Resolving Autocorrelation Bias in the Determination of the Extinction Efficiency of Fugitive Dust from Cattle Feedyards

Extended Abstract # 8

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INTRODUCTION

The atmospheric extinction coefficient (B_{ext}) represents the light attenuation in the atmosphere resulting from the absorption and scattering of light by gases and particles.
Equation 1. Expressed in units of inverse distance (e.g., km^{-1}), B_{ext} is the sum of the absorption and scattering coefficients for particles and gases[1],

$$B_{ext} = B_{scat} + B_{abs} = B_{Ray} + B_{s,p} + B_{a,g} + B_{a,p}$$

In Equation 1, the subscripts "*scat*" (or "s") and "*abs*" (or "a") refer to total scattering and total absorption, respectively; g and p refer to gases and particles, respectively; and B_{Ray} refers to Rayleigh scattering, which is the wavelength-dependent scattering by native gases in the earth's atmosphere. The Rayleigh extinction coefficient is zero in the limit as barometric pressure tends to zero; its value in clear air at sea level is approximately 0.010-0.012 km^{-1}.

Aerosol mass-concentration measurements may be used to estimate the atmospheric extinction if the atmospheric extinction efficiency and mass fraction of each independent aerosol component are known[2].
Equation 2. The atmospheric extinction efficiency of an aerosol component is defined as:

$$\varepsilon_i = 10^3\ \delta B_{ext}/\delta C_i$$

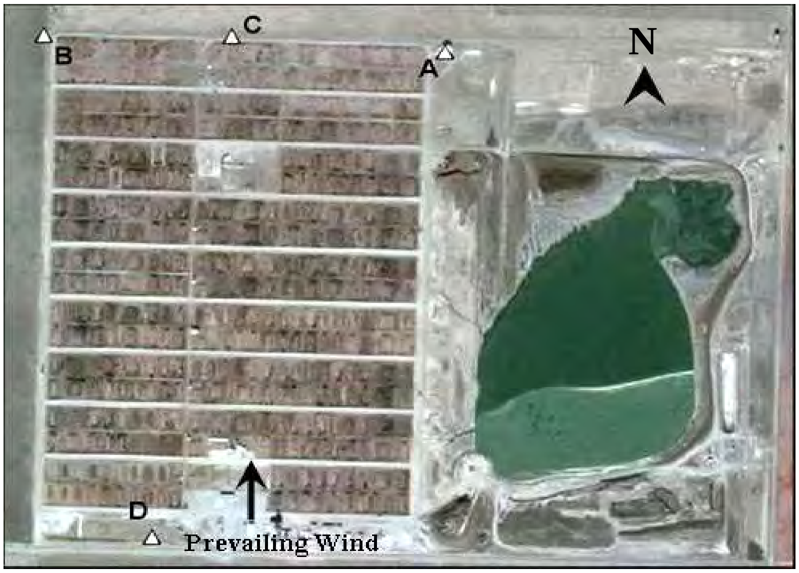
in which C_i is the mass concentration ($\mu g\ m^{-3}$) of each independent aerosol component (denoted by the subscript i), ε_i is the extinction efficiency ($m^2\ g^{-1}$) of aerosol component i, and 10^3 is a units-conversion constant ($\mu g\ km\ g^{-1}\ m^{-1}$).
This study was designed to determine the atmospheric extinction efficiency associated with the fugitive dust from a commercial cattle feedyard[3]. As a reference value, Malm published a value of 0.6 $m^2\ g^{-1}$ for the extinction efficiency of generic, coarse particles[4].

EXPERIMENTAL DESIGN

Field studies were conducted at a commercial beef cattle feedyard (capacity 45,000+) in the Texas Panhandle. PM_{10} and total suspended particulate (TSP) mass concentrations ($\mu g\ m^{-3}$) and B_{ext} (km^{-1}) were measured simultaneously along the downwind edge of the feedyard corrals in September 2005.

Figure 1 shows the experimental design for this study. A long-path visibility transmissometer (Model LPV-3; Optec, Inc., Lowell, MI) was deployed on an E-W path along the northern perimeter of the feedyard corrals[5]. The transmitter was installed at a 10-m height atop a large water tank on the NE corner of the feedyard, and the photometer was placed on a short pillar at ground level on the NW corner of the feedyard (Figure 1). Under prevailing winds from the S-SSW, this LPV measured the downwind extinction resulting from the combination of the background aerosol load and the fugitive emissions of particulate matter from the feedyard surface and unpaved roads. The path length from transmitter (location A) to receiver (location B) was approximately 900 m. The PM mass concentrations were measured at one upwind and one downwind location (locations D and C, respectively) using two tapered-element, oscillating microbalances (TEOMs; Model 1400a, Thermo Scientific, Inc., Waltham, MA). Two TEOMs were installed at location C, one with a TSP inlet and one with a PM_{10} inlet. All measurements were integrated over a one-minute averaging time.

Figure 1. Overhead photograph of the cooperating feedyard.



To restrict our analysis to those aerosol measurements that best represent feedyard dust emissions (i. e., as opposed to other, off-site sources), we removed from the regression analysis all data collected while the wind direction was outside the 90-degree sector subtended by the SE and SW vectors. We also excluded all zero values associated with B_{ext}, PM_{10} and TSP in our analyses. From the remaining data, we plotted 5-minute average B_{ext} values against the corresponding PM_{10} and TSP mass concentrations. We then subjected daily ensembles of those data to simple, linear regression to estimate the extinction efficiency for each data set (PM_{10} and TSP). Because we were unable to measure the upwind B_{ext} as a reference value, we assumed that the background extinction coefficient was equal to B_{Ray}[6], which for Big Bend National Park (BBNP), is approximately 0.01 km^{-1}. The altitudes of BBNP and our experimental site are similar, and both represent semi-arid to arid climates. The details of our preliminary research can be found in Upadhyay et al[7].

METHODS

Confirming the Presence of Autocorrelation. Five-minute average values of B_{ext} were plotted against corresponding, five-minute PM_{10} and TSP concentrations for September 2005 to estimate daily extinction efficiencies of the two dust fractions using a simple, linear regression model.

Equation 3. The linear regression model is:

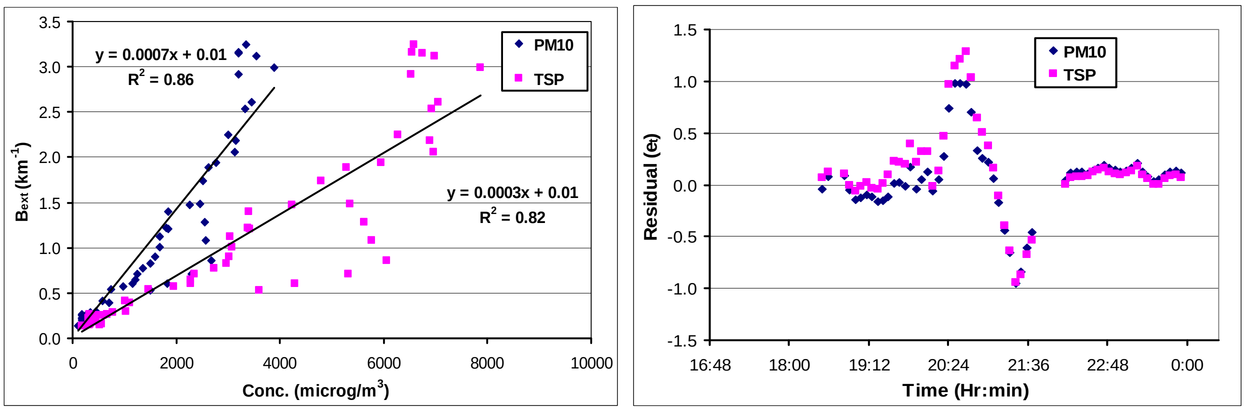
$B_{ext} = \varepsilon_t C_i + B_{Ray} + e$

in which e is a random error term. Coefficients of determination (R^2) for the regression models were excellent (0.87 for PM_{10} and 0.82 for TSP) with $p<0.05$ in both cases. One of the most obvious features of the daily scatter plots, however, is the hysteretic "looping" behavior of B_{ext}/concentration scatter plots (Fig. 2a).

Equation 4. We then computed the residuals as a time series using the rearranged form of Equation 3,

$e(t) = B_{ext,measured} - (\varepsilon_t C_i(t) + B_{Ray})$
and plotted the residuals as a time series. The looping behavior shown in Figure 2a and the residuals plot in Figure 2b are *prima facie* evidence that the errors e(t) are not independent; they are said to be *autocorrelated* or *serially correlated*.

Figure 2. (a) Correlation between five-minute average values of extinction coefficient and downwind particulate matter concentrations during the six-hour "evening dust peak" at an experimental feedyard. Note that the regression equations are forced through an intercept equal to $B_{Ray} = 0.01$ km^{-1} in accordance with Malm and Johnson [8]. (b) Time-series plot of the residuals at time t using equation 4.



Measuring Autocorrelation in Time-Series Data. The most widely used test for determining the presence of autocorrelation in time-series data is the Durbin-Watson (D) test.

Equation 5. The Durbin-Watson test statistic, D, is as follows:

$$D = \frac{\sum_{t=2}^{n}(e_t - e_{t-1})^2}{\sum_{t=1}^{n} e_t^2}$$

in which the values e_t are the residuals computed with equation 4, and n is the number of sequential, equally spaced measurements.

Equation 6. The test assumes that the residuals' serial correlation can be approximated by the first-order equation,

$e(t) = \rho e(t-1) + u(t)$

in which ρ is the *autocorrelation parameter* between -1 and 1, and u(t) is a truly random error term. The null hypothesis for the Durbin-Watson test is that the parameter ρ in equation 6 is zero, in which case e(t)=u(t), and the residuals are not serially correlated.

Mitigating Serial Correlation via Variable Transformation. Where first-order autocorrelation is present, as was the case in nearly all of our 24-hour data sets, the primary remedial measure is to transform the raw data using a linear operator and derive new estimates of the regression coefficients from the transformed variable space.

Equation 7. For raw data sets consisting of the ordered pairs (X_t, Y_t) and having an SLR slope β_1 and intercept β_0, the transformed variables (X'_t, Y'_t) are computed as:

$Y_t' = Y_t - \rho Y_{t-1}$

$X_t' = X_t - \rho X_{t-1}$

Equation 8. It can be shown[9] that a linear regression of the transformed dataset (X'_t, Y'_t), now consisting of (n-1) ordered pairs, yields the following SLR coefficients:

$\beta_1' = \beta_1$

$\beta_0' = \beta_0(1-\rho)$

If the autocorrelation parameter, ρ, is selected properly, the transformed data should exhibit considerably less autocorrelation than the raw data.

Determining the Autocorrelation Parameter, ρ. There are at least three ways of estimating ρ[9]. Here we have used a method known as the Cochrane-Orcutt (C-O) procedure, in which the value of ρ is selected that minimizes the sum of the squared residuals. The C-O procedure consists of three steps:

1. Estimate ρ, and transform (X_t, Y_t) into (X'_t, Y'_t) using equation 7.
2. Compute the SLR coefficients of the transformed data using equation 8.
3. Compute the new residuals and a new value of D from the transformed data.

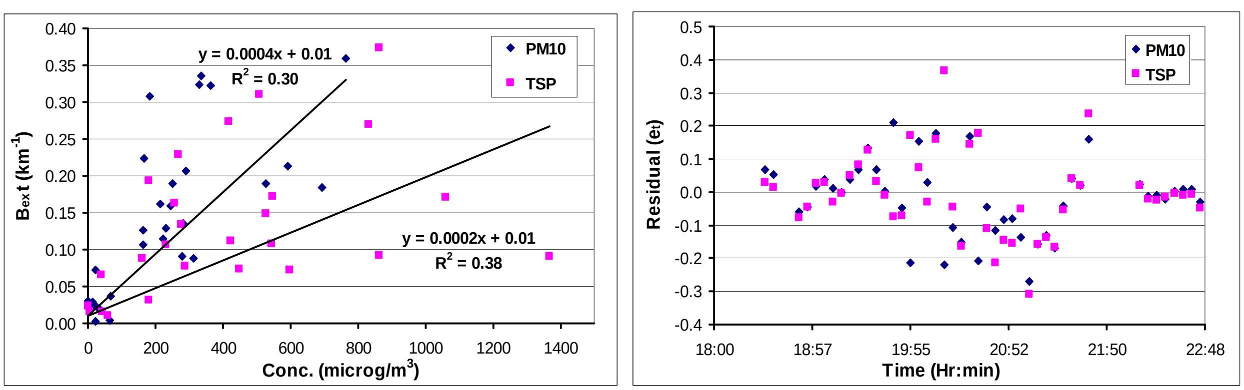
If the new value of D indicates that autocorrelation is still present, the data (X'_t, Y'_t) can be transformed again into a new dataset (X''_t, Y''_t) using a new value of ρ; steps 1-3 can then be repeated again and again until the D statistic indicates that autocorrelation is no longer present.

Results and Discussion

Extinction efficiencies were estimated for 13 days of data collected during September 2005. Each dataset was subjected to SLR, and D statistics were calculated. Those datasets exhibiting statistically significant autocorrelation were subjected to C-O transformation iteratively until the null hypothesis for the D-W test could no longer be rejected.

Figure 3a illustrates the scatter plot of B_{ext} versus particulate concentrations after C-O transformation for the same dataset shown in Figure 2. As a result, the estimates of the extinction efficiencies ε_t of PM_{10} and TSP decreased from 0.7 to 0.4 $m^2\ g^{-1}$ and from 0.3 to 0.2 $m^2\ g^{-1}$, respectively. The error terms (e_t) are no longer significantly autocorrelated (Figure 3b), but the coefficients of determination (R^2) have decreased significantly.

Figure 3. (a) Correlation between B_{ext} and 5-min downwind particulate matter concentrations, and (b) time series of the residual after Cochrane-Orcutt transformation.



We applied the C-O transformation (as required) to each dataset from September 2005. Table 1 shows the extinction efficiencies (ε_t) of PM_{10} and TSP calculated before and after C-O transformation. In most cases, the apparent extinction efficiencies of PM_{10} and TSP decreased after correcting for autocorrelation. The root mean square errors (RMSE) of the extinction efficiencies (ε_t) of PM_{10} and TSP decreased as a result of C-O transformation.

Table 1. Extinction efficiencies (ε_t in $m^2\ g^{-1}$) of PM_{10} and TSP for September 2005, before and after Cochrane-Orcutt transformation.

Day	ε_t ($m^2\ g^{-1}$) before C-O transformation				ε_t ($m^2\ g^{-1}$) after C-O transformation			
	PM_{10}	RMSE	TSP	RMSE	PM_{10}	RMSE	TSP	RMSE
9/03/2005	0.5	0.5	0.2	0.6	0.5	0.2	0.3	0.2
9/04/2005	0.6	0.3	0.3	0.4	0.5	0.1	0.2	0.1
9/05/2005	0.7	0.4	0.3	0.4	0.4	0.1	0.2	0.1
9/06/2005	0.5	0.4	0.2	0.5	0.6	0.2	0.3	0.2
9/09/2005	0.5	0.4	0.3	0.4	0.4	0.3	0.3	0.1
9/10/2005	0.6	0.5	0.3	0.5	0.5	0.1	0.3	0.2
9/12/2005	0.9	0.8	0.2	0.4	0.7	0.3	0.2	0.3
9/13/2005	0.8	0.5	0.4	0.5	0.5	0.2	0.3	0.2
9/16/2005	0.8	0.5	0.4	0.5	0.5	0.1	0.3	0.2
9/17/2005	0.7	0.5	0.3	0.5	0.6	0.2	0.3	0.2
9/18/2005	0.6	0.5	0.3	0.5	0.6	0.2	0.3	0.3
9/29/2005	2.5	0.4	0.5	0.4	0.9	0.2	0.5	0.2
9/30/2005	1.1	0.4	0.2	0.5	0.5	0.3	0.1	0.1

CONCLUSIONS

The use of the Cochrane-Orcutt procedure successfully mitigated autocorrelation in our time-series visibility data. The absolute values of ε_t decreased substantially after Cochrane-Orcutt transformation, but their orders of magnitude remained the same. It is not yet clear whether or not the corrected extinction efficiencies will yield more accurate predictions of feedyard aerosol concentration from extinction measurements.

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