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Summary and analysis of approaches linking visual range, PM_{2.5} concentrations, and air quality health impact indices for wildfires

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Several U.S. state and tribal agencies and other countries have implemented a methodology developed in the arid intermountain western U.S. where short-term (1- to 3-hr) particulate matter (PM) with aerodynamic diameters less than 2.5 μm (PM_{2.5}) concentrations are estimated from an observed visual range (VR) measurement. This PM_{2.5} concentration estimate is then linked to a public health warning scale to inform the public about potential health impacts from smoke from wildfire. This methodology is often used where monitoring data do not exist (such as many rural areas). This work summarizes the various approaches, highlights the potential for wildfire smoke impact messaging conflicts at state and international borders, and highlights the need to define consistent short-term health impact category breakpoint categories. Is air quality "unhealthy" when 1- to 3-hr PM_{2.5} is $\geq 139 \mu\text{g}/\text{m}^3$ as specified in the Wildfire Smoke, A Guide for Public Health Officials? Or is air quality unhealthy when 1- to 3-hr PM_{2.5} is $\geq 88.6 \mu\text{g}/\text{m}^3$ as specified in the Montana categorizations? This work then examines the relationship between visual range and PM_{2.5} concentrations using data from the Interagency Monitoring of PROtected Visual Environments (IMPROVE) program and the IMPROVE extinction coefficient (β_{ext}) equation to simulate an atmosphere dominated by smoke for sites in the arid intermountain western U.S. and great plains. This was accomplished by rearranging the β_{ext} equation to solve for organic mass as a function of VR. The results show that PM_{2.5} and VR are related by $\text{PM}_{2.5} = 622 * \text{VR}^{-0.98}$ with a correlation of 0.99 and that at low VR values (<10 km) a small change in VR results in a large change in PM_{2.5} concentrations. The results also show that relative humidity and the presence of hygroscopic pollutants from sources other than fire can change the VR/PM_{2.5} relationships, especially at PM_{2.5} concentrations less than approximately 90 $\mu\text{g}/\text{m}^3$.

Implications: This work illustrates the limitations of current approaches linking VR, PM_{2.5} concentrations, and air quality health impact indices. It is the first published summary of known VR/PM_{2.5}/health impact approaches nationally and internationally and the first application of the IMPROVE data and extinction coefficient equation to investigate these approaches scientifically for smoke-filled atmospheres. These VR/PM_{2.5}/health impact indices are used to estimate PM_{2.5} concentrations when monitoring data are not available in order to inform the public during periods of wildfire smoke impacts. This work also offers discussion points to inform future work.

Short-Term Exposure Categorizations

Smoke from wildfires can impact air quality locally and on regional scales, causing concerns for public health. Several U.S. state and tribal agencies and other countries have implemented a methodology developed in the arid intermountain western U.S. where short-term (1- to 3-hr) particulate matter (PM) with aerodynamic diameters less than 2.5 μm (PM_{2.5}) concentrations are estimated from an observed visual range (VR) measurement. This PM_{2.5} concentration estimate is then linked to a public health warning scale to inform the public about potential health impacts from smoke from wildfire. This methodology is often used where monitoring data do not exist (such as many rural areas).

The linkage between VR and short term (1- to 3-hr) PM_{2.5} concentrations in smoky conditions was originally created from an empirical study performed in Helena, Montana, in the summer of 2000. Then, based on expert local knowledge, a table was created linking VR, 1-hr PM_{2.5}, and a health effect category drawn from the U.S. Environmental Protection Agency's (EPA) air quality index (AQI). The Montana study correlated airport Automated Surface Observing System VR measurements with PM measurements made with a tapered element oscillating microbalance during a period when the Helena, Montana, airport was heavily impacted by smoke from wildfires. Data were taken every 5 min and resulted in a correlation where $\text{VR} \times \text{PM} = 450$ and VR is in units of miles. Expert knowledge was then applied to establish various short-term health impact breakpoints of

PM_{2.5} concentrations (“unhealthy” etc.). These breakpoints were color-coded by AQI levels and AQI terminology was used, but the breakpoints do not correspond with the AQI. Note that the AQI levels for PM are established by the EPA and are based on 24-hr PM_{2.5} concentrations. Helena, Montana, is a city located in a rural wide mountain valley where relative humidity (RH) is typically low and background air pollution is also typically low, especially in the summertime when this analysis was conducted. This leads to two important caveats about the application of this study:

- (1) It should only be applied if RH < 65%.
- (2) It should only be applied when the majority of air pollution is from wildfire smoke.

Because a VR can be estimated by the human eye, this VR and PM_{2.5} relationship was useful for situations where monitoring data measuring PM_{2.5} concentrations did not exist (such as many rural areas) and there was a need to inform the public about potential health consequences from regional-scale smoke episodes.

In 2001 (with updates in 2008 and 2013), the EPA, California Department of Public Health, California Office of Environmental Health Hazard Assessment, California Air Resources Board, and Missoula County Health Department authored the *Wildfire Smoke, A Guide for Public Health Officials* (Lipsett et al., 2008). The *Wildfire Smoke Guide* is used nationally and internationally by public health officials to inform the public when wildfire smoke impacts occur. Within the *Wildfire Smoke Guide* is a table linking 1-, 8-, and 24-hr PM_{2.5} concentrations with VRs and health impact categories (see Figure 1). The visibility column in Figure 1 only corresponds to the 1- to 3-hr PM_{2.5} concentrations. This table is a variation on the Montana table where additional expert logic was used to set the PM_{2.5} breakpoint levels for the health impact categories.

Other state and tribal agencies have since adopted either the Montana table or the *Wildfire Smoke Guide* table or created a variation of their own. Figure 2 summarizes many of the U.S. state and tribal agencies using a VR, PM_{2.5}, and health index relationship including Fairbanks, Alaska; California; Colorado; Idaho; Montana; the Navajo Nation, New Mexico; and Oregon. Also included in Figure 2 is the Canadian Air Quality Health Index (AQHI) and the Canadian province of Manitoba. The Canadian AQHI is a

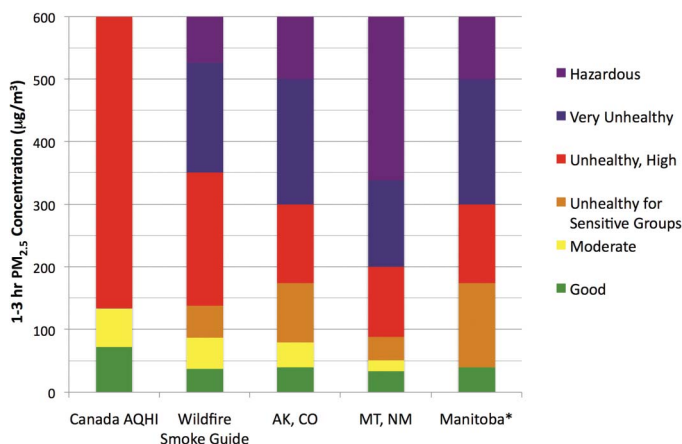


Figure 2. Summary of several of the U.S. state and tribal agencies and countries applying a relationship between 1- and 3-hr PM_{2.5} concentrations and human health impact categories. The Canadian AQHI includes 3-hr average PM_{2.5}, ozone, and NO₂; however, for this figure, the ozone and NO₂ concentrations are set to zero. The “Wildfire Smoke Guide” is the *Wildfire Smoke, A Guide for Public Health Officials* (Lipsett et al., 2008) publication and it is used by California, Idaho, Oregon, and the Navajo Nation. *Manitoba is using the same scale as Fairbanks, Alaska, and Colorado with the exception that the “Moderate” and “Unhealthy for Sensitive Groups” categories are combined into a single category, which for purposes of this figure has been color-coded to the “Unhealthy for Sensitive Groups” category color.

multipollutant index combining PM_{2.5}, ozone, and nitrogen dioxide (NO₂); however, in Figure 2 the values for ozone and NO₂ are not included. Table 1 summarizes the publicly available agency websites and references used in Figure 2. Note, neither Table 1 nor Figure 2 is designed to give an exhaustive listing of VR/PM_{2.5}/health index relationships, and other states/tribes/agencies may use other approaches. Many of these VR, PM_{2.5} concentration, and air quality category tables use different health impact category breakpoints. For example, Montana gives air quality an unhealthy rating if short-term PM_{2.5} exposure is at a concentration greater than 88.6 µg/m³, whereas the *Wildfire Smoke, A Guide for Public Health Officials* (used by neighboring Idaho) gives air quality an unhealthy rating if short-term PM_{2.5} exposure is greater than 139 µg/m³. Thus, there is the potential for different health impact messages to be told to the public for wildfire smoke crossing state lines.

Air Quality Index Category	PM _{2.5} or PM ₁₀ Levels (µg/m ³ , 1- to 3-hr avg.)	PM _{2.5} or PM ₁₀ Levels (µg/m ³ , 8-hr avg.)	PM _{2.5} or PM ₁₀ Levels (µg/m ³ , 24-hr avg.)	Visibility - Arid Conditions (miles)
Good	0 – 38	0 – 22	0 – 12	> 11
Moderate	39 – 88	23 – 50	12.1 – 35.4	6 – 10
Sensitive Groups	89 – 138	51 – 79	35.5 – 55.4	3 – 5
Unhealthy	139 – 351	80 – 200	55.5 – 150.4	1.5 – 2.75
Very Unhealthy	352 – 526	201 – 300	150.5 – 250.4	1 – 1.25
Hazardous	≥ 526	> 300	> 250.5 – 500	≤ 1

Figure 1. The *Wildfire Smoke, A Guide for Public Health Officials* (Lipsett et al., 2008) linkage of air quality index categories with 1-, 8-, and 24-hr PM_{2.5} concentrations and visibility for arid conditions.

Table 1. Table of U.S. state and tribal agencies and Canadian agencies using a short-term health impact categorization

State, tribe, country	Website/reference
<i>Wildfire Smoke, A Guide for Public Health Officials</i>	Lipsett et al. (2008)
Canada Air Quality Health Index	Steib et al. (2008)
Alaska	Fairbanks, Alaska (2013)
California	Lipsett et al. (2008)
Colorado	State of Colorado (2013)
Idaho	State of Idaho (2013), Lipsett et al. (2008)
Montana	State of Montana (2013)
New Mexico	State of New Mexico (2013)
Navajo Nation	Navajo Nation (2013), Lipsett et al. (2008)
Manitoba, Canada	State of Oregon (2013), Lipsett et al. (2008)

Notes: The first column lists the agency and the second column lists the reference where the categorizations can be found. The short-term (1- to 3-hr) PM_{2.5} categories are summarized in Figure 2.

The EPA (2007) acknowledges that there is a need for a public advisory system based on short-term (e.g., 1- to 3-hr) exposures to PM_{2.5} concentrations during events such as wildfires but that there is not enough information on which to base a national standard. Canada, meanwhile, has also been trying to address short-term exposures and has used epidemiological data to develop a multipollutant Air Quality Health Index (Stieb et al., 2008) that is based on 3-hr average concentrations of PM_{2.5}, ozone, and NO₂. The Canadian AQHI is an example of an index that addresses the potentially compounding impacts of multiple pollutants.

This paper further investigates the relationship between VR and PM_{2.5} concentrations using data and equations from the Interagency Monitoring of PROtected Visual Environments (IMPROVE) program. The analysis includes how the VR/PM_{2.5} relationship may change with increased organic mass in the atmosphere, which can occur in large wildfire smoke impact situations. The analysis also includes how the presence of other pollutants and higher RH conditions can also influence the VR/PM_{2.5} relationship.

IMPROVE Data Analysis

A PM_{2.5} concentration can “look” very different in the atmosphere (and thus translate to a variety of VR estimates) depending on the physical and chemical characteristics of the particles, atmospheric conditions, and the relationship of the human eye with sun angle and reflectance off of objects. For example, Figures 3a and 3b show Great Smoky Mountains National Park when the PM_{2.5} concentration is 21 µg/m³, with (a) RH = 30% and (b) RH = 90%. With an RH of 30%, the VR was 47 km, whereas at an RH of 90% the VR was 19 km. Figure 3 was generated by the WinHaze program (Molenar, n.d.) using 20% worst-day data from the IMPROVE project. Ammonium sulfate concentrations comprise approximately two thirds of the total PM_{2.5} concentrations. Ammonium sulfate is highly hygroscopic; thus, at a higher humidity (such as 70%) it will absorb water, causing



Figure 3. Great Smoky Mountains National Park when PM_{2.5} concentrations are 21 µg/m³ for (a) RH = 30% and (b) RH = 90%. Visual range is 47 km in (a) and 19 km in (b). Figures and calculations provided by the WinHaze program (Molenar, n.d.).

the aerosol particle to grow and change its light scattering properties, creating a hazier view.

The second version of the IMPROVE extinction coefficient (β_{ext}) equation (Pitchford et al., 2007; eq 1) and the equation relating β_{ext} and VR (eq 2) developed by Koschmieder (1924) were applied to investigate the relationship between VR and PM_{2.5} concentration.

$$\begin{aligned} \beta_{\text{ext}} = & 2.2 \times \text{fs}(\text{RH}) \times [\text{Small Sulfate}] + 4.8 \times \text{fl}(\text{RH}) \\ & \times [\text{Large Sulfate}] + 2.4 \times \text{fs}(\text{RH}) \times [\text{Small Nitrate}] + 5.1 \\ & \times \text{fl}(\text{RH}) \times [\text{Large Nitrate}] + 2.8 \times [\text{Small Organic Mass}] \\ & + 6.1 \times [\text{Large Organic Mass}] + 10 \times [\text{Elemental Carbon}] \\ & + 1 \times [\text{Fine Soil}] + 1.7 \times \text{fss}(\text{RH}) \times [\text{Sea Salt}] + 0.6 \\ & \times [\text{Coarse Mass}] + \text{Rayleigh Scattering (Site Specific)} \\ & + 0.33 \times [\text{NO}_2(\text{ppb})], \end{aligned} \quad (1)$$

where fs(RH), fl(RH), and fss(RH) are water growth function values for small (fs), large (fl), and sea salt (fss) parameters, respectively, from Pitchford et al. (2007).

$$\beta_{\text{ext}} = K/\text{VR}, \quad (2)$$

where K = the Koschmieder coefficient, 3.9.

Equations 1 and 2 were set equal to each other and then rearranged to solve for organic mass as a function of VR (eq 3). Thus, as VR decreases, organic mass increases. This was done because organic mass is one of the primary aerosols emitted from fires (followed by elemental carbon) and in this way the VR/PM_{2.5} relationship could be investigated mathematically for a smoky atmosphere. The organic mass components of the equation were further split out to have an organic mass from background/anthropogenic concentrations and organic mass from fire. Though the relationship between VR, β_{ext} , and PM_{2.5} concentrations has long been known and is well studied, this rearrangement of the equations to specifically mathematically simulate a smoky atmosphere is unique and useful to investigate given the various health impact indexes linking VR and PM_{2.5} that are used to inform the public during regional smoke-filled wildfire episodes.

$$\begin{aligned} & 2.8 \times [\text{Small Organic Mass, fire}] + 6.1 \\ & \times [\text{Large Organic Mass, fire}] = K/\text{VR} - 2.2 \\ & \times \text{fs}(\text{RH}) \times [\text{Small Sulfate}] - 4.8 \times \text{fl}(\text{RH}) \\ & \times [\text{Large Sulfate}] - 2.4 \times \text{fs}(\text{RH}) \times [\text{Small Nitrate}] \\ & - 5.1 \times \text{fl}(\text{RH}) \times [\text{Large Nitrate}] - 2.8 \\ & \times [\text{Small Organic Mass, background}] \\ & - 6.1 \times [\text{Large Organic Mass, background}] - 10 \\ & \times [\text{Elemental Carbon}] - 1 \times [\text{Fine Soil}] \end{aligned}$$

$$\begin{aligned} & -1.7 \times \text{fss}(\text{RH}) \times [\text{Sea Salt}] - 0.6 \times [\text{Coarse Mass}] \\ & - \text{Rayleigh Scattering (Site Specific)} \\ & - 0.33 \times [\text{NO}_2(\text{ppb})] \end{aligned} \quad (3)$$

The IMPROVE β_{ext} algorithm used here and as described in Pitchford et al. (2007) accounts for the increase in light scattering efficiencies with concentration in the atmosphere for the various PM components. The “large” mode terms represent aged and/or cloud processed particles, whereas the “small” mode terms represent freshly formed particles. The fraction of the fine particle component (sulfate, nitrate, or organic mass) that is in the large mode is estimated by dividing the total concentration of the component by 20 $\mu\text{g}/\text{m}^3$. If the total concentration of a component exceeds 20 $\mu\text{g}/\text{m}^3$, then all of it is assumed to be in the large mode (Pitchford et al., 2007). The Koschmieder equation assumes that the sky brightness of the observer is similar to the sky brightness of the observed object, that there is a homogeneous distribution of pollutants, that the viewing distance is horizontal, that the Earth’s curvature can be ignored, that the viewing object is a black object, and that the threshold contrast is 0.02 (EPA, 1979). The threshold contrast of 0.02 indicates that a typical person can perceive a 2% change in visibility and the natural log of 0.02 is 3.9; the value of the Koschmieder coefficient used in this analysis (see EPA [1979, ch. 2] for further details). Once the organic mass from fire was solved for using eq 3, the total PM_{2.5} concentration was obtained by adding the sulfate, nitrate, organic mass, elemental carbon, and fine soil PM components together.

Calculations were made using eq 3 for IMPROVE sites in the intermountain west and northern Great Plains for months when wildland fire is most likely to occur. IMPROVE sites had been grouped by region in Hand et al. (2011) and monthly averages were calculated for each aerosol specie by region and month. Specifically, nine regions from Hand et al. (2011) were used: Northern Rockies, Hells Canyon, Northern Great Plains, Great Basin, Central Rockies, Colorado Plateau, Mogollon Plateau, Southern Arizona, and West Texas. IMPROVE monthly average values for each of the regions for 2005–2008 for ammonium sulfate, ammonium nitrate, organic mass, light-absorbing carbon, fine soil, sea salt, and coarse mass were applied from Hand et al. (2011). Rayleigh scattering was assumed to be 10/Mm, and NO₂ was neglected. Figure 4 shows how PM_{2.5} varies with VR for the IMPROVE sites in the nine regions. For VR values of 2, 5, 10, 20, and 50 km the rearranged β_{ext} equation (eq 3) was solved for each region and identified fire month. The black diamonds in Figure 4 are the median PM_{2.5} values calculated for each of the VR distances. A power law curve fit then yields the relationship shown in eq 4 with a regression correlation of 0.99.

$$\text{PM}_{2.5} = 622 * \text{VR}^{-0.98}. \quad (4)$$

Figure 4 and eq 4 illustrate the nonlinear relationship between VR and PM_{2.5} concentration. For VR = 1–10 km, on average a

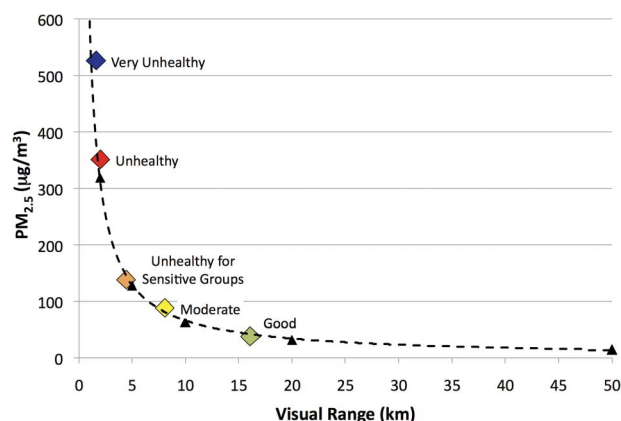


Figure 4. $PM_{2.5}$ as a function of VR for IMPROVE sites in the intermountain west and northern Great Plains for months when wildland fire is most likely to occur. IMPROVE sites had been grouped by region in Hand et al. (2011) and monthly average values for each of the regions for 2005–2008 for ammonium sulfate, ammonium nitrate, organic mass, light-absorbing carbon, fine soil, sea salt, and coarse mass were applied from Hand et al. (2011). For VR values of 2, 5, 10, 20, and 50 km the rearranged beta equation (eq 3) was solved for each region and identified fire month. The black diamonds are the median $PM_{2.5}$ values calculated for each of the VR distances. A power law curve fit yields the relationship $PM_{2.5} = 622 * VR^{-0.98}$ with a regression correlation of 0.99.

1-km change in VR results in a $62 \mu\text{g}/\text{m}^3$ change in $PM_{2.5}$ per kilometer. Then, for VR = 10–100 km, on average a 1-km change in VR results in a $1 \mu\text{g}/\text{m}^3$ change in $PM_{2.5}$ per kilometer. This illustrates how a small (e.g., 1 km) error in a VR estimate (such as what can happen with the human eye) can have a large impact on estimated $PM_{2.5}$ concentrations. Figure 4 also includes the VR/ $PM_{2.5}$ breakpoints from the *Wildfire Smoke, A Guide for Public Health Officials* (Figure 1) for the 1-hr $PM_{2.5}$ concentrations.

Further analysis using eq 3 was conducted for a humid environment that experiences greater background anthropogenic $PM_{2.5}$ concentrations than the arid intermountain western U.S. Shenandoah National Park, located in the Appalachian Mountains of Virginia, was utilized for this and 1988–1998 IMPROVE 20% worst days average background concentrations for ammonium sulfate ($14.21 \mu\text{g}/\text{m}^3$), ammonium nitrate ($0.45 \mu\text{g}/\text{m}^3$), background organic mass carbon ($4.17 \mu\text{g}/\text{m}^3$), light-absorbing carbon ($0.53 \mu\text{g}/\text{m}^3$), fine soil ($0.74 \mu\text{g}/\text{m}^3$), and coarse mass ($6.47 \mu\text{g}/\text{m}^3$) were applied (Molenaar, 2001). Rayleigh scattering was assumed to be 10/Mm, and sea salt and NO_2 were not accounted for. Figure 5 is a table of $PM_{2.5}$ concentrations and it illustrates how $PM_{2.5}$ concentrations can change as a function of RH and VR using eq 3. Color-coded cells contain $PM_{2.5}$ concentrations; the two left columns are VR in miles and kilometers, respectively, and RH is across the top of the table. $PM_{2.5}$ concentration cells are color-coded according to the *Wildfire Smoke, A Guide for Public Health Officials* health effect categories in Figure 1 and the 1-hr $PM_{2.5}$ breakpoints.

Figure 5 shows how the relationship between VR and $PM_{2.5}$ is most sensitive to RH in the lower ranges of $PM_{2.5}$ values (and longer/higher VR values). For example, at 30% RH, air quality is “good” (e.g., green) when the VR is 12 miles or greater, but at 90% RH, air quality is good when the VR is 7 miles or greater. Good air quality, as listed in the *Wildfire Smoke, A Guide for Public Health Officials*, is when 1- to 3-hr $PM_{2.5}$ concentration is between 0 and $38 \mu\text{g}/\text{m}^3$. In the “moderate” air quality categorization, the influence of RH becomes less pronounced, where air quality is moderate at 30% RH when the VR is 5–11 miles, but at 90% RH, air quality is moderate when the VR is 4–6 miles. Moderate air quality, as listed in the *Wildfire Smoke, A Guide for Public Health Officials*, is when 1- to 3-hr $PM_{2.5}$ concentration is

VR (miles)	VR (km)	RH 10%	RH 20%	RH 30%	RH 40%	RH 50%	RH 60%	RH 70%	RH 80%	RH 90%	RH 95%
19	30.6										
18	29.0										
17	27.4										
16	25.8										
15	24.2										
14	22.6										
13	21.0										
12	19.4										
11	17.7										
10	16.1										
9	14.5										
8	12.9										
7	11.3										
6	9.7										
5.50	8.9										
5.00	8.1										
4.50	7.3										
4.00	6.5										
3.50	5.6										
3.00	4.8										
2.50	4.0										
2.00	3.2										
1.50	2.4										
1.00	1.6										
0.75	1.2										
0.50	0.8										
0.25	0.4										

Figure 5. Calculated $PM_{2.5}$ concentrations for Shenandoah National Park as a function of VR and RH based on rearranging the second form of the IMPROVE extinction coefficient equation to solve for organic mass as a function of VR. As VR is decreased, organic mass will increase, simulating a smoke-filled atmosphere. IMPROVE 20% worst-day base data for ammonium sulfate, ammonium nitrate, light-absorbing carbon, fine soil, and coarse mass were included. Color-coding is according to the 1-hr $PM_{2.5}$ breakpoints from the *Wildfire Smoke, A Guide for Public Health Officials* (Lipsett et al., 2008; see Figure 1).

between 39 and 88 $\mu\text{g}/\text{m}^3$. At the higher impact categories (e.g., unhealthy, etc.), the difference in VR between RH = 30% and RH = 90% is half a mile or less, and below 2.5 miles VR, the categorizations are not greatly influenced by RH. This is because the organic mass is dominating the atmospheric aerosol loading and $\text{PM}_{2.5}$ concentration becomes independent of RH. Potential organic aerosol hygroscopicity was not addressed in this work.

Discussion

Several U.S. state and tribal agencies and other countries have implemented a methodology developed in the arid intermountain western U.S. where short-term (1- to 3-hr) $\text{PM}_{2.5}$ concentrations are estimated from an observed VR measurement. This $\text{PM}_{2.5}$ concentration estimate is then linked to a public health warning scale to inform the public about potential health impacts from smoke from wildfire. Figure 2 summarizes many of these approaches. This methodology is used in situations where monitoring data measuring $\text{PM}_{2.5}$ concentrations do not exist (such as many rural areas) and there is a need to inform the public about potential health consequences from regional-scale smoke episodes. This section discusses issues highlighted by the analysis in the previous two sections.

Consequence of a human-sighted visual range

The human eye operates much like a camera, detecting differences in brightness; thus, the geometry between an observer and the sun and the angle with which the sun illuminates a vista play a role in how a vista is perceived (Malm, 1999). Malm (1999) also discussed how sun angle can play a role, where with a higher sun angle there is less scattering of light and therefore a greater perceived scenic distance for the same particulate matter concentrations in the atmosphere. The *Wildfire Smoke, A Guide for Public Health Officials* includes instructions about how to estimate a VR with the human eye; however, the method cannot adjust for atmospheric conditions such as RH.

A human-sighted VR is an instantaneous value, which is then extrapolated to a time-averaged $\text{PM}_{2.5}$ concentration. The inherent assumption is that the conditions/concentrations “seen” at the moment are constant for the next 1–3 hr. Schichtel and Husar (1999) found that human-sighted VR did not correlate well with $\text{PM}_{2.5}$ concentrations. They analyzed data for the eastern U.S. for the time period 1948–1992 from stations operated by the National Weather Service, Navy, Air Force, and Federal Aviation Administration. Finally, this work shows that at the lower VR values (1–10 km) a small (1 km) error in a VR estimate can result in a large error in $\text{PM}_{2.5}$ concentration estimation (from 10 to over 100 $\mu\text{g}/\text{m}^3$). There is concern that a human-sighted VR can contain greater uncertainty than the $\text{PM}_{2.5}$ ranges in Figure 2, especially at the higher health impact levels.

Multiple approaches currently in use

Figure 1 and Table 1 summarize many of the approaches used to inform the public about potential short-term health impacts from wildfire smoke. Many of these approaches change when crossing state lines. For example, Montana gives air quality an unhealthy rating if short-term $\text{PM}_{2.5}$ exposure is at a

concentration greater than 88.6 $\mu\text{g}/\text{m}^3$, whereas the *Wildfire Smoke, A Guide for Public Health Officials* (used by neighboring Idaho) gives air quality an unhealthy rating if short-term $\text{PM}_{2.5}$ exposure is greater than 139 $\mu\text{g}/\text{m}^3$. If you have a wildfire at the Idaho/Montana border, what do you tell the public? Does the public in Idaho get a different message than the public in Montana? And which health category breakpoint is “correct”?

Need for a short-term health impact index

There is a need for a science-based short-term (1- to 3-hr) health impact index public advisory system, something the U.S. EPA recognizes (EPA, 2007). Canada also recognized a similar need and through a multistakeholder process developed an index for acute exposures in order to inform the public (Stieb et al., 2008). The Canadian AQHI is a multipollutant (O_3 , NO_2 , and $\text{PM}_{2.5}$) short-term (3-hr) exposure metric derived from urban-based epidemiological data.

$\text{PM}_{2.5}$ is the pollutant most commonly associated with wildfire smoke, and the current U.S. national ambient air quality standard for $\text{PM}_{2.5}$ is a 24-hr average of 35 $\mu\text{g}/\text{m}^3$ and an annual average of 12 $\mu\text{g}/\text{m}^3$. The U.S. AQI system is based on the 24-hr $\text{PM}_{2.5}$ value, and the various approaches to a 1- to 3-hr health index public advisory systems draw upon AQI terminology but should not be confused with being AQI values. With wildland fire there is also the potential for multipollutant impacts due to the mixing of the smoke plume with surrounding regional pollution and due to emissions from the fire itself, which can contain NO_2 , volatile organic compounds, carbon monoxide, and other trace gas species. Throughout this discussion the assumption has been made that it is biomass only that is burning; however, in cases where structures are burning (such as in the wildland urban interface), the chemical composition of the fire emissions can be very different, further complicating a potential index and the messaging that should go to the public.

Influence of relative humidity and other pollutant sources on the VR/ $\text{PM}_{2.5}$ relationship

Finally, though there is a need for consistency across state lines, there is also a need to recognize that different regional atmospheric conditions (such as RH) can influence the VR/ $\text{PM}_{2.5}$ relationship. The analysis described in this paper using Shenandoah National Park highlights how RH can play a large role in the $\text{PM}_{2.5}$ /VR relationship, especially when other hygroscopic pollutants are present. This influence of RH and other pollutant sources is most evident at the good and moderate short-term $\text{PM}_{2.5}$ categories as defined by the *Wildfire Smoke, A Guide for Public Health Officials* (e.g., when 1- to 3-hr $\text{PM}_{2.5}$ concentration is less than 88 $\mu\text{g}/\text{m}^3$). Once VR drops below approximately 2.5 miles, the influence of RH and other pollutant sources becomes negligible because the atmospheric aerosol loading is dominated by organic mass.

Summary and Recommendations

This work summarizes the VR, short-term (1- to 3-hr) $\text{PM}_{2.5}$ concentrations and health impact categorizations used by many U.S. state and tribal agencies as well as Canada to inform the

public during regional-scale wildfire smoke impacts. In addition, it examines the relationship between VR and $PM_{2.5}$ concentrations when regional-scale wildfire smoke impacts occur, using the IMPROVE data and β ext equation, and provides a discussion of concerns.

The summarization of the U.S. state and tribal agency and Canadian $PM_{2.5}$ /VR/health impact categorizations shows how many different approaches exist and highlights the potential for wildfire smoke impact messaging confusion at state and international borders. It also highlights the need to know what the short-term health impact category breakpoints should be set at.

The application of the IMPROVE data and β ext equation to simulate a smoky atmosphere is unique and was accomplished by rearranging the IMPROVE β ext equation (eq 1) and the Koschmieder VR/ β ext relationship (eq 2) to solve for organic mass as a function of VR (eq 3). Thus, as VR decreases, organic mass increases, mathematically simulating a smoke-filled atmosphere. Calculations were made using eq 3 for IMPROVE sites in the intermountain west and northern Great Plains for months when wildland fire is most likely to occur. IMPROVE monthly average values for each of the regions for 2005–2008 for ammonium sulfate, ammonium nitrate, organic mass, light-absorbing carbon, fine soil, sea salt, and coarse mass were applied from Hand et al. (2011). Analysis yielded a VR/ $PM_{2.5}$ relationship of $PM_{2.5} = 622 * VR^{-0.98}$ with a correlation of 0.99. These results also illustrate how at low VR values (<10 km) a small change in VR results in a large change in $PM_{2.5}$ concentration.

Finally, there is a need for a short-term health impact categorization system applicable outside the U.S. arid intermountain west. This was investigated for Shenandoah National Park, an environment more humid than the arid intermountain west and an area impacted by other hygroscopic pollutant sources. The results show that the relationship between VR and $PM_{2.5}$ is most sensitive to RH in the lower ranges of $PM_{2.5}$ values (and longer/higher VR values). For example, at 30% RH, air quality was good when the VR was 12 miles or greater, but at 90% RH, air quality was good when the VR was 7 miles or greater. Good air quality, as listed in the *Wildfire Smoke, A Guide for Public Health Officials*, is when 1- to 3-hr $PM_{2.5}$ concentrations are between 0 and $38 \mu\text{g}/\text{m}^3$. Below 2.5 miles VR, the air quality categorizations are not greatly influenced by RH because the organic mass is dominating the atmospheric aerosol loading and, using the methods in this analysis, $PM_{2.5}$ concentration becomes independent of RH.

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References

- Canada, 2013. <http://www.gov.mb.ca/health/publichealth/wildlandfiresmokeexposure.pdf> (accessed June 14, 2013).
- Fairbanks, Alaska, 2013. <http://co.fairbanks.ak.us/AirQuality/Docs/ParticulateLevels.pdf> (accessed June 14, 2013).
- Hand, J.L., S.A. Copeland, D.E. Day, A.M. Dillner, H. Indresand, W.C. Malm, C. E. McDade, C.T. Moore, B.A. Schichtel, and J.G. Watson. Spatial and Seasonal Patterns and Temporal Variability of Haze and Its Constituents in the United States: Report V [Online], 2011. <http://vista.cira.colostate.edu/improve/Publications/Reports/2011/2011.htm> (accessed April 7, 2013).
- Interagency Monitoring of PROtected Visual Environments. WinHaze [Online]. http://vista.cira.colostate.edu/improve/tools/win_haze.htm (accessed April 7, 2013).
- Koschmeider, H. 1924. Theories der Horizontalen Sichtweite. *Beitr. Phys. Frei. Atmos.* 12:33–53.
- Lipsett, M., B. Materna, S.L. Stone, S. Theriault, R. Blaisdell, J. Cook, J. Waldman, L. Wohl-Sanchez, L. Kent, P. Jenkins, D. Westerdahl, T. Phillips, L. Smith, J. Behrman, S. DuTeaux, R. Lam, D. Gold, B. Nakamura, A. Smith, and M. Brauer. *Wildfire Smoke, A Guide for Public Health Officials* [Online], 2008. http://oehha.ca.gov/air/risk_assess/wildfirev8.pdf (accessed April 7, 2013).
- Malm, W.C. Introduction to Visibility. Cooperative Institute for Research in the Atmosphere (CIIRA) NPS Visibility Program [Online], 1999. <http://www.epa.gov/visibility/pdfs/introvis.pdf> (accessed April 7, 2013).
- Molenar, J. WinHaze - A computer-imaging software program. Air Resources Specialists Inc. [Online], n.d. http://vista.cira.colostate.edu/improve/tools/win_haze.htm (accessed April 7, 2013).
- Navajo Nation, 2013. <http://www.navajonationepa.org/airq/wildfire11.html> (accessed June 14, 2013).
- Pitchford, M., W. Malm, B. Schichtel, N. Kumar, D. Lowenthal, and J. Hand. Revised Algorithm for Estimating Light Extinction from IMPROVE Particle Speciation Data. 2007. *Journal of the Air & Waste Management Association* 57: 1326–1336. doi:10.3155/1047-3289.57.11.1326
- Schichtel, B.A., and R.B. Husar. 1999. Evaluation of the Models-3C/MAQ System—Relationship between Airport Visibility and $PM_{2.5}$ Concentrations in the Eastern U.S., Grant No. 827981. Research Triangle Park, NC: U.S. Environmental Protection Agency.
- State of Colorado, 2013. <http://www.colorado.gov/airquality/wildfire.aspx> (accessed June 14, 2013).
- State of Idaho, 2013. <http://www.deq.idaho.gov/media/883596—visibility—guide.pdf> (accessed June 14, 2013).
- State of Montana, 2013. <http://www.deq.mt.gov/FireUpdates/BreakpointsRevised.mcp> (accessed June 14, 2013).
- State of New Mexico, 2013. <http://www.nmenv.state.nm.us/aqb/Wildfire—PM.html> (accessed June 14, 2013).
- State of Oregon, 2013. <http://www.deq.state.or.us/aq/aqi/docs/ForestFireCatBreak.pdf> (accessed June 14, 2013).
- Stieb, D.M., R.T. Burnett, M. Smith-Doiron, O. Brion, H.H. Shin, and V.A. Economou. New Multipollutant, No-Threshold Air Quality Health Index Based on Short-Term Associations Observed in Daily Time-Series Analyses 2008. *Journal of the Air & Waste Management Association* 58(3): 435–450. doi:10.3155/1047-3289.58.3.435
- U.S. Environmental Protection Agency. 1979. *Protecting Visibility: An EPA Report to Congress* Research Triangle Park, NC: U.S. Environmental Protection Agency Office of Air, Noise, and Radiation Office of Air Quality, Planning, and Standards.

U.S. Environmental Protection Agency. OAQPS Issue Paper for Discussion at National Air Quality Conference, February 2007 [Online], 2007. http://www.epa.gov/airnow/aqi_issue_paper_020707.pdf (accessed April 7, 2012).

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