Management-scale atmospheric modeling:
Exploring fire-induced turbulent flows in forested environments

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NAFSE SERDP webinar series
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Outline

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Context within SERDP project

From Nick Skowronski’s May 2 overview webinar:

**Technical objectives**

1) **Physical processes at multiple scales**
   - Heat transfer: Radiative and convective
   - Ignition
   - Thermal degradation
   - Flaming and smoldering combustion
   - Mass consumption
   - Fire propagation particles and fuel layers scale.

2) **Fuel-bed characteristics**
   - Spatial variability in fuel particle type
   - Fuel moisture status
   - Bulk density
   - Arrangement of fuel components

3) **Multi-scale atmospheric dynamics**
   - Understanding of the effects of multi-scale atmospheric dynamics:
     - Ambient and fire- and forest overstory-induced turbulence on fire spread and convective heat transfer

- Atmosphere
  - +
  - Fire
  - +
  - Forest canopy
Context within SERDP project

From Nick Skowronski’s May 2 overview webinar:

Scales: order of 100 m to 10 km; minutes to hours
Context within SERDP project

A quick note on terminology

In this presentation: “forest canopy” includes all layers (overstory, midstory, and understory)

Source: http://www.riverpartners.org/
Motivation for using models

Why use models to study ambient and fire- and forest canopy-induced turbulence?
- Fill in gaps in our knowledge of fire-atmosphere-canopy interactions
- Help answer questions that field campaigns alone are unable to address
  - Gaps between data points in space, impossible to control all degrees of freedom, limits on repeatability

What are some possible applications of this work? Improvements to predictions of:
- Smoke dispersion
- Tree mortality
- Fire behavior

Eric Mueller’s webinar:
25 July
Model components
Atmospheric model component

- Computational Fluid Dynamics (CFD) models
  - Useful for studying smaller-scale atmospheric phenomena (e.g., fire whirls, turbulent eddies at fire front)
  - Limited applicability at “management scale”
  - Examples: HIGRAD/FIRETEC, WFDS*  

- “Full physics” models (aka “weather models”)
  - Useful for studying larger-scale atmospheric phenomena (e.g., smoke plumes, pyrocumulus clouds)
  - Limited applicability at “fire front scale”
  - Examples: ARPS*, ARPS-CANOPY, WRF*-SFIRE

*WFDS: Wildland Fire Dynamics Simulator; *ARPS: Advanced Regional Prediction System; *WRF: Weather Research and Forecast model
Model components
Fire model component

- **Two-way coupled**
  - Combustion products (e.g., heat, moisture, smoke) exchanged with atmosphere; fire-perturbed atmosphere influences fire evolution; Two-way interactive
  - Examples: HIGRAD/FIRETEC, WFDS, WRF-SFIRE

- **One-way coupled**
  - Combustion products exchanged with atmosphere; fire is static and does not respond to atmospheric changes
  - Example: ARPS, ARPS-CANOPY [heat exchange only]

- **Uncoupled**
  - No representation of combustion products in model
  - Example: National Weather Service (NWS) operational models
Model components

Forest canopy model component

- **Bulk canopy approach**
  - The bulk effect of forest canopy on the atmosphere is computed in a single layer, beneath the lowest model grid point.
  - Common approach in weather models, including NWS models. Examples: ARPS, WRF, WRF-SFIRE

- **Multi-level canopy approach**
  - Accounts for the effect of forest canopy on mean and turbulent flow and on atmospheric heat/moisture inside the canopy.
  - Multiple atmospheric levels inside forest canopy.
  - More computationally expensive.
  - Examples: WFDS, HIGRAD/FIRETEC, ARPS-CANOPY.
Model components

Model selection

- Selection of model is problem-dependent. Ask:
  - What atmospheric scales are most relevant?
  - Is it important to simulate within-canopy flows?
  - Is it important to represent two-way fire-atmosphere feedback?
- For SERDP management-scale modeling, we choose ARPS-CANOPY
  - Decision based on desire to simulate a **broader range of atmospheric scales**, and simulate **flow within the forest canopy**
  - However, it is important to keep in mind that all models have advantages **and** disadvantages
Modeling challenges

- Resolving and/or parameterizing multiscale processes

- Uncertainty with parameters in canopy and fire models (e.g., canopy drag coefficient)
  - Small- and mid-scale lab experiments and modeling may provide guidance

Modeling challenges

- Synthesizing complex multi-scale forest and fire patterns into forms that can be implemented in models.

Plant area density [m²/m³]

Photo credits: Wikipedia (top), Warren Heilman (bottom)
Sources of uncertainty
(not an exhaustive list)

- Models can only fully resolve phenomena that are about 5x grid spacing or larger
- Representation of unresolved processes
  - Subgrid-scale turbulence
  - Land-vegetation-atmosphere exchanges
  - Combustion processes
- Canopy and fire information
  - Simplifying complex patterns for ingestion into models
- Simulating stochastic (random) processes
Modeling study examples

Outline

- HIGRAD/FIRETEC (CFD, multi-level canopy, 2-way fire)
  - “Impacts of tree canopy structure on wind flows and fire propagation simulated with FIRETEC” (Pimont et al. 2011)

- WRF-SFIRE (“full physics”, bulk canopy, 2-way fire)
  - “Coupled Fire–Atmosphere Simulations of the Rocky River Fire Using WRF-SFIRE” (Peace et al. 2016)

- ARPS-CANOPY (“full physics”, multi-level canopy, 1-way fire)
  - Model background
  - Fire and forest canopy representation
  - Three example studies [case study and idealized]
Modeling study examples
HIGRAD/FIRETEC

- Pimont et al. (2011): Impacts of tree canopy structure on wind flows and fire propagation simulated with FIRETEC

Simulated within-canopy wind field

Simulated fire behavior

Domain: 640-m x 320-m
Modeling study examples

WRF-SFIRE

- Peace et al. (2016): Coupled Fire–Atmosphere Simulations of the Rocky River Fire Using WRF-SFIRE

- Simulate weather across multiple scales (nesting)
- Simulate fire spread in complex terrain & fuels
- Simulate fire-perturbed atmospheric boundary layer

Height above mean sea level (z MSL) [m]
Z MSL [m]; fire perimeter
Vertical velocity [m s\(^{-1}\)]; wind vectors

Domain: 600-km x 600-km
Domain: 22-km x 22-km
Modeling study examples

ARPS-CANOPY

--Preliminary: Background--

- Core: Advanced Regional Prediction System (ARPS) (Xue et al. 2000,2001):
  - Atmospheric model suitable for weather prediction across multiple scales (original focus: thunderstorms)

- ARPS-CANOPY (Kiefer et al. 2013) contains a canopy sub-model to account for canopy drag, turbulent processes, and heat/moisture exchange between vegetation and atmosphere.

- Fire is represented as surface sensible heat source (one-way coupled to atmosphere):
  - Atmosphere does not feed back on fire (as it does in HIGRAD/FIRETEC, WFDS, WRF-SFIRE)
Modeling study examples

ARPS-CANOPY
--Preliminary: Fire representation--

Observed fire line (NJ Pine Barrens, 20 March 2011)

Case study representation (fire propagation prescribed)

Idealized representation (stationary heat source)

Infrared imagery source: Bob Kremens (RIT)
Modeling study examples

ARPS-CANOPY

--Preliminary: Forest canopy representation--

1. Idealized canopy profiles*

plant area density \( (A_p) \): one-sided plant area per unit volume

plant area index (PAI): total plant area per unit ground area

* Images from Natural Fuels Photo Series
Modeling study examples

ARPS-CANOPY

--Preliminary: Forest canopy representation--

2. 3D plant area density data (LiDAR-derived)

Thanks to Nick Skowronski for LiDAR data
**Modeling study examples**

**ARPS-CANOPY [Idealized]**


1. Apply static line source of sensible heat (“fire”)

2. Vary background atmospheric conditions

3. Vary density of vegetation elements

4. Explore sensitivity of fire-induced flow to variations in canopy density and background weather

Total of 14 simulations

- Full sun scenario
- Cloudy scenario

Density of vegetation elements
Modeling study examples

ARPS-CANOPY [real case]


1. Simulate weather across multiple scales (nesting)
   - $Z \text{ msl [m]}$

2. Simulate “Large-scale” weather
   - Air temp. [$^\circ\text{C}$]: wind vectors

3. Represent forest canopy and fire sensible heating

4. Simulate turbulent flow within ~1 km of fireline
   - $TKE [m^2s^{-2}]$

Fire heat source

- 500 m
Modeling study examples

ARPS-CANOPY/FLEXPART-WRF [real case]

Charney et al. (2018*): Assessing Forest Overstory Impacts on Smoke Concentrations using a Coupled Numerical Model

(1) Use FEPS\textsuperscript{+} to estimate emissions during NJ prescribed fires

(2) Use ARPS-CANOPY simulated winds to drive FLEXPART-WRF particle dispersion model

Use FLEXPART-WRF to:

(3) Simulate smoke plumes with canopy

(4) Examine sensitivity of smoke plumes to canopy

\textsuperscript{+}FEPS: Fire Emissions Production Simulator
SERDP management-scale modeling strategy

- Technical Approach: "Augment the management-scale field experiments with numerical model simulations of coupled fire-atmosphere dynamics under differing environmental conditions to further understanding of how those dynamics affect management-scale fire propagation and heat transfer."

  1. Pre-burn guidance simulations: guide placement of instrumentation
  2. Post-burn validation simulations: illustrate strengths and weaknesses of model, informing future model development
  3. Sensitivity simulations: examine relative impacts of ambient atmospheric conditions and forest overstory patterns on fire-induced turbulent flows

- This is intended to be an iterative process
Models can help fill in gaps in our knowledge of fire-atmosphere-canopy interactions and help answer questions that field campaigns alone are unable to address.

However, keep in mind that all models have advantages and disadvantages.

ARPS-CANOPY has been applied previously in model studies of ambient, fire-induced, and canopy-induced turbulence.

For SERDP, model will be applied to management-scale fires in an iterative process.
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References


