Evaluation of Different MODIS AOD Retrieval Algorithms for $PM_{2.5}$ Estimation in the Western, Midwestern and Southeastern United States with Implications for Public Health

Mohammad Al-Hamdan[1], William Crosson[1], Erica Burrows[2], Shane Coffield[3], Breanna Crane[4]

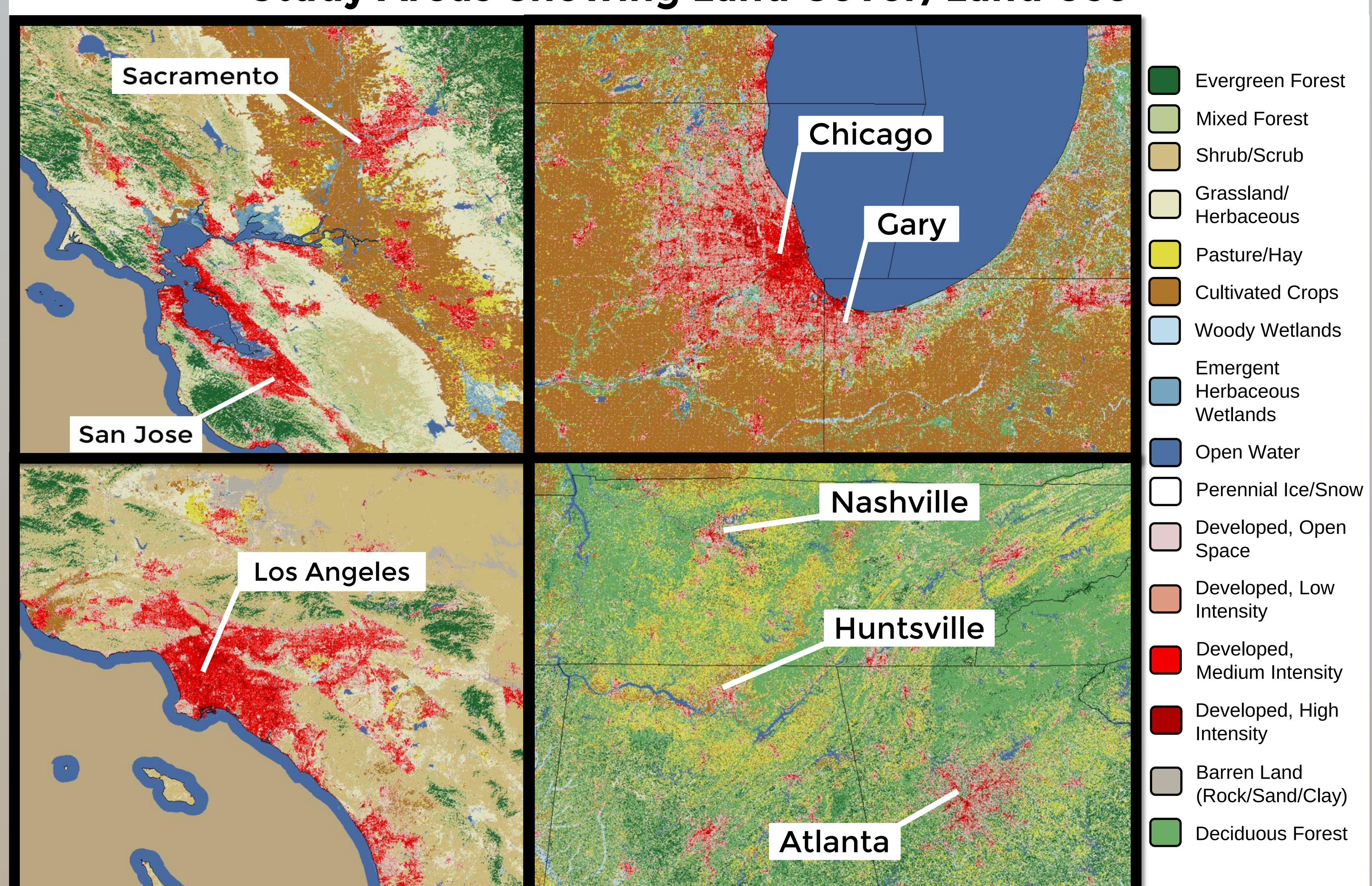
[1]Universities Space Research Association at NASA/MSFC, [2]San Jose State University, [3]University of Chicago, [4]University of Alabama in Huntsville

Email: mohammad.alhamdan@nasa.gov

Abstract

This study was part of the research activities of the Center for Applied Atmospheric Research and Education (CAARE) funded by the NASA MUREP Institutional Research Opportunity (MIRO) Program. Satellite measurements of Aerosol Optical Depth (AOD) have been shown to be correlated with ground measurements of fine particulate matter less than 2.5 microns ($PM_{2.5}$), which in turn has been linked to respiratory and heart diseases. The strength of the correlation between AOD and $PM_{2.5}$ varies for different AOD retrieval algorithms and geographic regions. We evaluated several Moderate Resolution Imaging Spectrometer (MODIS) AOD products from different satellites (Aqua vs. Terra), retrieval algorithms (Dark Target vs. Deep Blue), Collections (5.1 vs. 6) and spatial resolutions (10-km vs. 3-km) for cities in the Western, Midwestern and Southeastern U.S. We developed and validated $PM_{2.5}$ prediction models using remotely-sensed AOD data, which were improved by incorporating meteorological variables (temperature, relative humidity, precipitation, wind speed, and wind direction) from the North American Land Data Assimilation System Phase 2 (NLDAS-2). Adding these meteorological data significantly improved the predictive power of all the $PM_{2.5}$ models, especially in the Western U.S. Temperature, relative humidity and wind speed were the most significant meteorological variables throughout the year in the Western U.S. Wind speed was the most significant meteorological variable for the cold season while temperature was the most significant variable for the warm season in the Midwestern and Southeastern U.S. Our study re-establishes the connection between $PM_{2.5}$ and public health concerns including respiratory and cardiovascular diseases (asthma, high blood pressure, coronary heart disease, heart attack, and stroke). Using $PM_{2.5}$ data and health data from the Centers for Disease Control and Prevention (CDC)'s Behavioral Risk Factor Surveillance System (BRFSS), our statistical analysis showed that heart attack and stroke occurrences had the strongest correlations with $PM_{2.5}$.

Study Areas Showing Land Cover/Land Use



Objectives

1: Evaluate different MODIS Aerosol Optical Depth retrieval algorithms for $PM_{2.5}$ estimation
2: Use the Center for Disease Control (CDC) data to find the effects of $PM_{2.5}$ on respiratory and cardiovascular diseases

Methodology

We developed a linear regression model from $PM_{2.5}$ concentrations against remotely-sensed aerosol optical depth (AOD) data for 2010 through 2012. For the $PM_{2.5}$ concentrations, we used EPA Air Quality Systems (AQS) data 24 hour average data. For AOD, we used NASA MODIS satellite data for the following combinations: Aqua and Terra Satellites, Collection 6 and 5.1, 10 km and 3 km spatial resolutions, and the Deep Blue and Dark Target algorithms. The models were validated using 2013 AOD data to derive the $PM_{2.5}$ concentrations. The robustness of the model was measured using the root mean square error. The model was improved by incorporating North American Land Data Assimilation System (NLDAS) meteorological data (relative humidity, peak gust speed, wind direction, precipitation and temperature). The cold season (October-March), warm season (April-September), and all year data were analyzed to verify the seasonal variation with $PM_{2.5}$. The second part of the study was to use Center for Disease Control (CDC) data to determine the correlation between $PM_{2.5}$ concentrations and the following public health outcomes: stroke, heart attack, quality of health, asthma, high blood pressure, and coronary heart disease.

$PM_{2.5}$ Model Results

Single Variable Linear Regression Models ($PM_{2.5}$ vs. AOD)

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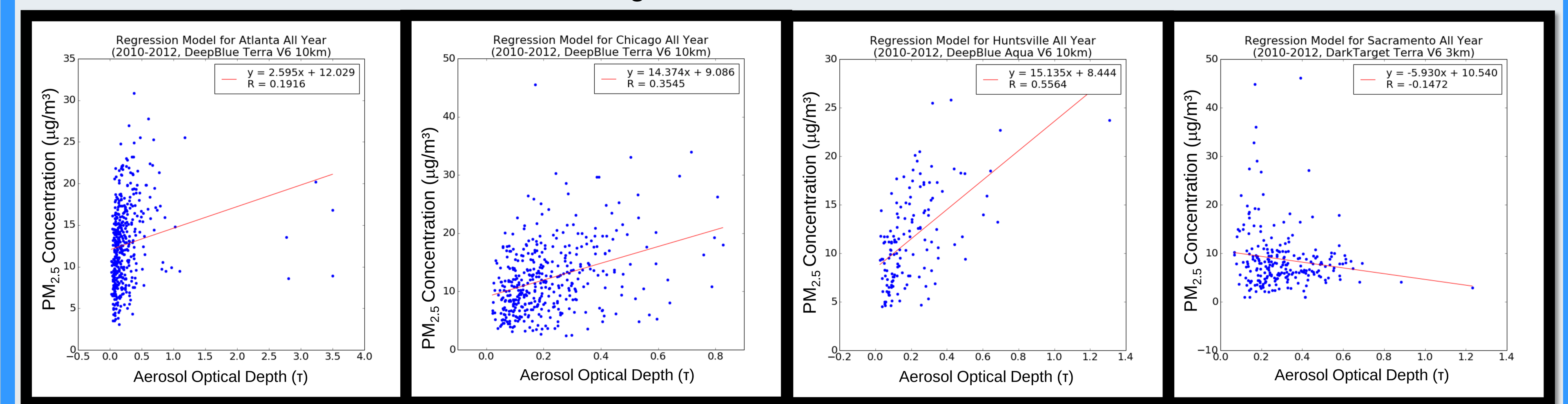

Validation of Single Variable Model

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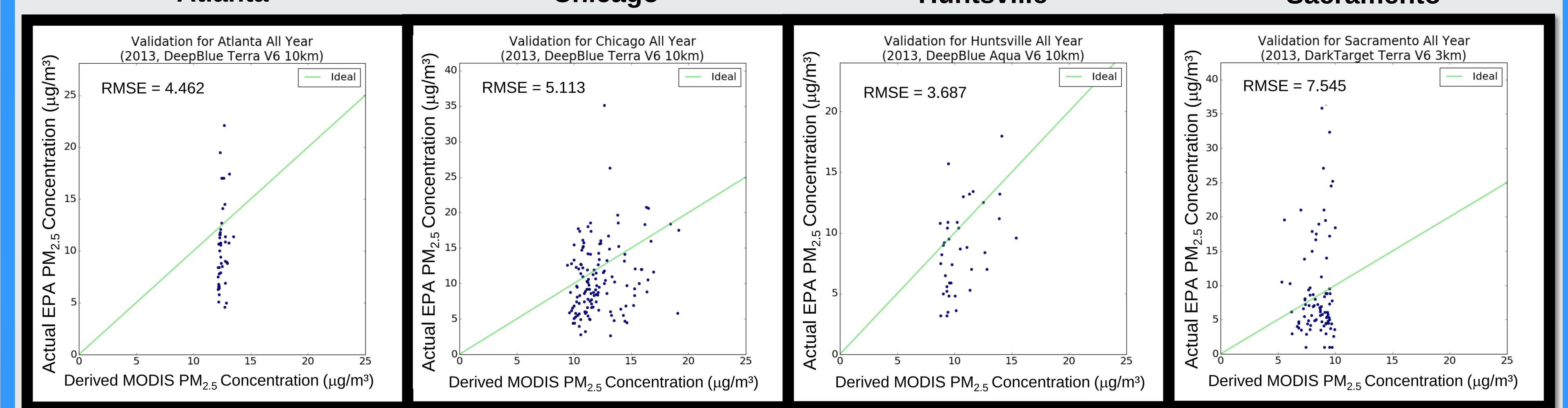

Validation of Multivariable Model

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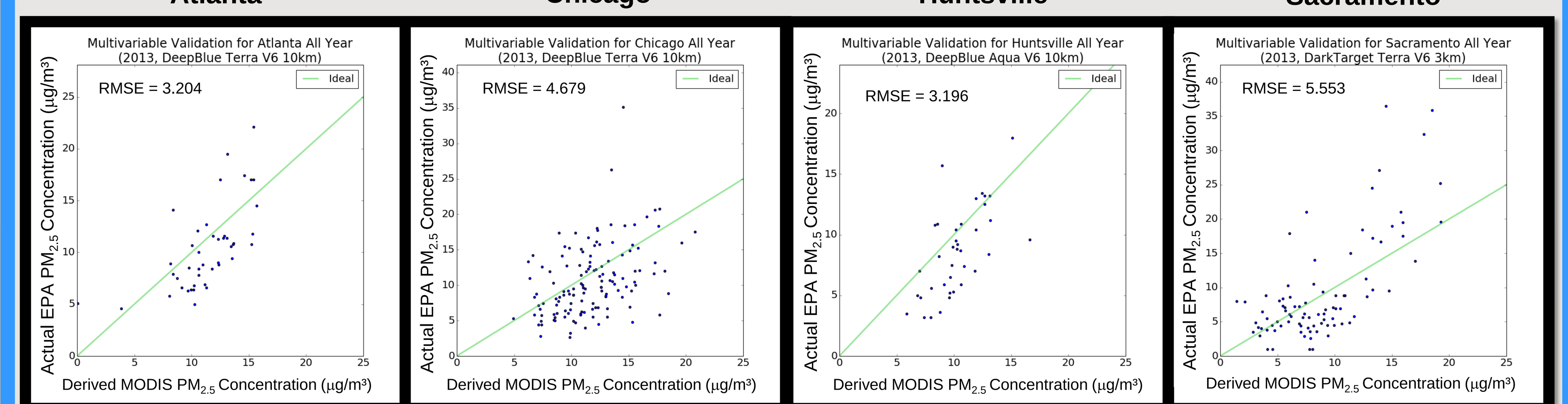


R Enhancements

Algorithm	Los Angeles Original	New	Difference	N	Sacramento Original	New	Difference	N	San Jose Original	New	Difference	N	Chicago Original	New	Difference	N
DarkTarget Aqua V5.1 10km	-0.212	0.574	0.786	173	-0.159	0.564	0.723	174	-0.09	0.471	0.561	301	0.249	0.41	0.161	123
DarkTarget Aqua V6 3km	-0.224	0.541	0.765	242	-0.227	0.587	0.814	223	-0.273	0.501	0.774	395	0.389	0.523	0.134	304
DarkTarget Aqua V6 10km	-0.262	0.531	0.793	231	-0.233	0.567	0.8	191	-0.197	0.463	0.66	343	0.339	0.502	0.163	225
DarkTarget Terra V5.1 10km	-0.229	0.546	0.775	162	-0.065	0.517	0.582	186	-0.122	0.492	0.614	279	0.373	0.523	0.15	198
DarkTarget Terra V6 3km	-0.202	0.552	0.754	237	-0.147	0.57	0.717	234	-0.197	0.479	0.676	399	0.304	0.471	0.167	338
DarkTarget Terra V6 10km	-0.25	0.521	0.771	209	-0.137	0.562	0.699	223	-0.174	0.472	0.646	339	0.334	0.469	0.135	305
DeepBlue Aqua V5.1 10km	0.025	0.546	0.521	208									0.248	0.42	0.172	83
DeepBlue Aqua V6 10km	0.016	0.568	0.552	247	0.224	0.597	0.373	210	-0.063	0.488	0.551	397	0.311	0.462	0.151	311
DeepBlue Terra V6 10km	-0.171	0.523	0.694	221	0.129	0.577	0.448	248	-0.109	0.477	0.586	387	0.354	0.493	0.139	405

Algorithm	Atlanta Original	New	Difference	N	Huntsville Original	New	Difference	N	Nashville Original	New	Difference	N	Gary Original	New	Difference	N
DarkTarget Aqua V5.1 10km	0.505	0.615	0.11	323	0.567	0.643	0.076	115	0.458	0.608	0.15	374	0.571	0.646	0.075	93
DarkTarget Aqua V6 3km	0.427	0.572	0.145	427	0.508	0.579	0.071	155	0.428	0.577	0.149	465	0.398	0.497	0.099	133
DarkTarget Aqua V6 10km	0.482	0.599	0.117	363	0.561	0.624	0.063	133	0.491	0.605	0.114	423	0.361	0.477	0.116	112
DarkTarget Terra V5.1 10km	0.494	0.629	0.135	368	0.447	0.62	0.173	125	0.428	0.607	0.179	425	0.312	0.466	0.154	109
DarkTarget Terra V6 3km	0.429	0.581	0.152	480	0.458	0.575	0.117	164	0.378	0.597	0.219	493	0.375	0.514	0.139	141
DarkTarget Terra V6 10km	0.476	0.607	0.131	402	0.478	0.604	0.126	132	0.453	0.606	0.153	451	0.348	0.484	0.136	124
DeepBlue Aqua V5.1 10km									0.407	0.65	0.243	33				
DeepBlue Aqua V6 10km	0.229	0.538	0.309	425	0.556	0.638	0.082	141	0.316	0.565	0.249	478	0.309	0.435	0.126	136
DeepBlue Terra V6 10km	0.192	0.534	0.342	453	0.484	0.623	0.139	142	0.325	0.541	0.216	493	0.246	0.439	0.193	139

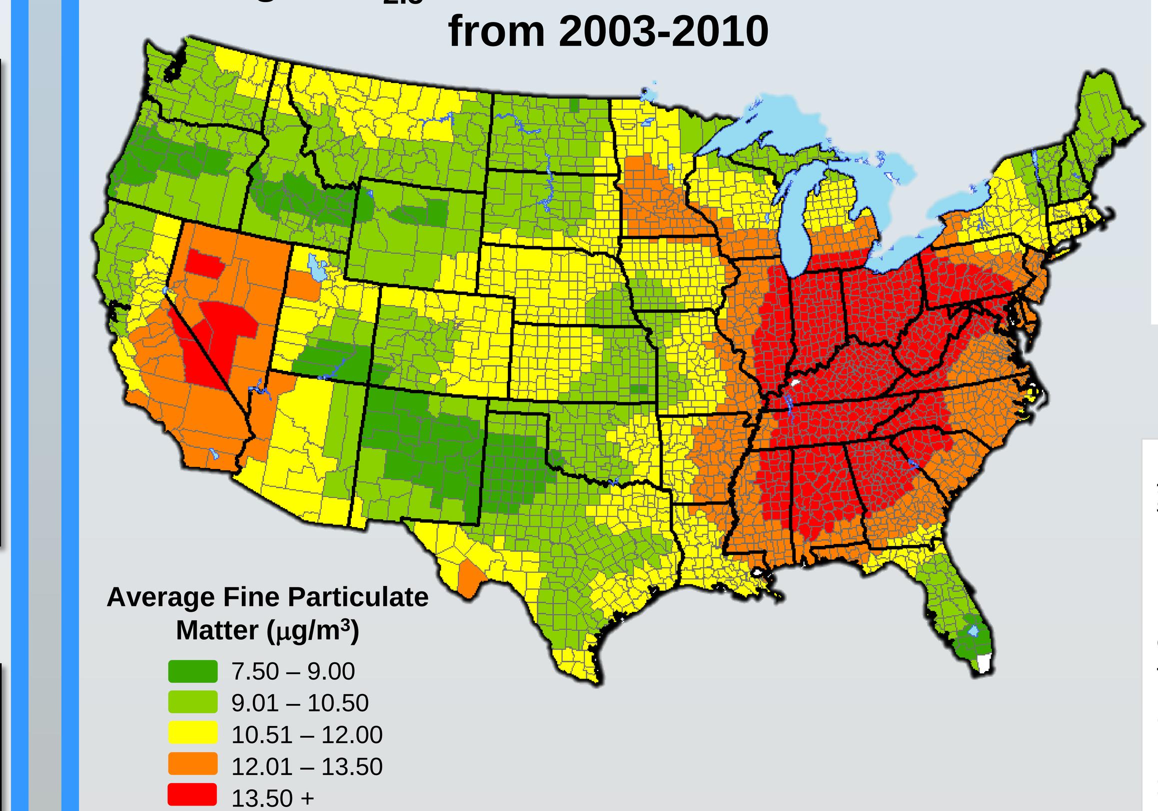
RMSE Enhancements

Algorithm	Los Angeles Original	New	Enhancement	N	Sacramento Original	New	Enhancement	N	San Jose Original	New	Enhancement	N	Chicago Original	New	Enhancement	N
DarkTarget Aqua V5.1 10km	4.268	4.108	3.70%	55	7.75	5.621	27.50%	70	6.831	5.686	16.80%	248	4.125	3.761	8.80%	25
DarkTarget Aqua V6 3km	4.471	4.24	5.20%	81	8.067	6.183	23.40%	90	6.811	5.742	15.70%	294	4.828	4.803	0.50%	85
DarkTarget Aqua V6 10km	6.017	4.014	33.30%	77	7.694	5.924	23.00%	87	6.748	5.656	16.20%	264	4.684	4.879	-4.20%	56
DarkTarget Terra V5.1 10km	4.312	3.86	10.50%	63	8.006	6.136	23.40%	68	6.94	5.749	17.20%	233	5.208	4.602	11.60%	62
DarkTarget Terra V6 3km	4.116	4.033	2.00%	76	7.545	5.553	26.40%	88	7.191	6.065	15.70%	286	4.839	4.513	6.70%	92
DarkTarget Terra V6 10km	4.394	4.124	6.10%	73	8.092	6.175	23.70%	71	7.169	6.022	16.00%	247	5.12	4.784	6.60%	83
DeepBlue Aqua V5.1 10km	4.438	4.285	3.40%	67									4.131	4.316	-4.50%	24
DeepBlue Aqua V6 10km	6.069	4.231	30.30%	83	7.49	5.606	25.20%	94	6.844	5.475	20.00%	274	4.65	4.537	2.40%	103
DeepBlue Terra V6 10km	4.602	4.334	5.80%	79	8.15	6.165	24.40%	79	7.456	6.122	17.90%	280	5.113	4.679	8.50%	133

Algorithm	Atlanta Original	New	Enhancement	N	Huntsville Original	New	Enhancement	N	Nashville Original	New	Enhancement	N	Gary Original	New	Enhancement	N
DarkTarget Aqua V5.1 10km	3.235	2.566	20.70%	28	3.433	3.194	7.00%	32	3.666	3.231	11.90%	82	4.906	4.853	1.10%	29
DarkTarget Aqua V6 3km	3.267	2.955	9.60%	36	3.678	3.385	8.00%	41	3.914	3.326	15.00%	106	5.029	4.948	1.60%	39
DarkTarget Aqua V6 10km	3.352	2.699	19.50%	29	3.459	3.203	7.40%	38	3.571	3.222	9.80%	89	5.084	5.07	0.30%	34
DarkTarget Terra V5.1 10km	3.721	2.746	26.20%	35	3.722	3.58	3.80%	42	3.458	3.048	11.90%	95	5.387	4.527	16.00%	32
DarkTarget Terra V6 3km	3.77	2.99	20.70%	38	3.999	3.731	6.70%	51	3.674	3.194	13.10%	114	4.981	4.849	2.70%	40
DarkTarget Terra V6 10km	3.366	2.915	13.40%	36	4.104	3.884	5.40%	42	3.635	3.41	6.20%	98	5.256	4.976	5.30%	32
DeepBlue Aqua V5.1 10km																
DeepBlue Aqua V6 10km	4.134	3.147	23.90%	33	3.687	3.196	13.30%	38	5.283	3.735	29.30%	106	5.069	4.86	4.10%	41
DeepBlue Terra V6 10km	4.462	3.204	28.20%	44	4.637	4.295	7.40%	45	4.025	3.447	14.40%	106	5.735	5.348	6.70%	36

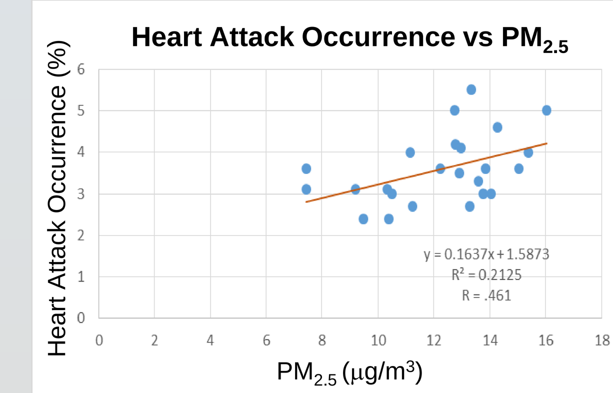
Implications for Public Health

Average $PM_{2.5}$ Concentrations across the U.S. from 2003-2010



Health Concern	R
Poor Health	0.105
Asthma	0.010
High Blood Pressure	0.128
Heart Attacks	0.461
Coronary Heart Disease	0.348
Strokes	0.404

Correlations between Respiratory and Cardiovascular Diseases and $PM_{2.5}$ in various Metropolitan Areas (2003-2010)



Conclusions

We confirmed that there is seasonal variability in PM2.5 concentration, as found in Al-Hamdan et al. (2009). With the incorporation of meteorological variables, we successfully developed more robust PM2.5 models for each region, especially in the West. The most frequently statistically significant meteorological variables depended both on region and season. For example, only in the West was relative humidity repeatedly significant in predicting PM2.5 concentrations. Also in the West, temperature, relative humidity and gust were always more significant than AOD. For every region, peak gust speed was also more significant in the cold season than in the warm season.

We determined that the most useful MODIS product in each case varies by region. In the Midwest and Southeast, the Dark Target algorithm yielded stronger models than Deep Blue, as measured by the correlation coefficient. In the West and Midwest, the Collection 6 3-km resolution yielded more improvement between the single and multivariable models than did the 10-km spatial resolution. These findings promote the role of remotely-sensed AOD data, which can be applied with broader coverage than ground stations for determination of PM2.5 concentrations.

We re-established the connection between PM2.5 and respiratory and cardiovascular diseases, as was found by other studies including Al-Hamdan et al. (2014). Heart attack and stroke occurrence showed the highest correlations with PM2.5, and all the other health outcomes analyzed also illustrated positive correlations.

Future Work

We hope to build generalized regional models using satellite data to better understand $PM_{2.5}$ concentrations on a broader scale without the need for ground stations and to confirm the discovery made about NLDAS enhancement with meteorological variables. Future work will also continue improving these models for additional cities across the globe and to investigate potential causal relationships between AOD, $PM_{2.5}$, and public health.

Acknowledgements

We would like to thank the NSSTC, Center for Applied Atmospheric Research and Education (CAARE) Program, NASA Marshall Space Flight Center (MSFC), Universities Space Research Association (USRA), and Dr. Sen Chiao from San Jose State University. Support was provided by NASA Office of Education's Minority Research and Education Project Contract Number NNX15AQ02A.

References

1. Al-Hamdan, M. Z., Crosson, W. L., Limaye, A. S., Rickman, D. L., Quattrochi, D. A., Estes, M. G., Qualters, J. R., Sinclair, A. H., Tolsma, D. D., Adeniyi, K. A., and Niskar, A. S., 2009: Methods for Characterizing Fine Particulate Matter Using Ground Observations and Remotely Sensed Data: Potential Use for Environmental Public Health Surveillance. J. Air & Waste Manage. Assoc. 59: 865-881. DOI: 10.3155/1047-3289.59.7.865.

2. Al-Hamdan, M. Z., Crosson, W. L., Economou, S. A., Estes, M. G., Estes, S. M., Hemmings, S. N., Kent, S. T., Puckett, M., Quattrochi, D. A., Rickman, D. L., Wade G. M., and McClure, L. A., 2014: Environmental public health applications using remotely sensed data. Geocarto International. 29: 85-98, DOI: 10.1080/10106049.2012.715209

American Geophysical Union (AGU) Fall Meeting, San Francisco, CA, December 12-16, 2016