P2 DEVELOPMENT OF A FINE SCALE SMOKE DISPERSION MODELING SYSTEM. PART I - VALIDATION OF THE CANOPY MODEL COMPONENT

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1. INTRODUCTION

Smoke dispersion from wildland fires is a critical health and safety issue, impacting air quality and visibility across a broad range of space and time scales. Predicting the dispersion of smoke from low-intensity fires is particularly challenging due to the fact that it is highly sensitive to factors such as near-surface meteorological conditions, local topography, vegetation, and atmospheric turbulence within and above vegetation layers. Prescribed fires are useful tools for forest ecology and management and generally are low in intensity, confined to small areas, and capable of producing smoke that may linger in an area for extended periods of time. Existing integrated smoke dispersion modeling systems, which are designed for predictions of smoke from multiple sources on a regional scale [e.g., BlueSky (Larkin et al., 2009)], do not have the necessary resolution to accurately capture smoke from low-intensity fires that tends to meander around the source and may stay underneath forest canopies for a relatively long period of time. Simple dispersion models [e.g., SASEM, VSMOKE (Riebau et al., 1988; Lavdas, 1996)], which typically are location specific, are limited by their simplistic nature in treating the emissions source, topography, canopy, and the atmospheric conditions.

In order to simulate smoke dispersion within a forest canopy as well as possible transport of smoke through the canopy - free atmosphere interface and into the planetary boundary layer, use of a large-eddy simulation (LES) model is essential. However, application of LES to simulation of flow inside a forest canopy requires that the effects of the canopy on air flow be accounted for. In this paper, we describe the development of a new canopy flow modeling system, based on the Advanced Regional Prediction System (ARPS) (Xue et al., 2000, 2001), and present preliminary results from a validation study of the canopy model component (without fire parameterization). Ongoing efforts to apply the new canopy modeling system to simulation of the meteorology observed during a recent prescribed burn in the New Jersey Pine Barrens are described in a companion paper (Kiefer et al., 2011).

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2. MODEL DESCRIPTION

a. Modifications made to ARPS

The numerical model utilized for this study is ARPS Version 5.2.12 (Xue et al., 2000, 2003). ARPS is a three-dimensional, compressible, nonhydrostatic atmospheric modeling system with a terrain-following coordinate system. ARPS is designed to simulate microscale through regional scale flows, and has been validated extensively over the last ten years (e.g., Xue et al., 2000, 2001). However, the standard ARPS formulation lacks the capability to model atmospheric variables (e.g., wind velocity, temperature) within a multi-layer canopy. A modified version of ARPS has been developed by Dupont and Brunet (2008) that accounts for the effects of vegetation elements on flow through a multi-layer canopy, but is applicable to neutral boundary layers only. The need for a modeling system capable of simulating mean and turbulent components of flow through a canopy under all stability regimes, including regimes generated by wildland fires, motivated the following modifications to ARPS.

Following Dupont and Brunet (2008), we have added a term to the momentum equation to account for pressure and viscous drag that occurs due to the presence of the canopy elements,

$$-\eta\bar{\rho}C_d A_f \tilde{V}\tilde{u_i} \tag{1}$$

where the overtilde indicates grid volume-averaged variables. In this equation, $u_i(u_1 = u, u_2 = v, u_3 = w)$ is the instantaneous velocity component along $x_i(x_1 = x, x_2 = y, x_3 = z)$, $\bar{\rho}$ is the base state air density, C_d is the mean drag coefficient of the canopy, and A_f is the frontal leaf area density of the vegetation (m^2 m^{-3}). The magnitude of the resolved-scale velocity, V, is defined as $V = \left(u^2 + v^2 + w^2\right)^{\frac{1}{2}}$. A slight modification has been made to the original term proposed by Dupont and Brunet (2008) in that a factor of η is included to incorporate effects of vegetation fraction less than unity, following the work of Yamada (1982) and Sun et al. (2006). Similar changes have also been made to the other dynamics terms presented below.

As in Dupont and Brunet (2008), we have also added a term to the subgrid-scale (SGS) turbulent kinetic energy (TKE) equation, to account for the enhancement of turbulence dissipation in the canopy air space,

$$-2\eta C_d A_f \tilde{V} e \tag{2}$$

where e is the SGS TKE (m^2 s^{-2}). The additional TKE dissipation term is required to account for the loss of SGS TKE to both heat and very small (and thus dissipative) wake-scale eddies, a process often referred to as a "short-circuit" of the intertial eddy cascade (Finnigan, 2000). Following Kanda and Hino (1994), we have also added a production term to the SGS TKE equation to represent the production of SGS TKE in the wakes of canopy elements, at scales large enough that the turbulence does not dissipate immediately yet small enough that it remains unresolved:

$$+\alpha \eta C_d A_f \tilde{V}^3 \tag{3}$$

The coefficient α represents the fraction of energy lost due to leaf drag that contributes to wake production in SGS flow. A value of 0 means that no kinetic energy is lost from the grid-scale flow to wake scales, whereas a value of 1 means that all energy lost from the grid-scale flow due to leaf drag goes to the production of wake-scale turbulence.

The canopy heat source and modifications to the surface energy budget were made following Sun et al. (2006), who based their methodology on a 1D model developed by Yamada (1982). The net radiation flux at canopy top is computed as

$$R_{Nh} = (1 - \alpha_t)\, S + \varepsilon_c \left(R_{Lh} \downarrow - R_{Lh} \uparrow\right) \tag{4}$$

where α_t is the canopy albedo [set uniformly to 0.1, following Sun et al. (2006)], S represents the incoming solar radiation flux intercepting the top of the canopy, ε_c is canopy emissivity [set to 0.98, as in Sun et al. (2006)], and $R_{Lh} \uparrow$ and $R_{Lh} \downarrow$ are upward and downward longwave radiation.

Following Sun et al. (2006), we have also prescribed a profile of net radiation that produces an approximately exponential decay within the canopy,

$$R_{Np}(z) = R_{Nh}[exp\{-kL(z)\} - \eta\left(1 - \frac{z}{h}\right) exp\{-kL(0)\}] \tag{5}$$

In Eq. (5), the local leaf area index, $L(z) = \int_z^h A_f(z)dz$, indicates the leaf area per unit horizontal area of the canopy above height z, while the extinction coefficient k is fixed at 0.6, following Shaw and Schumann (1992) and Sun et al. (2006).

The heat source at each grid point within the canopy is computed as:

$$\frac{\partial \theta}{\partial t} = \frac{(1-\eta)}{\rho_a C_p}\frac{\partial R_N}{\partial z} + \frac{\eta}{\rho_a C_p + \rho_c C_c}\left(1 + \frac{1}{B}\right)^{-1}\frac{\partial R_{Np}}{\partial z} \tag{6}$$

where θ is the potential temperature of the air, R_N is the net radiation flux within the clearing fraction of each grid box, C_p is the specific heat of air, and ρ_a is air density. For values of local canopy density (ρ_c), specific heat of canopy elements (C_c), and the Bowen ratio (B) inside the canopy, we follow Sun et al. (2006).

Lastly, the net radiation budget at the ground is given by:

$$R_{NG} = \eta R_{Nh} exp\left[-kL(0)\right] + (1-\eta)\left[(1-\alpha_G)\, S + \varepsilon_G \left(R_{LG} \downarrow - R_{LG} \uparrow\right)\right] \tag{7}$$

where symbols with subscript "G" refer to ground surface equivalents of the canopy parameters in Eq. (4). Here we make a simplifying assumption that the ground net radiation in the clearing fraction [the portion of Eq. (7) with the leading $(1-\eta)$ factor], is equivalent to the unattenuated net radiation flux at the top of the canopy.

b. *Model Configuration*

Three-dimensional simulations are performed with a homogeneous, continuous forest canopy and flat terrain. The domain consists of 83 x 83 x 83 grid points, with horizontal grid spacing of 90 m and vertical grid spacing of 2 m (up to a height of 84 m, above which vertical stretching is applied). The top of the model domain is at 12 km, with a rigid lid upper boundary condition and a Rayleigh damping layer in the uppermost 2 km, to prevent reflection of waves from the upper boundary. Due to the homogeneous vegetation field utilized in this study, periodic lateral boundary conditions are applied.

3. MODEL VALIDATION

For preliminary validation efforts, we compare ARPS simulations to 30-m flux tower data collected inside a walnut orchard near Dixon, CA during the 2007 Canopy Horizontal Array Turbulence Study (CHATS) (Patton et al., 2011). Two cases are considered, one during the early spring when the trees were dormant (pre leaf-out: 29 March) and one following the growth of mature leaves in the late spring (post leaf-out: 20 May). Figure 1 presents profiles of plant area density for the two cases; plant area density is defined as the one-sided area of all plant material (e.g., leaves, branches), per unit volume of

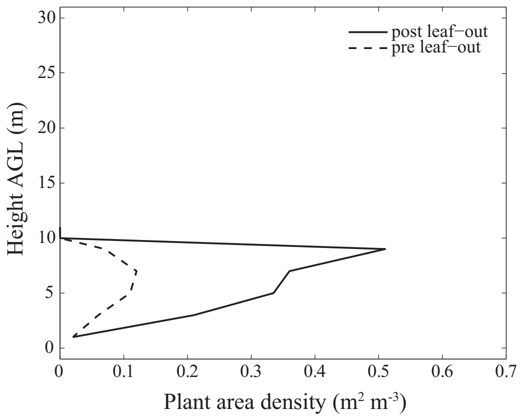

Figure 1: Vertical profiles of plant area density (m^2 m^{-3}) observed during the CHATS experiment.

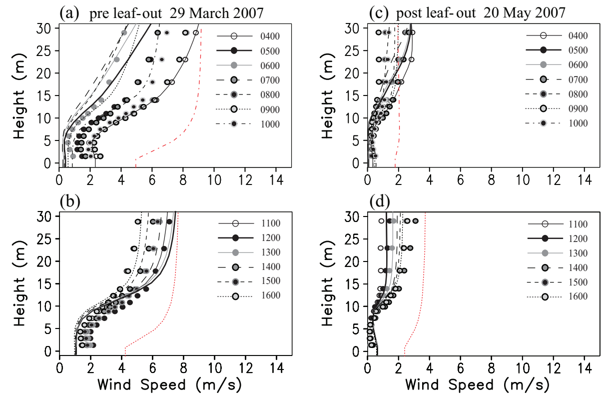

Figure 2: Comparison of simulated mean wind speed (m s^{-1}) to values measured during the CHATS experiment, for the (a-b) pre leaf-out (29 March 2007) and (c-d) post leaf-out (20 May 2007) cases. Line profiles are from ARPS simulations and circles denote the observed values. Red lines depict selected mean profiles from simulations run with the standard ARPS model, i.e. no canopy parameterization; 1000 LST (1600 LST) profiles are shown in the upper (lower) panel. Both simulated and measured hourly wind speeds are averaged over a 30-minute window, with the simulated data also averaged spatially over the domain. Times in legend are in local standard time (LST: UTC-8).

canopy. Frontal leaf area density is defined identically to plant area density except that only leaf matter is considered. Since differences between the two are typically small (Bréda, 2003), we assume the two canopy metrics are equivalent for the purposes of this study and use plant area density values wherever frontal area density appears in the canopy model equations (Section 2.*a.*). Note that the leaf area index (LAI), defined as the vertical integrated frontal area density, is approximately 2.75 (0.75) for the post (pre) leaf-out case. All simulations are initialized at 0400 local standard time (LST) and run for a total of 12 hours.The initial atmospheric state for the two cases can be seen by examining the 0400 LST mean wind speed profiles in Fig. 2a-c and mean temperature profiles in Fig. 3a-c.

In order to assess the ability of the new ARPS canopy modeling system to simulate flow through a vegetation canopy, the simulated mean wind and temperature profiles are compared to observations and the results are presented in Figs. 2 and 3, respectively. The profiles of mean wind speed indicate that the new canopy modeling system is capable of replicating the observed mean flow vertical structure inside as well as outside of the vegetation canopy. In addition, the model is able to reproduce the evolving wind profile above the canopy during the afternoon in both cases (Fig. 2b-d). Examining profiles of mean temperature for the two cases (Fig. 3), it is apparent that in both cases, ARPS reproduces the profile shapes throughout the morning, including the transition from stable to daytime boundary layer structure. The afternoon assessment reveals mixed results for both cases (Figs. 3b and 3d). While the model is able to reproduce the temperature trends observed during the afternoon, it is clear that a 3-6 C cool bias exists in the model, particularly above the canopy top, and is largest for the post leaf-out case. This bias can be traced in both cases back to the morning period following 0800 LST when the boundary layer is developing. In spite of the cold bias, it is important to emphasize that the model is capable of reproducing the mean profile shapes, a critical factor for simulating smoke dispersion.

In an effort to better understand the impact of the canopy model on momentum and heat in and above the canopy, we examine sensitivity experiments in which the pre and post leaf-out cases are run with the standard ARPS model (i.e., no canopy). Although the no canopy simulations were initialized with the same soundings as in the canopy model simulations, the standard ARPS model produces wind speeds that are too strong compared to the CHATS observations (see red lines in Fig. 2). Examining the mean temperature profiles (red lines in Fig. 3), it is apparent that stronger, shallower superadiabatic layers develop without the canopy model, and also that the aforementioned cool bias above the canopy persists even when the canopy model is omitted.

4. CONCLUSIONS

The development and preliminary validation of a new integrated canopy flow modeling system, developed from the ARPS model, has been presented. The standard ARPS model has been modified to account for the effect of vegetation elements on mean and turbulent flow and on the net radiation flux profiles within the canopy. As an important step in the model development process, the atmospheric model has been validated against data from the CHATS experiment. Comparisons of mean

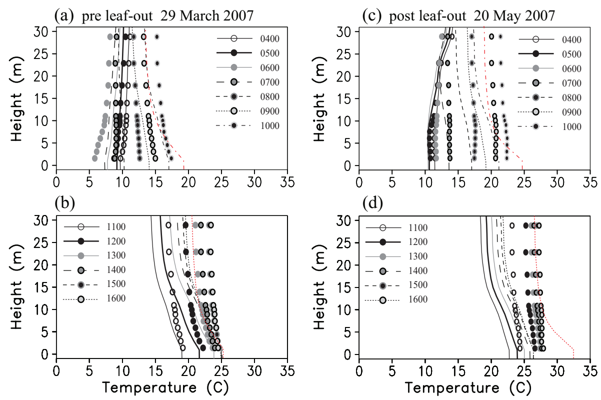

Figure 3: As in Fig. 2, but for mean temperature (C).

flow properties have been presented for two cases, one prior to and one following leaf-out.

Preliminary validation tests of the new canopy modeling system have revealed both strengths and weaknesses of the model. The model has been shown to reproduce the mean wind speed profiles observed during the CHATS experiment, as well as the overall shape of the mean temperature profiles. The model has also been shown to exhibit a cold bias away from the surface, particularly in the layer above the canopy top. Sensitivity experiments with identical initial conditions and model parameters, but without the canopy model, reveal that this bias is not directly associated with the canopy, although the issue may be exacerbated by the canopy model. Future work planned includes examining the ARPS model cold bias through thermodynamic budget analysis and performing additional simulations with a broader set of frontal area density profiles, LAI's, and large-scale weather conditions. Despite the limitations of this study, the important work of modeling smoke dispersion from low-intensity fires may now proceed (Kiefer et al., 2011).

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