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# A decade of dust: Asian dust and springtime aerosol load in the U.S. Pacific Northwest

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[1] We integrate SeaWiFS aerosol optical thickness (AOT) over the Taklamakan and Gobi Deserts with U.S. aerosol observations to study surface aerosol variability in the Northwest U.S. in relation to Asian dust emissions. The results indicate that ~50% of the interannual variability in springtime average $PM_{2.5}$ and $PM_{10}$ can be explained by changes in Asian dust emissions. On a seasonal timescale, variations in dust emissions appear to be more important in determining the total material crossing the Pacific than the variations in meteorology represented by the PNA or the LRT3 indices. We are able to explain ~80% of the interannual variability using three variables: AOT, a transport index, and regional precipitation. This suggests that a strong source, favorable transport and sufficient residence time are needed for Asian dust to have a maximum seasonal impact in the Northwest. The results contextualize case studies and demonstrate the utility of the Deep Blue algorithm. **Citation:** Fischer, E. V., N. C. Hsu, D. A. Jaffe, M.-J. Jeong, and S. L. Gong (2009), A decade of dust: Asian dust and springtime aerosol load in the U.S. Pacific Northwest, *Geophys. Res. Lett.*, *36*, L03821, doi:10.1029/2008GL036467.

## 1. Introduction

[2] The deserts of western China and Mongolia are a large source of dust on a hemispheric scale, especially during spring when meteorological conditions are favorable for lofting and long range transport. The two major Asian sources of dust are the Gobi and the Taklamakan Deserts, thus most Asian dust storms originate within a zone spanning between 35–45°N and 80–110°E [*Sun et al.*, 2001]. Although Asian dust impacts the U.S. boundary layer throughout the year [*VanCuren and Cahill*, 2002], spring is the preferred season due to the intense frontal activity that causes dust mobilization into the mid-troposphere, and allows for significant outflow from East Asia. There is significant loss and dilution of the plumes as they cross the Pacific; approximately 3% of the dust aerosol is transported to North America [*Zhao et al.*, 2006]. Higher plume transport heights and a lower wet scavenging efficiency allow ~3 times more fine (<2.5 $\mu$m) dust aerosols to reach the U.S. than other types of aerosols [*Chin et al.*, 2007].

[3] Data from the U.S. IMPROVE (Interagency Monitoring of Protected Visual Environments) network has been used previously to identify trends in aerosol loading and regional patterns in aerosol composition [*Malm et al.*, 1994]. Annually averaged, crustal materials comprise up to 20% of fine aerosol mass and 30–90% of coarse mass at western IMPROVE sites [*Malm et al.*, 2007]. Fine dust concentrations in the North American boundary layer are between 0.2 and 1.5 $\mu g/m^3$ [*VanCuren and Cahill*, 2002; *Fairlie et al.*, 2007], and can exceed 5 $ug/m^3$ during events. It has been shown that Asian dust is the main component of dust at IMPROVE monitoring sites in the western U.S. during spring [*Wells et al.*, 2007], and springtime average $PM_{10}$ at these sites tracks the number of major Chinese dust storms [*Zhao et al.*, 2007; *Yang et al.*, 2008].

[4] Here we use observational data to determine the relationship between the intensity of the major dust storms in Asia and seasonally averaged $PM_{2.5}$ and $PM_{10}$ in western North America. The previous long-term observational estimate of *VanCuren and Cahill* [2002] was based on an analysis of elemental ratios of 6 elements common in dust. This type of analysis is subject to two assumptions: 1) other sources do not emit these elements in the same ratio, and 2) each plume is processed similarly. VanCuren and Cahill identify the monthly variability in the frequency of Asian dust at IMPROVE sites. We offer a different approach by integrating satellite measurements of aerosol optical thickness (AOT) over the Taklamakan and the Gobi Deserts, with IMPROVE surface aerosol observations from the western U.S. We use the Deep Blue algorithm, which is designed to retrieve aerosol properties over reflective surfaces, using data from SeaWiFS (Sea-viewing Wide Field-of-view Sensor) or MODIS (Moderate Resolution Imaging Spectroradiometer) sensors [*Hsu et al.*, 2004]. This paper demonstrates the power of the Deep Blue algorithm, and our approach provides a new framework to understand how these two metrics are related on an interannual timescale.

## 2. Methods

[5] IMPROVE monitoring sites are situated in National Parks and Class I Wilderness areas across the U.S. (http://vista.cira.colostate.edu/improve/). Speciated fine aerosol (<2.5 $\mu$m), $PM_{2.5}$ mass and $PM_{10}$ mass are measured at all IMPROVE sites. Samples are collected every three days [*Malm et al.*, 1994]. To be included in the present analysis, aerosol records from individual monitoring sites in the western U.S. must extend back to 1998 and have at least 5 samples each month for all spring months (MAM). Sites south of 40°N, where local sources can contribute up to 60%

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of the fine dust [*Fairlie et al.*, 2007], were also removed. The included sites span the western U.S. and are located at a range of elevations.

[6] The Deep Blue algorithm was designed to retrieve aerosol properties over reflective surfaces, including bright deserts, semiarid and urban areas [*Hsu et al.*, 2004]. Retrieving aerosol properties over bright surfaces is accomplished using the blue spectral region since the surface reflectance is much darker in this region compared to the red portion of the spectrum. The successful application of Deep Blue on radiance measurements taken from SeaWiFS and MODIS was demonstrated for East Asia during the ACE-Asia campaign [*Hsu et al.*, 2006].

[7] The SeaWiFS instrument, onboard the SeaStar spacecraft, was launched in August 1997. This dataset was recently reprocessed using the Deep Blue Algorithm for a geographic region covering East Asia and the Pacific (N. C. Hsu et al., manuscript in preparation, 2008). We used a subset of this data for the present analysis. Seasonal and area-averaged AOT values at 550 nm were calculated using data over the two main dust source regions. The area extends from 75°E to 115°E and from 35°N to 45°N, encompassing the Taklamakan and the Gobi Deserts, but not the industrial areas of Eastern China. Using the SeaWiFS and IMPROVE data sets, our analysis extends over a 10-year period from 1998 to 2007. We have also compared MODIS Aqua AOT at 550 nm derived from the Deep Blue algorithm, which is available from 2003 to 2007.

[8] In a second analysis, the SeaWiFS AOT (550 nm) data was segregated based on the Ångstöm exponent ($\alpha$) calculated from the 412–490 nm wavelength pair. The $\alpha$ is the exponent in the formula that describes the dependency of AOT on wavelength. Smaller values of $\alpha$ are associated with larger dust particles. To generate this time series, only pixels with $\alpha \leq 0.7$ were used to create the monthly area-averaged AOT, which corresponds to conditions characterized by approximately a 50/50 contribution of coarse and fine mode aerosols to the total observed AOT at 550 nm. AOT can be larger than AOT ($\alpha < 0.7$) because the segregation does not imply a higher aerosol load.

[9] Sorting by $\alpha \leq 0.7$ should identify pixels dominated by dust, and separate dust from smoke. Thus we hypothesize that this data set may be a better measure of dust present in the atmospheric column and have practical use. However we recognize that this segregation results in a smaller data set, and that it also subtly changes the nature of the data set. Different years may have different numbers of days and pixels that satisfy this criterion, which may impact the meaning of the seasonal averages. For this reason, we present all portions of our analysis using both the full and the $\alpha \leq 0.7$ AOT dataset.

[10] To add a precipitation component to the analysis, we used monthly average precipitation data available from the NOAA National Data Center (NNDC) for all the state climatic divisions surrounding the IMPROVE monitoring sites (http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp#). The monthly averages within a climatic division were calculated by NNDC by giving equal weight to stations reporting precipitation within a given division. We averaged the monthly values to create a seasonal springtime average.

[11] Sand dust storms (SDS) in China were pre-selected by the Chinese Meteorological Administration (CMA) in terms of visibility and wind speed. Large episodes are recorded when weather stations across northeast Asia observe dust storm conditions under the same synoptic regime. The classification is discussed by *Yang et al.* [2008].

[12] Mount Bachelor (MBO) (44.0°N, 121.7°W, 2763 m amsl) is a free tropospheric monitoring site in Oregon. The site has proven to be well positioned to observe both Asian air pollution and biomass burning plumes. Analysis of the first two years of data collected at MBO indicates that this site is impacted by free tropospheric air ~50% of the time and sees very little influence from North American industrial emissions [*Weiss-Penzias et al.*, 2006]. Mid-visible (530 nm) sub-$\mu$m aerosol scattering ($\sigma_s$) during spring months 2004–2007 was measured using a Radiance Research (M903) nephelometer. All reported values have been corrected to STP (273.15 K and 1 atm). A more detailed description of the scattering measurements is given by *Weiss-Penzias et al.* [2006].

## 3. Relationship Between Dust Emissions, $PM_{10}$ and $PM_{2.5}$ in the Western U.S.

[13] Figures 1a and 1b show the region used for the AOT analysis and the surface monitoring sites used to calculate average springtime aerosol mass in the western U.S. Figure 1c shows area-averaged SeaWiFS AOT and spring average IMRPOVE $PM_{10}$ and $PM_{2.5}$. Also shown in Figure 1c is a similar time series for average SeaWiFS AOT segregated by the $\alpha$ associated with each pixel. Figure 1c also includes the number of springtime major dust storms reported in China. The $\alpha$ segregated SeaWiFS AOT tracks this metric more closely than the all-inclusive SeaWiFS AOT (Table 1). MODIS and SeaWiFS AOT in this region are well correlated ($R^2$ = 0.95), so MODIS data is not shown.

[14] The IMPROVE parameters track the dust metrics closely. A relationship also exists between dust storms in Asia and seasonal sub-$\mu$m aerosol scattering measured at MBO. This is shown in Figure 1c using a 4-year record of average mid-visible sub-$\mu$m aerosol scattering. Obviously a longer time series would improve our confidence in this relationship. Plumes of Asian origin are routinely observed at MBO in spring, and the plumes contain varying amounts of Asian industrial pollution, biomass burning aerosols and dust [*Weiss-Penzias et al.*, 2006].

[15] A linear correlation (Table 1 and Figures 1d and 1e) between the area averaged AOT over the desert region and averaged aerosol parameters in the western U.S. indicates that a large fraction of the interannual variability in $PM_{2.5}$ and $PM_{10}$ concentrations at these sites can be explained by changes in the dust metric. The SeaWiFS AOT ($\alpha \leq 0.7$) is more strongly correlated with fine $Ca^{2+}$ and Fe (Table 1), lending confidence to our hypothesis that this may better represent dust storm intensity and its impact in the Pacific Northwest.

## 4. Relationship Between Dust Emissions and PM at Select IMPROVE Sites

[16] Based on the work of *VanCuren and Cahill* [2002], we expect the relative impact of Asian dust to increase with elevation, with a persistent effect at higher elevations in the Rocky Mountains. We did not observe this. Despite a

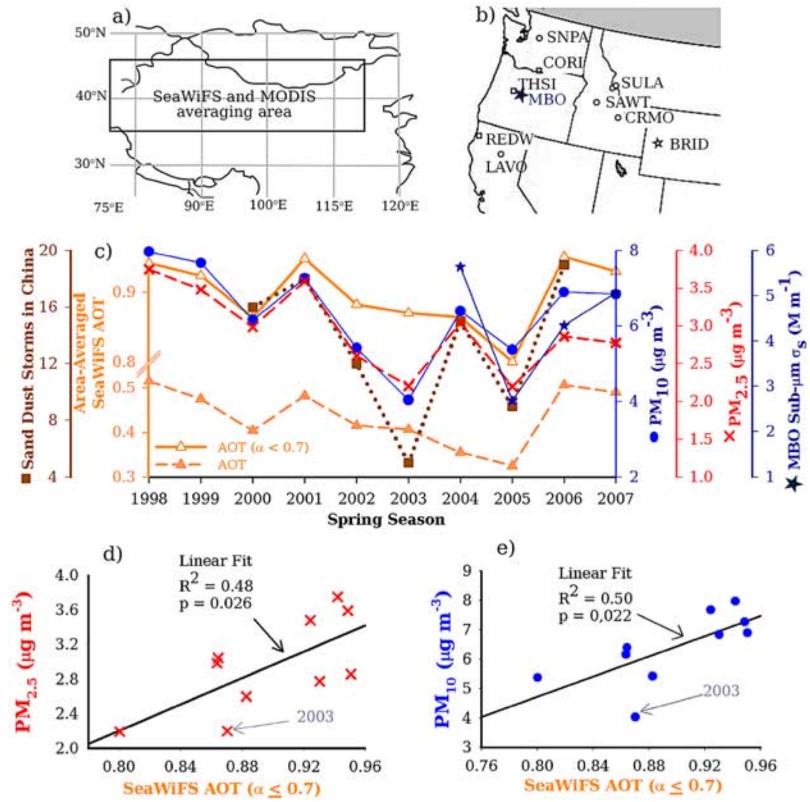


**Figure 1.** (a) Location of the SeaWiFS averaging area. (b) Map of the IMPROVE sites that met data availability criteria for $PM_{2.5}$ mass. The elevation of each site is noted as star (>2000 masl), dot (1000–2000 masl), or square (<1000 masl). CRMO, SAWT and SULA did not meet the availability criteria for $PM_{10}$. (c) Time series of spring area averaged SeaWiFS AOT, spring area averaged SeaWiFS AOT ($\alpha$ < 0.7), IMPROVE average $PM_{10}$ and $PM_{2.5}$ mass, Mount Bachelor sub-$\mu$m scattering ($\sigma_s$ MBO), and the number of dust storms reported in China. (d) Regression of IMPROVE $PM_{2.5}$ mass against SeaWiFS AOT ($\alpha$ < 0.7). (e) Regression of IMPROVE $PM_{10}$ mass against SeaWiFS AOT ($\alpha$ < 0.7). See Figure S1 for a time series of average fine Ca and Fe mass.[1]

relatively low elevation, the strongest relationship ($R^2$ = 0.62) between $PM_{2.5}$ and SeaWiFS AOT ($\alpha \leq 0.7$) was observed for Columbia River Gorge (CORI, 178 m). The strongest correlation with $PM_{10}$ ($R^2$ = 0.48) was observed at Three Sisters Wilderness (THIS, 885 m). However, the strongest correlation with $Ca^{2+}$ ($R^2$ = 0.69) was observed at Bridger Wilderness (BRID, 2626 m), the highest site used in our analysis. When only sites located north of 42°N were included in the regression, a stronger relationship was observed ($R^2$ = 0.54 and $R^2$ = 0.61 for $PM_{2.5}$ and $PM_{10}$ respectively).

[17] Average springtime $PM_{2.5}$ and $PM_{10}$ for the sites included in this study vary between 2.2 and 3.8 $\mu g/m^3$ and between 5.4 and 8.0 $\mu g/m^3$ respectively. Over the period 1998 to 2007 the average difference between the site with the highest and the site with the lowest seasonal average concentration was 2.2 $\mu g/m^3$ and 8.8 $\mu g/m^3$ for $PM_{2.5}$ and $PM_{10}$ respectively. The unexpectedly large difference in $PM_{10}$ was driven by high concentrations at the CORI site. Neglecting this site, the difference drops to 4.3 $\mu g/m^3$. Linear correlations between sites for seasonally averaged $PM_{10}$ over the study period indicated that although most sites were correlated, CORI did not have a significant relationship ($p < 0.05$) with any of the other sites. This was not the case for $PM_{2.5}$, where CORI was significantly correlated with CRMO, SNPA, SULA, and BRID and nearly significantly correlated with LAVO and SAWT. This may indicate that local sources make a dominant contribution to springtime coarse mode particulate matter at CORI, whereas regional to global sources make a significant contribution to $PM_{2.5}$.

## 5. Interannual Variability in Trans-Pacific Transport

[18] *Gong et al.* [2006] used a modeling approach to compare interannual variability of dust loading in North America with various climate indices, and a significant relationship with the Pacific North American teleconnection (PNA) pattern was identified [*Gong et al.*, 2006]. We used both the PNA, the prominent mode of low-frequency variability in the N. Hemisphere Pacific, and LRT3 (Long-Range Transport Index 3) [*Liang et al.*, 2005], an index based on monthly sea level pressure anomalies over the Pacific, to add a transport component to our analysis. Positive LRT3 values indicate strong Pacific High and Aleutian Low pressure systems. LRT3 is correlated with the PNA (R = 0.69).

[19] LRT3 and PNA alone are poor predictors of aerosol concentration (Table 2). However a multiple linear regression that includes the PNA index and area averaged SeaWiFS

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL036467.

**Table 1.** Correlation Matrix ($R^2$ values) for Average Spring Aerosol Parameters, Area Averaged SeaWiFS AOT Over the Region in Figure 1a, and the Number of Major Dust Storms Reported in China[a]

| | AOT | AOT ($\alpha \leq 0.7$) | Major Dust Storms in China | $PM_{10}$ | $PM_{2.5}$ | Ca |
|---|---|---|---|---|---|---|
| AOT ($\alpha \leq 0.7$) | 0.93* | | | | | |
| Major Dust Storms in China | 0.36 | 0.45*** | | | | |
| $PM_{10}$ | 0.47** | 0.50** | 0.93* | | | |
| $PM_{2.5}$ | 0.40*** | 0.48** | 0.72** | 0.81* | | |
| Ca | 0.59** | 0.73* | 0.71** | 0.57** | 0.61** | |
| Fe | 0.47** | 0.61** | 0.63** | 0.49** | 0.50** | 0.97* |

[a]Storm data from *Yang et al.* [2008]. The SDS parameter is available for 2000–2006. Ca and Fe are available for 1998–2006. Asterisks indicate p-value: single asterisk, value less than 0.01; double asterisk, value less than 0.05; and triple asterisk, value less than 0.10.

AOT ($\alpha \leq 0.7$) or SeaWiFS AOT has more explanatory power for $PM_{10}$ and $PM_{2.5}$. There is a slight increase for fine Ca and Fe when we include the PNA with the AOT parameter. A regression that includes LRT3 and SeaWiFS AOT ($\alpha \leq 0.7$) or SeaWiFS AOT also has more explanatory power for IMPROVE $PM_{2.5}$ and $PM_{10}$ but not for the other parameters. These results are presented in Table 2 and Table 3.

[20] It appears that to a modest degree meteorology does help to explain more of the variability in $PM_{10}$ and $PM_{2.5}$ mass (~60–70%), but it is disconcerting that there is not a parallel improvement for fine Ca or Fe. The relatively minor improvements in explanatory power indicate that on seasonal timescales variations in dust source strength are more important in determining the total flux of material crossing the Pacific than the variations in transport captured by the PNA and LRT3 parameters.

## 6. Impact of Regional Precipitation

[21] If 2003 is removed from the analysis in Figures 1d and 1e, the correlations improve, with $R^2 = 0.49$ and $R^2 = 0.65$ for $PM_{2.5}$ and $PM_{10}$ versus SeaWiFS AOT ($\alpha \leq 0.7$) respectively. Two factors made 2003 unusual: enhanced precipitation in the Pacific Northwest and record forest fire activity in Siberia. We argue that precipitation is the main factor distinguishing this year.

[22] Above normal precipitation was measured throughout the Pacific Northwest in March and April. The low average aerosol mass in spring 2003 is the result of low concentrations during these months (Figure S2). Elevated precipitation likely led to enhanced wet-deposition and a lower aerosol lifetime in this region. We found an expected inverse relationship between precipitation and PM using NNDC monthly average precipitation data for all the state climatic divisions surrounding the IMPROVE sites (Figure S3). A regression that included average precipitation for these regions and SeaWiFS AOT had more explanatory power for all the aerosol parameters, $R^2 = 0.58$ and $R^2 = 0.63$ for $PM_{2.5}$ and $PM_{10}$ respectively. When SeaWiFS AOT, LRT3, and regional precipitation were included in a regression, the predictive power for $PM_{2.5}$ and $PM_{10}$ increased further with $R^2 = 0.77$ and $R^2 = 0.88$ respectively. These results are presented in Tables 2 and 3.

[23] We recognize that the spatial variability of precipitation across the study area is enormous due to the range of topography, and there are valid arguments against comparing point aerosol measurements to regional precipitation. However, it is reasonable to assume that precipitation in regions surrounding and to the west of the IMPROVE sites impacted the aerosol concentrations. After comparing individual sites with corresponding regional climate zone precipitation averages, we noted that there is a relationship not only with the surrounding region, but often also with the precipitation recorded to the west of the sites.

[24] During May there was higher AOT over the northeastern portion of the averaging region due to smoke from Russian forest fires. During May 2003 northerly winds pushed a portion of this smoke plume southward [*Kwon et al.*, 2005]. The highest 2003 springtime monthly average AOT over the eastern Pacific was observed during May, consistent with the export of the fire smoke. The smoke did impact the Pacific Northwest in late May and early June [*Jaffe et al.*, 2004], and the impact is obvious in several IMPROVE samples. However, removing May 2003 did not bring the 2003 seasonal average AOT more in line with either the number of reported dust storms or the observed PM. Furthermore, segregating AOT by the $\alpha$ criterion should have removed most of the effects of smoke. For these reasons, we

**Table 2.** $R^2$ Values for Linear and Multiple Linear Regression(s) of Spring Aerosol Parameters Against a Variety of Predictors[a]

| | AOT ($\alpha \leq 0.7$)[b] | PNA[b] | LRT3[b] | Regional Precip[b] | PNA & AOT ($\alpha \leq 0.7$)[c] | LRT3 & AOT ($\alpha \leq 0.7$)[d] | Precip & AOT ($\alpha \leq 0.7$)[e] | Precip, LRT3, AOT ($\alpha < 0.7$)[f] |
|---|---|---|---|---|---|---|---|---|
| $PM_{10}$ | 0.50** | 0.069 | 0.17 | 0.40* | 0.70* | 0.65* | 0.58** | 0.88** |
| $PM_{2.5}$ | 0.48** | 0.001 | 0.16 | 0.35*** | 0.53** | 0.62* | 0.63** | 0.80** |
| Ca | 0.73* | 0.014 | 0.00 | 0.31*** | 0.76* | 0.73* | 0.79* | 0.79** |
| Fe | 0.61** | 0.002 | 0.00 | 0.18 | 0.65* | 0.61** | 0.62** | 0.62* |

[a]Asterisks indicate p-value: single asterisk, value less than 0.01; double asterisk, value less than 0.05; and triple asterisk, value less than 0.10.
[b]$R^2$ values for a linear regression of spring aerosol parameters versus SeaWiFS AOT ($\alpha < 0.7$), PNA, LRT3, or average regional precipitation.
[c]$R^2$ values for a multiple linear regression of average spring aerosol parameters against SeaWiFS AOT ($\alpha \leq 0.7$) and seasonally averaged PNA.
[d]$R^2$ values for a multiple linear regression of average spring aerosol parameters against SeaWiFS AOT ($\alpha < 0.7$) and seasonally averaged LRT3.
[e]$R^2$ values for a multiple linear regression of average spring aerosol parameters against SeaWiFS AOT ($\alpha < 0.7$) and seasonally averaged precipitation.
[f]$R^2$ values for a multiple linear regression of average spring aerosol parameters against SeaWiFS AOT ($\alpha < 0.7$), seasonally averaged precipitation, and LRT3.

**Table 3.** $R^2$ Values for a Linear Regression of Spring Aerosol Parameters Versus SeaWiFS AOT, and $R^2$ Values for Multiple Linear Regressions of Average Spring Aerosol Parameters Against AOT and Other Parameters[a]

| | AOT[b] | PNA & AOT[c] | LRT3 & AOT[d] | Precip & AOT[e] | Precip, LRT3, AOT[f] |
|---|---|---|---|---|---|
| $PM_{10}$ | 0.47** | 0.60* | 0.56* | 0.67** | 0.88** |
| $PM_{2.5}$ | 0.40*** | 0.42*** | 0.49* | 0.58* | 0.77** |
| Ca | 0.59** | 0.59* | 0.60* | 0.74** | 0.74* |
| Fe | 0.47** | 0.49*** | 0.48*** | 0.54* | 0.54*** |

[a]Asterisks indicate p-value: single asterisk, value less than 0.01; double asterisk, value less than 0.05; and triple asterisk, value less than 0.10.
[b]$R^2$ values for a linear regression of spring aerosol parameters versus SeaWiFS AOT.
[c]$R^2$ values for a multiple linear regression of average aerosol parameters against SeaWiFS AOT for spring months over the region shown in Figure 1a and seasonally averaged PNA.
[d]$R^2$ values for a multiple linear regression of average aerosol parameters against SeaWiFS AOT and LRT3.
[e]$R^2$ values for a multiple linear regression of average spring aerosol parameters against SeaWiFS AOT and seasonally averaged precipitation.
[f]$R^2$ values for a multiple linear regression of average spring aerosol parameters against SeaWiFS AOT, averaged precipitation, and LRT3.

do not believe that these fires have significantly impacted our analysis.

## 7. Implications

[25] We have shown that springtime satellite measurements of AOT over Asian deserts correlate well with aerosol data over the northwestern U.S. The Deep Blue algorithm provides an enhanced measure of AOT over the major dust sources in Asia, while the IMPROVE data provides a policy-relevant measure of aerosol loading. Based on Table 1, variations in Asian dust emissions explain ~50% of the interannual variability in background $PM_{2.5}$ in the Pacific Northwest. The addition of a transport index increases the explanatory power to 60–70%. The addition of a regional precipitation measure further increased the explanatory power to ~80%. Taken together the results imply that for Asian dust to have a maximum seasonal impact on particulate matter in the western U.S. there must be a strong source, favorable transport and a long residence time. Our results also suggest that on seasonal timescales variations in dust source strength are more important in determining the total flux of material crossing the Pacific than variations in the meteorology captured by indices such as the PNA or LRT3. Although most easily observed at remote sites, the use of low elevation sites in our analysis indicates that Asian dust could also have a quantifiable impact on springtime aerosol mass in urban areas in the Pacific Northwest.

## References


Chin, M., T. Diehl, P. Ginoux, and W. C. Malm (2007), Intercontinental transport of pollution and dust aerosols: Implications for regional air quality, *Atmos. Chem. Phys. Discuss.*, *7*, 5501–5517.

Fairlie, T. D., D. J. Jacob, and R. J. Park (2007), The impact of transpacific transport of mineral dust in the United States, *Atmos. Environ.*, *41*, 1251–1266.

Gong, S. L., X. Y. Zhang, T. L. Zhao, X. B. Zhang, L. A. Barrie, I. G. McKendry, and C. S. Zhao (2006), A simulated climatology of Asian dust aerosol and its trans-Pacific transport. Part II: Interannual variability and climate connections, *J. Clim.*, *19*, 104–122.

Hsu, N. C., S.-C. Tsay, M. D. King, and J. R. Herman (2004), Aerosol properties over bright-reflecting source regions, *IEEE Trans. Geosci. Remote Sens.*, *42*, 557–569.

Hsu, N. C., S.-C. Tsay, M. D. King, and J. R. Herman (2006), Deep blue retrievals of Asian aerosol properties during ACE-Asia, *IEEE Trans. Geosci. Remote Sens.*, *44*, 3180–3195.

Jaffe, D. A., I. Bertschi, L. Jaegle, P. Novelli, J. S. Reid, H. Tanimoto, R. Vingarzan, and D. Westphal (2004), Long-range transport of Siberian biomass burning emissions and impact on surface ozone in western North America, *Geophys. Res. Lett.*, *31*, L16106, doi:10.1029/2004GL020093.

Kwon, L. H., J. E. Kim, Y. J. Kim, J. Kim, and W. von Hoyningen-Huene (2005), Impact of the smoke aerosol from Russian forest fires on the atmospheric environment over Korea during May 2003, *Atmos. Environ.*, *39, 85–99.*

Liang, Q., L. Jaeglé, and J. M. Wallace (2005), Meteorological indices for Asian outflow and transpacific transport on daily to interannual timescales, *J. Geophys. Res.*, *110*, D18308, doi:10.1029/2005JD005788.

Malm, W. C., J. F. Sisler, D. Huffman, R. A. Eldred, and T. A. Cahill (1994), Spatial and seasonal trends in particle concentration and optical extinction in the United States, *J. Geophys. Res.*, *99*, 1347–1370.

Malm, W. C., M. L. Pitchford, C. McDade, and L. L. Ashbaugh (2007), Coarse particle speciation at selected locations in the rural continental United States, *Atmos. Environ.*, *41*, 2225–2239.

Sun, J., M. Zhang, and T. Liu (2001), Spatial and temporal characteristics of dust storms in China and its surrounding regions, 1960–1999: Relations to source area and climate, *J. Geophys. Res.*, *106*, 10,325–10,333.

VanCuren, R. A., and T. A. Cahill (2002), Asian aerosols in North America: Frequency and concentration of fine dust, *J. Geophys. Res.*, *107*(D24), 4804, doi:10.1029/2002JD002204.

Weiss-Penzias, P., D. A. Jaffe, P. Swartzendruber, J. B. Dennison, D. Chand, W. Hafner, and E. Prestbo (2006), Observations of Asian air pollution in the free troposphere at Mount Bachelor Observatory during the spring of 2004, *J. Geophys. Res.*, *111*, D10304, doi:10.1029/2005JD006522.

Wells, K. C., M. Witek, P. Flatau, S. M. Kreidenwei, and D. J. Westphal (2007), An analysis of seasonal surface dust concentrations in the western US (2001–2004): Observations and model predictions, *Atmos. Environ.*, *41*, 6585–6597.

Yang, Y. Q., Q. Hou, C. H. Zhou, H. L. Liu, Y. Q. Wang, and T. Niu (2008), Sand/dust storm processes in northeast Asia and associated large-scale circulations, *Atmos. Chem. Phys. Discuss.*, *8*, 25–33.

Zhao, T. L., S. L. Gong, X. Y. Zhang, J.-P. Blanchet, I. G. McKendry, and Z. J. Zhou (2006), A simulated climatology of Asian dust aerosol and its trans-Pacific transport. Part I: Mean climate and validation, *J. Clim.*, *19*, 88–102.

Zhao, T. L., S. L. Gong, X. Y. Zhang, and D. A. Jaffe (2007), Asian dust storm influence on North American ambient PM levels: Observational evidence and controlling factors, *Atmos. Chem. Phys. Discuss.*, *7*, 9663–9686.



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