OPEN-PATH TRANSMISSOMETRY TO DETERMINE ATMOSPHERIC EXTINCTION EFFICIENCY ASSOCIATED WITH FEEDYARD DUST

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Introduction

The atmospheric extinction coefficient (B_{ext}) is a measure of the attenuation of light in the atmosphere by gases and particles. Its physical measurement, in units of inverse distance (e.g., km^{-1}), is generally regarded as the sum of the absorption and the scattering coefficients (Malm et al., 1986). Two methods can be applied for the light extinction measurement: (a) transmission measurements by open-path transmissometers can be converted electronically to the path-averaged light extinction, and (b) gaseous and aerosol concentration measurements can be directly related to the atmospheric extinction using the “atmospheric extinction efficiency” (Sisler et al., 1996). The atmospheric extinction efficiency (km^{-1} $[\mu g\ m^{-3}]^{-1}$) represents the functional relationship between time-resolved particulate matter (PM) mass concentration and atmospheric extinction values (or, more precisely, $\Delta B_{ext}/\Delta[PM]$), and this study was designed to determine the atmospheric extinction efficiency associated with the fugitive dust from cattle feedyards. As a reference value, Malm (1999) published a value of 6.0×10^{-4} km^{-1} $[\mu g\ m^{-3}]^{-1}$ for the extinction efficiency of generic coarse particles.

The factors contributing to atmospheric extinction include: (a) mass concentration of airborne PM, (b) size and shape of the PM, (c) meteorological factors, and (d) phase of the matter.

(a) Mass Concentration: In general, increasing PM concentrations reduce visibility via light absorption and scattering.

(b) Size and Shape: The size of an aerosol particle of arbitrary shape must be generalized in some contextually meaningful way. For studies related to the impact of airborne PM on respiratory health, the generalized dimension is the aerodynamic equivalent diameter (AED), and the designation PM_x refers to those particles whose AED is less than or equal to x, usually measured in microns. Malm (1999) reported that finer particles are more efficient at scattering light than coarser particles. Young (2000) mentioned that there is more scattering from anisotropic molecules than from spherical ones.

(c) Meteorological Factors: The Continental Steppe climate, which is prevalent in the Texas High Plains, is characterized by large variations in the range of daily temperature extremes and relative humidity, and irregularly spaced rainfall of moderate amounts (Nitchell et al., 1974). The changing position of the boundary between Gulf of Mexico influence and Mexican Plateau influence, often referred to as the "dry line," may be responsible for wide, short-term swings in the relative humidity. Auvermann (2000) suggested that increased cattle activity in the late afternoon and early evening often coincides with lower wind speeds at the earth's surface, cooler temperatures, and reduced turbulence, confining feedyard dust to a shallow layer of air near the ground and consequently increasing ground-level concentrations of PM.

(d) Phase Factor: Normally, most of the extinction in the Earth's atmosphere is due to scattering, but absorption becomes important when the visibility interrupters are in gas (i.e., water vapor) phase (Young, 2000). Marek et al. (2004) and Razote et al. (2004) showed that feedyard dust has a strong affinity to water and water vapor. The absorption of water to feedyard particles is highly likely to change the particle's scattering and absorption behavior, although that has not been tested.

There are currently no federal guidelines that regulate visibility loss caused by fugitive dust emissions from CAFOs. To protect local visibility via management decisions and technology selection in the agricultural sector, we have begun to investigate visibility measures as a real-time surrogate for time-averaged concentration measurements. Open-path transmissometry may provide an intuitive, reliable and cheaper surrogate for traditional, filter-based gravimetry.

Experimental Design

Field studies were conducted at an approximately 45,000 head beef cattle feedyard in Swisher County, Texas. The experimental set-up was organized in a way that PM_{10} and TSP mass concentration ($\mu g\ m^{-3}$) and atmospheric extinction (km^{-1}) were simultaneously measured along the downwind boundary of the feedyard to compute light extinction efficiency ($km^{-1}\ [\mu g\ m^{-3}]^{-1}$).

The Long Path Visibility Transmissometer© (Optec Inc, 2002) consists of a constant output light source transmitter and a computer-controlled photometer receiver. The irradiance at 550 nm wavelength from the transmitter can be measured to a high degree of accuracy both day and night, and over a path length of up to 15 km depending on atmospheric extinction values.

The Series 1400a Ambient Particulate Monitor (Rupprecht & Patashnick Co., Inc., 2002), which has the USEPA equivalency designation for PM_{10}, employs the tapered element oscillating microbalance (TEOM), which is a patented, inertial technique measuring particle mass directly and in quasi-real time. The TEOM has a nominal precision of $\pm 5.0\ \mu g/m^3$ for 10-minute averaged data and $\pm 1.5\ \mu g/m^3$ for 1-hour averages.

Figure 1 shows our study's experimental design. A calibrated transmissometer was deployed on an E-W path along the northern perimeter of the feedyard corrals and was the nominal "downwind" transmissometer, measuring the path-averaged extinction resulting from the combination of the background aerosol load and the fugitive emissions of particulate matter from the feedyard surface. The path length from transmitter (location C) to receiver (location A) was approximately 900 meters and was selected to measure only the emissions from the feedyard proper. PM mass concentrations were measured at one upwind and one downwind location (locations D and B, respectively). One TEOM was installed at location D with an inlet for total suspended particulate (TSP) measurement on the upwind side. Two TEOMs were installed at location B, one with a TSP inlet and one with an inlet for PM_{10}.

One-minute average extinction values and mass concentrations, as well as time-averaged (smoothed) values [2 min, 5 min, 10 min, and 30 min for each], were then plotted for regression analysis to estimate the extinction efficiency. The weather data were also used in statistical analysis to refine the regression model and identify outliers and trends. The meteorological parameters chosen were relative humidity (RH, %), air temperature (AirTemp, °C), and wind speed (WindSpd, m/s).

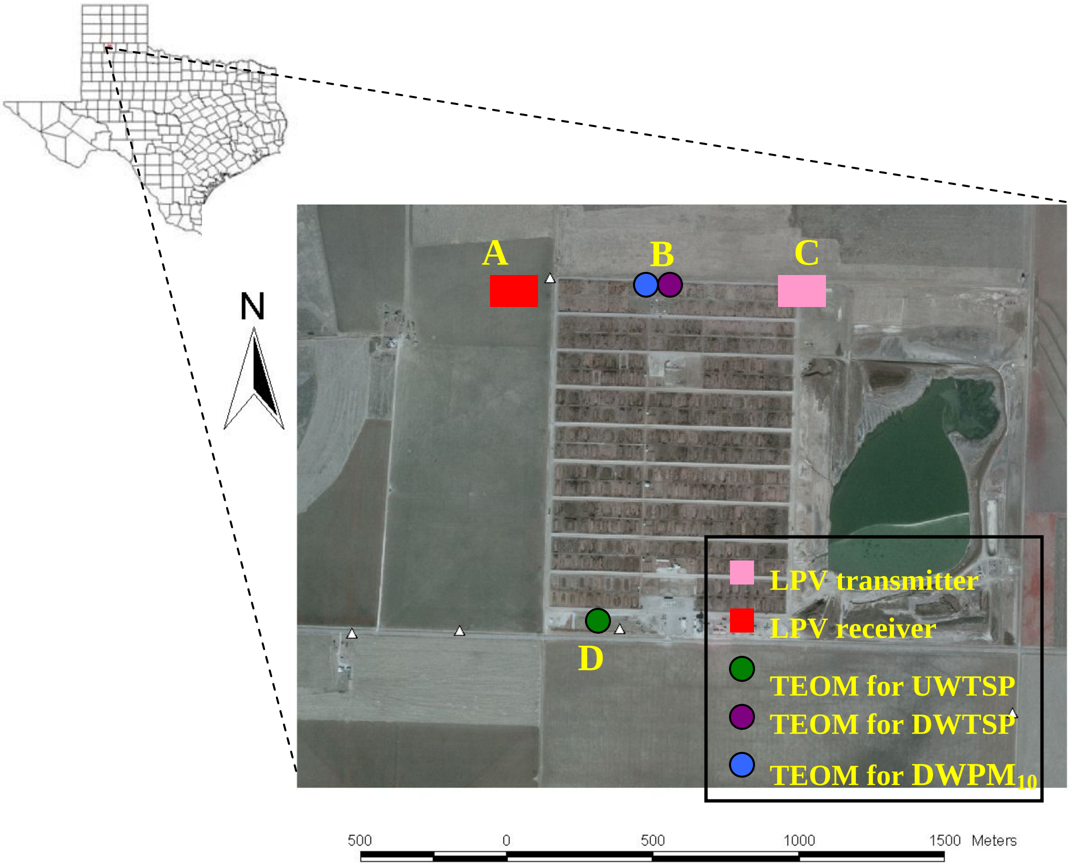

Figure 1. The experimental set-up was designed so that PM_{10} and TSP mass concentration and atmospheric extinction were simultaneously measured along the downwind boundary of the feedyard.

Results and Discussion

Figure 2 shows the regression between mass concentrations and B_{ext}. The summary of all regressions are given in Tables 1 and 2. The strong correlations between B_{ext} and PM concentration values appear to confirm that the higher the concentration of PM in the atmosphere. As shown in Table 1 and 2, the atmospheric extinction efficiency associated with feedyard dust was determined as 5.78 $\times 10^{-4}$ km^{-1} [$\mu g\ m^{-3}$]$^{-1}$ for PM_{10} as well as 3.26 $\times 10^{-4}$ km^{-1} [$\mu g\ m^{-3}$]$^{-1}$ for TSP.

The non-linear regression equations for calculating B_{ext} as a function of [PM] and dew point depression (DD) that was computed from AirTemp and RH is described by the following equations:

$$B_{ext} = 0.571\,[PM_{10}] - 0.079\,[(DD)^{-2}] + 0.197 \qquad (R^2 = 0.808)$$

$$B_{ext} = 0.341\,[TSP] - 0.079\,[(DD)-2] + 0.149 \qquad (R^2 = 0.658)$$

in which, B_{ext} is in km^{-1}, PM_{10} is in $mg\ m^{-3}$, and DD is in °C. Dew point depression is computed as the difference between AirTemp and the dew-point temperature; low DD reflects high RH.

The paired, parametric, multiple-correlation tests for all four meteorological data were performed to satisfy 5-min averaged B_{ext} data based on data range/distribution and, then, to examine the effect of individual weather parameter on B_{ext}.

The result showed that high B_{ext} would result when DD is less than 5°C even though dust concentrations were low (Figure 3). The total interference to light transmission by water vapor or droplets is greater than that by PM in the atmosphere. Thus, B_{ext} could be high despite the dust free condition. B_{ext} could also be high when RH ranges 0 to 40% and 80 to 100%, respectively (Figure 4). The following four different processes of reducing light transmission could be considered:

- High humidity (RH>80%) indirectly increases B_{ext}, possibly due to the hydration of dust particles and a consequent increase in scattering and/or absorption.
- Low air temperature (<5 °C) likely observed in the early morning associated with low DD, increasing B_{ext} despite low dust concentrations (Figure 5).
- Dry ambient conditions (AirTemp >15 °C and RH<40%) in the afternoon have driven off surplus moisture, increasing the intrinsic dustiness of the feedyard surface (Figure 6).

- Manure particles suspended in the air by cattle activity tend to remain near the ground, with the atmosphere's tendency to become more stable at low wind speed (<4 m/s), thereby increasing B_{ext}.

Summary and Conclusion

The following conclusions were drawn from this investigation;

- The atmospheric extinction efficiency associated with feedyard dust, 5.8×10^{-4} km^{-1} $[\mu g\ m^{-3}]^{-1}$ for PM_{10} and 3.3×10^{-4} km^{-1} $[\mu g\ m^{-3}]^{-1}$ for TSP, are close to the reference value of 6.0×10^{-4} km^{-1} $[\mu g\ m^{-3}]^{-1}$ published by Malm (1999) for coarse mass.
- In the case of a highly hygroscopic aerosol like feedyard dust, meteorological conditions significantly affect B_{ext}, complicating the relationship between atmospheric extinction and ambient PM concentration.
- The hygroscopic nature of feedyard dust appears to make its atmospheric extinction efficiency highly sensitive to delequescence of the dust particles.
- The greatest values of B_{ext} associated with feedyard dust are expected when RH <40%, wind speed is 0 to 4 m/s, and air temperature >15 °C.
- B_{ext} could be high despite relatively dust-free conditions when the weather condition meets more than one of the followings; DD<5 °C, RH>80%, and/or wind speed is 0 to 4 m/s.
- Open-path transmissometry appears to a viable monitoring tool for feedyard-derived aerosols.

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Table1. Regression summary for relation between PM_{10} and B_{ext}

PM_{10}

Time Resolution of Data (min)	Background B_{ext} [y-Intercept] (km^{-1})	Extinction Efficiency [Slope] (10^{-4} km^{-1} [µg m^{-3}]$^{-1}$)	r^2
1	0.199	5.64	0.691
2	0.200	5.69	0.693
5	**0.198**	**5.78**	**0.730**
10	0.203	5.84	0.712
30	0.211	5.82	0.711
Range	0.198 – 0.211	5.64 – 5.84	0.691 – 0.730

Table2. Regression summary for relation between TSP and B_{ext}

TSP

Time Resolution of Data (min)	Background B_{ext} [y-Intercept] (km^{-1})	Extinction Efficiency [Slope] (10^{-4} km^{-1} [µg m^{-3}]$^{-1}$)	r^2
1	0.173	3.04	0.418
2	0.174	3.06	0.424
5	**0.168**	**3.26**	**0.484**
10	0.168	3.52	0.466
30	0.179	3.65	0.560
Range	0.168 – 0.179	3.04 – 3.65	0.418 – 0.560

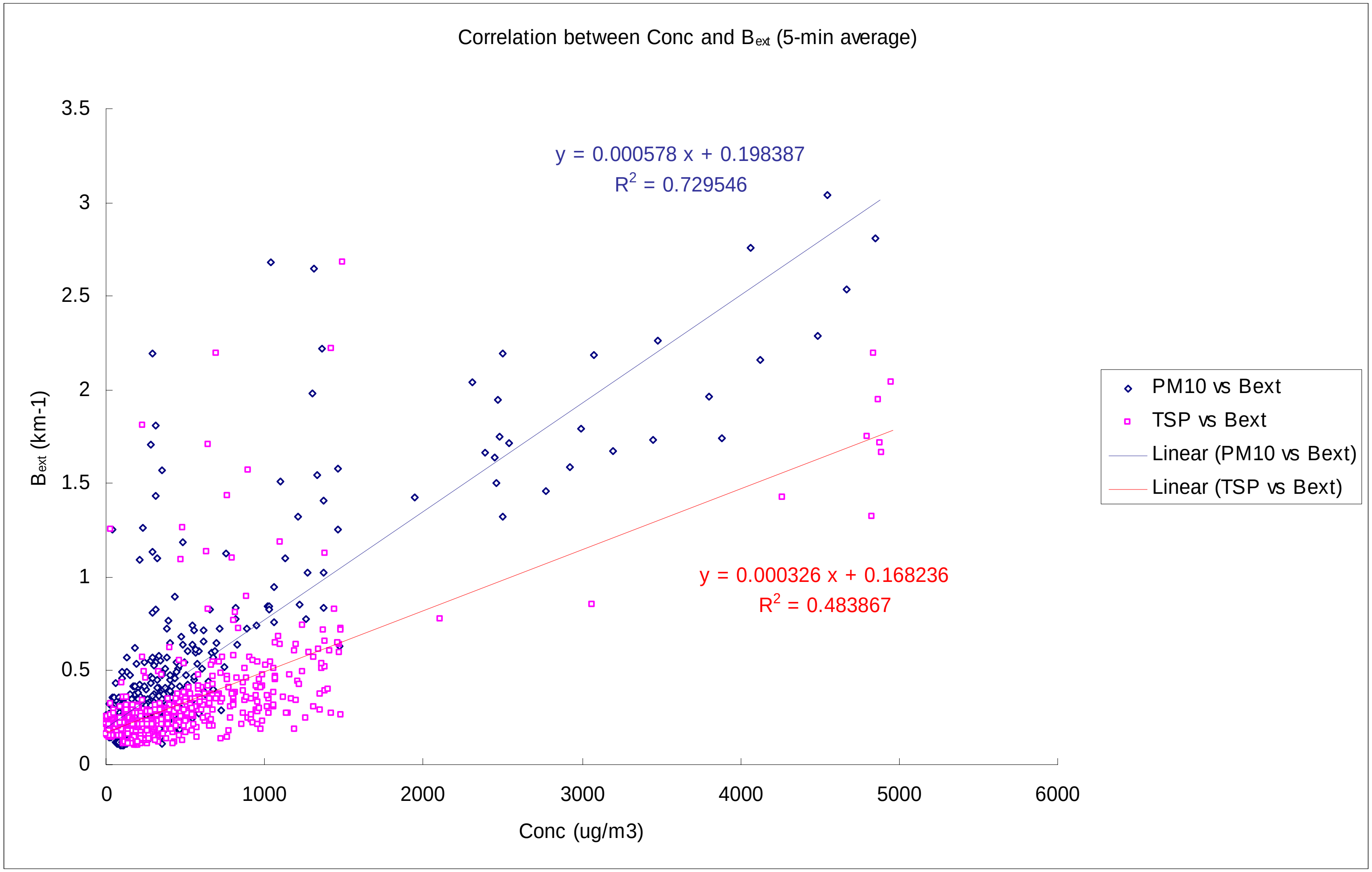

Figure 2. 5-min averaged extinction and concentration data: Blue line represents the correlation between B_{ext} and DWPM$_{10}$; red line shows the correlation between B_{ext} and DWTSP. 5-min averaged data showed the highest r^2 values for the correlation between B_{ext} and both PM (PM$_{10}$ and TSP), and this was used as a standard for later analysis.

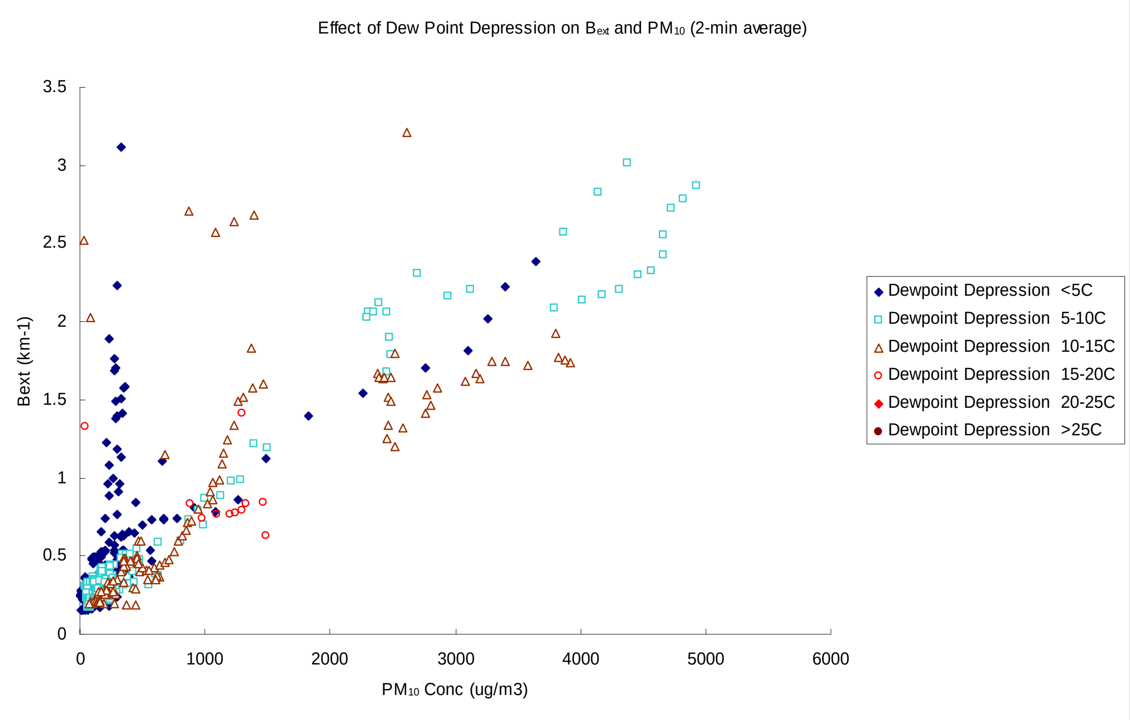

Figure 3. The effects of six different DD conditions on B_{ext} and PM_{10} were visualized on the scatter using 2-min averaged data. Lower dew point depression values mean that the air is very moist. 2-min averaged data was used because identified outlines and trends were more obvious than 5-min averaged data.

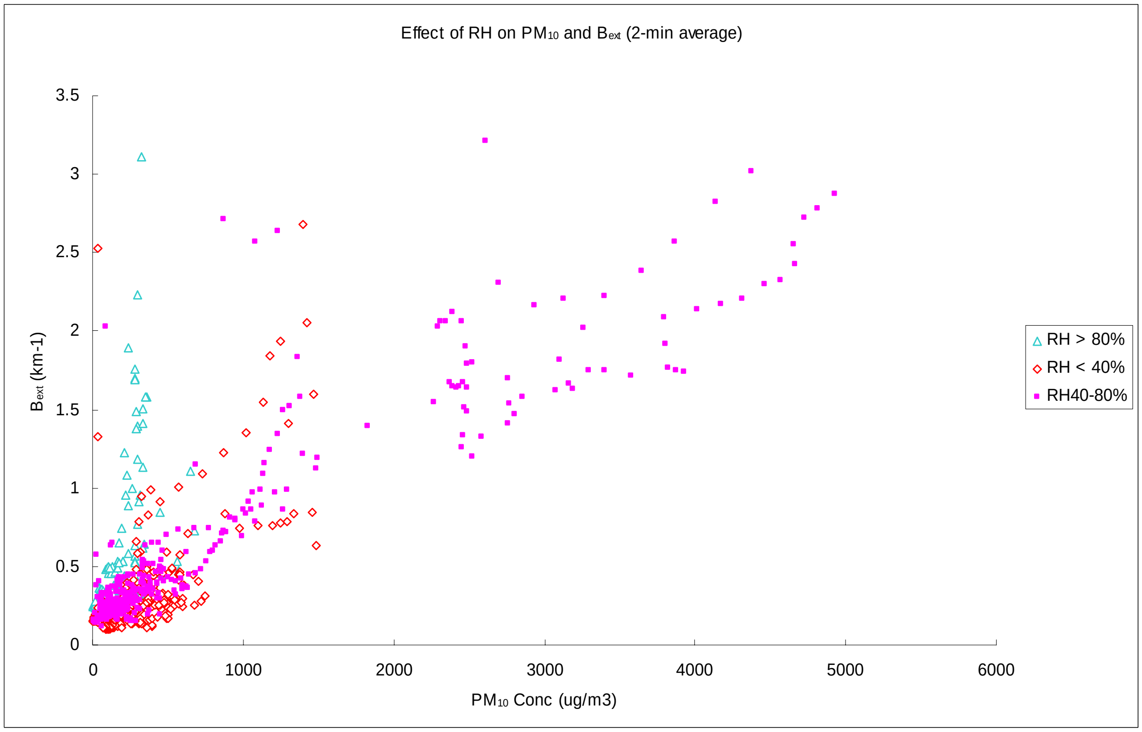

Figure 4. The effects of three different RH conditions on Bext and PM_{10} were visualized on the scatter graph by extracting the data that are categorized within RH of 0 to 40%, 40 to 80%, and higher than 80% from 2-min averaged data.

Figure 5. Distribution of Bext and PM_{10} were visualized on the scatter graph based on six different data acquisition periods.

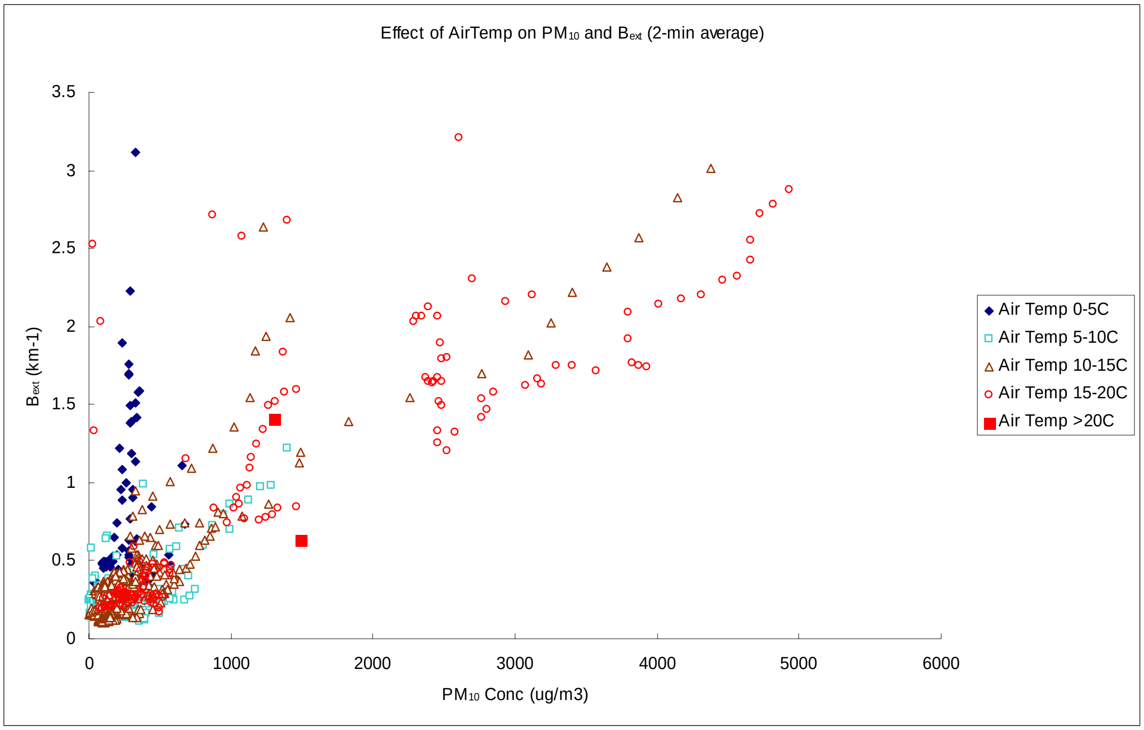

Figure 6. The effects of five different AirTemp conditions on Bext and PM_{10} relation were visualized on the scatter using 2-min averaged data

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