Analysis of Multiple Smoke Intrusion Events into Bend, OR, in Autumn 2014 and Spring 2015

Report to USDA Forest Service Region 6 and the Washington and Oregon Offices of the Bureau of Land Management

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Executive Summary

Several intrusions of smoke into Bend, OR from prescribed burns on the Deschutes NF led the Forest Service to execute a study to determine what caused smoke to travel into Bend, and identify ways of preventing intrusions in the future. An array of portable weather stations and air quality monitors were placed in strategic locations around Bend to test the accuracy of predictions available from meteorological and smoke dispersion models. Fuel consumption was measured and compared to modeled results. The study found that 1) most intrusions were the result of terrain-driven, down drainage winds carrying smoldering smoke into Bend at night, 2) consumption of fuels that are likely to smolder for long periods was underestimated by existing models leading to errors in predicted emissions, especially at night, 3) modeling errors in wind speed and direction can lead to complete "misses" of smoke intrusions, and 4) in any given year, the number of days with weather conditions in prescription and favorable wind directions (both day and night) that will keep smoke out of Bend is very limited, making it difficult to achieve fuel treatment objectives with fire alone. High resolution (e.g. 1-km) meteorological and dispersion modeling showed promise in simulating these conditions, and would likely improve the prediction of both the timing and locations of potential smoke intrusions.

Background

Prescribed burning is carried out on the Deschutes National Forest (DNF) to improve forest health, create a diversity of plant and wildlife habitat and to protect communities and quality of life. To safely conduct planned burns, weather conditions must be within a pre-defined range to ensure the fuels are dry enough, but not too dry or too moist, and temperatures and winds are moderate, so that fires will carry but not grow out of control. Wind speed and direction are also very important for determining where smoke will go. Because of health and visibility concerns, State and Federal regulations prohibit allowing unhealthy levels of smoke to be carried into smoke-sensitive areas – typically towns, populated areas, or any place where there are schools, hospitals, and/or individuals sensitive to smoke. Under the Oregon Smoke Management Plan (http://www.oregon.gov/ODF/Documents/Fire/smd.pdf), Oregon Department of Forestry meteorologists regulate the number and size of burns, based on weather and wind conditions, to minimize smoke intrusion into populated areas. All burning on the Deschutes National Forest is done in compliance with state smoke management regulations and daily guidance advice. Because it can be very difficult to anticipate where the smoke will carry, the Forest Service uses smoke dispersion models to help predict smoke impacts from wildland burning.

Despite careful planning, nine smoke intrusion events brought smoke into Bend, OR during 2014 and 2015. A "smoke intrusion" is defined as the verified entrance of smoke from prescribed burning into designated smoke sensitive areas at ground level (Smoke Management 2014). An intrusion is characterized by the one-hour average $PM_{2.5}$ concentration above the previous three-hour average $PM_{2.5}$ concentration in the clean air background.

We analyzed six of those smoke intrusion events that occurred in Bend in the autumn of 2014 and spring of 2015. The primary goals of this study were first, to determine whether smoke intrusions were the result of smoke transported up-drainage during active daytime burning returning down-drainage into town at night, or if the nighttime smoke was the result of smoldering emissions carried into town by down-drainage winds, and secondly, to characterize the meteorological conditions (specifically winds) that result in the intrusions. To accomplish these goals, we deployed a suite of $PM_{2.5}$ and meteorological measurement stations for approximately 9 months, during which 5 of the 6 analyzed smoke intrusions occurred. These portable weather and particulate monitoring stations supplemented permanent Remote Automated Weather Stations (RAWS) and nephelometers (particulate monitors) located in and around the DNF near Bend. We also used high-resolution dispersion models to evaluate their utility for predicting when intrusions are likely to occur.

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, and the prescribed fires responsible for the smoke intrusions. We analyzed six intrusion events, focusing on fuels, weather, smoke dispersion modeling, and also undertook a burn day analysis, to determine how frequently weather conditions are "in prescription" based on data collected at the permanent RAWS sites. Table 1 lists the prescribed burns responsible for smoke intrusions into Bend, Oregon for Fall 2014 and Spring 2015

Figure 1. Study area in and around Bend, OR, showing locations of co-located smoke and meteorological monitors (smoke icon), weather stations only (cloud icon), and prescribed fires (fire icon).

Fuel Consumption

Consumption of stumps, logs and basal accumulations (litter and duff deposits at the base of standing trees) was measured at two sites in the DNF – the West Bend unit (located less than 5 km WSW of downtown Bend) and the Glaze Meadow unit (approximately 40 km NNW of downtown Bend) (Ottmar et al. 2014). The smoldering combustion of these fuel elements was thought to have contributed to a smoke intrusion in spring 2014. The Ottmar et al. (2014) work was a retrospective study, therefore estimates of the timing and duration of smoldering combustion could not be determined.

Weather & Smoke Measurements

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, 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 $PM_{2.5}$ concentration data in addition to temperature, wind speed, and wind direction. All the sensors were 1.5 m to 2 m above ground level (AGL). Four of the E-samplers recorded at 1-hr averages and one at 10-min average in 2014. All three used 15-min averages in 2015. The State of Oregon operates two permanent nephelometers in the area, one at the Sisters Ranger Station in Sisters, OR, and the other at the Bend Pump Station. The nephelometers measure light scattering due to particulate matter in the atmosphere which is then converted to $PM_{2.5}$ concentration by correlation equations developed by the Oregon Department of Environmental Quality. Three 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 placed at a height of 6 m 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, accessed 18 August 2016). See Table 2 for a list of instrument locations and instrument details and Figure 1 for instrument locations during spring 2015.

Smoke Dispersion Modeling

Six intrusion events were analyzed for this study, one occurred in October 2014, and five in spring (May – June) 2015. The portable monitors were in place for the 2015 cases, but not for the 2014 intrusion. We therefore relied only on the permanent particulate monitors and weather stations for analysis of the 2014 intrusion. The BlueSky smoke modeling framework (Larkin et al. 2009) was used to model the smoke intrusions into Bend. BlueSky links 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 used by BlueSky requires meteorological parameters to predict movement and concentration of smoke. Table 3 lists the models used in the BlueSky framework. For the current study, we used actual fire location and size for each of the prescribed burns.

Fire location and burn size was obtained from the intrusion reports prepared by the DNF District Office that was responsible for the burn. Table 1 contains the dates, times, locations, sizes, and fuel loadings in tons/acre. 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 1. Table 4 lists the intrusion start time and length (in hours), the maximum 1-hr and 24-hr average $PM_{2.5}$ concentration, and the direction and distance of the burn from Bend.

A three dimensional wind field from the Weather Research and Forecast (WRF) model (Michalakes et al. 2001; Skamarock et al. 2005), and the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used for the smoke dispersion simulations in BlueSky (Stein et al. 2015; Draxler and Hess 1998). The spatial and temporal resolutions of the BlueSky smoke dispersion predictions 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 output 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. With the availability of the two different meteorological models to drive the BlueSky simulations, we were able to evaluate the benefit of using high-resolution smoke dispersion for $PM_{2.5}$ predictions.

Burn Window Analysis

To determine the percentage of time weather conditions meet the prescription necessary for a successful prescribed fire, we compiled ten years of wind speed and direction data (2006-2015) from the permanent RAWS sites. Table 5 lists conditions necessary for conducting prescribed burns on the DNF, and include ranges of 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, Lava Butte RAWS, and Round Mountain RAWS were used to identify days when burning would have been within prescription for the ten year period of 2006-2015. Because the criteria listed in Table 5 do not include wind direction, 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. We followed the methodology used by the Western Regional Climate Center to define “day” and “night” (http://www.wcc.nrcs.usda.gov/climate/windrose.html, accessed 19 August 2016). 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.

Results

Fuels

In a companion study, post burn measurements of fuels were collected at two locations in the DNF, the West Bend unit and the Meadow Glade unit (Ottmar et al. (2014)). Pre-burn fuel loadings were not available because the measurements were collected after the intrusions occurred. Specifically of interest were the fuel types most likely to smolder, including stumps, logs, and accumulations around the bases of trees. Total maximum smoldering fuel 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. These smoldering fuels are often underestimated and/or not well represented in the consumption and emissions models; therefore the dispersion models also tend to underestimate smoldering emissions, which are often responsible for the smoke intrusions.

Winds

One of the motivating questions prompting this study was whether the smoke intrusions were the result of smoke transported up-drainage at the time of active burning during the day, with a "return flow" down-drainage at night, or if it is primarily night-time smoldering combined with down-drainage winds that resulted in the intrusions. When analyzing winds it is important to know the height of the anemometer collecting the data. Most of the permanently located RAWS have anemometers at 20 feet (about 6 meters) above ground, and are sited on relatively high terrain. Being farther from the ground than temporary stations, they are less likely to represent winds influenced by friction and other surface effects, and less likely to measure very light or calm wind conditions. Anemometers located closer to the ground, such as those on temporary weather stations, are affected by friction and more likely to see calm winds, especially at night. For this reason we will present winds from both permanent and portable stations.

First, we present wind roses based on 10 years of data on the DNF using the three closest RAWS sites to Bend: Tumalo Ridge, Round Mountain, and Lava Butte (see Figure 1). The wind roses were generated using hourly data from 2006 – 2015. Wind roses for every season, day and night, at each RAWS site, were created, following the Northwest Coordination Center (NWCC) format. These wind roses are shown in Appendix 1. Following is a summary of the results.

Tumalo Ridge: Daytime wind roses in spring and fall (prescribed burn seasons) show a generally western component with no primary maxima, except for fall which has S and N maxima. At night, for all seasons, winds are typically from the SW. Tumalo Ridge is located to the west of Bend, and this suggests that any nighttime smoldering SW of Bend could result in smoke advection into Bend.

Round Mountain: During spring and fall, both day and night winds are most frequently from the NW. Round Mountain is the farthest of the three RAWS from Bend, to the SW of town. With winds most frequently from the NW, it is less likely that nighttime smoldering smoke in this area would be carried into Bend.

Lava Butte: Spring and fall winds are primarily from the SW, especially at night. Lava Butte is south-southwest of Bend, and closer than Round Mountain. The SW winds indicate that smoke from daytime burning and nighttime smoldering could result in intrusions.

At all RAWS sites, calm winds occurred less than about five percent of the time, except for Lava Butte, which had calm winds ranging from 9 to just over 15 percent during nighttime hours. The RAWS are sited at locations of relatively higher terrain, and may register winds that are not detected in the drainages, especially when wind speeds are light. The drainages west of Bend all flow toward town, therefore nights with calm winds are conducive to terrain-influenced down-drainage winds which could result in intrusions if smoke is present.

Four temporary meteorological stations were deployed from mid-October 2014 through most of June 2015. These stations were located (north to south) at Sisters, Bridges Boys Academy, Cascade Academy, and Miller Elementary School (in the town of Bend). See Appendix 1 for wind roses from these sites. At the Sisters location, calm winds dominated 49% to 95% of the time. When not calm, winds were mostly lest than 2 m/s out of the west. At Bridges Boys Academy, winds were calm at night 79% to 91% of the time. During the day winds were light out of the NW to NE for all seasons, with the strongest winds (in the 2-4 m/s range) in the summer. Finally, at Miller Elementary, in the town of Bend, calm winds persisted at night more than 50% of the time for all seasons, and when wind data were measured, winds were out of the SW. In the fall and winter, daytime winds were strongly out of the SW. In the spring this daytime SW flow was also seen but in combination with NE winds. Summer daytime winds ranged from NW-NE.

Burn Window Analysis

Land managers conduct prescribed burns when fuel conditions and meteorological parameters are within defined ranges. 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. On average, 26-28 burn days exist every year at the three RAWS sites. Figure 2 shows the average number of burn days by month for these RAWS locations. During mostly the winter periods, significant data gaps exist in the RAWS data, therefore those data are probably biased low. 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. A similar analysis, using hourly rather than daily RAWS data, and adding 1000-hr fuel moisture as a variable, resulted in significantly fewer days on average in prescription.

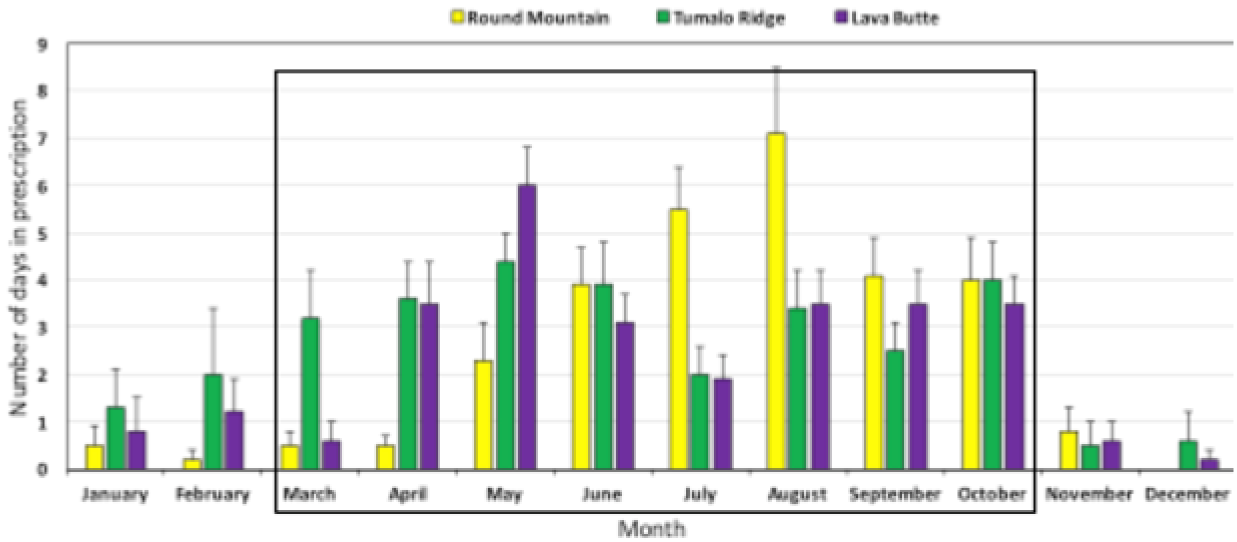

Figure 2. Mean number of days weather conditions are within prescription, by month, 2006 - 2015 for Lava Butte, Round Mountain, and Tumalo Ridge RAWS sites. The whiskers represent the maximum for each month over the 10-year period. The box encompasses months when data are complete.

Not included in the variables listed in Table 5 is wind direction, which is an important factor when trying to anticipate smoke intrusions. Additional analysis was therefore 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 south to southwesterly winds occur during the nighttime, (to determine if nighttime drainage flows are responsible for the smoke intrusions from the smoldering fuels). These numbers are summarized in Table 6. "Ideal" wind conditions for burning are when daytime wind directions are out of the North (which includes NW – NE), transporting smoke away from Bend, and nighttime wind patterns are not from the south (which includes SW - SE, again, to keep smoke out of Bend). Including only those days that are in prescription (per Table 5), annually, this ideal pattern exists on 8% of the days. During spring burn days, 13% of the days have this pattern while on fall burn days, 5% of the days have this pattern. This suggests that in any given year, the number of days with weather conditions in prescription and favorable wind directions (both day and night) that will keep smoke out of Bend is very limited, making it difficult to achieve fuel treatment objectives with fire alone.

Smoke Intrusions

We analyzed six smoke intrusions from prescribed burns into the Bend, one that occurred in October 2014, and five in May and June of 2015. An intrusion is defined by the Oregon Department of Forestry (2014) as a 1-hr average $PM_{2.5}$ concentration greater than the previous three hourly average $PM_{2.5}$ concentrations. Intrusions are not tied to the National Ambient Air Quality Standards (NAAQS) and may or may not exceed the NAAQS. Table 4 lists the dates of the six intrusions, the maximum 1-hr $PM_{2.5}$ concentration measured, the time of the maximum, and the duration of elevated $PM_{2.5}$ 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 $PM_{2.5}$ concentrations up to 245 µg/m^3. 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 using the 4-km resolution University of Washington WRF meteorological forecasting system with a domain over the Pacific Northwest. We compared the observed with modeled $PM_{2.5}$ only for cases where the model predicted smoke in Bend. On days when the model "missed", there was no $PM_{2.5}$ to compare with the observations. Appendix 2 lists the calculated daytime and nighttime statistics of mean wind direction error, mean wind speed error, and mean wind speed bias for all locations and intrusions.

May 4-6, 2015 Smoke Intrusions

A 46 ha planned burn was ignited at 0930 PDT May 4, 2015 approximately 55 km southwest of Bend, Oregon (Figure 3). Of the six intrusions studied, this was the only intrusion that occurred during daytime hours. Smoke was transported into Bend within 3.5 hours of ignition and a maximum concentration of 13 µg/m^3 was recorded at the Bend Pump Station nephelometer. Concentrations were elevated for approximately 2 hours. Figure 4 shows the 1-hr average $PM_{2.5}$ concentrations measured at the Bend Pump Station and three other E-Samplers deployed as part of this study. The red vertical lines indicate the burn ignition times on May 4 and

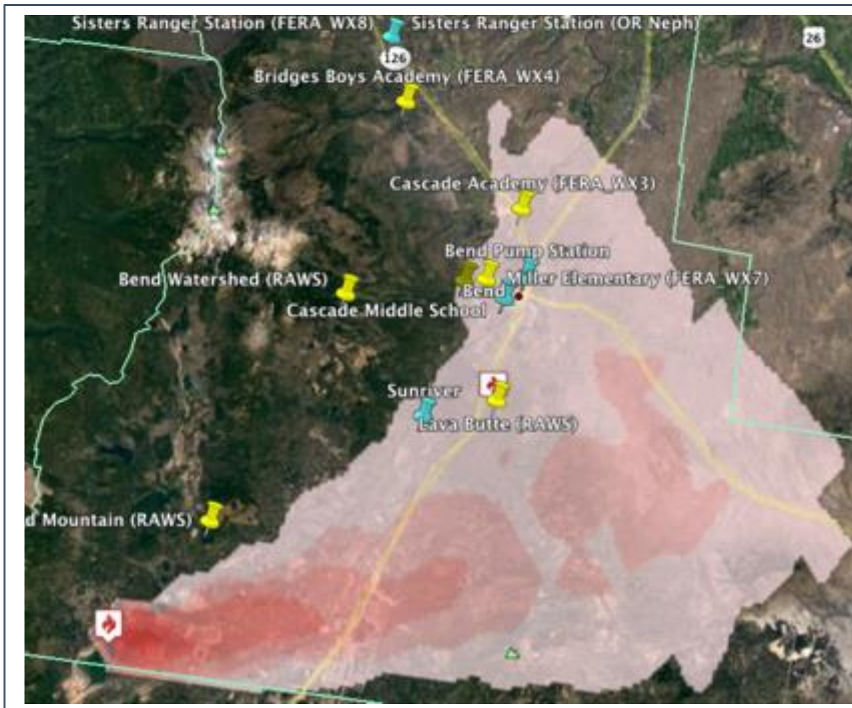

Figure 3. Meteorological and smoke measurement locations in the town of Bend, Oregon and south of town and the burn locations for the May 4-6, 2015 smoke intrusion period. The red contours are the near-surface 1-hr PM2.5 concentrations predicted by the BlueSky smoke modeling framework May 4, 2015 at 1400 PDT.

May 5 and the shaded areas indicate the time periods of elevated $PM_{2.5}$ concentrations. This was also a period when there were anecdotal reports of long-range transport of smoke from Korea impacting the western US, elevating background $PM_{2.5}$ concentrations by approximately 5 µg/m^3.

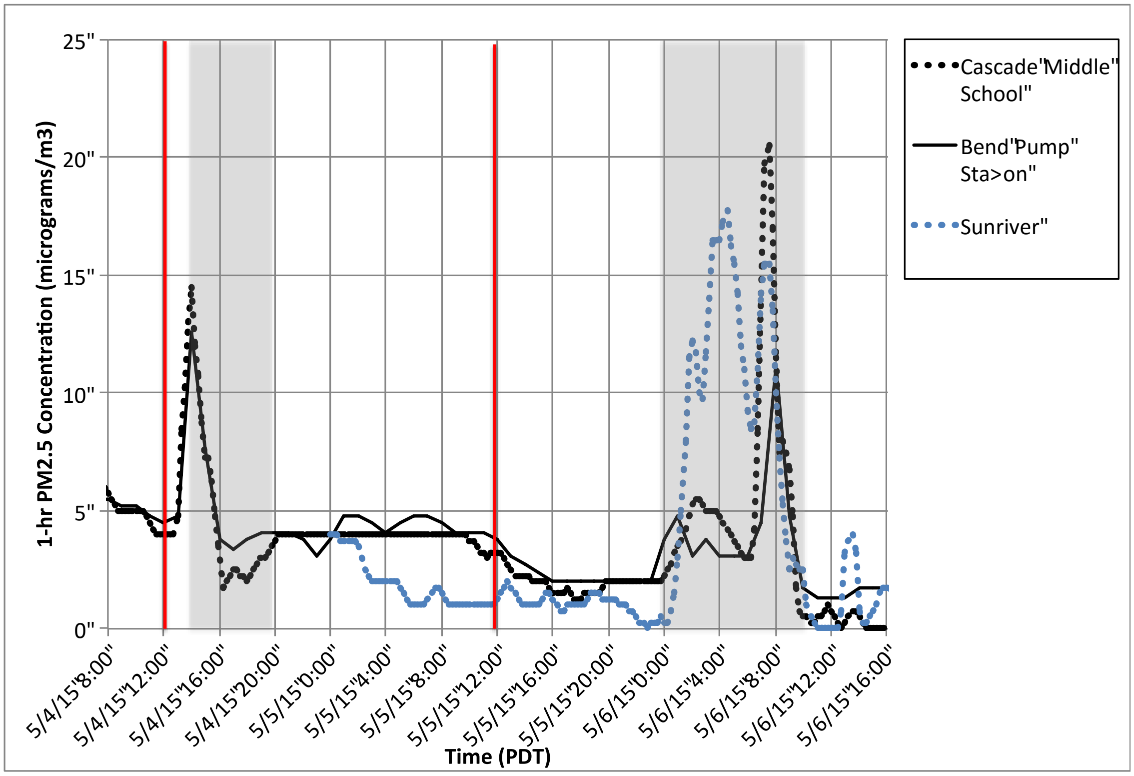

Figure 4. Measured 1-hr PM2.5 concentrations at four locations. Red lines indicate burn ignition times and gray-shaded areas indicate the smoke intrusion periods into Bend, Oregon.

Before ignition on May 4, the Tumalo Ridge RAWS measured north winds, however by the time of ignition the winds had switched to the south. Winds were steady from the WSW during the intrusion period, which would indicate 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, similar to the Tumalo Ridge RAWS. Figure 5 shows the daytime mean wind direction error between measured and 4-km WRF modeled wind direction data at the ten meteorological station locations. Daytime mean wind direction error range from 7.6 (Round Mountain RAWS) to 50 degrees (Cascade Academy and Miller Elementary). It should be noted that the meteorological model performed best at all three RAWS locations out of the 9 total meteorological station locations with daytime mean wind direction errors of 17 degrees at Tumalo Ridge and 19 degrees at Lava Butte (in addition to the 7.6 degrees at Round Mountain). Mean wind speed bias and error ranged from 0.54 to 5 m/s with modeled data biased greater than measured data. Best agreement was at Cascade Middle School located within the town of Bend with a daytime mean bias of 0.54 m/s and daytime mean error of 0.85 m/s.

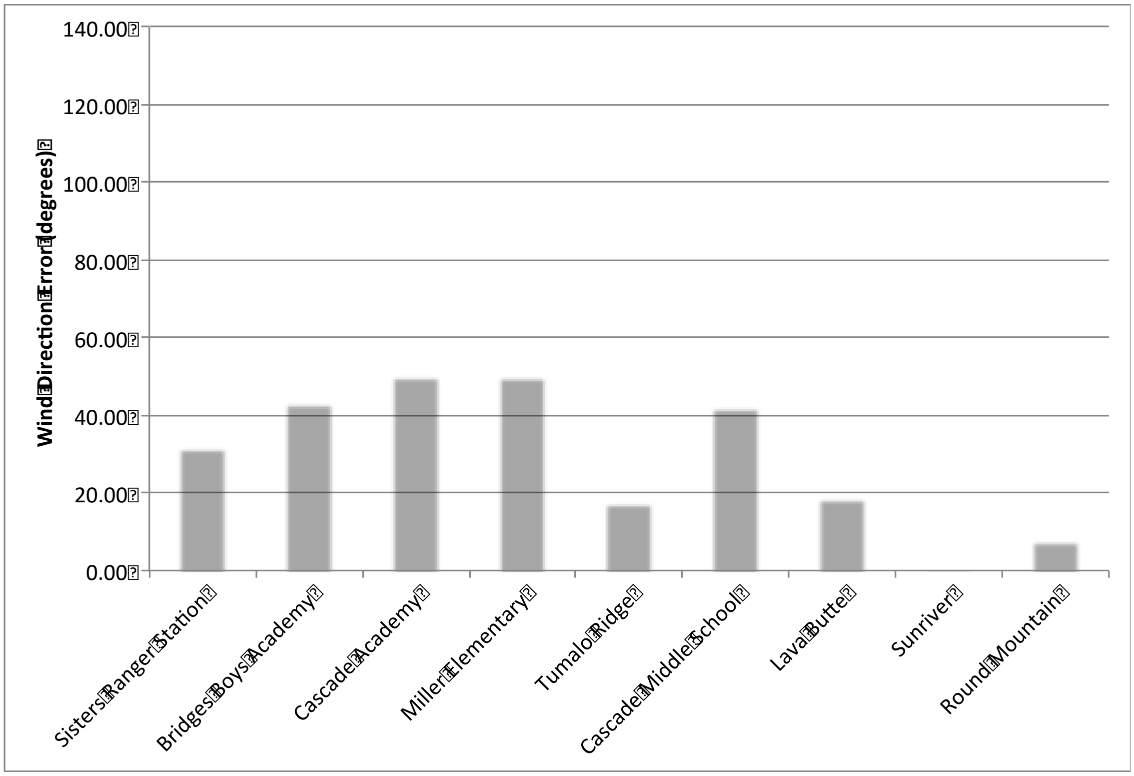

Figure 5. May 4, 2015. Daytime mean wind direction error (modeled (4-km WRF) – observed). The Sunriver monitor did not measure data on this day.

BlueSky smoke modeling results simulate well the timing of the transport of the smoke into Bend (Figure 3). However, the modeled BlueSky 1-hr $PM_{2.5}$ 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/m^3 predicted between 1300 and 1500 PDT, compared to the observed results of 4.8 to 12.6 µg/m^3. There are several possible reasons for this. First, Figure 3 shows how the modeled plume centerline is pushed to the south of town, and thus only the plume fringes are modeled to impact Bend. This can also be seen in Figure 6 (first intrusion gray-shaded area) which shows measured and modeled wind speed and wind direction data at Cascade Middle School. Modeled winds are more northerly than measured even though the wind directions track well with each other. The second possible reason is that the default modeled fuel loadings do not capture the smoldering of duff, stumps and basal accumulations that Ottmar et al. (2014) identified as also being consumed and likely contributing additional smoke in the atmosphere. Increasing the duff depth from 2 inches to 5 inches approximately doubled the pre-burn fuel load burning, 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 there was no change in the predicted winds (these are the PM2.5 concentration field results shown in Figure 3). Thirdly, we are only simulating primary $PM_{2.5}$ emissions from the fires. This work does not take into account the possibility of elevated background concentrations due to smoke from Korea or other local sources. Finally, note that Bluesky-predicted concentrations are an average across a 4-km grid cell when using a 4-km resolution meteorological model whereas the observed value at a monitoring site is a point observation.

On May 5, 2015 an additional 5 ha were ignited approximately 10 km southwest of Bend (a distance less than three 4-km modeling grid cells). The winds were from the NW and the main smoke plume was transported away from town. However, a smoke intrusion occurred the next morning between 0600 - 0800 PDT May 6 with a maximum 1-hour average concentration of 11 µg/m^3. During the evening of May 5 winds became light and variable, switching to a SW flow along the drainages – down-drainage flow that carries smoke directly into Bend. If duff, large woody debris and basal accumulations had continued to smolder overnight (as indicated by Ottmar et al. 2014), then this smoldering smoke would have stayed close to the ground and been transported down drainage with the light SW winds. BlueSky weakly simulated this down-drainage intrusion by bringing some smoke into town at approximately 2200-0100 PDT, corresponding to the measured concentrations of approximately 5 µg/m^3, however it missed bringing smoke into town during the intrusion period of 0600-0800 PDT. Again, modeled concentrations were an order of magnitude lower than observed. Figure 6 compares the measured and modeled wind speeds and wind directions at Cascade Middle School. During the overnight intrusion period (second gray-shaded area) the 4-km WRF model output simulated wind speeds similar to the observed wind speeds of less than 1.5 m/s, however modeled wind direction remained out of the WNW while the measured winds were out of the SSW.

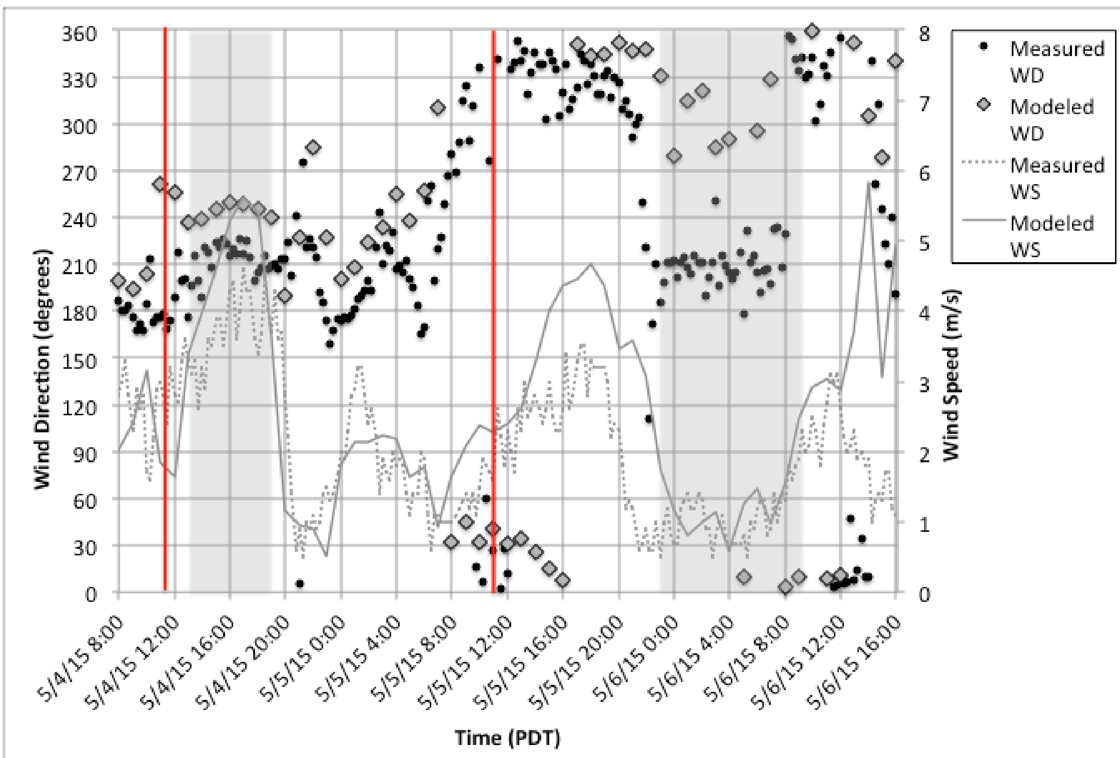

Figure 6. Measured and modeled wind direction and wind speed at Cascade Middle School for May 4-6, 2015. Red lines indicate burn ignition times and gray-shaded areas indicate the smoke intrusion periods into Bend, Oregon.

The May 5, 2015 Rx burn led to an overnight smoke intrusion, therefore a statistical comparison of modeled and measured wind speed and wind direction was conducted for both day and night periods (as described in the Methods section). Figure 7 shows both day and night mean wind direction error calculated for the 9 locations. Periods with greater than 50% calm conditions are excluded. Daytime mean wind direction statistics are similar to May 4 with the 4-km WRF-predicted winds in better agreement with the Round Mountain RAWS (mean difference of modeled – observed direction of 8 degrees) than at the other wind monitors. At night, only 5 of the 10 stations had > 50% calm conditions and mean wind direction error is larger than for daytime, ranging from 14 degrees (Round Mountain) to 124 degrees (Sunriver). Four out of five stations had mean wind direction errors > 50 degrees. Maximum mean wind speed error was less than 1 m/s.

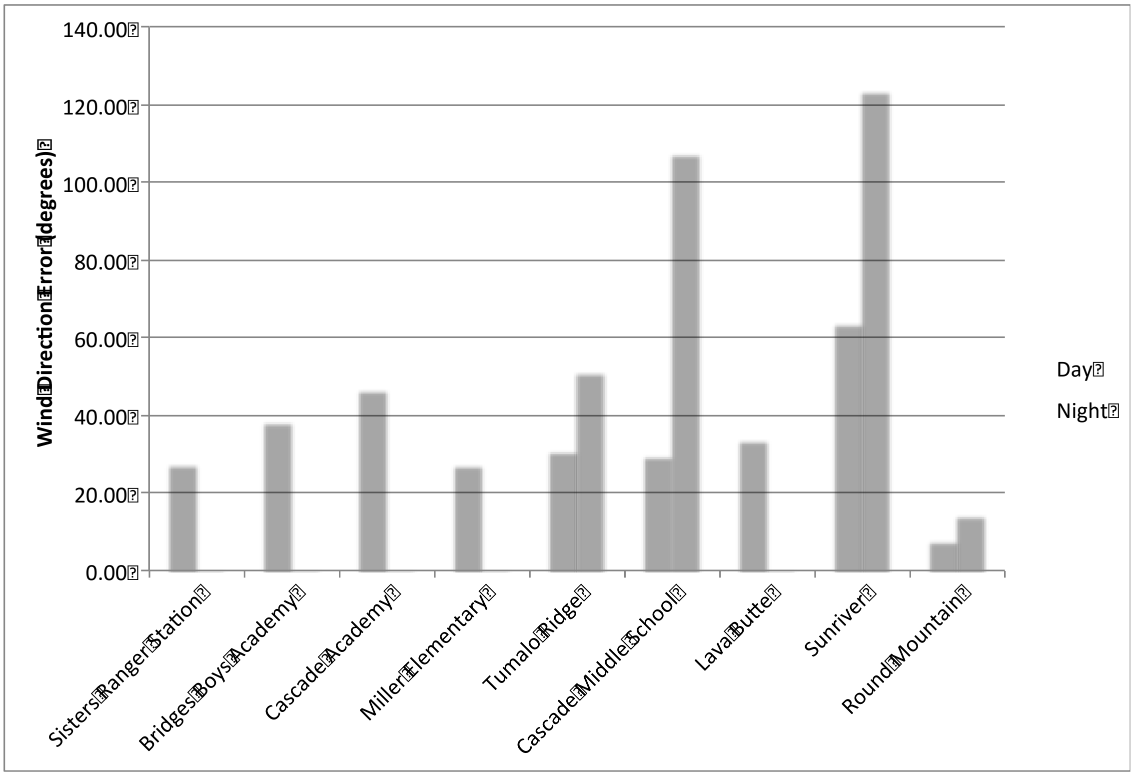

Figure 7. May 5, 2015. Daytime (red) and nighttime (blue) mean wind direction error of modeled (UW 4-km resolution WRF) minus measured wind direction at ten locations. Locations are listed north to south. Missing data indicate calm conditions prevailed more than 50% of the time.

May 28, 2015 Smoke Intrusion

Figure 8. May 28, 2015 burn location and monitors.

On May 28, 2015 a 28 ha planned burn was ignited at 1125 PDT approximately 8 km WSW of Bend, Oregon (Figure 8). At midnight, 1-hr PM2.5 concentrations became elevated at the Bend Pump Station nephelometer with a maximum of 181 µg/m^3 recorded at 0100 PDT on May 29, 2015 (Figure 9). The smoke intrusion lasted approximately 7 hours. During ignition and throughout the day surface winds were out of the NW transporting smoke away from town. At approximately 2000 PDT wind speeds began to drop and wind directions shifted to the SW and SSW (as measured at Tumalo Ridge and Cascade Middle School respectively) and smoke arrived in Bend soon after. Analysis of the 4-km WRF-predicted meteorological wind fields shows winds maintaining out of the NNW throughout the night and therefore the BlueSky smoke model simulations did not transport the plume into Bend. This can be seen in the shaded portion of Figure 10 which gives modeled and measured wind speed and wind direction at Cascade Middle School for May 28-29, 2015. Daytime performance of the meteorological model was not as good as it was for May 4 and May 5, 2015 with mean wind direction errors ranging from 26 degrees to 84 degrees (Figure 11). The best modeled wind direction performance again corresponded to a RAWS location (Lava Butte). Daytime wind speed mean errors ranged up to 2 m/s. and modeled winds are mostly biased high. At night, five out of the 9 locations measured calm wind conditions greater than 50% of the time and mean wind direction error is over 80 degrees. Smoke modeling simulations did not successfully transport the plume into Bend.

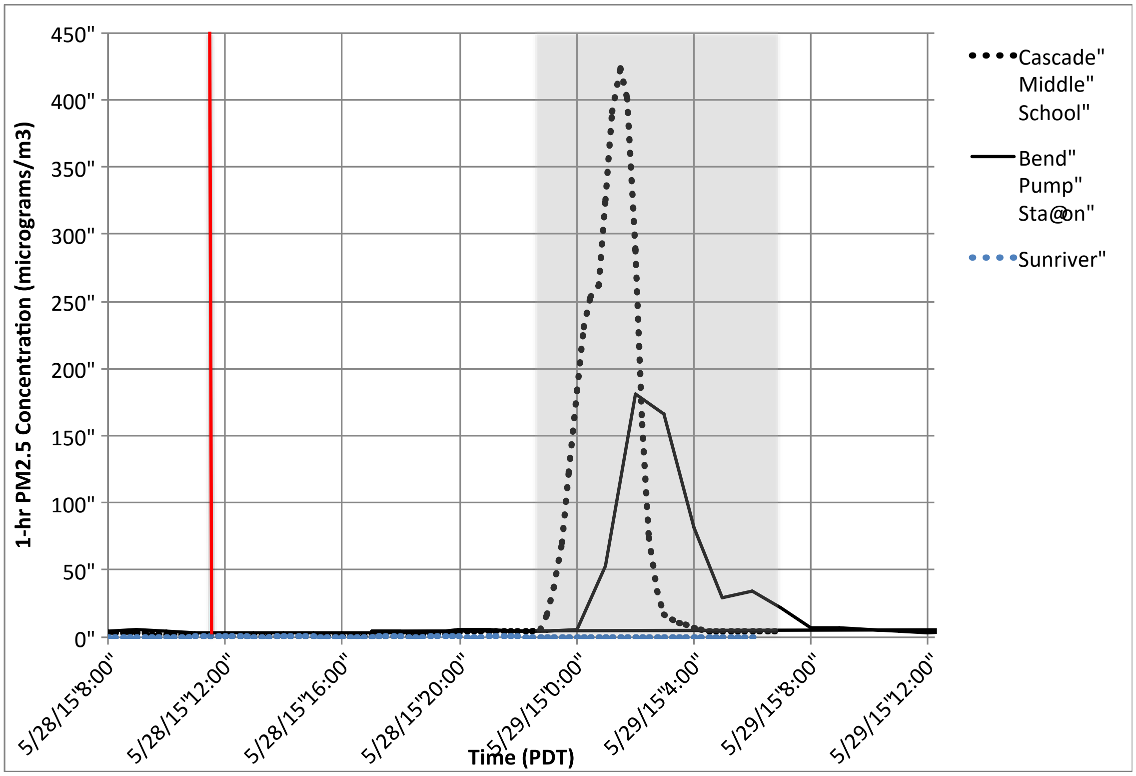

Figure 9. PM2.5 concentrations, May 28 – 29, 2015. The red line designates ignition time, and the shaded area represents the duration of the intrusion.

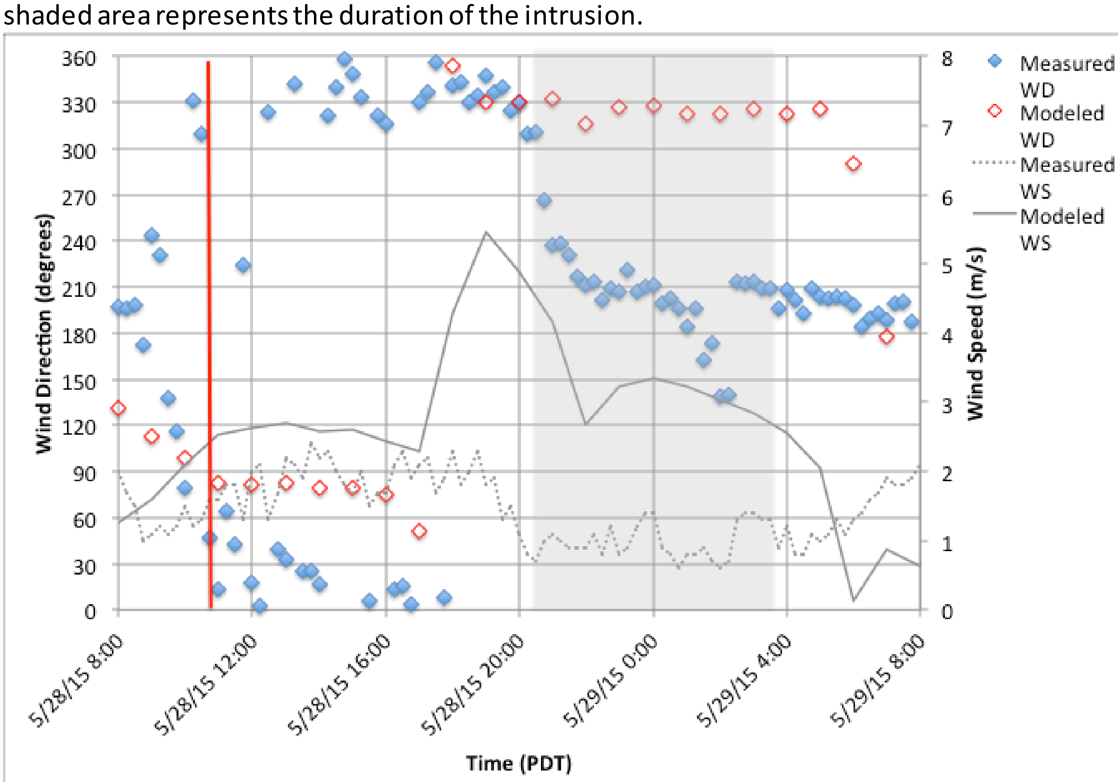

Figure 10. Measured and modeled wind speed and direction at Cascade Middle School, May 28, 2015 Rx burn. The red line designates ignition time, and the shaded area represents the duration of the intrusion

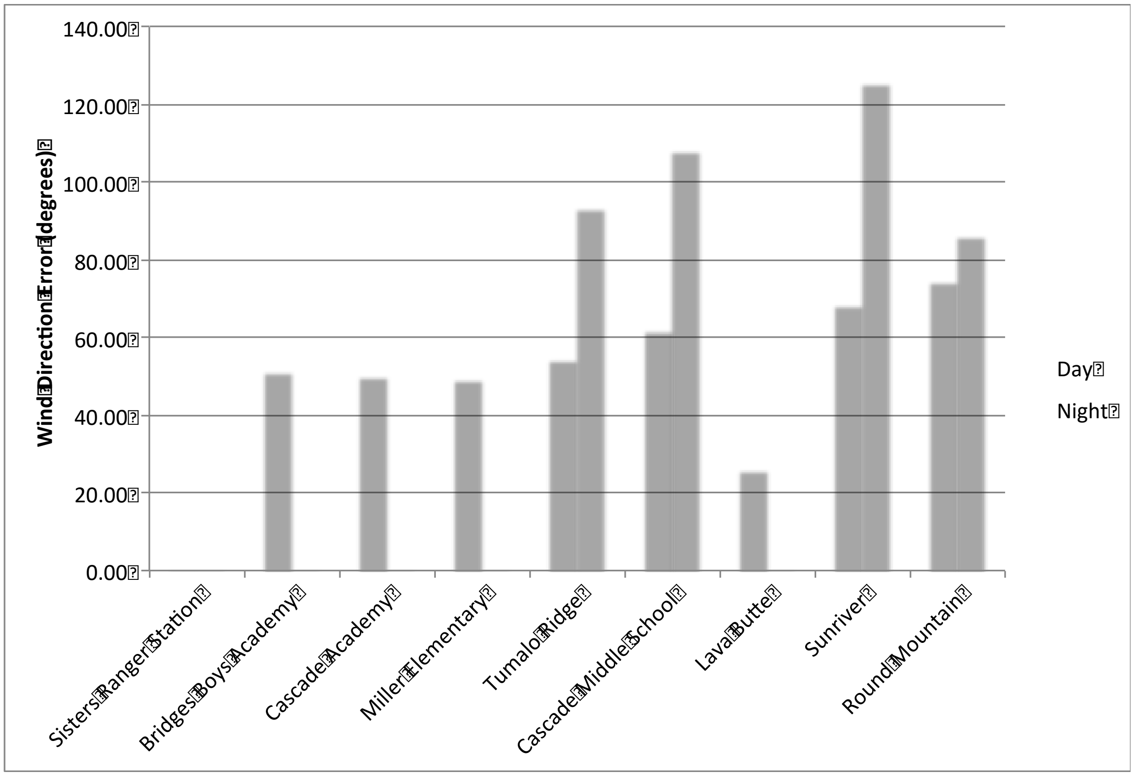

Figure 11. May 28, 2015. Daytime (red) and nighttime (blue) mean wind direction error of modeled (UW 4-km resolution WRF) minus measured wind data at ten locations. Locations are listed north to south. Missing data indicate calm conditions prevailed more than 50% of the time.

June 5-7, 2015 Smoke Intrusions

A 49 ha planned burn was ignited at 1100 PDT June 5, 2015, and another 56 ha planned burn was ignited at 1000 PDT June 6, 2015. The burns were approximately 7 km and 9 km SW of Bend respectively. Figure 12 shows the burn locations and smoke and meteorological measurement locations in relationship to Bend. During ignition and throughout the afternoon, winds were out of the N and NE transporting the smoke plume away from town. Overnight however, smoke was transported into town. Figure 13 shows the 1-hr PM2.5 concentrations measured at three locations (from south to north), Sunriver, Cascade Middle School, and the Bend Pump Station, and the burn ignition time (red line). The gray-shaded area shows smoke intrusion periods. Sunriver is located south of the burns and was impacted by the smoke plume soon after ignition due to the prevailing N-NE winds. The monitors in Bend itself (Cascade Middle School and Bend Pump Station) were impacted beginning approximately midnight both nights. Smoke behavior was very similar for these two burns and time periods and a maximum 1-hr $PM_{2.5}$ concentration of 245 μg/m^3 was recorded at Bend Pump Station at 0400 PDT June 7, 2015. The duration of smoke impacts was from 8-10 hours each evening and early morning.

Figure 12. June 5-6, 2016 burn locations and monitor locations.

The meteorological stations south of Bend show very similar patterns with NW, N, NE winds during the day and lighter S, SW winds overnight. Figure 14 shows a typical wind direction pattern as measured at Cascade Middle School. Figure 14 also shows the modeled wind speed and wind direction at Cascade Middle School. During the day measured and modeled winds were more similar with measured winds generally out of the NW and modeled winds out of the NE. Nighttime winds were very different with measured winds out of the SW and modeled winds out of the NW (see the shaded areas). Statistical comparison of the winds (Figure 15) gives wind direction errors ranging from 27.2 degrees (Bridges Boys Academy north of town) to 74.3 degrees (Cascade Middle School located in town). Wind speed bias (not shown) ranged from 0.1 to 2.8 m/s and error ranged from 1.1 to 2.8 m/s. A large percentage of calm winds prevailed at four of the meteorological stations, which suggests calm, stable conditions were favorable for light, down-drainage smoke transport.

Smoke dispersion predictions were generated by BlueSky but did not show the intrusions. The simulations correctly captured the daytime transport of the smoke plumes to the SW but did not capture the wind reversal to SW drainage flows during the evening which were responsible for the transport of smoke into Bend. Note that at a grid resolution of 4-km, the burn locations were approximately 2 grid cells away from Bend.

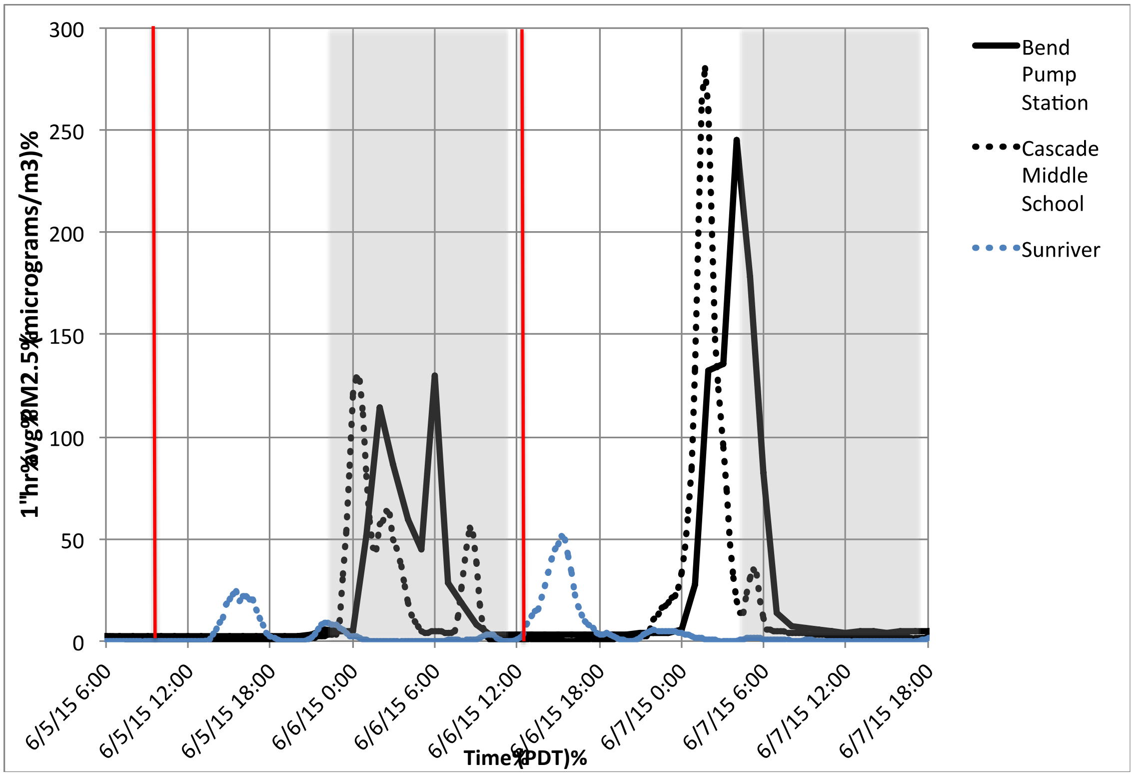

Figure 13. June 5-6, 2015 smoke intrusions 1-hr PM2.5 concentrations. The red lines designate ignition time, and the shaded area represents the duration of the intrusion.

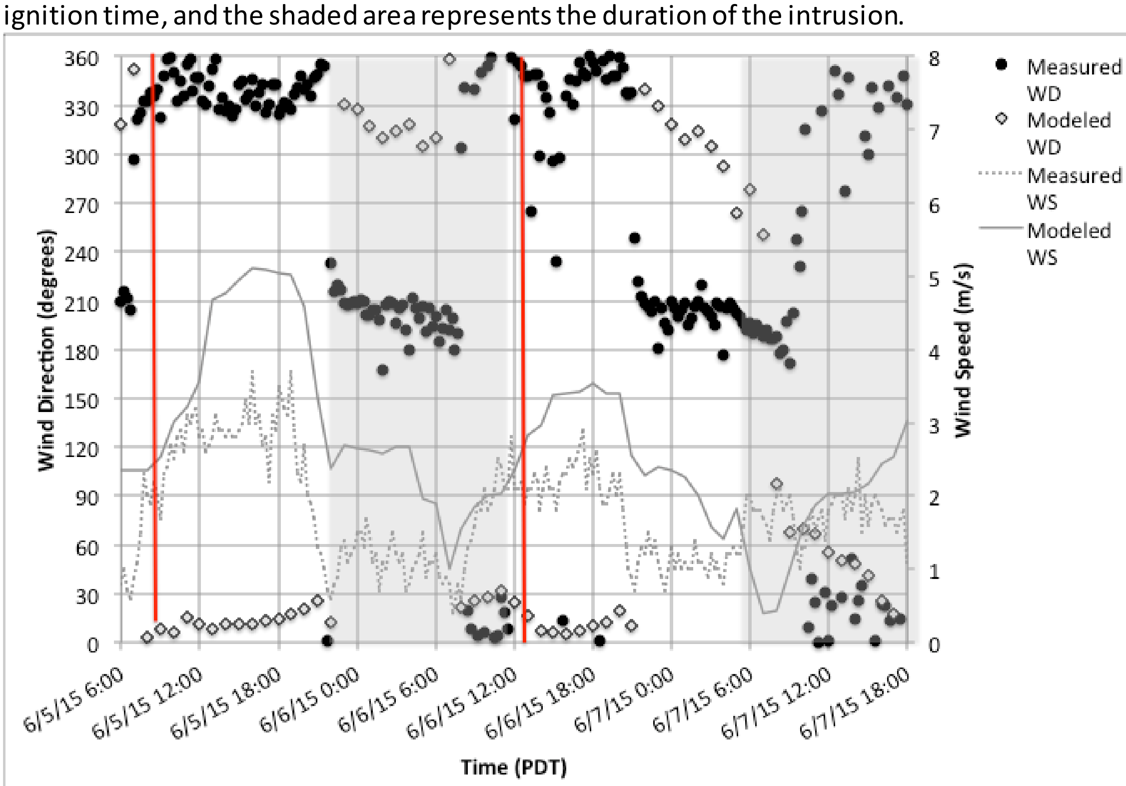

Figure 14. Measured and modeled wind speed and direction at Cascade Middle School, June 5 – 7, 2015. The red lines designate ignition time, and the shaded area represents the duration of the intrusion.

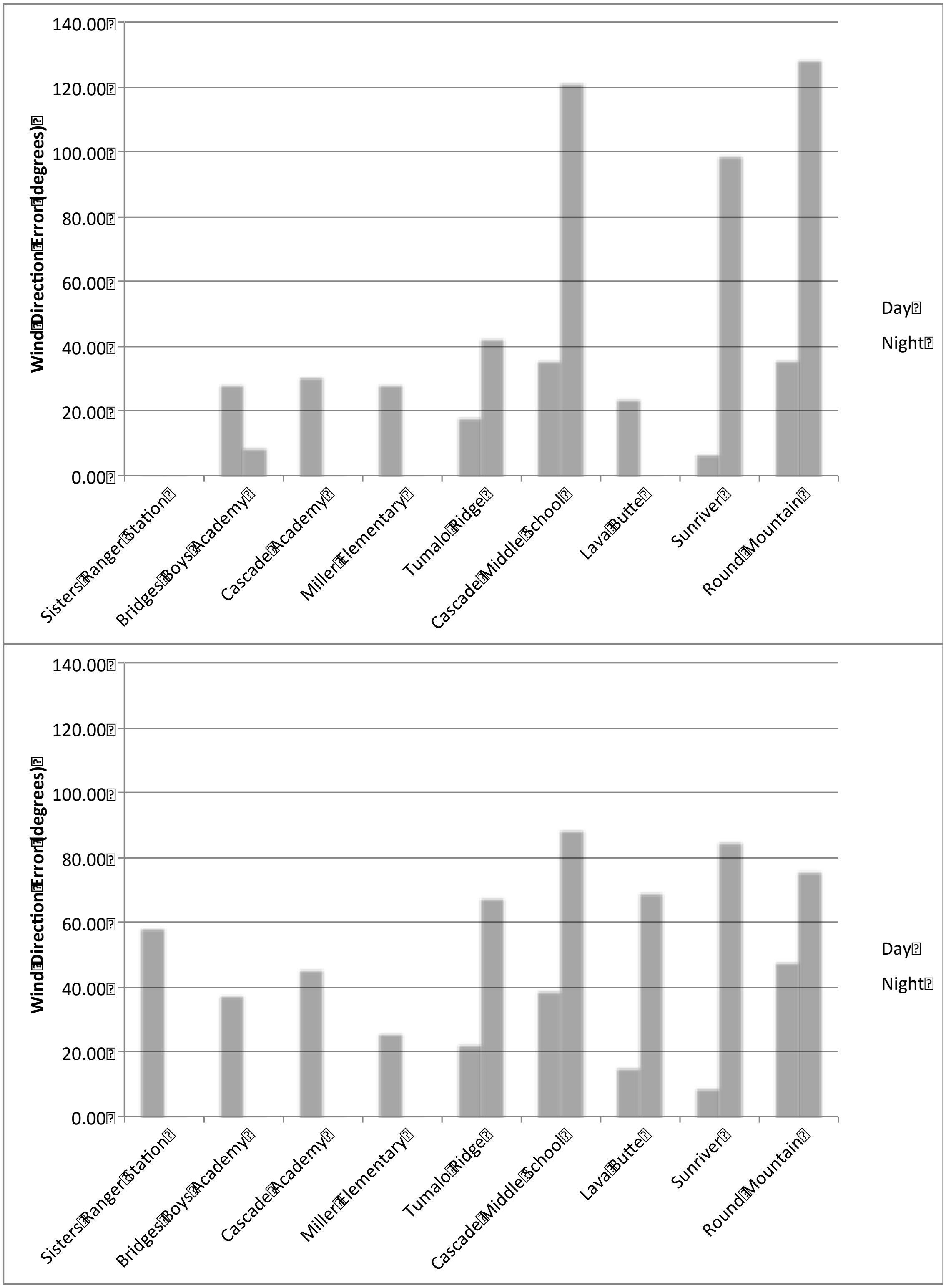

Figure 15. June 5 and 6, 2015. Daytime (red) and nighttime (blue) mean wind direction error of modeled (4-km WRF) minus measured wind data at ten locations. Locations are listed north to south. Missing data indicate calm conditions prevailed more than 50% of the time.

October 4-5, 2014 Smoke Intrusion

Three planned burns were ignited on October 4, 2014 approximately 44 km SSW of Bend (Figure 16). 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 monitoring values registered an intrusion starting at 0200 PDT October 5 and dissipating by 1200 PDT. A maximum 1-hr $PM_{2.5}$ concentration of 96 μg/m^3 was recorded at the Bend Pump Station at 0300 PDT, with a second peak of 94 μg/m^3 at 0900 PDT. (Figure 17).

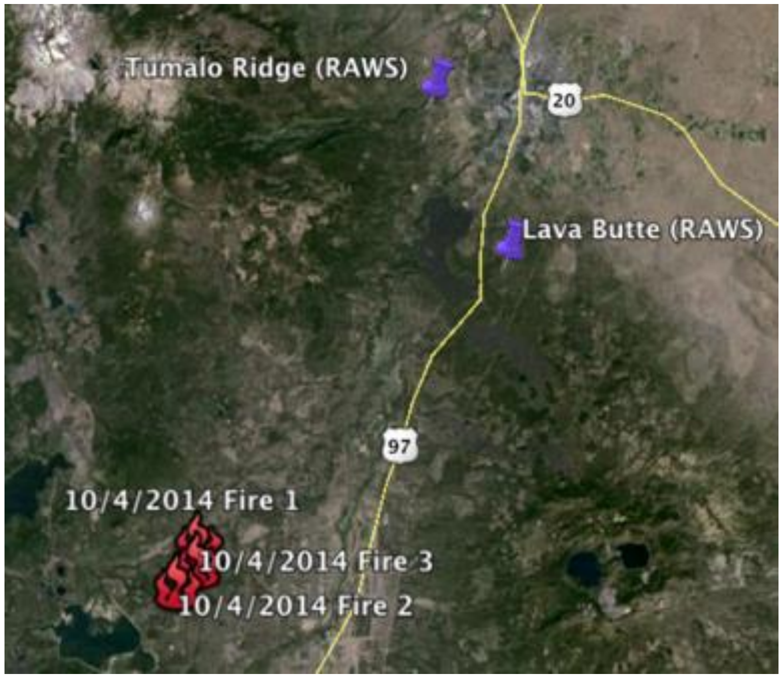

Figure 16. October 4, 2014 burn locations and measurement locations.

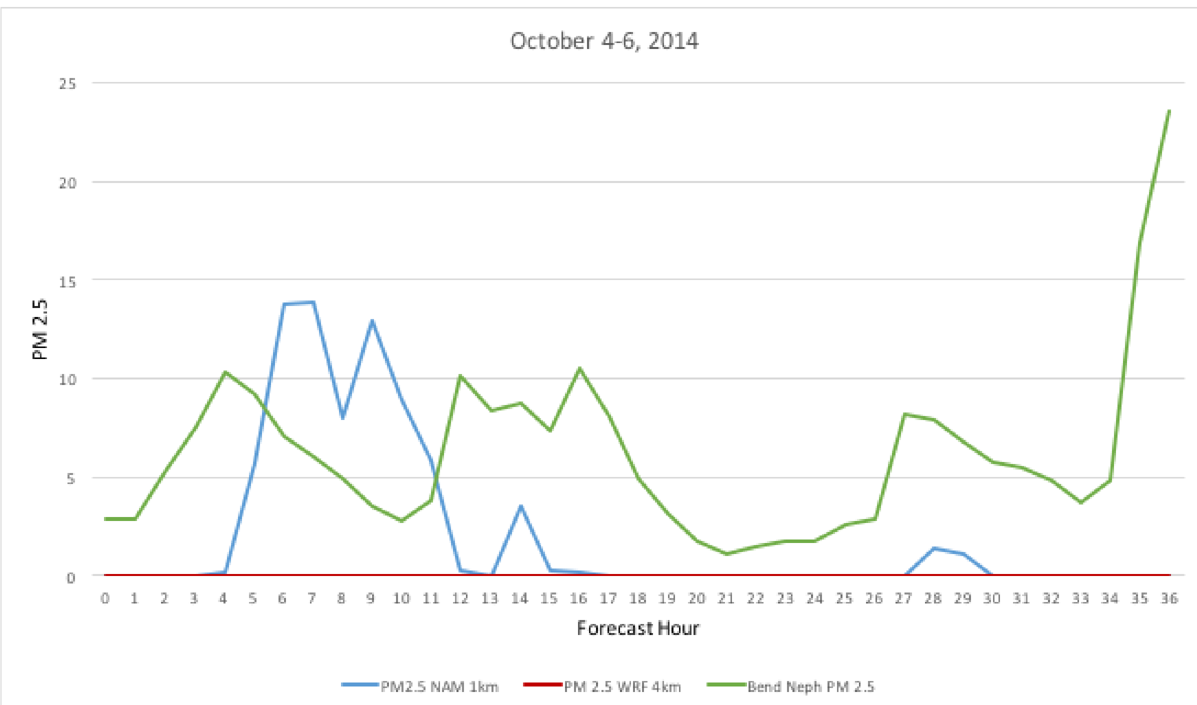

Figure 17. Modeled and observed PM2.5 concentrations from 1700 PDT 10/4/2014 (Forecast Hour 0) to 0500 PDT 10/6/2014 (Forecast Hour 36). Blue line represents NAM 1km prediction, red line represents WRF 4km prediction, and green line shows observed values at the Bend nephelometer.

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 meteorological model domain 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). Figure 16 shows the burn locations and the two closest meteorological station locations.

Average differences in wind direction (modeled minus observed) for both 1-km (left side of Figure 18) and 4-km (right side of Figure 18) resolutions, day and night, are shown for the 36-hour period when both models provided predictions for this intrusion (Figure 18). Mean daytime errors between modeled and observed at 1-km ranged from about 45 to 80 degrees, while nighttime errors ranged from 20 to 80 degrees. For the 4km model output, mean daytime errors ranged from 38 to 60 degrees, and nighttime errors were from less than 10 to greater than 80 degrees.

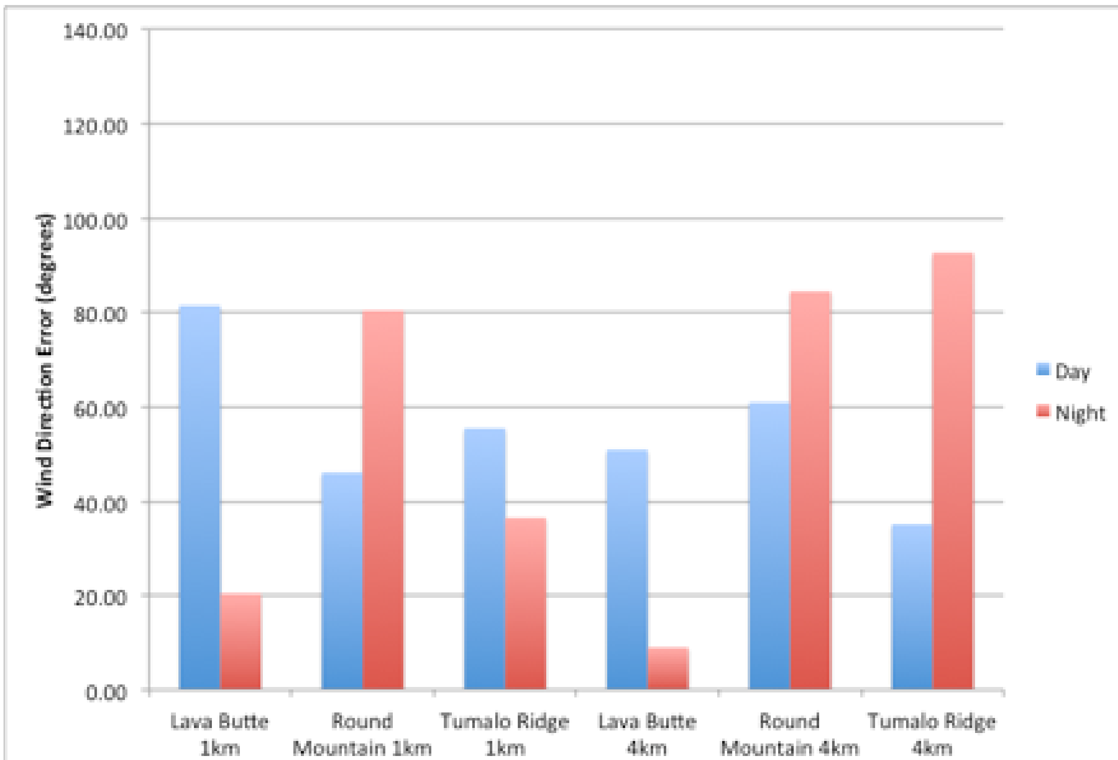

Figure 18. October 4 - 6, 2014. Daytime (red) and nighttime (blue) mean wind direction error of modeled (1km NAM on the left side; 4-km WRF on the right side) minus measured wind data at the three RAWS.

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 19 and 20), with the plume arriving at 0300 PDT (in agreement with the measured data). Predicted concentrations were lower than measured (approximately 10 μg/m^3 for the 1-km NAM output and less than 1 μg/m^3 for the 4-km WRF output; Figure 17) probably because BlueSky is 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, while the 4-km WRF simulation carries smoke towards Bend overnight but weakly (Figures 19a and 19b shows model output for 0300 PDT). Similar outputs are seen in the predictions four hours later at 0700 PDT (Figures 20a and 20b), where the higher resolution 1-km NAM run more accurately characterizes the smoke transport along the drainage, while the lower resolution WRF model run has a less well-defined smoke plume, because the model is too coarse to adequately represent the terrain of the drainages. This example shows that higher resolution meteorological models can improve smoke dispersion predictions. While this may not always the case, higher resolutions have been shown to provide better results when compared with coarser resolutions in modeling fire danger indices (Hoadley et al. 2006).

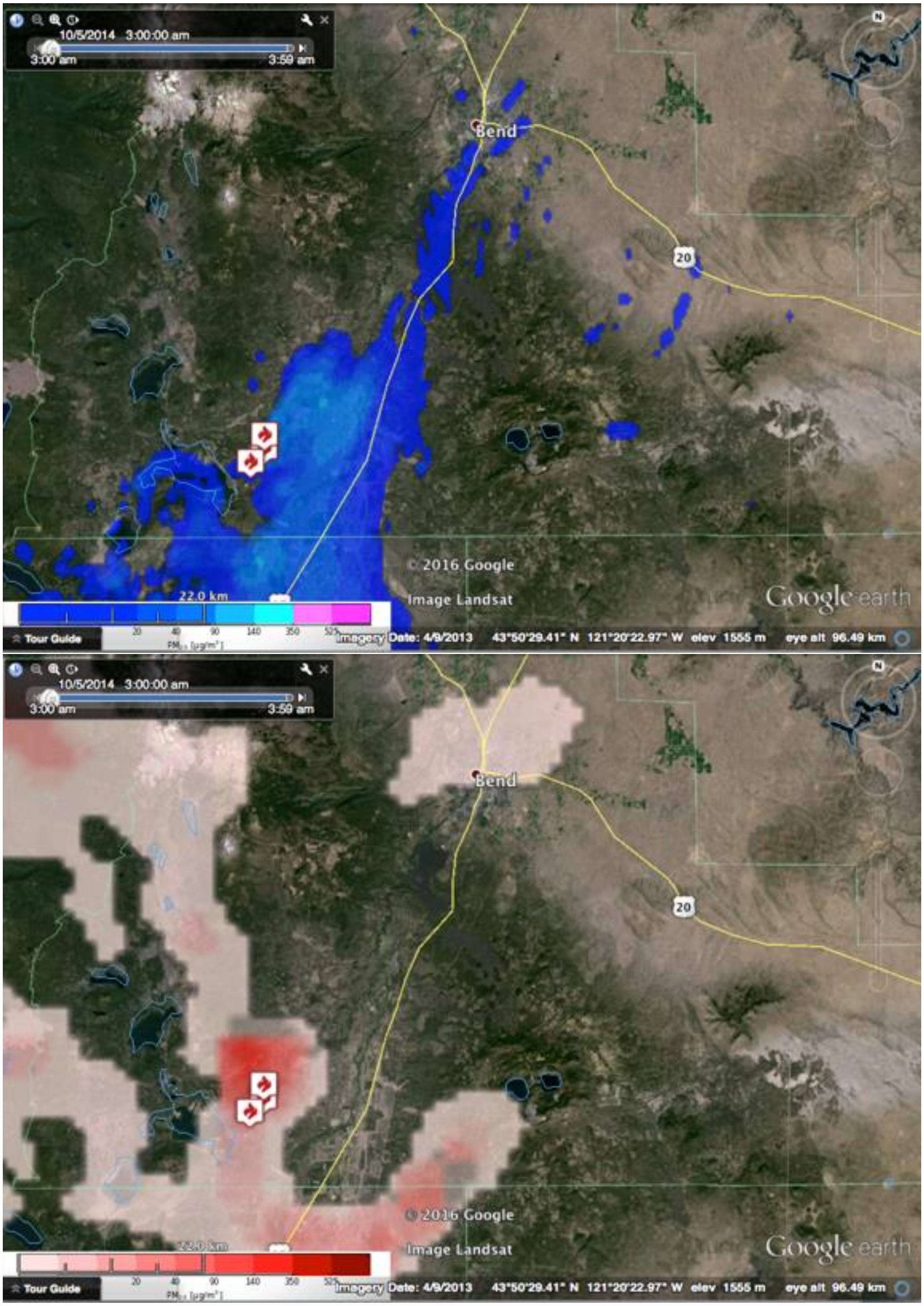

Figure 19. BlueSky smoke predictions using a) 1-km NAM model and 2) 4-km WRF model for 0300 PDT, October 5, 2014.

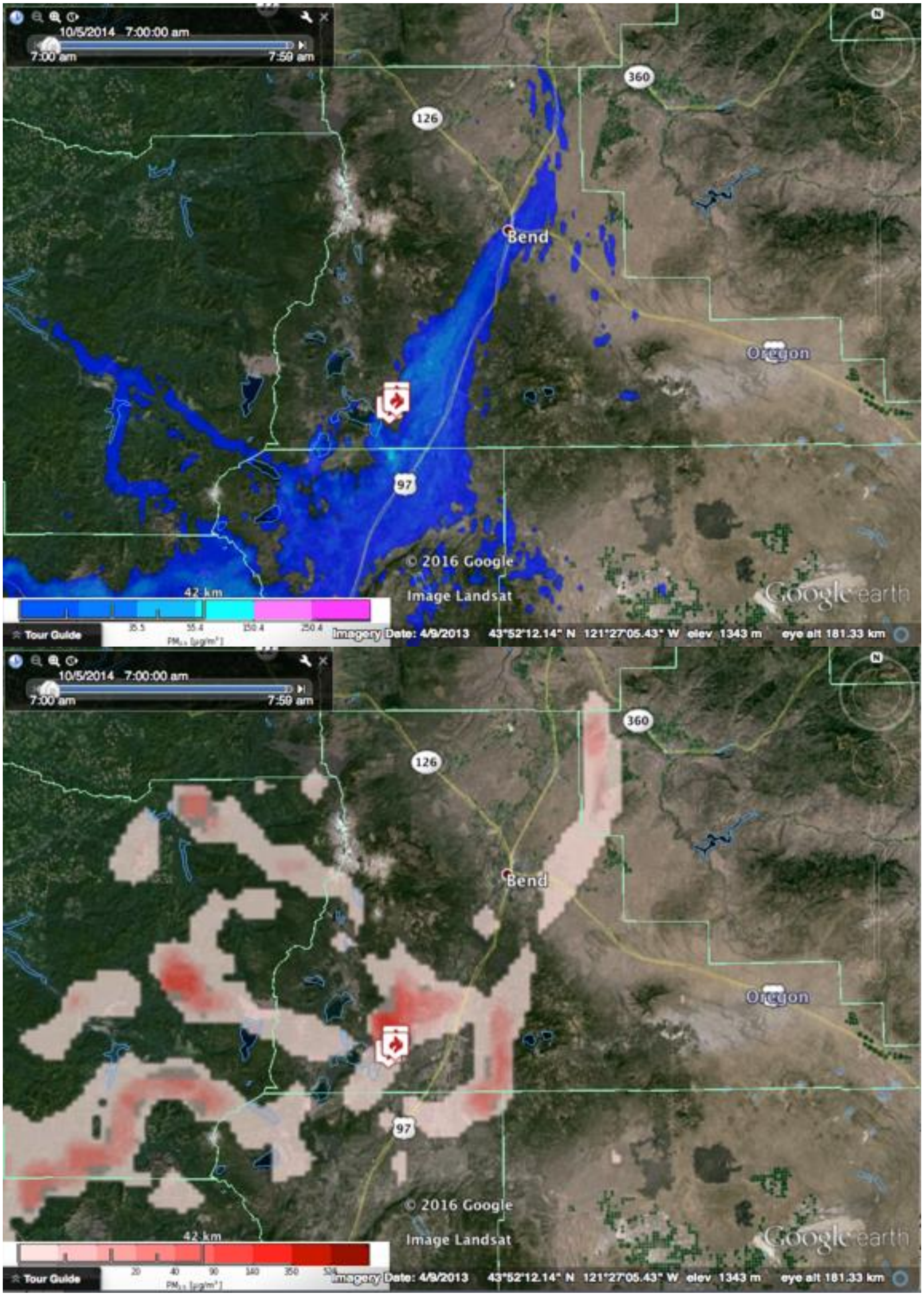

Figure 20. BlueSky output using a) 1-km NAM model and b) 4-km WRF model for 0700 PDT, October 5, 2014.

Key Findings

- Most of the intrusion events were the result of terrain-driven, down-drainage winds carrying smoldering smoke into Bend, well after active burning was complete
- Loading of fuels prone to smoldering (duff, dead logs, accumulations around the base of trees) is often underestimated and their consumption and emissions are not well modeled,
- Dispersion modeling can be useful for anticipating smoke intrusions, but significant errors in wind speed and direction in the underlying meteorological models can lead to complete "misses" of smoke intrusion events
- Using higher resolution meteorological and dispersion models can improve the prediction of both timing and location of these events.

Management Implications

A comprehensive study was undertaken of several smoke intrusion episodes in the autumn of 2014 and spring of 2015 in Bend, OR, including measured and modeled $PM_{2.5}$ emissions, post-burn fuel loadings, and measured and modeled winds. Several of the results have implications for future prescribed burning on the DNF.

First, the burn day analysis showed, on average, a low percentage of days (8% annually) when wind directions are "ideal" for prescribed burning in the West Bend Project area. These are the days and nights when winds would NOT carry smoke into Bend. Because this percentage is so low, it is important to more accurately identify days when intrusions are not likely to occur.

Second, the fuels likely to smolder (large dead logs, basal accumulations around trees, duff, etc.) are underestimated by current consumption and emissions models. Land managers need to take this into account when planning burns using the currently available fuels information and models.

Third, data collected from the meteorological and particulate monitors indicated, in most cases, terrain-driven nighttime down-drainage flow is responsible for the smoke intrusions into Bend. Land Managers may want to consider this when planning timing of burns if calm, clear conditions are expected overnight.

Fourth, in addition to fuels, meteorological models are a primary component of smoke dispersion models. There can be large and significant errors in the modeled winds compared with observations. In these cases, even if fuels are well modeled, the meteorological and dispersion models can completely "miss" the intrusions, with predicted $PM_{2.5}$ concentrations never reaching the smoke sensitive receptors.

Finally, higher resolution models better represent the complex terrain in areas such as the DNF. When able to model dispersion at resolutions down to 1km, the location and timing of the intrusions are better predicted when compared with coarser resolution models. While model resolution is mostly out of the control of the land manager, they should understand the limitations of using models which do not accurately represent the local terrain.

Future Work Needed

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. 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 wildland urban interface. Furthermore, plans may need to be in place to limit the ignition of fuelbed components that have the potential of long-term smoldering, and initiate mop-up on fuelbed components that ignited and have the potential to continue to smolder into the evening hours.

Acknowledgments

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References

Anderson, G.K, D.V. Sandberg, and R. A. Norheim, 2004. Fire Emissions Production Simulator (FEPS) Users Guide, Version 1.0. http://www.fs.fed.us/pnw/fera/feps/FEPS_users_guide.pdf

Bradshaw, Larry; McCormick, Erin 2000. FireFamily Plus user''s guide, Version 2.0. Gen. Tech. Rep. RMRS-GTR-67WWW. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Draxler, R.R., and G.D. Hess, 1998: An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition. *Aust. Meteor. Mag.*, **47**, 295-308.

Hoadley JL, Rorig ML, Bradshaw L, Ferguson SA, Westrick KJ, Goodrick SL, 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. http://dx.doi.org/10.1071/WF05015

Larkin, NK, O'Neill, SM, Solomon, 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, C. F., Albright, M., Ovens, D., Steed, R., et al., 2003. Regional environmental prediction over the pacific northwest. *Bulletin of the American Meteorological Society, 84*(10), 1353-1366,1328.

Michalakes, J, Chen, S, Dudhia, J, Hart, L, Klemp, J, Middlecoff, J, and 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.

Oregon Department of Foresty, 2014. Oregon Administrative Rules, Division 48, Smoke Management. http://arcweb.sos.state.or.us/pages/rules/oars_600/oar_629/629_048.html.

Ottmar, Roger, Joseph Restaino, Robert Vihnanek, and Conamara Burke, 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, S.J.; Sandberg, D.V.; Ottmar, R.D.; Eberhardt,E.; Andreu, A.; Eagle, P.; Swedin, K., 2013. **Fuel Characteristic Classification System Version 3.0: Technical Documentation** – Gen. Tech. Rep. PNW-GTR-887. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Portland, Oregon. 79 p.

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

Stein, A.F., Draxler, R.R, Rolph, G.D., Stunder, B.J.B., Cohen, M.D., and Ngan, F., (2015). NOAA's HYSPLIT atmospheric transport and dispersion modeling system, Bull. Amer. Meteor. Soc., **96**, 2059-2077, http://dx.doi.org/10.1175/BAMS-D-14-00110.1.

Tables

Table 1. Prescribed burns responsible for smoke intrusions into Bend, Oregon for Fall 2014 and Spring 2015.

Burn Date	Latitude (deg)	Longitude (deg)	Elevation (meters)	Hectares	kg/ha	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 2. Meteorological stations and smoke sampler 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.

Station	Latitude (deg)	Longitude (deg)	Elevation (ft)	Measurement Type	Relationship to Bend, Oregon (km, direction)
Sisters Ranger Station	44.2925	-121.5552	3200	WX	32 km, NNW
Sisters Ranger Station	44.2925	-121.5552	3200	Nephelometer	32 km, NNW
Bridges Boys Academy	44.2274	-121.5212	3540	WX	25 km, NW
Cascade Academy	44.1327	-121.3323	3243	WX	8 km, NNW
Tumalo Ridge	44.0494	-121.4003	4000	RAWS	7 km, WSW
Bend Pump Station				Nephelometer	In Town
Miller Elementary	44.0543	-121.3692	3829	WX	5 km, W
Cascade Middle School	44.0370	-121.3397	3758	Smoke	4 km, SW
Lava Butte	43.93	-121.33	4407	RAWS	15 km, S
Sunriver	43.9033	-121.4329	4164	Smoke	20 km, SSW
Round Mountain	43.6739	-121.7167	5900	RAWS	47 km SW

Table 3. The BlueSky Smoke Modeling Framework configuration used for modeling smoke production and transport from the prescribed burns.

BlueSkyFramework	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) (Pritchard et al. 2013)
Consumption model	CONSUME Version 3 (Pritchard et al. 2005)
Emissions model	FEPS Version 1 (Anderson et al. 2004)
Dispersion model	HYSPLIT Version 4.9

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

Burn Date	Intrusion Start (PDT)	Intrusion Duration (hours)	Maximum 1-hr PM2.5 ($\mu g/m^3$)	Maximum 24-hr PM2.5 ($\mu g/m^3$)	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. Prescription parameters for prescribed fires 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 of days when nighttime southwest through southeast winds and daytime northwest through northeast 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.

	Desirable Winds for Burning Near Bend		Undesirable Winds for Burning Near Bend		
	Daytime North Wind Yes	Nighttime South Wind No	Daytime North Wind No	Nighttime South Wind Yes	"Ideal" Wind Conditions
Annual	36%	15%	45%	77%	7%
Annual Burn	46%	17%	38%	75%	8%
Spring	45%	12%	36%	77%	7%
Spring Burn	50%	21%	36%	69%	13%
Fall	35%	17%	44%	77%	9%
Fall Burn	46%	14%	38%	80%	5%