Smoke transport and dispersion from prescribed burns: complications posed by mountainous terrain

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1. INTRODUCTION

Plume-rise models for smoke from prescribed fires are more accurately simulating how land managers spread fire over the landscape and therefore how heat columns organize to disperse smoke through the atmosphere. For small burns, smoke is dispersed mostly within the planetary boundary layer (mixing layer). For larger burns, particularly those ignited by stripping or aerial ignition, heat released from combustion can loft much of the smoke into the free atmosphere above the boundary layer. Given tiny terminal velocities of fine particulate matter, this smoke could remain aloft indefinitely for long distances until taken up as condensation nuclei and precipitated out.

There are instances when smoke transported long distances within the free atmosphere is injected back into the mixing layer and mixed to the ground in high concentration. One of a number of explanations for plume collapse holds that the top of the boundary layer (mixing height) is higher where plume collapse occurs.

We ran the MM5 meso-meteorological weather model for the southern Appalachian Mountains near the Tennessee/North Carolina border for 18 March 2006. An elevation map at 4 km resolution is shown in Figure 1. The first objective was to map the evolution of the planetary boundary layer on a day when heating and winds impacted the depth and location of the boundary layer. The second objective was to simulate plume collapse. Our approach to modeling is described in the next section. Results and discussion for each objective follow.

2. MATERIALS & METHODS

The National Center for Atmospheric Research (NCAR)/Penn State Mesoscale Model (MM5) (Grell, *et al.,* 1994) was used for providing meteorological conditions for emission calculation and SMOKE and CMAQ simulations. The MM5 model was configured with the Kain-Fritsch (Kain and Fritsch, 1993) convective parameterization, the Medium Range Forecast (MRF) boundary layer scheme (Hong and Pan, 1996), the simple ice microphysics scheme and a 5-layer soil model for the land surface scheme. The MM5 outputs were processed through the Meteorology-Chemistry Interface Processor (MCIP) v2.2 for use of SMOKE and CMAQ.

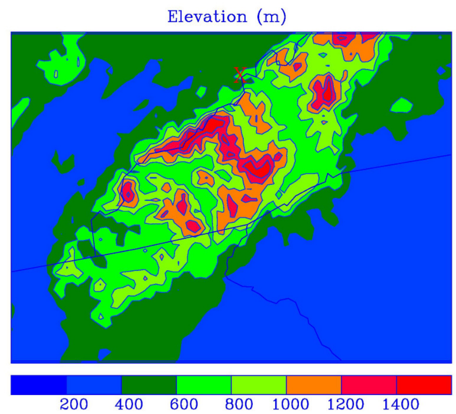

Figure 1. Elevation (m) of the southern Appalachian Mountains as represented in MM5 at 4 km resolution.

Daysmoke was used to calculate smoke plume rise. Daysmoke is an empirical/dynamical model to simulate movement and deposition of smoke particles. It was first developed for burn of sugar cane (Achtemeier, 1998), and recently modified for applications to burns of various forest ecosystems. An example of the use of these models is found in Liu *et al.,* (2008).

3. RESULTS & DISCUSSION

a) Boundary Layer Evolution

An elevation map for the southern Appalachian Mountains is shown in Figure 1. The mountains rise from a plateau elevated from 600 – 800 m above sea level (medium green shading). Higher mountains (red shadings) rise above 1200 m. A contoured overlay of the 600 m, 1000m, and 1200 m elevations was placed on the map of mixing height (Figure 2) simulated by MM5.

Figure 2 shows that highest mixing heights were approximately coincident with highest terrain at 1300 LST. Winds were blowing from the north. Evidences for beginning downwind advection of the

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high mountain mixing layers are shown by the arrows.

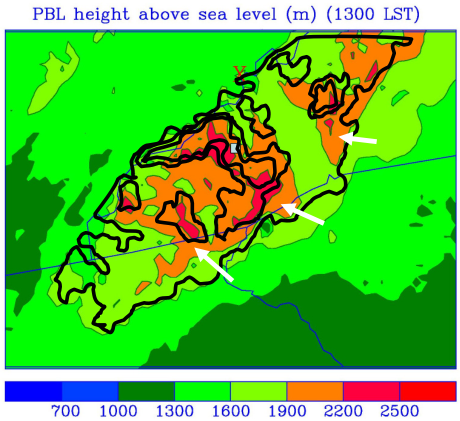

Figure 2. Map of mixing height (m) overlain with a semi-transparent map of elevation for 1300 LST, 18 March 2006.

Figure 3 shows the depth of the boundary layer at 1300 LST. Boundary layer depths are relatively uniform at 1000-1200 m (medium green). Exceptions are highest mountains (600 – 800 m – blue shading), the northwest side (upwind) of the Appalachian Plateau (800 – 1000 m - dark green), and the southeast side (downwind) of the Appalachian Plateau (1200 – 1600 m - dark green). Therefore there is some evidence for advection of low elevation boundary layers into high terrain (black arrows) and advection of high terrain boundary layers over low elevation (white arrows).

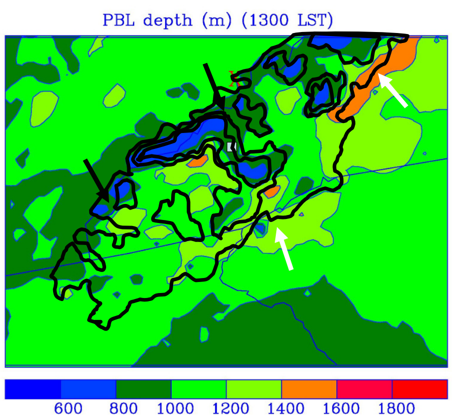

Figure 3. Map of depth of the boundary layer for regions surrounding the Southern Appalachian Mountains.

Advection of the lowland boundary layer into the mountains on the northwest side of the Appalachian Plateau (black arrows) and advection of the mountain boundary layer over lowlands southeast of the Appalachian plateau (white arrows) by 1700 LST is clearly apparent in Figure 4. The depth of the boundary layer (Figure 5) is less than 600 m (black arrows on the upwind side and greater than 1800 m (white arrows) on the downwind side of the plateau.

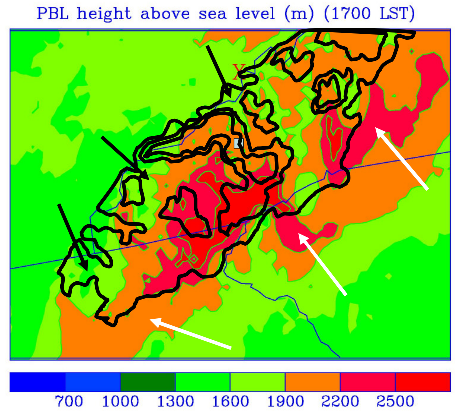

Figure 4. Same as for Figure 2 but for 1700 LST.

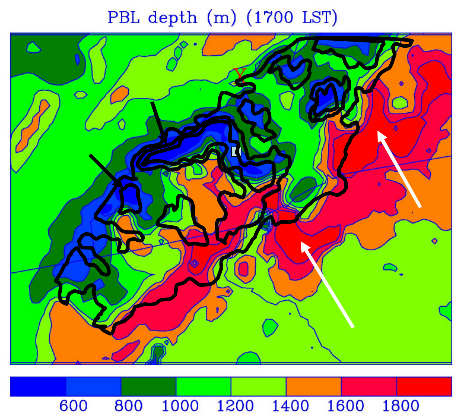

Figure 5. Same as for Figure 3 but for 1700 LST.

The National Weather Service provides forecasts of mixing height for land managers involved with prescribed burning. This analysis shows the precision required for providing mixing height forecasts for a point. For land managers, the difference in mixing height from 600 m to 1800 m is enormous. It is the difference between not burning or burning maximum area. Knowledge that mixing heights over lowlands downwind from high terrain may increase from 200 – 600 m because of advection of mountain boundary layers can significantly impact decisions on whether and how much to burn.

b) Plume Collapse

Several mechanisms for plume collapse – the unexpected return of smoke to the boundary layer from the free atmosphere above – have been proposed. One argument holds that smoke lofted into the free atmosphere resides there until re-entering the boundary layer through an elevated mixing layer. Three mechanisms that elevate mixing layers have been identified. These are urban heat islands, elevated terrain, and intense diurnal heating. Elevated terrain seems to be the major factor in the simulated plume collapse on 18 March 2006. Figure 6 summarizes this plume collapse mechanism for elevated terrain. On entering the free atmosphere, smoke does not disperse much as the air there is typically stable. Thus smoke may travel 50 – 100 km downwind and re-enter the boundary layer in high concentration, mixing to the surface to degrade air quality there.

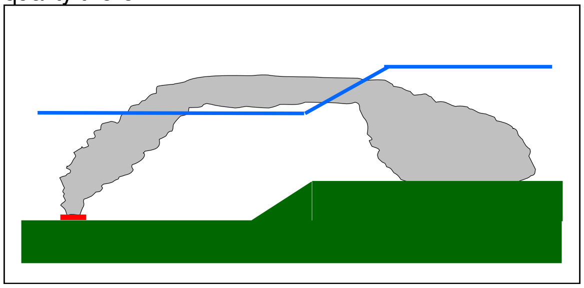

Figure 6. Schematic showing the ejection of a smoke plume into the free atmosphere above the mixing height (blue line) and its subsequent re-introduction to the boundary layer where the mixing height elevates over high terrain.

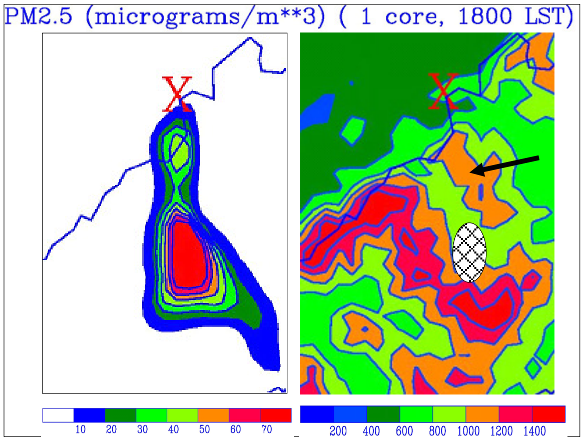

Figure 7. Maximum simulated plume collapse (left panel) at 1800 LST 18 March 2006. Right panel: Terrain of the Southern Appalachian Mountains. Distance from the fire start (X) to collapse (crosshatched ellipse) is 50 km (32 mi).

Figure 7 shows ground level $PM_{2.5}$ concentrations (left panel) and the location of the plume collapse relative to high terrain in the southern Appalachian Mountains (right panel) at 1800 LST 18 March 2006. The distance from the burn site (X) to the plume collapse is 50 km (32 mi). Maximum smoke concentrations were found in the range of 70 ug m^{-3}.

A 743 ha fire was started 1220 LST 18 March 2006 at the location identified by the 'X' in Figure 8. The location was at the ridge of a mountain located at the western edge of the southern Appalachian Mountains. The right panel of Figure 8 shows a small area of mixing heights in the range of 1600 -1900 m located beneath the 'X'. Thus at 1400 LST, mixing heights from the location of the burn to the location of the collapse at 1800 LST were not higher than the 1600 – 1900 m range.

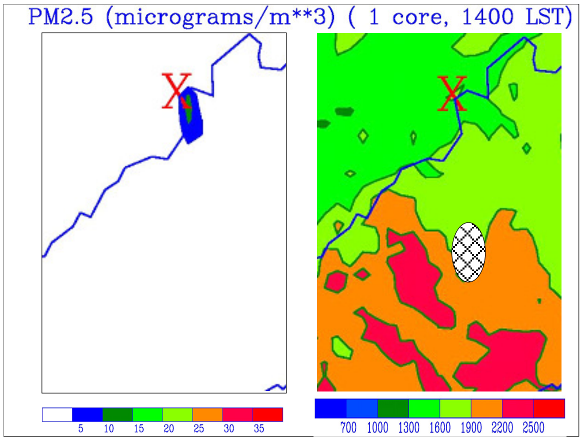

Figure 8. Left panel: $PM_{2.5}$ concentrations from simulated smoke plume at 1400 LST 18 March 2006. Right panel: Mixing heights (m).

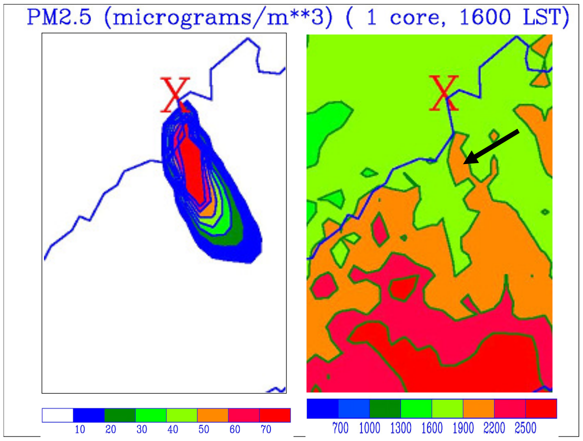

Figure 9. Same as for Figure 8 but for 1600 LST.

Plume collapse has commenced 10–20 km (7-15 mi) downwind from the burn. Figure 9 shows mixing heights elevated to the range 1900-2200 m (arrow) at a site collocated with a broad, low mountain range (arrow in Figure 7). Maximum $PM_{2.5}$ concentrations remained at approximately 70 ug m^{-3}.

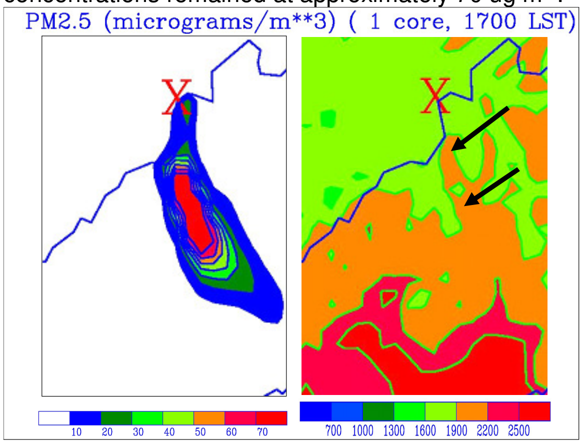

Figure 10. Same as for Figure 8 but for 1700 LST.

By 1700 LST, The area of smoke on the

ground had expanded but without expected dispersion (right panel in Figure 10). The inference is that smoke in greater concentration was being transported from aloft to the ground. The orientation of the concentration pattern is parallel to and collocated with higher mixing heights (arrows - right panel) also collocated with higher terrain in Figure 7.

By 1800 LST, the pattern of mixing heights calculated from the MM5 temperature data were no longer descriptive due to the lateness of the day. The smoke plume concentration field had assumed the pattern shown in Figure 7 about 50 km from the burn.

4 . CONCLUSION

Mountainous terrain challenges strategies currently used by land managers when conducting prescribed burns under conditions whereby winds transport smoke into high terrain. The distribution of mixing heights over the southern Appalachian Mountains was found to be highly variable. Furthermore, because of advection within the boundary layer, elevation is not a good predictor of mixing height. Deepest mixing layers were found over downwind low terrain. Therefore it is extremely difficult to predict mixing heights with accuracy for prescribed burn locations near to and within mountainous terrain. This uncertainty makes it difficult to determine the land area that can be burned without seriously compromising air quality.

Furthermore, mountainous terrain increases the likelihood of plume collapse. When burning large tracts of land in remote areas, land managers prefer aerial ignition. Aerial ignition spreads fire over the landscape so that heat from combustion organizes into warm convective plumes that transport smoke out of the boundary layer into the free atmosphere above where it can be transported away without compromising air quality. However, when smoke is transported over higher terrain where higher mixing heights are present, smoke may be returned to the boundary layer and mixed to the ground in high concentration (plume collapse).

5. REFERENCES

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