Analysis of Meteorological Conditions for the Yakima Smoke Intrusion Case Study, 28 September 2009

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Abstract

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On 28 September 2009 the Naches Ranger District on the Okanogan-Wenatchee National Forest in south-central Washington State ignited an 800-hectare prescribed fire. Later that afternoon, elevated $PM_{2.5}$ concentrations and visible smoke were reported in Yakima, WA, about 40 kilometers east of the burn unit. The United States National Weather Service forecast for the day had predicted good dispersion conditions and winds that would carry the smoke to the less populated area north of Yakima. We undertook a case study of this event to determine whether the conditions leading to the intrusion of the smoke plume into Yakima could have been predicted before the burn was ignited, either from forecasts and model output available in on the day of the burn, and/or from higher resolution model output made available only after the event. We evaluated three different meteorological model predictions: (1) 4-km resolution hourly weather predictions from the Weather Research and Forecasting (WRF) model that were available to forecasters on the day of the burn; (2) 4-km resolution WRF predictions at 10-minute intervals; and (3) 1.33-km resolution WRF predictions at 10-minute intervals. We found that predicted winds from the 4 km and 1.33 km model resolutions compared well with each other, while there were some differences in the predicted planetary boundary layer height over Yakima. We also used the high-resolution 1.33-km WRF output to generate smoke dispersion predictions using the BlueSky Smoke Modeling Framework. The results showed that forecasters and regulators using either the model output available on the day of the burn, or the higher-resolution model output generated afterward, would not have anticipated the meteorological conditions that resulted in the smoke intrusion that day.

Keywords: smoke dispersion, smoke modeling, fire weather, decision support

Summary

Prescribed fire is one of many techniques used by federal, state, and private land owners to manage forest and range lands. While prescribed burning is an effective method for reducing hazardous fuels and restoring ecosystems, problems arise when smoke impacts nearby communities. Such impacts occurred when managers on the Naches Ranger District, on the Okanogan-Wenatchee National Forest, located on the eastern slopes of the Cascade Mountains in Washington State, ignited a prescribed underburn in late September 2009.

Weather forecasts obtained the day of the burn, including a spot weather forecast specifically requested for the burn location, indicated both surface and transport winds would be from the southwest, and an approaching cold front would ensure mixing heights would be sufficient to allow for good smoke dispersion. Based on these forecasts, approval for the burn was given by state regulators. Ignition commenced at approximately noon local time, and continued for several hours. During active burning and shortly after ignition was complete, smoke was observed to disperse to the northeast, rising to 600 – 1200 meters above ground level over mostly unpopulated or sparsely populated areas. At approximately 16:00 local time (4:00 PM), smoke was evident in the city of Yakima, WA, located about 40 km due west of the burn unit. Visibility was significantly reduced, and at the same time, an air quality monitor in downtown Yakima recorded elevated hourly average $PM_{2.5}$ concentrations for several hours, with the maximum 1-hour reading above 100 $\mu g/m^3$.

The purpose of this study was to analyze the forecasts and observational data that were available on the day of burn, to determine if, in hindsight, there was evidence that would have led the burners and/or regulators to cancel the burn that day or stop ignition earlier. We analyzed the meteorological model output that was available to the decision makers in real time, and also obtained higher resolution (both spatially and temporally) model output that became available only after the fact. We also used the higher resolution meteorological model output as input to smoke dispersion models. There was no indication, either in the low or high resolution model output, that smoke from this prescribed burn would impact Yakima. More observations (both meteorological and air quality) are needed to understand the meteorological conditions that can cause a smoke intrusion into Yakima, so that burning under similar conditions can be avoided in the future.

Introduction

Prescribed burning is an important tool used by land managers to mitigate potential future impacts from destructive wildfires, and to restore the natural role of fire in ecosystems. There are several potential barriers to prescribed burning, including negative perceptions of fire and smoke by the general public, air quality regulations, and risk of smoke intrusions (Haines et al. 2001). When smoke from a prescribed burn impacts local communities, it can become even more difficult to obtain approval for future burning. In this study we undertook a detailed case study of a prescribed underburn to determine whether we could, from model output or observations, identify the meteorological conditions that resulted in a smoke intrusion in a nearby community.

Located on the eastern slopes of the Cascade Range in south central Washington State, the Naches Ranger District marks the southernmost lands managed by the Okanogan-Wenatchee National Forest. The Naches Ranger District is bordered on the north and west primarily by public forest lands, and by the Yakama Indian Reservation to the south. To the east is the greater Yakima Valley area, a region characterized by fertile agricultural lands and the city of Yakima with a 2010 population of 91,067 and a metropolitan population of 243,231. The forest lands of the Naches Ranger District are highly fire dependant and the Okanogan-Wenatchee Forest, through its Forest Restoration Strategy, uses prescribed fires as a tool to help reduce the threat of uncharacteristically severe wildfires and to increase resiliency of unhealthy forest ecosystems.

On 28 September 2009 the Naches Ranger District received approval from the Washington Department of Natural Resources (DNR) to ignite an 800-hectare prescribed underburn on Bethel Ridge (the "Kaboom" Unit), located about 40 kilometers due west of Yakima, WA. The spot weather forecast for the day, obtained from the National Weather Service (NWS), predicted winds from the southwest, with surface wind speeds of 1-2 m/s, increasing to 3-4 m/s, gusting to 6 m/s, and transport wind speeds of 4-6 m/s. Mixing heights were predicted to be 1400 meters during the day, lowering to 450 meters over night. These predictions indicated a good day for dispersion with little chance that smoke would impact the public.

Ignition of the underburn began at approximately 12:30 PDT through a combination of hand and helicopter methods. Initially the smoke plume was observed to travel to the NNE, rising to 600-1200 meters above ground level (AGL), consistent with forecasts. Then at approximately 16:30, the plume was observed at ground level, and smoke impacts were reported throughout upper Yakima County. The air quality monitor in downtown Yakima recorded elevated hourly average $PM_{2.5}$ concentrations for about seven hours, from approximately 16:00 to 23:00, with a maximum 1-hour average just above 110 $\mu g/m^3$ reported at 18:00 PDT. The meteorological conditions that resulted in the smoke intrusion in Yakima had not been predicted by the standard NWS zone forecast, or by the spot weather forecast obtained the morning of the burn.

The objective of this case study was to determine whether, with benefit of hindsight, the conditions leading to the drainage of smoke into the Yakima area could have been predicted from the Weather Research and Forecasting (WRF) meteorological model predictions available to forecasters on the day of the burn, and if not, whether higher-resolution model output (not available on the day of the burn), using the same configuration and parameterizations as the real-time low-resolution simulation, could have predicted the conditions that led to the smoke intrusion. In addition, we compared observed surface meteorological data with the model output to determine the quality of both the forecast that was provided in real time, and the higher-resolution model predictions. The purpose of this study was not to determine why the mesoscale models did not accurately capture boundary layer effects or how those models could be improved. Rather, our goal was to determine what meteorological conditions led to the smoke intrusion, and if there was anything in the operational models run at the time, or afterward (using a higher resolution model output that was not available at the time), that could have been useful in the decision-making process by indicating the possibility of a smoke intrusion event, so as to prevent future similar events.

In addition to evaluating the outputs from the meteorological models, we used the high-resolution WRF output to simulate smoke dispersion from the burn using the BlueSky Smoke Modeling Framework (BlueSky; Larkin et al. 2009). BlueSky was originally developed as a tool to facilitate prescribed burn activities by providing simulated smoke dispersion impacts for land managers and regulators, however BlueSky is now used nation-wide as a smoke prediction tool for both wildfire and prescribed fire. BlueSky is not a single model; rather it is a framework that allows several different models (meteorological, fuel consumption, emission, plume rise, and dispersion) to run seamlessly, in series, to produce predicted surface concentrations of $PM_{2.5}$ and trajectories aloft. BlueSky is currently run in real time regionally and nationally with estimated fire sizes and fuel loadings; however, for this case study we were able to run BlueSky with the actual number of acres burned and measured fuel loadings.

Methods

Meteorological and Air Quality Observations

Meteorological observations were compiled from four nearby surface weather stations: two Northwest Weather and Avalanche Center (NWAC) weather stations at Chinook Pass and White Pass, one Remote Automated Weather Station (RAWS) site at Sawmill Flats, and the National Weather Service station at Yakima Air Terminal, located in the city of Yakima (Table 1 and Figure 1). We used the surface observations (shown in Figure 2) to assess the accuracy of the real-time weather forecasts provided by the NWS, and to compare with model output. The NWS forecast for the area called for a cold front to move across the Cascades late in the afternoon of the 28th with breezy winds shifting to the southwest and west, and little chance for precipitation (Dave Grant [DNR], personal communication). The spot weather forecast for Bethel Ridge, obtained by the Forest Service the morning of the 28th, called for southwest surface (6-meters above ground) winds of 1 – 2 m/s increasing to 3 – 4 m/s with gusts to 6 m/s. Winds aloft were also predicted to be from the southwest at 4 – 6 m/s, with a mixing height of 1370 m (Jim Bailey [US Forest Service], Documentation for Kaboom Underburn, 09/28/2009). There were no available local upper-air data, therefore we used sounding data from the nearest and most representative upper-air station, located at Spokane, WA, approximately 250 km northeast of Yakima.

Hourly air quality observations were retrieved from the nephelometer (Radiance Research M903) located in downtown Yakima (402 S 4th Avenue; latitude 46.59495, longitude -120.51228). Figure 3 shows that elevated $PM_{2.5}$ concentrations were recorded from about 15:00 – 16:00 PDT until about 23:00 PDT on the 28th. Visibility dropped dramatically at the same time. The maximum hourly concentration briefly peaked above 110 μg/m^3. National Ambient Air Quality Standards (NAAQS) set by the U.S. Environmental Protection Agency (EPA) to protect human health are based on a 24-hour averaging time. The 24-hour NAAQS for PM2.5 is currently 35 μg/m3 and the 24-hour average $PM_{2.5}$ value measured in Yakima on September 29, 2009 was 23.2 μg/m^3, meaning there was no exceedence of the NAAQS. We also obtained data from the air quality monitor in the town of Naches, which is located between the burn unit and Yakima. The $PM_{2.5}$ concentration never exceeded background levels at that monitor.

Meteorological Model Predictions

The Northwest Regional Modeling Consortium (NRMC) based at the University of Washington, Seattle, provided model runs for this study from the Advanced Research WRF (WRF-ARW) core of the Weather Research and Forecasting (WRF) model (Michalakes et al. 2001, 2005; Wicker and Skamarock 2002; Skamarock et al. 2005; Klemp et al. 2007), initialized at 00Z on 28 September 2009 (17:00 PDT on 27 September 2009) at a 4 km spatial resolution and hourly temporal resolution. (While this model prediction was nearly 24 hours old by the time of smoke intrusion, the smoke dispersion prediction from this 00Z model run would have been the latest available at the time of the go/no-go decision.) The 4 km domain encompasses all of Washington and Oregon, and parts of the surrounding states. For this analysis we used the WRF mesoscale model because the meteorological conditions that resulted in the smoke intrusion were on a spatial and temporal scale finer than would be resolved by global models such as the Global Forecast System (GFS), which provided initial and boundary conditions for the WRF model runs. The NRMC WRF model also has the advantage of being optimized for the northwestern U.S. These forecast products were available to the public, including weather forecasters and regulators on the morning of the burn. The NRMC also provided us with two WRF model runs not available on the day of the prescribed burn – one at 4 km spatial resolution with output every 10 minutes (which is the same as the 4 km hourly output with additional output every ten minutes between the hour), and one at 1.33 km spatial resolution with output every 10 minutes. The 1.33 km domain is nested within and initialized by the 4 km domain. We extracted the winds and planetary boundary layer heights for the model grid cells corresponding to the locations of the underburn, and downtown Yakima, where the air quality monitor that recorded the elevated

$PM_{2.5}$ readings is located. All model runs were initiated at 17:00 PDT on 27 September 2009, with the simulation period lasting 36 hours (1.33 km domain) to 72 hours (4 km domain).

Results

Surface and Upper-air Observations

The time series of wind speed and direction from the surface observation stations are shown in Figure 2. The surface wind direction at the three mountain stations (Chinook Pass, Sawmill Flats, and White Pass) was generally from the ESE to SE (from about 100 to 140 degrees) in the early morning hours of September 28. Between about 03:00 and 06:00 the wind direction shifted to the NW (280 to 320 degrees), which is indicative of a frontal passage. NW winds persisted for the remainder of the day. Figure 2 also shows wind speed and direction at Yakima Air Terminal (located on the south side of the city of Yakima, approximately 3 to 4 km from the air quality monitor downtown). At this location early morning winds were less than 5 m/s from the west (270 degrees), then from about 07:00 PDT to 12:00 generally light and variable (less than or equal to 2 m/s and from the N to NE). After about 13:00 the winds veered to the WSW (between 200 and 240 degrees) and speeds increased to 8 – 10 m/s with higher gusts (not shown in the figure). Wind speed decreased to 5 m/s or less after 20:00. The changes in wind speed and direction suggest a frontal passage at approximately 13:00, which is later than indicated at the mountain stations. There are two possible explanations for this. First the mountain stations are west of Yakima, so it is reasonable to assume a front approaching from the west would be evident there earlier than at Yakima. Second, because the remote sites are located in complex terrain, the winds are likely affected to some degree by the surrounding terrain (e.g. upslope/downslope flows, channeling of winds, etc.). The weather observation station at the Yakima Air Terminal is on relatively unobstructed flat terrain, and therefore more likely to reflect regional (synoptic) rather than local conditions.

WRF Model Predictions

Predicted wind speeds (10 meters above ground level) were similar (but not identical) in the 10-minute output from both the 4 km and 1.33 km WRF model runs at the location of the underburn (Figure 4a). Modeled wind speeds were approximately 2-4 m/s until 06:00 on the 28th, when they decreased briefly to less than 1 m/s. Between 07:00 – 11:00, speed increased to greater than 6 m/s, with the increase occurring about two hours earlier in the 4 km model simulation. It is not clear why there is a difference in timing of the increased wind speed between the 1.33 km and 4 km model simulations. After about 13:00, wind speed remained at about 6 m/s in the 4 km simulation, but decreased to between 2 – 4 m/s in the 1.33 km simulation. The modeled wind speeds were 2 – 5 m/s higher than the spot weather forecast in the 4 km simulation, but closer to forecast in the 1.33 km simulation. This may be due to the finer resolution domain better capturing the rough terrain and its effect on surface winds. Wind direction was also similar between the two model resolutions at the underburn location (Figure 4b). Both simulations predicted wind direction from the NE (50 to 100 degrees) until about 05:00, followed by a gradual clockwise wind shift over 3 to 5 hours to the WSW (about 250 degrees). This predicted wind shift occurred about two hours later than what was observed in the mountain weather stations; however both simulations agreed reasonably well with the general NWS forecast of SW to W surface winds.

At Yakima, (Figure 5), both simulations predicted wind speeds between about 1 and 4 m/s over night prior to the burn, although the time series did not vary together (Figure 5a). Shortly before 05:00 speed decreased below 1 m/s in the 1.33 km domain, with the decrease coming about two hours later in the 4 km domain. Both then predicted wind speeds increasing between 10:00 and 13:00 to greater than 4 m/s, with the 1.33 km simulation predicting a higher peak speed at 8 m/s compared to a peak of about 5 m/s from the 4km domain. The 1.33 km simulation agreed well with observations, which also indicated wind speeds of about 8 m/s. While the agreement is encouraging, the relatively high wind speeds in Yakima at the time of the smoke intrusion confounds the scenario of drainage flows carrying smoke into Yakima. After 17:00 the 1.33 km speed varied between less than 1 m/s and 4 m/s, while the 4 km speed was somewhat higher, varying between 3 – 5 m/s until midnight, when speeds decreased to less than 2 m/s.

The 1.33 km simulation wind direction at Yakima (Figure 5b) was from the NNW (300 - 350 degrees) until about 05:00 PDT on the 28^{th}, gradually shifting to SSE (150 – 180 degrees) until after noon, then veering to the SSW (200 – 230 degrees) until about midnight when it became variable, consistent with light wind speed. The 4 km modeled wind direction was from the ENE until about 7:00 PDT, when it shifted to northerly for 2 to 3 hours before switching to SW for the remainder of the day (in rough agreement with the observed winds at Yakima Air Terminal, Figure 2). Despite the differences in details between the two model simulations, the broad patterns were the same, with a morning wind shift from the N or NE to WSW, and an increase in afternoon wind speeds.

The time series of planetary boundary layer (PBL) height for both model resolutions at the underburn location and Yakima are shown in Figures 6 and 7. The PBL is the layer of the atmosphere that is closest to the ground, and is directly influenced by surface friction and surface heating. It is not the mixed layer, nor is the PBL height the same as the mixing height, but the two are related, in that the PBL height is less than the mixing height, and the higher the PBL, the higher the mixing height. Therefore one would expect better ventilation with a higher PBL height. The Yonsei University (YSU) PBL scheme (Hong et al. 2006) was used for both the 1.33 km and 4 km simulations. The model-generated PBL height at the underburn location for both resolutions was near 500 meters at the start of the simulation (17:00 on the 27th), then gradually decreased to less than 100 meters in the early morning hours of the 28th. After about 10:00 both markedly increased (Figure 6). The PBL heights were similar until about 17:00, when the 4 km simulation PBL height increased while the 1.33 km simulation height decreased significantly.

The predicted PBL heights at Yakima from the 4 km and 1.33 km model simulations also showed some differences (Figure 7) between the two model resolutions. Heights from both resolutions remained below 500 meters from the start of the simulation until about 11:00, when both increased. The 4 km PBL height increased to 1800 – 2000 meters, before decreasing below 500 meters after 18:00 to 19:00. The 1.33 km PBL height increased only to about 1000 meters, and started decreasing earlier than in the 4 km simulation. The decrease in the 1.33 km run occurred about the same time (just before) smoke was first detected in the Yakima valley. It stayed below 500 meters for the rest of the night, except for a few short-lived spikes (which may reflect issues with the model rather than real-world fluctuations). The Spokane upper-air soundings from 05:00 and 17:00 on the 29th (not shown) did not show any indication of a surface-based inversion or an inversion layer aloft. Without having nearby upper-air data, it is not possible to know which simulation of PBL height was closer to “reality.” Mesoscale models such as WRF have known biases in temperature, winds, and humidity in the PBL, and a finer resolution does not necessarily indicate the biases will be less than in coarser resolution simulations (Mass et al. 2002; Hoadley et al. 2004). Whether or not the height of the boundary layer did actually start decreasing in the mid-afternoon hours as seen in the 1.33 km simulation, it was not predicted by the 4 km model output that was available on the day of the burn.

BlueSky Smoke Concentrations and Trajectories

To obtain predictions of smoke concentrations from the underburn, we ran the BlueSky Framework using the 1.33 km WRF model output at 10 minute intervals. The fuel loadings used in the simulation (Table 2) were obtained from the burn plan prepared by the Naches Ranger District. The models used at each step of the Framework are listed in Table 3. We used 730 hectares as the size of the burn (which was the reported estimate of blackened acres after the burn), with ignition starting at 12:40 and ending at 15:40. Forty hectares were ignited every 10 minutes for a total ignition time of three hours. Figure 8 shows predicted surface $PM_{2.5}$ concentration every two hours from 13:00 to 23:00 on the 28th. This simulation shows all of the surface-based $PM_{2.5}$ dispersing to the northeast of the burn unit, with no measureable $PM_{2.5}$ reaching Yakima (note the yellowish rectangle in the figures over Yakima is an artifact of Google Earth and not $PM_{2.5}$ from the BlueSky output).

We then ran forward trajectories (using the 1.33 km WRF output and Hysplit [Draxler and Hess, 1997]) originating from the underburn (Figures 9a and 9b). Regardless of the beginning hour for the trajectories, all indicated smoke from the fire would be carried to the ENE, and not impact Yakima. Figure 9a shows forward trajectories starting at 13:00 and 15:00 from an elevation of 1000 meters (we used 1000 meters because the smoke plume was observed by Forest Service personnel at between about 600 meters and 1200 meters AGL [2000 – 4000 feet]). Both cases are very similar (indicating no significant change in predicted transport winds during that time period) and show the smoke plume dipping below 1000 meters before rising again to above 1000 meters AGL.

By 16:00 (Figure 9b) the trajectory released from 1000 meters immediately lowered to between 500 meters and 1000 meters AGL, then got closer to the ground than 500 meters (with a minimum height of about 300 meters AGL), before increasing again to above 500 meters. This decrease in trajectory heights AGL could reflect the smoke plume being transported over higher terrain rather than the plume descending closer to the ground. Nevertheless, the plume was not predicted to reach ground level, or be transported over Yakima.

To explore a more conservative scenario where smoke would not be lofted as high above the fire as was observed, we generated trajectories starting at 200 meters AGL (Figure 9c). The 13:00 trajectory is shown, but the subsequent hours revealed a very similar pattern. Once again, the predicted plume initially dropped below the release height (200 meters), only to rise again to above 200 meters AGL for the duration of the simulation.

Discussion

On 28 September 2009, air quality monitor data and public reports indicated a significant smoke intrusion in and around Yakima, WA. On that same day, the Naches Ranger District was conducting a large underburn about 40 kilometers to the west. It is believed that smoke from the underburn was the source of the smoke in and around Yakima. While the NAAQS for $PM_{2.5}$ was not exceeded during this event, high $PM_{2.5}$ concentrations persisted for several hours. The NWS spot weather forecast predicted good mixing during the day, with S to SW winds to carry the smoke away from Yakima. The burn was carried out by Forest Service personnel in accordance with the plan they registered with the Washington DNR, who approved the burn based on the current weather and forecast information available on the morning of the 28th. For the duration of the burn, smoke was indeed lofted and carried to the NW, away from the populated areas in and around Yakima. It was only after ignition was completed that the smoke plume was observed to veer to the west and impact ground level.

We studied this event to answer two questions. First, could this smoke intrusion have been anticipated with the tools available to the decision-makers on the day of the burn, and second, if not, could this event have been predicted with higher-resolution meteorological models that became available subsequent to the burn event? It is expected that these higher-resolution models will soon be available operationally. We analyzed the 4 km hourly WRF output that was available on the day of the burn, 4 km WRF output at 10-minute intervals, and also 1.33 km

WRF output at 10-minute intervals, which was not available to forecasters in real time. We also used the 1.33 WRF output in BlueSky smoke dispersion and trajectory simulations of the underburn. The finer resolution was used because it further resolved the features of the terrain and their effect on the wind regime.

Our results indicate model predictions available on the day of the burn would not have indicated smoke from the underburn would impact Yakima late in the afternoon and into the evening of 28 September 2009. Winds were forecast to be from the SW, and the PBL height in the vicinity of the burn unit was forecast to be about 1000 meters (approximately 3300 feet) throughout the afternoon and evening. In fact, at the time of the smoke intrusion, observed winds in Yakima were strong (> 8 m/s) and from the SW.

Additionally, with the possible exception of the PBL height, we found no evidence in the high-resolution WRF model run to indicate the meteorological conditions that led to the smoke intrusion could have been predicted. The winds were predicted to be from the SW, and PBL height at the burn unit was predicted to remain high throughout the night following the burn in the 4 km simulation, but decrease over night in the 1.33 km simulation. The results from BlueSky runs using the high-resolution WRF output reinforced the prediction that smoke ($PM_{2.5}$) from the burn would be transported to the NE of the burn unit, not ESE toward Yakima. Trajectories showed the upper air transport flow was also from the SW, in agreement with NWS forecasts.

The PBL height at Yakima was predicted to decrease earlier in the 1.33 km simulation than in the 4km simulation. This is the only indication that the higher resolution model might have suggested the possibility of smoke getting trapped close to the ground on the night following the burn. The 4 km simulation kept the PBL height high at the burn unit compared to the 1.33 km simulation, and at Yakima, the 1.33 km PBL height decreased hours earlier than that in the 4 km simulation. Because there is no upper-air data from the day of the burn in Yakima or near the burn site, we cannot know which simulation more accurately represented the PBL heights. Predicted conditions in the boundary layer (including the PBL height) are dependent on which boundary layer parameterization scheme and initial conditions are used in the model, so it is possible that neither model run accurately represented actual PBL heights in the hours following the burn. This model configuration was used for this study because it is used for the NRMC operational runs, and is what is currently available to forecasters and regulators for their decision making process. Nevertheless, land managers and regulators typically do not use PBL heights (or other variables) from individual grid cells in the model domain for prescribed burn planning, so a close scrutiny such as was undertaken here would not have been done prior to the burn. In addition, models do not always adequately characterize conditions in the boundary layer, which is important for accurately predicting vertical mixing of smoke and other pollutants (Hu et al. 2010).

Despite this study it remains unclear what meteorological conditions resulted in smoke transport from the underburn to Yakima. One possible explanation is that, as daytime heating waned, stability increased and terrain-induced downslope flow increasingly dominated the synoptic-scale southwesterly flow, such that the smoke that had been advected to the northeast of the burn unit settled into the lower elevation areas in and around Yakima. The strong SW winds recorded in Yakima late in the afternoon does not support this. Another possibility is that downward flow set up as a thermal or lee-side trough moved east of the Cascade Range. Observational data are unavailable to verify or dispute this possible scenario. On the scale of 1.33 km and 4 km the model simulations do not show smoke advecting into Yakima. To better predict smoke dispersion from burns in this area, knowledge of the specific local drainage flows, and timing of the shift from synoptic flows to drainage flows, is required. Collecting additional observational data of both smoke and meteorological variables would increase this local knowledge and help to better anticipate smoke dispersion patterns from complex burns.

Conclusions

We carried out a detailed meteorological and smoke dispersion analysis of a smoke intrusion event in Yakima, WA, that occurred after an 800-hectare prescribed burn 40 km to the west, on the Naches Ranger District. We found that the smoke intrusion could not have been easily predicted using the forecasts and models available on the day of the burn. Nor could it have been foreseen from enhanced, higher-resolution meteorological models that were not widely available at the time. In fact, after doing a careful "hindsight" analysis, we found that there is not adequate observational data (surface or upper-air) to definitively explain exactly what occurred meteorologically on 28 September 2009 that caused the high $PM_{2.5}$ concentrations at the monitoring site in Yakima.. The 1.33 km and 4 km meteorological modeled wind data are similar and while their boundary layer predictions vary, neither explains the occurrence of smoke at the ground in Yakima.

As computing capability increases with faster, more cost-effective computers, weather forecasts are also improving. We now have available higher-resolution forecasts than were available just a few years ago, and the quality of those forecasts is also improving. Nevertheless, there are limitations in the models, and the forecasts are not always accurate. Hopefully, in the not-too-distant future, meteorological models will improve to the point where the event that caused the smoke intrusion can be predicted. We performed a detailed case study of the smoke intrusion event that occurred in Yakima, WA, after a prescribed burn on the Naches Ranger District on 28 September 2009. We determined that this event could not have been predicted with the data and forecasts available on the day of the burn. Furthermore, if the decision-makers had had higher-resolution forecasts not available in real time, they likely would have made the same decision to accomplish the burn on that day because the forecast would not have been significantly different.

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English Equivalents

When you know:	Multiply by:	To get:
Meters (m)	3.28	Feet
Kilometers (km)	0.621	Miles
Hectares (ha)	2.47	Acres

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Table 1. Locations of the burn unit on Bethel Ridge, Cascade Range, United States, nearby surface weather stations used in this study, and the air quality monitoring site in Yakima, Washington State, United States.

Site	Latitude	Longitude	Elevation (m)
Bethel Ridge Underburn	46.687° N	121.086° W	1065
Chinook Pass (NWAC)	46.882° N	121.518° W	1900
Sawmill Flats (RAWS)	46.967° N	121.084° W	915
White Pass (NWAC)	46.624° N	121.388° W	1830
Yakima Air Terminal (NWS)	46.567° N	120.533° W	325
Yakima Air Quality Monitor	46.595° N	120.512° W	100

Table 2. Fuel loadings used in the BlueSky simulation of the Bethel Ridge underburn.

1-hour	0.53 tons/acre
10-hour	0.78 tons/acre
100-hour	1.75 tons/acre
1000-hour	2.33 tons/acre
10000-hour	2.54 tons/acre
10000-hour+	0 tons/acre
Litter	0.3 tons/acre
Grass/herb	0.2 tons/acre
Shrub	1.0 tons/acre
Duff depth	1.2 inches

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

BlueSky Framework	Version 3.1.4
Meteorological model	WRF 3.1.1 (1.33km, 10-minute intervals)
Fuel loadings	Measured (see Table 2)
Consumption model	CONSUME Version3
Emissions model	FEPS Version 2
Dispersion model	HYSPLITVersion 4.8 (March 2007)

List of Figures:

Figure 1a. Map showing the location of the burn unit (Bethel Ridge), surface meteorological observation station locations (Chinook Pass NWAC, White Pass NWAC, Sawmill Flats RAWS, and Yakima Air Terminal), and surface $PM_{2.5}$ monitors (Naches, Yakima).

Figure 1b. Map of the Pacific Northwest showing the extent of the 4 km (outer box) and the 1.33 km (inner box) NRMC WRF model domains.

Figure 2. Observed wind speed (a) and direction (b) at Chinook Pass, White Pass, Sawmill Flats, and Yakima, before, during, and after the underburn and smoke intrusion. The yellow triangle indicates burn ignition time (12:30) and the blue triangle indicates time of first smoke reports in and around Yakima (16:30). Typically time series are smoothed lines (wind speed).

Figure 3. A steep drop in visibility (green line) and its corresponding sudden spike in $PM_{2.5}$ concentration (dark red line) was recorded at the air quality monitor in Yakima late in the day of September 28, 2009.

Figure 4. WRF modeled (a) wind speed and (b) direction at the Bethel Ridge burn location 40 km west of Yakima for the 10-minute interval 4km and 1.33km domains. ”I” indicates burn ignition time (12:30); ”S” indicates time of first smoke reports in and around Yakima (16:30).

Figure 5. WRF modeled (a) wind speed and (b) direction for Yakima, for the 10 minute interval 4km and 1.33km domains. ”I” indicates burn ignition time (12:30); ”S” indicates time of first smoke reports in and around Yakima (16:30).

Figure 6. WRF modeled planetary boundary layer height at the Bethel Ridge burn site 40 km to the west of Yakima, at 10-minute intervals for 4 km and 1.33 km spatial resolution. “I” indicates burn ignition time (12:30); “S” indicates time of first smoke reports in and around Yakima (16:30).

Figure 7. WRF modeled planetary boundary layer height at Yakima, at 10-minute intervals for the 4 km and 1.33 km resolution. “I” indicates burn ignition time (12:30); “S” indicates time of first smoke reports in and around Yakima (16:30).

Figure 8. BlueSky predicted ground level smoke concentrations from the underburn location for a)13:00; b) 15:00; c) 17:00; d) 19:00; e) 21:00; f) 23:00 on 28 September 2009. Times are Pacific Daylight Time.

Figure 9a. 24-hour trajectories beginning at 13:00 PDT (red dots) and 15:00 PDT (gold dots). Trajectories start at 1000 meters AGL. Green dots represent downwind trajectories (for both hours) above 1000 meters AGL.

Figure 9b. 24-hour trajectories beginning at 16:00 PDT. Trajectories start at 1000 meters AGL. Green dots represent downwind trajectories above 500 meters AGL.

Figure 9c. 24-hour trajectories beginning at 13:00 PDT. Trajectories start at 200 meters AGL. Green dot represent downwind trajectories above 200 meters AGL.


Sawmill Flats RAWS
Chinook Pass NWAC
Naches
Bethel Ridge
White Pass NWAC
Yakima
Ellensburg
Seattle
Tacoma
Olympia
Portland
Bellingham
Wenatchee
East Wenatchee
Moses Lake
Ritzville
Pasco
Walla Walla
Sunnyside
Goldendale
The Dalles
Heppner
Salem
Madras
Eugene
Canyon City
Kelso
Saint Helens
Tillamook
Chehalis
Randle
South Bend
Port Angeles
Lakewood
Everett
Bellevue
Victoria
Saanich
Nanaimo
Richmond
Burnaby
Diablo
Okanogan
Republic
Penticton
30 15 0 30 60 90 120
Kilometers

Figure 1a

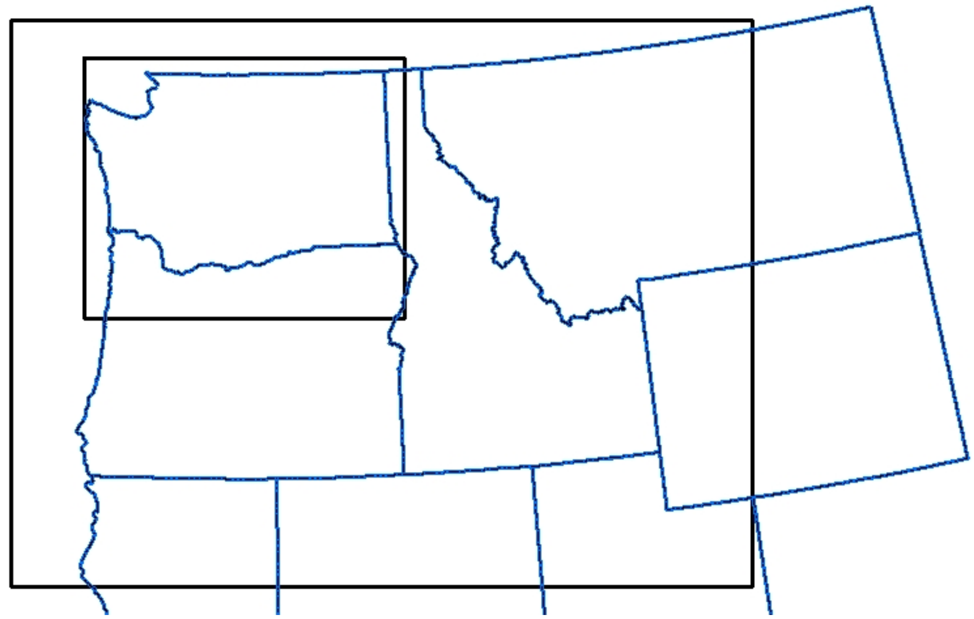

Figure 1b

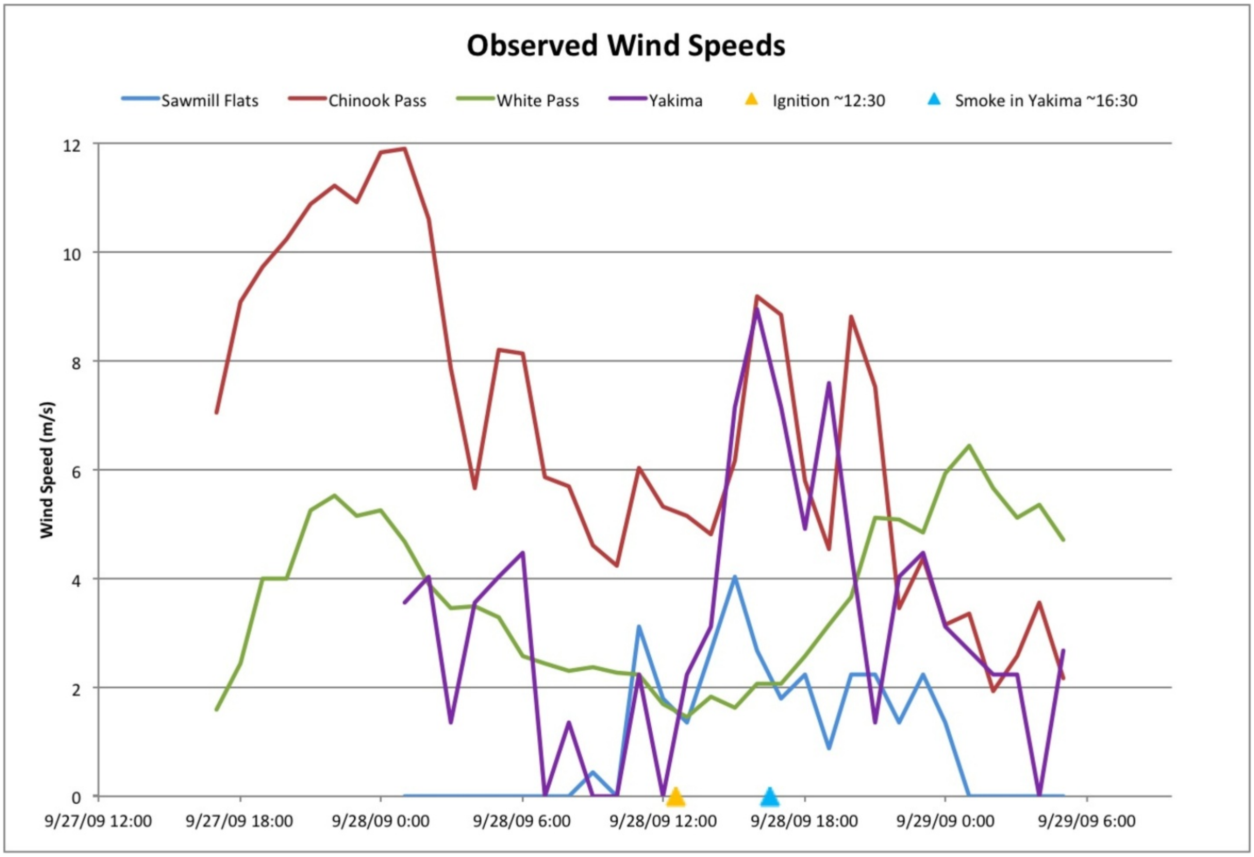
Observed Wind Speeds
Sawmill Flats
Chinook Pass
White Pass
Yakima
Ignition ~12:30
Smoke in Yakima ~16:30
Wind Speed (m/s)
12
10
8
6
4
2
0
9/27/09 12:00
9/27/09 18:00
9/28/09 0:00
9/28/09 6:00
9/28/09 12:00
9/28/09 18:00
9/29/09 0:00
9/29/09 6:00

Figure 2a

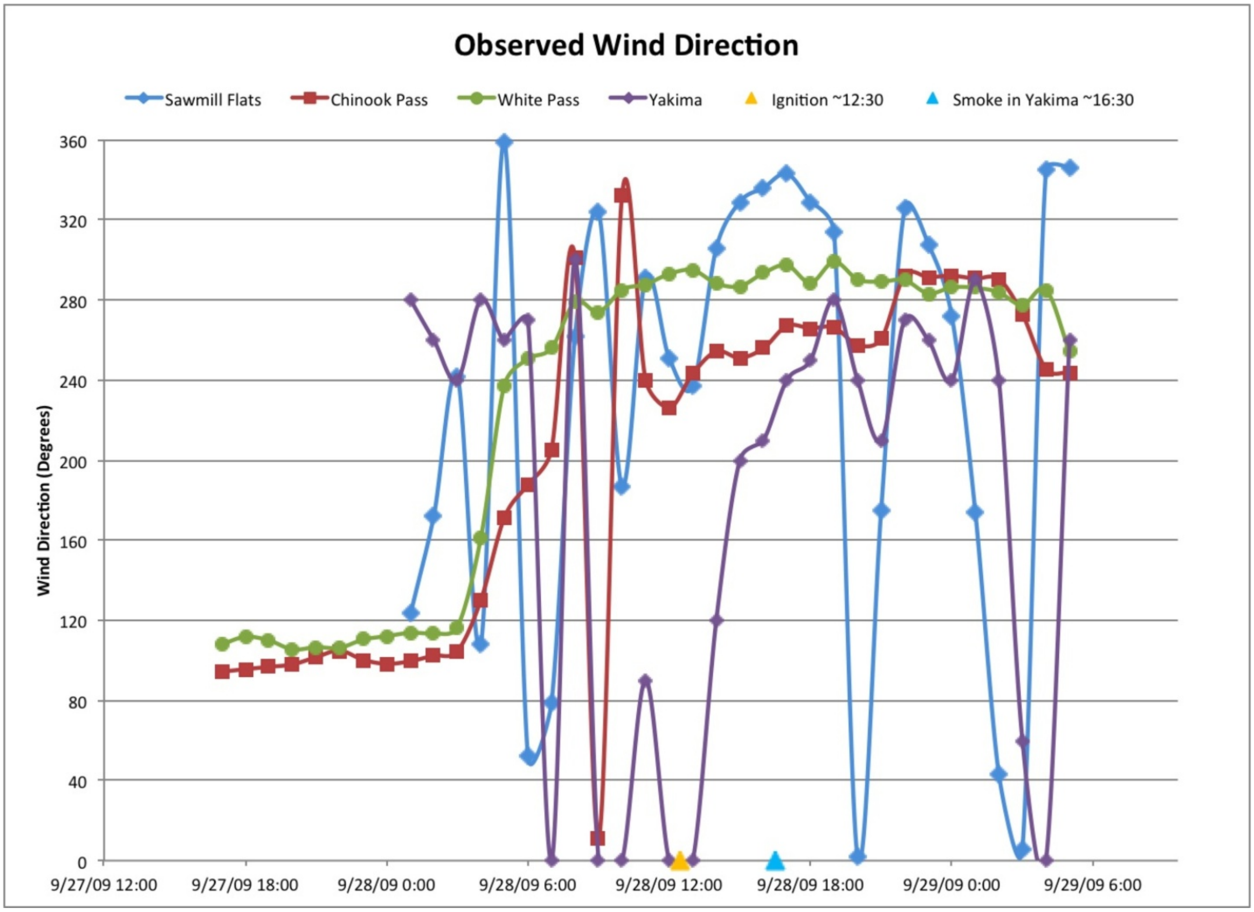

Figure 2b

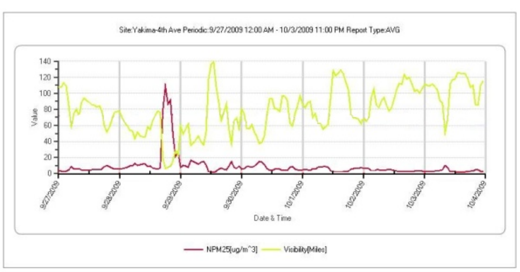

Figure 3

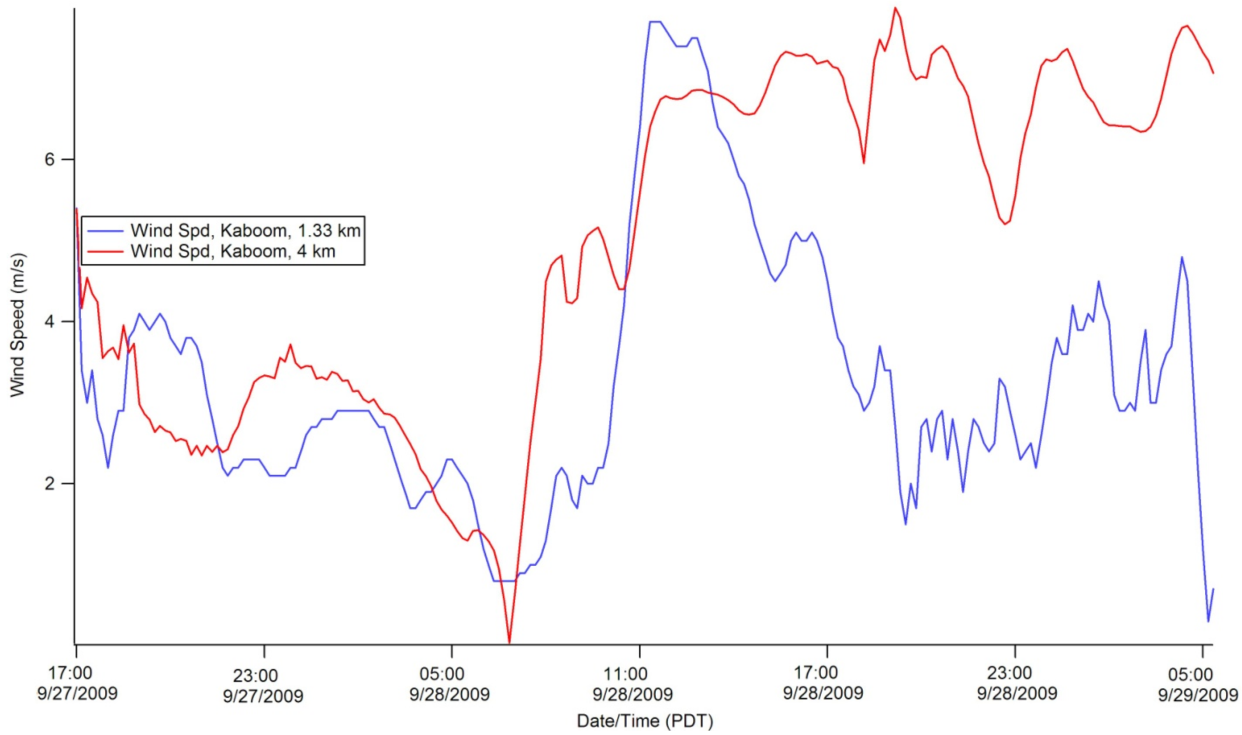

Figure 4a

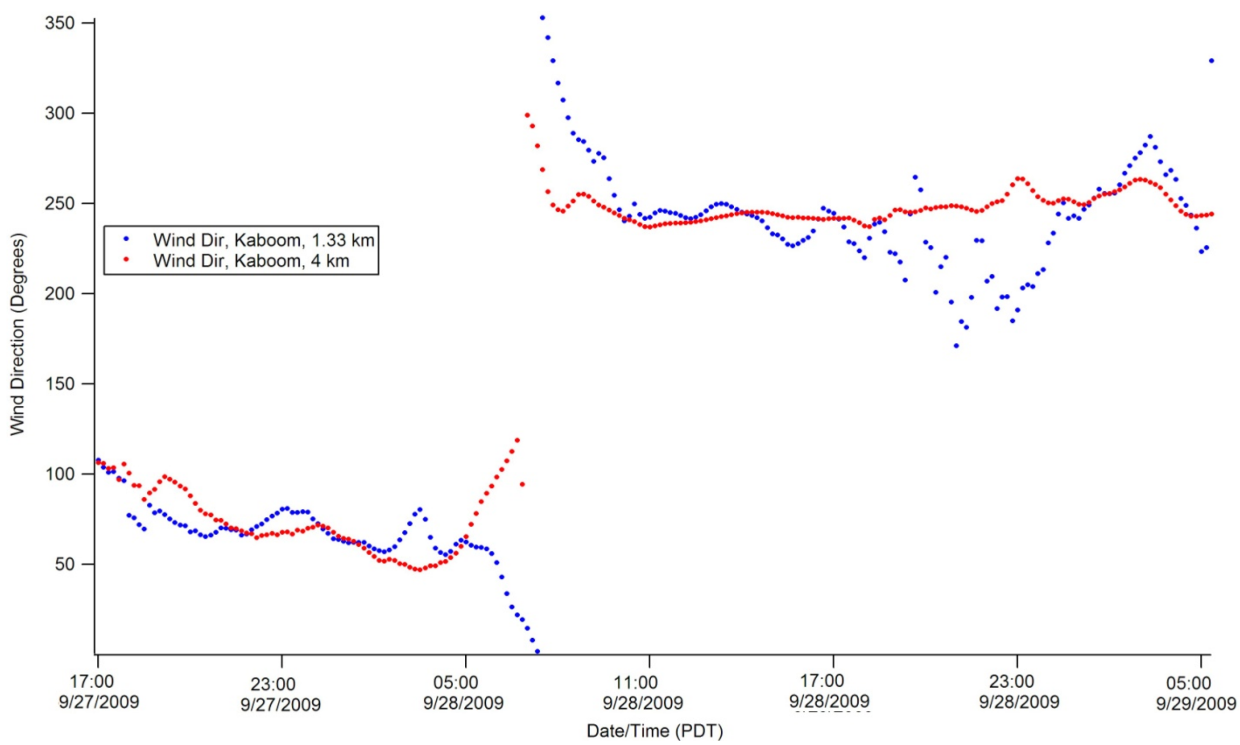

Figure 4b

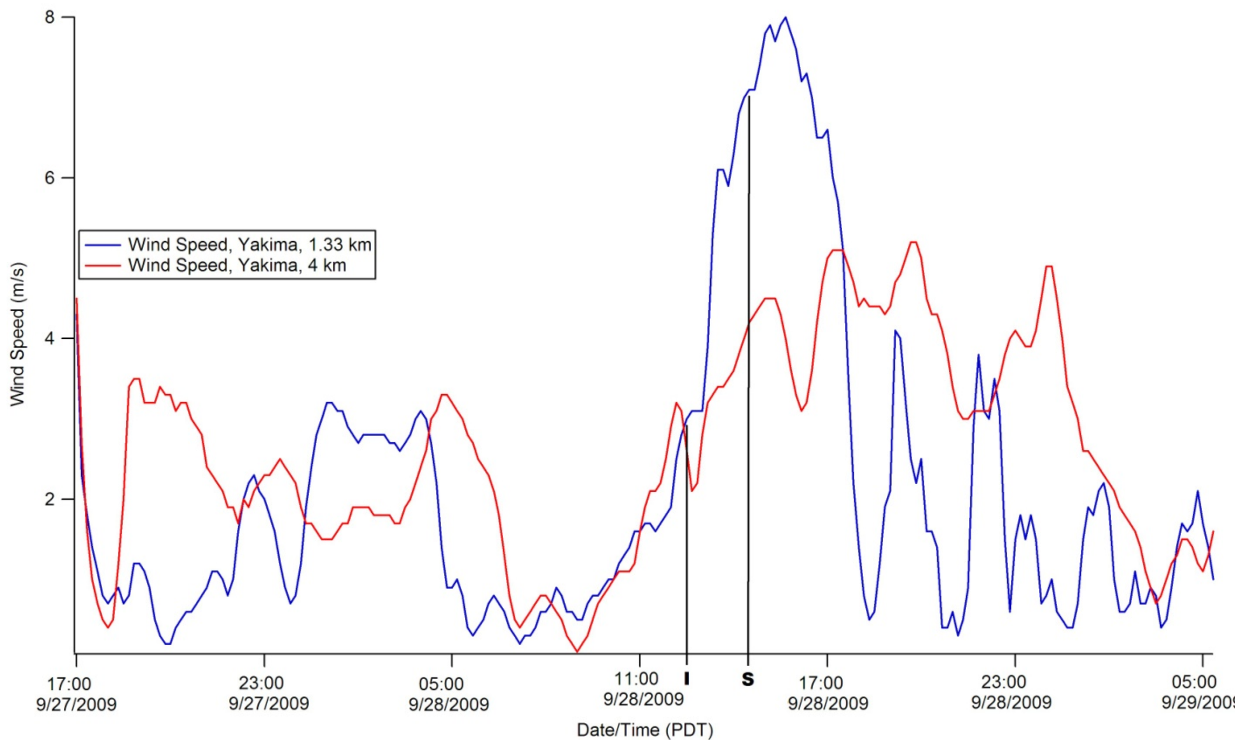

Figure 5a

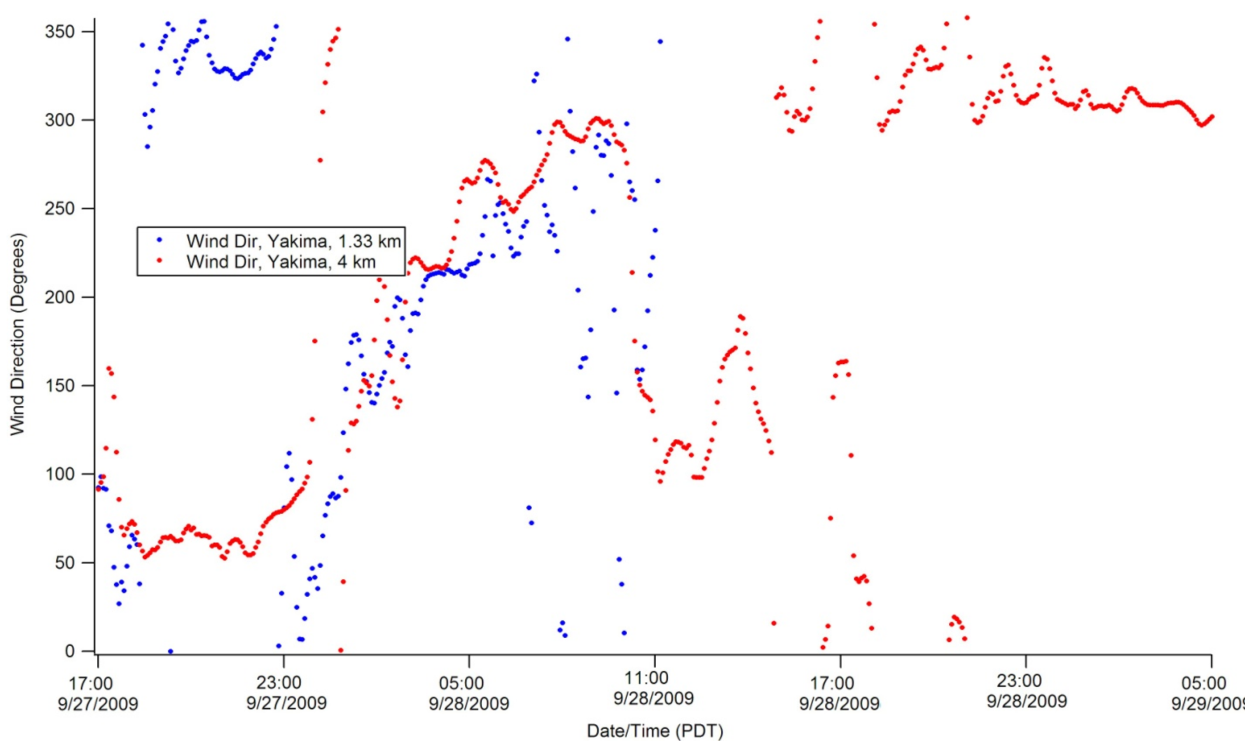

Figure 5b

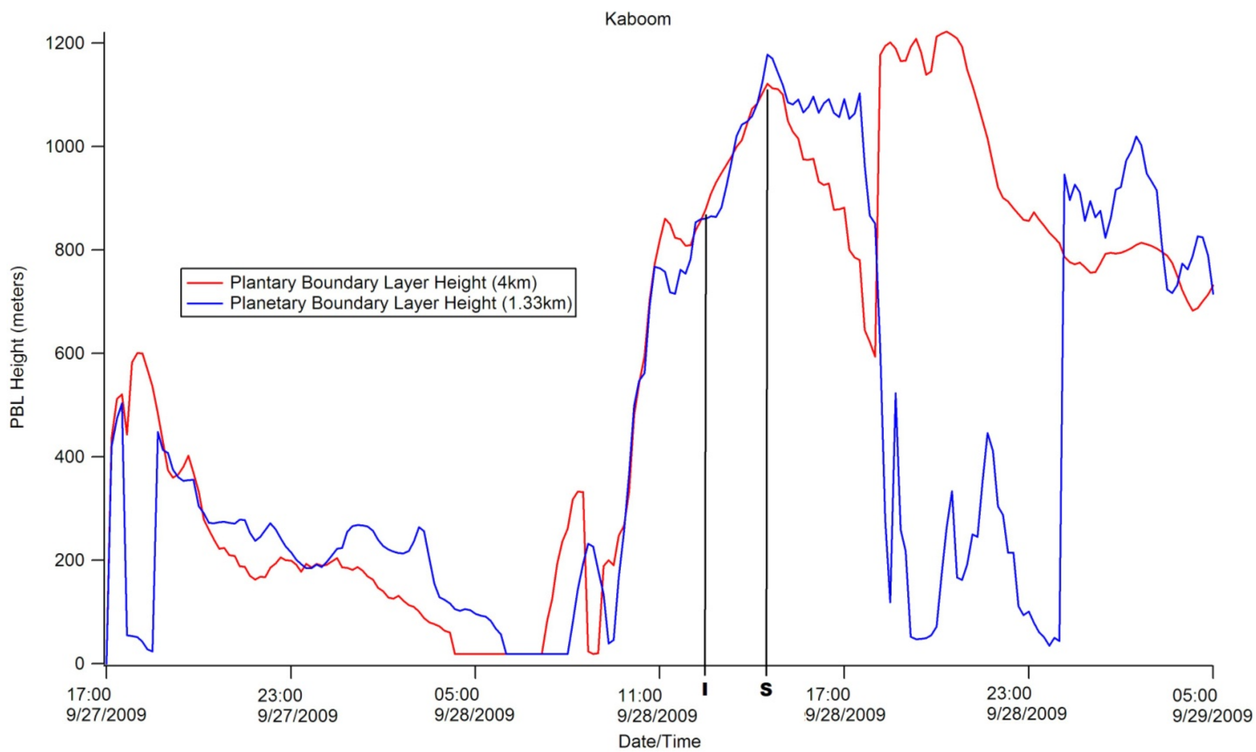

Figure 6

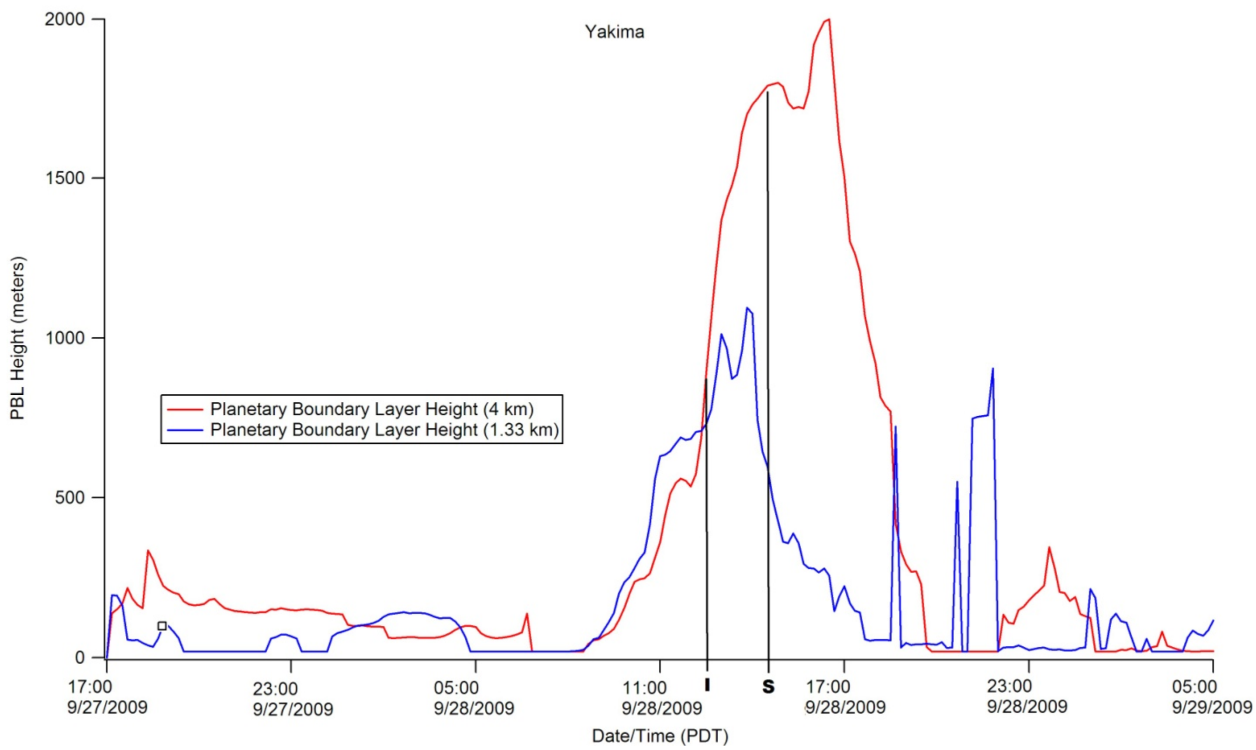

Figure 7

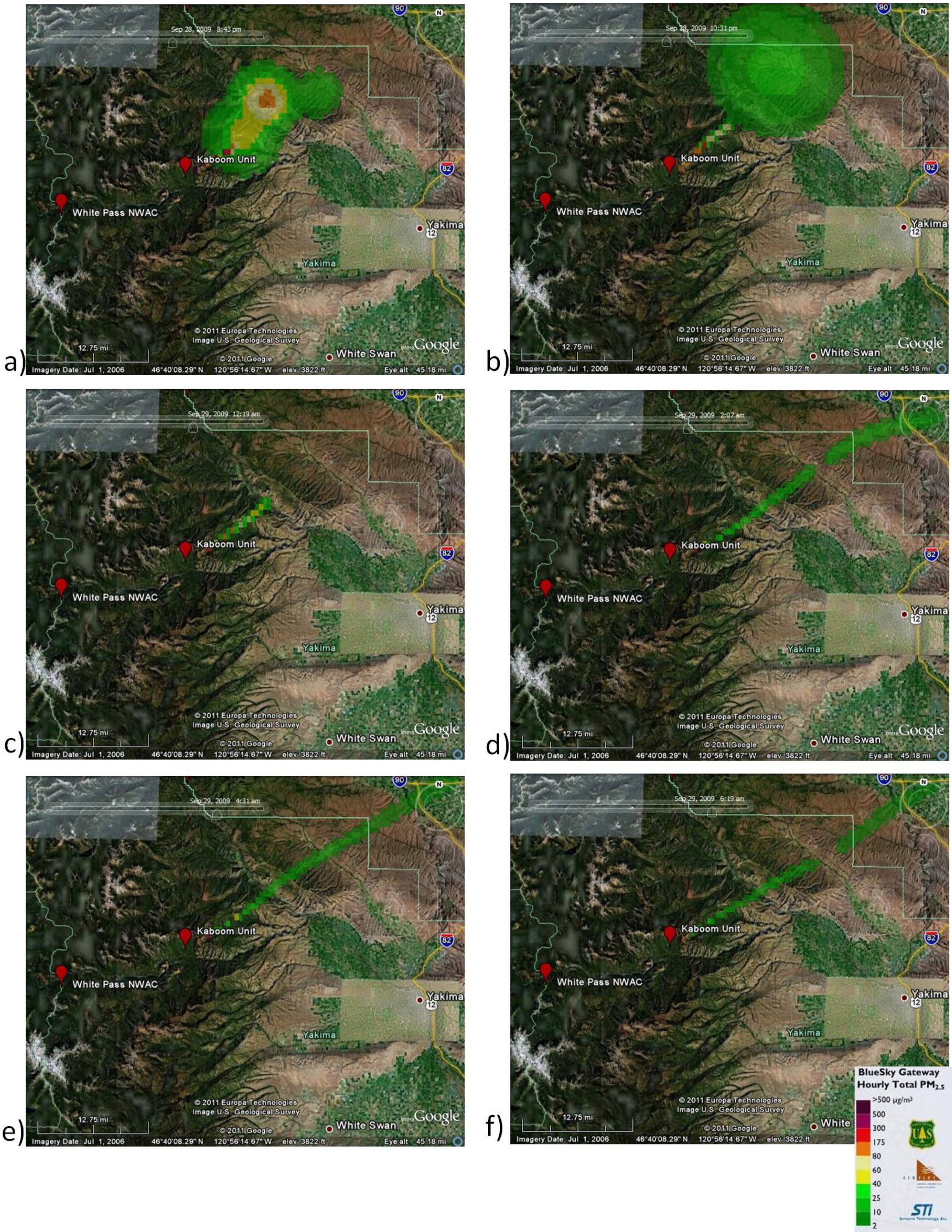
a)
Sep 28, 2009 8:43 pm
b)
Sep 28, 2009 10:31 pm
c)
Sep 29, 2009 12:19 am
d)
Sep 29, 2009 2:07 am
e)
Sep 29, 2009 4:31 am
f)
Sep 29, 2009 6:19 am
Kaboom Unit
White Pass NWAC
Yakima
White Swan
12.75 mi
© 2011 Europa Technologies
Image U.S. Geological Survey
© 2011 Google
Imagery Date: Jul 1, 2006
46°40'08.29" N 120°56'14.67" W elev. 3822 ft
Eye alt 45.18 mi
BlueSky Gateway
Hourly Total PM2.5
>500 µg/m³
500
300
175
80
60
40
25
10
2

Figure 8

285
East
Wenatchee
Wenatchee
WASHINGTON
903
970
Kittitas
County
Ellensburg
Yakima
Yakima County
82
97
Klickitat County
Goldendale

Figure 9a

East
Wenatchee
Wenatchee
285
WASHINGTON
903
970
Kittitas
County
Ellensburg
Yakima
Yakima County
82
97
Klickitat County
Goldendale

Figure 9b

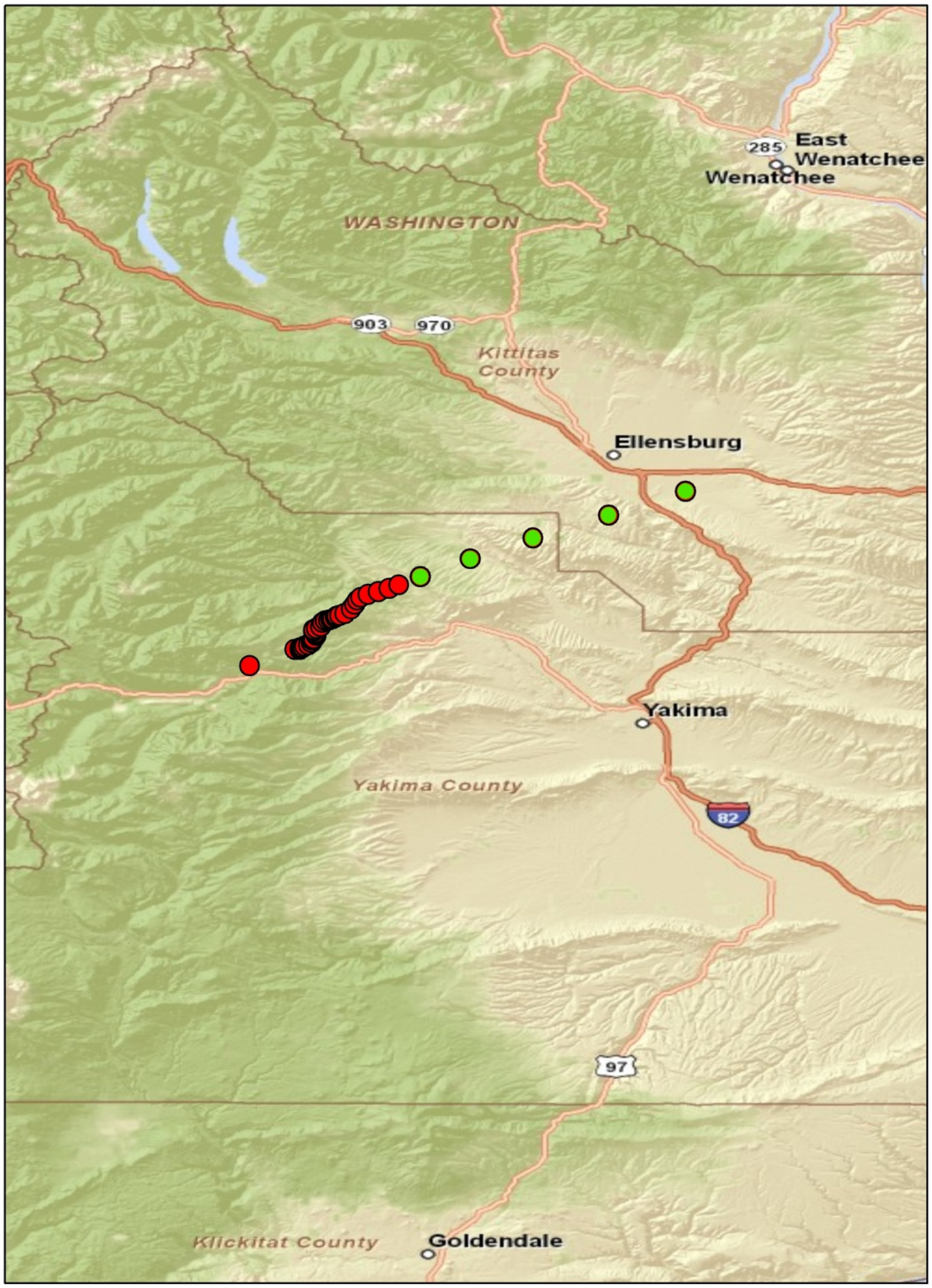
285
East
Wenatchee
Wenatchee
WASHINGTON
903
970
Kittitas
County
Ellensburg
Yakima
Yakima County
82
97
Klickitat County
Goldendale

Figure 9c.