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APPLICATION OF A VEGETATION CANOPY PARAMETERIZATION TO WILDLAND FIRE MODELING

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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 critical factors such as near-surface meteorological conditions, local topography, vegetation, and atmospheric turbulence within and above vegetation layers. Existing integrated smoke dispersion modeling systems, which are designed for predictions of smoke from multiple sources on a regional scale (e.g., 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, which quite often are location specific, are limited by their simplistic nature in treating the emissions source, topography, canopy, and the atmospheric conditions.

The primary goal of our project is to build a smoke management tool specifically for low-intensity fires by taking advantage of recent developments in fine-scale atmospheric dispersion modeling. In order to achieve this, available fine-scale atmospheric dispersion modeling systems are being extensively evaluated using existing datasets and data from a prescribed burn in the New Jersey Pine Barrens, planned for late winter 2011. The modeling systems constitute several atmospheric models, including the Advanced Regional Prediction System (ARPS) (Xue et al., 2000, 2001) and the Weather Research and Forecast Model (WRF), coupled to a lagrangian particle dispersion model, FLEXPART (Fast and Easter, 2006). In the interim period during which the modeling systems are being developed, the ARPS model has been utilized to examine the impact of a low-intensity fire on the mean and turbulent motion of air through a vegetation canopy, and the sensitivity of such motion to various parameters (e.g., fire intensity).

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2. METHODOLOGY

As a first step toward modeling low-intensity wildland fires, the modeling procedure has being calibrated with a test case: the 2002 Double Trouble State Park Wildfire (Charney et al., 2003) of 2 June 2002. A series of one-way nested simulations, with horizontal grid spacing ranging from 9-km to 100-m, have been performed. Initial and boundary conditions are supplied to the outermost nest from the North American Regional Reanalysis (NARR) (Mesinger et al., 2006); terrain and landuse data for all nests is generated from high resolution U.S. Geological Survey (USGS) datasets. To account for the effect of a vegetation canopy on boundary layer flow, the canopy parameterization developed by Dupont and Brunet (2008, 2009) has been adopted here. Canopy effects are accounted for by adding a pressure and viscous drag force term to the momentum equation, and by adding a sink term to the turbulence kinetic energy (TKE) equation to account for the more efficient dissipation of TKE within the canopy. Direct effects of a vegetative layer on moisture and temperature are neglected; however, ARPS does contain a soil and vegetation model component to simulate the vertical exchange of such quantities at the surface. For all simulations considered in this paper, the canopy parameterization is applied only to the innermost nest, with a horizontally-homogeneous forest of depth 18 m and leaf area index (LAI) equal to 2.

Further parameterization development has addressed the lack of a vegetation shading effect in the modified ARPS version developed by Dupont and Brunet (2008); application of the parameterization is limited to modeling neutral boundary layers. The question of how to account for variation of sensible heat flux through a forest canopy is of particular relevance to our study, since one or more cases used to validate the modeling system is likely to feature a convective boundary layer. A review of existing literature on the subject of heat fluxes in canopies in large eddy simulation (LES) models reveals few studies that have considered convective boundary layers. One exception, Shaw and Schumann (1992), accounted for the effect of vegetation shading in a rather simple manner by prescribing a vertical profile of heat flux to account for the absorption of incoming shortwave radiation by foliage and the heating of the adjacent air (albedo effects were ignored). We have adopted in ARPS their method of prescribing a heat flux profile with peak upward heat flux at the canopy top, exponentially decaying downward through the canopy to the surface.

Lastly, to account for the first order effects of a wildland fire, we impose upward sensible heat fluxes appropriate to a low-intensity fire in a fixed area of the innermost domain. Although recent ARPS modeling of fire-atmosphere interactions (e.g., Kiefer et al., 2009) have been performed with a fire parameterized by sensible heat fluxes confined to the lowest model level, the non-idealized nature of the current experiments suggests that an alternate approach may be prudent. Following an examination of buoyant plumes in coupled fire-atmosphere models, Sun et al. (2006) found that allowing sensible heat fluxes to exponentially decay above the fire yielded plume profiles most consistent with experimental data and theory. Such variation accounts crudely for the impact of soot on thermal radiation from the fire. In these preliminary simulations, we have opted to prescribe a heat flux profile with an e-folding depth adopted by Sun et al. (2006) of approximately 25 m. For the simulations examined here, a 1.2 km diameter fire centered at point (x,y) = (3.2,6.8) km in the northwest quadrant of the innermost domain is "ignited" at 1700 UTC 2 June 2002. The fire intensity, as measured by surface heat flux, is varied between sensitivity experiments from 400 to 1000 W m^{-2}; as a point of reference, the mean surface heat flux measured during the 2006 Fireflux grassfire experiment was approximately 800 W m^{-2} (Clements et al., 2007), while a typical background surface heat flux in a convective boundary layer is 200-300 W m^{-2} (Stull, 1988).

3. RESULTS

a. Boundary Layer Assessment

The nature of flow near and above the canopy top is addressed first due to the impact of such flow on particle transport. An examination of the vertical velocity field in and above the canopy (Fig. 1) reveals several scales of motion. Alternating updrafts and downdrafts with wavelengths of 500-600 m are apparent in and above the forest canopy, while a broader scale of convection is evident in the upper portion of the cross-section. Separate from the boundary layer convection, the warm plume above the fire is seen extending out of the canopy and downstream toward one of the transverse rolls. Comparison of Fig. 1 to horizontal cross-sections of vertical velocity at 40 m and 167 m AGL (not shown) clarifies the nature of

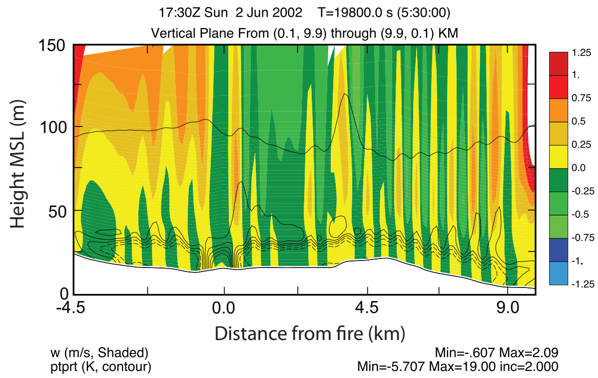

Figure 1: Vertical cross-section of vertical velocity (shaded, m s^{-1}), and perturbation potential temperature (K; solid-positive, dashed-negative), at 1730 UTC 2 June 2002. Cross-section is aligned northwest-southeast through the center of the fire. Contour interval of perturbation potential temperature is 2 K.

convection above the canopy. Transverse rolls above the canopy are found below broader scale rolls aligned with the mean flow. The presence of transverse rolls above the canopy is expected given the inflectional mean wind profile near the canopy top (Fig. 2) (Finnigan and Brunet, 1995), while convective rolls aligned with the mean wind are a common feature of the planetary boundary layer in the presence of vertical wind shear (Stull, 1988).

b. Parcel Behavior

As a first step toward understanding how a low-intensity fire impacts the vertical exchange of air parcels through the vegetation canopy and planetary boundary layer (PBL), we examine the maximum height achieved by air parcels released in the innermost grid simulations with and without a parameterized fire (surface heat flux in fire radius: 800 W m^{-2}). We are interested here in examining how the vertical exchange of air parcels is impacted by the fire, not only in the immediate vicinity of the burn, but also at distances of 1-2 kilometers from the fire. To help accomplish this goal, a "wall" of air parcels is released immediately upstream of the fire, and back and forward trajectories are computed. The "wall" of air parcels consists of 8 lines of air parcels spaced evenly between 1 m and 36 m AGL, for a total of 104 parcels (13 parcels per level). Note that this is done as a post-processing step; the trajectory code reads in wind data from the model output. In Fig. 3 a scatterplot of parcel height above ground level is displayed for multiple release times and for simulations with and without a fire. This figure shows that in general, parcels released within the vegetation canopy are most sensitive to the presence of the fire, while parcels released above the top of the canopy are most sensitive to release time. Espe-

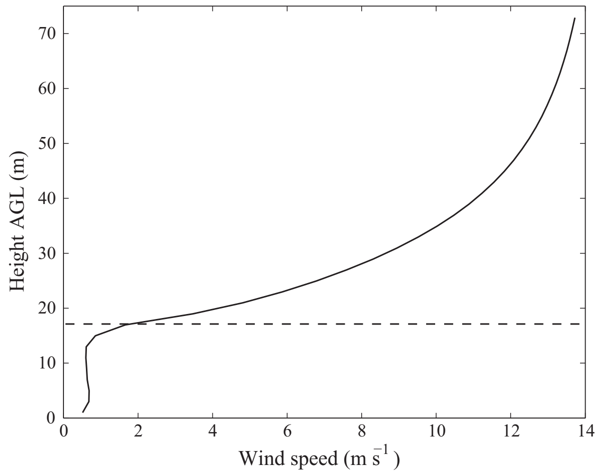

Figure 2: Vertical profile of mean wind speed for innermost nest simulation with canopy, but no fire. Profile is constructed by averaging horizontally in the x- and y-direction, and subsequently averaging temporally between 1730 and 1800 UTC 2 June 2002. Dashed line denotes top of canopy.

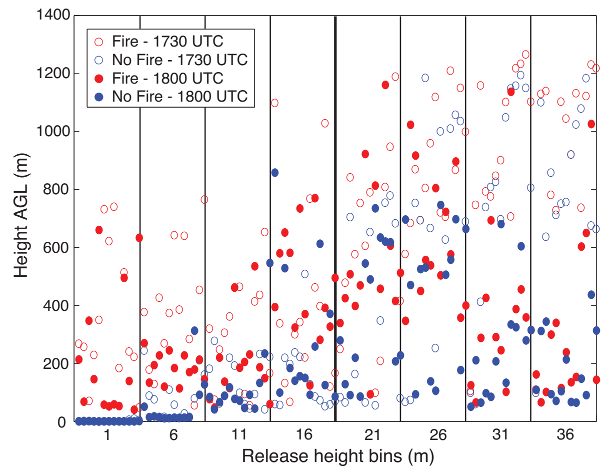

Figure 3: Scatterplot of maximum parcel height above ground level (AGL), organized by release height. Parcels to the left (right) of thick vertical line are released below (above) the canopy top. Red (blue) circles indicate parcels from simulations with (without) fire; hollow (filled) circles indicate parcels released at 1730 (1800) UTC 2 June 2002.

cially noteworthy is the fact that air parcels released at 1 m AGL do not move upward from their initial position unless the fire is present. Also of note are the substantially higher maximum parcel heights for parcels released above the canopy; the relationship between maximum parcel height and release height is not linear but rather exhibits a discontinuity between the 16 and 21 m release height bins (near the canopy top).

We next discuss the issue of parcel exchange between the forest, the PBL and the overlying free atmosphere. The question being asked is whether a fire of the intensity considered here (800 W m^{-2} surface sensible heat flux) is capable of injecting smoke generated inside the forest layer into the free atmosphere, where stronger winds may transport the smoke well away from the fire. For this purpose, timeseries of parcel height and PBL height are presented in Fig. 4, for parcels released at 1730 UTC (coinciding with a local plume rise maximum) and 1800 UTC 2 June 2002 (coinciding with a local plume rise minimum). In this study, the height of the PBL is determined by computing the height of the base of the inversion atop the mixed layer. As a reminder, the fire is ignited at 1700 UTC 2 June 2002, the approximate start time of the Double Trouble fire (Charney et al., 2003). One can see in Fig. 4 that parcels released below the canopy top exhibit greater sensitivity to the fire than parcels released above the canopy. Most importantly, the fire enables air parcels that would otherwise have remained in the lower portion of the PBL to ascend into the free atmosphere, although the buoyancy imparted on in-canopy air parcels by the 800 W m^{-2} fire is insufficient to loft air parcels into the free atmosphere. However, large eddies in the convective boundary layer (not associated with the fire itself) are capable of lofting smoke from a low-intensity fire out of the PBL.

c. *Plume Rise*

Additional work has been directed toward computing plume height as a function of time for various fire intensities (as measured by the prescribed surface sensible heat flux from the fire). Upon researching methods of objectively determining the height of a buoyant plume, we found the Briggs plume rise method (Briggs, 1971, 1972) to be best suited for our purpose. The computation is simple, the method is well known, and the method has been validated against available data over the past 30+ years (e.g., Bennett et al., 1992). Plume rise is computed by first calculating buoyancy flux

$$F = 0.25 * G * V_s * D_s^2 * (T_s - T)/T_s \qquad (1)$$

where G is mean gravitational acceleration, V_s is stack gas ejection speed, D_s is stack diameter, T_s is the plume temperature at stack height, and T is the surface background temperature. If the background stratification is neutral to unstable, then Briggs plume rise is computed as

$$H = H_s + 38.87776061 * (F^{0.6}/U) \qquad (2)$$

where H_s is physical stack height, and U is the mean horizontal wind speed in the layer of the atmosphere containing the plume. Note that this method was developed specifically for plumes above smoke stacks but has also

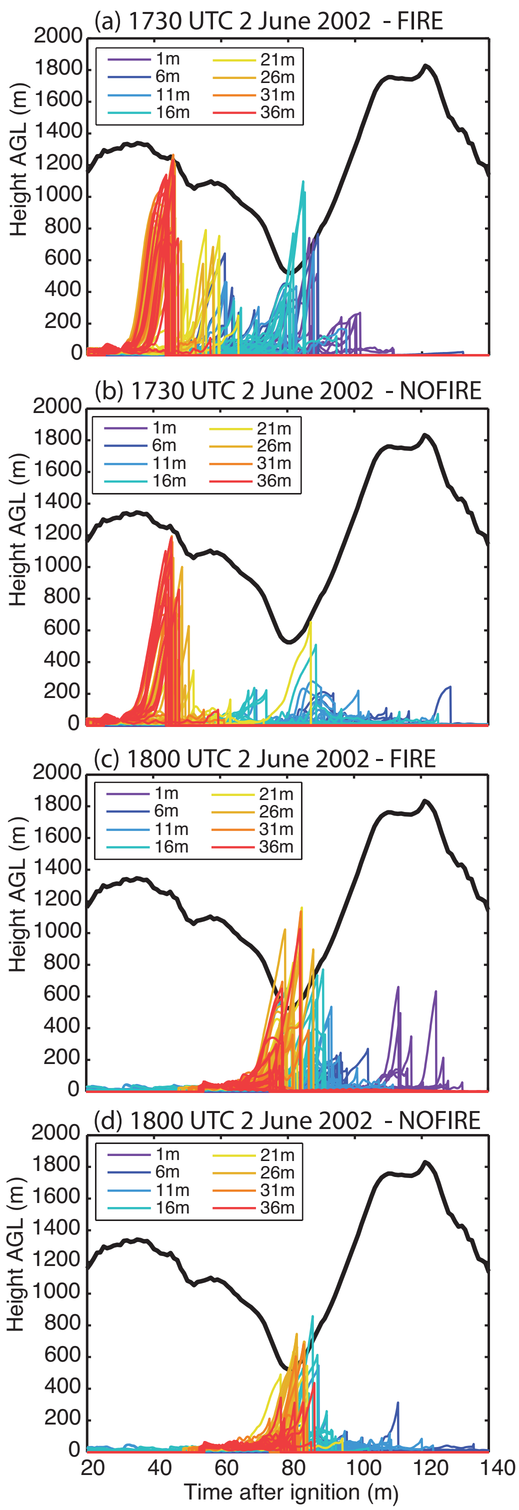

Figure 4: Parcel height above ground level as a function of time after ignition for (a-b) 1730 and (c-d) 1800 UTC 2 June 2002 parcel release times; panels (b) and (d) are from simulations with no fire. Each color indicates a different parcel release height (13 parcels per release height); see legend. Thick contour denotes height of planetary boundary layer (PBL) at a point 1.7 km upstream of fire center (see text for description of method used to compute PBL height).

been applied to fires (e.g., Larkin et al., 2009). For application to fires, stack-specific components in Eq. (1) are replaced with fire parameters; e.g., fire diameter is specified in place of stack diameter, and surface vertical velocity inside the fire perimeter is specified in place of stack gas ejection speed. Additionally, we compute U as the mean horizontal wind speed in the planetary boundary layer (PBL) upstream of the fire, with the expectation that any plume will be contained predominately in the PBL.

Figure 5 shows that the relationship between fire intensity and Briggs plume rise is linear, but also indicates that plume rise varies substantially with time in all of the cases. An analysis of correlation coefficient (Table 1) indicates that Briggs plume rise is negatively correlated with upstream PBL mean wind speed, while plume rise is positively correlated with temperature at the base of the plume, although the correlation is not as strong as with wind speed. As these results show, the buoyant plume is sensitive to conditions upstream, and thus awareness of the synoptic-mesoscale pattern is essential to anticipating plume behavior. It is important to note that the analysis of Briggs plume rise is not intended to ascertain the height of buoyant plumes in an absolute sense; the value of this analysis lies in the ability to compare plume rise between cases in which parameters (such as fire intensity) are varied.

Table 1: Correlation coefficients for various simulations; Note that Q_s is the surface heat flux within the fire and Z_i is PBL height (computed at point upstream of fire); For explanation of other symbols, see Eqs. (1,2).

Q_s (W m^{-2})	H:T_s	H:T	H:U	H:Z_i
1000	0.4626	-0.2336	-0.8246	0.6779
800	0.4712	-0.2261	-0.8407	0.6849
600	0.4558	-0.2012	-0.8496	0.6702
400	0.3731	-0.1776	-0.8696	0.6351

4. CONCLUSIONS

As part of an effort to model smoke dispersion from low-intensity fires, we have modified the Advanced Regional Prediction System model to include a canopy parameterization for use in a convective boundary layer, and to model an isolated low-intensity fire within a forested layer. Based on a review of the literature, we believe ours may be the first numerical modeling study of its kind to evaluate fire-induced convection in and above a well-resolved forested layer. The ultimate goal is to simulate the New Jersey Pine Barrens prescribed burn scheduled for late winter 2011; however, in the interim the modeling strategy has been applied to a test case, the Double

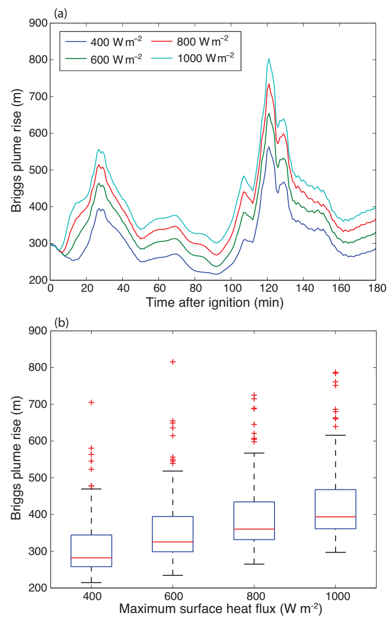

Figure 5: Briggs plume rise (a) timeseries and (b) box plots for cases with 400, 600, 800 and 1000 W m^{-2} surface heat flux magnitudes inside fire perimeter. In (b), the red lines indicates the median, the edges of the boxes indicate the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually.

Trouble State Park wildfire (2 June 2002). We have utilized the modified ARPS model to examine the impact of a low-intensity fire on the mean and turbulent motion of air through a vegetation canopy.

A series of experiments have been conducted to examine the sensitivity of air motion in and around an 18 m tall forest to the presence of a low-intensity fire and subsequently to evaluate the sensitivity to fire intensity. Our results suggest that even a low-intensity fire is critical to the vertical exchange of air parcels through a canopy, particularly for air parcels in the lower portion of the vegetation layer. Most air parcels were able to move out of the canopy and through the boundary layer regardless of whether a fire was present or not, as a result of convective activity present in and above the canopy. However, air parcels initially located near the surface within the canopy remained within the vegetation layer unless a fire was present to contribute to parcel buoyancy. Additional experiments in which fire intensity was varied between simulations indicate a linear relationship between plume rise and fire intensity for the range considered.

The findings of this study provide valuable insight into how low-intensity fires impact flow through vegetative layers. In the coming weeks and months, the aforementioned smoke dispersion modeling systems will be validated against datasets collected from low-intensity prescribed burns. The lack of research on smoke transport from low-intensity fires and the lack of operational modeling tools for predicting smoke dispersion within and in the vicinity of forest vegetation layers makes this work particularly relevant and motivates further efforts.

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