
# Wildfire Behavior and Smoke Research at UBC

## RESEARCH LEADING TO IMPROVEMENT IN OPERATIONAL SMOKE AND FIRE INDEX FORECASTING

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Interagency Meeting | February 12, 2020

## OVERVIEW

# UBC Wildfire and Smoke Research

- **Part I: Using a Large-Eddy Simulation Model to Understand Wildfire Plume Dynamics**
  - Model evaluation
  - Flow dynamics
  - Smoke injection height parameterization
- **Part II: Investigating Wildfire Smoke Behavior using Simplified Large-Eddy Simulations**
  - Idealized studies
  - Convergence zone and lateral flow
  - Fireline dimensions
- **Part III: Use of Field Observations for Model Validation of Wildland Fires: A Focus on Smoke Plume Rise**
  - Big picture: smoke modelling frameworks
  - Prescribed burns and experimental design

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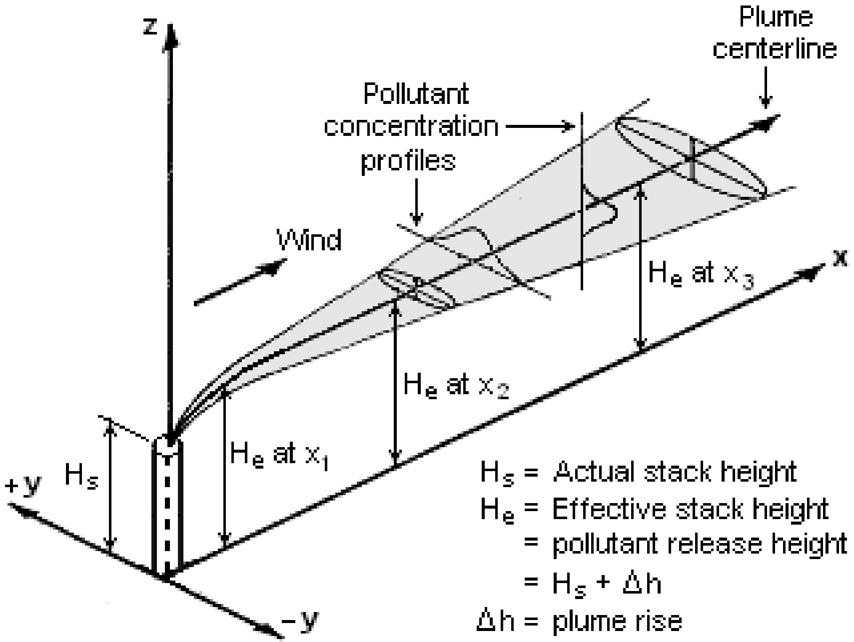
# Understanding smoke plume rise

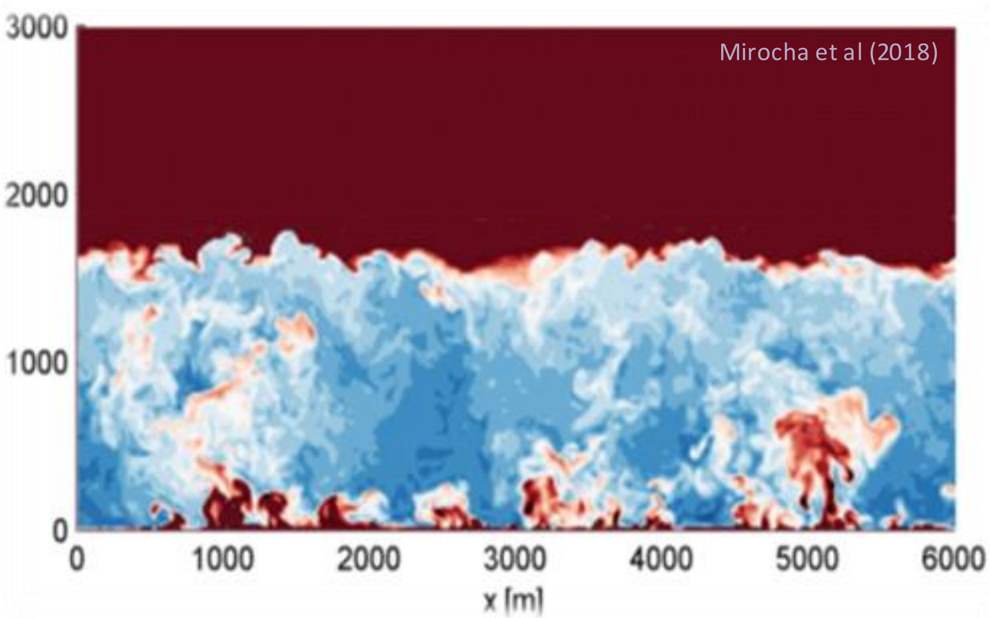
- plume rise: one of the largest sources of uncertainty in wildfire smoke emissions modelling
- traditional models (e.g. Gaussian/Briggs): suitable for smoke stacks, small point and area sources




- large fires modify the ambient environment
  **HOW?**

## APPROACH
# Using large-eddy simulations

- approach: use large eddy simulation (LES) model
  - WRF-SFIRE: atmosphere coupled to a semi-empirical fire model



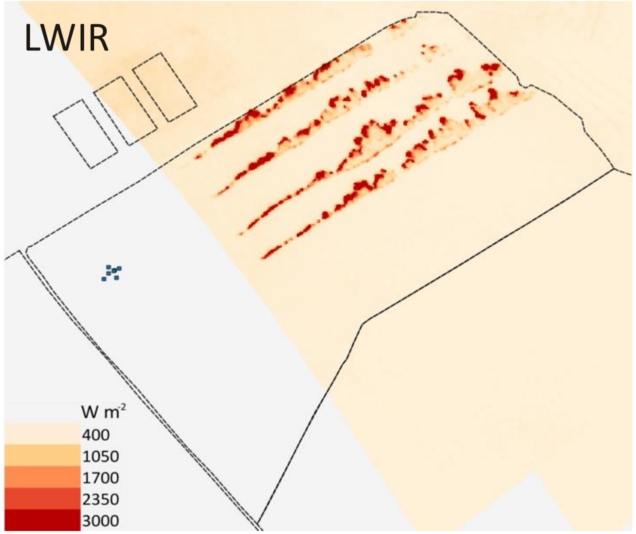

- end goal:

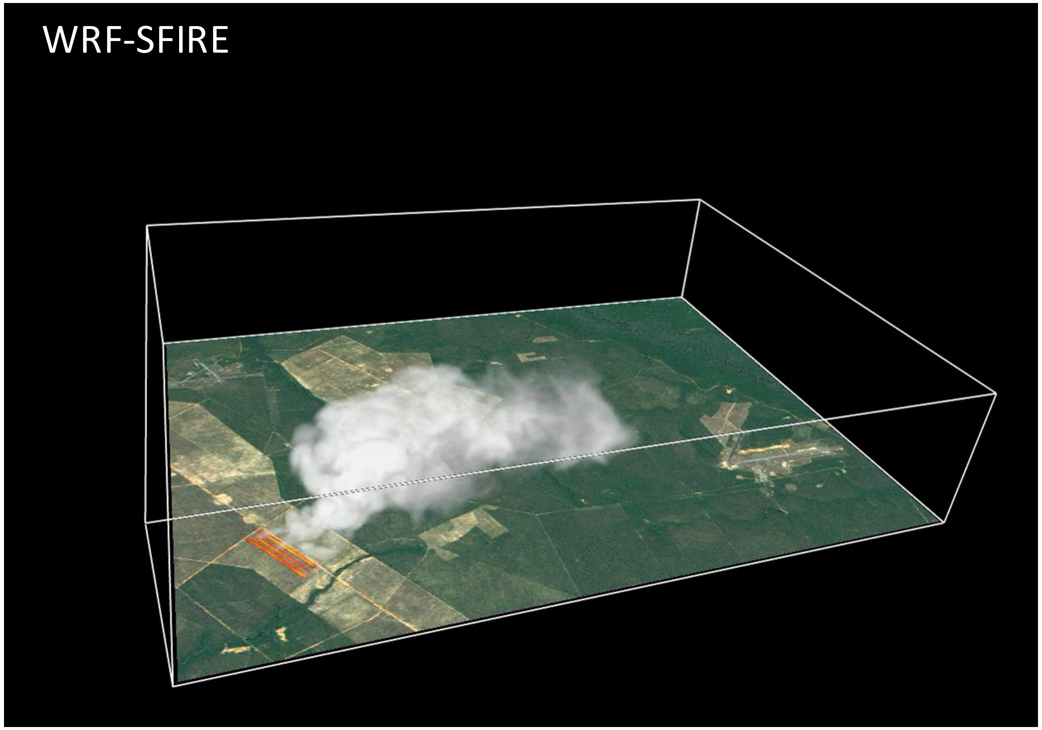
to develop a new simple parameterization of plume rise suitable for operational smoke forecasts

# MODEL EVALUATION

## RxCADRE 2012 campaign: burn design

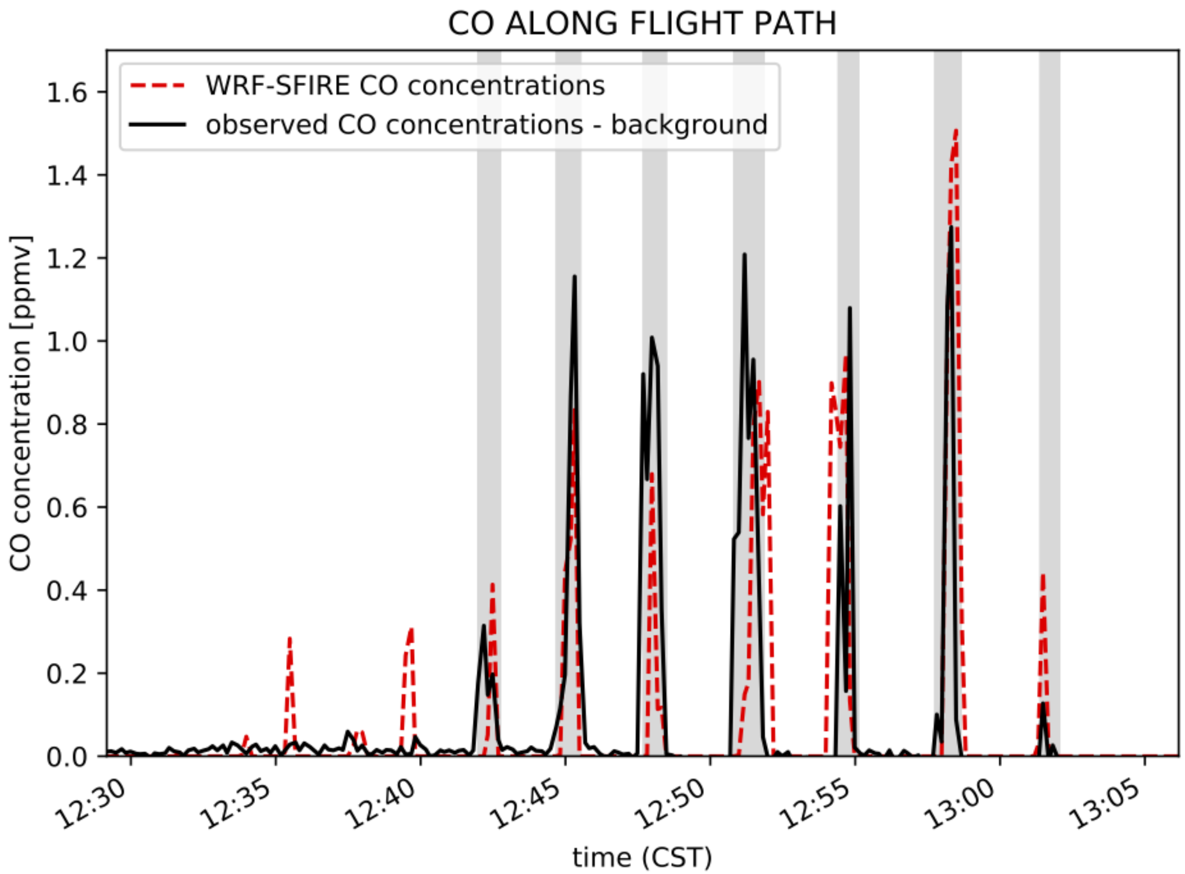
- Elgin Air Force Base (Florida, US) – November 10, 2012



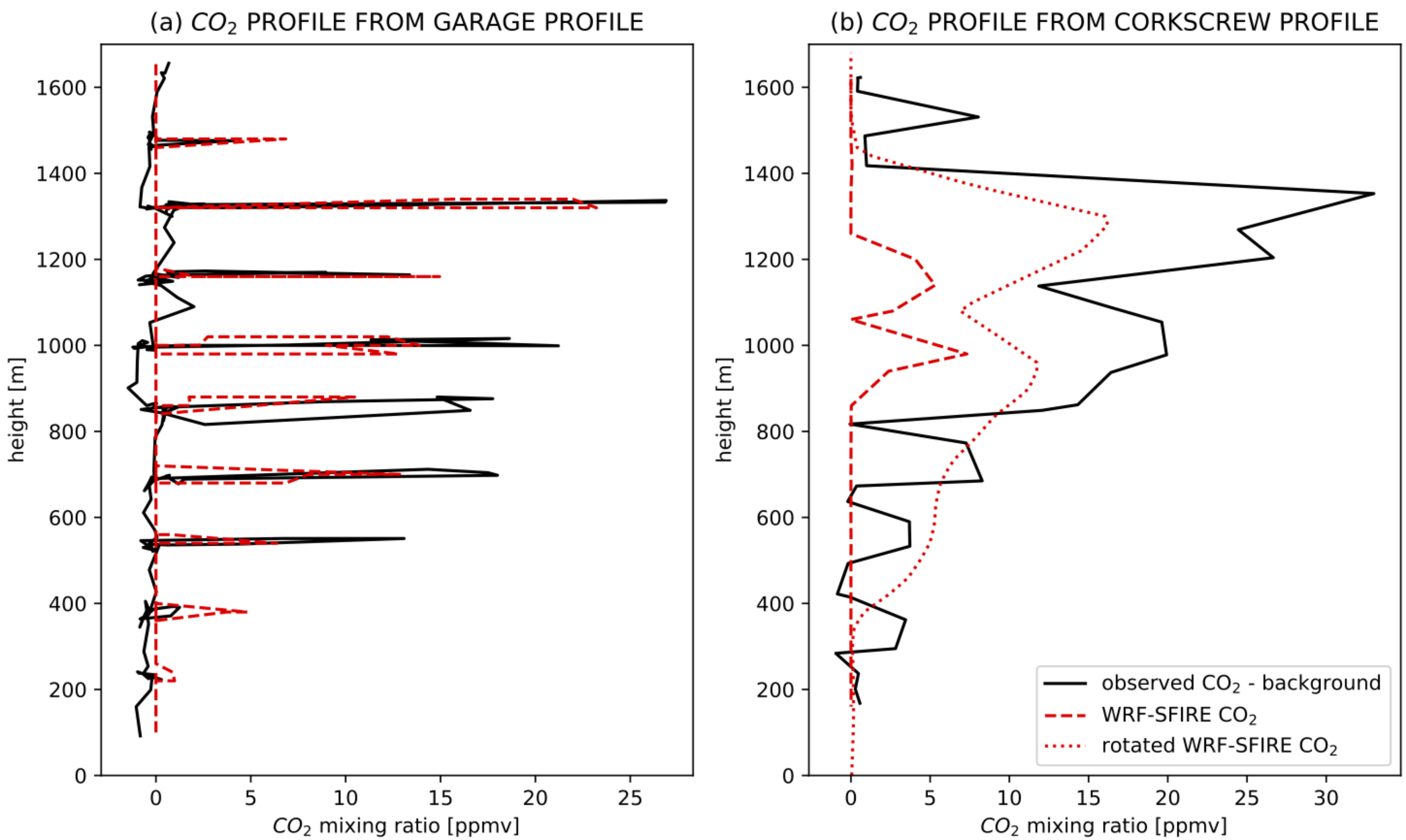
MODEL EVALUATION

# RxCADRE 2012 campaign: flight path concentrations



MODEL EVALUATION

# RxCADRE 2012 campaign: concentration profiles

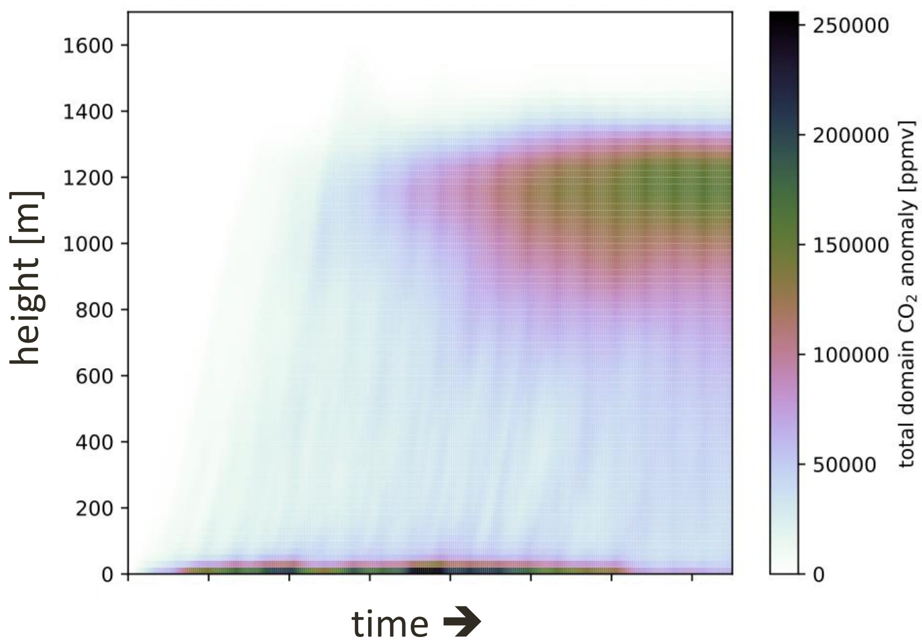


MODEL EVALUATION

# RxCADRE 2012 campaign: findings

- evaluation results:
  - WRF-SFIRE reasonably captures smokes dispersion given
    - steady mesoscale conditions
    - accurate representation of fire behavior

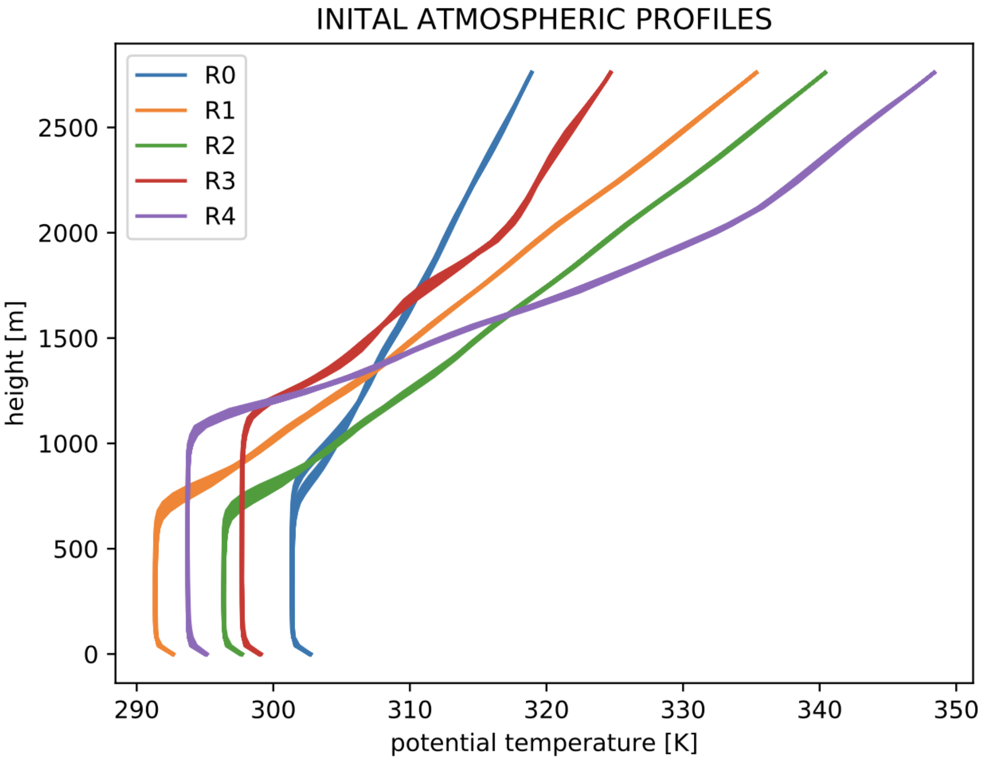
CONCENTRATION COLUMN



FLOW DYNAMICS

# Idealized studies: creating a synthetic dataset

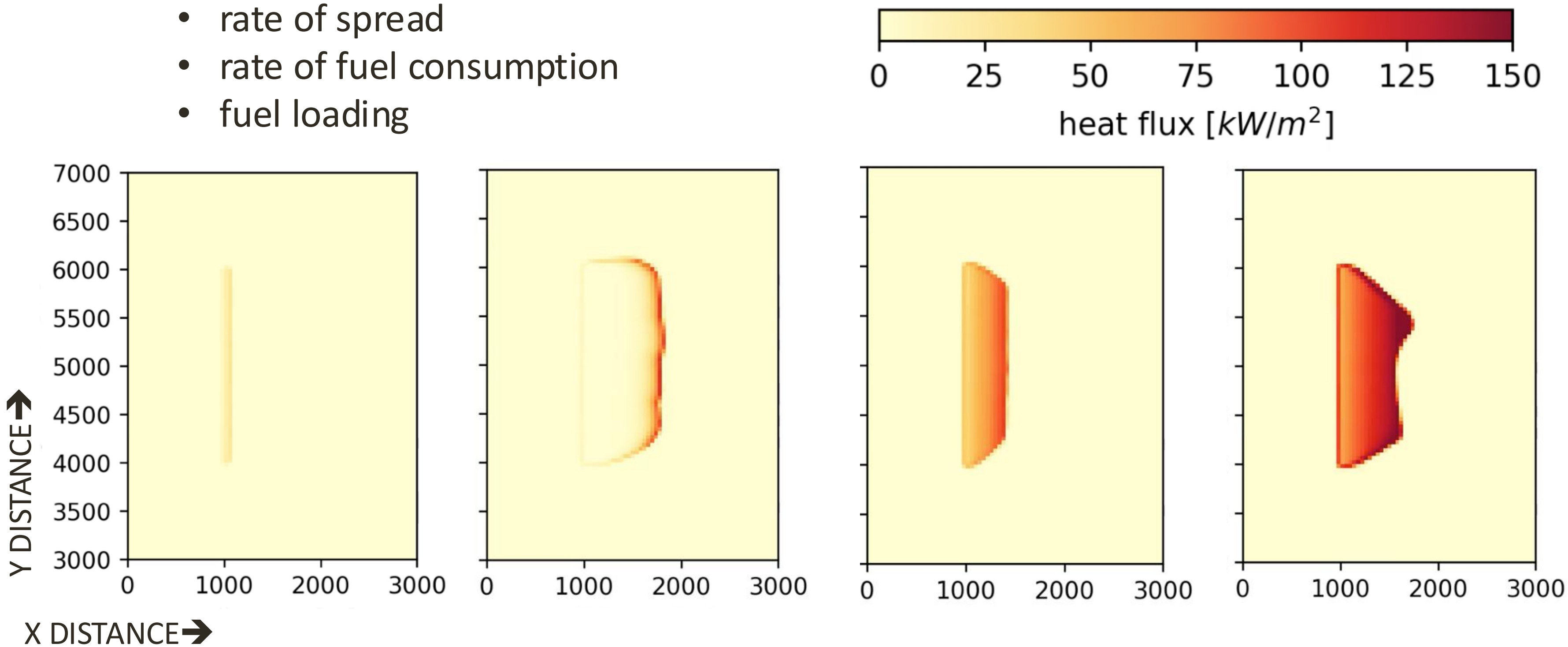
- Capture a wide range of atmospheric and fuel conditions:
  - winds 3 – 12 m/s
  - all 13 fuel categories
  - 5 different atmospheric profiles
  - 1 – 4 km fireline lengths
  - 115 runs total



FLOW DYNAMICS

# Idealized studies: fire behavior

- Accounting for diverse fire behavior through fuel categories
  - burn intensity
  - fireline depth
  - fireline shape
  - rate of spread
  - rate of fuel consumption
  - fuel loading



# FLOW DYNAMICS

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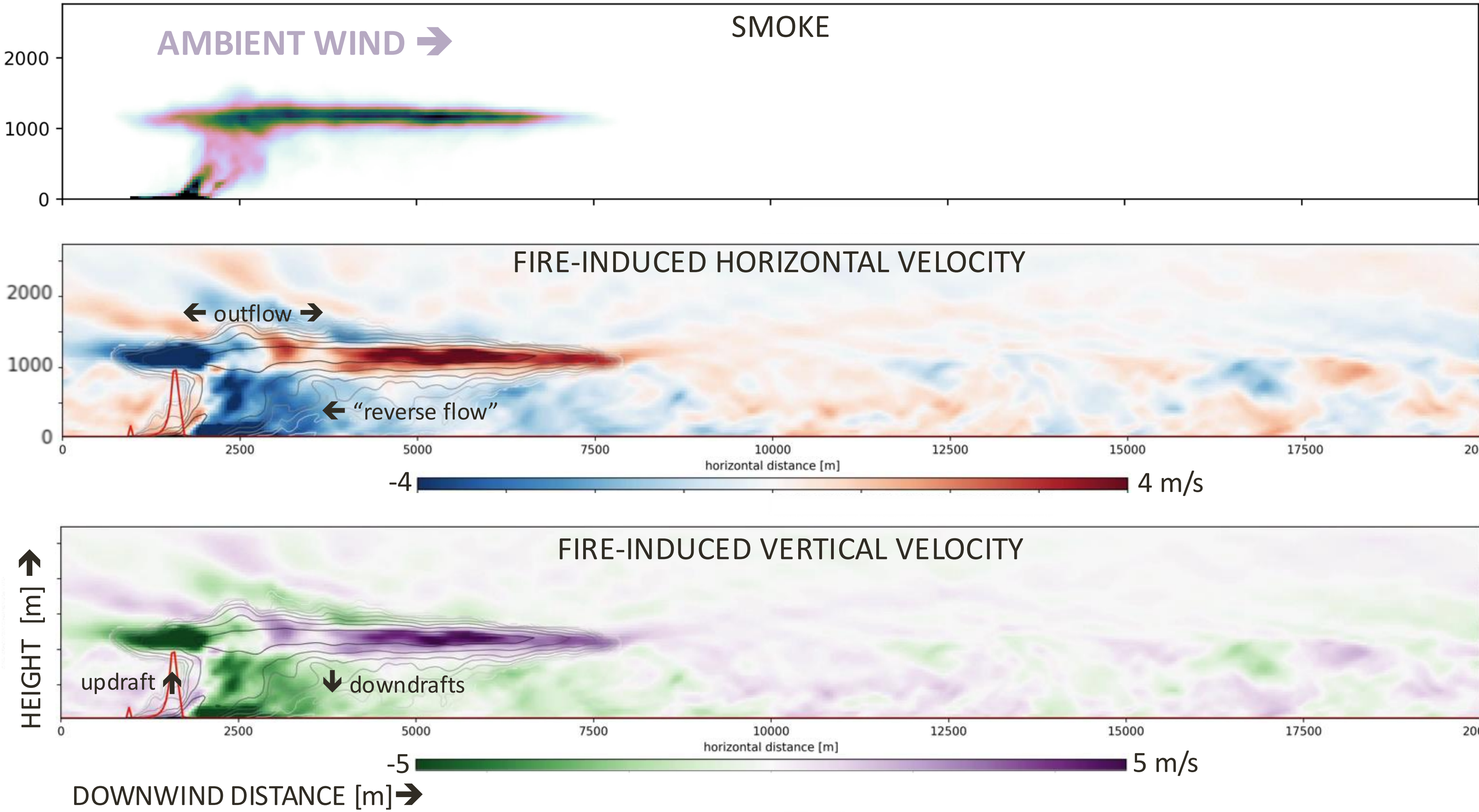
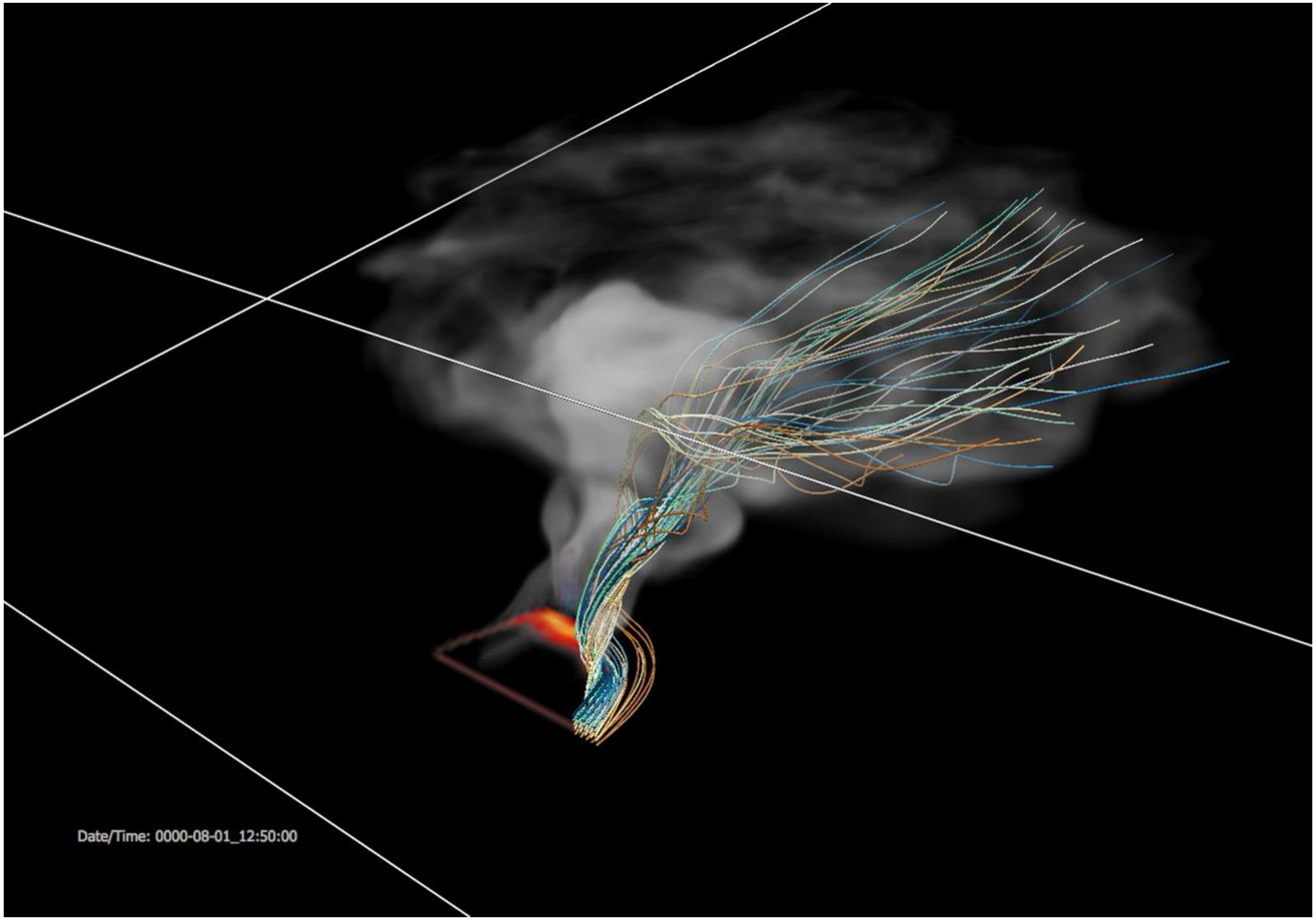


## FLOW DYNAMICS

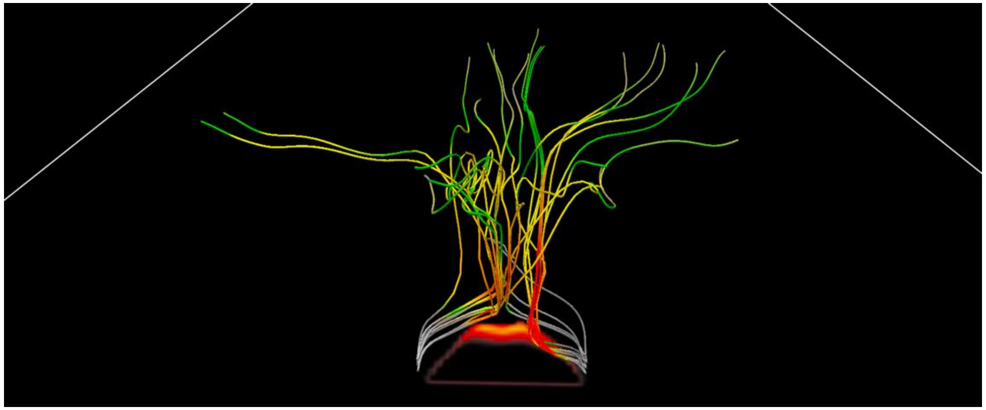
# Idealized studies: fire-induced 3D flow and vorticity



FLOW DYNAMICS

# Idealized studies: fire-induced 3D flow and vorticity

- fire-atmosphere coupling:
  near-surface 3D winds are generated in response to the fire
    - low pressure at the center of the fire updraft results in a pressure gradient force
    - 3D winds induce vortices that bring clean air into the plume and reduce the strength of the "reverse flow"
    - this cross-wind flow produces a curved fireline
- NOT Gaussian plume behavior



## FLOW DYNAMICS

# Idealized studies: 3D flow and vorticity

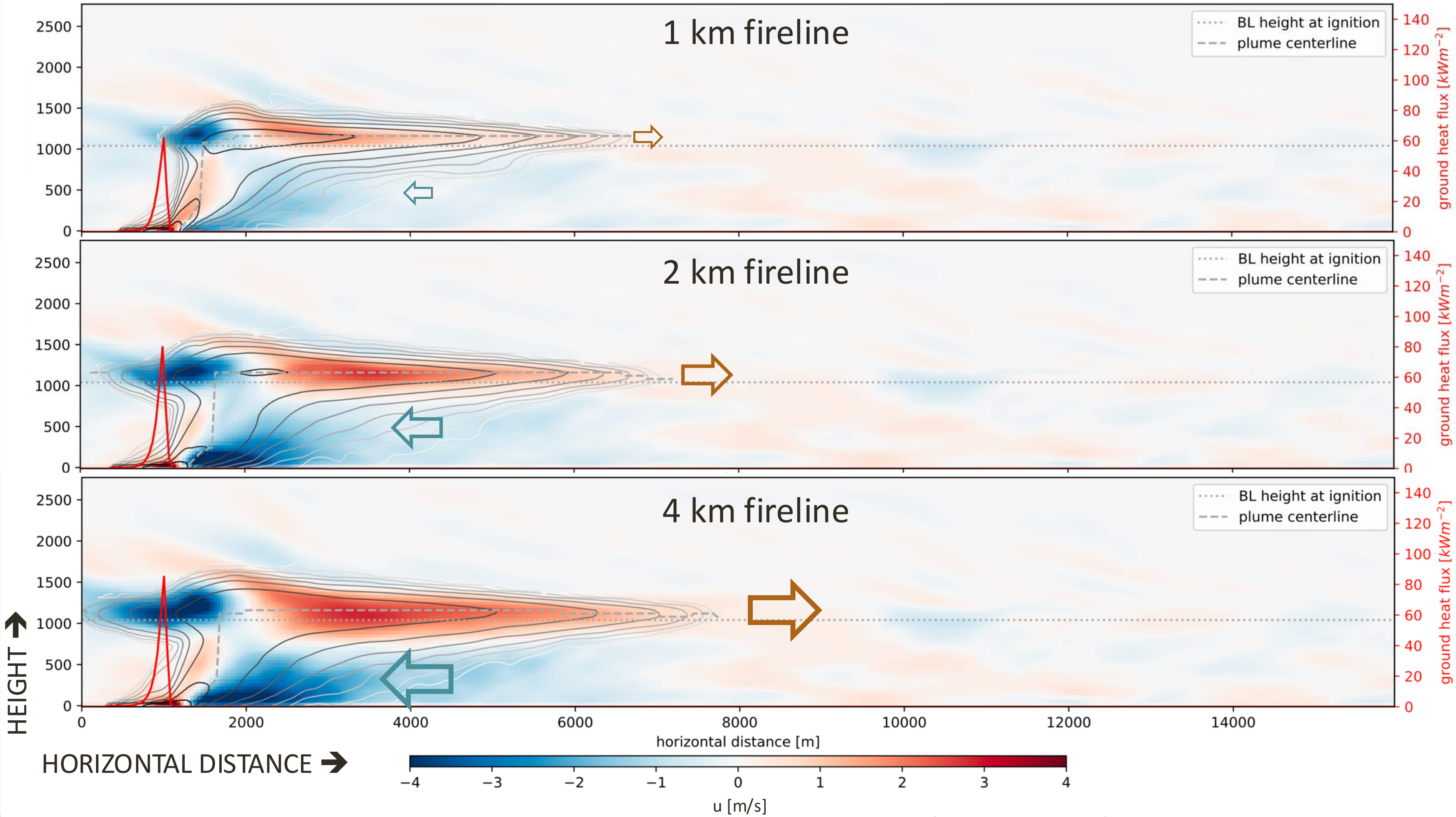

Acknowledgement: Alberta Fire, CFS, FP Innovations

## FLOW DYNAMICS
# Idealized studies: fireline length

- what happens with longer firelines?
    - effect on the magnitude of the “reverse flow”
    - effect on vertical smoke distribution
    - location of the convergence zone
- case study runs to compare 1 km, 2 km and 4 km firelines

## FLOW DYNAMICS

# Idealized studies: along-wind flow



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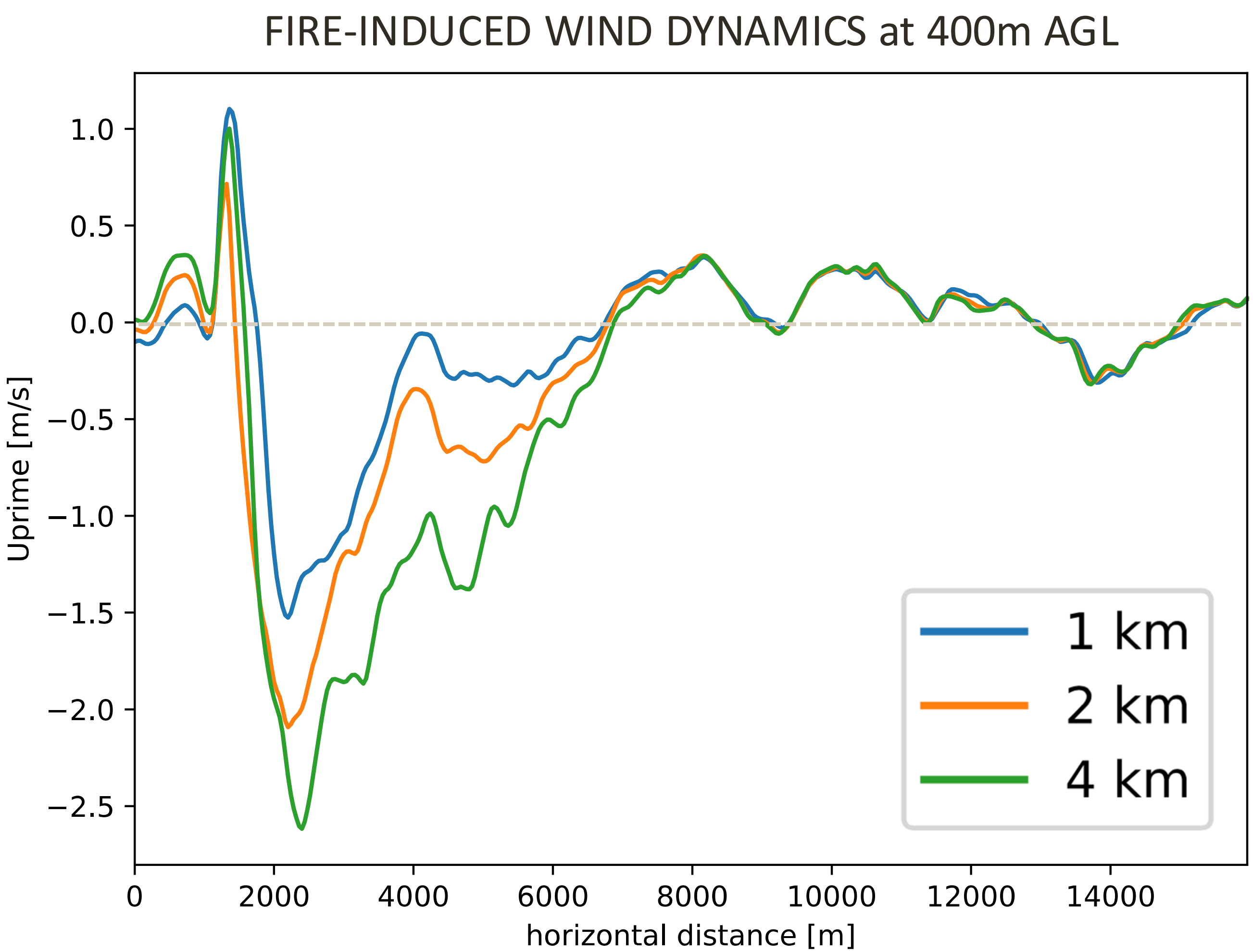
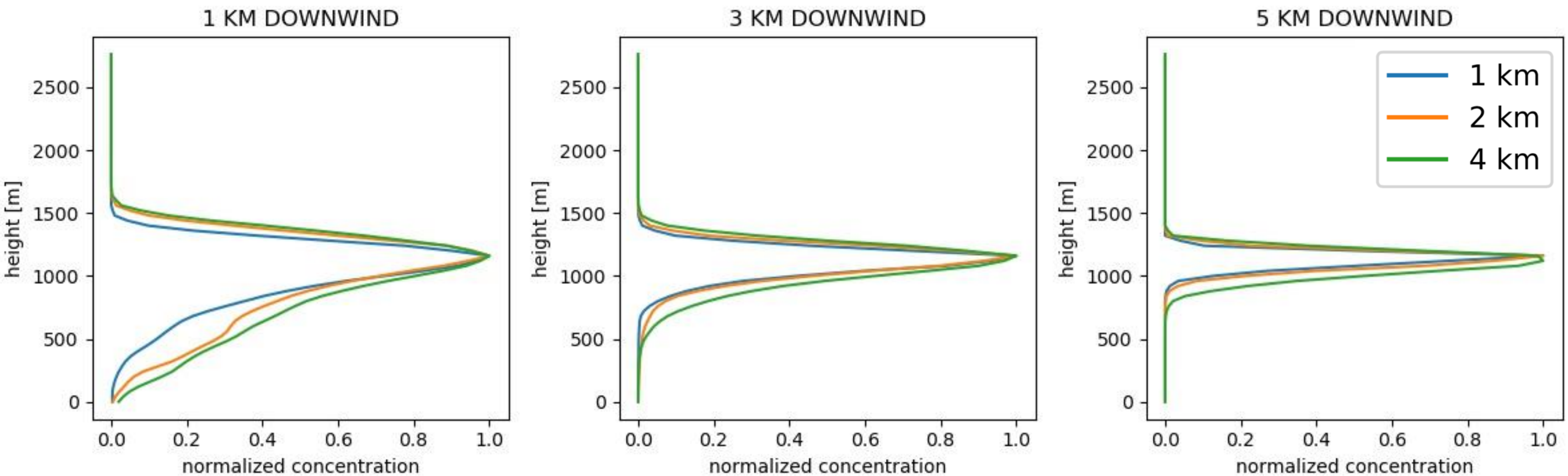


# FLOW DYNAMICS

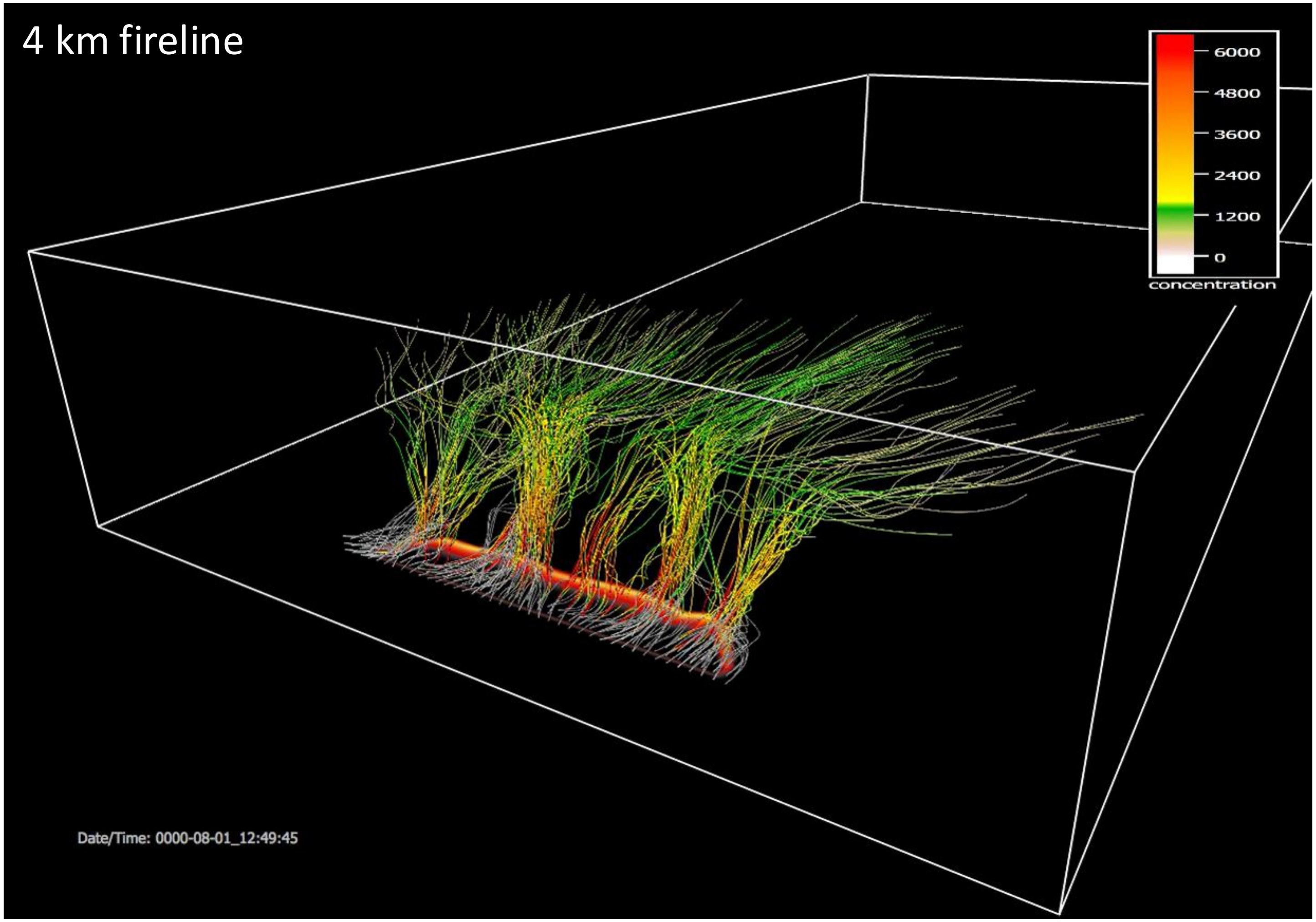
## Idealized studies: vertical smoke distribution

CROSSWIND INTEGRATED TIME-AVERAGED CONCENTRATIONS



# FLOW DYNAMICS

## Idealized studies: longer fireline = multi-vortex structure



SMOKE INJECTION HEIGHT

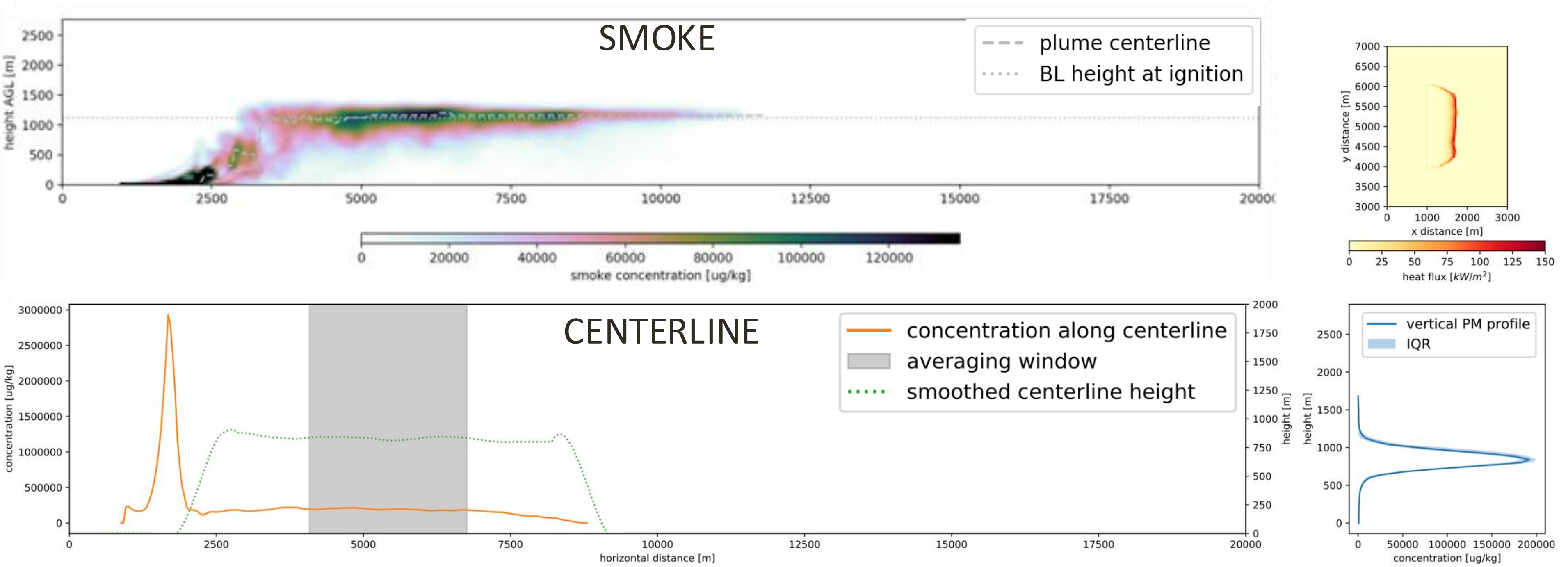
# Defining downwind distribution

- when can we say the plume has reached equilibrium level?
  - stable centerline height
  - stable concentration along the centerline

- varies for each combination of ambient atmospheric profile and fire behavior!

SMOKE INJECTION HEIGHT

# Defining downwind smoke distribution



SMOKE INJECTION HEIGHT

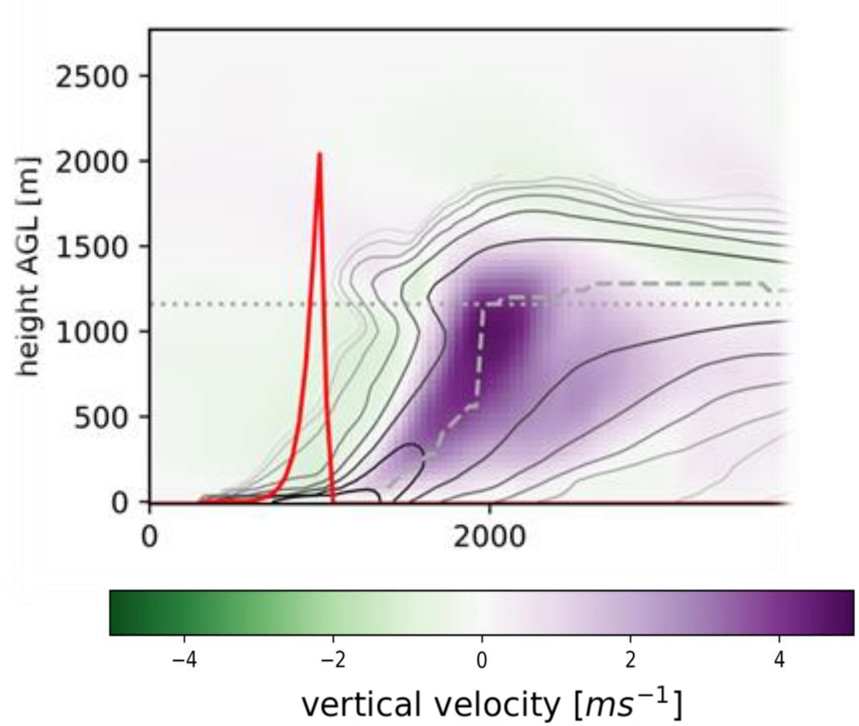
# Characteristic vertical velocity

- analytical theories characterizing vertical updraft
  - cloud theory: based on CAPE (Convective Available Potential Energy)
  - boundary layer turbulence theory: Deardorff's velocity

- can we define our own velocity scale $w_{f*}$ such that:

$$z_{cl} = z_{cl}(w_{f*})$$

where $z_{cl}$ = smoke injection height



## SMOKE INJECTION HEIGHT

# Characteristic vertical velocity

$$w_{f*} = \left( \frac{z_i \cdot g \cdot \int_0^r I dr}{\int_0^{z_{cl}} d\theta dz} \right)^{\frac{1}{3}}$$

SMOKE INJECTION HEIGHT

# Characteristic vertical velocity

boundary layer height gravity fireline intensity

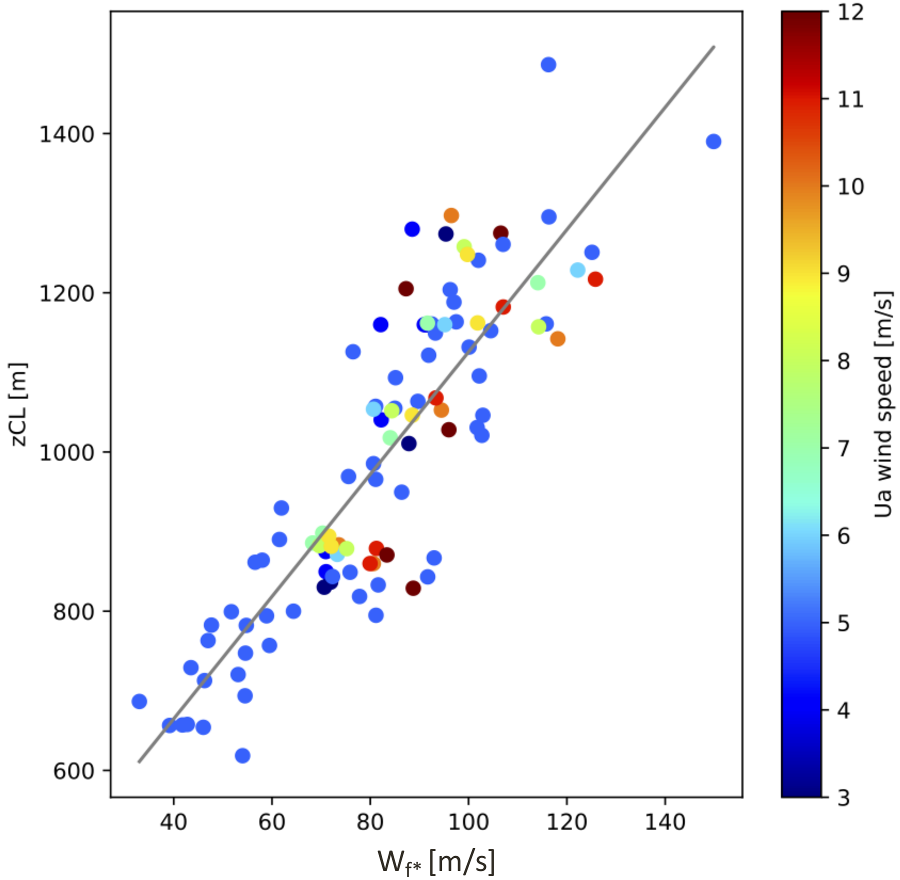
$$w_{f*} = \left( \frac{z_i \cdot g \cdot \int_0^r I dr}{\int_0^{z_{cl}} d\theta dz} \right)^{\frac{1}{3}}$$

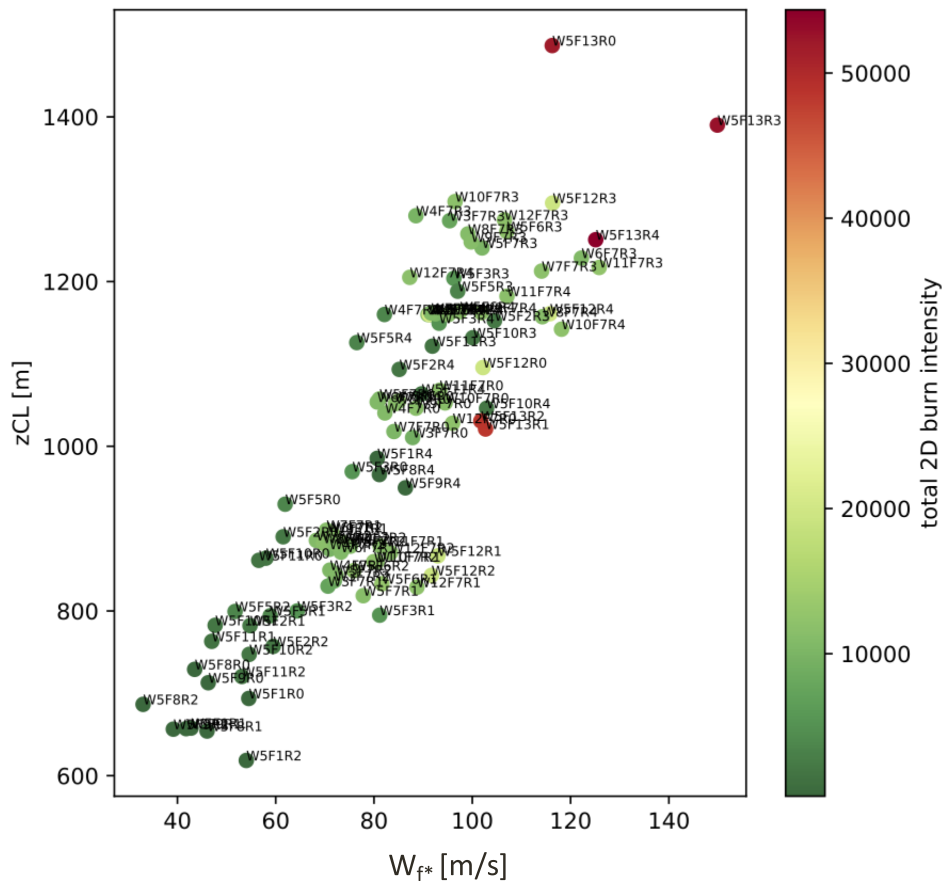
atmospheric profile effects

# SMOKE INJECTION HEIGHT

## Characteristic vertical velocity

$z_{CL}(w_{f*})$: R=0.87



SUMMARY

# Understanding smoke plume dynamics

We use WRF-SFIRE model to show that…

- **a coupled fire-atmosphere LES model can reasonably capture plume rise and dispersion of a real fire**, given
  - detailed atmospheric and fire inputs
  - stable ambient conditions
  - accurate representation of fire behavior

- **wildfire plumes do not behave like Briggs/Gaussian plumes**
  - modify local winds
  - generate vorticity

- **injection height can be parameterized using a new vertical velocity scale $w_{f*}$**
  - current research: extension of parameterization to a vertical distribution

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# DALES: what does it contribute?

- Dutch Atmospheric Large-Eddy Simulation (DALES) model:
  - More simplistic
  - Removes complexity
  - Isolate parameters
  - Focus on atmosphere
- To support and supplement Nadya's work

- To understand how wildfires and smoke interact with the atmosphere
  - Near-fire circulation
  - Downwind effects
- To inform smoke behaviour for public health

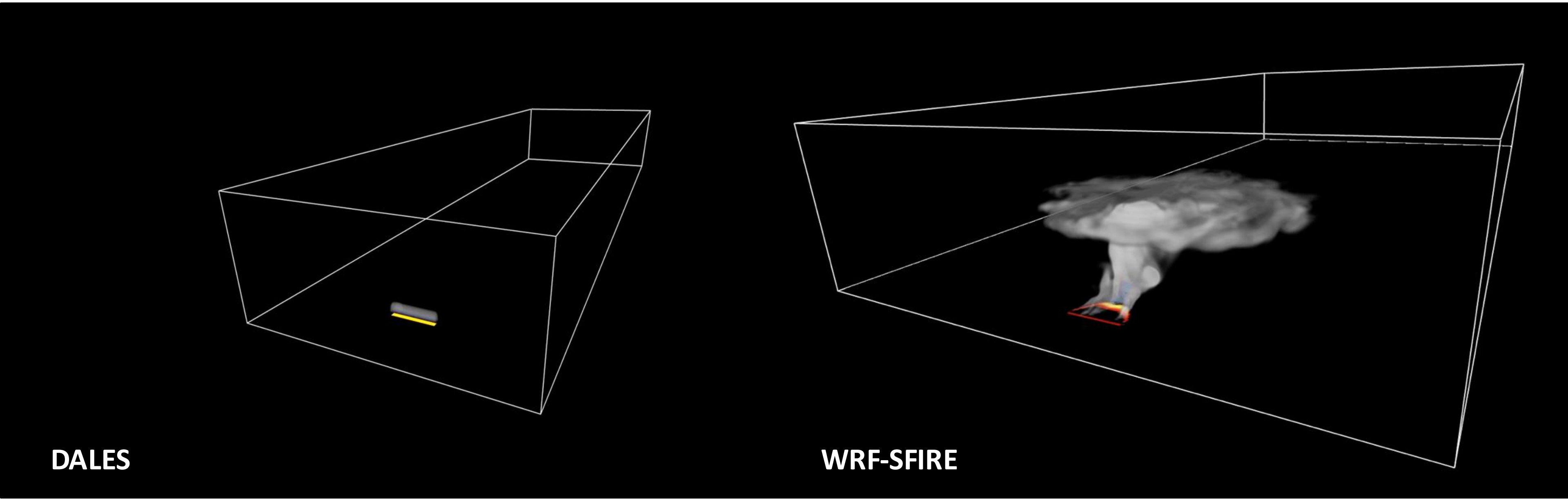
# Model differences: physics

| Model | Dutch Atmospheric LES (DALES) | Weather Research and Forecasting LES coupled with SFIRE (WRF-SFIRE) |
|---|---|---|
| Non-hydrostatic | Yes | Yes |
| Compressibility | Boussinesq approximation | Fully compressible |
| Turbulence closure | K theory based on TKE | 3D 1.5-order TKE |
| Terrain | Flat/sloped | Complex |
| Smoke | Passive tracer emitted at constant rate | Passive tracer emitted proportional to fuel consumption |

# Model differences: fire behaviour

| Model | Dutch Atmospheric LES (DALES) | Weather Research and Forecasting LES coupled with SFIRE (WRF-SFIRE) |
|---|---|---|
| Fire spread | Stationary | Spread model (SFIRE) |
| Fire heat | Constant flux | Variable based on fuel |
| Fire size | Constant | Variable based on spread |
| Fire line length | Finite or Infinite | Finite |
| Fire-atmosphere coupling | N/A | Two-way coupling |

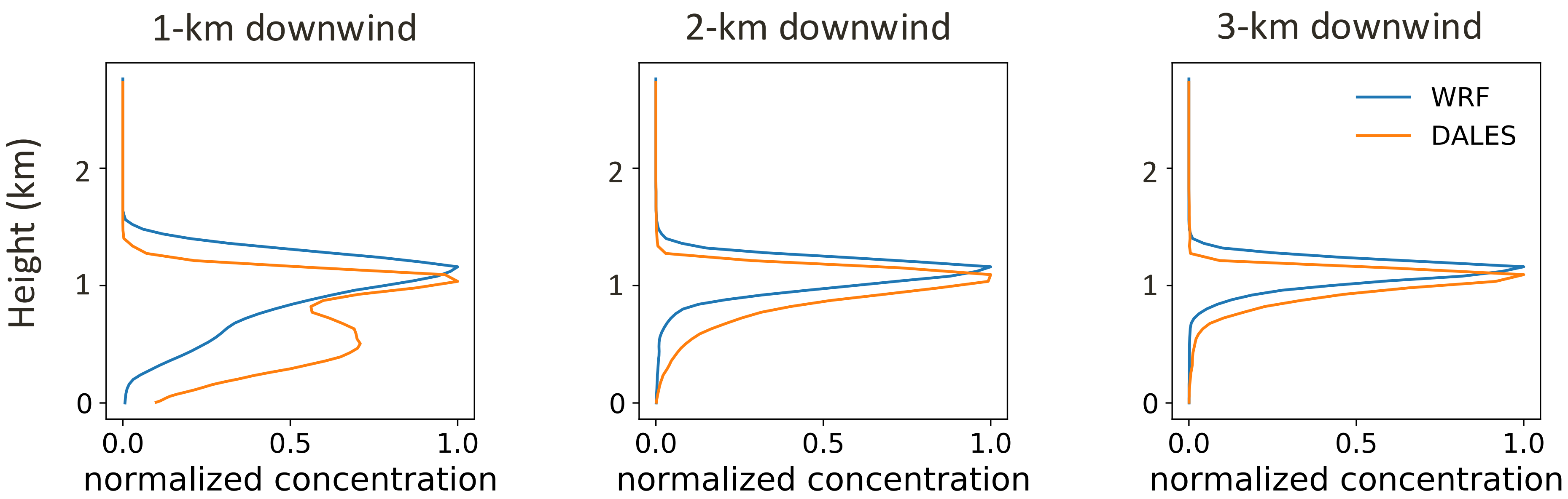
# Model comparison: qualitative

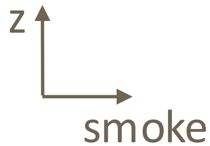



| Model | DALES | WRF-SFIRE |
|---|---|---|
| Domain size | 20 km x 6 km | 20 km x 10 km |
| Grid spacing | 10 m | 40 m (atmosphere), 4 m (fire) |
| Horizontal boundary conditions | Cyclic | Cyclic |
| Fire line | 1 km long; 100 m wide | 1 km long initially; variable width |
| Ambient wind | 4 m/s | 4 m/s |
| Fire heat flux | 50 kW/m$^2$ | Peak 61 kW/m$^2$, mean 35 kW/m$^2$ |

# Model comparison: quantitative

Crosswind-integrated time-averaged smoke concentration



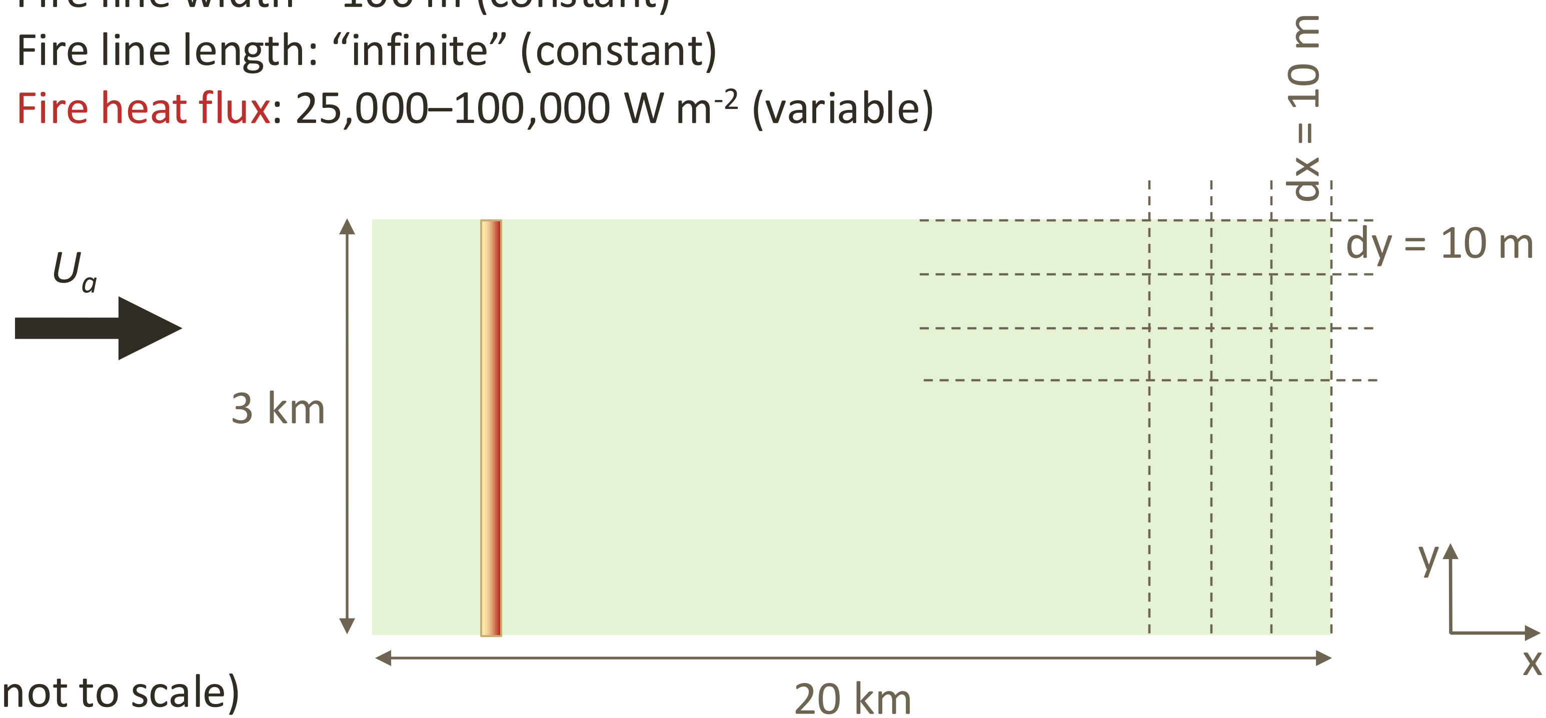
# DALES: initial experiments

**A. 2-hour spin-up** creates background convective boundary layer

- dx = dy = 10 m
- Surface heat flux: ~120 W $m^{-2}$
- Ambient wind speed ($U_a$): 1–12 m $s^{-1}$ (variable)

**B. 30-min smoke** simulation

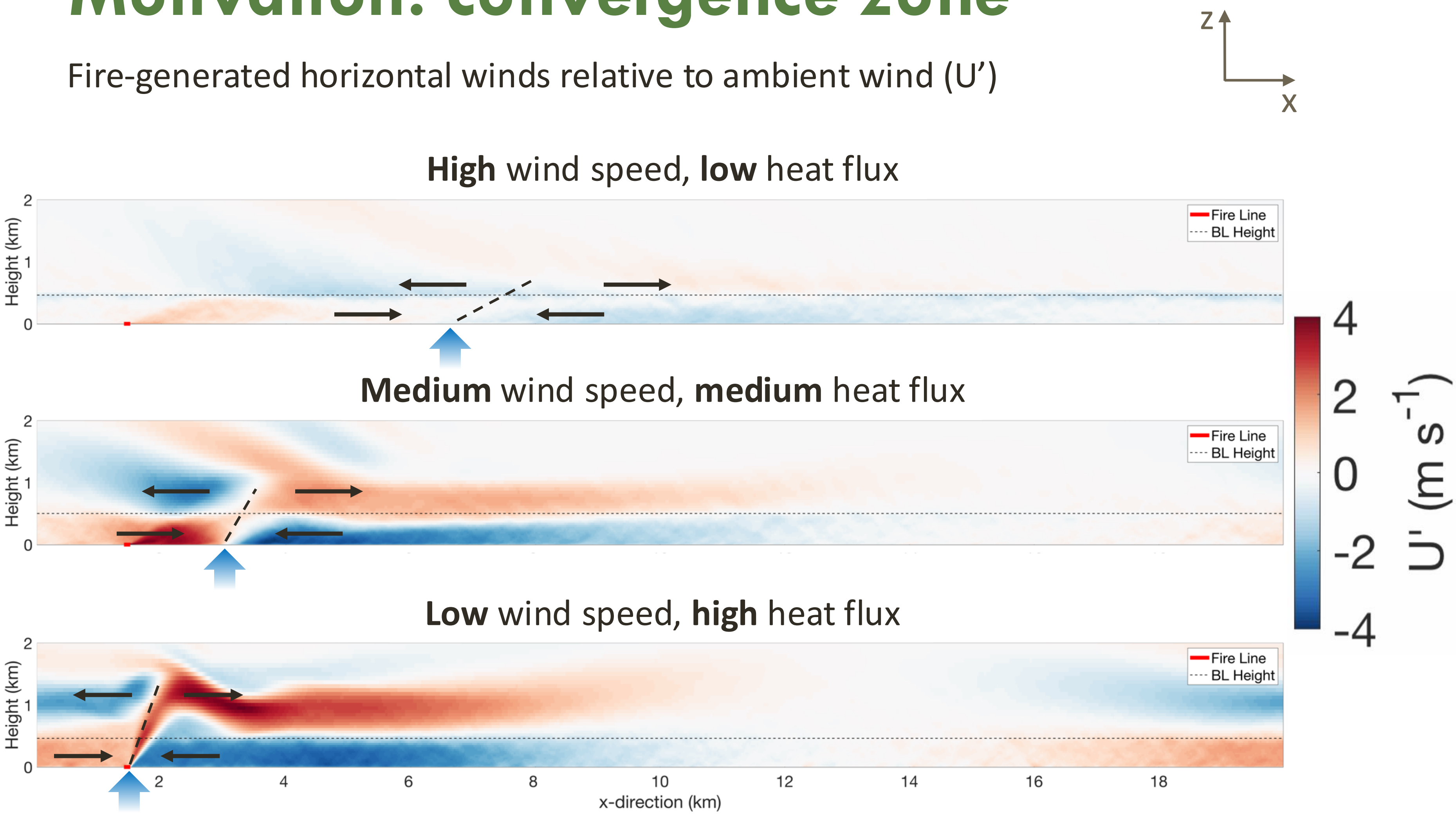
- Fire line width = 100 m (constant)
- Fire line length: “infinite” (constant)
- Fire heat flux: 25,000–100,000 W $m^{-2}$ (variable)




(not to scale)

# Motivation: convergence zone

Fire-generated horizontal winds relative to ambient wind (U')



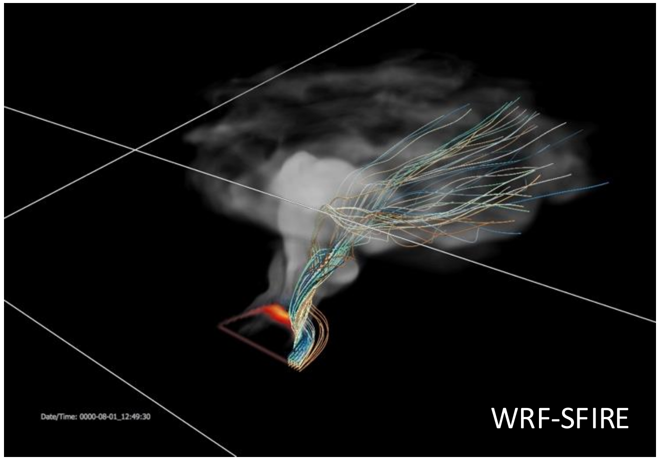

"Infinite" fire line, cross-wind, and 15-min averages

# Current research direction

- Infinite fire line:
  - Inhibits lateral flow
  - Essentially 2-D in x-z plane

- Finite fire lines:
  - Lateral flow develops
  - Observed in prescribed burn at Pelican Mountain
  - Modelled by WRF-SFIRE

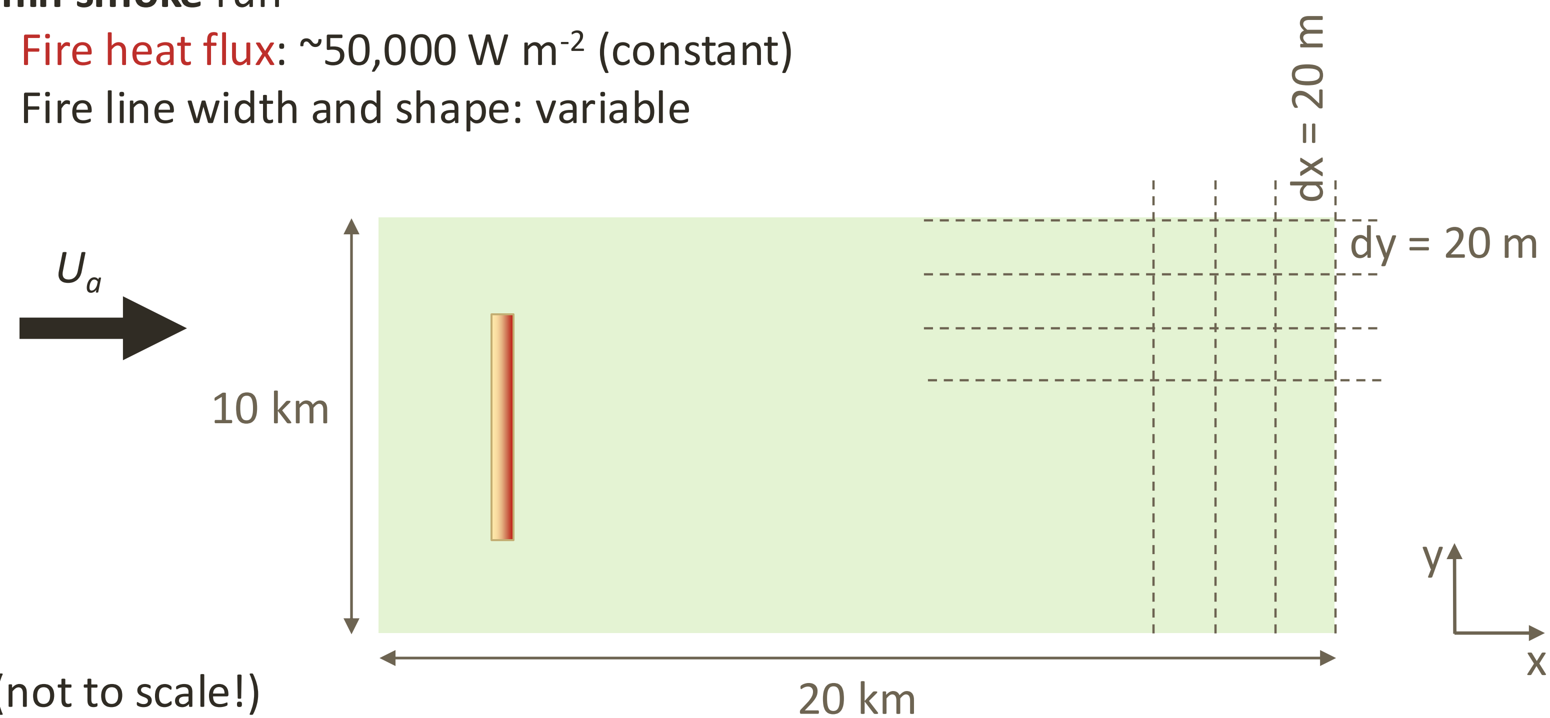
- Research question:
  How does fire line length interact with local and downwind dynamics?

# DALES: new model set-up and experiments

- **2-hour spin-up** creates background convective boundary layer
  - Surface heat flux: ~ 300 W $m^{-2}$
  - Ambient wind speed ($U_a$): 4 m $s^{-1}$ (constant)
  - dx = dy = 20 m

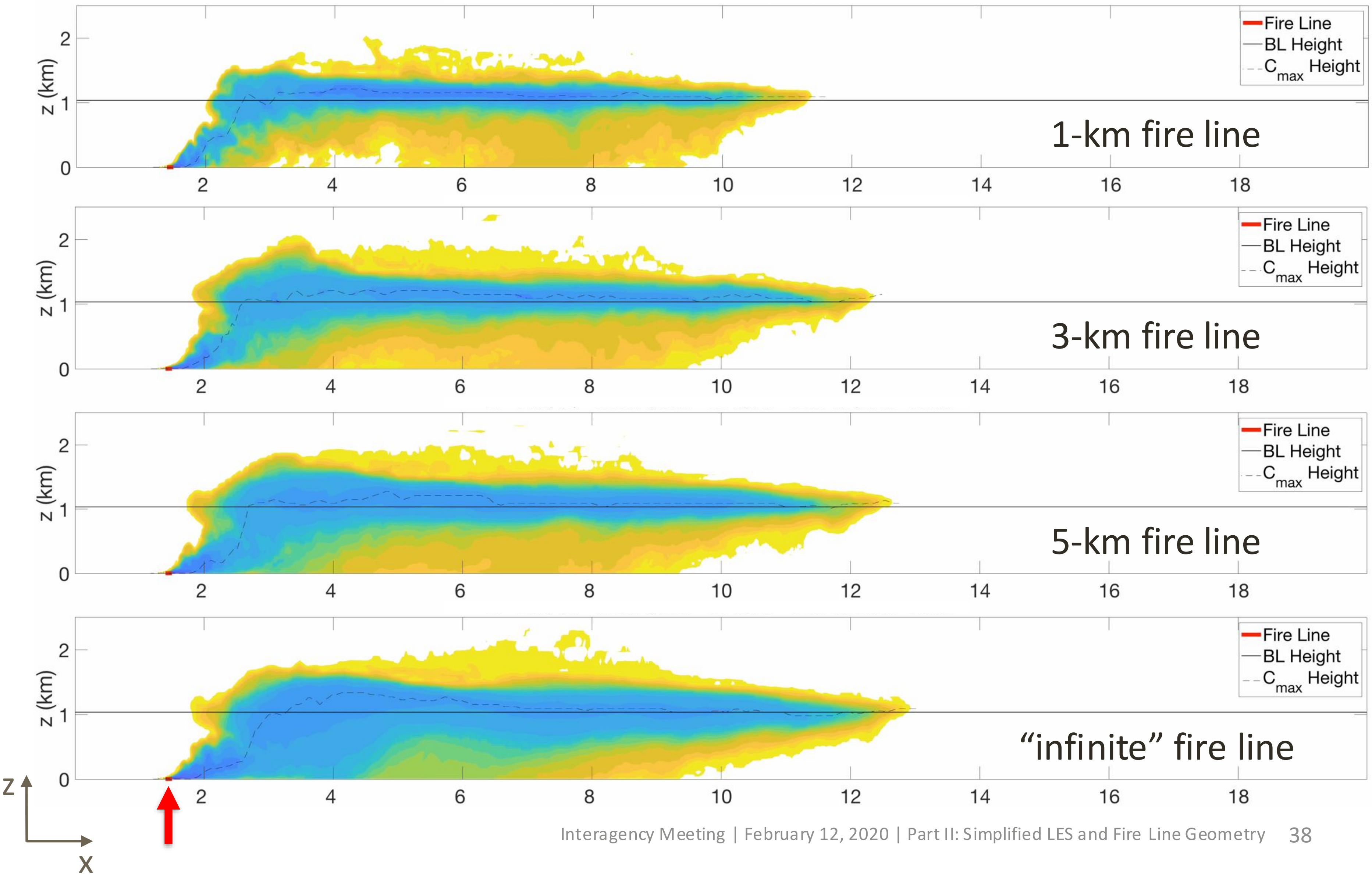
A. **30-min smoke** run
  - Fire heat flux: ~50,000 W $m^{-2}$ (constant)
  - Fire line width and shape: variable



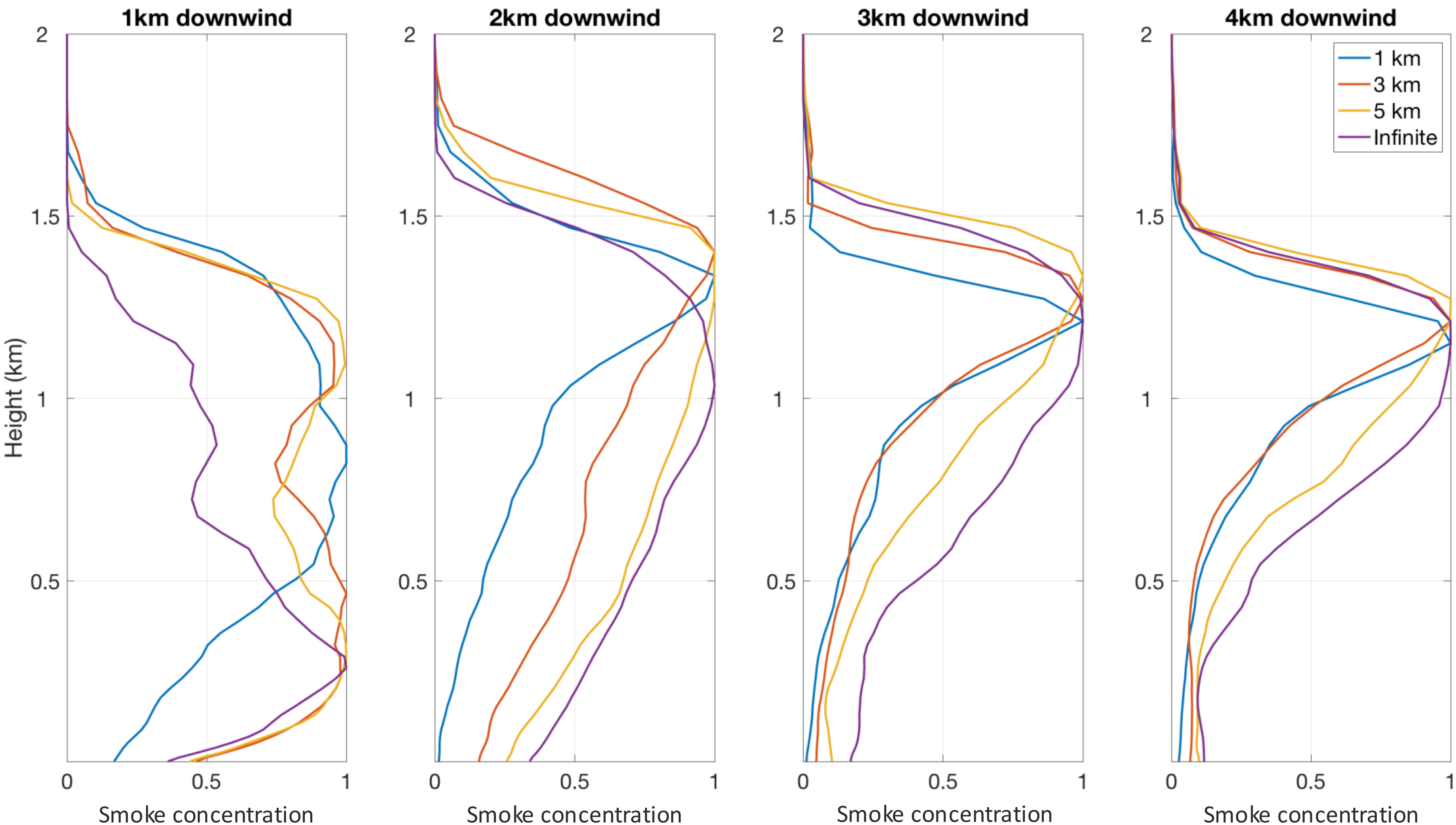

(not to scale!)

# Crosswind-integrated smoke concentrations

After $t$ = 30 minutes



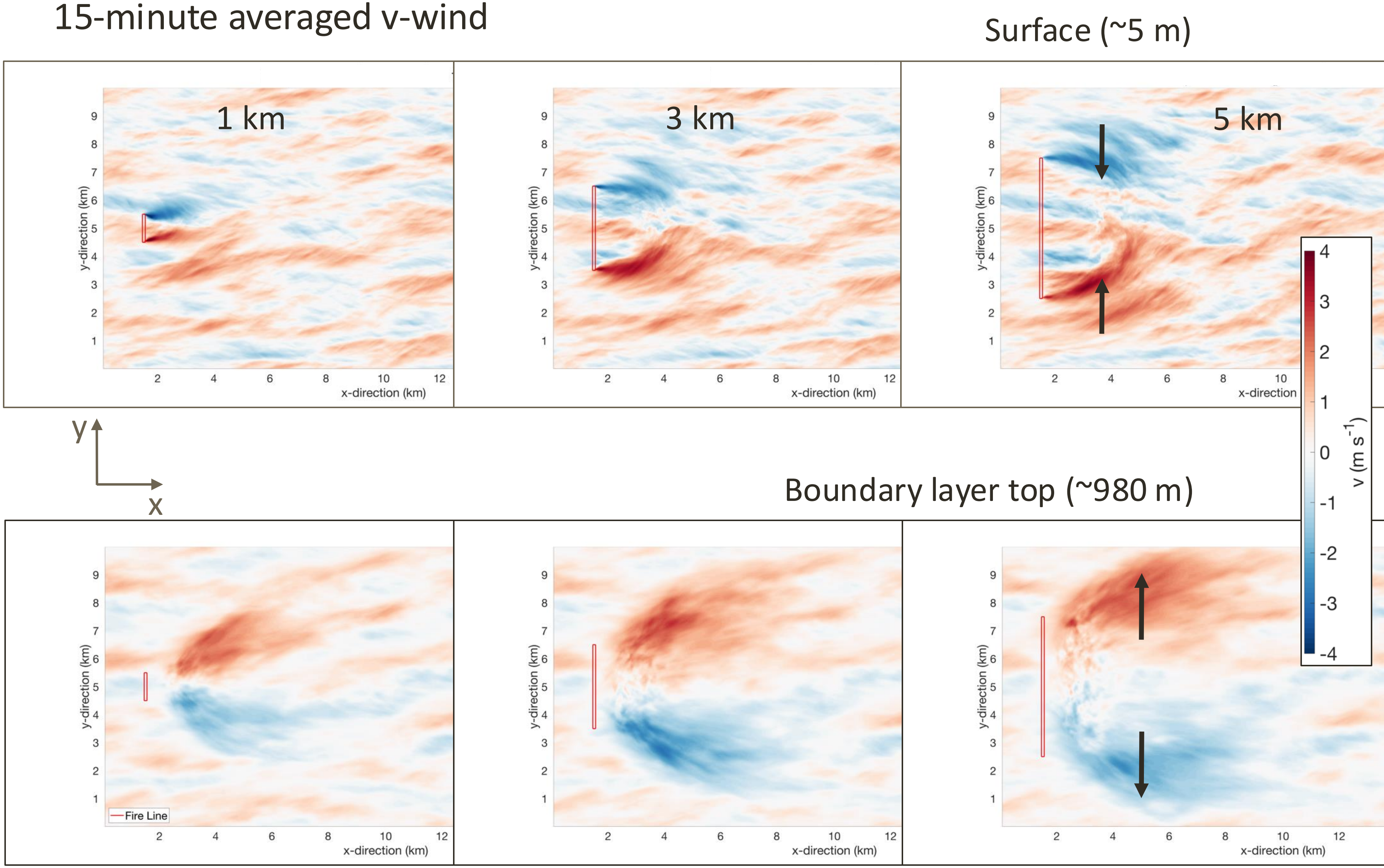
# Vertical smoke distributions (normalized)




15-minute averages

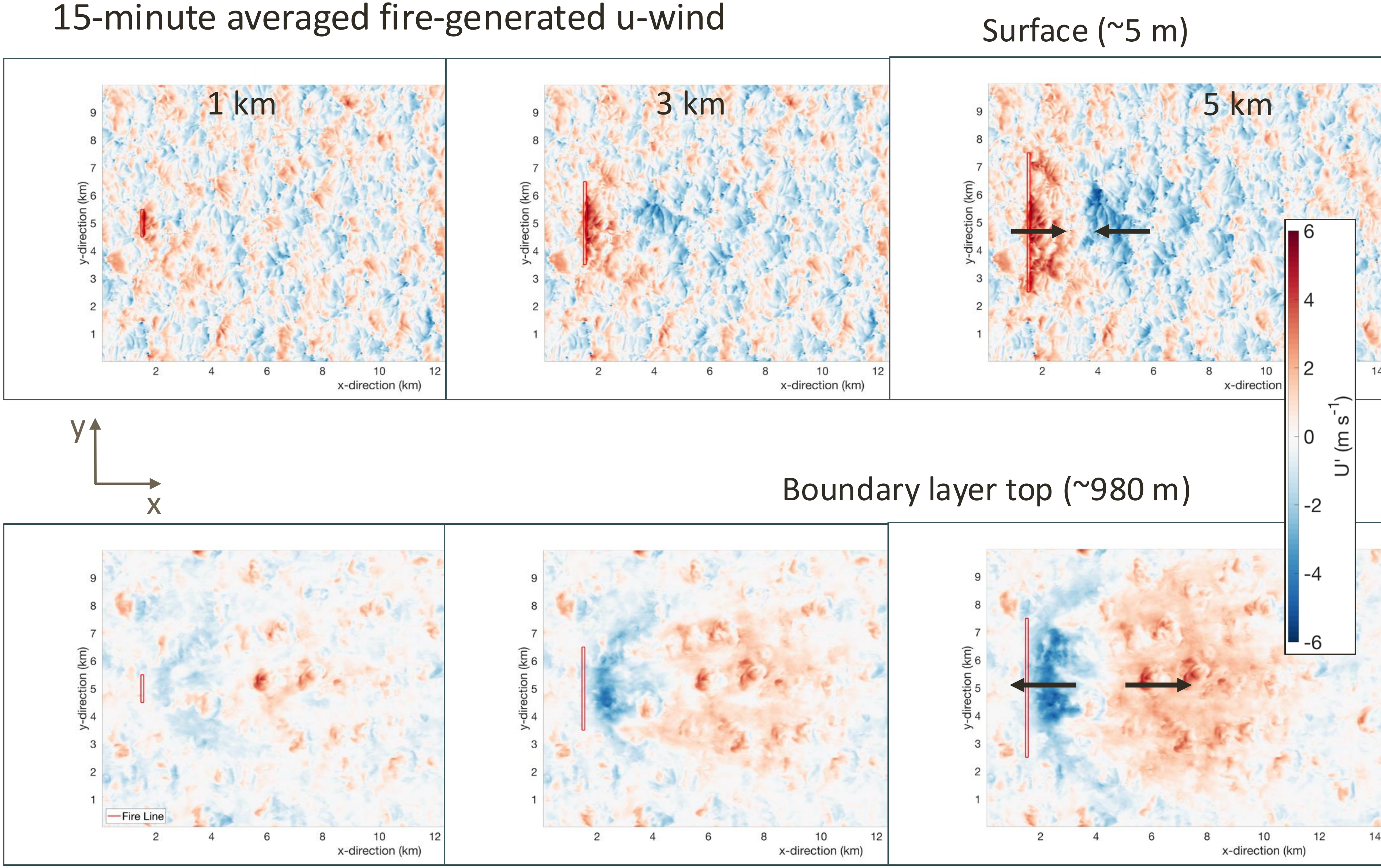
# Cross-wind flow

15-minute averaged v-wind

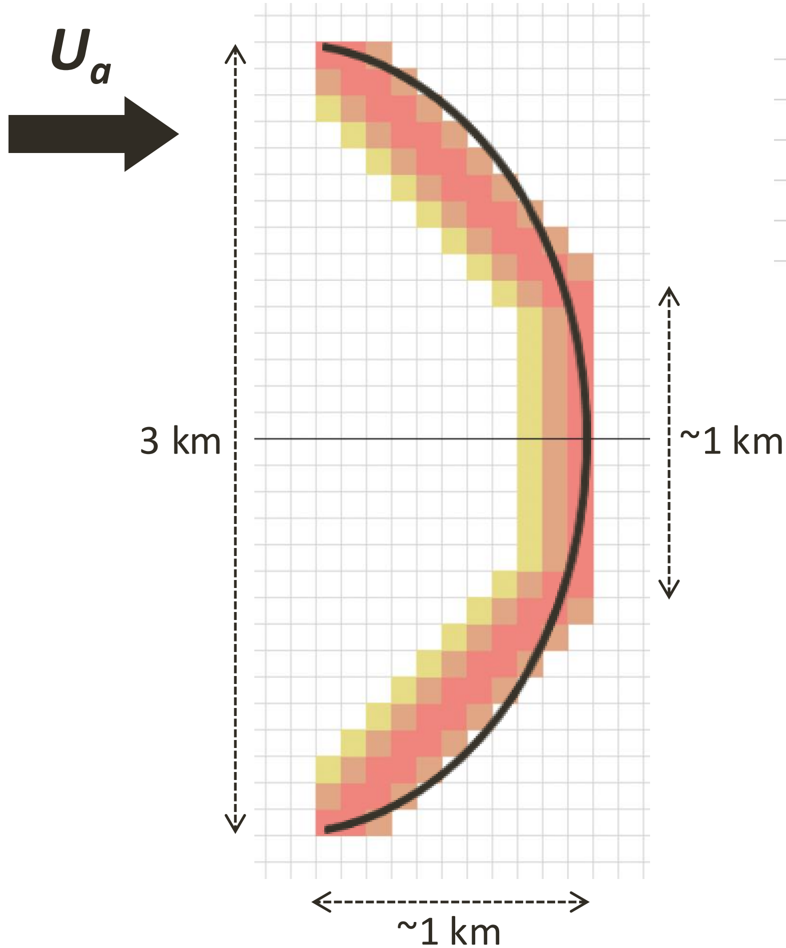


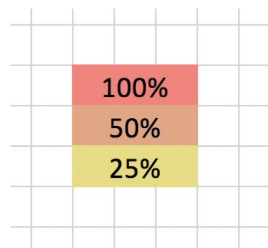
# Along-wind turbulence

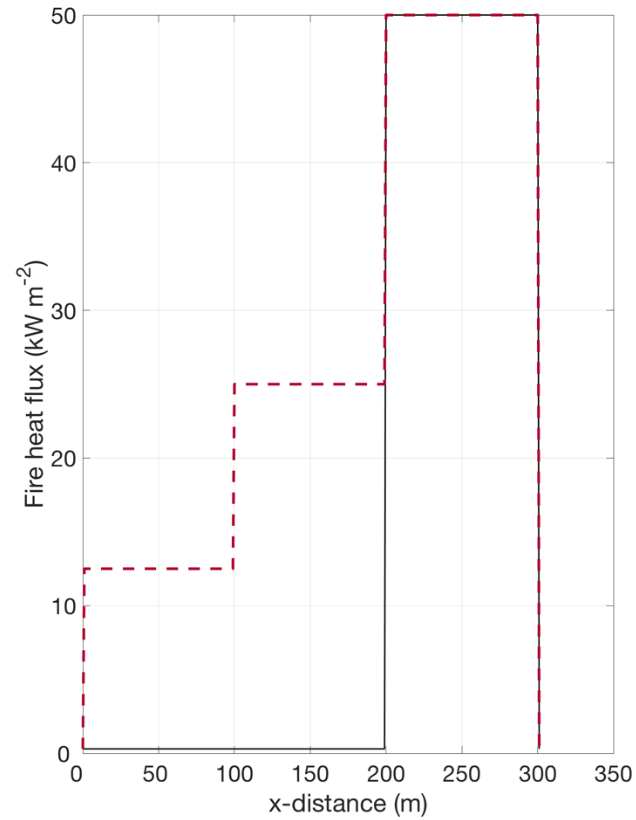
15-minute averaged fire-generated u-wind



# Fire line geometry

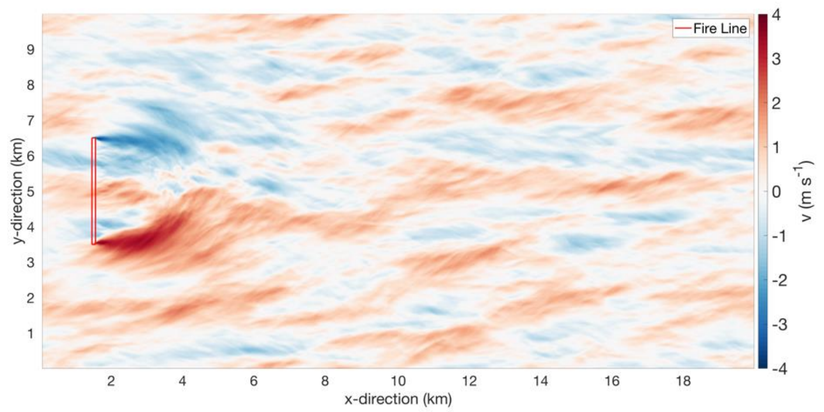


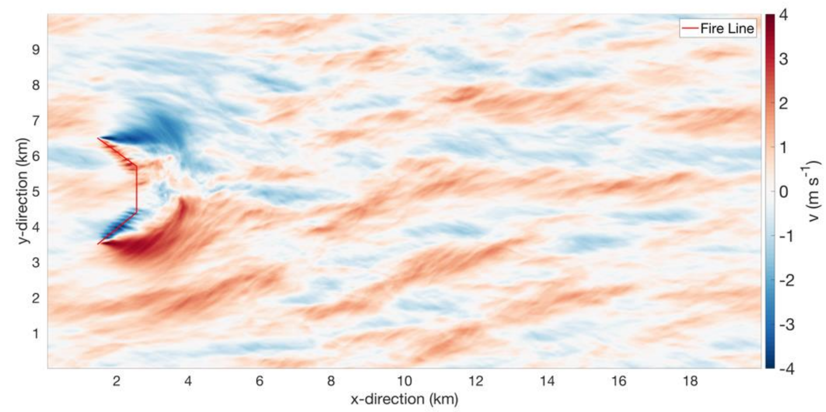



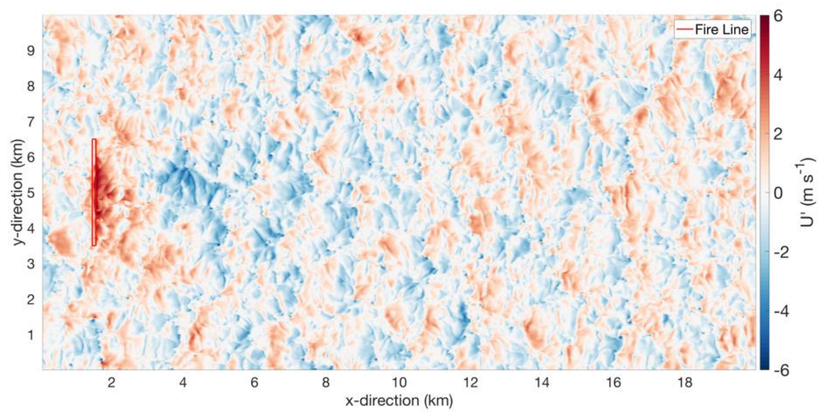
# Straight vs. curved fire line

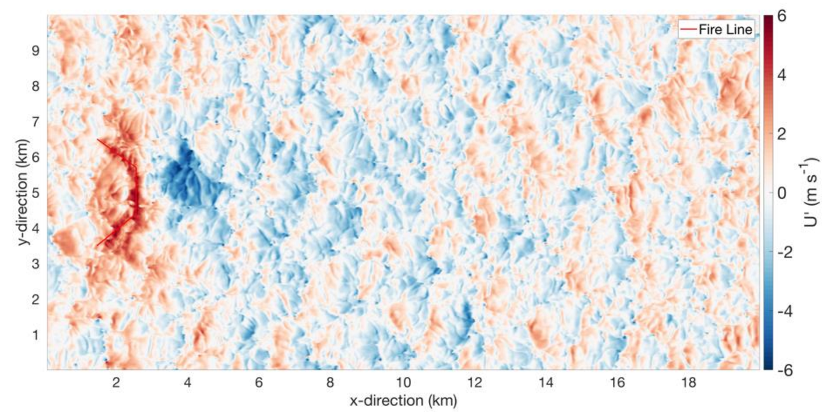
15-minute averaged v-wind at surface



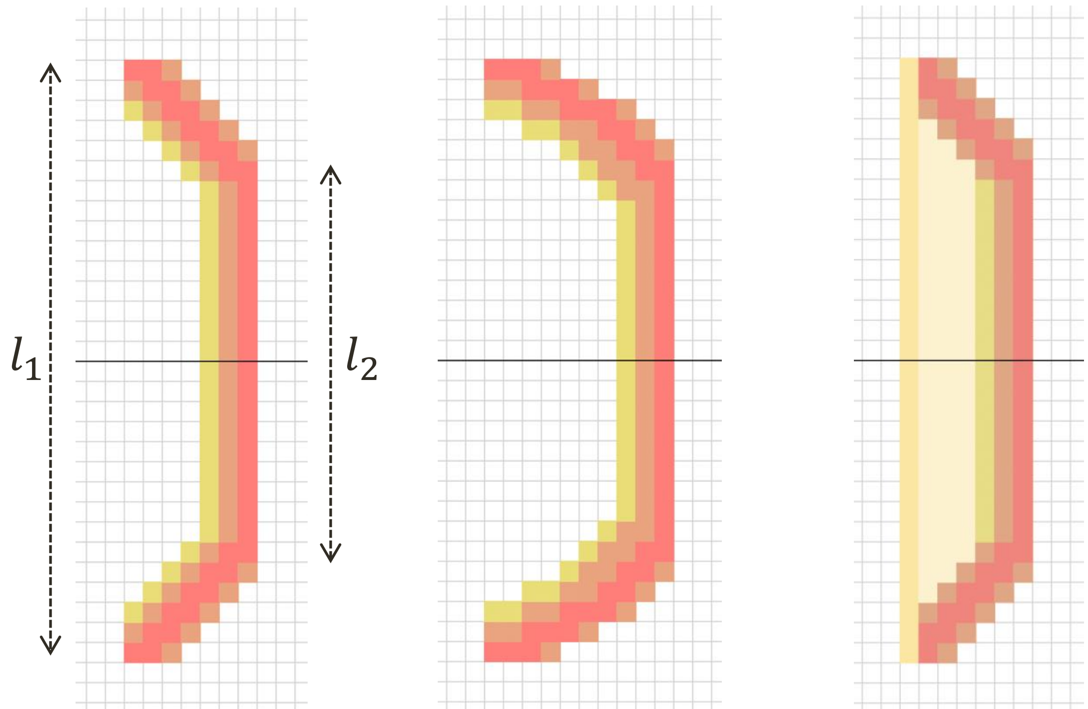

15-minute averaged fire-generated u-wind at surface

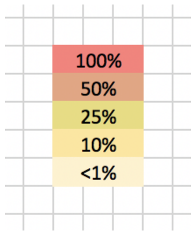


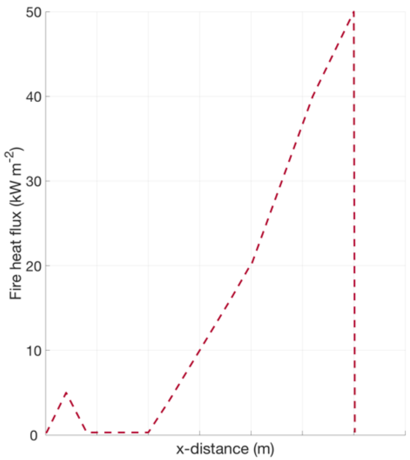



# Fire line geometry: what's next?

- More fire line shapes (inspired by Nadya's runs)



# Fire line geometry: goal

- Define convergence zone (and updraft) size, position, and intensity, in terms of:
  - Fire line geometry
  - BL height…
- Test this with different ambient winds and fire heat fluxes

# Investigating wildfire smoke behavior using simplified large-eddy simulations

**Summary:**

- Preliminary results promising, and indicate:
    - Near-surface smoke recirculation weaker for shorter fire lines
    - Smoke does not reach as far downwind for shorter fire lines
    - Curved fire line appears to allow “correct” dynamics near the fire

- Future work includes more model runs:
    - Varying fire line shapes
    - Finding systematic way of defining convergence zone/updraft
- Eventually test for different wind speeds and fire heat fluxes

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    - Big picture: smoke modelling frameworks
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    - Fire Behavior

BACKGROUND

# Smoke Forecast Framework

## Example: BlueSky Canada


Meteorology

Wildfire locations

Fire behavior

Plume rise

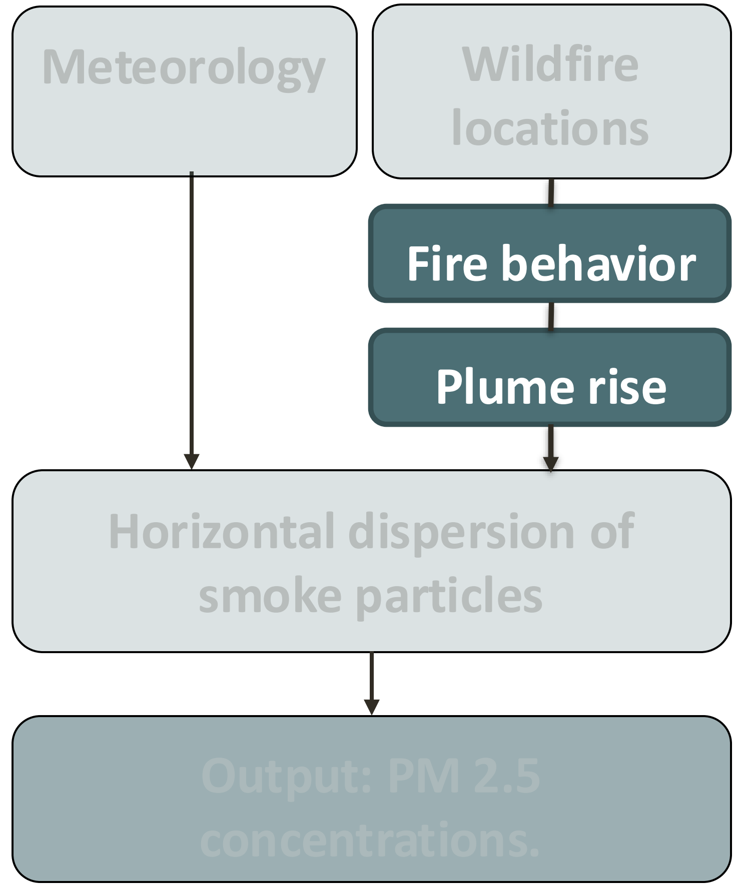
Horizontal dispersion of smoke particles

**Output: PM 2.5 concentrations.**

# BACKGROUND

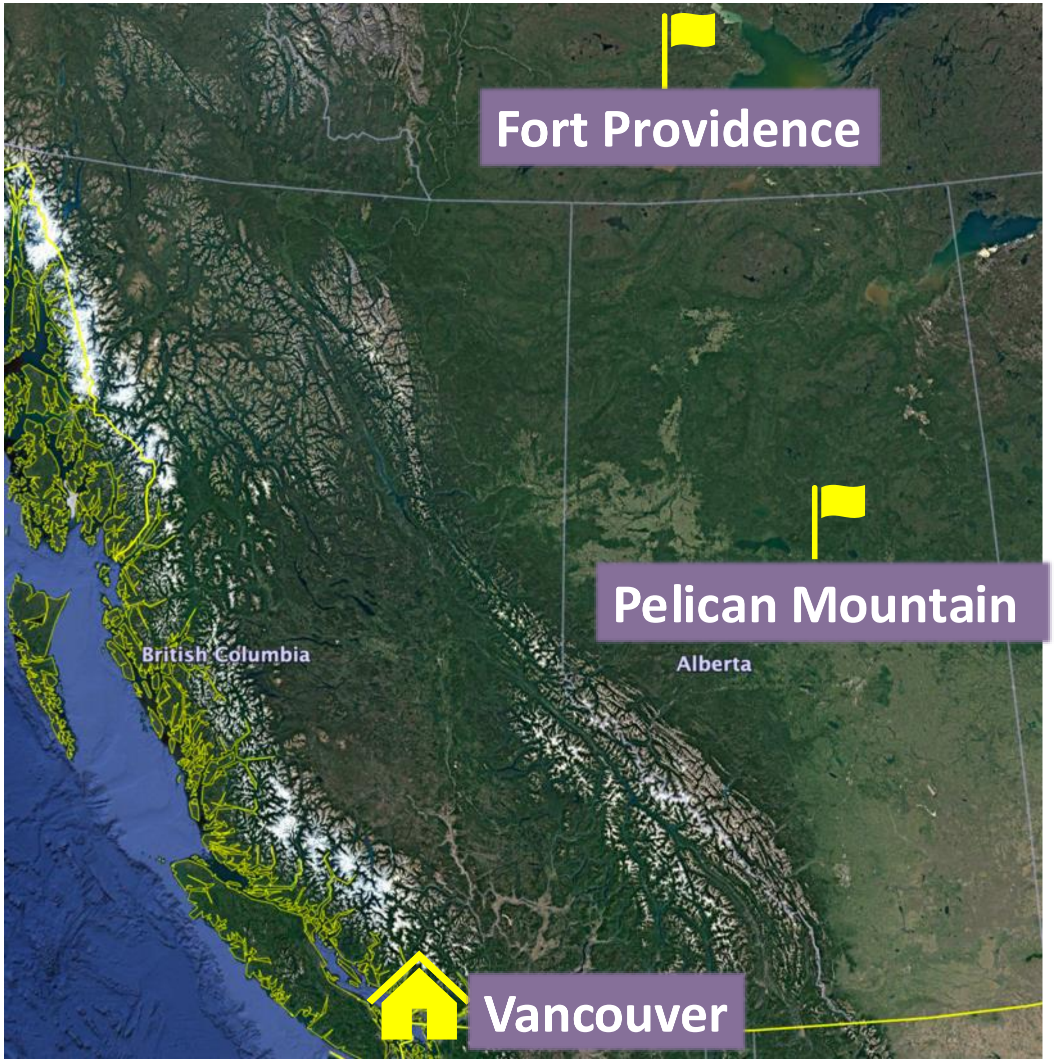
## Smoke Forecast Framework

### Example: BlueSky Canada

## FIELD OBSERVATIONS

# Site Locations




**Pelican Mountain May 2019**

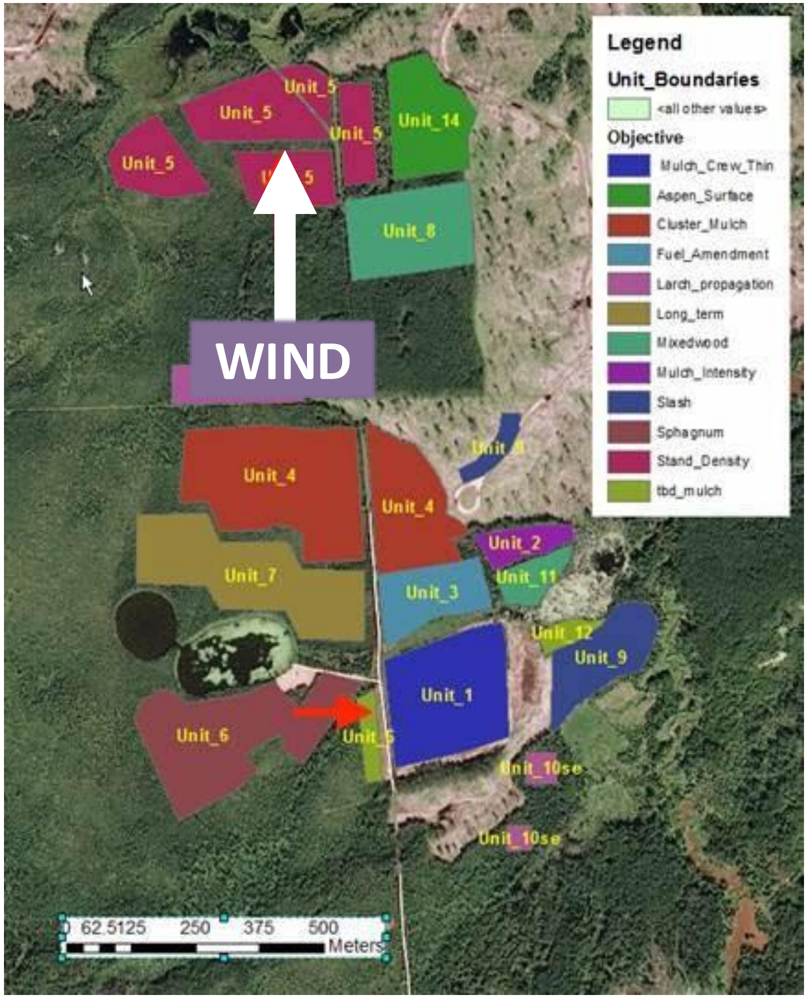
Alberta Wildfire

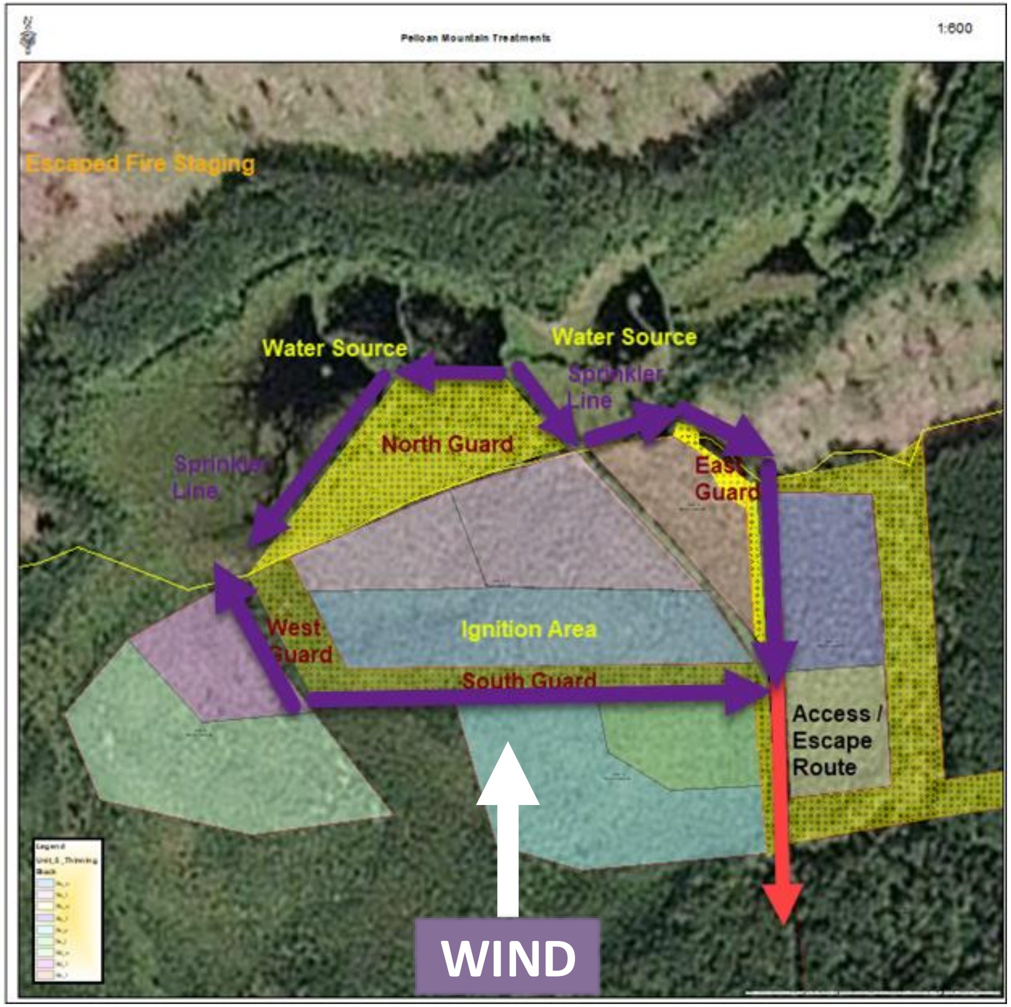
**Fort Providence July 2019**

FPInnovations

## FIELD OBSERVATIONS

# Pelican Mountain

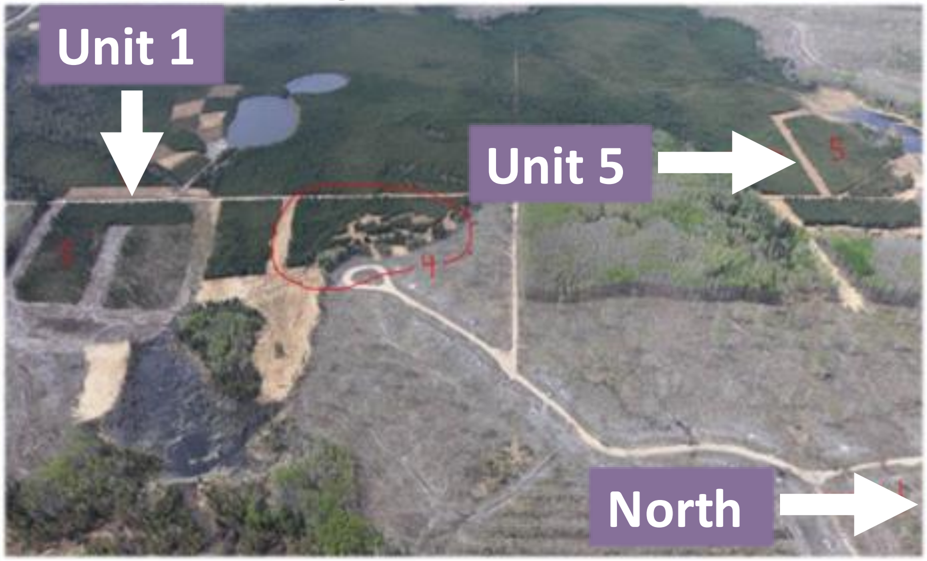


FIELD OBSERVATIONS

# Pelican Mountain


## Unit 5 May 2019

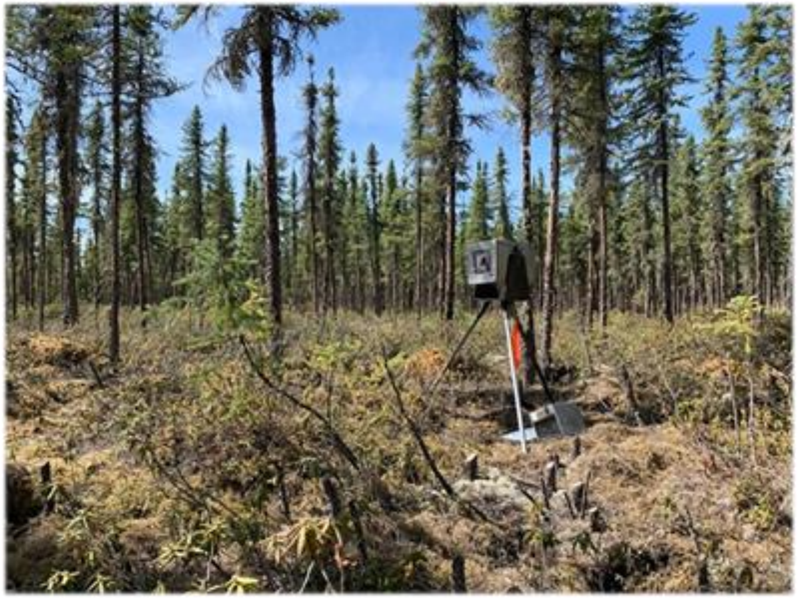



## Unit 1 May 2020

**(fingers crossed)**

## FIELD OBSERVATIONS

# Instruments



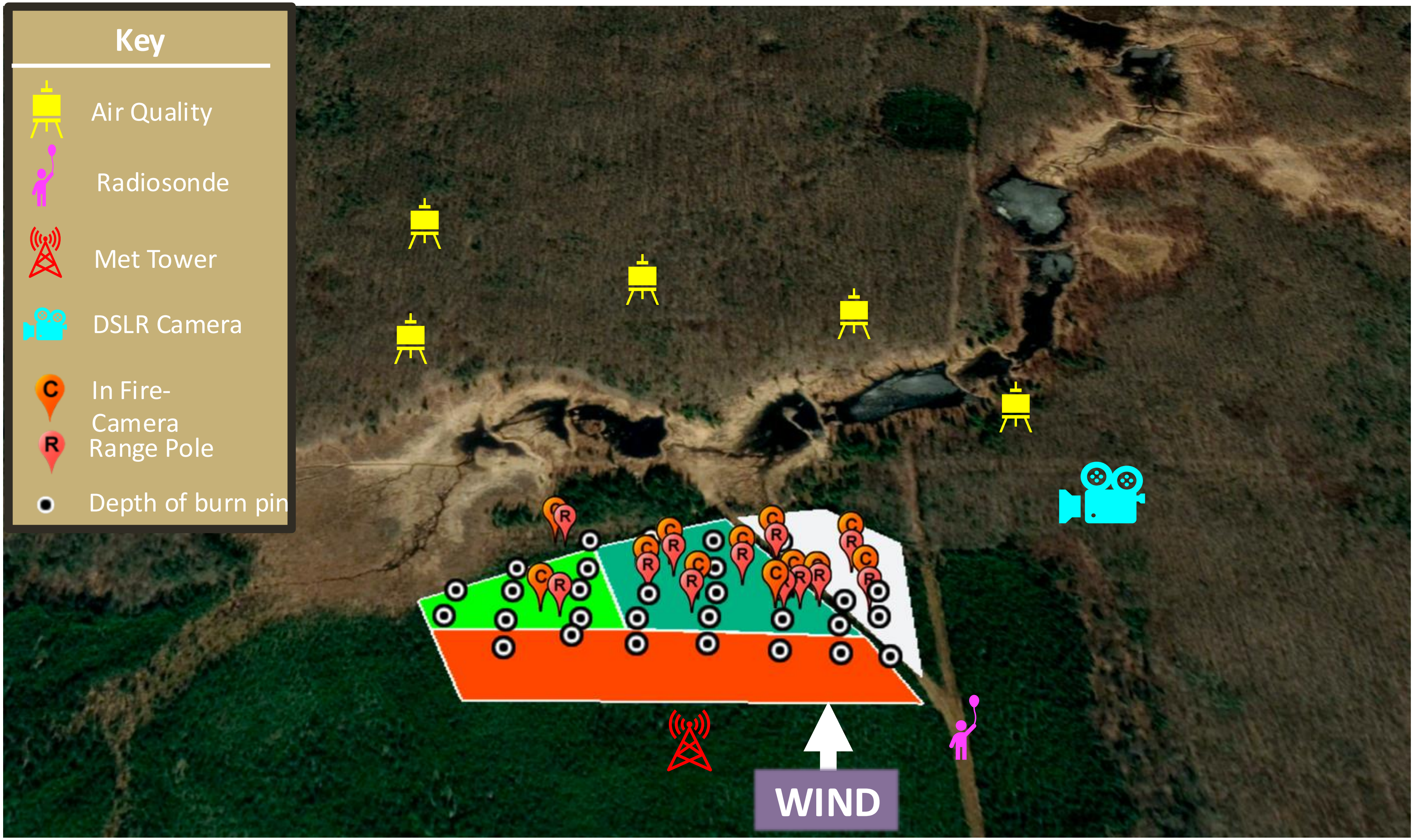
FPInnovations

| Category | Instruments / Variables |
|---|---|
| **Atmospheric** | HOBOS, ATMOS 41, Radiosonde and Micro Air Monitoring Station Data |
| | Temperature, Relative Humidity Wind Speed and Direction, Solar Irradiance, Total VOC, HCHO, CO2, PM2.5, PM1 and O3 |
| **Forestry** | Heat Flux Sensor, Range Pole |
| | Depth of burn, Fireline Intensity |
| **Cameras** | DSLR, FLIR |
| | High resolution visible footage, Infrared Imagery |

# FIELD OBSERVATIONS

## Instruments

Alberta Wildfire



## FIELD OBSERVATIONS

# Cameras

### In-Fire Cameras

### Cameras at Observation Zone

## FIELD OBSERVATIONS

# Weather Instruments

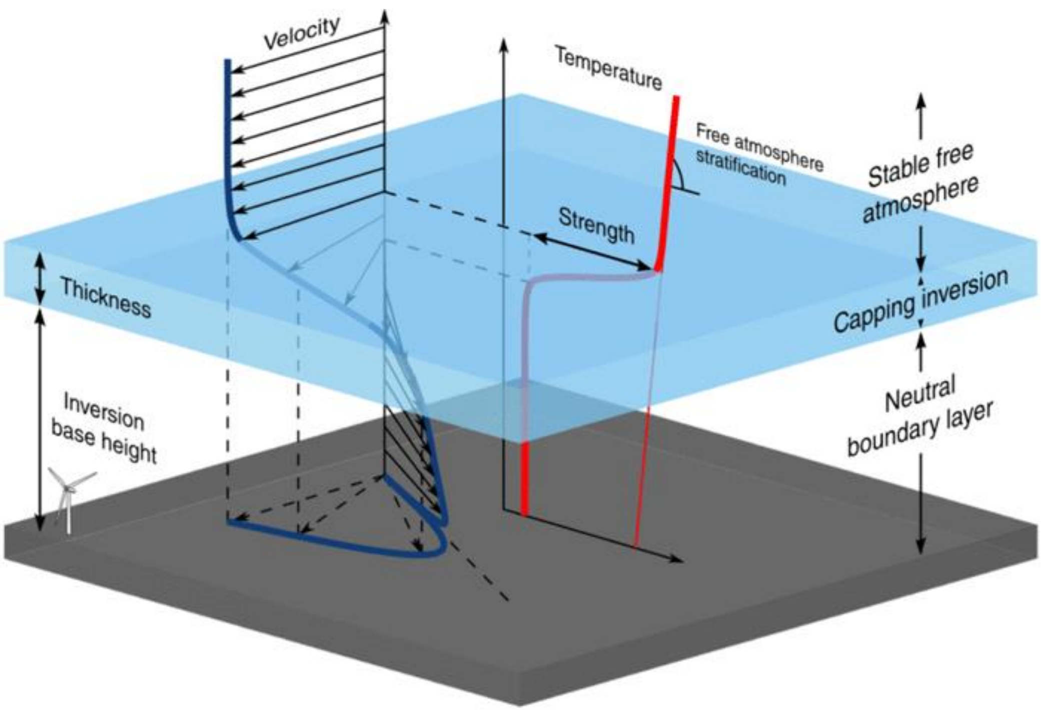
### HOBO Temp/RH

### Met-Tower

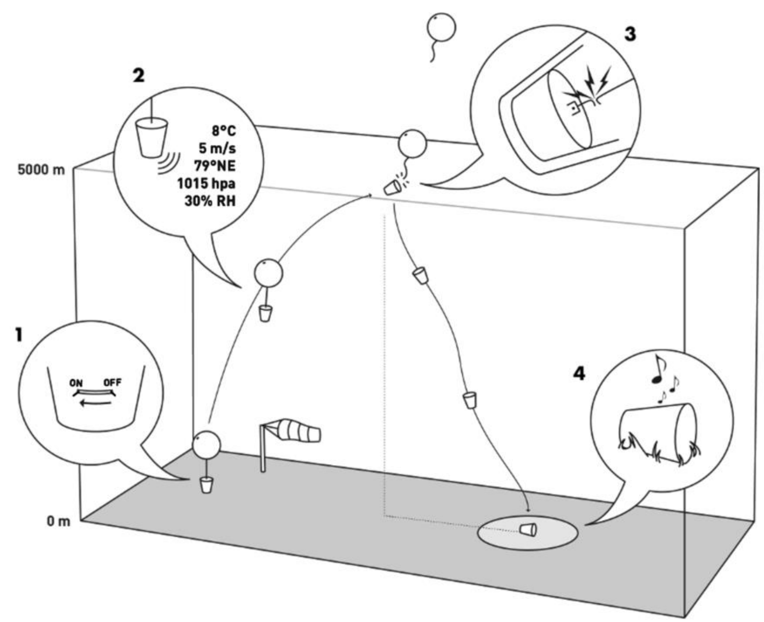
### Air Quality Sensor

## FIELD OBSERVATIONS

# Atmospheric Profile




**Boundary Layer Schematic**

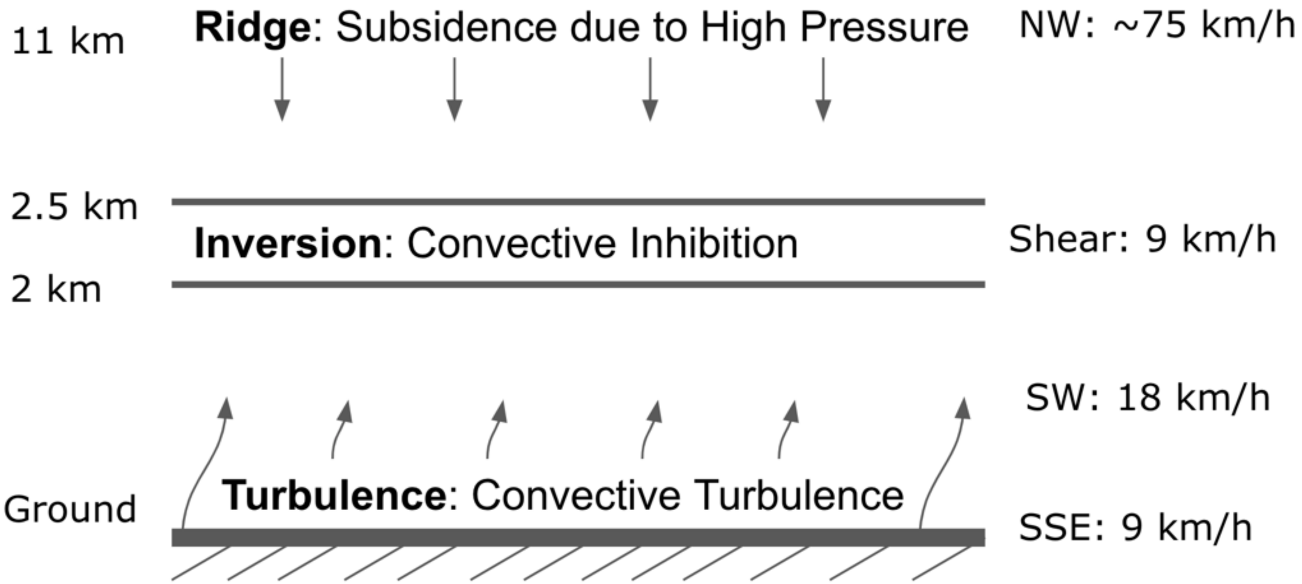



**Windsonde System**

## FIELD OBSERVATIONS

# Windsonde Sounding System

**Windsonde**



# FIELD OBSERVATIONS
## Observation Zone

FIELD OBSERVATIONS

# Observation Zone

Alberta Wildfire

Canada
Natural Resources Canada
Canadian Forest Service

FIELD OBSERVATIONS

# In-Fire Camera

FIELD OBSERVATIONS

# In-Fire Camera

## FIELD OBSERVATIONS
# Pre/Post Fire

## FIELD OBSERVATIONS
# Pre/Post Fire

Alberta Wildfire

FIELD OBSERVATIONS

# Pelican Mountain Science Team

FIELD OBSERVATIONS

# Pelican Mountain Science Team

UBC

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Alberta Wildfire

Canada
Natural Resources Canada
Canadian Forest Service

FIELD OBSERVATIONS

# Pelican Mountain Science Team

UBC

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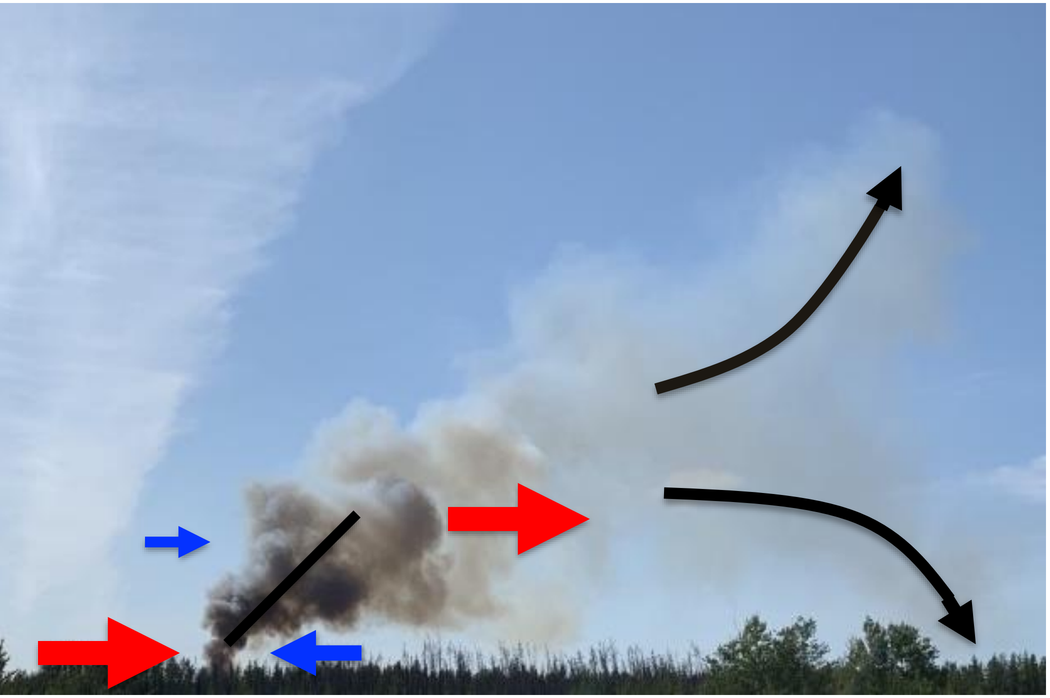
Alberta Wildfire

Canada

Natural Resources Canada
Canadian Forest Service

# Insights



**Smoke Plume Dynamics**

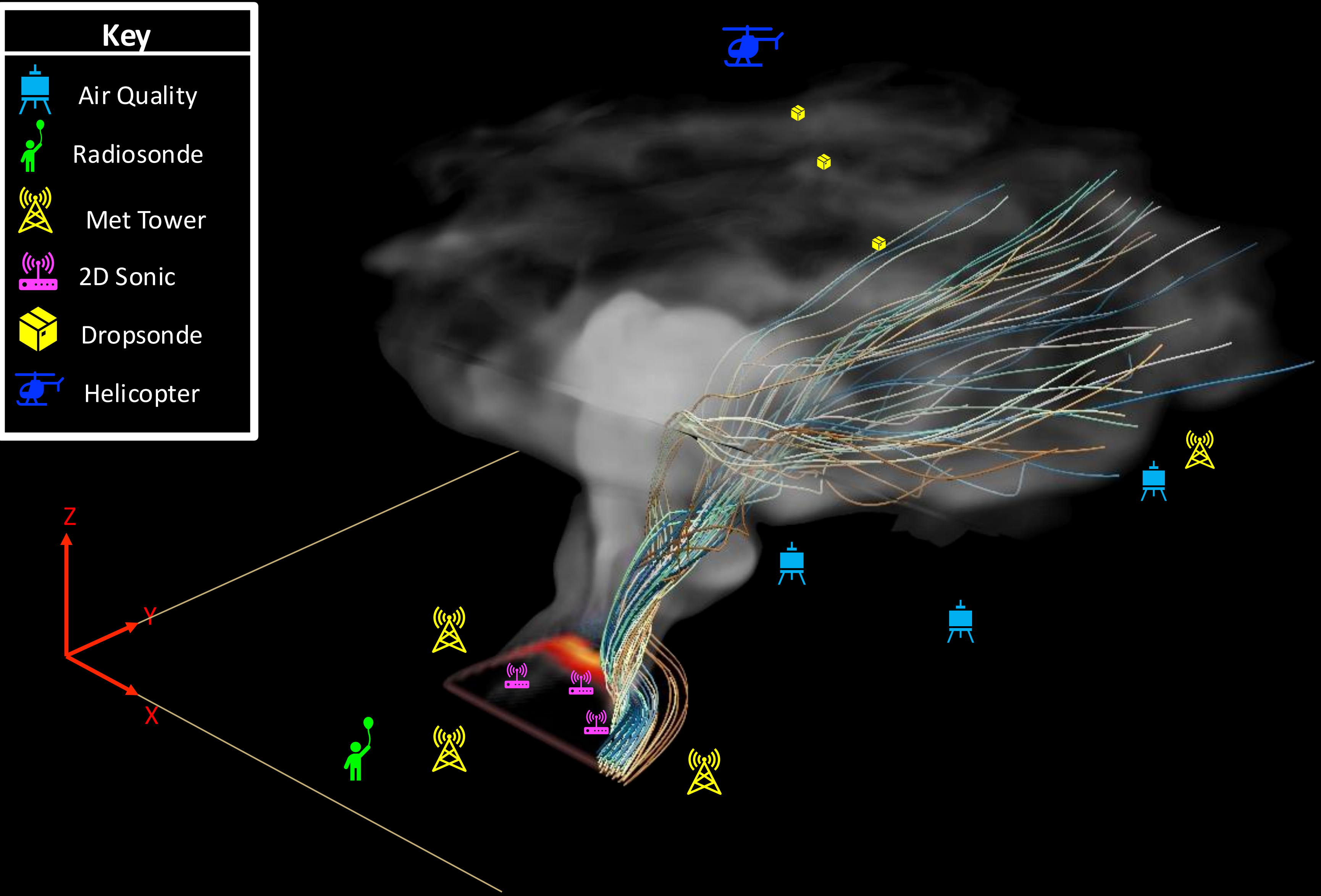
We see the same dynamic features that our models produce.

How can we measure these features?

Luckily we have more chances!

With better understating of logistics
- Operations
- Travel
- Gear (zip ties!)

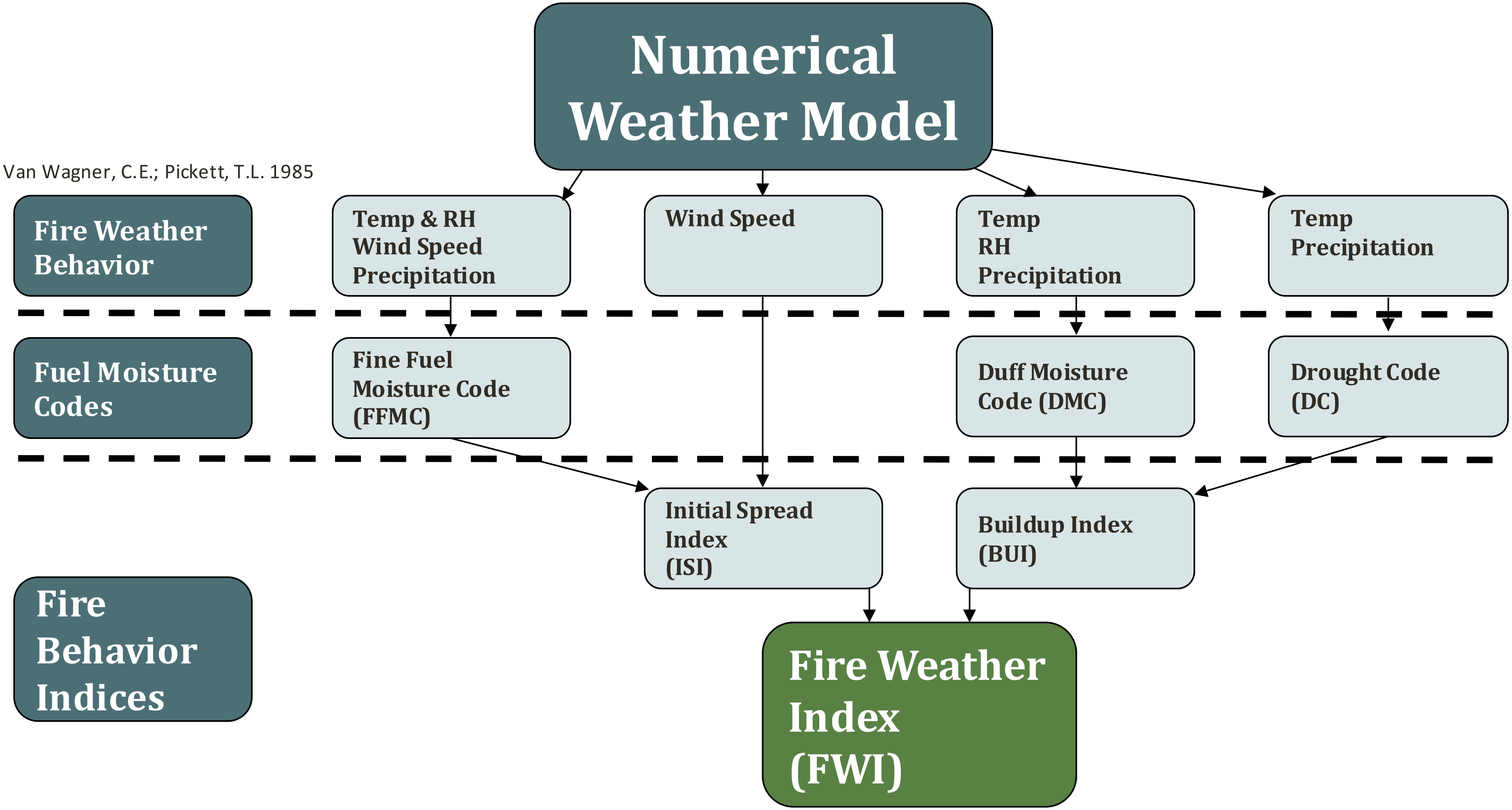
Instruments
- Types
- Placement
- Response Times
- What's allowed


Key
Air Quality
Radiosonde
Met Tower
2D Sonic
Dropsonde
Helicopter
Z
Y
X

FIRE BEHAVIOR

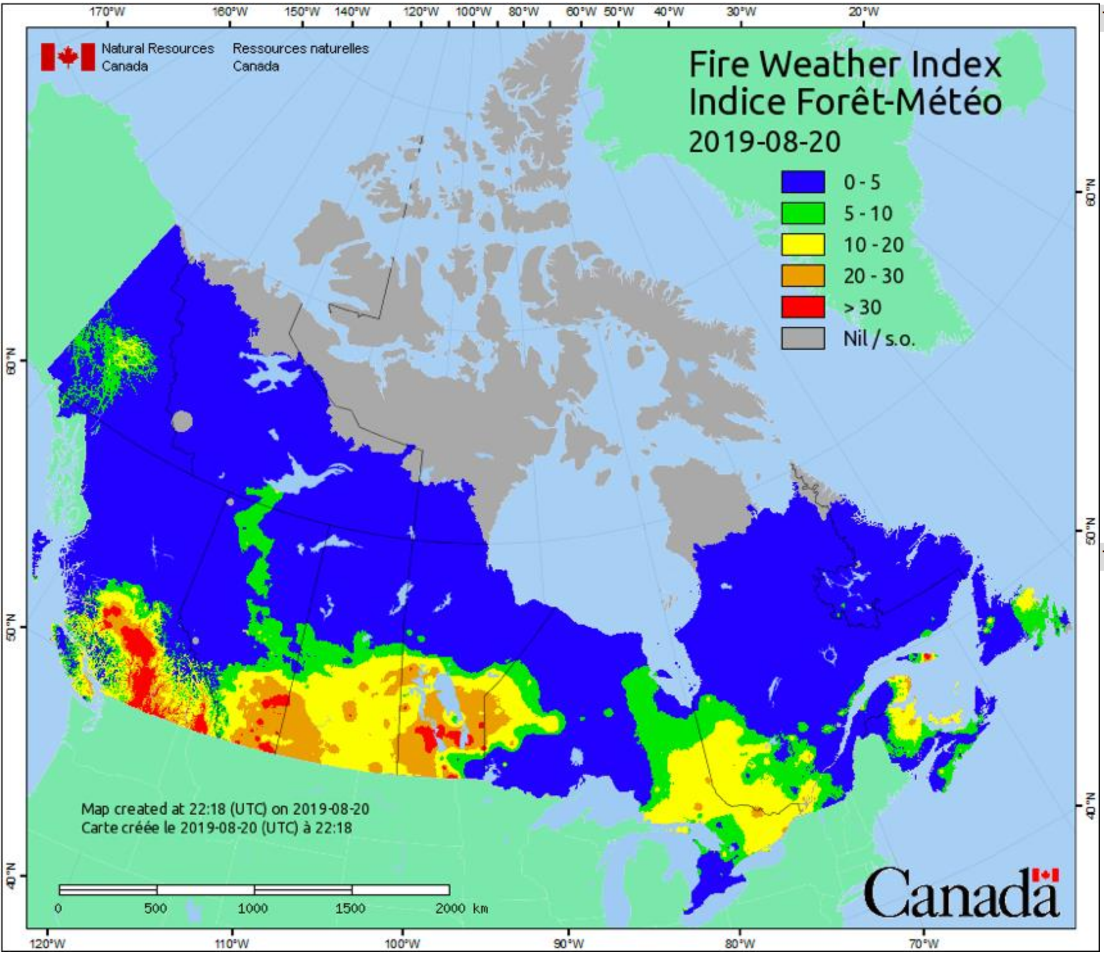
# Fire Weather Index System

Van Wagner, C.E.; Pickett, T.L. 1985



## FIRE BEHAVIOR

# Current Fire Weather Index Systems




Mark A Newman (FBAN)

| Time: | 1000h | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Wx | T | 23.7 | RH | 53 | Wind | SSW5g10 | Ppt | 0.0 |
| FWI | hFFMC | 84.5 | hISI | 2.5 | BUI | 101 | hFWI | 11.6 |

| FBP | Fuels | Loc. | Int. Class | ROS | FT | CFB |
|---|---|---|---|---|---|---|
| | C-1 | H | 1 | <1 | S | 0% |
| | | F | 1 | <1 | S | |
| | | B | 1 | <1 | S | |
| | C-2 | H | 4 | 2 | IC | 21% |
| | | F | 3 | 1 | S | |
| | | B | 3 | 1 | S | |
| | C-3 | H | 2 | <1 | S | 0% |
| | | F | 2 | <1 | S | |
| | | B | 2 | <1 | S | |
| | C-4 | H | 4 | 2 | IC | 14% |
| | | F | 3 | 1 | S | |
| | | B | 3 | 1 | S | |
| | M-2(50) | H | 3 | 1 | S | 0% |
| | | F | 3 | 1 | S | |
| | | B | 2 | 1 | S | |

| Time: | 1300h | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Wx | T | 27.7 | RH | 43 | Wind | SSW8g18 | Ppt | 0.0 |
| FWI | hFFMC | 89.2 | hISI | 5.7 | BUI | 106 | hFWI | 22.1 |

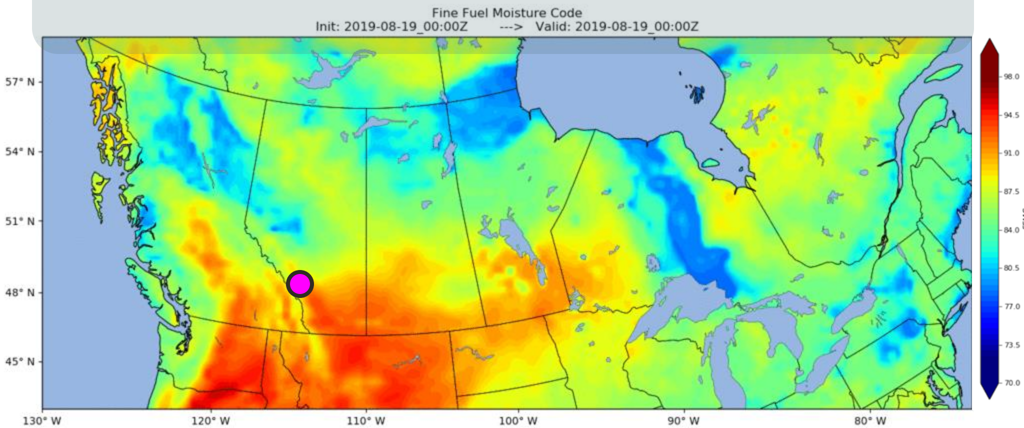
| FBP | Fuels | Loc. | Int. Class | ROS | FT | CFB |
|---|---|---|---|---|---|---|
| | C-1 | H | 2 | <1 | S | 0% |
| | | F | 2 | <1 | S | |
| | | B | 1 | <1 | S | |
| | C-2 | H | 5 | 7 | IC | 76% |
| | | F | 5 | 4 | IC | |
| | | B | 4 | 2 | IC | |
| | C-3 | H | 3 | 1 | S | 0% |
| | | F | 3 | 1 | S | |
| | | B | 2 | <1 | S | |
| | C-4 | H | 5 | 7 | IC | 73% |
| | | F | 4 | 4 | IC | |
| | | B | 4 | 2 | IC | |
| | M-2(50) | H | 4 | 4 | S | 3% |
| | | F | 3 | 2 | S | |
| | | B | 3 | 1 | S | |

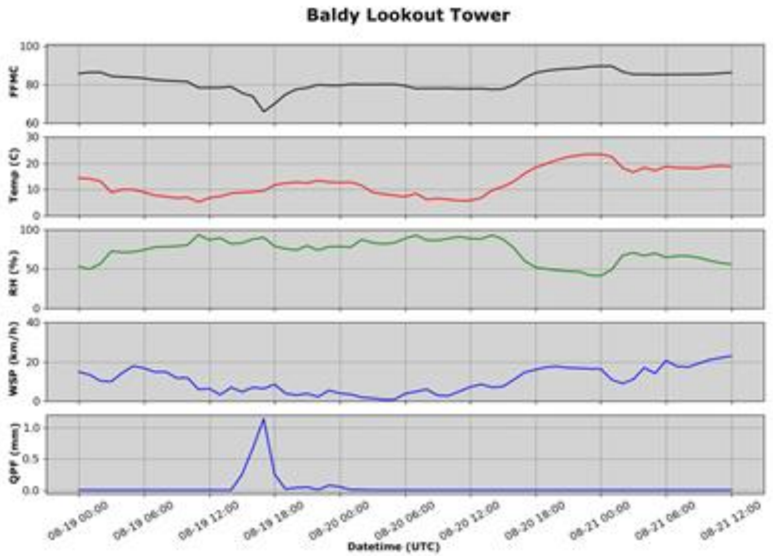
# FIRE BEHAVIOR

## NWP Derived Fire Weather Index Systems

Van Wagner, C.E.; Pickett, T.L. 1985

**Fine Fuel Moisture Code**

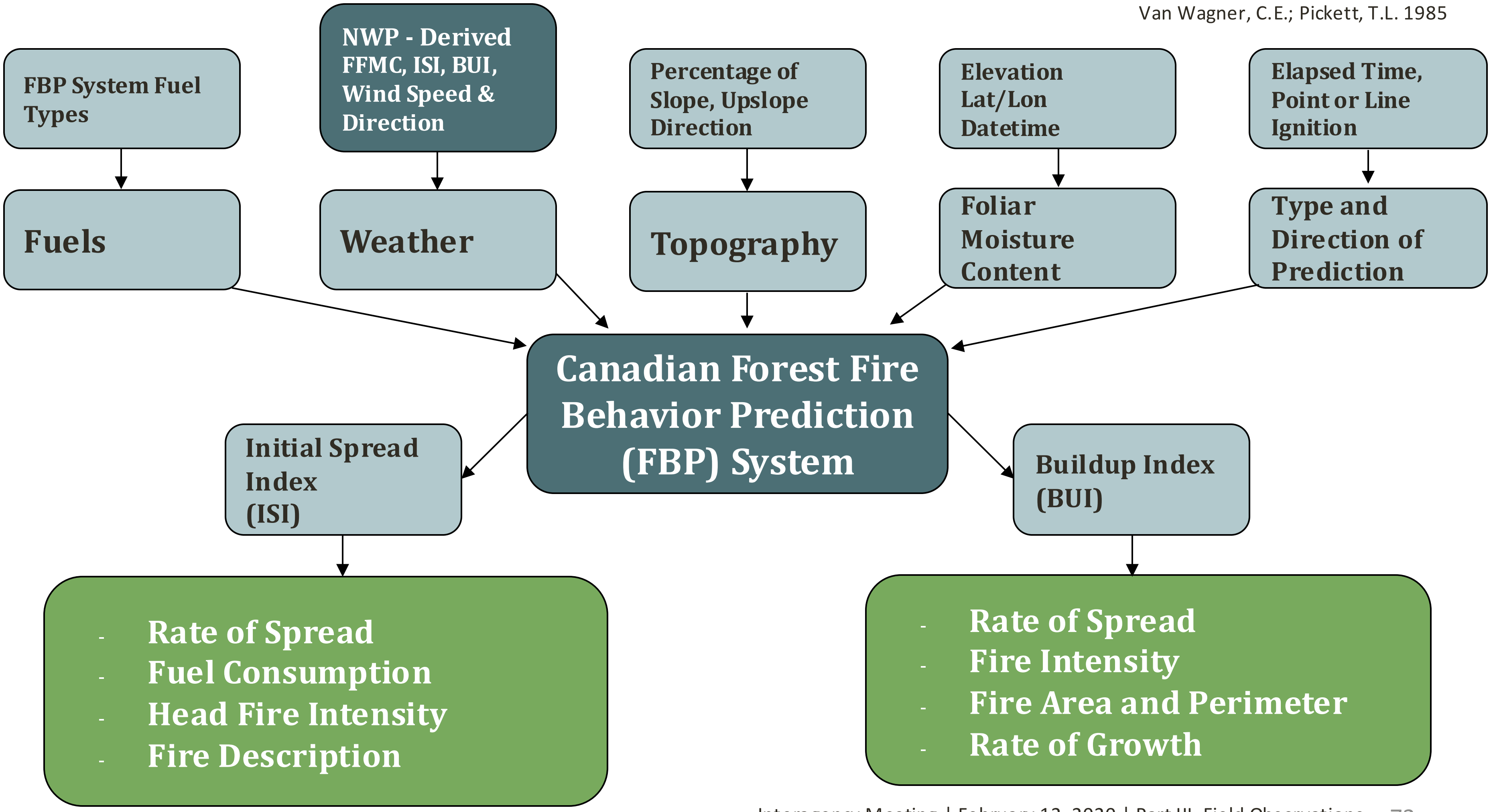



**Pink Dot Indicates Baldy Fire Lookout Tower**

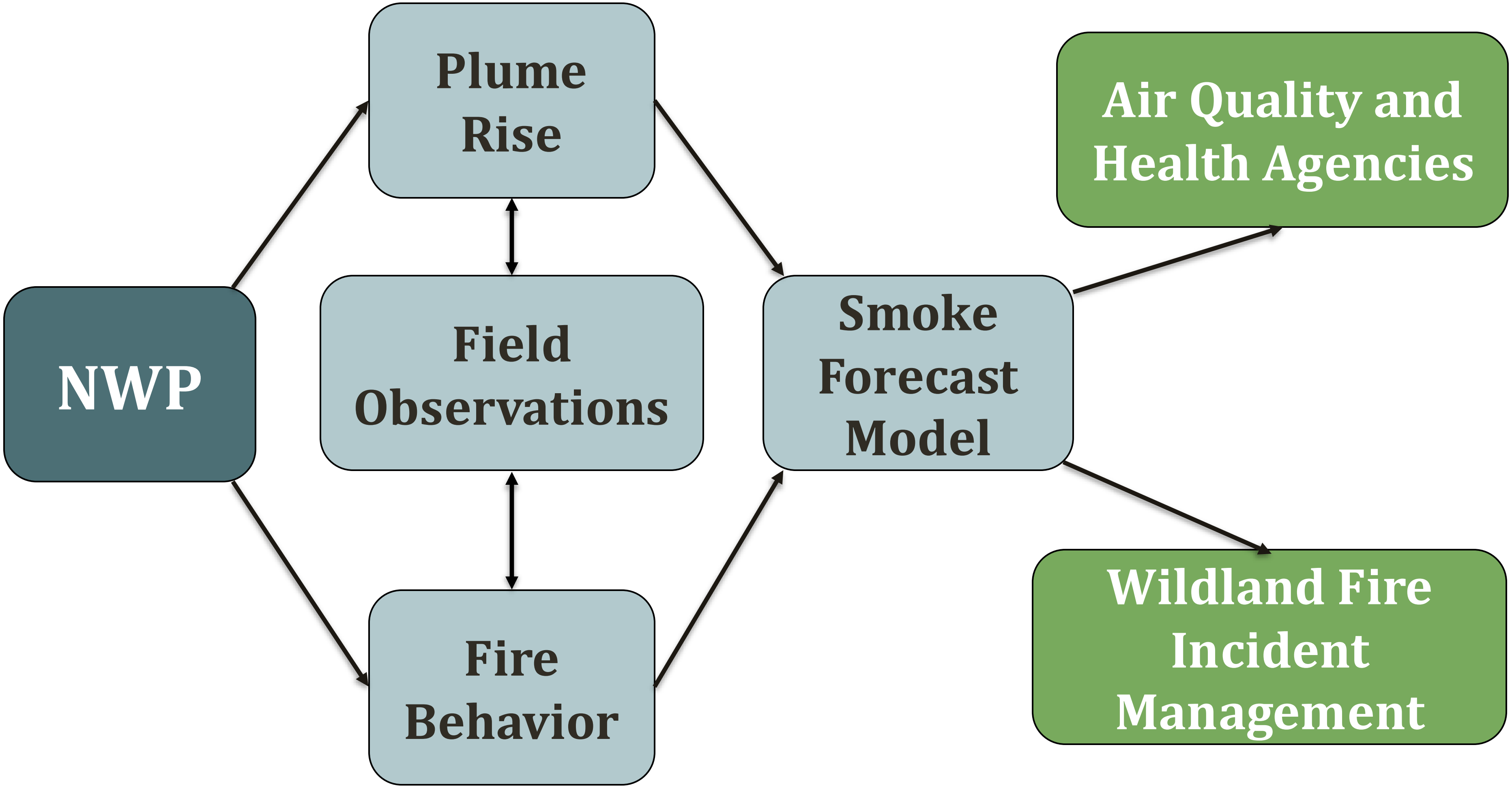
# NWP Future Research: NWP-Derived fire behavior prediction system

Van Wagner, C.E.; Pickett, T.L. 1985



OVERVIEW

# UBC Wildfire and Smoke Research



# ACKNOWLEDGEMENTS

## Thank you to our Sponsors

### Current operations supported by:

British Columbia
Alberta
Northwest Territories
Canada — Natural Resources Canada, Canadian Forest Service
UBC

### Development & past operations supported by:

British Columbia
Alberta
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Canada — Natural Resources Canada / Ressources naturelles Canada, Environment Canada / Environnement Canada, Parks Canada / Parcs Canada
Forest Service U.S. Department of Agriculture
Manitoba
Government of Saskatchewan
Ontario
Canada — Canadian Safety and Security Program

# UBC Wildfire and Smoke Research

**Department of Earth, Ocean and Atmospheric Sciences | University of British Columbia**

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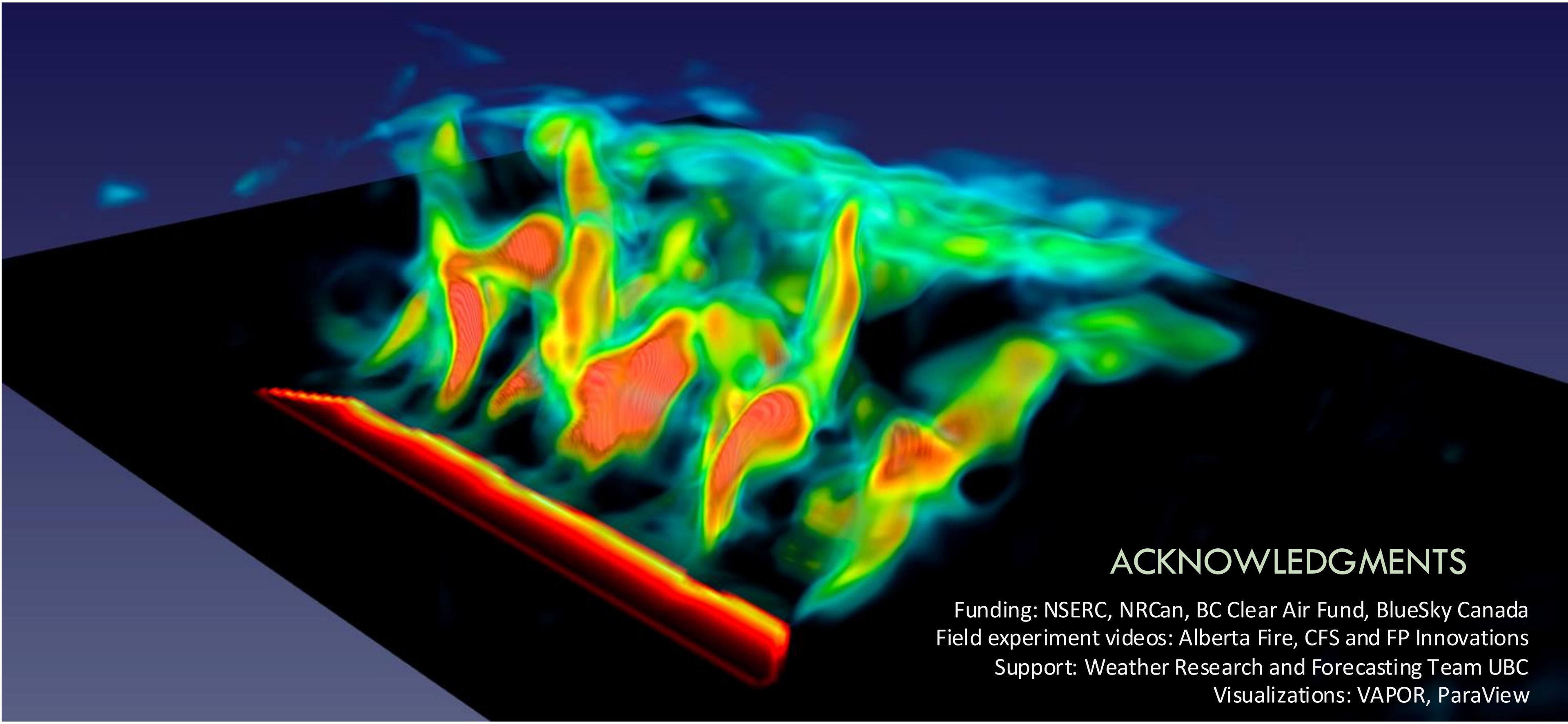
**Dr. Rosie Howard (DALES):** **rhoward@eoas.ubc.ca**

**Christopher Rodell (Field Experiments):** **crodell@eoas.ubc.ca**

**Prof. Roland Stull:** **rstull@eoas.ubc.ca**



## ACKNOWLEDGMENTS

Funding: NSERC, NRCan, BC Clear Air Fund, BlueSky Canada

Field experiment videos: Alberta Fire, CFS and FP Innovations

Support: Weather Research and Forecasting Team UBC

Visualizations: VAPOR, ParaView

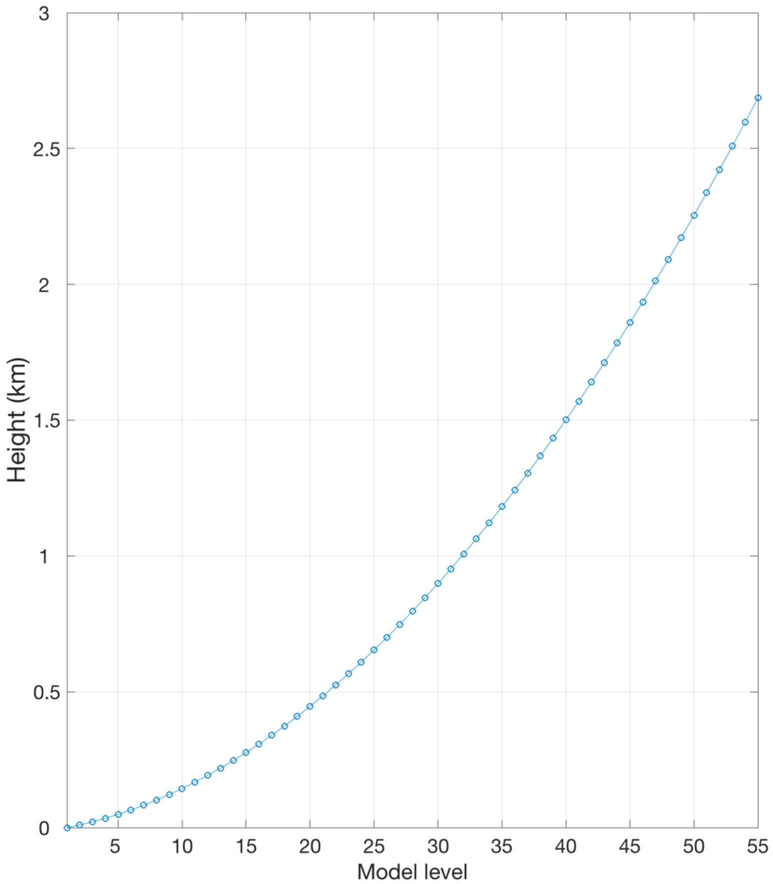
## OVERVIEW

# UBC Wildfire and Smoke Research

- **Part I: Using a Large-Eddy Simulation Model to Understand Wildfire Plume Dynamics**
    - Model evaluation
    - Flow dynamics
    - Smoke injection height parameterization
- **Part II: Investigating wildfire smoke behavior using simplified large-eddy simulations**
    - Idealized studies
    - Convergence zone and lateral flow
    - Fireline dimensions
- **Part III: The use of field observations for model validation of wildland fires: A focus on smoke plume rise.**
    - Big picture: smoke modelling frameworks
    - Prescribed burns and experimental design
    - Fire Behavior

# DALES: vertical levels

- 55 vertical levels
- Hyperbolically stretched
  - 31 within the boundary layer for my test cases



## APPENDIX

# WRF-SFIRE: Model Evaluation

atmosphere

MDPI

*Article*

## Capturing Plume Rise and Dispersion with a Coupled Large-Eddy Simulation: Case Study of a Prescribed Burn

**Nadya Moisseeva * and Roland Stull**

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Received: 16 August 2019; Accepted: 23 September 2019; Published: 25 September 2019

check for updates

**Abstract:** Current understanding of the buoyant rise and subsequent dispersion of smoke due to wildfires has been limited by the complexity of interactions between fire behavior and atmospheric conditions, as well as the uncertainty in model evaluation data. To assess the feasibility of using numerical models to address this knowledge gap, we designed a large-eddy simulation of a real-life prescribed burn using a coupled semi-emperical fire–atmosphere model. We used observational data to evaluate the simulated smoke plume, as well as to identify sources of model biases. The results suggest that the rise and dispersion of fire emissions are reasonably captured by the model, subject to accurate surface thermal forcing and relatively steady atmospheric conditions. Overall, encouraging model performance and the high level of detail offered by simulated data may help inform future smoke plume modeling work, plume-rise parameterizations and field experiment designs.