Management-scale atmospheric modeling:

Exploring fire-induced turbulent flows in forested environments

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NORTH ATLANTIC FIRE SCIENCE EXCHANGE

Outline

1. Context within SERDP project
2. Motivation for using models
3. Model components
4. Modeling challenges
5. Sources of uncertainty
6. Modeling study examples
7. SERDP management-scale modeling strategy
8. Summary

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.

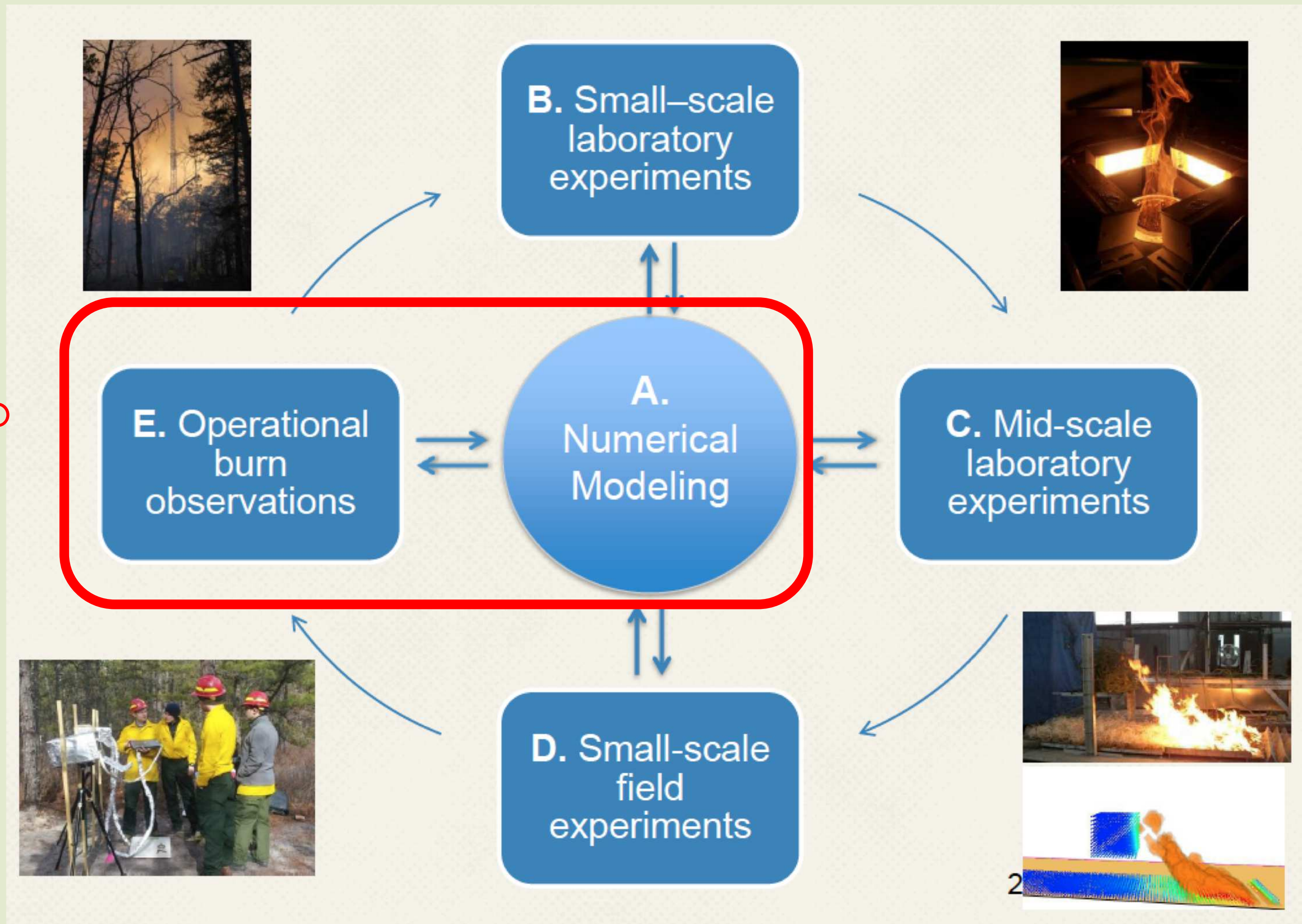
2) Fuel-bed characteristics
- Spatial variability in fuel particle type
- Fuel moisture status
- Bulk density
- Arrangement of fuel components

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

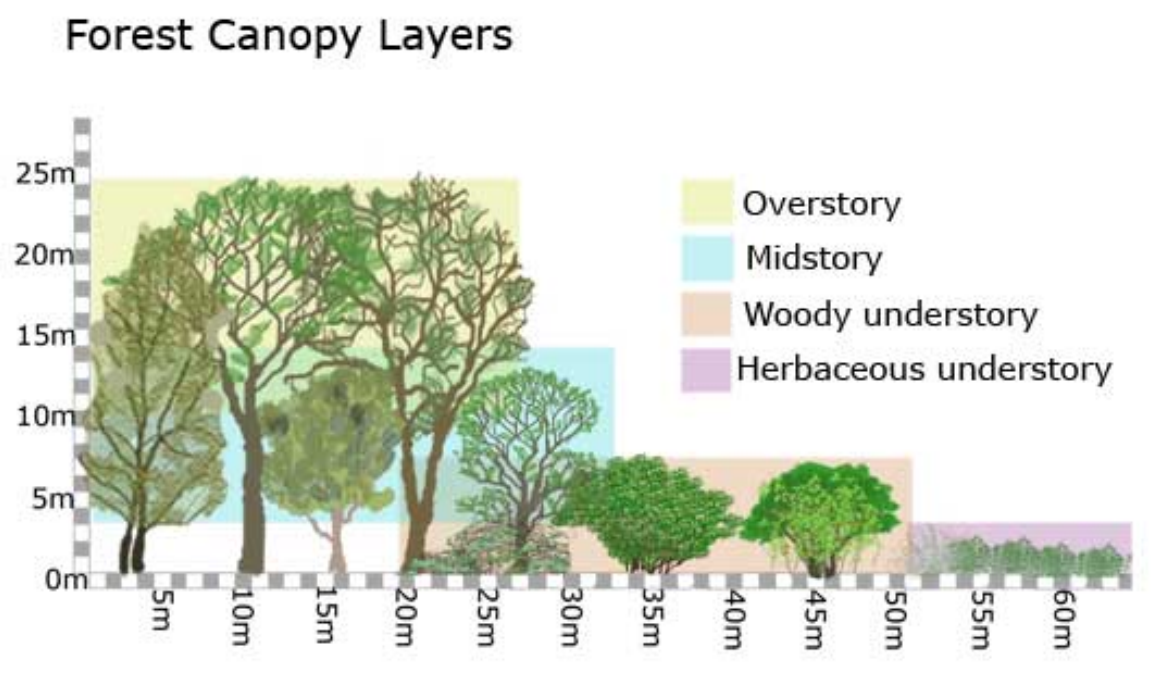
From Nick Skowronski's May 2 overview webinar:



Scales: order of 100 m to 10 km; minutes to hours

Context within SERDP project

A quick note on terminology



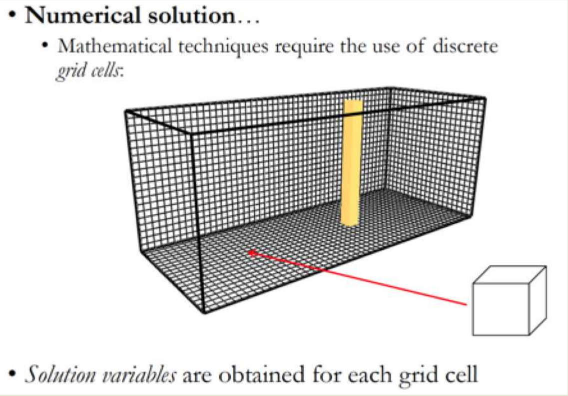
Source: http://www.riverpartners.org/

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

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 25 July webinar:



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*

SERDP management-scale

- "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

SERDP management-scale

- 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

SERDP management-scale

- 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

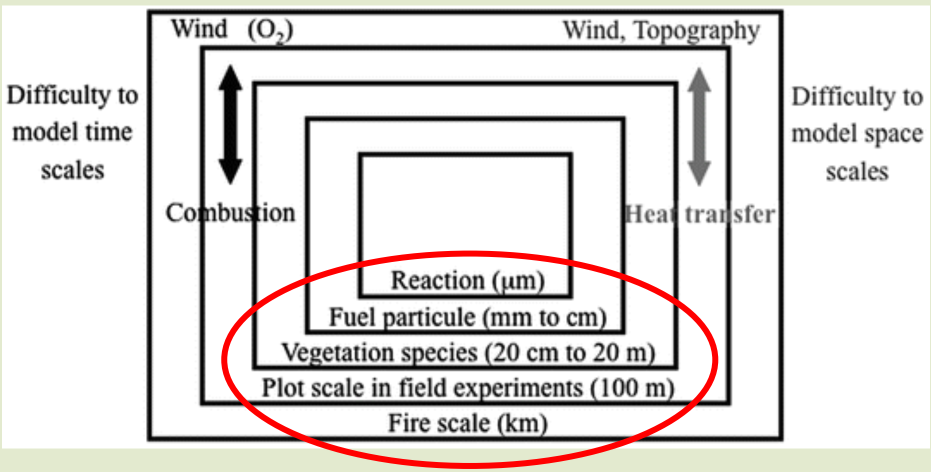
Model components

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



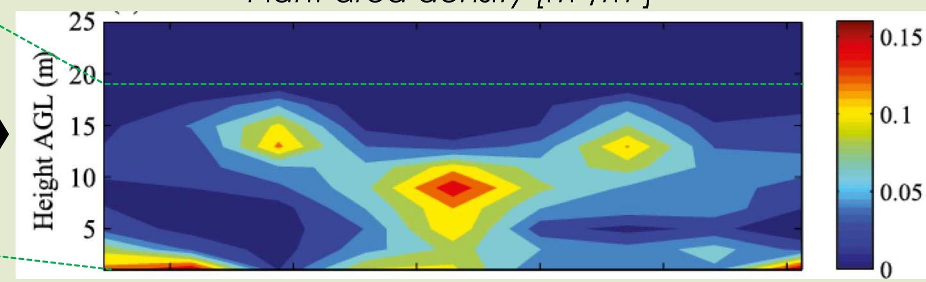
Simeoni A. (2016) Wildland Fires. In: Hurley M.J. et al. (eds) SFPE Handbook of Fire Protection Engineering. Springer, New York, NY

- 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 [m^2/m^3]



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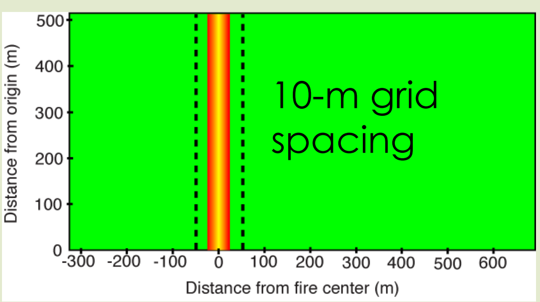


Photo credits: Wikipedia (top), Warren Heilman (bottom)

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)

SERDP management-scale

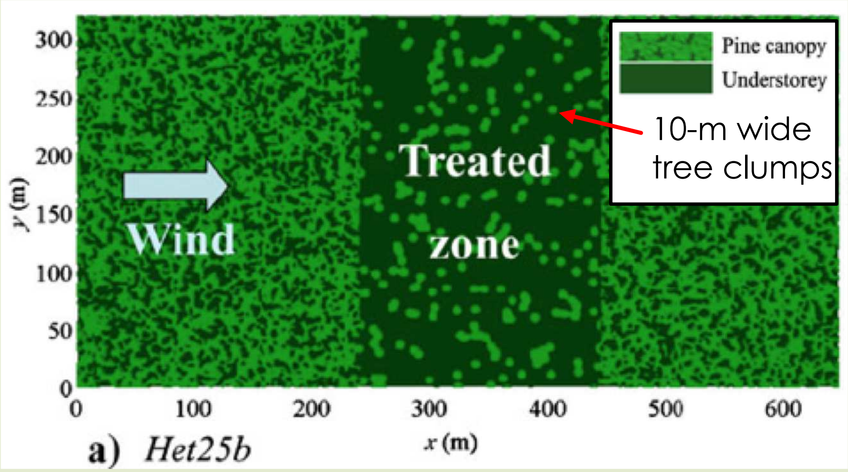
- ARPS-CANOPY ("full physics", multi-level canopy, 1-way fire)
  - Model background
  - Fire and forest canopy representation
  - Three example studies [case study and idealized]

Modeling study examples

HIGRAD/FIRETEC

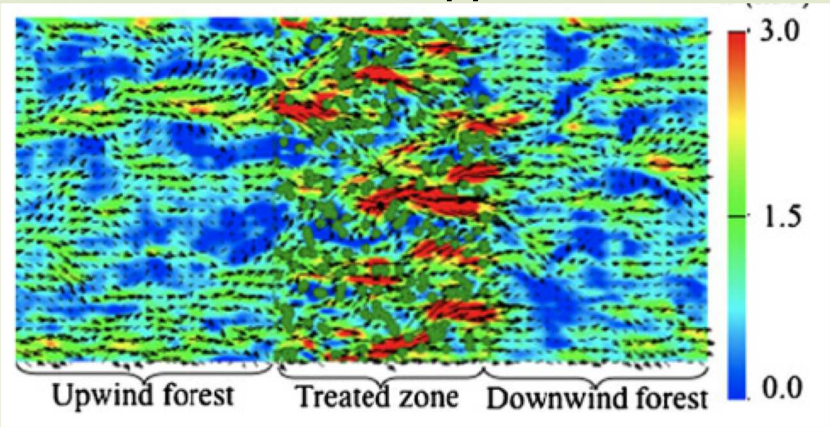
- Pimont et al. (2011): Impacts of tree canopy structure on wind flows and fire propagation simulated with FIRETEC

Fuels pattern

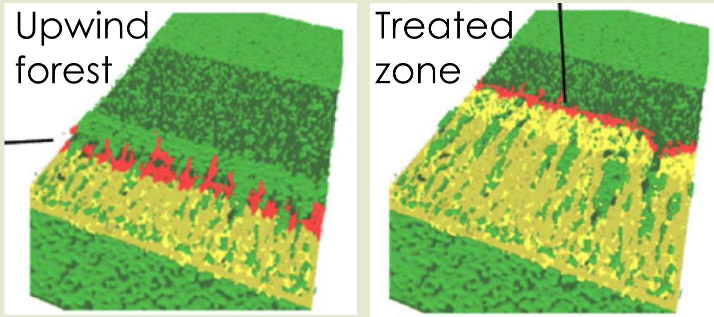


Domain: 640-m x 320-m

Simulated within-canopy wind field WS [ms^{-1}]



Simulated fire behavior



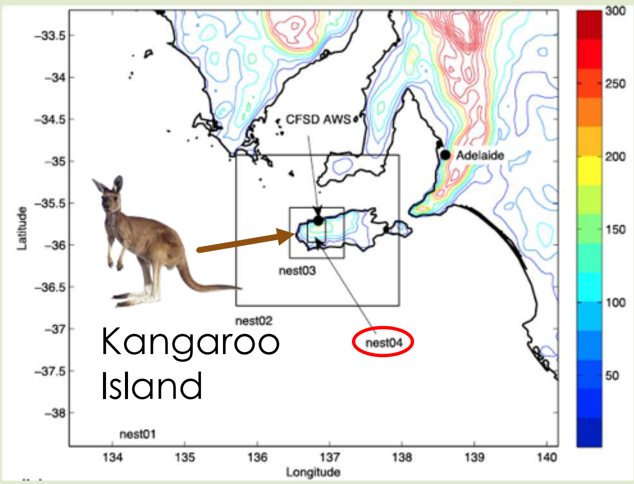
Modeling study examples

WRF-SFIRE

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

Simulate weather across multiple scales (nesting)

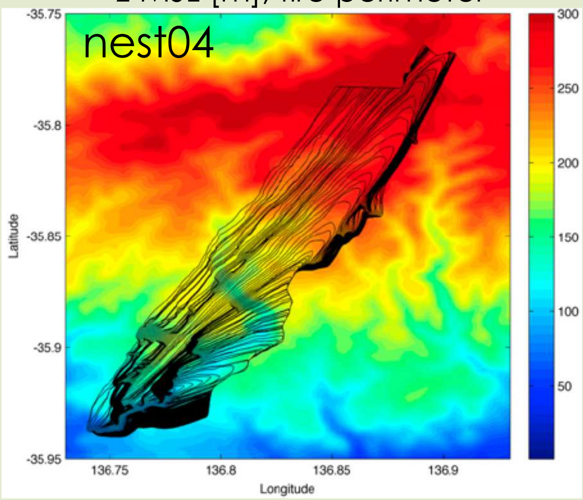
Height above mean sea level (z MSL) [m]



Domain: 600-km x 600-km

Simulate fire spread in complex terrain & fuels

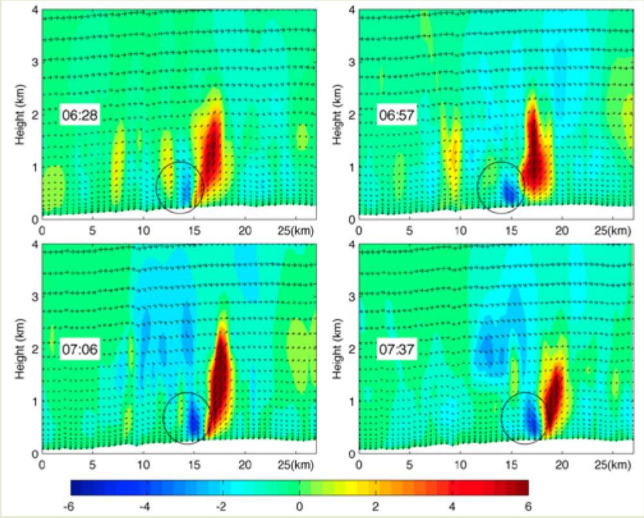
Z MSL [m]; fire perimeter



Domain: 22-km x 22-km

Simulate fire-perturbed atmospheric boundary layer

Vertical velocity [m s^{-1}]; wind vectors



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)

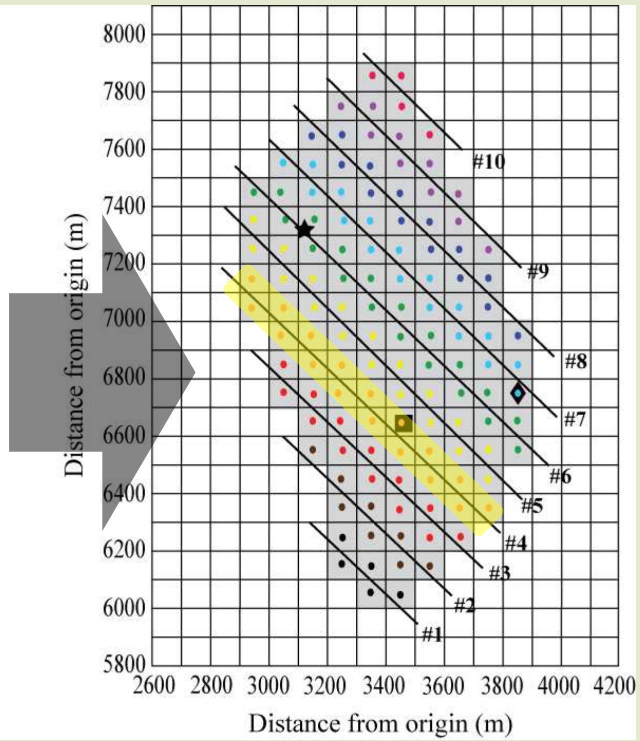
Modeling study examples

ARPS-CANOPY

--Preliminary: Fire representation--

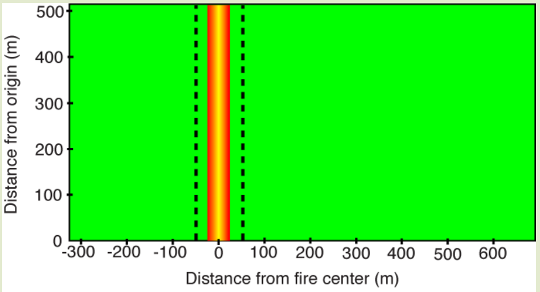
Observed fire line
(NJ Pine Barrens,
20 March 2011)

Case study representation
(fire propagation prescribed)



-or-

Idealized representation
(stationary heat source)



Infrared imagery source:
Bob Kremens (RIT)

* Images from
Natural Fuels Photo Series

Modeling study examples

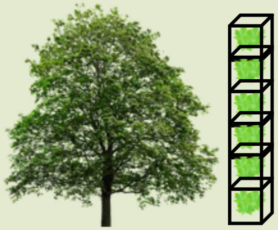
ARPS-CANOPY

--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



Longleaf Pine

Pitch Pine/
Blueberry-Black Huckleberry

Pitch Pine/Bear Oak/
Roundhead Lespedeza

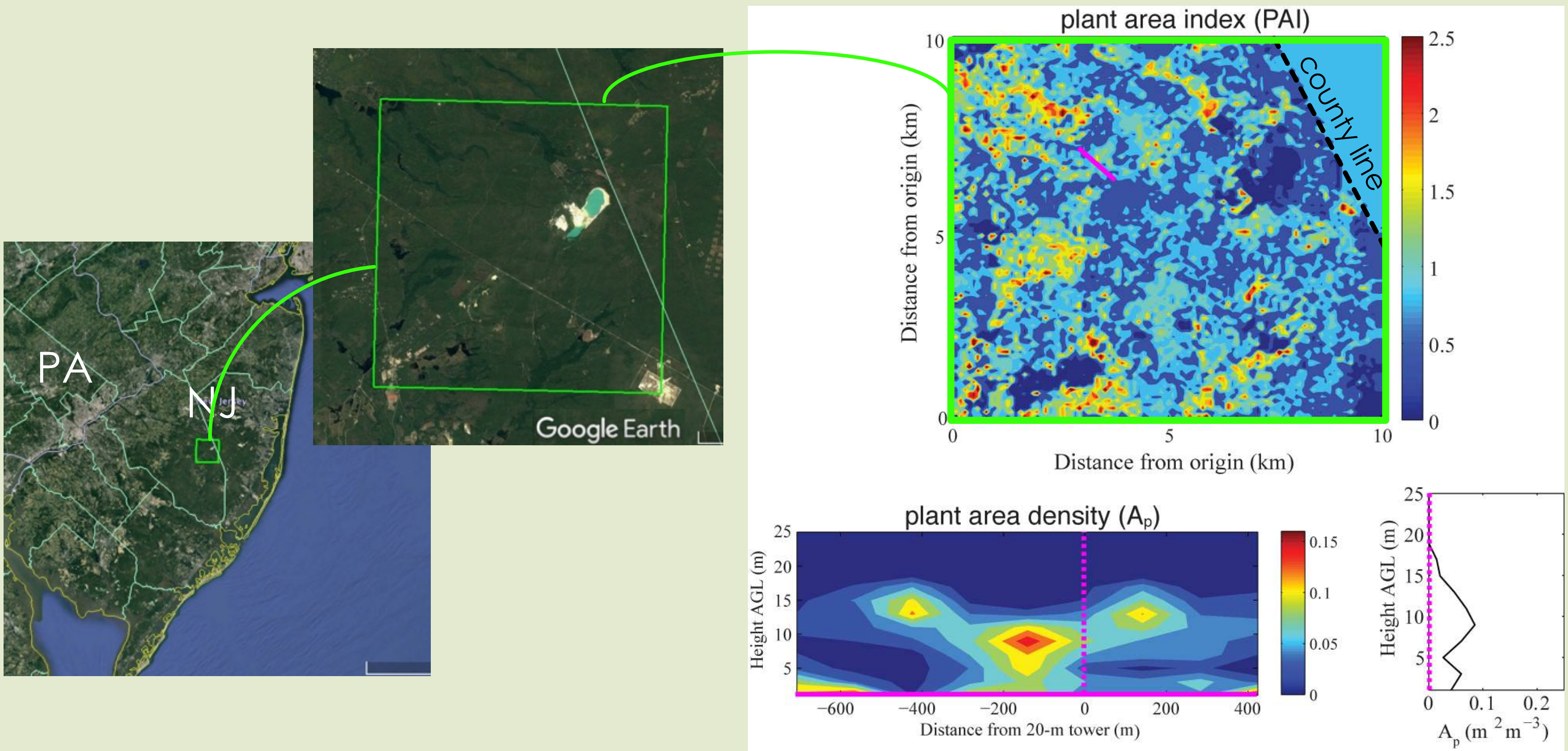
Chestnut Oak

Modeling study examples

ARPS-CANOPY

--Preliminary: Forest canopy representation --

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



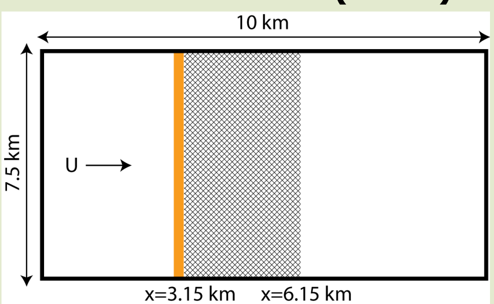
Thanks to Nick Skowronski for LiDAR data

Modeling study examples

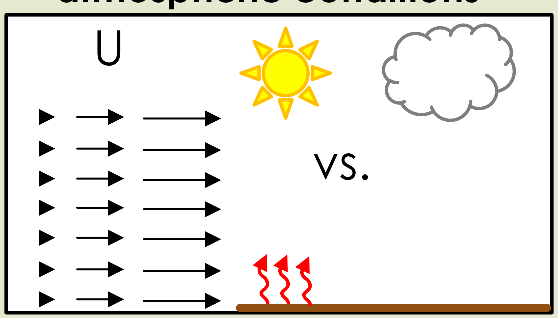
ARPS-CANOPY [Idealized]

- Kiefer et al. (2015): Mean and Turbulent Flow Downstream of a Low-Intensity Fire: Influence of Canopy and Background Atmospheric Conditions

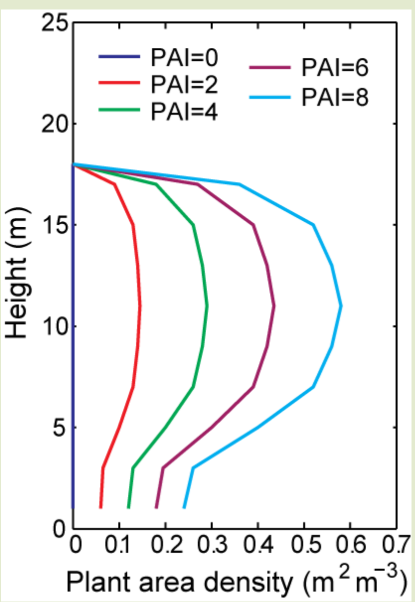
(1) Apply static line source of sensible heat ("fire")



(2) Vary background atmospheric conditions



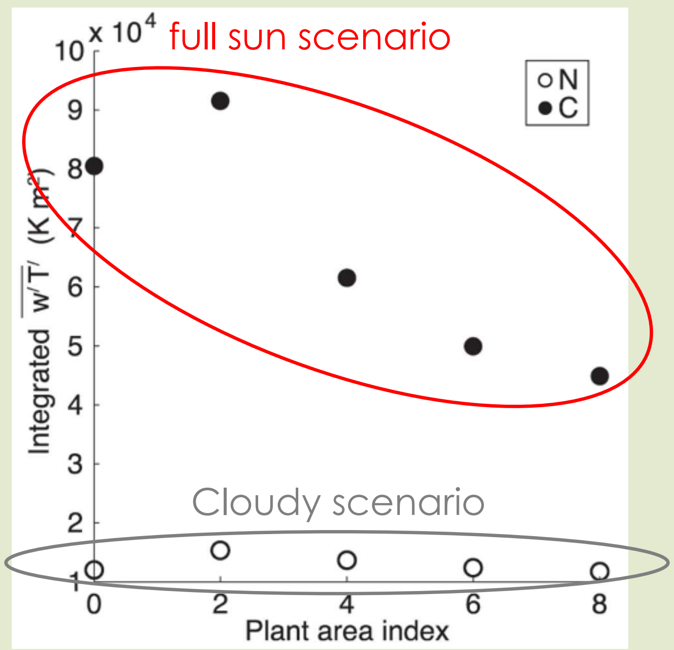
(3) Vary density of vegetation elements



<u>Total of 14 simulations</u>

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

Vertical heat transport through ~1-km layer



Density of vegetation elements

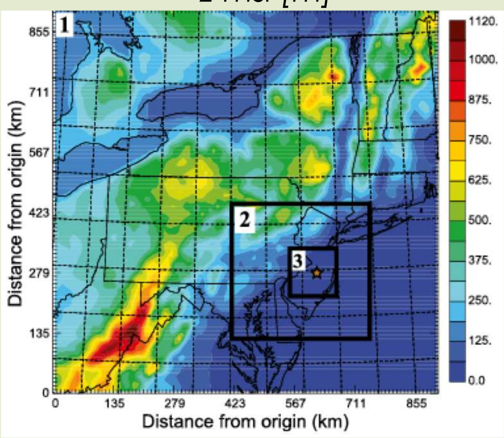
Modeling study examples

ARPS-CANOPY [real case]

- Kiefer et al. (2014): Multiscale Simulation of a Prescribed Fire Event in the New Jersey Pine Barrens Using ARPS-CANOPY

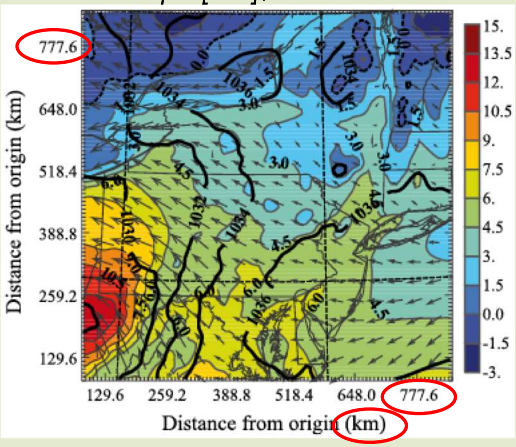
(1) Simulate weather across multiple scales (nesting)

Z msl [m]



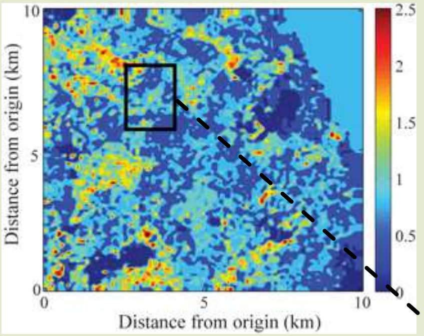
(2) Simulate "Large- scale" weather

Air temp. [°C]; wind vectors

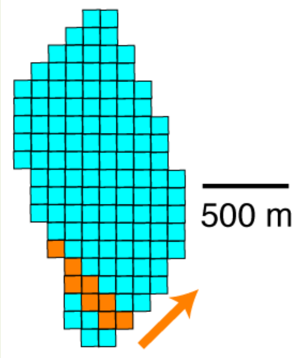


(3) Represent forest canopy and fire sensible heating

PAI

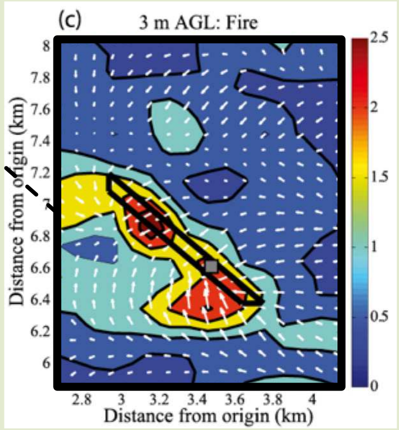


Fire heat source



(4) Simulate turbulent flow within ~1 km of fireline

TKE [$m^2 s^{-2}$]



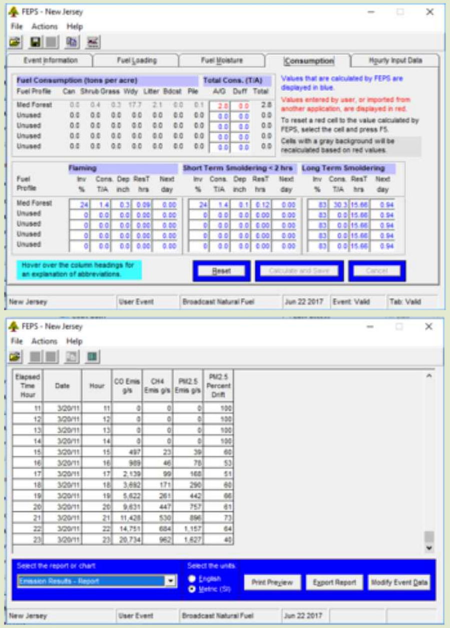
*In preparation

Modeling study examples

ARPS-CANOPY/FLEXPART-WRF [real case]

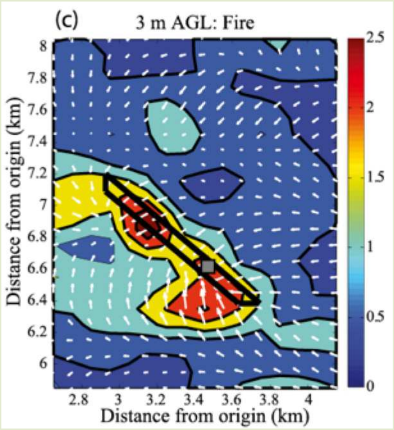
- Charney et al. (2018*): Assessing Forest Overstory Impacts on Smoke Concentrations using a Coupled Numerical Model

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



$^{+}$*FEPS: Fire Emissions Production Simulator*

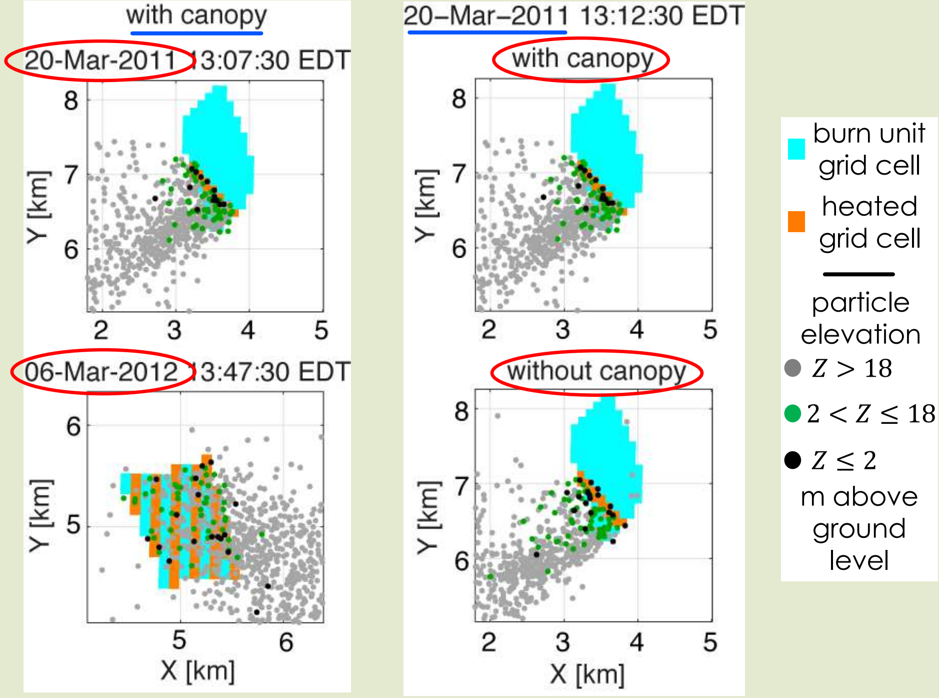
(2) Use ARPS-CANOPY simulated winds to drive FLEXPART-WRF particle dispersion model



Use FLEXPART-WRF to:

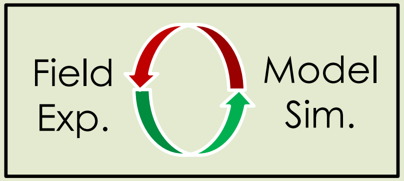
(3) Simulate smoke plumes

(4) Examine sensitivity of smoke plumes to canopy



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



Summary

- 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

Acknowledgements

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  - Shiyuan Zhong, Warren Heilman, Jay Charney, Xindi Bian, and Jovanka Nicolic [East Lansing, MI]
  - Nick Skowronksi, John Hom, Ken Clark, Michael Gallagher, and Matthew Patterson [Silas Little, NJ; Newtown Square, PA]
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