Large-eddy simulations of pyro-convection and its sensitivity to environmental conditions

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• Pyro-convection is responsible for the **lofting** of embers downwind of fires
  
  • *Unpredictable* and *accelerated* fire spread

• With a sufficient source of moisture, *moist* pyro-convection (Cu/Cb) may occur
  
  • Enhanced *plume updrafts*
  • Variable and intense *near-surface winds*
  • PyroCb *lightning*
  • (Stratospheric aerosol injection)

• The importance of the environment and moisture source remains unclear:
  
  • Cunningham & Reeder (2009) – moisture from fire required
  • Trentmann et al. (2006) – environmental moisture is sufficient

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*How do changes in the environment modify the behavior of pyro-convection?*
UK Met Office Large Eddy Model (LEM)

- Think of as a **simplified** numerical weather prediction model, but run at a **very-high resolution** (here grid spacing = 50 m)
  - Able to explicitly resolve plumes, entrainment/detrainment of air

- Historically used for more traditional high-resolution atmospheric applications:
  - Boundary-layer turbulence
  - Clouds and convection

  Khairoutdinov and Randall (2006) - Simulated explicitly resolved clouds:

- Recently the ability of the Met Office LEM to model both observed and theoretical plumes has been confirmed
Plume modelling methodology

- Spin up convective boundary layer under atmospheric profiles representative of high fire danger days
  - Initialise model with horizontally homogeneous potential temperature and moisture profiles (zero wind today)
  - Apply random perturbations (± 0.2 K) to potential temperature field
  - Impose uniform 50 W m\(^{-2}\) sensible heat flux
  - 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 (radius = 250 m)
  - No moisture source
  - No feedback of atmosphere onto fire behaviour
  - No surface spread
  - Allows us to isolate the way plumes respond to different environments
Modelling strategy

- Five different atmospheres
  - Identical temperature profiles
  - 4-km deep, warm boundary layer
  - Boundary-layer specific humidity $q_{bl} = 2.0, 2.5, 3.0, 3.5$ and 4.0 g kg$^{-1}$

- Four fire intensities
  - $Q = 5, 10, 20, 30$ kW m$^{-2}$
  - Smoothly increased for 5 min
  - Held at peak for 60 min
  - Smoothly decreased for 5 min

- 20 simulations in total
Q = 30 kW m$^{-2}$, $q_{bl} = 2.0$ g kg$^{-1}$
\[ Q = 30 \text{ kW m}^{-2}, \quad q_{bl} = 2.0 \text{ g kg}^{-1} \]
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\((Q, q_{bl})\) parameter space
((Q, q_{bl}) parameter space

[Diagram showing a grid with axes labeled Q and q_{bl}, with a color scale indicating values from 0.1 to 1.75 g kg^{-1}].
(Q , q_{bl}) parameter space
Formation of moist pyro-convection

- Pyrocumulus form in most-intense fires and most-moist atmospheres
- Pyrocumulus is able to form without a source of moisture from the fire
- Pyrocumulus formation leads to updraft resurgence at altitude
- More intense fires lead to taller and broader pyrocumulus
- Increasing environmental moisture reduces cloud-base height
- The most-intense pyro-convection generates evaporatively cooled downdrafts
Downdraft vertical cross-sections
Downdraft vertical cross-sections
Downdraft vertical cross-sections
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Downdraft vertical cross-sections

55.8 min

(m s$^{-1}$)

x (km)

z (km)

-4.0  -2.0   0.0   2.0   4.0
Gust-front evolution: 10-m wind speed
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- 76.8 min
Gust-front point time-series

![Graph showing a time-series of gust-front speeds over time. The x-axis represents time in minutes, ranging from 0 to 100. The y-axis represents speed in meters per second, ranging from 0 to 10. The graph displays a series of peaks and troughs, indicating fluctuations in wind speed.](image-url)
Formation of downdrafts

• If the fire is intense enough and the atmosphere moist enough, substantial precipitation occurs

• As the precipitation falls through warmer, drier air it evaporates and generates negatively buoyant air

• These evaporatively cooled downdrafts have a complex structure and interact with the main plume updraft

• Upon impacting upon the surface, the downdrafts spread out as a series of gust fronts with strong, highly variable winds for > 20 minutes
• Intense fires in moist atmospheres produce pyrocumulus clouds.
• This leads to enhanced updrafts, both in intensity and in altitude
• The most-intense pyro-convection generates evaporatively cooled downdrafts
• Downdrafts impact upon the surface as a series of complex, turbulent gust fronts
• Both the updrafts and the downdrafts have implications for fire spread
• Future work will quantify the relative importance of moisture from the fire and moisture from the environment