On the Sensitivity of Wind and Temperature in the PBL and Roughness Sub-Layer to Canopy and Fire Properties

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Introduction

- Prescribed fires are useful tools for the management of forest ecology:
  - Generally low in intensity and confined to small areas
  - Smoke may linger in an area and affect air quality and public health
- Critical factors for managing smoke dispersion from low-intensity burns include near-surface meteorological conditions, local topography, vegetation, and atmospheric turbulence within and above vegetation layers
- The interplay between low-intensity fires, forest canopies, and background atmospheric properties is complex, and the impact of fire processes on nearby turbulent and mean flow is poorly understood
- We utilize the recently developed ARPS-CANOPY modeling system to explore these complex relationships

Prescribed burn in the New Jersey Pine Barrens, March 2010; photo credit: M. Kiefer

ARPS-CANOPY Model Summary

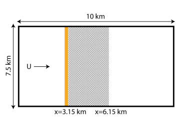
- Advanced Regional Prediction System (ARPS) Version 5.2.12 (Xue et al. 2003)
  - Three-dimensional atmospheric modeling system
  - Designed to simulate microscale [O(10 m)] through regional scale [O(10^6 m)] flows
- Standard version of ARPS has been modified in the following ways:
  - Impact of drag forces on mean and turbulent flow through a vegetation canopy is accounted for via production and sink terms in the momentum and subgrid-scale (SGS) turbulent kinetic energy (TKE) equations [proportional to frontal area density (A_f); $m^2\ m^{-3}$]
  - Attenuation of net radiation by vegetation elements is accounted for with a downward decaying net radiation profile inside the canopy, and by attenuating ground net radiation before it is passed to the ARPS soil model

Model Setup and Experiment Design

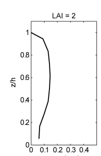
- 3D simulations with NX x NY x NZ = 211 x 155 x 78 grid points
- $\Delta x,y = 50$ m, $\Delta z = 2$ m up to z = 84 m, stretched from z = 84 m to top (3 km)
- Initial sounding: neutral (stable) atmosphere below (above) 1km AGL
- Two PBL stability classes: neutral (no canopy or ground net radiation) and unstable (steady canopy top net radiation applied; ground net radiation computed)
- Dry atmosphere; contribution of moisture from fire neglected
- Homogeneous canopy [canopy height (h) = 18 m]; uniform flat terrain
- Initialized at 1200 LST, run for 4 hours with surface heat flux representing fire turned on at hour 3 (Q_o = 5 kW m^{-2})

Case Name:	U5 N	U10 N	U0 N	LAI0 N	U5 U	U10 U	U0 U	LAI0 U
U (m s^{-1})	5.0	10.0	0.0	5.0	5.0	10.0	0.0	5.0
Q_o (kW m^{-2})	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
LAI	2	2	2	0	2	2	2	0
Neutral/ Unstable PBL	N	N	N	N	U	U	U	U

* LAI: Leaf area index (m^2 leaf area per m^2 ground area)

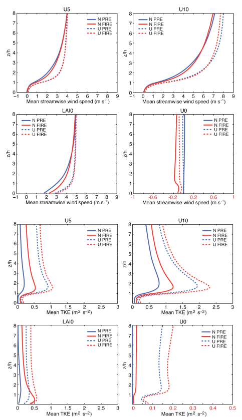


** Orange shading indicates fire position, gray shading denotes averaging zone used for analysis



Case Comparison: Vertical Profiles

- **Objective: Evaluate how sensitivity of mean and turbulent flow to a low-intensity fire differs as background wind speed, static stability, and canopy cover are varied**



- In U5 & U10 neutral cases, ~ 0.3 m s^{-1} increase in mean wind speed occurs in layer from z/h = 1 to z/h = 4; shear increases correspondingly
- Largest change noted in LAI0 case, with greatest impact from surface to z/h = 2
- Response in unstable cases generally weaker
- In U10 cases, wind speed *decreases* above 3 or 4 times canopy height
- In U0 cases, weak (0.1-0.2 m s^{-1}) easterly flow develops east of fire

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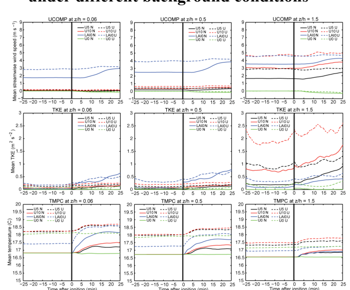
- In all cases, TKE increases due to fire
- For non-zero background wind and non-zero LAI, greatest change occurs near z/h = 1.5-1.7
- For LAI0 case, maximum change occurs near z/h = 0.5
- Sensitivity greatest in neutral cases
- Strongest response occurs in LAI0 neutral case

Vertical profiles of mean (top) streamwise wind component and (bottom) turbulent kinetic energy (TKE), averaged temporally over 25-min period and spatially over area downstream of fire (see schematic, lower left). PRE refers to 25 min period before fire begins; FIRE refers to 25 min period after fire begins. Note that different x-axis limits are used for the U0 cases.

Case Comparison: Timeseries

- **Objective: Examine timeseries of wind speed, TKE and temperature to explore how atmospheric properties evolve before and after fire ignition, under different background conditions**

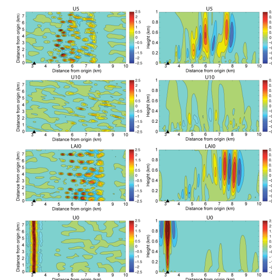


- Increase in streamwise wind due to fire occurs mainly above z/h = 1, except for LAI0 neutral case
- Largest changes to streamwise wind and TKE occur in neutral cases
- Inside canopy, TKE and temperature response to fire is delayed compared to LAI0 case
- Strongest temperature response occurs at surface (z/h = 0.06)

Timeseries of spatially averaged streamwise wind component (UCOMP), turbulent kinetic energy (TKE), and temperature (TMPC), at surface (z/h = 0.06), mid-canopy (z/h=0.5) and above canopy (z/h=1.5). Fire start time indicated by vertical line.

Convection: Horizontal and Vertical Structure

- **Objective: Assess sensitivity of fire-induced convective structure to background wind speed and canopy cover, for neutral cases.**



- Multicellular convection dominates for cases with background wind speed of 5 m s^{-1} or greater
- Convection weaker in intensity with stronger background wind
- Upright plume develops in U0 case; updraft flanked by pair of downdrafts
- In unstable PBL case (not shown), region of fire-enhanced convection embedded within field of PBL convection
- Convection enhances vertical mixing of momentum (see vertical profiles)

Left: Horizontal cross-sections of 500 m AGL vertical velocity (m s^{-1}), 20 minutes after fire start. Right: Vertical cross sections of vertical velocity (m s^{-1}) averaged in y-direction, 20 minutes after fire start. Note the different colorbar used for the U0 vertical cross section (bottom right panel). Fireline located 3.15 km from origin (see triangle symbol).

Relevance of Findings to Smoke Dispersion

- Strengthening of mean wind speed above canopy may impact the advection of smoke from source
- Increase in TKE downstream of fire may serve to enhance horizontal and vertical dispersion of smoke downstream of fire
- Despite weak nature of heat source, smoke has potential to be transported by fire-generated convection through PBL and exchanged with free atmosphere
- Greatest potential for smoke to enter free atmosphere occurs when flow is weak and single upright convection column develops

Conclusions

- Sensitivity of mean and turbulent flow downstream of low-intensity fire to background wind, static stability, and forest canopy has been examined
- Response to fire is generally weaker with unstable background compared to neutral
- With non-zero background wind, convective cells promote increased vertical mixing of momentum, yielding stronger winds above canopy (LAI not equal to zero) or above ground surface (LAI equal to zero)
- In U0 cases, weak easterly flow develops east of fire
- Under all scenarios, TKE increases; response largest in neutral LAI0 case
- *Practical application*: Development of new operational predictive tools for local smoke dispersion management during low-intensity prescribed burns
- *Future work*: Examine additional parameters, including fire intensity, canopy morphology and canopy density

Acknowledgements

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