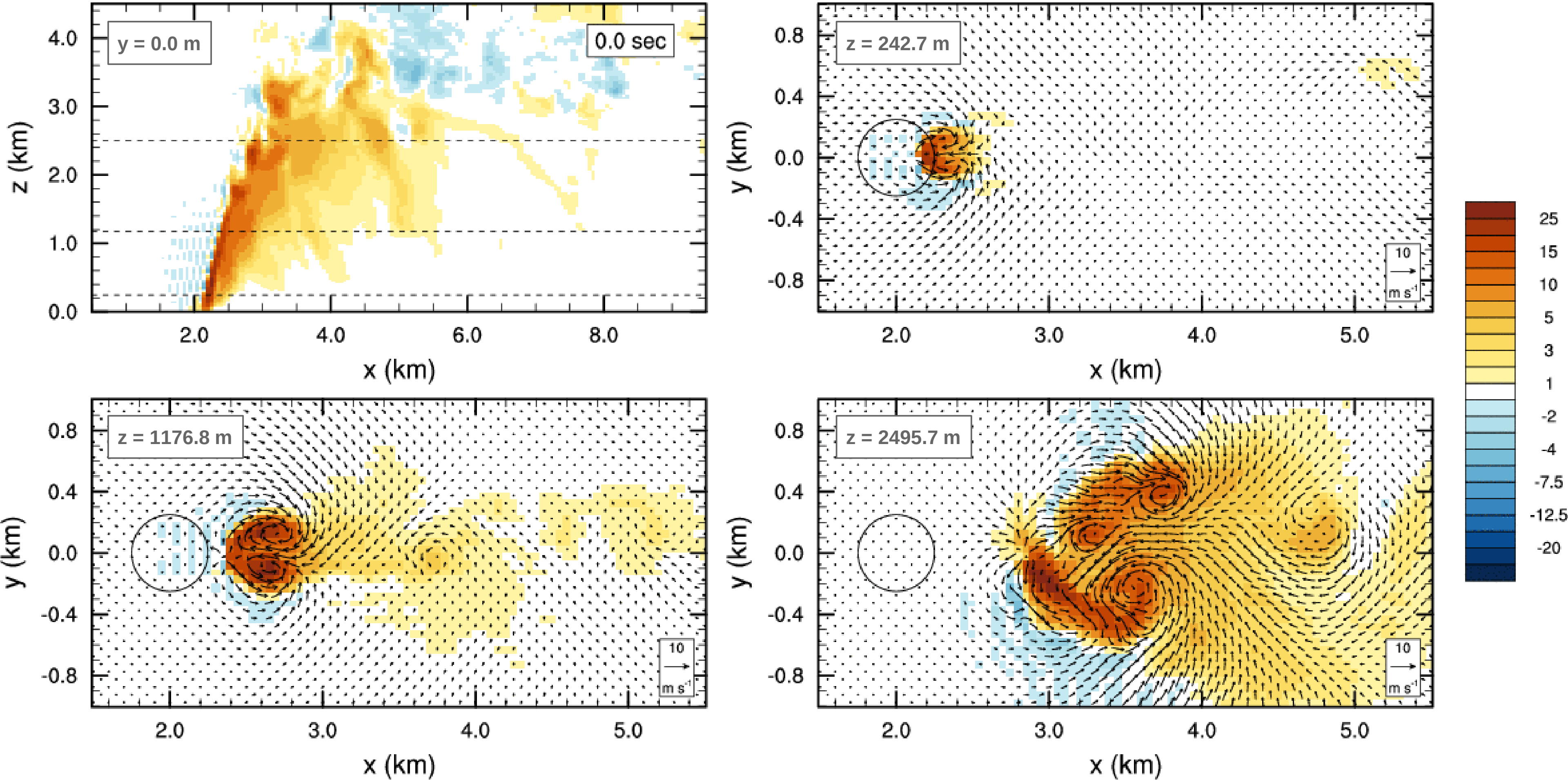
Plume dynamics – 5 m s^{-1} wind



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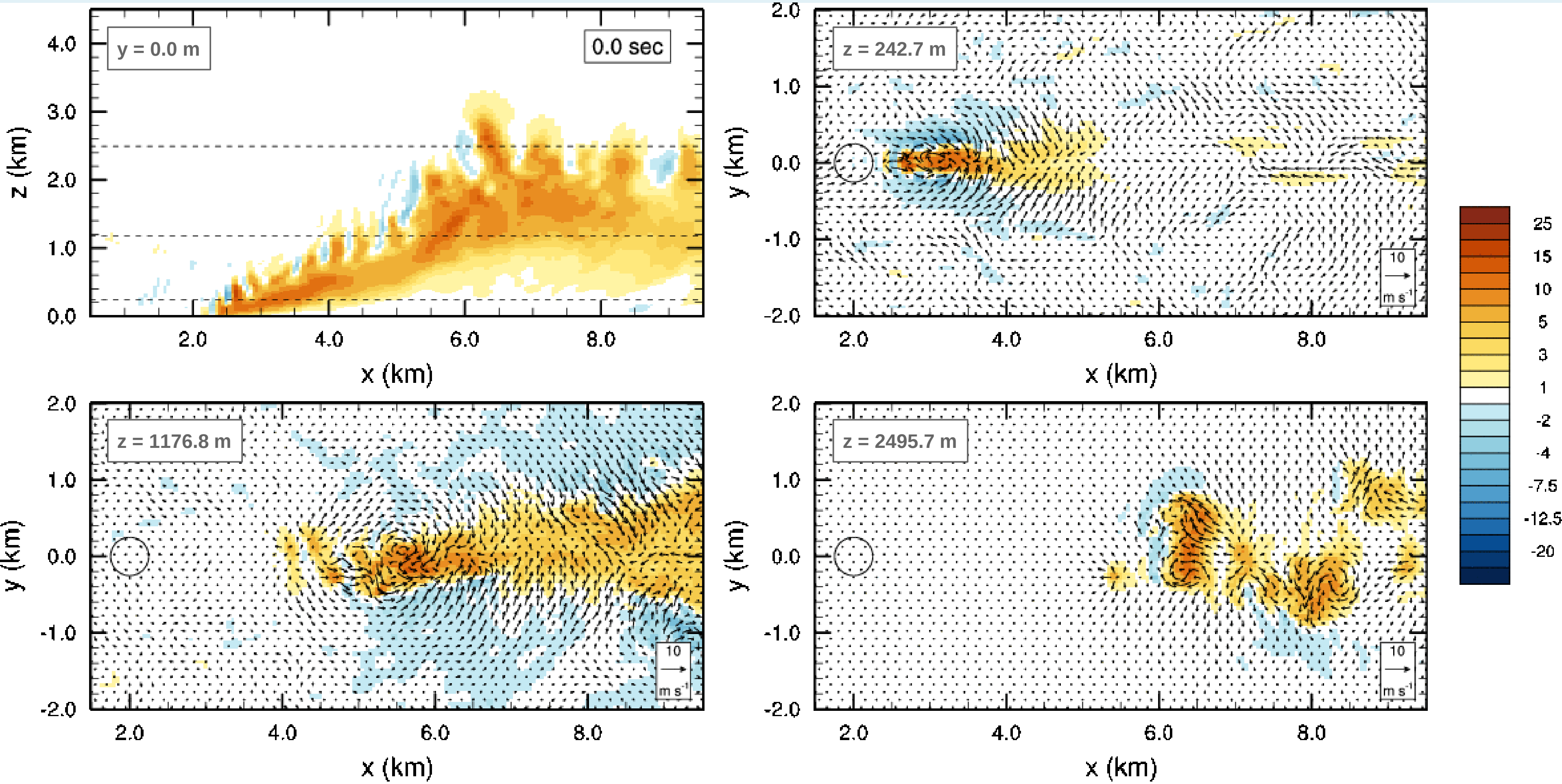
Plume dynamics – 15 m s^{-1} wind



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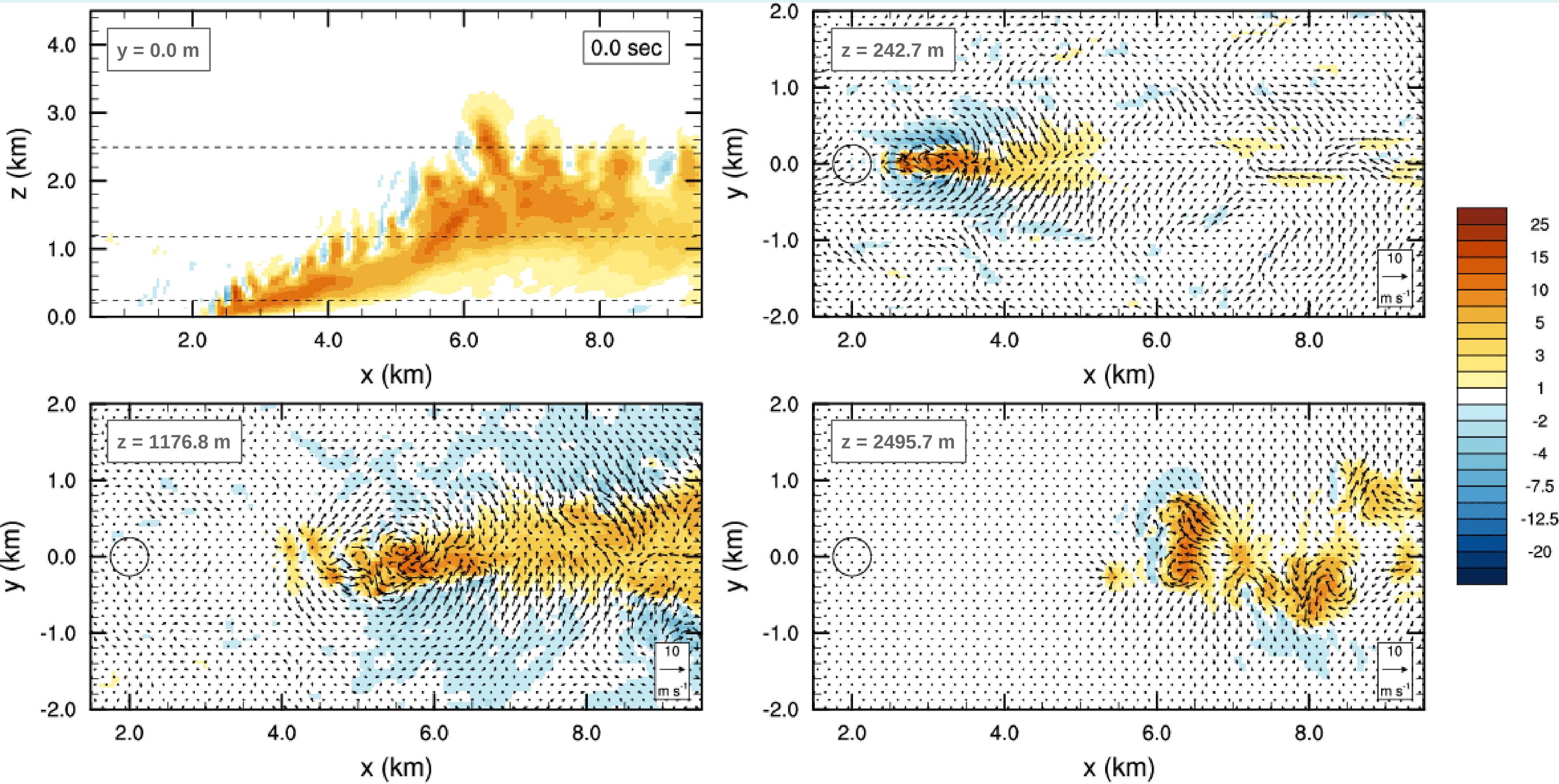

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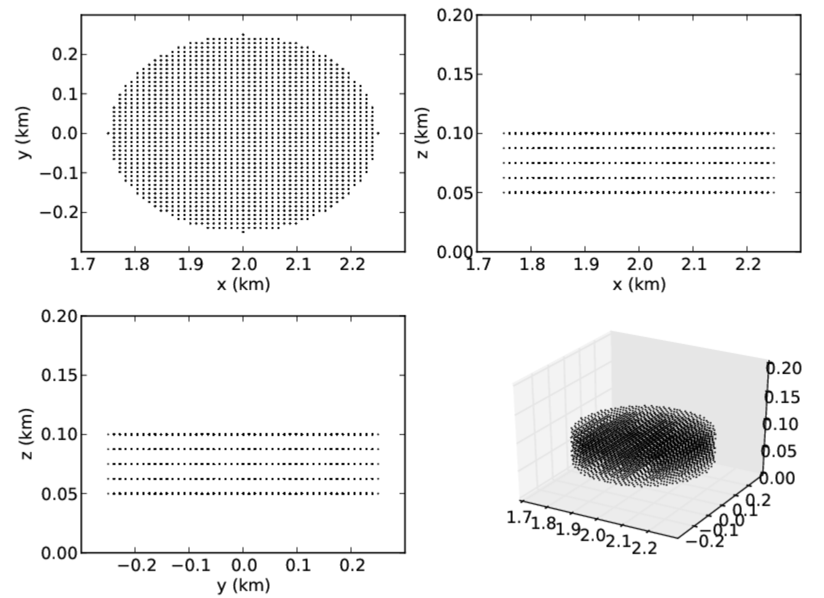
Particle transport calculations

- Three-dimensional velocity fields from the LEM are used to drive a simple Lagrangian particle-transport model
- Particles are initialised near the base of the plume and advected by the velocity field plus a constant fall velocity of $6.0\ m\ s^{-1}$
- Particles are released in a cylindrical "blob" of radius 250 m, located between z = 50 and z = 100 m.
- 8265 particles released every 5 s for 15 minutes, resulting in almost 1.5 million particles being tracked per plume

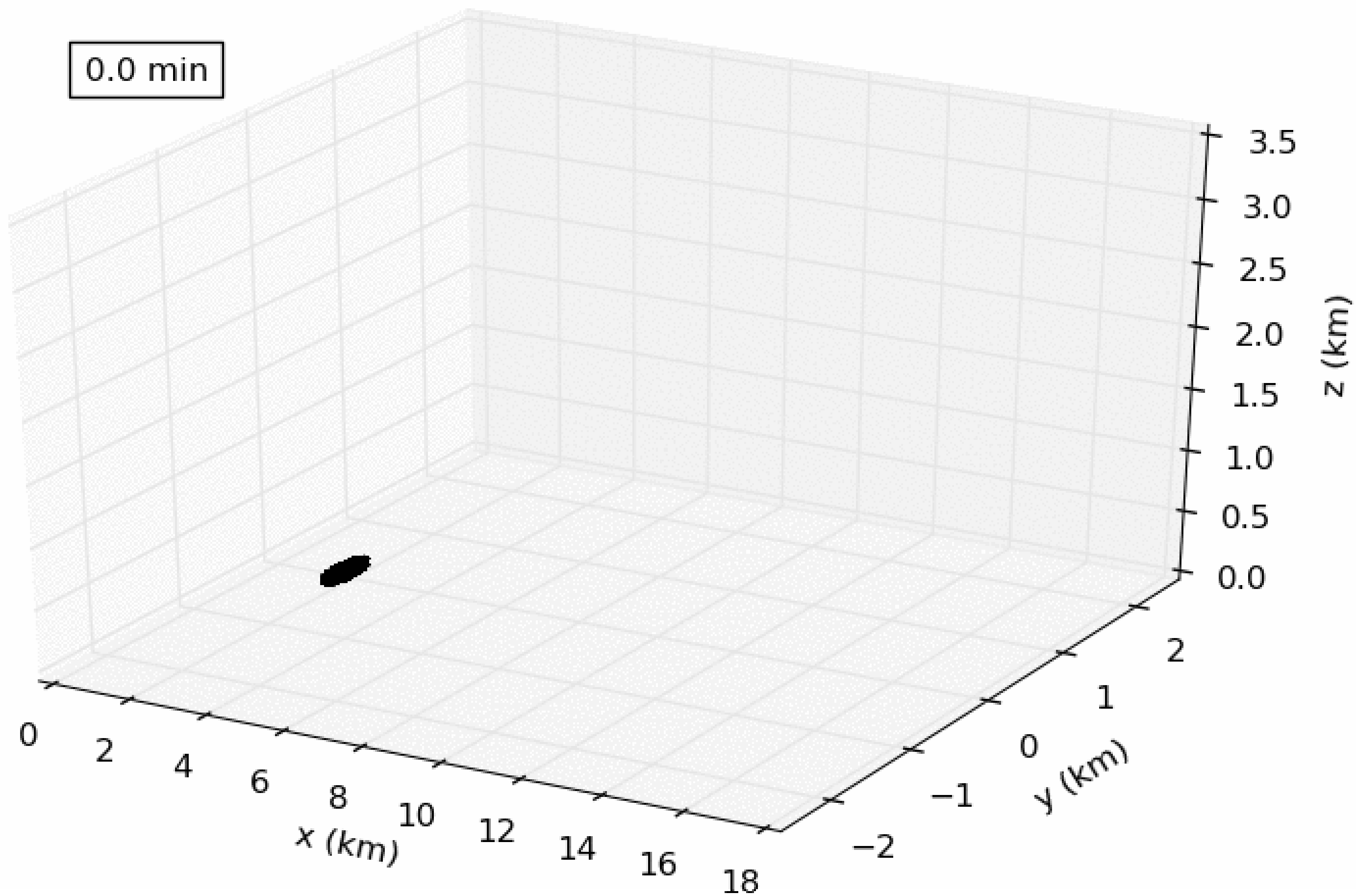


- Particle positions integrated forwards until they land

Firebrand transport – 5 m s^{-1} wind

8265 particles released every 5 s for 15 min = 1,487,700 total

Only every 100th particle is shown here



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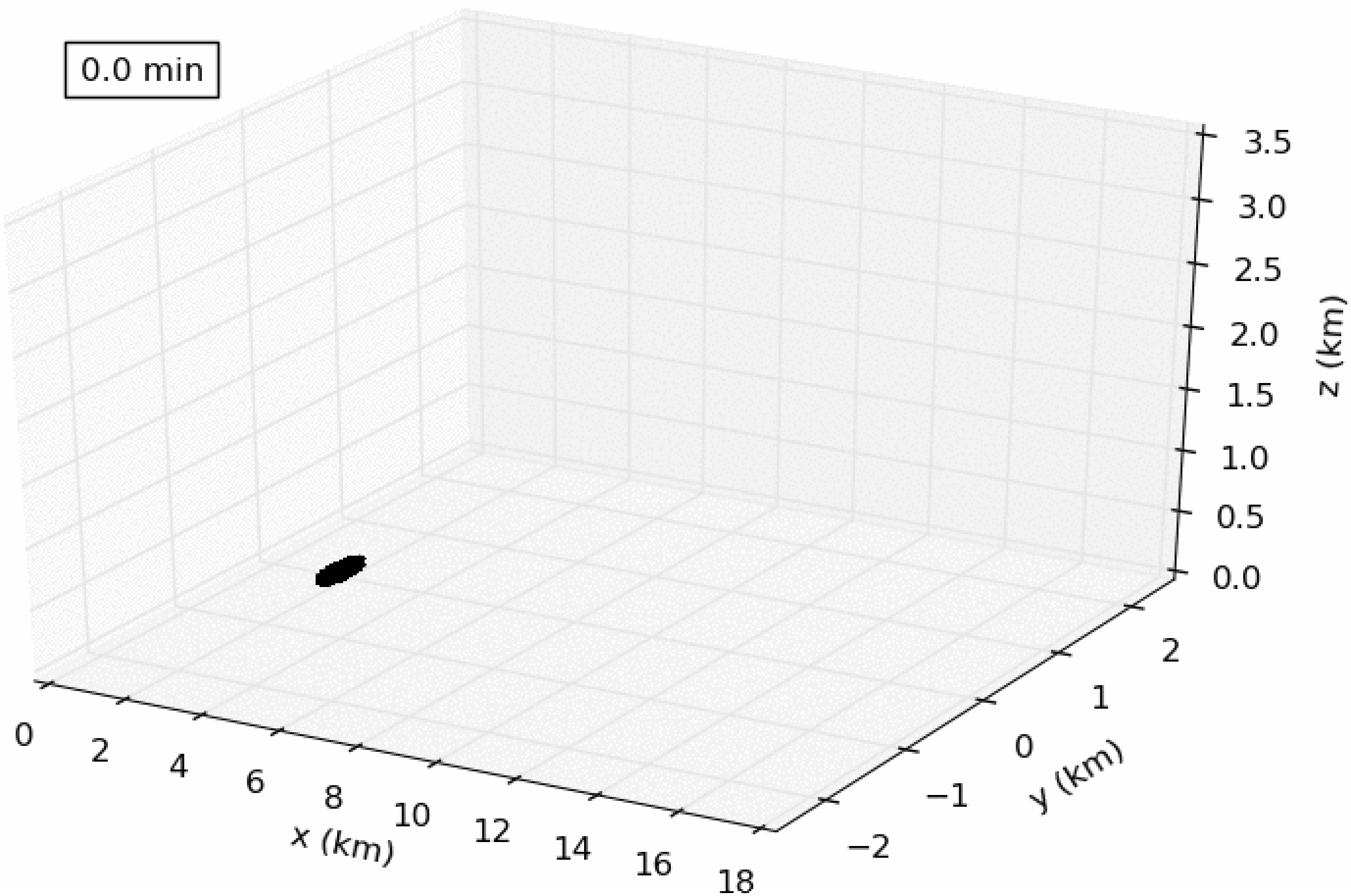
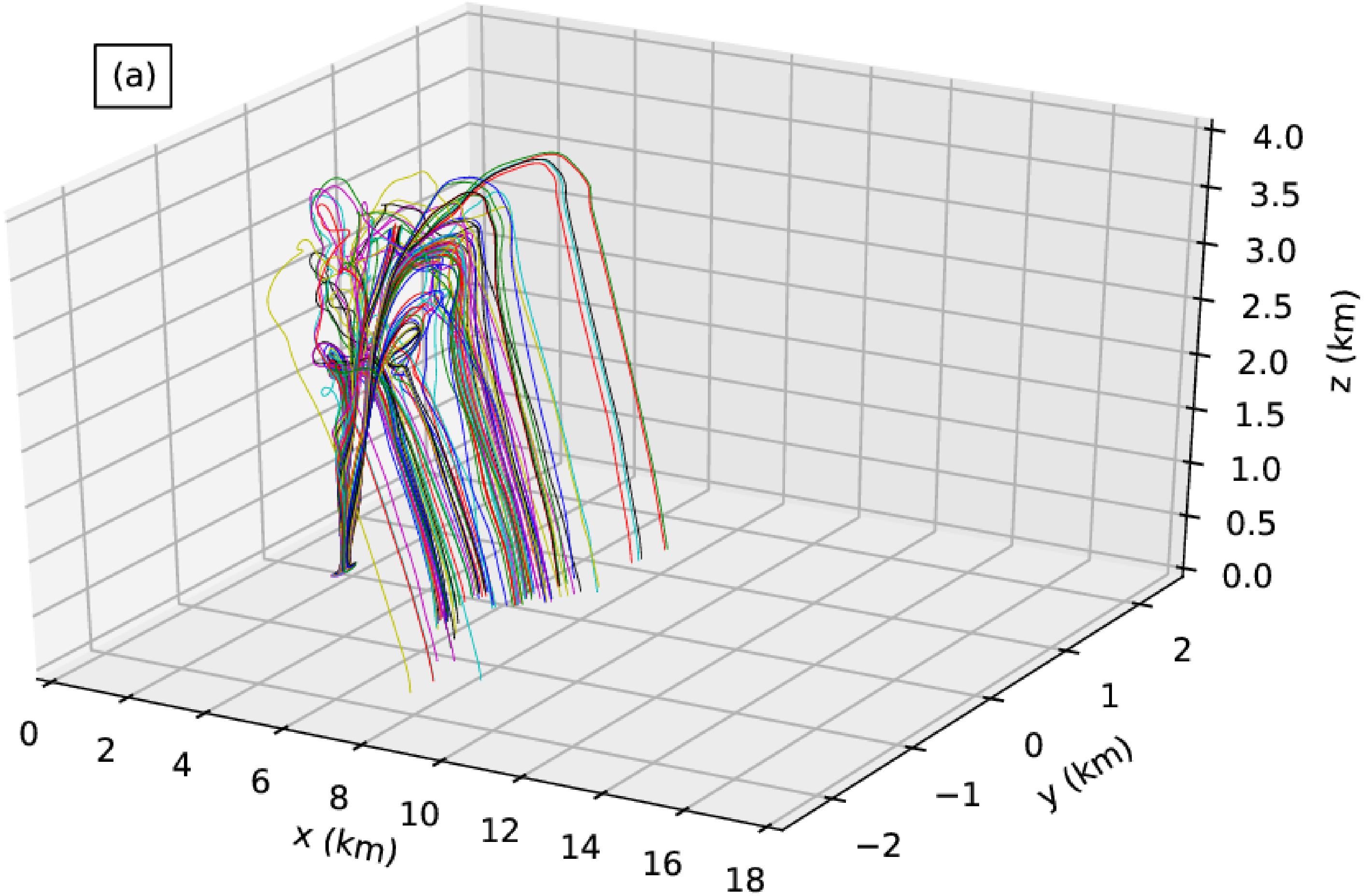
471,004 (31.7 %) travel > 1 km



100 random trajectories – 5 m s^{-1} wind



Firebrand transport – 15 m s^{-1} wind

8265 particles released every 5 s for 15 min = 1,487,700 total

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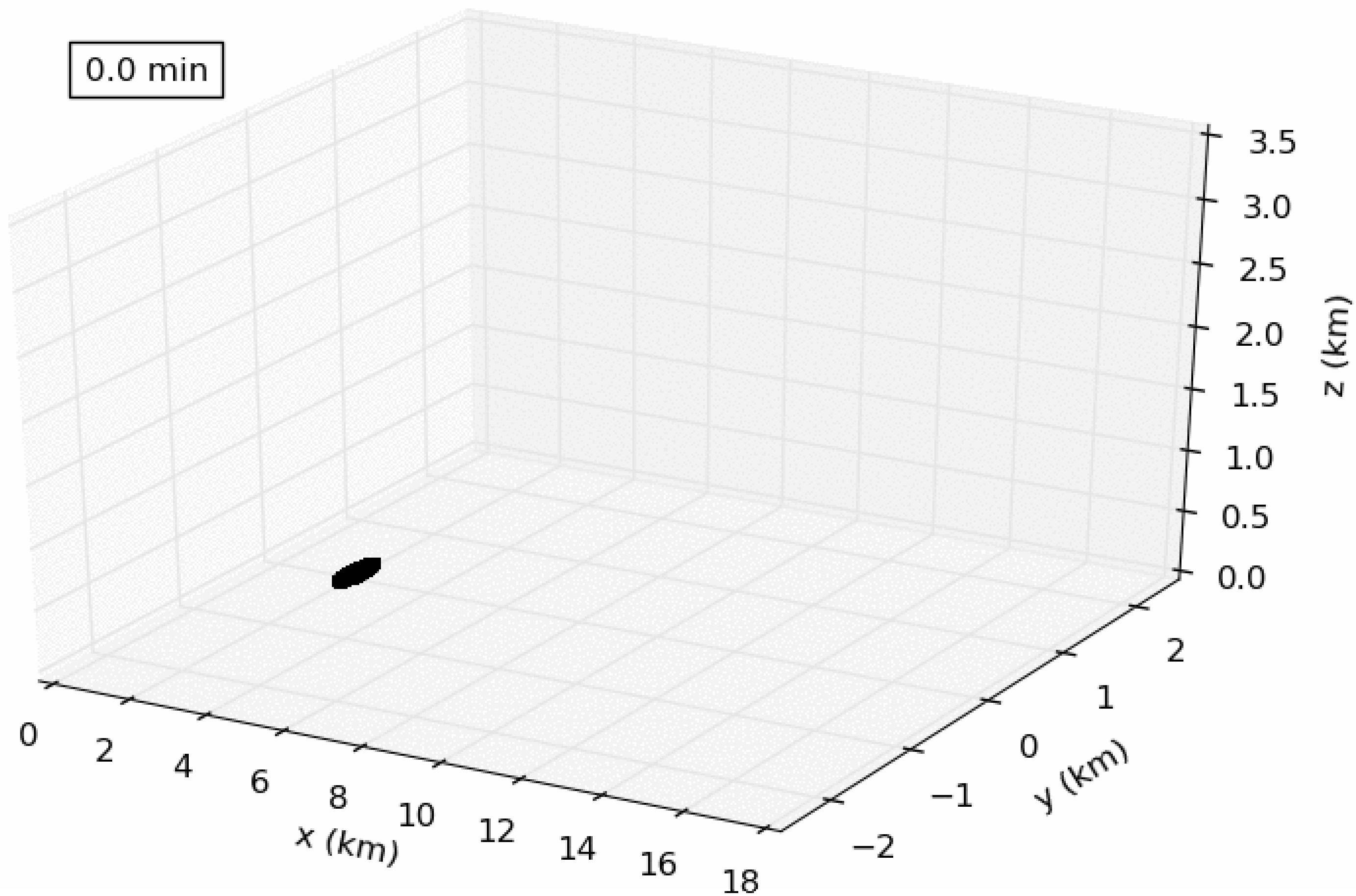
478,058 (32.1 %) travel > 1 km



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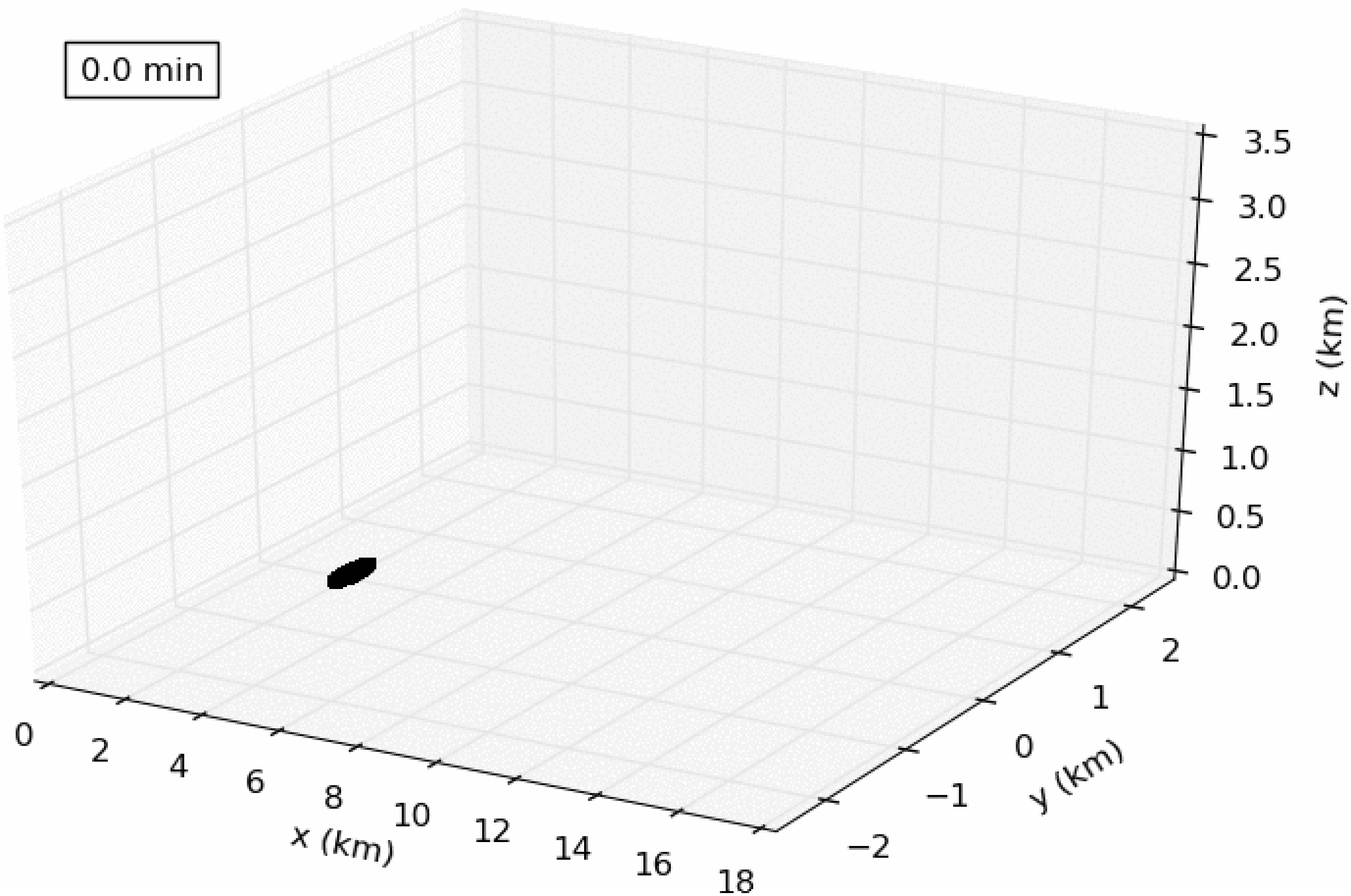

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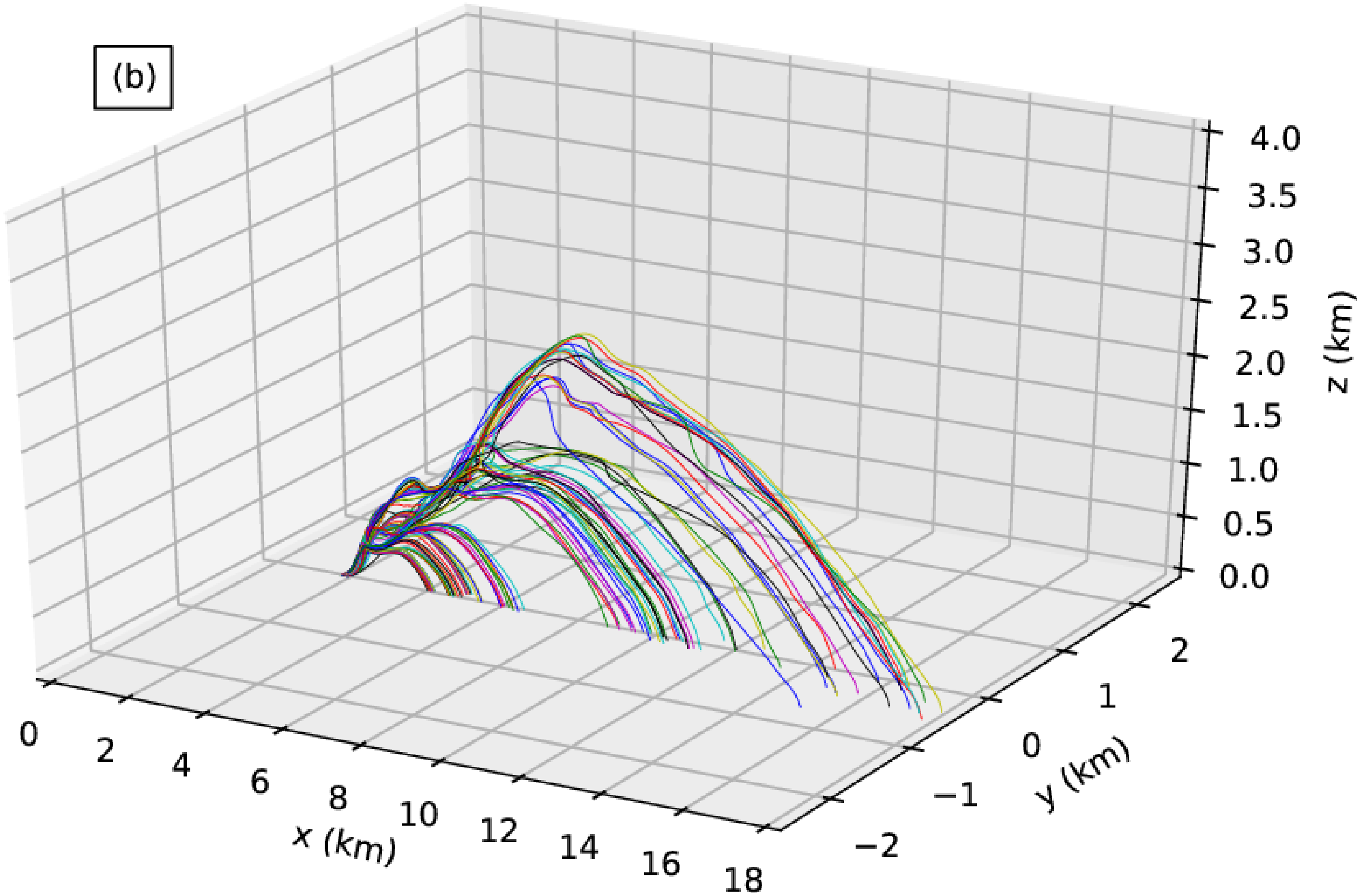

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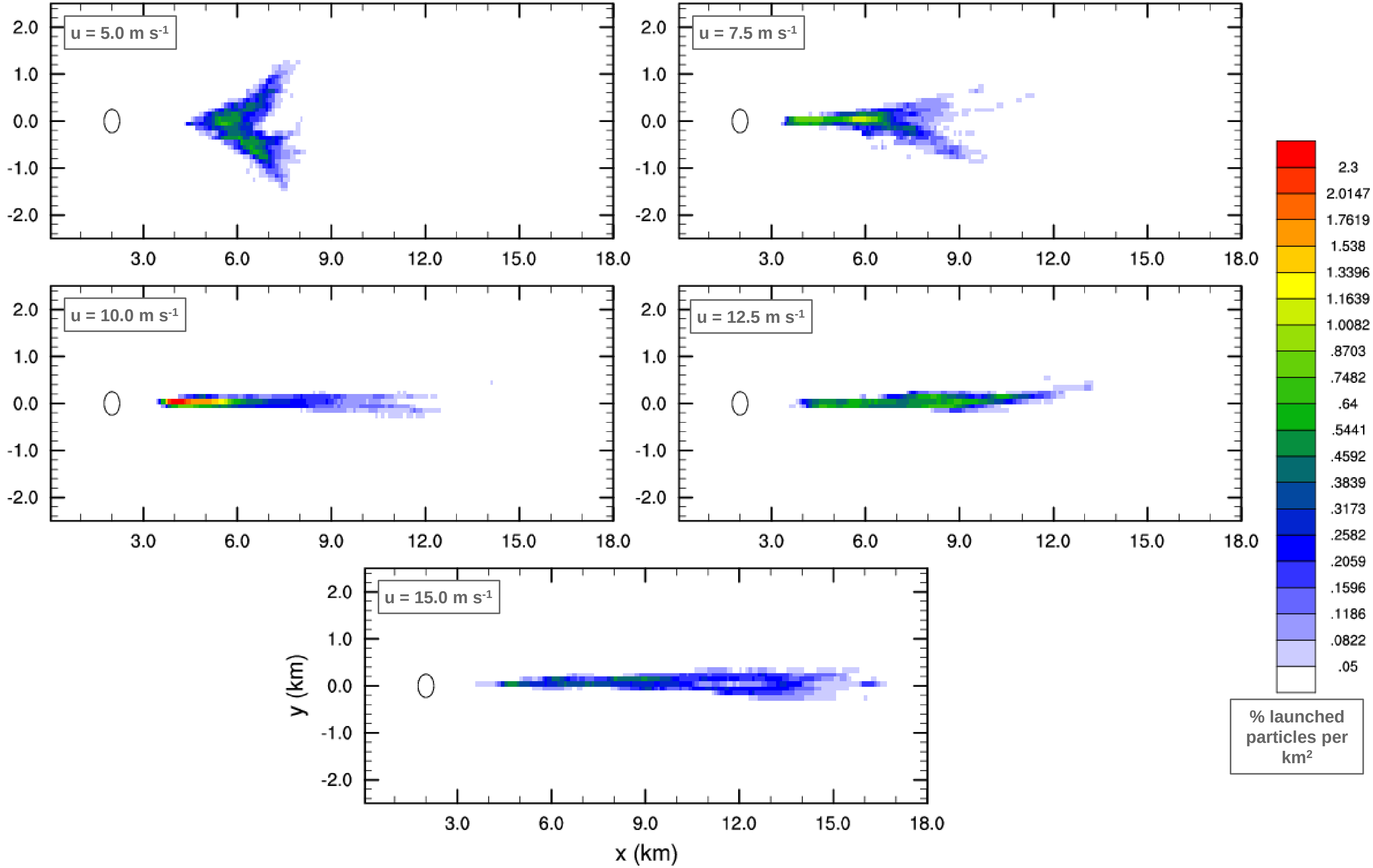
Two-dimensional landing distributions



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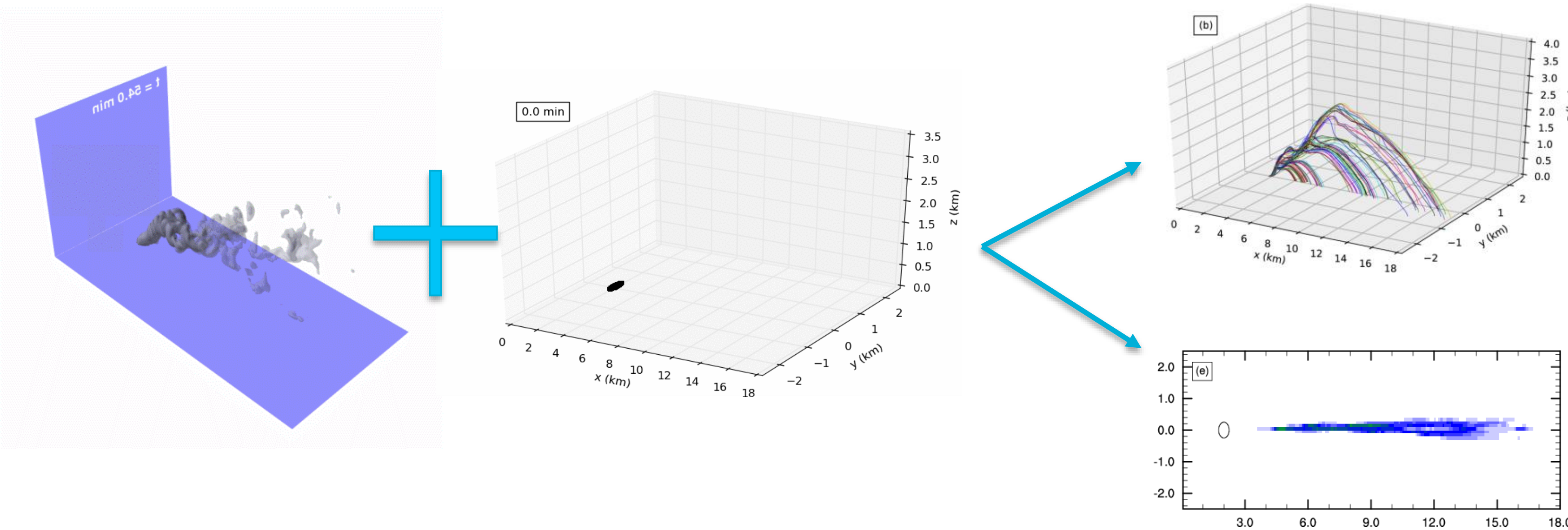
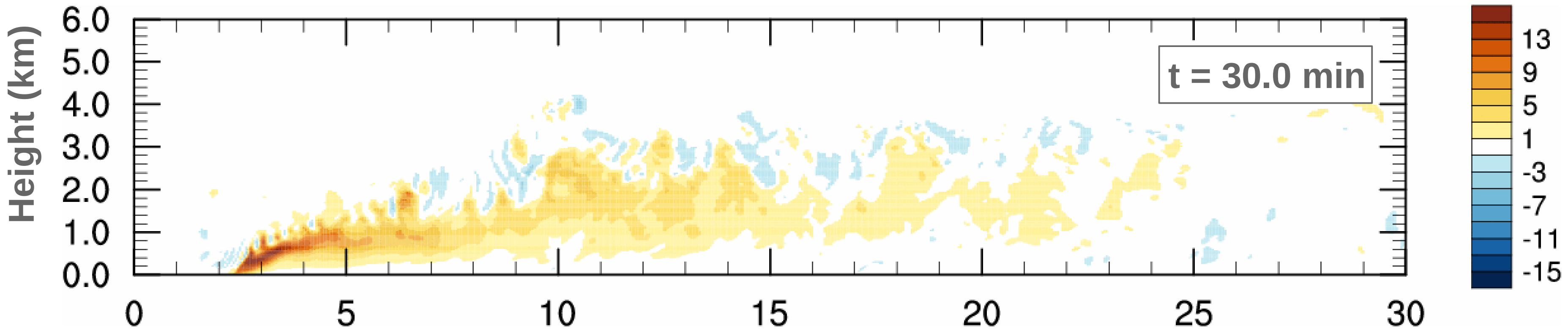
Recap…



How does the ***turbulent*** component of the plume dynamics affect ember transport…?

Steady-state plume calculations



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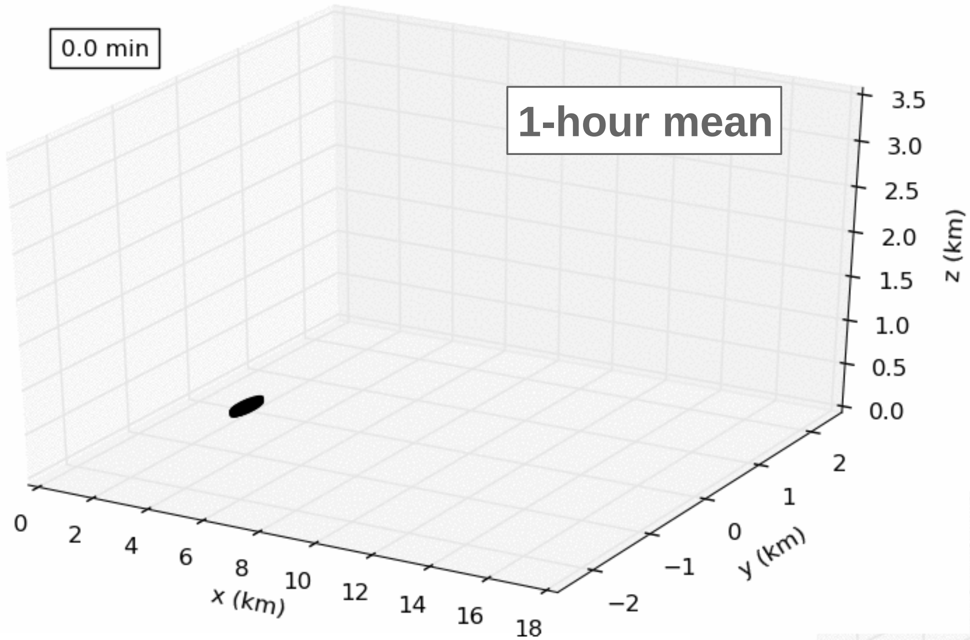
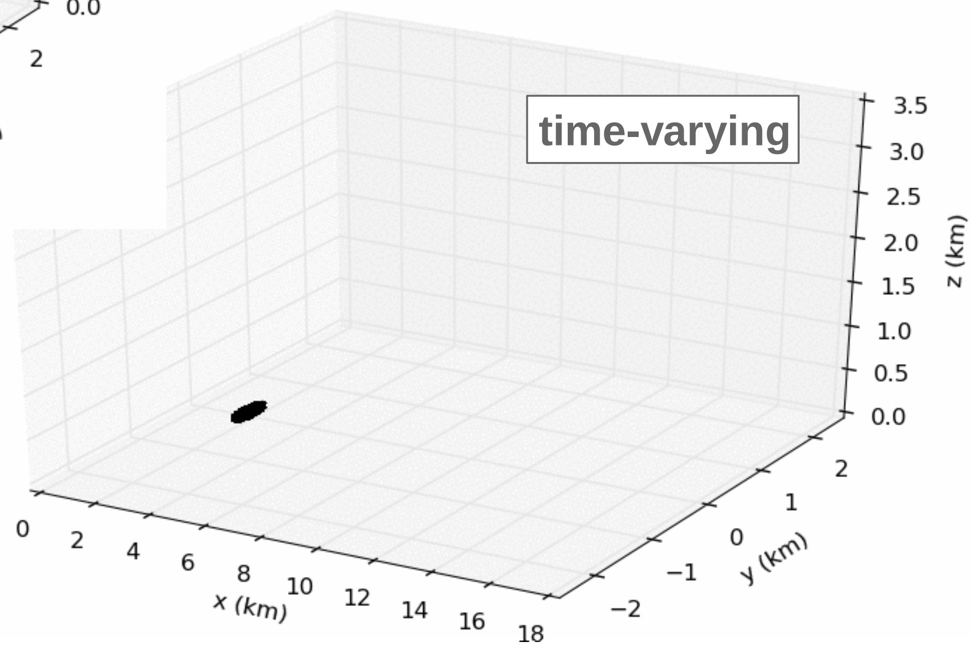
Firebrand transport – 5 m s^{-1} wind





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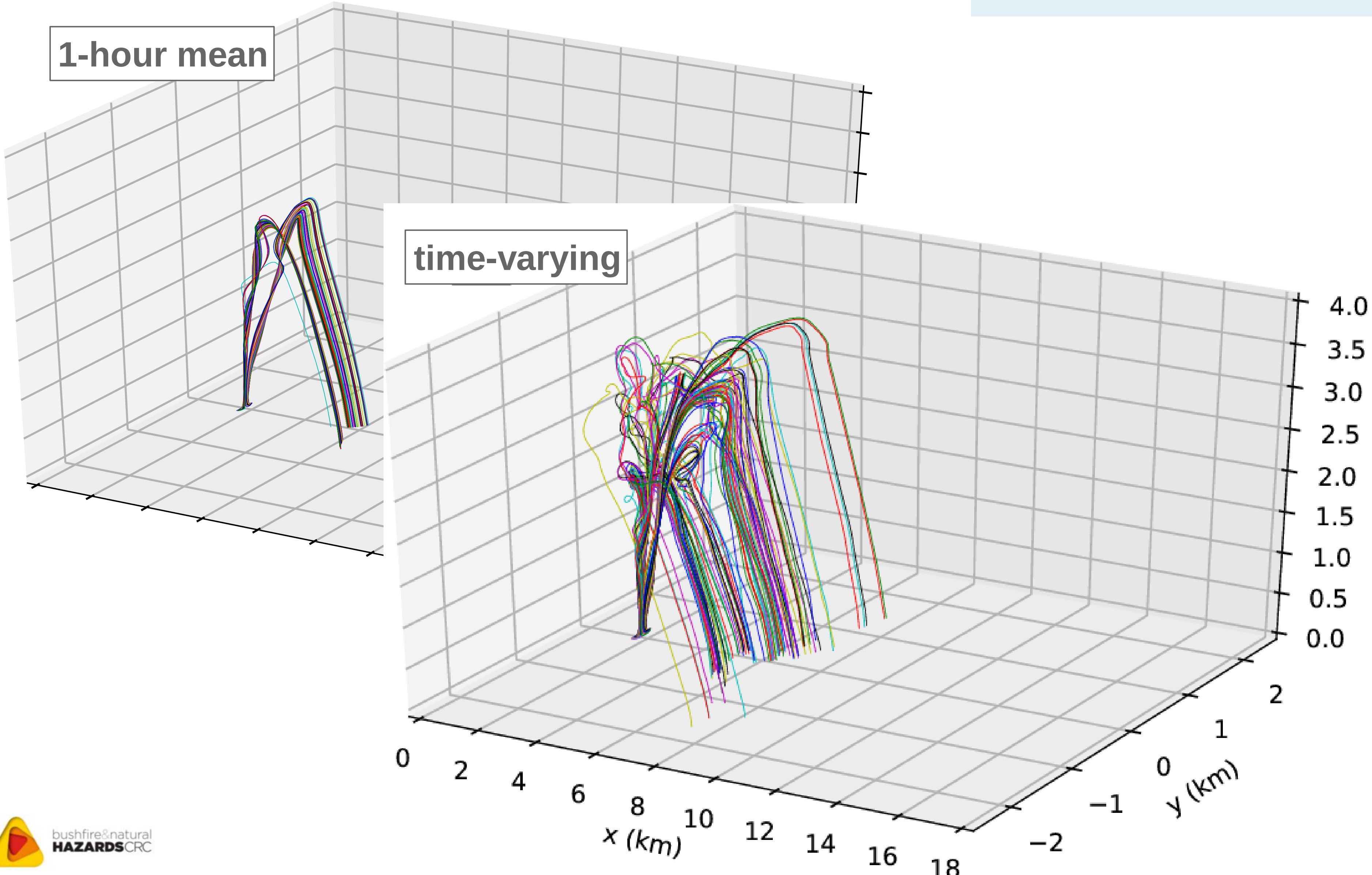
Mean vs time-varying plume



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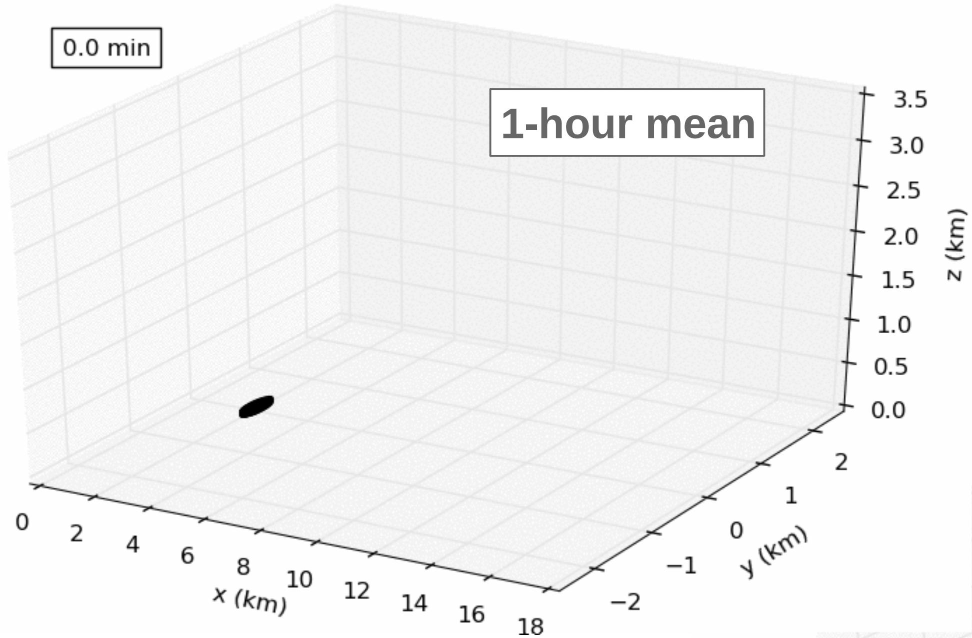
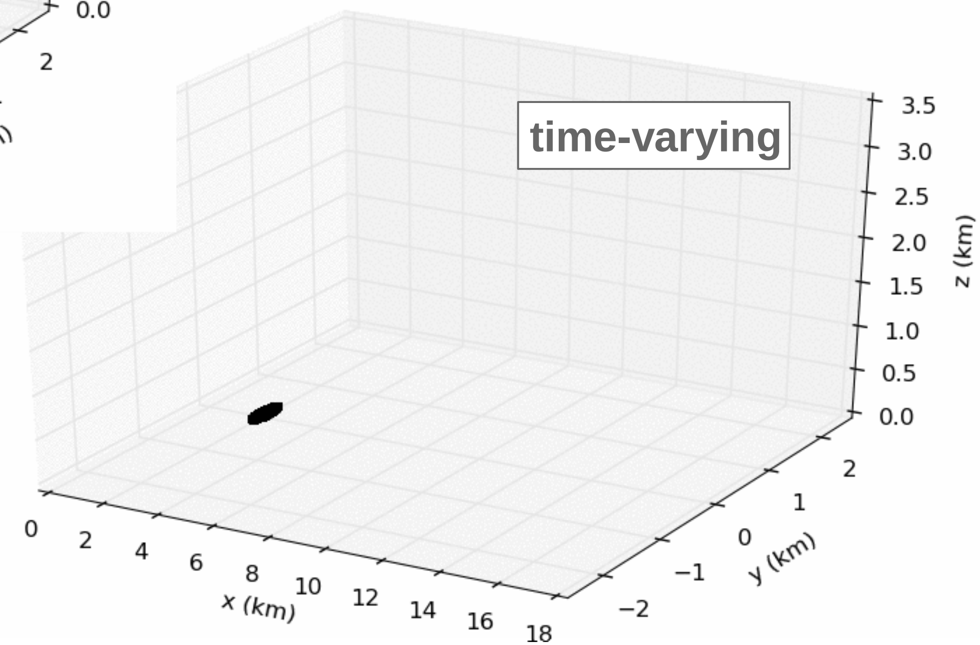
Firebrand transport – 15 m s^{-1} wind





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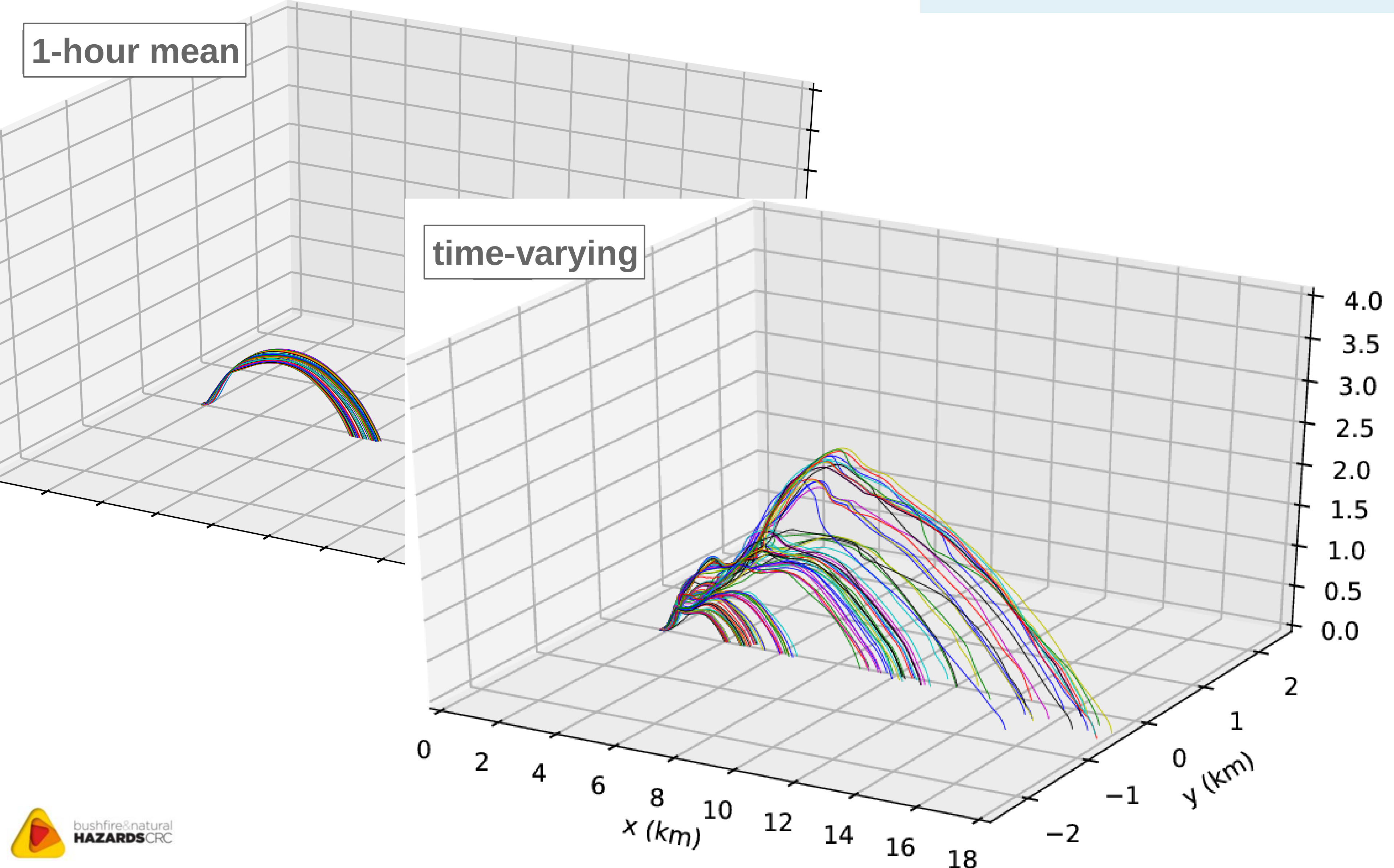
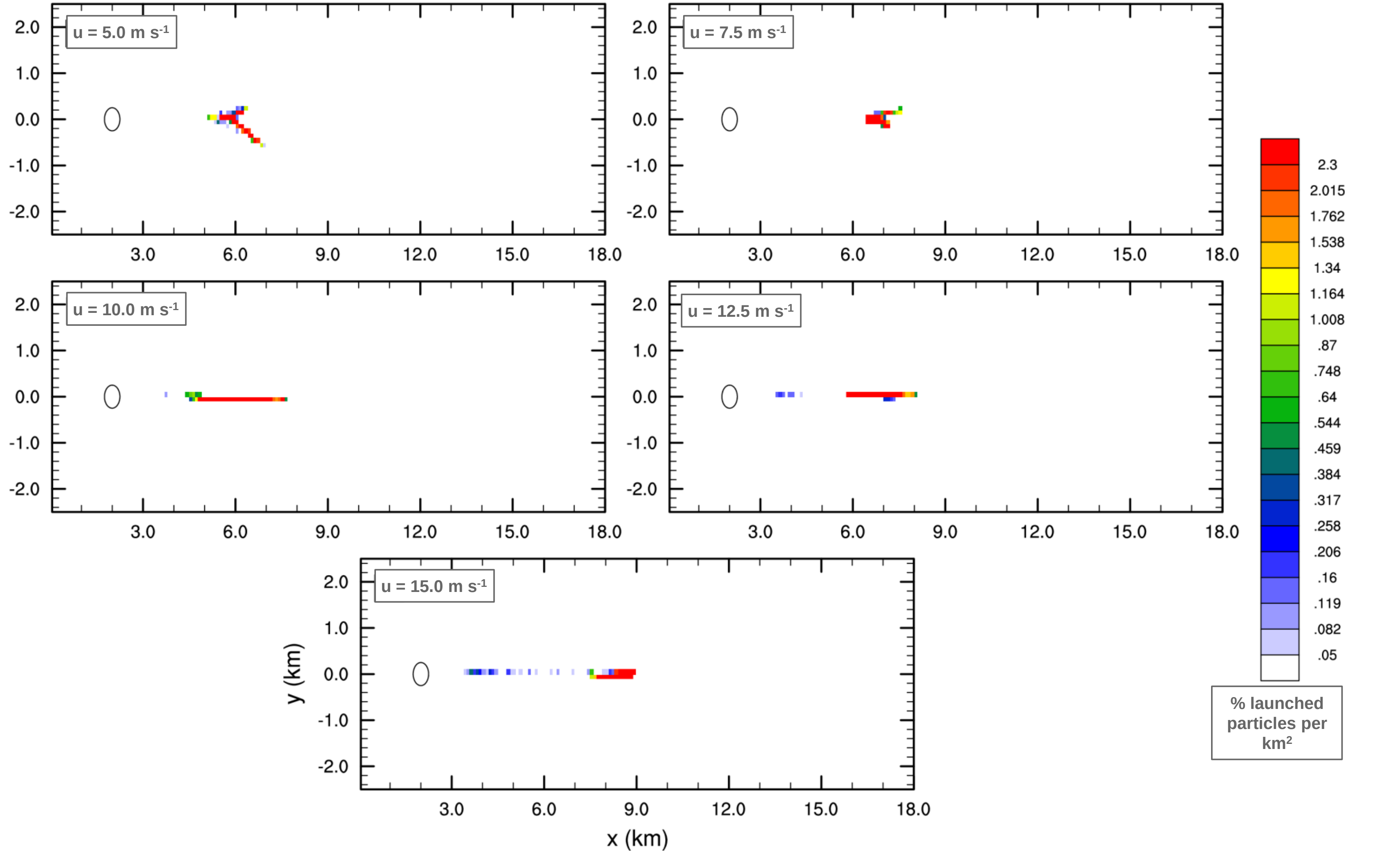


Two-dimensional landing distributions



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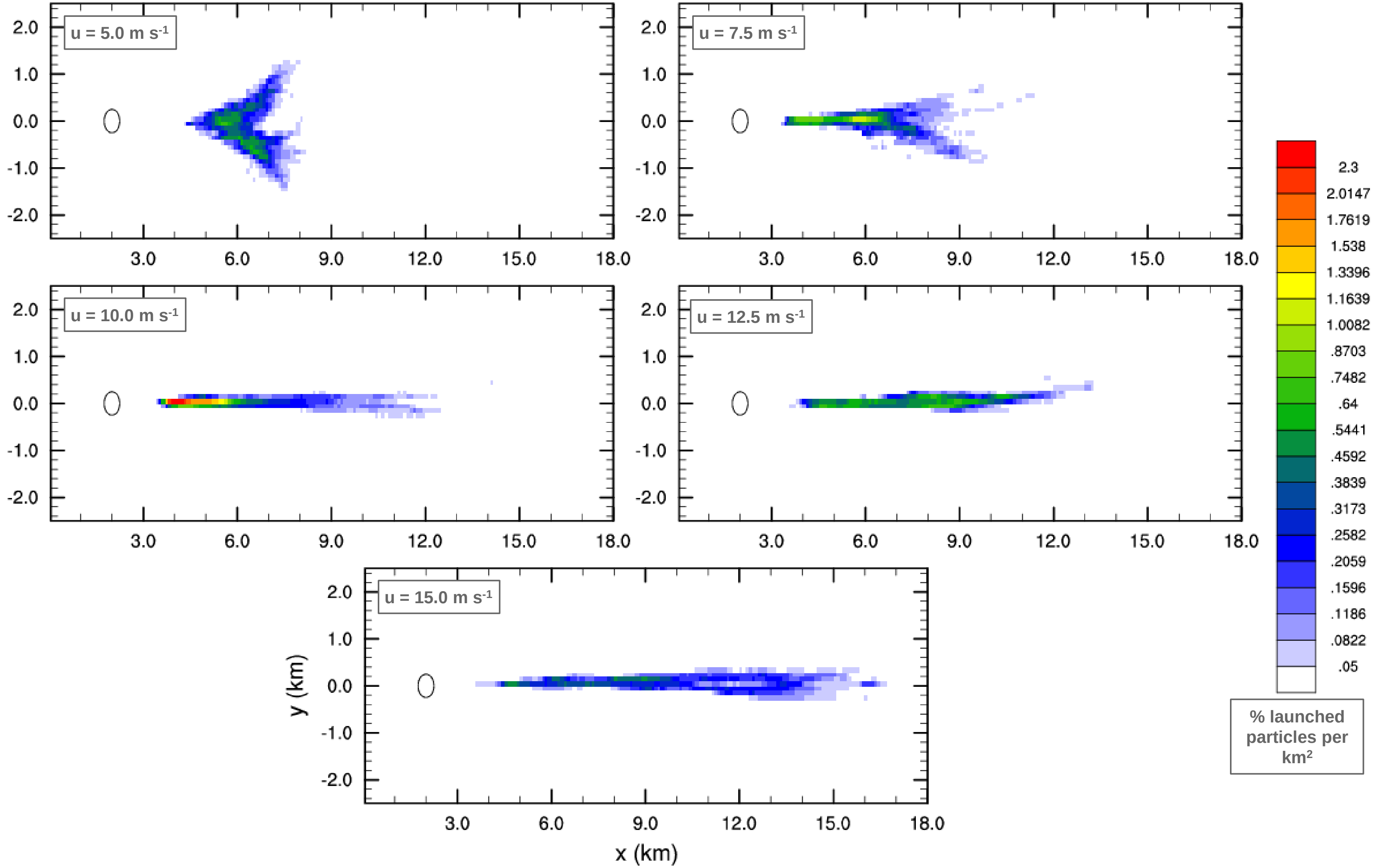
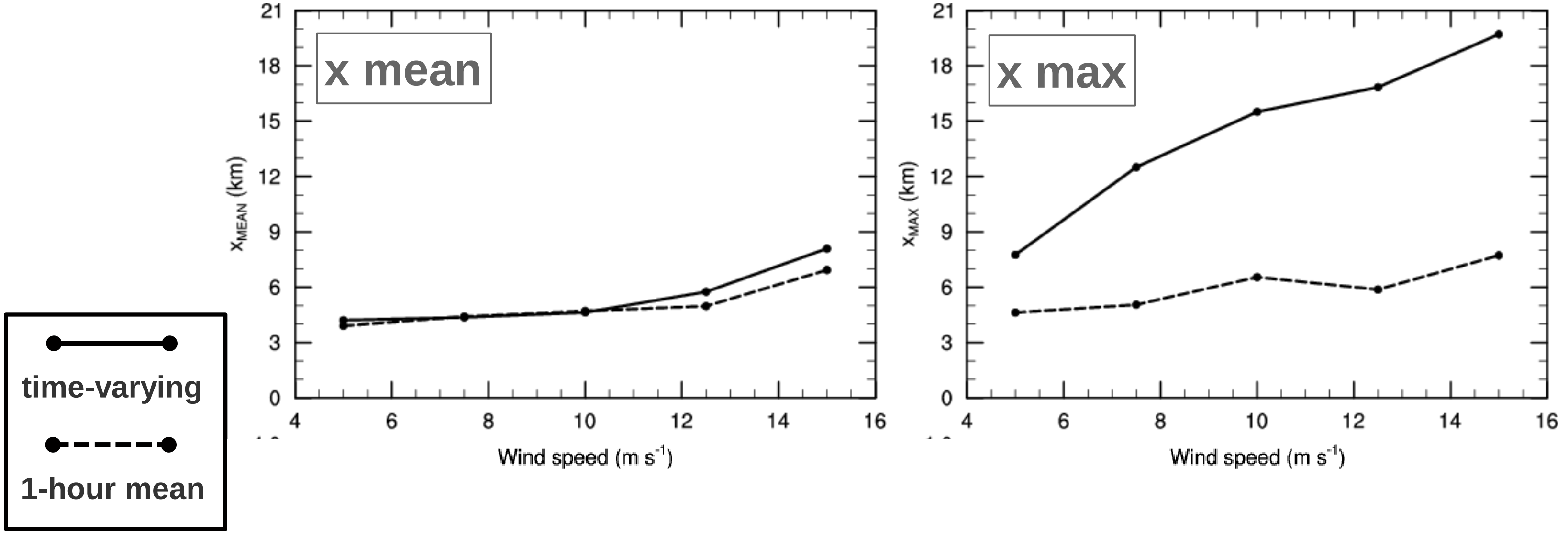


Turbulent / non-turbulent statistics



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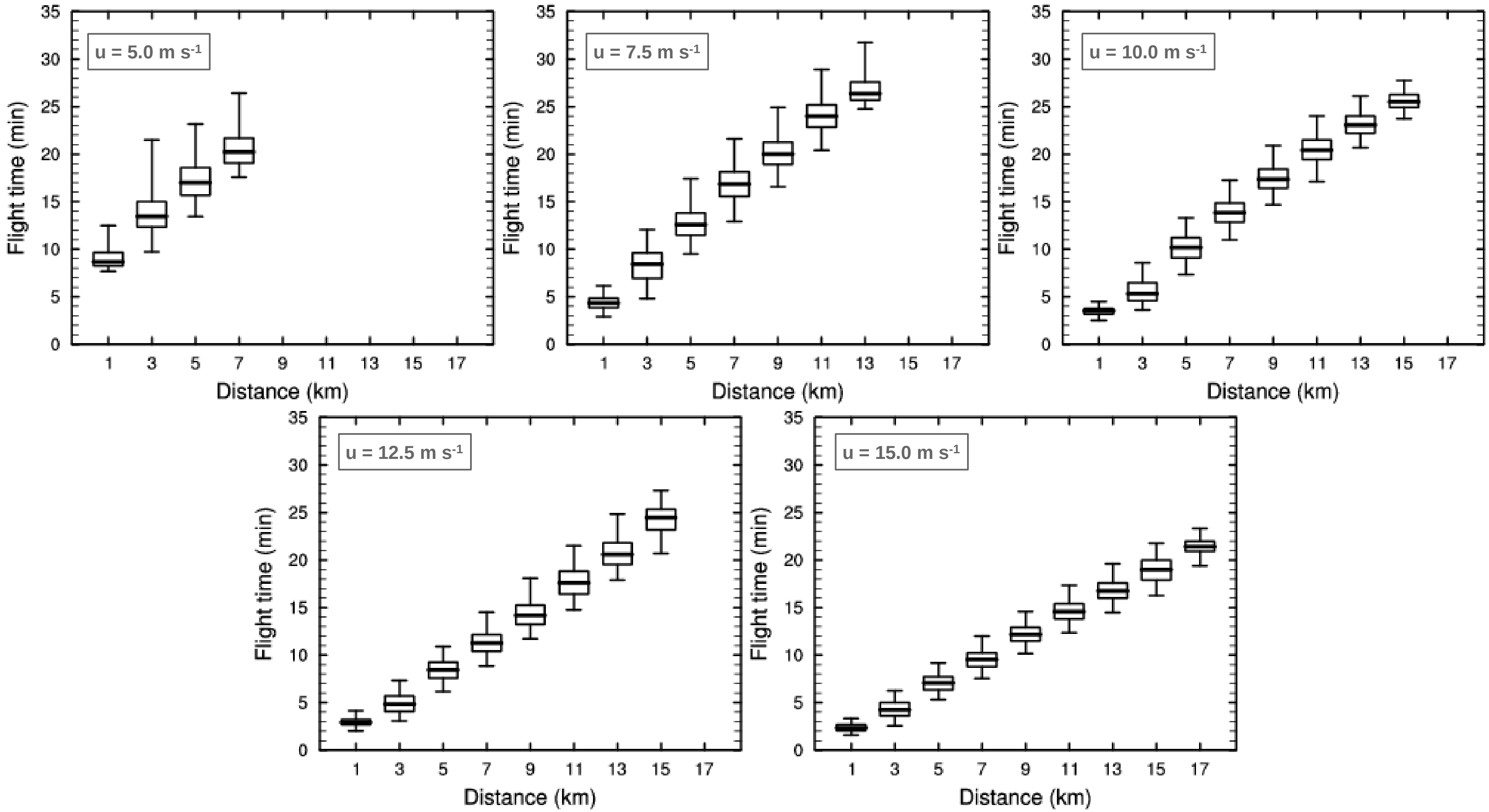
Ember flight time



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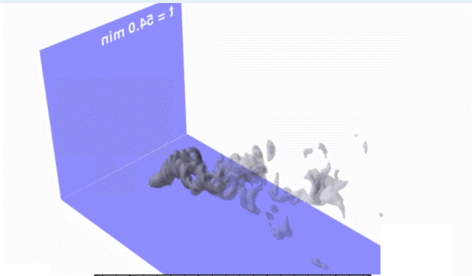
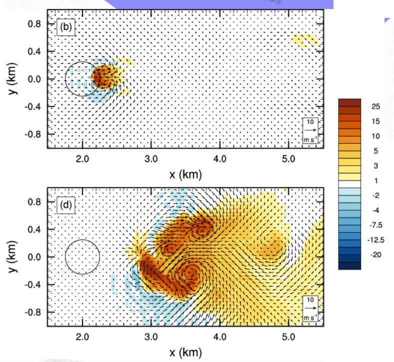
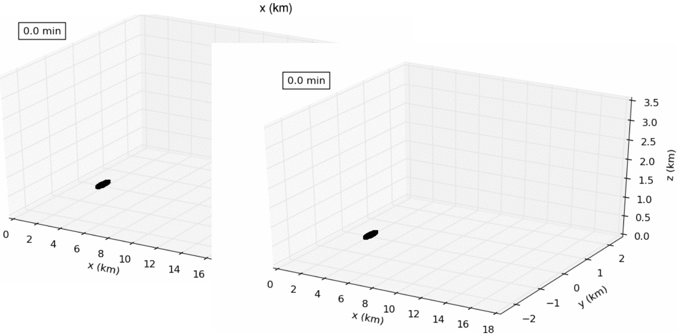
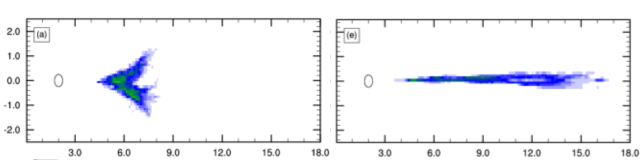
Summary









- Large-eddy simulations of bushfire plumes have been combined with ember trajectory calculations
- Trajectories heavily dependent on plume structure
  - Weak winds -> plume vortices -> lateral spread
  - Strong winds -> turbulent plume -> longitudinal spread
- Two-dimensional landing-position distributions constructed
- In-plume turbulence causes spread in landing-position distribution
- **In-plume turbulence can increase maximum spotting distance by a factor of more than two**
- Potential for spotting parameterization development

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