Development of a Fine Scale Smoke Dispersion Modeling System: Part I – Validation of the Canopy Model Component

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Introduction

- Prescribed fires are useful tools for forest ecology and management:
  - Such fires generally are low in intensity and confined to small areas
  - Produce smoke that may linger in an area for extended periods of time, affecting air quality and public health
- Critical factors for modeling smoke dispersion from low-intensity burns include near-surface meteorological conditions, local topography, vegetation, and atmospheric turbulence within and above vegetation layers
- What is needed are modeling tools capable of simulating smoke transport and dispersion from low-intensity fires
- **Objective: Add a canopy layer to an atmospheric model and perform validation of the canopy model component (without fire parameterization)**

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

Model Development

- Advanced Regional Prediction System (ARPS) v. 5.2.12 (Xue et al. 2003)
- ARPS levels within a prescribed canopy layer are modified to enable the simulation of mean and turbulent flow within a vegetation canopy:

(1) Pressure and viscous drag force term added to momentum equation

$$-\eta\bar{\rho}C_d A_f \sqrt{\tilde{u}_j\tilde{u}_j}\,\tilde{u}_i$$

(2a) Wake energy cascade sink term added to turbulent kinetic energy (TKE) equation

$$-2\eta C_d A_f \sqrt{\tilde{u}_j\tilde{u}_j}\,e$$

(2b) Wake energy production term added to TKE equation

$$+\eta a C_d A_f \sqrt{\tilde{u}_j\tilde{u}_j}^{\,3}$$

(3) Net radiation vertically distributed to account for attenuation of incoming shortwave radiation by canopy

$$R_{Nh} = (1-\alpha_t)S + \varepsilon_c\left(R_{Lh\downarrow} - \sigma T_c^4\right)$$

$$R_{Np}(z) = R_{Nh}\left[\exp\{-kL(z)\} - \eta\left(1-\frac{z}{h}\right)\exp\{-kL(0)\}\right] \qquad L(z) = \int_z^h A_f\,dz$$

$$R_{NG} = \eta R_{Nh}\exp[-kL(0)] + (1-\eta)\left[(1-\alpha_G)S + \varepsilon_G\left(R_{LG\downarrow} - R_{LG\uparrow}\right)\right]$$

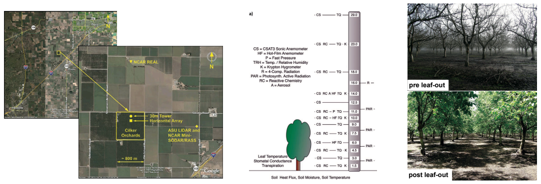
(1,2a) Dupont and Brunet (2008); (2b) Kanda and Hino (1994); (3) Yamada (1982),Sun et al. (2006)

η : Vegetation fraction	e : Subgrid-scale TKE ($m^2 s^{-2}$)	α_t : Canopy albedo	$R_{Np}(z)$: Net radiation flux profile in canopy ($W m^{-2}$)
C_d : Canopy drag coefficient	S : Incoming solar rad. ($W m^{-2}$)	α_G : Ground albedo	R_{Nh} : Net radiation flux at canopy top ($W m^{-2}$)
A_f : Frontal area density ($m^2 m^{-3}$)	ε_c : Emissivity of trees	h : Canopy height (m)	$R_{Lh}\downarrow$: Longwave absorbed at canopy top ($W m^{-2}$)
$\tilde{u}_i$: Instantaneous velocity component ($m s^{-1}$)	ε_G : Emissivity of ground	$L(z)$: Local leaf area index	R_{NG} : Net radiation flux at ground ($W m^{-2}$)
a : Wake production coefficient	$\bar{\rho}$: Base state density ($kg m^{-3}$)	T_c : Canopy top temperature (K)	R_{LG} : Longwave radiation at ground ($W m^{-2}$)
σ : Stefan-Boltzmann constant	θ : Potential temperature (K)	k : Attenuation coefficient	

Validation Dataset:

Canopy Horizontal Array Turbulence Study (CHATS)

Walnut Orchard near Dixon, CA: 15 March – 12 June 2007

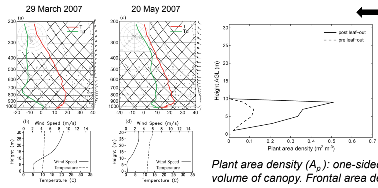


From left: (1) Google Earth image depicting the location of the orchard and locations of various instrumentation; (2) 30-m tower sensor configuation; (3) Photos of orchard pre and post leaf-out.

Above images from Patton et al. (2011, Bull. Amer. Met. Soc., V 92, 593-611)

Model Setup and Experiment Design:

- 12 hour runs initialized at 0500 local time (LT), with soundings derived from North American Regional Reanalysis (NARR), SODAR, and 30-m tower data
- Two cases: pre leaf-out (29 March 2007) and post leaf-out (20 May 2007)
- 90 m horizontal grid spacing; 2 m vertical grid spacing up to 84 m AGL
- Flat terrain with uniform surface characteristics; periodic boundary condition

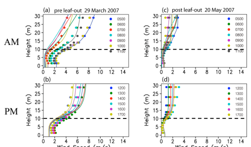


Far left: Summary of initial state for pre leaf-out (29 March) and post leaf-out (20 May) cases. Skew-T/ Log-P diagrams (a-c) and vertical profiles of 30-min mean wind speed and temperature (b-d) are depicted. Left: Monthly mean plant area density profiles measured during CHATS. For this study, we assume that plant area and frontal area density are equivalent.

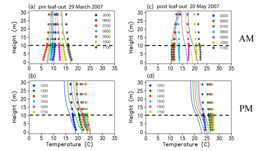
Plant area density (A_p): one-sided area of all plant material, per unit volume of canopy. Frontal area density (A_f): As in A_p, but only leaf area.

Model Validation Results: Mean Flow Properties

- **Objective: Assess the ability of the new ARPS canopy modeling system to simulate mean flow through a vegetation canopy**



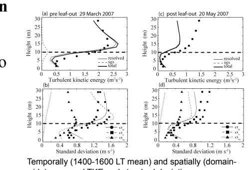
- Profiles of 30-minute mean wind speed indicate that the canopy modeling system is capable of replicating the observed mean flow vertical structure inside and above the canopy
- The model is also shown to reproduce the observed temporal evolution of mean wind speed
- Shape of 30-minute mean temperature profiles qualitatively agrees with observations during morning. Also, note the transition from nocturnal to daytime surface layer structure
- Cool bias exists in the model, particularly above the canopy top during afternoon



Model Validation Results: Turbulent Kinetic Energy

- **Objective: Assess the ability of the new ARPS canopy modeling system to simulate mean TKE and standard deviation**

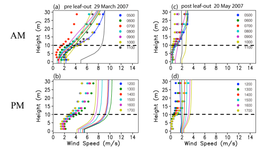
- Ratio of model subgrid-scale TKE to total TKE ranges from less than 5% at the surface to about 25% in the upper 2/3 of canopy and less than 10% above the canopy
- The model replicates the shape and overall, the magnitude of TKE inside the canopy



Temporally (1400-1600 LT mean) and spatially (domain-wide) averaged TKE and standard deviation

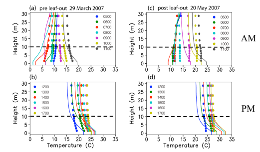
Sensitivity Experiment: No Canopy Test

- **Objective: Better understand the impact of the parameterized canopy on momentum and heat in the surface layer**



- Although the no canopy simulations were initialized with the same soundings as in the canopy model simulations, the no canopy runs exhibit mean wind speeds that are too strong compared to CHATS observations (especially for the pre leaf-out case)

- Stronger, shallower superadiabatic layers are found to develop without the canopy model
- The noted cool bias above the canopy persists even when the canopy model is omitted



Conclusions

- Preliminary validation tests of the new canopy modeling system have revealed both strengths and weaknesses
- The model has been shown to reproduce the mean wind speed and TKE vertical profiles observed during the CHATS experiment, as well as the overall shape of the mean temperature profiles
- ARPS has been shown to exhibit a cold bias, particularly in the layer above the canopy top
- Sensitivity experiments without the canopy model reveal that the canopy model is essential for proper simulation of flow in the surface layer
- Future work includes examining the model cold bias via thermodynamic budget analysis and performing additional simulations with a broader set of frontal area density profiles, LAI's, and large-scale weather conditions

Acknowledgements

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