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An Investigation of the Sensitivity of Wind and Temperature in the Lower Atmosphere to Canopy and Fire Properties

Michael T. Kiefer[1]*, Warren E. Heilman[2], Shiyuan Zhong[1], Joseph J. Charney[2], and Xindi Bian[2]

[1]*Department of Geography, Michigan State University, East Lansing, MI 48824*
[2]*USDA Forest Service, Northern Research Station, East Lansing, MI 48824*

*mtkiefer@msu.edu

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 structure, 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 model to explore these complex relationships

Flames and smoke during prescribed burn in New Jersey Pine Barrens (March 2012). Photos courtesy Warren Heilman.

ARPS-CANOPY Model Summary

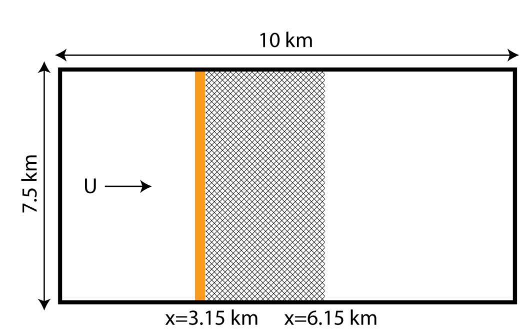
- Advanced Regional Prediction System (ARPS) Version 5.2.12 (Xue et al. 2003)
  - Three-dimensional atmospheric modeling system
  - Designed to simulate microscale [O(10 m)] - synoptic scale [O(10^7 m)] flows
- Standard version of ARPS has been modified in the following ways:
  - Impact of drag forces 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 plant area density (A_p); $m^2\ m^{-3}$]
  - Attenuation of net radiation by vegetation elements is accounted for with a downward decaying net radiation profile inside the canopy, and by reducing ground net radiation before it is passed to the ARPS soil model

Model Setup and Experiment Design

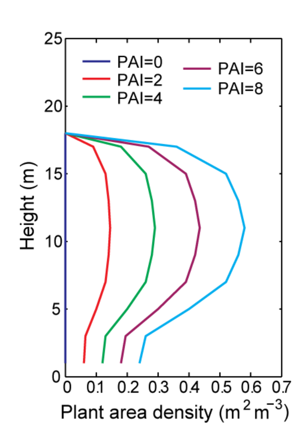
- 3D simulations with NX x NY x NZ = 211 x 155 x 78 grid points
- $\Delta x,y$ = 50 m, Δz = 2 m up to z = 84 m, stretched from z = 84 m to top (3 km)
- Initial condition: neutral (stable) atmosphere below (above) 1km AGL; dry profile
- Two stability classes: neutral (no background heat source) and convective (steady canopy top net radiation specified; ground net radiation computed)
- Homogeneous canopy [canopy height (h) = 18 m]; uniform flat terrain
- Initialized at 1200 local standard time, run for 4 hours with surface heat flux (Q_{fire} = 5 kW m^{-2}) representing low-intensity fire introduced at hour 3

Experiment	U0	PAI	Qo (Y/N)?
U0P2N ("quiescent")	0	2	N (neutral)
U0P2C ("quiescent")	0	2	Y (convective)
U5P0N ("no canopy")	5	0	N (neutral)
U5P0C ("no canopy")	5	0	Y (convective)
U5P2N ("sparse canopy")	5	2	N (neutral)
U5P2C ("sparse canopy")	5	2	Y (convective)
U5P8N ("dense canopy")	5	8	N (neutral)
U5P8C ("dense canopy")	5	8	Y (convective)
U10P2N ("strong wind")	10	2	N (neutral)
U10P2C ("strong wind")	10	2	Y (convective)

PAI: Plant area index ($PAI = \int_0^h A_p(z)dz$)
Uo: Base state wind speed (m s^{-1})
Qo: Ground/canopy heat source outside of fire

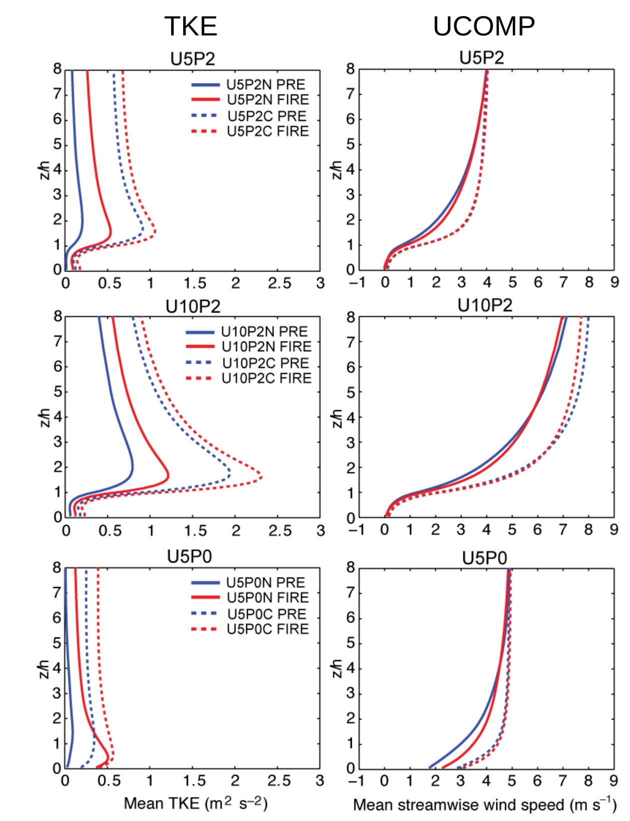


Orange shading indicates fire position, gray shading denotes averaging zone used for analysis



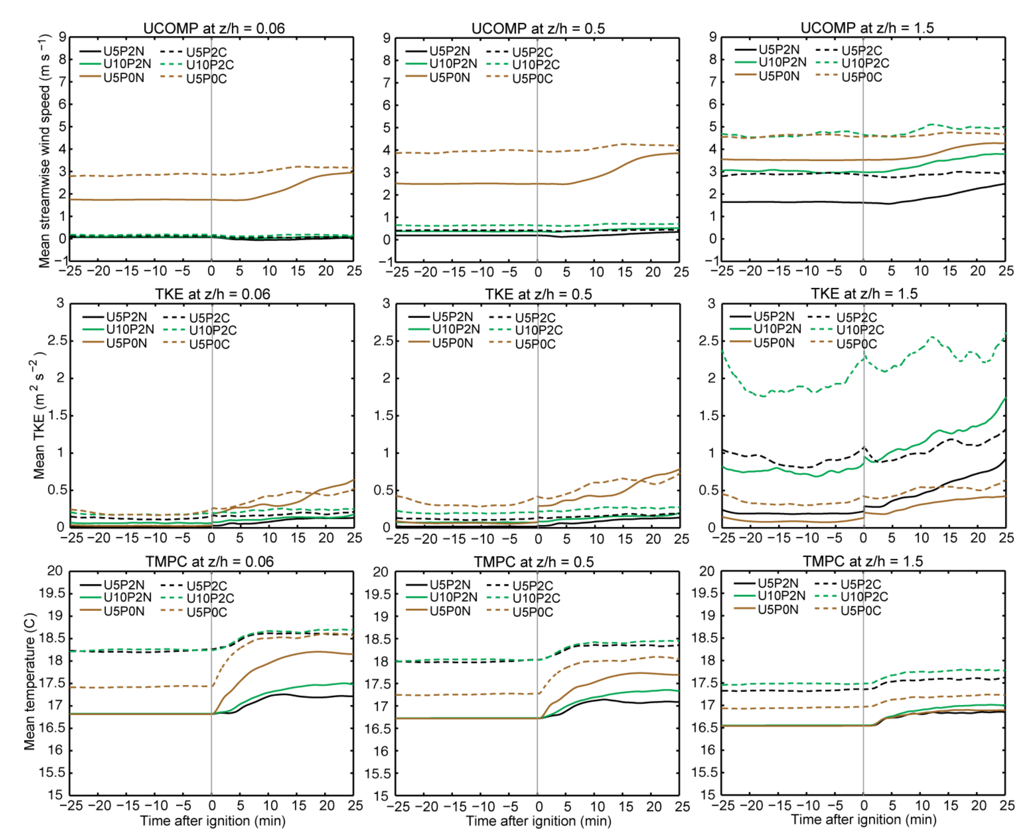
Sensitivity to Wind, Static Stability, and Forest Cover

- **Objective: Evaluate how atmospheric response to a low-intensity fire varies as background wind speed, stability, and canopy cover are varied**



- In all cases, TKE increases due to fire
- For PAI > 0, greatest TKE change occurs near z/h = 1.5-1.7; For PAI = 0, maximum TKE change occurs near z/h = 0.5 (9 m AGL)
- For PAI > 0, increase in TKE coincides with increase in vertical wind shear near z/h = 1.5
- Sensitivity greater in neutral cases
- Strongest overall response occurs in U5P0 neutral case

Vertical profiles of (left) mean turbulent kinetic energy (TKE) and (right) streamwise component of wind (UCOMP), 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.

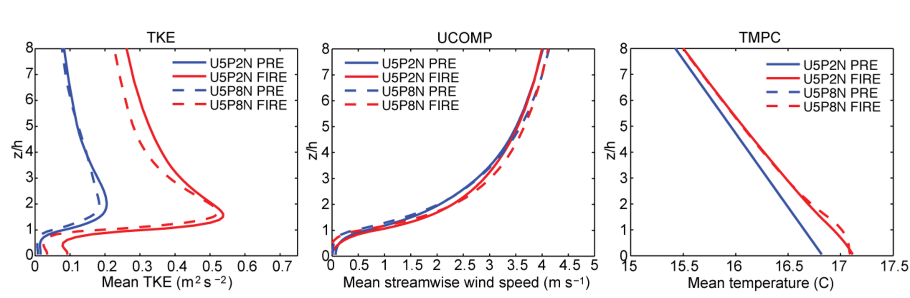


- Largest changes to streamwise wind and TKE occur in neutral cases
- Considerable variability in pre-fire mean TKE in cases with convective background stability
- Changes to streamwise wind, TKE muted inside canopy
- Strongest temperature response occurs at surface (z/h = 0.06)
- Temperature response to fire inside canopy is delayed compared to no canopy cases

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.

Sensitivity to Canopy Density

- **Objective: Evaluate role of canopy density in atmospheric response to fire**

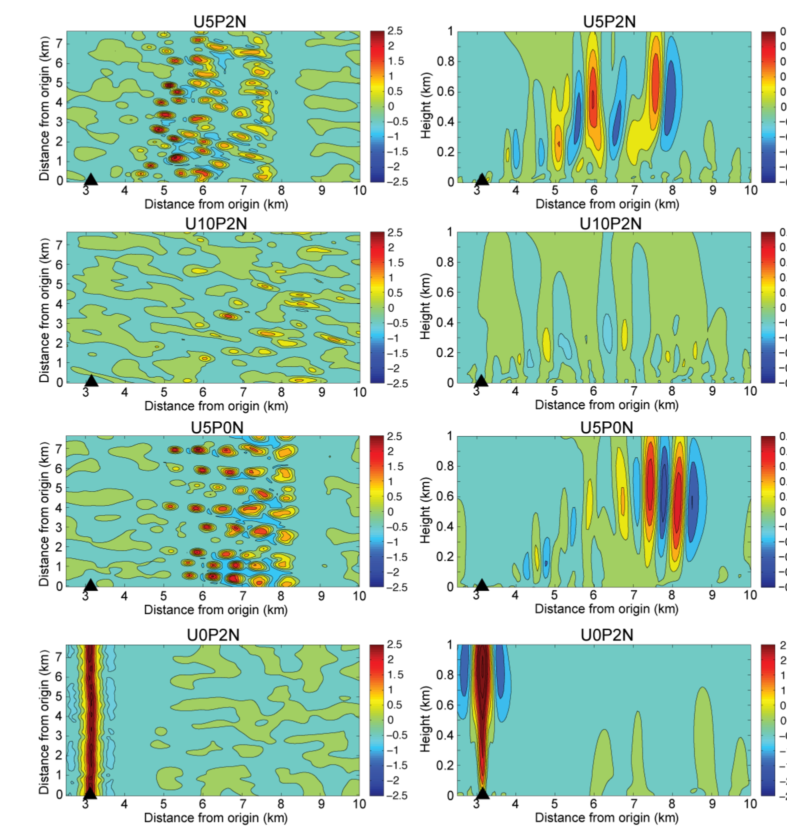


Vertical profiles of (left) mean turbulent kinetic energy (TKE), (center) streamwise component of wind, and (right) mean temperature, averaged temporally over 25-min period and spatially over area downstream of fire. PRE refers to 25 min period before fire begins; FIRE refers to 25 min period after fire begins. Only cases with neutral background are shown.

- Pre-fire: TKE slightly smaller above dense canopy than sparse canopy
- Response to fire weaker in dense canopy case, especially below z/h=1 and above z/h=2
- Canopy drag overwhelms buoyant production of TKE inside dense canopy
- Wind shear increases due to fire in both cases
- Warming due to fire similar, but lapse rates below z/h = 2 sensitive to PAI

Fire-Induced Convection: Horizontal and Vertical Structure

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



- Multicellular regime dominates for cases with background wind speed of 5 m s^{-1} or greater
- Fire-generated convection weaker in intensity with stronger background wind
- Upright plume develops in quiescent case; updraft flanked by pair of downdrafts
- In case with convective background (not shown), region of fire-generated convection embedded within field of planetary boundary layer (PBL) convection
- Fire-induced 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

- 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
- Muted response of TKE to fire inside dense canopy suggests the potential for smoke to linger inside canopy, close to source

Summary and Conclusions

- Sensitivity of mean and turbulent flow downstream of low-intensity fire to background wind, stability, and forest canopy has been examined
- In all cases, TKE increases; response to fire largest in neutral no-canopy case
- With non-zero background wind, fire-induced convective cells promote increased vertical mixing of momentum, yielding stronger winds above canopy (PAI not equal to zero) or above ground surface (PAI equal to zero)
- Canopy drag dampens response to fire for sparse and dense canopies, and overwhelms buoyant production of TKE inside dense canopy
- *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 and canopy morphology

Acknowledgements

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