# THE USE OF HUMAN OBSERVED VISUAL RANGE TO ESTIMATE AMBENT ATMOSPHERIC MASS CONCENTRATIONS


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The U.S. Environmental Protection Agency (EPA), California Department of Public Health, California Office of Environmental Health Hazard Assessment, California Air Resources Board, and Missoula County Health Department co-authored a document titled Wildfire Smoke, A Guide for Public Health Officials (http://www.ehib.org/papers/wildfire_smoke_july_2008.pdf)

# The Air Quality Index

**The AQI tells the public how clean or polluted the air is using standard descriptors (Good, Moderate, Unhealthy for Sensitive Groups, Unhealthy, Very unhealthy, and Hazardous).** This index converts sometimes difficult-to-interpret particulate mass per volume (µg/$m^3$) numbers to an AQI category and number more easily understood by the public.  An AQI value of 100 corresponds to the level of the National Ambient Air Quality Standard for a given pollutant.

$$PM=CNST/V_r$$

| Air Quality Index Category | PM2.5 or PM10 Levels (µg/m3, 1-3hr avg) | PM2.5 or PM10 Levels (µg/m3, 8hr avg) | PM2.5 or PM10 Levels (µg/m3, 24hr 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 | <1 |

# FROM THE QUIDANCE DOCUMENT

Many communities do not have access to continuous PM monitoring, and therefore need other ways to estimate particle levels. This is true even in areas which do have continuous monitors, **because smoke concentrations can vary widely within a couple miles and can change rapidly**. **Visibility can sometimes serve as a good surrogate**. In addition, a visibility index gives the public a quick way to assess smoke levels for themselves.

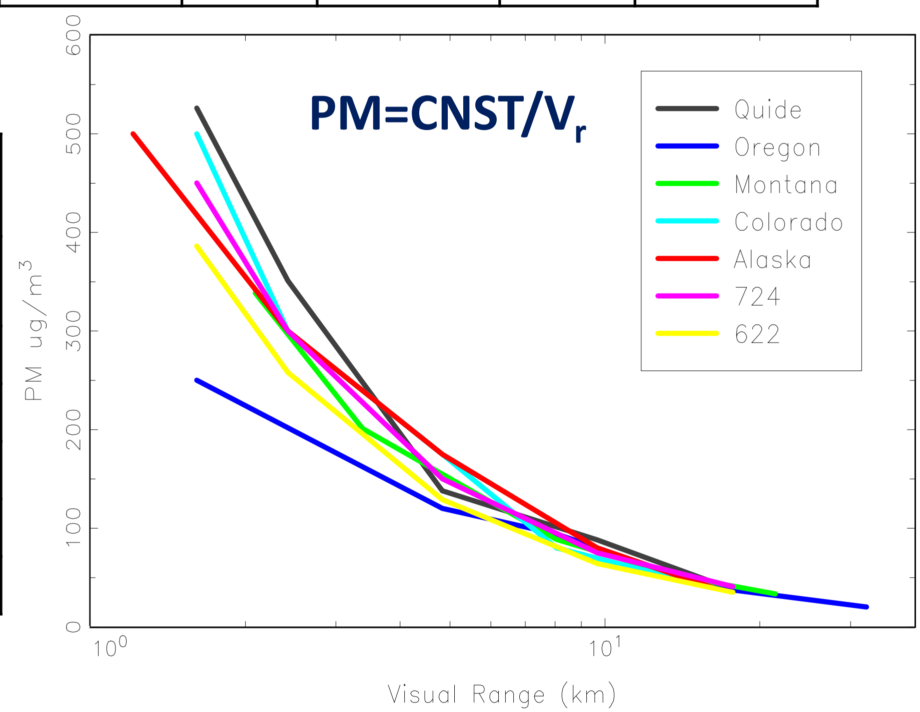
When using the visibility index to determine smoke concentrations, it is important to:

- **Face away from the sun**.
- Determine the limit of your visibility range by looking for targets at known distances (miles). **The visible range is the point at which even high-contrast objects (e.g., a dark forested mountain viewed against the sky at noon) totally disappear.**
- After determining visibility in miles, use Tables 2 and 3 to identify potential health effects and appropriate cautionary statements.

# Other PM, Mass, and $V_r$ Relationships Currently in Use

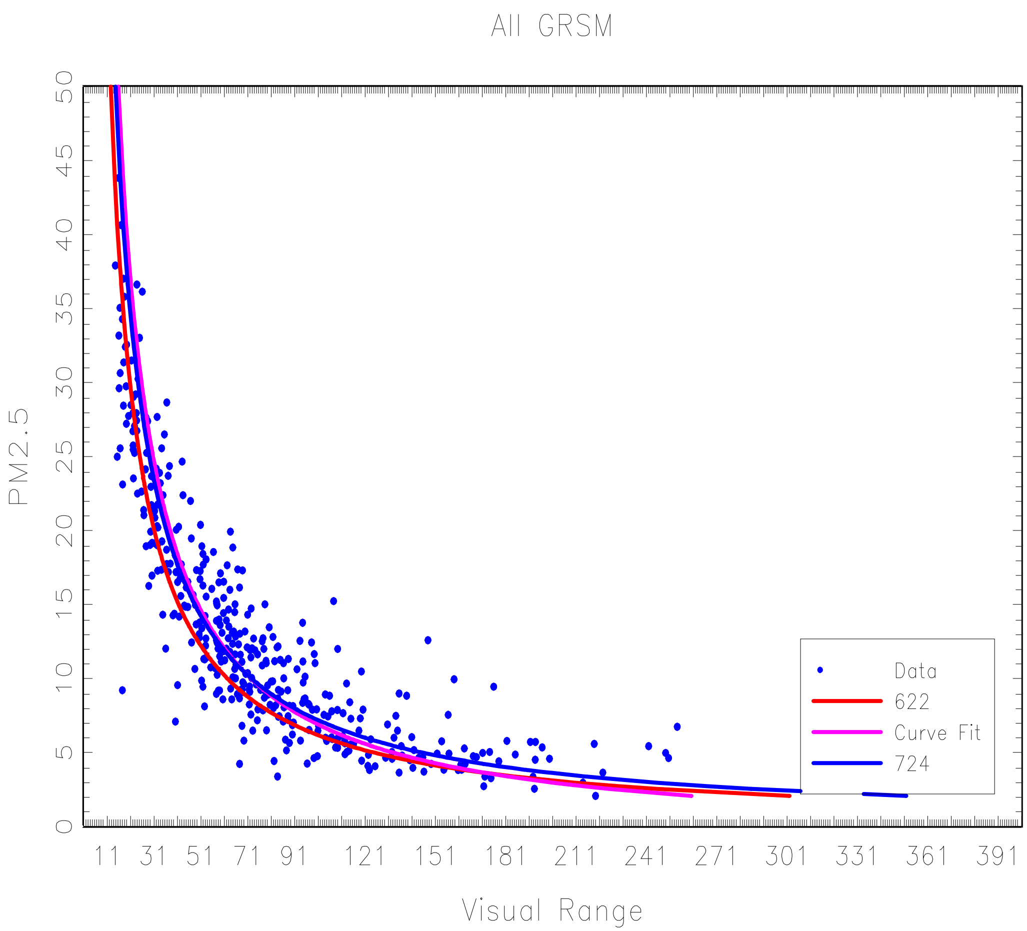
| | Smoke guide (2008) | | Montana (2013) | | Colorado (2013) | | Alaska (2013) | |
|---|---|---|---|---|---|---|---|---|
| Air Quality Index Category | $V_r$ (km) | Mass (µg/m³) | $V_r$ (km) | Mass (µg/m³) | $V_r$ (km) | Mass (µg/m³) | $V_r$ (km) | Mass (µg/m³) |
| Good | 17.71 | 38 | 21.41 | 33.6 | 16.1 | 40 | 16.1 | 40 |
| Moderate | 9.66 | 88 | 14.01 | 51.1 | 8.05 | 80 | 9.66 | 80 |
| Sensitive Groups | 4.83 | 138 | 8.05 | 88.6 | 4.83 | 175 | 4.83 | 175 |
| Unhealthy | 2.42 | 351 | 3.38 | 201 | 2.42 | 300 | 2.42 | 300 |
| Very Unhealthy | 1.61 | 526 | 2.09 | 338.5 | 1.61 | 500 | 1.21 | 500 |
| Hazardous | <1.61 | >526 | <2.09 | >338.5 | <1.61 | >500 | <1.21 | >500 |

| | Montana equation | | O'Neill et al. equation | |
|---|---|---|---|---|
| Air Quality Index Category | $V_r$ (km) | Mass (µg/m³) | $V_r$ (km) | Mass (µg/m³) |
| Good | 17.71 | 40.88 | 17.71 | 35 |
| Moderate | 9.66 | 74.95 | 9.66 | 64 |
| Sensitive Groups | 4.83 | 149.90 | 4.83 | 129 |
| Unhealthy | 2.42 | 299.17 | 2.42 | 258 |
| Very Unhealthy | 1.61 | 449.69 | 1.61 | 386 |



# PM vs Visual Range Relationships

## $V_r PM = CNST$ or $\underline{PM = CNST/V_r}$




**Montana (TEOM vs ASOS):**
**CNST=724**

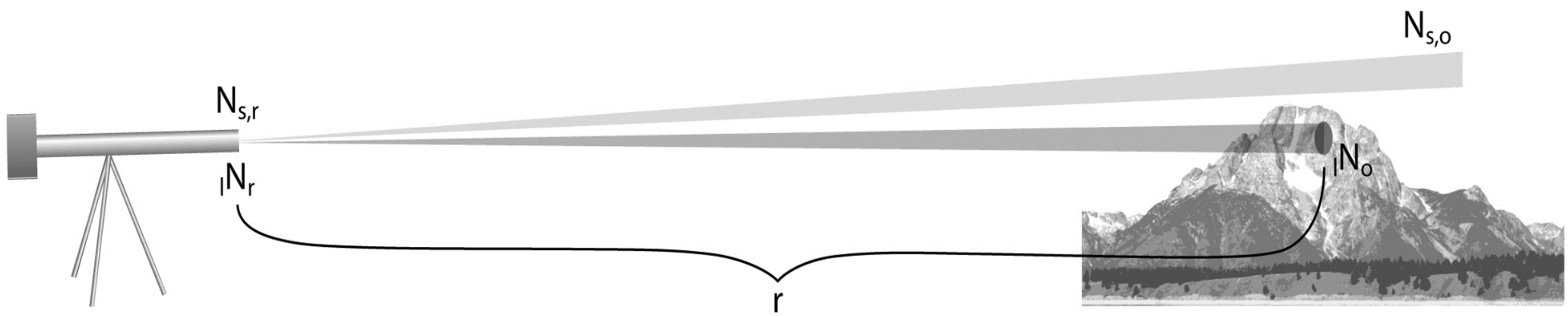
**O'Neill et al (IMPROVE):**
**CNST≈622**

**Curve fit:**
**CNST=787 (GRSM)**
**CNST=1300 (Grand Canyon)**

# OBJECTIVES

- **Examine the validity of a PM = CNST/$V_r$ relationship,**
- **Assess the uncertainty in the CNST value, based on known physical and optical characteristics of an aerosol,**
- **Assess the effects of uncertainties in estimating VR,**
- **Examine how this relationship may change as a function of national annual average background conditions and as a function of season and location within the continental United States,**
- **Make recommendations for using this equation under varied background and location differences.**

# THE CONTRAST EQUATION




$$C_r = \frac{{}_I N_r - N_{s,r}}{N_{s,r}} \qquad C_o = \frac{{}_I N_o - N_{s,o}}{N_{s,o}}$$

$$C_r = C_o \frac{{}_s N_o}{{}_s N_r} e^{-\bar{b}_{ext} r} = C_o \gamma \, e^{-\bar{b}_{ext} r}$$

If $\gamma = \frac{{}_s N_o}{{}_s N_r} = 1$, *$C_o$=-1, and $C_r$=-0.02*
then

$$\boldsymbol{r} = V_r = 3.912 / b_{ext}$$

**Now**

$$b_{ext} = \alpha m + \ b_{sg}$$

**Where m is the atmospheric mass concentration, α is the mass extinction efficiency and $b_{sg}$ is blue sky scattering.**

$$V_r = \frac{3.912}{\alpha m \ + b_{sg}}$$

$$m = \frac{3.912}{\alpha V_r} - \frac{b_{sg}}{\alpha} = \frac{3.912/\alpha}{V_r} - \frac{b_{sg}}{\alpha}$$

$$TM = \frac{3.912/\alpha_w}{V_r} - \frac{b_{sg}}{\alpha_w} \approx \frac{3.912/\alpha_w}{V_r} = \frac{CNST}{V_r}$$

For low $V_r$ the term $\frac{3.912/\alpha}{V_r}$ is much greater than $\frac{b_{sg}}{\alpha}$

Then ***m=CNST/$V_r$*** where *CNST=3.912/α* . This is the form of the visual range mass concentration relationship which forms the basis of the AQI visual range relationship.

The uncertainty in estimating TM is directly related to our knowledge of and the variability in the mass extinction coefficient, $\alpha_w$, and our ability to judge visual range, $V_r$.

$$TM \approx \frac{3.912/\alpha_w}{V_r} = \frac{CNST}{V_r}$$

## Uncertainties in Estimating Mass Extinction Efficiency

$$\frac{dTM}{TM} = -\frac{d\propto_w}{\propto_w}$$

$$\alpha_{mix,w} = \frac{1}{TM_d}(\propto_{s,w} TM_s + \propto_{bg,w} TM_{bg})$$

$$\alpha_{i,w} = \alpha_{i,dry} f(RH)$$

# Therefore :

$$\frac{d\alpha_w}{\alpha_w} = \frac{TM_s\left(d\overset{(1.0)}{\alpha_{s,d}}f_s(RH) + \alpha_{s,d}\overbrace{df_s(RH)}^{(0.32)}\right)}{TM_d\alpha_w} + \frac{TM_{bg}\left(d\underset{(1.36)}{\alpha_{bg,d}}f_{bg}(RH) + \alpha_{bg,d}\overbrace{df_{bg}(RH)}^{(2.67)}\right)}{TM_d\alpha_w}$$

**Variability in total wet mass extinction efficiency, $\alpha_w$, as a function of variability of background and smoke f(RH) and dry mass extinction efficiencies, $\alpha_s$ and $\alpha_{bg}$.**

*One standard deviation is used represent incremental uncertainty.

Average and one standard deviation of mass scattering efficiencies. “Fine”, “Coarse”, and “Total” correspond to the size range of the aerosol. “Mixed” refers to a mixed-composition aerosol. Sulfate efficiencies correspond to dry ammonium sulfate, nitrate entries correspond to dry ammonium nitrate, POM efficiencies have been normalized to an $R_{oc}$ value of 1.8, and sea salt efficiencies have been adjusted to a dry state. The final column gives the overall average for all methods for the mixed-composition aerosols, and the average of three methods (theoretical, MLR, and partial) for the remaining species. The number of observations is given in parentheses. Estimates are for visible wavelengths (near 550 nm).

| SPECIES/ MODE | THEORETICAL ($M^2$ $G^{-1}$) | MEASUREMENT ($M^2$ $G^{-1}$) | MLR ($M^2$ $G^{-1}$) | PARTIAL ($M^2$ $G^{-1}$) | ALL METHODS ($M^2$ $G^{-1}$) |
|---|---|---|---|---|---|
| Fine mixed | 4.3±0.7 (*26*) | 3.4±1.2 (54) | 3.1±1.4 (*16*) | 3.4±1.6 (2) | 3.6±1.2 (*98*) |
| Coarse mixed | 1.6±1.0 (*21*) | 0.40±0.15 (4) | 0.7 ± 0.4 (*26*) | | 1.0±0.9 (*51*) |
| Total mixed | 2.2±1.0 (*9*) | 1.7±1.1 (11) | | | 1.9±1.1 (*20*) |
| Fine Sulfate | 2.1±0.7 (*34*) | | 2.8±0.5 (*53*) | 2.2±0.7 (*6*) | 2.5±0.6 (*93*) |
| Fine Nitrate | | | 2.8±0.5 (*42*) | 2.3±0.5 (*6*) | 2.7±0.5 (*48*) |
| Fine POM | 5.6±1.5 (*19*) | | 3.1±0.8 (*39*) | | 3.9±1.5 (*58*) |
| Coarse POM | 2.6±1.1 (19) | | | | 2.6±1.1 (*19*) |
| Total POM | 3.8±0.5 (7) | | 1.4 (1) | | 3.5±1.0 (*8*) |
| Fine Dust | 3.4±0.5 (*19*) | | 2.6±0.4 (*4*) | | 3.3±0.6 (*23*) |
| Coarse Dust | 0.7±0.2 (*20*) | | 0.40±0.08 (*2*) | | 0.7±0.2 (*22*) |
| Total Dust | 1.2±0.3 (*9*) | 0.9±0.8 (5) | 0.7±0.2 (*3*) | | 1.1±0.4 (*12*) |
| Fine Sea Salt | 4.5±0.7 (*22*) | | 3.7±1.7 (*3*) | | 4.5±0.9 (*25*) |
| Coarse Sea Salt | 1.0±0.2 (*19*) | | 0.72±0.02 (*2*) | | 1.0±0.2 (*21*) |
| Total Sea Salt | 2.2±0.5 (*8*) | | 1.8±0.3 (*2*) | | 2.1±0.5 (*10*) |

# Likely optical properties for dry biomass-burning smoke at 550 nm

| Parameter | IPCC Fresh | IPCC Aged | Temperate /Boreal Forest Fresh | Temperate/ Boreal Forest Aged | Grass/ Savanna Fresh | Grass/ Savanna Aged | Tropical Forest Fresh | Tropical Forest Aged |
|---|---|---|---|---|---|---|---|---|
| Mass Extinction Efficiency ($m^2/g$) | 4.1±1.0 | 4.0±1.1 | 4.3±0.5 | 4.7±0.5 | 4.4±0.5 | 4.6±0.5 | 4.2±0.5 | 4.7±0.4 |
| Mass Scattering Efficiency ($m^2/g$) | 3.6±1.0 | 3.6±1.1 | 3.8±0.4 | 4.3±0.4 | 3.6±0.4 | 4.0±0.4 | 3.6±0.4 | 4.2±0.4 |
| Mass Absorbing Efficiency ($m^2/g$) | 0.54±0.2 | 0.45±0.2 | 0.5±0.3 | 0.4±0.3 | 0.80±0.3 | 0.65±0.3 | 0.6±0.3 | 0.50+0.2 |
| Single Scattering Albedo | 0.87±0.06 | 0.89±0.06 | 0.88±0.05 | 0.92±0.05 | 0.82±0.05 | 0.86+0.05 | 0.85±0.05 | 0.89±0.05 |
| Hygroscopic Growth, f (80%RH) | 1.1±0.1 | 1.2±0.2 | 1.35±0.2 | 1.35±0.2 | 1.35±0.2 | 1.35±0.2 | 1.35±0.2 | 1.35±0.2 |

**Value and one standard deviation of f(RH) and mass extinction efficiencies used to estimate total uncertainty or variability of mass extinction efficiency of background plus smoke aerosol mix.**

| | West | CNST (West) | East | CNST (East) |
|---|---|---|---|---|
| f(RH) Background | 2.67±2.67 | | 4.64±4.0 | |
| f(RH) Smoke | 1.2±0.32 | | 1.44±0.48 | |
| α Background,dry | 2.1±1.36 ($m^2/g$) | 1863 | 2.59±1.20 ($m^2/g$) | 1510 |
| α Background,wet | 3.0±1.45 ($m^2/g$) | 1304 | 5.29±1.32 ($m^2/g$) | 740 |
| α Smoke,dry | 4.5±1.0 ($m^2/g$) | 869 | 4.5±1.0 ($m^2/g$) | 869 |
| α Smoke,wet | 5.3±1.2 ($m^2/g$) | 738 | 6.3±1.39 ($m^2/g$) | 621 |

## Summary of the uncertainties in mass extinction efficiencies of smoke and background and smoke plus background for the western and eastern United States.

| | Individual Uncertainty (West) | Combined Uncertainty (West) | Individual Uncertainty (East) | Combined Uncertainty (East) |
|---|---|---|---|---|
| $\frac{(d\alpha_{bg,d} f_{bg}(RH))}{\alpha_w}$ | 0.48 | | 0.25 | |
| $\frac{(\alpha_{bg,d} df_{bg}(RH))}{\alpha_w}$ | 1.87 | 2.35 | 1.96 | 2.21 |
| $\frac{(d\alpha_{s,d} f_s(RH))}{\alpha_w}$ | 0.23 | | 0.23 | |
| $\frac{(\alpha_{s,d} df_s(RH))}{\alpha_w}$ | 0.27 | 0.50 | 0.34 | 0.57 |
| **Uncertainty of α (smoke plus background PM)** | | | | |
| **38 (μg/m$^3$)** | | 0.71 | | 1.08 |
| **88(μg/m$^3$)** | | 0.59 | | 0.79 |
| **138(μg/m$^3$)** | | 0.56 | | 0.71 |
| **351(μg/m$^3$)** | | 0.52 | | 0.63 |
| **526(μg/m$^3$)** | | 0.52 | | 0.61 |

# Uncertainties in Estimating Visual Range

**There are three uncertainties that come into play when trying to estimate a visual range:**

1. **Judging when a target or landscape feature has reached the contrast that defines the visual range.**
2. **Variability in inherent contrast of any given target.**
3. **Influence of nonuniform distribution of aerosol mass and nonuniform lighting conditions resulting in violation of the Koschmieder assumptions, i.e., the sky radiance at the target and observer are equal.**

Perhaps even a greater uncertainty in a $V_r$ estimate than the three issues listed above is that there will rarely be a target or landscape feature exactly at the VR. Therefore estimating $V_r$ from targets that are at a contrast greater than the threshold or have disappeared introduces a $V_r$ estimate that would have an uncertainty far greater than those associated with the three issues discussed above.

# Uncertainties in Estimating Visual Range

**1. Perceptual Uncertainty**

$$\frac{dm}{m} = -\frac{k}{3.912 - V_r b_{sg}}$$

**(25%)**

**2. Inherent Contrast Uncertainty**

$$\frac{dm}{m} = \frac{\frac{dC_o}{C_o}}{3.912 - V_r b_{sg}}$$

**(15%)**

**3. Radiance Uncertainty**

$$\frac{dm}{m} = \frac{\frac{d\gamma}{\gamma}}{3.912 + \ln(\gamma)}$$

**(50%)**

# ESTIMATED UNCERTAINTY IN AMBIENT MASS DETERMINATION AS DETERMINED FROM A VISUAL RANGE OBSERVATION

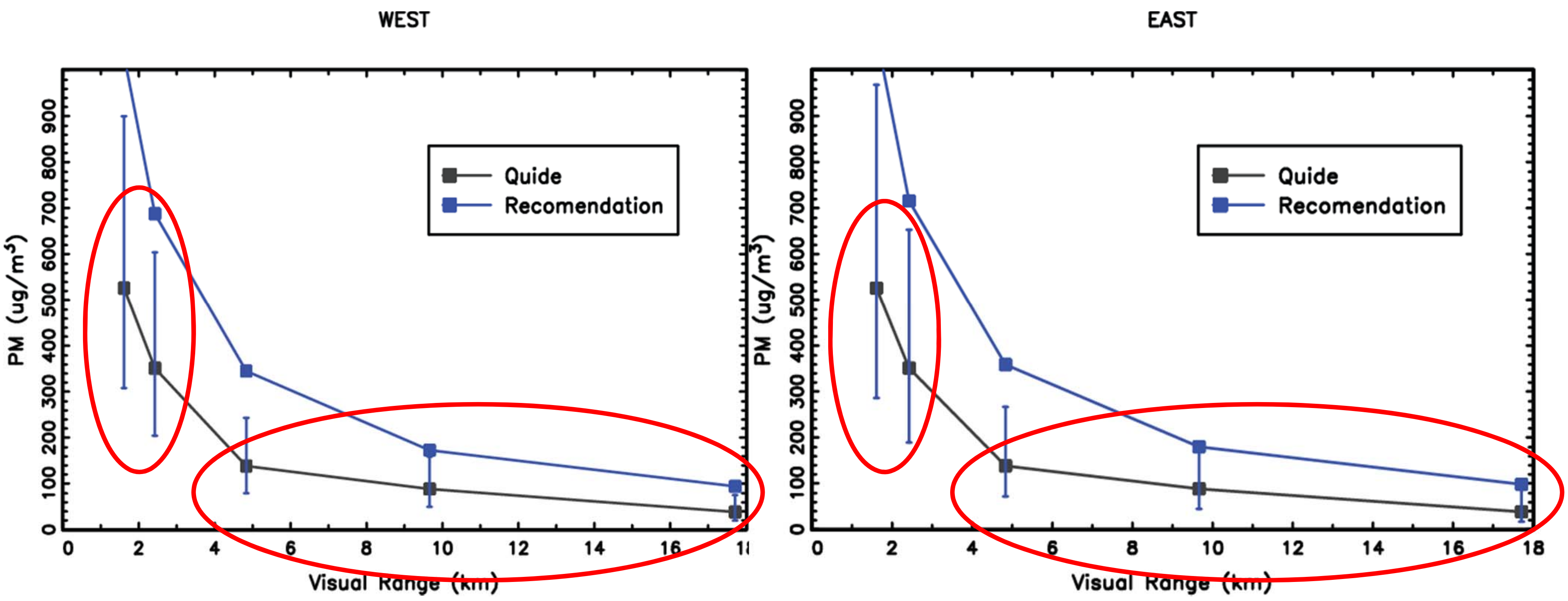
| Total Uncertainty (mass extinction efficiency plus visual range uncertainty) | (West) | (East) |
|---|---|---|
| 38 ($\mu g/m^3$) | 1.12 | 1.28 |
| 88($\mu g/m^3$) | 0.99 | 1.00 |
| 138($\mu g/m^3$) | 0.96 | 0.93 |
| 351($\mu g/m^3$) | 0.92 | 0.86 |
| 526($\mu g/m^3$) | 0.91 | 0.84 |

# A RECOMMENDATION FOR CNST

The uncertainty in making a visual range observation plus the uncertainty and variability in extinction to mass ratios results in an uncertainty in mass estimation of more than a factor of two. That is, any mass determination may be at least a factor of two high or a factor of two low. An issuance of an AQI warning should reflect the possibility that the mass determination may in reality be a factor of two higher than estimated .

| | Average Dry | Average Wet |
|---|---|---|
| Montana | 724 | |
| O'Neill | 622 | |
| Best Estimate(East) | 870 (4.5 $m^2/g$) | 621 (6.3$m^2/g$) |
| Best Estimate(West) | 870 (4.5 $m^2/g$) | 738 (5.3$m^2/g$) |
| Recommendation (East) | | **1732** |
| Recommendation (West) | | **1664** |

# GRAPHS OF RECOMMENDATIONS

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# ADDITIONAL RECOMMENDATION

- **Minimally refine the estimate of CNST to reflect unique climatological regions of the United States.** The above recommendations are based on an in depth analysis of only two IMPROVE sites, Grand Canyon and Great Smoky national parks, and these results have been generalized to the Inter Mountain West and eastern United States. The Northwest, Southwest, Sierra Nevada , etc., warrant specific attention.
- **More appropriately, develop a CNST value for every part of the United States and for a temporal resolution of seasonal or monthly.** Assess this information through a smart phone or PC app that recognizes its location and presents the appropriate CNST value. The CNST value would be dependent on local aerosol background conditions, RH, and fuel types. If, as in the case of a prescribed fire, the fuel type could be used to determine a CNST value.

# RECOMMENDATIONS CONCERNING VISUAL RANGE ESTIMATION

- An actual visual range determination should not be attempted. Moreover, it is highly unlikely that a landscape feature can be found that is exactly at the visual range. More typically, the landscape feature will be at a distance that is greater or less than the visual range. A more defensible procedure would be to **identify landscape features that have not disappeared or can be seen or identified. Then it is possible to state that the mass concentration is some value (corresponding to the distance to the landscape feature) or less.**
- **A smart phone app be developed to directly measure landscape feature contrast that allows a visual range to be calculated and therefore allow for a more accurate assessment of mass concentration.**
- **A second method for estimating visual range would be to develop simple "contrast cards" that can be compared to landscape feature contrast that thus allow for a contrast estimation of that landscape feature and in turn a visual range estimation.**

# RECOMMENDATION CONCERNING AQI INDEX

Because the uncertainty in mass determination from a visual range estimation is at least a factor of two and could very well be closer to a factor of four it is recommended that

- **An AQI scale be developed that consists of no more than two levels of warning instead of the five now used.**