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Evaluation of 3-D Air Quality System Remotely Sensed Aerosol Optical Depth for the Baltimore/Washington Metropolitan Air Shed

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INTRODUCTION

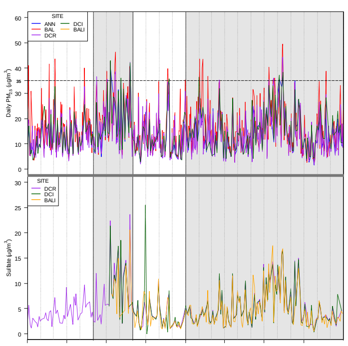
Satellite- and ground-based aerosol optical depth (AOD) products provide continuous observations of aerosol concentrations over the United States. Here, we evaluate the utility of using data from integrated databases being developed for NOAA and EPA through the 3D-AQS project for creating a surrogate measure of surface fine particulate matter ($PM_{2.5}$) concentrations that can be used to fill the gaps between the limited number of surface monitoring sites. To accomplish this, we examine the relationship between remotely sensed AOD and $PM_{2.5}$ concentrations for each observation platform for the summer of 2004 and the entire year of 2005 at five monitoring sites in the Baltimore/Washington region. Adjusting the AOD data using platform- and season-specific relationships for two case studies results in a more accurate representation of $PM_{2.5}$ concentrations when compared to a constant ratio, as is currently being used daily over the entire U.S. in the NOAA Infusing satellite data into environmental applications (IDEA) product [Al-Saadi et al., 2005]. This work demonstrates that quantitative relationships between remotely sensed and *in situ* aerosol observations in an integrated database can be computed and applied to improve the use of remotely sensed observations for estimating surface $PM_{2.5}$ concentrations.

DATA

The time frame covered in this study spans the summer (June, July, and August) of 2004 and the entire year of 2005. The summer of 2004 was added to provide a more robust dataset in the summer months when $PM_{2.5}$ concentrations are typically higher than other seasons, resulting in an increased risk of adverse health effects for the public, as well as National Ambient Air Quality Standards violations.

Datasets Included

- **$PM_{2.5}$ and Sulfate *[where available]* Concentrations:**
  - Washington, DC - McMillan Reservoir site (DCR);
  - Washington, DC - IMPROVE site (DCI);
  - Annandale, Virginia site (ANN);
  - Baltimore - Old Town site (BAL);
  - University of Maryland, Baltimore County (UMBC) - IMPROVE site (BALI).
- **Satellite-Based AOD Observations:**
  - Moderate Resolution Imaging Spectroradiometer (MODIS) - Level 2 Aerosol Product [MOD04 from the Terra platform]
    - Collections 4 and 5 *(v4 and v5)*
  - Multi-angle Imaging Spectroradiometer (MISR) - Level 2 Aerosol Product
  - GOES Aerosol and Smoke Product (GASP) AOD
- **Surface-Based AOD Observations:**
  - UMBC Polarization-diverse Elastic Lidar Facility (POLAR ELF)
  - Maryland Science Center Aerosol Robotic Network (AERONET) sun photometer - Level 1.5 AOD



Time series of 24-hour $PM_{2.5}$ (top panel) and sulfate (bottom panel) concentrations (μg/m³). Gray area represents time frame of analysis.

ANALYSIS RESULTS

Direct relationships between surface aerosol concentrations and each measure of AOD were computed using the following linear regression model:

$$Y = \beta_0 + \beta_1 X$$

The derived slope, β_1, and intercept, β_0, parameters of the regression models were combined to determine quantitative ratios that relate the remotely sensed AOD, X, to ground-level concentrations of $PM_{2.5}$, Y. In addition, the Pearson correlation coefficient for each comparison was computed.

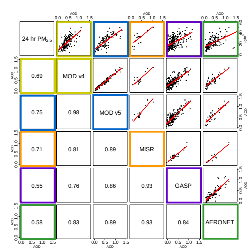
Analyzed by:
- **Remote-Sensing Platform**
  - MODIS [v4 & v5] — AERONET
  - MISR — Lidar - Total Column
  - GASP — Lidar – BPBL
- **Season [months]**
  - Winter [DJF] Spring [MAM] Summer [JJA] Fall [SON]
- **Sample Averaging Period**
  - 1-hour
  - 24-hour

The relationships were evaluated for both 1-hour and 24-hour fine aerosol concentrations to see if the correlations improved when comparing "snapshots" of AOD compared to daily averages. For the 1-hour relationships, the once-daily satellite-based AOD observations were matched with the concentration at the hour of the satellite overpass. For the 24-hour relationships, the GASP, AERONET and lidar AODs were averaged daily.

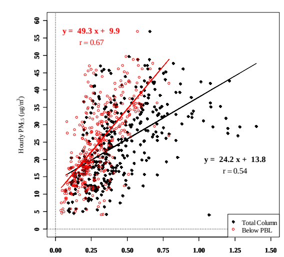
Table of regression parameters and correlation coefficients for the summer months (2004 and 2005)

	AOD	$PM_{2.5}$ Averaging Period	n	Slope[a] (stderr[b])	Intercept[a] (stderr)	r[a]	Ratio ($AOD:PM_{2.5}$)
Summer 2004-2005	MODIS Coll. 4	24 hour	172	33.4 (2.7)	7.7 (1.3)	0.69	1:41
		1 hour	177	35.3 (2.9)	3.3 (1.5)	0.68	1:39
	MODIS Coll. 5	24 hour	121	28.3 (2.3)	9.5 (1.4)	0.75	1:38
		1 hour	119	30.8 (2.7)	4.9 (1.7)	0.72	1:36
	MISR	24 hour	19	32.3 (7.7)	17.9 (3.4)	0.71	1:50
		1 hour	20	37.1 (8.6)	12.5 (4.0)	0.71	1:50
	GASP	24 hour	283	21.5 (1.9)	15.8 (0.7)	0.55	1:37
		1 hour	940	23.8 (1.2)	13.7 (0.4)	0.55	1:37
	AERONET	24 hour	135	18.6 (2.3)	13.7 (1.2)	0.58	1:32
		1 hour	732	25.2 (1.2)	12.5 (0.6)	0.62	1:38
	LIDAR						
	Total Column	24 hour	53	30.1 (4.6)	9.8 (2.2)	0.68	1:40
		1 hour	376	24.2 (1.9)	13.8 (1)	0.54	1:38
	Below PBL	24 hour	53	52.5 (6.5)	7.2 (2.1)	0.75	1:60
		1 hour	376	49.3 (2.8)	9.9 (1)	0.67	1:59

[a]All values significant with a p-value of <0.001 unless otherwise noted.
[b]stderr refers to the standard error.



Matrix of linear regression results (red) for each satellite dataset with the 24-hour $PM_{2.5}$ concentrations for the summer months [shown above the diagonal]. The correlation coefficient for each comparison is displayed in the corresponding panel below the diagonal. For reference, corresponding AOD/$PM_{2.5}$ panels are outlined in the same color.



1-hour surface $PM_{2.5}$ (μg/m³) versus ground-based lidar AOD for the BAL site for the summers of 2004 and 2005. The total column AODs are shown in black, while the AODs below the planetary boundary layer are shown in red.

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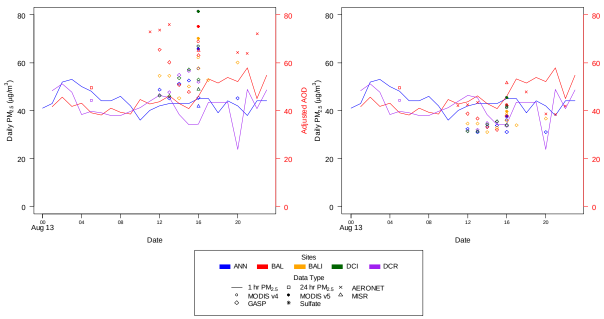
CASE STUDY

The IDEA product assumes that the ratio of AOD to $PM_{2.5}$ concentration (in μg/m³) is a constant value of 1:62 for the entire U.S., and that the ratio does not vary by location, satellite platform, or season. Gupta et al. [2006] determined that this ratio is not constant and is also dependent on other meteorological parameters. An expanded study of the MODIS AOD/$PM_{2.5}$ relationship over the U.S. [Zhang et al., 2008] shows how the linear model can be used to refine the relationship by geographic region and season.

The figure below displays the $PM_{2.5}$ concentrations for each of the five surface monitor locations along with the remotely sensed AOD data for August 13, 2004. In the left panel, the remotely sensed data are adjusted to estimate $PM_{2.5}$ values using the constant ratio of 1:62; in the right panel, AODs are adjusted using the corresponding, seasonally averaged ratio, as calculated in the regression analysis for the summer.



Time series of 1-hr and 24-hour $PM_{2.5}$ concentrations, sulfate concentrations, and remotely sensed AOD adjusted using a constant ratio (left panel) and using platform- and season-specific relationships (right panel).

A Wilcoxon signed rank test[1] of the residuals between the observed hourly $PM_{2.5}$ concentrations and the adjusted AOD estimates confirms that using seasonal- and platform-specific relationships significantly improves the prediction of $PM_{2.5}$ concentrations from AOD for this time period with a p-value of 0.003. A similar test for all of 2005 using both estimate methods also shows that using the season and platform-specific relationships can improve prediction ($p < 0.001$). In addition, an F-test of the variance for the estimated $PM_{2.5}$ concentrations derived from remotely sensed AOD indicates that using the calculated relationship significantly reduces the inter-platform and inter-monitoring site variance ($p < 0.001$).

[1]The Wilcoxon signed-rank test is a non-parametric test of a statistical hypothesis for the case of two related samples or repeated measurements on a single sample. It is used here as an alternative to the paired Student's t-test, because the sample of residuals can't be assumed to be normally distributed.

CONCLUSIONS

For the Baltimore/Washington air shed during the summers of 2004 and 2005, as well as the entire year of 2005, the satellite-derived AOD products from MODIS, MISR and GASP provided moderate to high correlations with daily and hourly averaged surface $PM_{2.5}$ concentrations ranging from 0.46 to 0.77. Ground-based AOD observations from lidar instruments, including a separation of the aerosols above and below the planetary boundary layer, and AERONET sun photometers also demonstrated a valuable ability to be incorporated into an integrated database for use in air quality applications at various scales. A case study was presented that demonstrated how the calculated ratios for each remotely sensed platform could be used to create better estimates of $PM_{2.5}$ concentrations when compared to a constant ratio applied across all observations. These relationships could be used for temporal and spatial infilling where such *in situ* $PM_{2.5}$ data are not available, and could be implemented on larger scales inside of analysis tools, such as IDEA.

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