**Characterizing Smoke Intrusions from Prescribed Burning in Bend, OR, USA**

Miriam Rorig1,4, Susan O’Neill1, Colton Miller2, Roger Ottmar1, and Rick Graw3

1 USDA Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Lab

2 University of Washington, Department of Forestry

3 USDA Forest Service, Region 6

4 Corresponding author. Email: mrorig@fs.fed.us

Additional keywords: PM2.5, Smoke, Dispersion modeling

**ABSTRACT**

Smoke from prescribed burns can have negative health and safety impacts in downwind communities. This is the case in and around Bend, Oregon, USA, where burning in the wildland-urban interface on the Deschutes National Forest has resulted in smoke intrusions. To better understand the conditions that lead to these intrusions, we deployed an array of portable weather and particulate monitors over the autumn of 2014 and spring of 2015, to augment permanent monitors in place. We used the data collected to characterize the winds, and compare with meteorological and smoke dispersion models. The results from this study were: (1) most of the intrusion events were the result of terrain-driven, down-drainage SW winds carrying smoldering smoke into Bend, after active burning was complete; (2) these SW nighttime winds setup 77% of the time on average annually; (3) smoldering-prone fuels are underestimated and their consumption and emissions are not well modeled; (4) dispersion modeling can be useful for anticipating smoke intrusions, but significant errors in wind speed and direction of the meteorological models can lead to “misses” of smoke intrusion events; and (5) using higher resolution meteorological and dispersion models can improve the prediction of both timing and location of these events.

**Summary:** A study was undertaken to understand smoke intrusions from prescribed burning into Bend, OR. Smoke dispersion modeling was compared with observations. We found better characterization of smoldering-prone fuels and higher resolution models, which better depict drainages that channel smoke, improved predictions of smoke movement into populated areas.

**Introduction**

Wildland fire is a naturally occurring ecological process, and many forests in the western United States (U.S.) were shaped by the periodic occurrence of fire (Covington and Moore 1994). Timber harvesting, grazing and decades of fire suppression have altered the historical role fire played on the landscape and in some cases caused shifts in the vegetation structure and composition (Hessburg et al. 2005). These changes have allowed fuels to accumulate on the landscape which can enhance the severity and destructiveness of wildfires (Graham et al. 2004). Planned (also called prescribed) burns are one of the many tools used by land managers to improve forest health and create a diversity of plant and wildlife habitat (Covington et al. 1997, Edmonds et al. 2010) as well as reduce forest fuels to mitigate the intensity and effects of severe wildfires. These planned burns, however, present challenges that make it difficult to rely solely on them to solve the problem of ecosystem restoration.

Increased burning may be beneficial for the ecosystem, but the smoke generated from all fires (wild and planned) has negative health impacts (Delfino et al. 2009, Morgan et al. 2010, Rappold et al. 2011). Costs associated with those impacts are also significant (Kochi et al 2010). Fine particulate matter (particles smaller than 2.5 micrometers in aerodynamic diameter – hereafter referred to as PM2.5) is the pollutant of most concern within smoke, and the U.S. Environmental Protection Agency (EPA), through the Clean Air Act (1970), has set standards (National Ambient Air Quality Standards or NAAQS) to protect the public. The maximum allowable level of PM2.5 averaged over a 24-hr period is 35 μg/m3.

In the U.S., states also implement their own regulations, in addition to the NAAQS specified by EPA. The state of Oregon Administrative Rules include regulations regarding smoke intrusions, where a “smoke intrusion” is defined as the verified entrance of smoke from prescribed burning into designated smoke sensitive areas at ground level (http://arcweb.sos.state.or.us/pages/rules/oars\_600/oar\_629/629\_tofc.html). An intrusion is characterized by the one-hour average PM2.5 concentration above the previous three-hour average PM2.5 concentration in the clean air background.

Forest management agencies, such as the Deschutes National Forest (DNF), west of Bend, OR, are increasingly moving away from fire exclusion towards policies that balance modified suppression with the use of prescribed fire, to achieve ecological objectives (Miyanishi 2001). The DNF is located in the Cascade Mountains of central Oregon, U.S. They use prescribed fire in the Wildland-Urban Interface (WUI) as part of a project designed to meet those objectives while protecting the public and quality of life in nearby communities. Therefore, predicting smoke impacts and probably more importantly, predicting conditions that will prevent smoke impacts is becoming increasingly necessary.

The motivation for this study was to characterize the conditions under which smoke intrusions occur so they could be better predicted and avoided in the future. Smoke from one prescribed burn in October 2014 and five prescribed burns in 2015 intruded into Bend. 1-hr PM2.5 concentrations during these episodes ranged from 11 μg/m3 to 245 μg/m3. The U.S. Forest Service (USFS) Research Team AirFire collaborated with the USFS DNF on a field measurement and modeling project to study the complex interaction of fire, fuels, topography and wind patterns to understand how smoke intrusions into Bend occur. Another motive was to identify burn conditions that protect public health and safety. This study is unique because few case studies bring all these factors together, especially for prescribed fires. Wildfires tend to be more well-studied and large scale evaluation of air quality prediction systems that include wildfire emissions have been done, for example, by Strand et al. (2012).

Fewer studies have been conducted for smoke impacts from prescribed burns (Rorig et al.2013; Garcia-Menendez et al. 2013) There have been comprehensive fuel, fire behavior and smoke measurements on prescribed burns (e.g. RxCADRE – Ottmar et al. 2015); however, these data have not yet been used to evaluate and improve smoke modeling systems. The relationship between winds, fire behavior, and smoke dispersion is especially complex in areas of complex terrain. Wind speed and direction are affected by topography, and vegetation moisture can change at time scales of hours, minutes, and even seconds (Andrews 2012). Topography can directly affect fire behavior and smoke transport (Edmonds *et al*. 2010; Hardy *et al*. 2001). Understanding how fire, fuels, topography and wind patterns interact for a particular region can improve the ability to predict how and where smoke will disperse.

To investigate the spatial variability in meteorological conditions and analyze smoke dispersion in the area surrounding Bend, we 1) deployed a suite of PM2.5 and meteorological measurement stations for approximately nine months, during which five smoke intrusions occurred, 2) collected fuels data from two locations on the DNF, 3) analyzed the performance of one modeled case with different spatial resolutions by comparing with observational data, 4) conducted smoke modeling of the intrusions, and 5) conducted a seasonal analysis of the detailed wind patterns of the region and prescription window analysis to identify burn window opportunities. This allows us to 1) identify meteorological conditions leading to smoke intrusions, 2) evaluate existing meteorological and smoke modeling systems performance for these intrusions, 3) characterize the local wind field seasonally and burn window parameters to finally 4) identify how often conditions occur that can successfully allow for prescribed burning within the DNF without impacting the town of Bend. This is one of the few studies gathering a comprehensive dataset of meteorological measurements, PM2.5 measurements, and documented burn information. Results will improve smoke dispersion modeling and support the planning of prescribed fires, leading to better predictions and fewer smoke intrusions.

**Methods**

The study area is located in central Oregon, near the cities of Sisters, Bend, and Sunriver. Figure 1 shows a map of the area, including locations of permanent and portable weather stations and particulate monitors. The DNF lies approximately six km to the west of Bend. Annual precipitation in Bend is about 288 mm/year, with the majority of precipitation occurring between November and February (Western Regional Climate Center; http://www.wrcc.dri.edu). The climate of Deschutes County is classified as moist subtropical mid-latitude climate with a dry and warm summer season (Köppen climate classification). These climates have generally warm and humid summers and mild winters. Prescribed burning in the DNF is typically conducted in the spring (April – June) and fall (September – November) months. Wildfires are a concern during the summer months (July, August, and into September) and prescribed burning is typically restricted during these periods.

**Smoldering Fuel Consumption Measurements**

Accurate fuel loadings and consumption are critical for smoke dispersion modeling. Ottmar et al. (2014) performed post-fire fuel consumption measurements of stumps, logs and basal accumulations (litter and duff deposits at the base of standing trees) at two sites in the DNF (Figure 1) – the West Bend unit (located less than five km WSW of downtown Bend) and the Glaze Meadow unit (approximately 40 km NNW of downtown Bend). The smoldering combustion of these fuel elements was thought to have contributed to a smoke intrusion in spring 2014. Because this was a retrospective study, estimates of the timing and duration of smoldering combustion could not be determined.

**Weather Stations & Smoke Measurement Stations**

WatchDog Weather Stations (Spectrum, Inc.) were deployed at six sites in 2014 and four sites in 2015. These weather stations collected observations of temperature, precipitation, relative humidity (RH), wind speed, wind direction, wind gust speed, wind gust direction, and dew point at 10- or 15-minute intervals. E-samplers (Met One Instruments, Inc.) were deployed at five sites in 2014 and three sites in 2015. These monitors are nephelometers that collect PM2.5 concentration data in addition to temperature, RH, wind speed, and wind direction. All the sensors were 1.5 meters to two meters above ground level (AGL). Four of the E-samplers recorded at 1-hr averages and one at 10-min averages in 2014. All three used 15-min averages in 2015. The State of Oregon operates two permanent nephelometers in the DNF, one at the Sisters, Oregon District Ranger Station in Sisters, and the other at the Bend Pump Station. These instruments measure light scattering due to particulate matter in the atmosphere. Four Remote Automated Weather Stations (RAWS) are also located in the region and maintained by the DNF and the Western Regional Climate Center (WRCC). These are permanently located stations, with sensors higher above the ground than the portable stations. Wind sensors on the RAWS are typically placed at a height of six meters AGL. Most RAWS units are owned by wildland fire agencies and placed in locations where they can monitor fire danger (<http://raws.fam.nwcg.gov>). Three of these RAWS were employed in this work. See Table 1 for a list of instrument locations and instrument details and Figure 1 for instrument locations during spring 2015.

**Smoke Dispersion Modeling**

The BlueSky smoke modeling framework (Larkin et al. 2009) was used to model the smoke intrusions into Bend. BlueSky is a framework linking together datasets and models of fire location and growth, fuel loadings and consumption, emissions from consumed fuels, plume rise, and smoke dispersion. The dispersion model requires meteorological model output to predict movement and concentration of smoke. Table 2 lists the models used in the framework. For the current study, we used actual fire location and size for each of the prescribed burns. This information was obtained from the intrusion reports prepared by the DNF District Office that was responsible for the burn. Table 3 contains the dates, times, locations, sizes, and fuel loadings, and Table 4 lists the intrusion start time and length (in hours), the maximum 1-hr and 24-hr average PM2.5 concentrations, and the direction and distance of the burn from Bend. Because the intrusion reports did not specify fuel loadings by category (1-hr, 10-hr, shrub, etc.), fuel loadings were obtained from the Fuel Characterization Classification System (FCCS) mapped at a 1-km resolution (Prichard et al., 2013). FCCS fuel models and total loadings used in the model runs are given in Table 3.

A three dimensional wind field from the Weather Research and Forecast (WRF) model (Michalakes et al. 2001; Skamarock et al. 2005) was used in BlueSky, and the Hybrid Single Particle Langrangian Integrated Trajectory (HYSPLIT) model was used for the dispersion simulations (Stein et al. 2015; Draxler and Hess 1998). The spatial and temporal resolutions of the BlueSky runs are determined by the meteorological model. In this case, we used the hourly 4-km resolution WRF model provided by the University of Washington Department of Atmospheric Sciences (Mass et al. 2003). Additionally, we had available a 1-km resolution meteorological model from the National Centers for Environmental Prediction (NCEP) North American (NAM) weather model (Rogers et al. 2009) for the October 4-5, 2014 smoke intrusion period. Both models provide hourly predictions. The suite of portable meteorological and PM2.5 monitors were not deployed for the October 2014 episode, but smoke dispersion modeling was possible and the modeled meteorological wind fields were compared with those obtained from RAWS stations. Modeled PM2.5 values were compared with PM2.5 measurements at the Bend Pump Station.

**Burn Day and Seasonal Wind Analyses**

To determine how frequently land managers can expect conditions that are favorable for prescribed burning, we compiled the number of days fuel and meteorological parameters meet required conditions. Table 5 lists conditions necessary for conducting prescribed burns on the DNF. The days were identified by data measured and calculated from the RAWS in the area, and include temperature, RH, mid-flame wind speed, and 1-hr, 10-hr, and 100-hr dead fuel moistures. Using Fire Family Plus (Bradshaw and McCormick 2000), daily (13:00 PST) data from the Tumalo Ridge RAWS (seven km west of Bend at an elevation of 1220 meters; Bend elevation is 1105 meters), Lava Butte RAWS (15 km south of town at an elevation of 1344 meters), and Round Mountain RAWS (47 km southwest of Bend at an elevation of 1798 meters) were used to identify days when burning would be within prescription for the ten-year period including 2006-2015. We also used only wind data from the Tumalo Ridge RAWS (the station closest to Bend) to determine how frequently daytime and nighttime winds were from a direction that would carry smoke away from Bend.

In addition to determining the frequency of days in prescription, we also generated seasonal wind roses, both for day and night, to better understand the winds in this area. We followed the methodology used by the Western Regional Climate Center to define “day” and “night.” Time windows for “daytime” winds include the interval from 11:00 am – 18:00 pm PST, and nighttime windows include the interval from 01:00 am – 07:00 am PST. These time periods capture the general wind patterns during the day and night and attempt to reduce the inclusion of transitions associated with sunrise and sunset. Additionally, the times generally cover daytime and nighttime hours throughout the year and minimize the difference between winter and summer.

**RESULTS AND DISCUSSION**

**Fuel Consumption Estimations**

Accurate estimates of fuel loadings and types are necessary for consumption and emissions predictions. Data on preburn fuel information for the three targeted fuelbed components were unavailable, so postburn data were collected approximately two months later to reconstruct the potential contribution of stumps, logs and basal accumulations to smoldering combustion and to smoke production (Ottmar et al. 2014)**.** Total maximum smoldering fuel component consumption was estimated at 3094 kg/ha in West Bend and 17553 kg/ha in Meadow Glade with over 50% of that consumption from smoldering stumps. West Bend had minimal smoldering of logs (247 kg/ha) while Meadow Glade had 6882 kg/ha. Consumption of basal accumulation was similar at 695 kg/ha and 852 kg/ha at West Bend and Meadow Glade respectively. This information about the smoldering combustion components is used in the smoke modeling to improve predicted PM2.5 concentrations from the intrusions analyzed in this work.

**Seasonal and Diurnal Wind Patterns**

Because smoke intrusions are wind-driven events, we characterized typical wind patterns on the DNF near Bend, using data from 2006 – 2015 at the three RAWS stations located closest to Bend: Tumalo Ridge, Round Mountain, and Lava Butte (see Figure 1). We created wind roses from the RAWS winds for every season, day and night, at each RAWS site. These wind roses are shown in Appendix 1. The Tumalo Ridge and Lava Butte stations show strong WSW – W flows at night for all seasons. During the day Lava Butte also has a similar pattern of SW flows with some northerly flows as well. Round Mountain was different in that it had a NW pattern, with some flows from all directions as well. This station is located at a higher elevation (1798 m) and was the furthest removed (47 km) from Bend.

**Burn Window Analysis**

Land managers conduct prescribed burns when fuel and meteorological conditions meet required parameters. Table 5 lists conditions necessary for conducting prescribed burns on the DNF. Using the methodology described above (in the Methods section), the number of days when conditions would be in prescription for the 10-year period at the three RAWS sites was compiled.

Tumalo Ridge had 259 burn days, Lava Butte had 264 burn days, and Round Mountain had 280 burn days within prescription. On average, 26-28 burn days exist every year. Figure 2 shows the average number of burn days by month for these three RAWS locations. During mostly the winter periods significant data gaps exist in the RAWS data, therefore those data are probably biased low during the winter months. Greater confidence is placed in the spring, summer and fall months of data (shown by the box around those months in Figure 2). Many of the days within prescription occur during the summer months, which coincide with wildfire season, when prescribed burning is typically not used.

The need to keep smoke away from populated areas further decreases the number of available burn days. The parameters listed in Table 5 do not include wind direction. Additional analysis was undertaken using wind directions from the Tumalo Ridge RAWS, to determine how often northwesterly through northeasterly winds occur during the day (to transport smoke from the DNF West Bend projects away from town) and how often southeasterly to southwesterly winds occur during the nighttime (to determine if nighttime drainage flows are responsible for the smoke intrusions from the smoldering of the large woody fuels and basal accumulations). These data are summarized in Table 6. In Table 6, “ideal” wind conditions are when north winds occur during the day and south winds do not occur at night. Nighttime southerly winds occur 69% – 80% of the time, making “ideal” wind conditions a somewhat rare occurrence (5% - 13%).

**Smoke Intrusions**

Smoke from prescribed burns intruded into Bend on one occasion in October 2014 and five occasions in May thru June 2015. Table 4 lists the dates of the six intrusions, the maximum 1-hr measured PM2.5 concentration, the time of the maximum, and the duration of elevated PM2.5 concentrations. The May 4, 2015 intrusion was the shortest duration and lowest concentration and occurred during the daytime hours. The other five intrusions occurred in the evening, over-night, and early morning hours, with 1-hr PM2.5 concentrations up to 245 μg/m3.  Presented here is a discussion of the measured meteorological conditions contributing to these intrusions, a graphical and statistical analysis of the modeled wind field from the 4-km WRF meteorological prediction system for all six intrusions and the modeled 1-km resolution wind field from the NWS for the October 2014 intrusion. Smoke modeling was undertaken with the BlueSky Smoke Modeling Framework.

***2015 Daytime Smoke Intrusion***

A 46 ha planned burn was ignited at 0930 PDT May 4, 2015 approximately 55 km southwest of Bend, Oregon (Figure 1).  Smoke was transported into Bend within 3.5 hours of ignition and a maximum concentration of 13 μg/m3 was recorded at the Bend Pump Station nephelometer. Concentrations were elevated for approximately two hours. Before ignition on May 4, the Tumalo Ridge RAWS measured north winds, however by the time of ignition the winds were from the south. Winds were steady from the WSW during the intrusion period, indicating that smoke could be transported into town. Conversely, the Round Mountain RAWS, which was the closest wind monitor to the burn, had WNW winds at the time of ignition and throughout the afternoon, suggesting the wind should have carried the smoke away from Bend. Other weather stations located along the Hwy 97 corridor between Bend and the burn measured predominantly southerly winds (see the first shaded area in Figure 4).

BlueSky smoke modeling results simulate the timing of the transport of the smoke into Bend (Figure 3). However, the modeled BlueSky 1-hr PM2.5 concentrations at the Bend Pump Station were an order of magnitude less than the concentrations measured by the nephelometer, with concentrations of 0.05 to 0.47 μg/m3 predicted between 1300 and 1500 PDT, compared to the observed results of 4.8 to 12.6 μg/m3.  Figure 3 shows how the modeled plume centerline is pushed to the south of town, and thus only the plume fringes are predicted to impact Bend. This can also be seen in Figure 4 (first intrusion gray-shaded area) which shows measured and modeled wind speed and wind direction data at Cascade Middle School. Modeled winds are WSW while measured winds are S-SW. Ottmar et al (2014) identified smoldering consumption of duff, stumps and basal accumulations as likely contributing additional smoke in the atmosphere. Increasing the duff depth from two inches to five inches approximately doubled the pre-burn fuel load, with most of that in the smoldering phase such that it was released close to the ground. This improved the BlueSky concentrations although the main plume was still simulated to miss town because predicted winds did not change. Figure 3 shows PM2.5 concentrations from the model run using the increased fuel loadings. Also, note that we are only simulating primary PM2.5 emissions from the fires and not taking into account secondary formation or other sources.

***2015 Nighttime Smoke Intrusions***

The five nighttime and early morning intrusions all exhibit similar characteristics. The burns were located 6-km to 10-km SSW of Bend. During the day NE - NW winds transported smoke away from town. Overnight, winds decreased and became SW with PM2.5 concentrations becoming elevated in Bend. BlueSky 4-km resolution simulations weakly simulated smoke transport into town for the May 5 intrusion around midnight but did not bring smoke into town during the intrusion period of 0600-0800 PDT. BlueSky smoke model simulations also failed to bring smoke into town for the May 28, June 5 and June 6 intrusions.

Figures 4, 5, and 6 illustrate the measured wind directions and wind speeds at the meteorological station in town, measured at Cascade Middle School, for each of the intrusions. During the overnight intrusion periods (see the second shaded area of Figure 4 and all the shaded areas in Figures 5 and 6) the 4-km WRF modeled winds remained from the NW while measured winds were from the SSW. Mean wind direction errors ranged from 89 – 108 degrees at night at this location (Appendix 2). Figure 7 shows box plots of the day and night wind direction mean error values for all the intrusion periods. In general, wind direction mean errors were greater at night than during the day. The modeled wind speeds were generally biased high within 1-3 m/s of the observed values and calm winds registered greater than 50% of the time at four out of the nine stations. (Table 7), largely due to calm winds overnight (Appendix 2).

***2014 Nighttime Smoke Intrusion***

Three planned burns were ignited on October 4, 2014 approximately 44 km SSW of Bend (Figure 1). The burns were between 18 and 20 ha each. Ignition was between 1100 PDT and 1400 PDT and smoke was initially carried away from town. Overnight, however, conditions changed and smoke was transported into town. Elevated PM2.5 values registered an intrusion starting at 0200 PDT October 5 and dissipating by 1200 PDT. A maximum 1-hr PM2.5 concentration of 96 μg/m3 was recorded at the Bend Pump Station at 0300 PDT, with a second peak of 94 μg/m3 at 0900 PDT.(Figure 8).

The suite of smoke and meteorological monitors were not deployed during the 2014 intrusion as were available for the 2015 intrusion periods, but a 1-km resolution NAM meteorological model domain (36-hour forecast) was available from the NWS in addition to the 4-km WRF meteorological domain. Comparison of winds and smoke dispersion was undertaken with the two resolutions and compared to the three available RAWS sites (Tumalo Ridge, Lava Butte, and Round Mountain). Wind direction mean errors for both 1-km (left side of Figure 9) and 4-km (right side of Figure 9) resolutions, day and night, are shown for the 36-hour period. For the 1-km resolution domain, daytime mean errors ranged from 45 to 80 degrees, while nighttime mean errors ranged from 20 to 80 degrees. For the 4km resolution domain, daytime mean errors ranged from 38 to 60 degrees, and nighttime mean errors ranged from less than 10 to greater than 80 degrees.

The BlueSky smoke model simulations using both the 1-km resolution NWS NAM and the 4-km WRF show smoke transported down the drainage from the SSW into Bend (Figures 10a and 10b respectively). The plume arriving at 0300 PDT (in agreement with the measured data). Predicted concentrations were lower than measured (approximately 10-15 μg/m3 for the 1-km NAM output and less than 1 μg/m3 for the 4-km WRF output; Figure 8) probably because BlueSky was not fully capturing the smoldering of basal accumulations and large woody debris. The smoke simulation using the 1-km NAM shows a well-defined plume transporting along the drainage. The lower resolution 4-km WRF simulation carries smoke towards Bend overnight but weakly. This example shows that higher resolution meteorological models, which can better resolve complex terrain features, can improve smoke dispersion predictions. While this may not always the case, higher resolutions have been shown to provide improved results when compared with coarser resolutions in modeling fire danger indices (Hoadley et al. 2006).

**SUMMARY/CONCLUSIONS**

A comprehensive study was undertaken of six smoke intrusion episodes in the autumn of 2014 and spring of 2015 in Bend, OR, USA. In addition to permanent RAWS (weather stations) and particulate monitors, data were collected from several portable weather and particulate monitors that were deployed for this study. State regulations prohibit smoke in populated areas, because of health and safety concerns. The goal was to better understand the conditions leading to the intrusions so they could be anticipated and prescribed burns be successfully accomplished.

Accurate assessments of fuel types and loadings are essential for realistic estimates of emissions. Unfortunately, current fuel models do not adequately represent the smoldering fuels that often are responsible for smoke intrusions. This was the case for several of the intrusions here, when total fuels (specifically duff) were underestimated. Those fuels continued smoldering overnight, well after the active burning had ended.

Close analyses of the predicted and observed winds and particulate matter indicated conditions that were common to all but one of the intrusions. The unique case was on May 4 2015, when daytime winds carried smoke into Bend in the early afternoon, two hours after ignition. All the other cases occurred during the late night and early morning hours, when winds were light or calm, and smoke movement was driven by terrain-induced down-drainage flows. In all cases the burns were located southwest of town and smoke was transported into town by southwest winds. Seasonal analysis shows that these wind conditions occur 77% of the time annually.

Smoke dispersion model results varied by intrusion. In some cases, (the daytime intrusions of May 4, and the nighttime intrusions of May 5 - 6 2015, and October 5, 2014) the model results showed smoke transport into Bend close to the time indicated by the observations. The model results for the other cases (May 28-29 2015, June 5 and 6 2015) were “misses,” with no smoke transport into Bend predicted. For the cases where both the observations and the model showed smoke in Bend, the modeled concentrations were less than observed, sometimes by an order of magnitude or more. As discussed above, emissions from smoldering fuels were likely underestimated. Furthermore, the dispersion model is only as good as the underlying meteorological model (Garcia-Menendez et al. 2013), and if that model does not accurately represent the winds (such as sub-grid scale drainage winds), the dispersion model will not accurately locate the smoke. Wind direction mean errors ranged from 14 – 94 degrees with even higher mean errors during the night. The one case where two resolutions were available (October 4 2014, 4km and 1km), the higher resolution model better predicted the location and timing of the smoke intrusion.

Improving the characterization of the smoldering fuels and using higher resolution meteorological data both improved the smoke modeling results. Future research is required to include pre-burn fuel loading measurements and to refine the measurement of the consumption of forest fuels during the flaming and smoldering phases of combustion, and the timing and the duration of that consumption. Continued improvement of meteorological models is critical in order to deliver the smoke to the correct location and high resolution model output shows promise for areas of complex terrain. For smoke managers, it may no longer be enough to base burn plans on the total amount of forest fuels, fuel consumption, and total smoke produced on site. Rather, a more detailed understanding of the timing of consumption and smoke production during periods of weak atmospheric dispersal may better help manage downwind smoke effects in communities near the WUI.

**ACKNOWLEDGEMENTS**

We thank the USDA Forest Service Region 6 and the Washington and Oregon Offices of the Bureau of Land Management for funding this study. We also would like to thank the many people who made this study possible, including: Deana Wall and everyone at the Deschutes National Forest Supervisors Office, Jinny Reed and others at the USDA Forest Service Sisters, Oregon Regional Office, Bridges Boys Academy, Cascade Academy, Miller Elementary, Cascade Middle School, Tumalo Golf Club, Colin Wills with Arnold Irrigation District, and Jason Schneider with the Sunriver Home Owners Association

**REFERENCES**

Anderson GK, Sandberg DV, Norheim RA, (2004). Fire Emissions Production Simulator (FEPS) Users Guide, Version 1.0.

http://www.fs.fed.us/pnw/fera/feps/FEPS\_users\_guide.pdf

Andrews PL. (2012). Modeling wind adjustment factor and midflame wind speed for Rothermel's surface fire spread model. USDA Forest Service, Gen. Tech. Rep. RMRS-GTR-266. Rocky Mountain Research Station. 39 p. (Fort Collins, CO).

Bradshaw L, McCormick E (2000). FireFamily Plus user's guide, Version 2.0. USDA, Forest Service, Gen. Tech. Rep. RMRS-GTR-67. Rocky Mountain Research Station Ogden, UT.

Covington WW, Moore MM (1994) Southwestern ponderosa forest structure: changes since Euro–American settlement. *Journal of Forestry* **92**, 39–47.

Covington WW, Fule PZ, Moore MM, Hart SC, Kolb TE, JN Mast (1997) Restoring ecosystem health in Ponderosa pine forests of the Southwest. *Journal of Forestry* **95**, 23-29.

Delfino RJ, Staimer N; Tjoa T, Gillen DL, Polidori A, et al. (2009) Air pollution exposures and circulating biomarkers of effect in a susceptible population: clues to a potential causal component mixtures and mechanisms. ***Environmental Health Perspectives*http://search.proquest.com/assets/r20161.5.0-10/core/spacer.gif117,**http://search.proquest.com/assets/r20161.5.0-10/core/spacer.gif1232-1238.

Draxler RR, Hess GD (1998) An overview of the HYSPLIT\_4 modeling system of trajectories, dispersion, and deposition. *Australian Meteorological Mag*azine **47**, 295-308.

Edmonds RL, Agee JK, Gara RI (2010) Forest health and protection, 2nd edition. Waveland Press Inc., Long Groove, IL.

Garcia-Menendez F, Hu Y, Odman MT (2013) Simulating smoke transport from wildland fires with a regional-scale air quality model: Sensitivity to uncertain wind fields. *Journal of Geophysical Research Atmosphere*, **118**, 6493–6504.

Graham R, McCaffrey S, Jain T (2004) Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-120, 43 pp.

Hardy CC, Ottmar RD, Peterson JL, Core JE (2001). Smoke management guide for prescribed and wildland fire: 2001 edition.

Hessburg PF, Agee JK, Franklin JF (2005) Dry forests and wildland fires of the inland Northwest USA: Contrasting the landscape ecology of the pre-settlement and modern eras. *Forest Ecology and Management* **211**, 117-139.

Hoadley, JL, Rorig ML, Bradshaw L, Ferguson SA, Westrick, KJ, Goodrick S, and Werth P (2006) Evaluation of MM5 model resolution when applied to prediction of National Fire Danger Rating indexes. *International Journal of Wildland Fire*, **15**, 147–154.

Kochi I*,* Donovan GH, Champ PA Loomis JB (2010). The economic cost of adverse health effects from wildfire-smoke exposure: a review. I*nternational Journal of Wildland Fire* **19** 803-817.

Larkin NK, O'Neill SM, Solomon R, Raffuse RS, Strand T, Sullivan D, Krull C, Rorig M, Peterson J, Ferguson SA (2009).  The BlueSky smoke modeling framework. *International Journal of Wildland Fire* **18***, 906-920.*

Mass, CF, Albright M, Ovens D, Steed, R, et al. (2003). Regional environmental prediction over the pacific northwest.*Bulletin of the American Meteorological Society,***84**, 1353-1366.

Michalakes J, Chen S, Dudhia J, Hart L, Klemp J, Middlecoff J, Skamarock W (2001) Development of a next generation regional Weather Research and Forecast model: Developments in teracomputing. *Proceedings of the Ninth ECMWF Workshop on the Use of High Performance Computing in Meteorology*, W. Zweiflhofer and N. Kreitz, Eds., World Scientific, 269-276.

Miyanishi K (2001) *Forest Fires: Behavior and Ecological Effects*. E. A. Johnson (Ed.). Academic Press.

## Morgan G, Sheppeard V, Khalaj B, Ayyar A, Lincoln D, Jalaludin B, Beard J, Corbett S, Lumley T (2010). Effects of Bushfire Smoke on Daily Mortality and Hospital Admissions in Sydney, Australia. *Epidemiology* 21, 47-55.

Oregon Administrative Rules, Division 48, Smoke Management, Oregon Department of Forestry.

http://arcweb.sos.state.or.us/pages/rules/oars\_600/oar\_629/629\_tofc.html

Ottmar R, Heirs K, Butler B, Clemens C, Dickinson M, Hudak A, O’Brien J, Potter B, Rowell E, Strand T, Zajkowski J (2015). Measurements, datasets and preliminary results from the RxCADRE project – 2008, 2011 and 2012. *International Journal of Wildland Fire* 25(1) 1-9.

Ottmar R, Restaino J, Vihnanek R, Burke C (2014) Final Report: Identifying fuelbed components that contribute to smoldering consumption to improve smoke management decisions for prescribed fire application east of the Cascades in Oregon and Washington. Pacific Northwest Research Station, Pacific Wildland Fire Sciences Lab, 400 N 34th St., Suite 201, Seattle, WA 98103. 20 pp. Available upon request.

Prichard SJ, Ottmar RD, Anderson GK (2005) ‘Consume User’s Guide Version 3.0.’ USDA Forest Service, Pacific Wildland Fire Sciences Laboratory. (Seattle, WA)

Prichard SJ, Sandberg DV, Ottmar RD, Eberhard E. Andreu A, Eagle P, Swedin K (2013) ‘Fuel Characteristic Classification System Version 3.0: Technical Documentation’ USDA Forest Service, Gen. Tech. Rep. PNW-GTR-887. (Portland, OR)

Rappold AG, Stone SL, Cascio WE, Neas LM, Kilaru VJ, et al. (2011) Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance. ***Environmental Health Perspectives***http://search.proquest.com/assets/r20161.5.0-10/core/spacer.gif**119,**http://search.proquest.com/assets/r20161.5.0-10/core/spacer.gif 1415-1420.

Rogers E, DiMego G, Black T, Ek M, Ferrier B, Gayno G, Janjic Z, Lin Y, Pyle M, Wong V, Wu W-S (2009) The NCEP North American Mesoscale Modeling System: Recent changes and Future Plans. 23rd Conference on Weather Analysis and Forecasting / 19th Conference on Numerical Weather Prediction, Omaha, NE.

Rorig M, Solomon R, Krull C, Peterson J, Ruthford J, Potter B (2013) Analysis of meteorological conditions for the Yakima Smoke Intrusion Case Study, 28 September 2009 USDA Forest Service, Res. Pap. PNW-RP-597. (Portland, OR):

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W, Powers, JG (2005) A description of the Advanced Research WRF version 2. NCAR Tech. Note NCAR/TN-468+STR, 88 pp.

Smoke Management (2014) Oregon Administrative Rules 629-048-0001.

Stein AF, Draxler RR, Rolph GD, Stunder BJB, Cohen MD, Ngan F (2015) NOAA's HYSPLIT atmospheric transport and dispersion modeling system, *Bulletin of the American Meteorological. Society,* **96**, 2059-2077.

Strand TM, Larkin N, Craig KJ, Raffuse S, Sullivan D, Solomon R, Rorig M, Wheeler N, Pryden D (2012) Analyses of BlueSky Gateway PM2.5 predictions during the 2007 southern and 2008 northern California fires. *Journal of Geophysical Research*, **117**, D17301.

**Table 1**. Meteorological stations and smoke monitor locations for Spring 2015. Locations are listed from North to South. WX = Watchdog meteorological measurement station (wind speed, wind direction). Smoke = MetOne Inc. E-Sampler measuring PM2.5 concentrations and wind data (wind speed, wind direction). RAWS = Remote automated weather station measuring wind speed and wind direction. Nephelometer = Radiance Research M903.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Station | Latitude (deg) | Longitude (deg) | Elevation (m) | Measurement Type | Relationship to Bend, Oregon (km, direction) |
| Sisters Ranger Station | 44.2925 | -121.5552 | 975 | WX | 32 km, NNW |
| Sisters Ranger Station | 44.2925 | -121.5552 | 975 | Nephelometer | 32 km, NNW |
| Bridges Boys Academy | 44.2274 | -121.5212 | 1079 | WX | 25 km, NW |
| Cascade Academy | 44.1327 | -121.3323 | 988 | WX | 8 km, NNW |
| Tumalo Ridge | 44.0494 | -121.4003 | 1220 | RAWS | 7 km, WSW |
| Bend Pump Station |  |  |  | Nephelometer | In Town |
| Miller Elementary | 44.0543 | -121.3692 | 1167 | WX | 5 km, W |
| Cascade Middle School | 44.0370 | -121.3397 | 1145 | Smoke | 4 km, SW |
| Lava Butte | 43.93 | -121.33 | 1344 | RAWS | 15 km, S |
| Sunriver | 43.9033 | -121.4329 | 1269 | Smoke | 20 km, SSW |
| Round Mountain | 43.6739 | -121.7167 | 1798 | RAWS | 47 km SW |

**Table 2**.  The BlueSky Smoke Modeling Framework configuration used for modeling smoke production and transport from  the prescribed burns.

|  |  |
| --- | --- |
| BlueSky Framework | Version 3.1.5 |
| Meteorological model | WRF 3.1.1 (4-km, 1-hr intervals), NAM (1-km, 1-hr intervals) |
| Fuel loadings | Fuel Characteristic Classification System (FCCS) |
| Consumption model | CONSUME Version 3 |
| Emissions model | FEPS Version 1 |
| Dispersion model | HYSPLIT Version 4.9 |

**Table 3**. Prescribed burns responsible for smoke intrusions into Bend, Oregon for Fall 2014 and Spring 2015. Vegetation types are those used for Bluesky runs.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Burn Date | Latitude  (deg) | Longitude (deg) | Elevation (meters) | Hectares | Kgs/Hectare | Vegetation  (FCCS #) | Ignition Start  (PDT) |
| 10/04/14 | 43.7250 | -121.6323 | 1301 | 18.2 | 101482 | Lodgepole Pine Forest (22) | 1357 |
| 10/04/14 | 43.6960 | -121.6529 | 1305 | 19.0 | 44498 | Pacific Ponderosa Pine – Douglas-fir (24) | 1114 |
| 10/04/14 | 43.7105 | -121.6329 | 1302 | 20.3 | 44498 | Pacific Ponderosa Pine – Douglas-fir (24) | 1130 |
| 05/04/15 \*\* | 43.6571 | -121.8360 | 1525 | 46.2 | 182990 | Lodgepole Pine Forest (22) | 0930 |
| 05/05/15 | 43.9611 | -121.3339 | 1266 | 4.9 | 30734 | Ponderosa Pine Savanna (28) | 1045 |
| 05/28/15 | 44.0242 | -121.3839 | 1312 | 27.9 | 21005 | Western Juniper/ Sagebrush Savanna (55) | 1125 |
| 06/05/15 | 44.0423 | -121.3975 | 1220 | 49.4 | 21005 | Western Juniper/ Sagebrush Savanna (55) | 1100 |
| 06/06/15 | 44.0136 | -121.3975 | 1234 | 55.9 | 21005 | Western Juniper/ Sagebrush Savanna (55) | 1000 |

\*\* 05/04/15 fuels customized from FCCS #22 by increasing duff depth from 2 to 5 inches

**Table 4.** Summary of smoke intrusion episodes into Bend, Oregon for Fall of 2014 and Spring of 2015.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Burn Date | Intrusion Start (PDT) | Intrusion Duration (hours) | Maximum 1-hr PM2.5 (g/m3) | Maximum 24-hr PM2.5 (g/m3) | Relationship to Bend  (km, direction) |
| 10/04/14 | 0300 10/05/14 | 10 | 96 | 26 | 45 km, SSW |
| 10/04/14 | 49 km, SSW |
| 10/04/14 | 47 km, SSW |
| 05/04/15 | 1300 | 2 | 13 | 5 | 60 km, WSW |
| 05/05/15 | 0700 05/06/15 | 1 | 11 | 2.3 | 11 km, SSW |
| 05/28/15 | 0100 05/29/15 | 7 | 181 | 27 | 7 km, SW |
| 06/05/15 | 2200 | 12 | 130 | 25 | 7 km, WSW |
| 06/06/15 | 0000 06/07/15 | 10 | 245 | 38 | 9 km, SW |

**Table 5.** Prescribed burn prescription parameters for fires conducted on the Deschutes National Forest.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Low | High | Minimal Acceptable Moisture Parameters |
| Air Temperature (F) | 40 | 80 | - |
| Relative Humidity (%) | 20 | 40 | - |
| Mid-flame Wind Speed (mph) | 0 | 8 | - |
| 1-hr Fuel Moisture (%) | 5 | 10 | 5 |
| 10-hr Fuel Moisture (%) | 6 | 12 | 6 |
| 100-hr Fuel Moisture (%) | 7 | 14 | 7 |
| 1000-hr Fuel Moisture (%) | - | - | 15 |
| Live Fuel Moisture (%) | - | - | 30 |

**Table 6.** Percent days when nighttime south winds and daytime north winds occur at the Tumalo Ridge RAWS from 2006 – 2015. Ideal wind conditions are when north winds occur during the day and south winds do not occur at night. “Annual” analysis takes into account all days of the year. “Annual Burn” analysis takes into account only days that meet the prescribed burn prescription window parameters. Similarly for Spring and Fall.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Night  South Wind  Yes | Night  South Wind  No | Day  North Wind  Yes | Day  North Wind  No | “Ideal” Wind Conditions |
| Annual | 77% | 15% | 36% | 45% | 7% |
| Annual Burn | 75% | 17% | 46% | 38% | 8% |
| Spring | 77% | 12% | 45% | 36% | 7% |
| Spring Burn | 69% | 21% | 50% | 36% | 13% |
| Fall | 77% | 17% | 35% | 44% | 9% |
| Fall Burn | 80% | 14% | 46% | 38% | 5% |

**Table 7.** Wind speed (WS) mean bias, wind speed mean error, and wind direction (WD) mean error at the meteorological measurement stations for the 2015 smoke intrusion periods. Model data are from the 4-km resolution Weather Research Forecast model operated by the University of Washington. Station locations are listed north to south.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Station/ Intrusion Period | May 4-6, 2015 | | May 28-29, 2015 | | June 5-7, 2015 | |
|  | WS Bias/ Error (m/s) | WD Error (degrees) | WS Bias/ Error (m/s) | WD Error (degrees) | WS Bias/ Error (m/s) | WD Error (degrees) |
| Sisters Ranger Station | 2.9/ 3.0  50% calm | 49.3 | 1.7/ 1.7 88% calm | 43.5 | 2.5/ 2.5 79% calm | 47.3 |
| Bridges Boys Academy | 1.3/ 1.5  40% calm | 43.1 | 1.1/ 1.4 63% calm | 48.0 | 1.1/ 1.1  44% calm | 27.2 |
| Cascade Academy | 2.0/ 2.0  67% calm | 43.8 | 1.3/ 1.3 71% calm | 45.4 | 2.8/ 2.8  63% calm | 38.3 |
| Tumalo Ridge RAWS | 0.6/ 1.1 | 42.9 | 0.6/ 0.9 | 58.6 | 0.9/ 1.1 | 40.8 |
| Miller Elementary | 1.6/ 1.8  52% calm | 33.8 | 1.8/ 1.8 79% calm | 70.2 | 2.6/ 2.6  56% calm | 29.7 |
| Cascade Middle School | 0.4/ 0.7 | 59.9 | 0.7/ 1.0 | 85.4 | 0.9/ 1.1 | 74.3 |
| Lava Butte RAWS | 0.7/ 1.4  10% calm | 34.8 | 0.9/ 1.3  33% calm | 59.4 | 2.0/2.0 19% calm | 39.2 |
| Sunriver | -0.6/ 1.0  31% NA | 71.2 | 0.4/ 1.2 | 94.0 | 0.9/ 1.1 | 55.4 |
| Round Mountain RAWS | -0.2/ 1.4 | 13.8 | -0.7/ 1.5 | 59.5 | 0.1/ 1.6 | 62.6 |