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Satellite Remote Sensing of Particulate Matter Air Quality: The Cloud-Cover Problem

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ABSTRACT

Satellite assessments of particulate matter (PM) air quality that use solar reflectance methods are dependent on availability of clear sky; in other words, mass concentrations of PM less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) cannot be estimated from satellite observations under cloudy conditions or bright surfaces such as snow/ice. Whereas most ground monitors measure $PM_{2.5}$ concentrations on an hourly basis regardless of cloud conditions, space-borne sensors can only estimate daytime $PM_{2.5}$ in cloud-free conditions, therefore introducing a bias. In this study, an estimate of this clear-sky bias is provided from monthly to yearly time scales over the continental United States. One year of the Moderate Resolution Imaging Spectroradiometer (MODIS) 550-nm aerosol optical depth (AOD) retrievals from Terra and Aqua satellites, collocated with 371 U.S. Environmental Protection Agency (EPA) ground monitors, have been analyzed. The results indicate that the mean differences between $PM_{2.5}$ reported by ground monitors and $PM_{2.5}$ calculated from ground monitors during the satellite overpass times during cloud-free conditions are less than $\pm 2.5\ \mu g\ m^{-3}$, although this value varies by season and location. The mean differences are not significant as calculated by *t* tests ($\alpha = 0.05$). On the basis of this analysis, it is concluded that for the continental United States, cloud cover is not a major problem for inferring monthly to yearly $PM_{2.5}$ from space-borne sensors.

IMPLICATIONS

Currently, environmental agencies are interested in using satellite-derived aerosol products to monitor and evaluate PM air quality. These products are only available under cloud-free conditions, which may introduce a bias in long-term evaluation of $PM_{2.5}$ air quality. The effect of cloud cover on monthly and yearly $PM_{2.5}$ mass concentration estimations is quantified.

INTRODUCTION

Ground-level or surface pollutants including ozone, carbon monoxide, sulfur dioxide, nitrogen dioxide, and aerosols are produced from various sources. This paper is focused only on aerosols or particulate matter (PM) less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$), also known as fine or respirable particles. These particles are injected into the atmosphere as primary emissions or form in the atmosphere by gas-to-particle conversion. There are various sources of $PM_{2.5}$, including emissions from automobiles, industrial exhaust, and vegetation fires. These fine particles have various effects, including reducing visibility; changing surface temperatures by blocking sunlight from reaching the ground; changing cloud properties by acting as cloud condensation nuclei (CCN)[1]; and, more importantly, becoming a health hazard.[2]

Typically $PM_{2.5}$ mass is measured from surface monitors, and in the United States there are nearly 600 continuous (hourly) stations managed by federal, state, local, and tribal agencies.[3] The $PM_{2.5}$ mass is typically measured by the tapered element oscillating microbalance (TEOM) instrument.[4] A vibrating hollow tube called the tapered element is set in oscillation at resonant frequency and an electronic feedback system maintains the oscillation amplitude. When the ambient airstream enters the mass sensor chamber and particulates are collected at the filter, the oscillation frequency of the tapered element changes, and the corresponding mass change is calculated as the change in measured frequency at time t to the initial frequency at time t_0. The mass concentration is then calculated from dust mass, time, and flow rate. Ideally, only the collection of aerosol mass on the filter should change the tapered element frequency. However, temperature fluctuations, humidity changes, flow pulsation, and change in filter pressure could affect the TEOM performance. Even in best-case scenarios when the operational parameters can be held constant, the heat-induced loss of volatile material could pose serious errors in the $PM_{2.5}$ mass.[5] However, various correction factors are usually applied to adjust for these factors, although the $PM_{2.5}$ mass usually represents the lower limits of a true value.[5]

These ground measurements are invaluable for measuring, monitoring, and establishing regulatory policies. The U.S. Environmental Protection Agency (EPA) has established guidelines for what constitutes good and hazardous air quality.[3] In 1971, EPA issued PM air quality standards that were revised first in 1987 and further in 1997. In 2006, EPA changed the standards for 24-hr averaged $PM_{2.5}$ mass values from 65 to 35 $\mu g\ m^{-3}$ primarily on the basis of scientific studies regarding public health.[2]

The ground monitors have obvious advantages. The measurement techniques can be standardized and applied across all locations. They can measure pollution 24 hr/day and provide hourly, daily, monthly, or any type of time average. They can measure pollution regardless of clouds because these are filter-based measurements that are usually fixed at the surface. They also have certain disadvantages. The obvious one is that they are point measurements and are not representative of pollution over large spatial areas. For example, Huntsville, AL, with an area of approximately of 3223 km^2, has only one PM$_{2.5}$ monitor and therefore it cannot capture pollution in and around the city, nor the gradients in pollution. These ground monitors often miss pollution that is not within the sampling area of the measurement. Other cities such as Birmingham, AL, have several PM$_{2.5}$ monitors[6] in the region but are still unable of capturing pollution for every square kilometer. Moreover these ground monitors are expensive and require regular maintenance. Also, the lack of a large-scale picture makes it difficult to assess where the pollution is coming from and where it is heading. The United States has the luxury of having more than 1000 ground monitors,[7] but most countries have very few or no ground monitors for PM$_{2.5}$ assessments although scientific studies have shown that exposure to high concentrations of PM$_{2.5}$ can affect mortality.[2]

Satellite Remote Sensing of Aerosol Optical Depth and PM$_{2.5}$

For every square kilometer of the Earth to be monitored, satellite remote sensing is the only viable method. There are several hundred satellites currently in orbit and not all of them have instruments that are suited for air quality measurements. In their critical review, Hoff and Christopher[8] list the sensors that are especially suited for monitoring PM air quality. Currently, the workhorse sensor for measuring global pollution from space on a reliable, repeated basis is the Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS measures reflected and emitted radiance in 36 channels from the ultraviolet to the thermal infrared part of the electromagnetic spectrum. These well-calibrated radiance measurements are converted to aerosol optical depth (AOD), which is a measure of the column (surface to top of atmosphere) integrated extinction (absorption plus scattering).[8,9] Although AOD retrievals from satellites are possible at multiple wavelengths, this paper refers to the AODs at 550 nm, which are interpolated from 470 and 660 nm. However, these AOD values are only available for cloud-free regions. If the pollution is below the cloud, the satellite cannot "see" this pollution and AOD cannot be inferred. Also, AOD values are not retrieved over bright regions such as snow and ice.

Most satellite-based studies are interested in estimating the PM$_{2.5}$ mass near the ground, whereas the satellites provide a unitless AOD value that is representative of the column.[10] The column-integrated AOD is related to PM$_{2.5}$ mass near the ground, but it requires ancillary information to estimate the surface PM$_{2.5}$ from a column measurement, such as vertical structure, relative humidity (RH), and other factors.[8] Perhaps the most critical piece of information is the height of the aerosol layer, because if the aerosols are lofted above, the ground monitor does not measure a value whereas the satellite will provide an AOD value.[11] More than 50 papers have examined the use of satellite AOD to infer PM$_{2.5}$ near the surface,[8] which is not the focus here.

The satellite-based estimates of PM$_{2.5}$ have some obvious advantages, including reliable, repeated coverage globally that is indeed cost-effective for monitoring pollution. There is nearly a 10-yr record of well-calibrated satellite measurements and validated AOD values over the globe that is freely available. The major disadvantage is that they represent columnar values and require other ancillary pieces of information (e.g., meteorology, height information from space/ground-based lidars) to estimate PM$_{2.5}$ mass values near the ground.[8] Moreover, the next generation of geostationary satellites will have sensors with improved spectral, temporal, radiometric resolution to tackle the air quality problem in ways that are not possible now.[12]

It has been shown that under conditions of a well-mixed boundary layer height with low ambient RH, the relationship between PM$_{2.5}$ and AOD is indeed excellent.[10]This is especially true for the southeastern United States, where the correlations between hourly PM$_{2.5}$ mass and satellite AOD are greater than 0.6 and those between daily PM$_{2.5}$ mass and AOD are greater than 0.9.[10,13] On the other hand, these relationships break down if only a two-variate (PM$_{2.5}$-AOD) regression is performed.[14] However, when height information coupled with meteorology is used, these relationships can be improved.[10,15]

The Cloud-Cover Problem

One of the major criticisms of the satellite-based methods is that they can provide AOD and therefore PM$_{2.5}$ estimations only when there are no clouds.[16] To address this issue, Gupta and Christopher[17] calculated PM$_{2.5}$ mass from daily ground measurements (PM$_{2.5}$) from monthly to yearly time scales (ALLPM) and compared these against the same ground-measurements only for those days when satellite data are available for clear-sky conditions (CLEARPM). It is important to note that they did not use the satellite-derived AOD; they simply used the PM$_{2.5}$ from the ground monitors during the time of the satellite overpass when MODIS did not report clouds. They reported these results over 38 ground monitors over the southeastern United States and concluded that although satellite data are generally available less than 50% of the time, mean differences between ALLPM and CLEARPM over monthly to yearly time scales is less than 2 μg m^{-3}, indicating that low sampling from satellites due to cloud cover and other reasons (e.g., bright snow/ice surfaces) is not a major problem for studies that require long-term PM$_{2.5}$ datasets. This means that on a certain day, over a location, the satellite may not provide a PM$_{2.5}$ mass value, but over monthly to yearly time scales the mean difference between the values averaged by the ground monitor and the satellite is within 2 μg m^{-3}, although this value can be higher over certain locations depending on variability in PM$_{2.5}$ mass. This is especially important because long-term exposure studies require global datasets on longer time scales,[2] and it is important to know the utility of satellite data, especially because they are not used in cloudy conditions.

Because analyzing only the southeastern United States limits the applicability of the results to other regions, this paper analyzed data from nearly 371 ground monitors over the entire United States to see if cloud cover poses a problem for reporting long-term (in this case monthly to yearly time scales) $PM_{2.5}$ statistics. Data from only 371 of the more than 600 ground monitors are used because of sampling issues that are explained in the section *Study Area, Data, and Methods*. The questions asked are still the same as those posed by Gupta and Christopher,[17] except that they are analyzed for the entire United States for all seasons, which represents a wide range of surface and climate regimes. The questions are as follows: What is the difference between ground-based $PM_{2.5}$ (ALLPM) and the $PM_{2.5}$ for only those days in which satellite data are available (CLEARPM) on monthly and yearly time scales? How many days of satellite data are available because of cloud-cover contamination and other limitations for $PM_{2.5}$ air quality research?

STUDY AREA, DATA, AND METHODS

To analyze these differences, the United States were categorized by 10 EPA zones (Figure 1) that have several unique aerosol types and climate regimes.[18] Twenty-four-hour average $PM_{2.5}$ mass concentration values were used from 600 ground monitoring stations (Figure 2) from January 1, 2006 to December 31, 2006, covering the entire continental United States. These daily $PM_{2.5}$ values were first used to calculate monthly means (ALLPM). Terra and Aqua MODIS satellite data (MODO4 and MYD04, Collection 5, respectively)[19] were obtained that contained AOD and other geophysical parameters in 10- by 10-km^2 spatial resolution. The Terra and Aqua overpasses occur at approximately 10:30 a.m. and 1:30 p.m. local time, respectively. The MODIS AOD data are available for cloud-free conditions and retrieval is performed when surface reflectance in the 2.1-μm channel is less than 0.4. The MODIS algorithm also considers the retrieved AOD as questionable if the 2.1-μm channel reflectance is more than 0.25.[19] For each one of the $PM_{2.5}$ ground monitors, a 5 × 5 group of the 10- by 10-km^2 MODIS pixels centered on the ground monitor is examined. This method of using 5 × 5 pixels is often the standard practice when comparing ground-based with satellite measurements.[13] The spatial resolution of one MODIS AOD pixel is approximately 10 × 10 km^2, whereas surface measurements are point values, which makes intercomparisons difficult. Even if the MODIS pixel was small enough, it does not represent the same viewing conditions because of differences between observation areas and varying path lengths through the atmosphere. Averaging level 2 MODIS AOD pixels using a 5- by 5-pixel box over the ground monitors and 15-min observations over 1 hr represents a similar air mass as observed by MODIS. Only the satellite data were used to check if AOD retrievals are available for the 5- by 5-pixel grid. Even if one of the pixels in the 5 × 5 grid had a reported AOD value, the ground-based $PM_{2.5}$ for these days are tagged and labeled as CLEARPM, because this is what MODIS will sample over time. If MODIS-retrieved

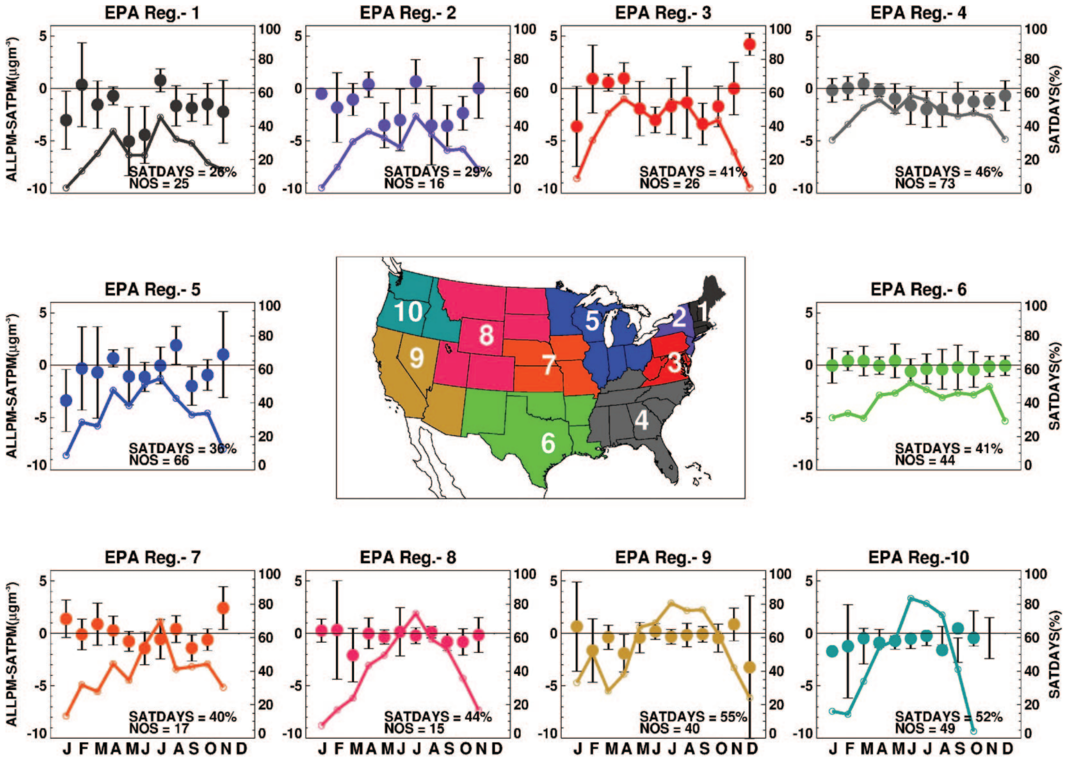

Figure 1. The center of the figure shows the EPA regions in various colors with the EPA regions marked from 1 to 10. The 10 panels surrounding show the number of days available from MODIS for estimating $PM_{2.5}$ shown as connected lines (0–100%), the ALLPM-CLEARPM differences for each month, and the standard deviation for each EPA region.

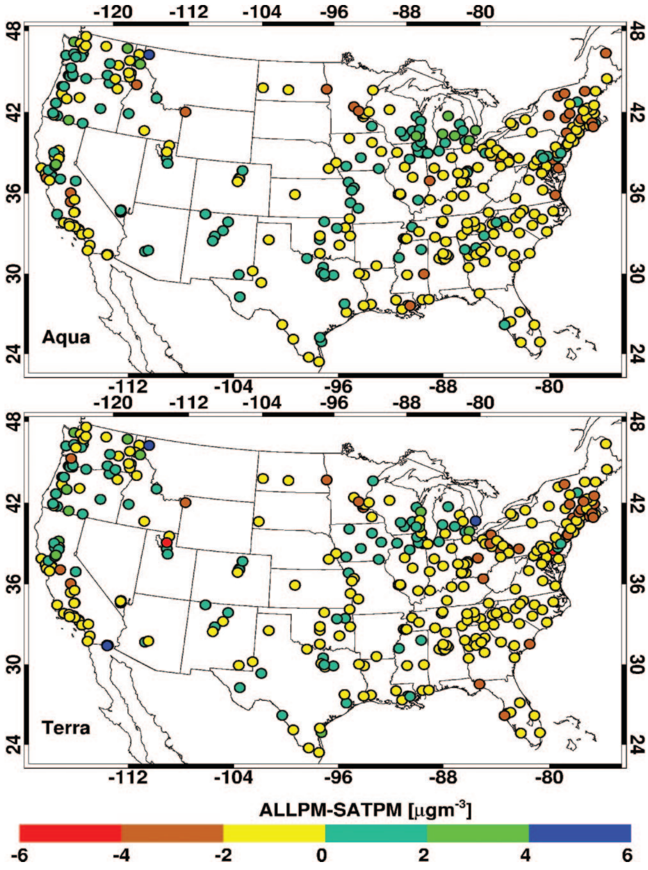

Figure 2. The difference between the annual mean ALLPM-CLEARPM in µg m^{-3} for each $PM_{2.5}$ ground monitor for (a) Aqua and (b)Terra.

AOD is present on any given day over the ground location, the $PM_{2.5}$ value from the ground was included in computing monthly means and is referred to as CLEARPM. Note that the satellite-derived AOD values are not used in the calculations. In this way, the difference between mean $PM_{2.5}$ values from the all-ground measurements (ALLPM) and $PM_{2.5}$ values from only those ground measurements for which the satellite-derived AOD values are available (CLEARPM) were measured. Also tracked were the number of days when satellite data are available in a given month, season, or year (referred to as SATDAYS throughout the paper). For example, if a 5 × 5 grid had reported AOD values for every single day in an entire month, then it would indicate that there was 100% data availability from the satellite during that month. For all of the following analysis, 85% thresholds were set on data availability from the surface data to maintain uniformity across all locations. For seasonal analysis 75 of 90 days, and for monthly analysis 25 of 30 days, corresponding to approximately 85% data availability, were used. Although there are more than 600 AirNow sites across the United States, because of this strict criterion, data from only 371 ground monitors were used. The Terra and Aqua satellites were used to assess if there are differences between ALLPM and CLEARPM due to differences in overpass time.

RESULTS AND DISCUSSION

Figure 1 shows the 10 EPA regions in various colors in the center. Each surrounding panel represents an EPA region and shows the number of days available from MODIS over each EPA region for each month (SATDAYS), which are shown as connected lines (secondary *y*-axis). Also shown in each panel is the mean difference between ALLPM and CLEARPM for each month and the standard deviations within that EPA region. The number of ground monitors and the mean SATDAYS for each EPA region are also indicated. For example, for EPA region 4 (southeastern United States), the highest numbers of SATDAYS are during spring and summer months, with slightly lower values available during the winter season. However, the seasonal ALLPM-CLEARPM (Table 1) ranges from −0.26 to 1.18 µg m^{-3}, indicating that there is very little sampling bias due to missing days when cloud cover (and snow/ice backgrounds) did not allow MODIS to obtain aerosol observations. Several interesting features can be seen in Figure 1. The number of ground monitors is not constant among the EPA regions. Note that only those ground monitors have been used where 85% of MODIS measurements are available. EPA regions 7 and 8 have only 15–17 monitors, whereas EPA region 4 (southeast) has the highest number of ground monitors (73). Although the selection of locations of ground monitors may be concentrated more in urban locations, EPA regions 7 and 8 often experience a high level of transported pollutants from biomass burning smoke from Canada[20] that are currently not monitored because of the lack of ground observations. Satellite remote sensing in this case can be a cost-effective option for monitoring PM pollution, especially those transported from outside of the continental United States.

In general, spring and summer months are the best for monitoring pollution from space. Some regions have a large month-to-month variation in SATDAYS primarily because of cloud/snow cover issues. For example EPA region 3 (northeast) has less than 10% SATDAYS (~3 days per month), whereas the drier climate of EPA region 9 allows for more SATDAYS, although some areas may not have AOD retrievals because of high surface reflectance and other retrieval limitations.

In general, ALLPM-CLEARPM should be largest when SATDAYS is low because fewer numbers of days for sampling produces larger standard deviations. This can be seen in almost all EPA regions (Figure 1) where winter months have the lowest number of SATDAYS and the corresponding differences in ALLPM and CLEARPM are higher, except in the case of EPA regions 4 and 6 where differences are higher during summer and fall seasons although SATDAYS are also high. However, there are some exceptions (EPA regions 4 and 6) because the value of ALLPM-CLEARPM may also depend more on day-to-day variability in $PM_{2.5}$ mass concentration in any given month associated with increased production of secondary aerosols due to enhanced photochemistry during summer months. This daily variability is a function of location, or, more precisely, the type and/or sources of aerosols that cannot be assessed from these datasets. The value of ALLPM-CLEARPM will be low for regions and seasons where day-to-day variability is lower compared with high-variability regions and seasons. Even low numbers of SATDAYS in a region of low variability in $PM_{2.5}$ should produce a smaller difference in ALLPM and CLEARPM. This can be seen in EPA region 1 during the winter season

Table 1. Statistics for all relevant parameters used in this study for each EPA region and for each season.

Season	EPA Region	ALLPM[a]	σ_{ALLPM}[b]	CLEARPM[c]	$\sigma_{CLEARPM}$[d]	AOD[e]	σ_{AOD}[f]	ALLPM-CLEARPM	SATDAY (%)
Winter	1	10.56	2.42	10.55	4.35	0.12	0.06	0.01	12
	2	10.47	2.27	12.09	3.16	0.19	0.08	−1.62	14
	3	11.99	3.27	12.72	4.97	0.11	0.05	−0.73	19
	4	10.59	2.07	10.85	2.59	0.08	0.05	−0.26	35
	5	12.72	4.18	13.98	5.57	0.20	0.08	−1.26	22
	6	8.12	3.56	8.03	3.54	0.10	0.05	0.09	31
	7	9.45	2.43	9.02	2.72	0.13	0.05	0.43	25
	8	9.92	3.36	9.61	5.40	0.20	0.10	0.31	13
	9	17.49	7.97	18.92	10.72	0.14	0.09	−1.43	36
	10	9.75	3.22	11.45	5.95	0.09	0.09	−1.7	16
Spring	1	7.37	2.03	9.83	3.97	0.17	0.09	−2.46	28
	2	7.77	2.04	9.16	3.37	0.20	0.08	−1.39	34
	3	12.37	2.78	12.48	4.33	0.17	0.05	−0.11	51
	4	14.07	1.94	14.31	2.41	0.17	0.06	−0.24	52
	5	12.20	3.85	12.58	4.98	0.23	0.09	−0.38	37
	6	11.15	4.09	10.90	4.01	0.18	0.06	0.25	40
	7	10.83	2.27	10.69	2.55	0.20	0.09	0.14	36
	8	7.43	2.54	8.19	2.81	0.26	0.10	−0.76	39
	9	10.92	5.44	11.80	5.85	0.25	0.15	−0.88	45
	10	5.65	1.50	6.47	2.08	0.13	0.07	−0.82	36
Summer	1	11.61	3.66	13.34	3.90	0.23	0.10	−1.73	34
	2	13.39	4.92	15.37	4.90	0.30	0.11	−1.98	36
	3	20.65	4.66	22.60	4.99	0.32	0.09	−1.95	51
	4	19.38	4.00	21.25	4.41	0.37	0.11	−1.87	54
	5	15.46	5.04	15.20	5.52	0.24	0.09	0.26	49
	6	12.59	4.78	13.03	5.21	0.22	0.08	−0.44	48
	7	13.10	3.15	13.54	3.64	0.19	0.05	−0.44	55
	8	9.36	3.28	9.34	3.44	0.22	0.09	0.02	65
	9	13.67	5.87	13.76	5.89	0.25	0.17	−0.09	75
	10	6.57	3.18	7.05	3.11	0.13	0.07	−0.48	74
Fall	1	8.36	2.58	10.19	3.56	0.13	0.06	−1.83	21
	2	9.81	3.42	11.82	3.96	0.17	0.10	−2.01	22
	3	13.65	3.64	15.35	4.39	0.14	0.09	−1.7	36
	4	12.78	2.64	13.91	2.76	0.12	0.07	−1.13	46
	5	12.16	4.12	12.85	4.31	0.15	0.07	−0.69	27
	6	9.65	3.79	9.89	4.21	0.11	0.06	−0.24	47
	7	9.60	3.09	9.50	2.87	0.11	0.06	0.1	39
	8	8.36	3.05	8.97	2.93	0.15	0.07	−0.6	37
	9	14.95	6.45	14.81	6.26	0.18	0.10	0.14	60
	10	9.61	3.29	10.15	3.79	0.14	0.11	−0.54	55

Notes: [a]ALLPM is mean $PM_{2.5}$ from ground monitor that uses all data; [b]σ_{ALLPM} is the ALLPM standard deviation; [c]CLEARPM is the $PM_{2.5}$ calculated only during the satellite overpass when there were no clouds; [d]$\sigma_{CLEARPM}$ is the standard deviation for CLEARPM; [e]AOD is MODIS AOD at 550 nm; [f]σ_{AOD} is the standard deviation in AOD.

(Table 1) where only 12% of days' satellite data were available but the difference in ALLPM and CLEARPM was almost negligible (0.01 $\mu g\ m^{-3}$). However, during other seasons in the same EPA region, SATDAYS are high enough (spring, 28%; summer, 34%; fall, 21%) but still the difference in ALLPM and CLEARPM is much larger (~2 $\mu g\ m^{-3}$), which clearly indicates the difference in variability in surface $PM_{2.5}$ mass concentration in the same region during different seasons. Table 1 provides the mean and standard deviation of ALLPM, CLEARPM, MODIS AOD, and SATDAYS as a function of season and EPA region. Two sample (ALLPM and CLEARPM) *t* tests were performed for each region with the null hypothesis $\mu_{ALLPM} - \mu_{CLEARPM} = 0$ for $\alpha = 0.05$. These results indicate that the differences are statistically not significant and therefore the null hypothesis was not rejected. Figure 2 shows the locations of the ground monitors and the yearly mean ALLPM-CLEARPM differences for each location in micrograms per cubic meter. These differences are also shown for Aqua (Figure 2a) and Terra (Figure 2b). The results can be interpreted along with information from Table 2 that shows the seasonal numbers for each EPA region. Although there are some differences between the Aqua and Terra in Figure 2, for the most part, the ALLPM-CLEARPM differences are not very different between the two sensors. Rather than focusing on individual locations, these differences are assessed as a function of EPA region. Smaller differences are seen in the southeast, whereas some locations in the northeast and west have higher differences primarily because of issues related to cloud cover. One of the largest seasonal changes in cloud cover is seen in EPA region 10 (northwest), which varies from 16 to 74% through the year. The ALLPM-CLEARPM differences range from -0.48 to -1.74 μg m^{-3}. In comparison, EPA region 4 (southeast) has smaller changes in cloud cover as a function of season (35–54%), and ALLPM-CLEARPM differences are between -0.24 and -1.87 μg m^{-3}. Note the seasonality in Table 1 in the ALLPM columns where the ALLPM values are high across most EPA regions during summer and vary markedly across regions during the winter months because of meteorological factors such temperature and precipitation (not shown). Remarkably, the ALLPM-CLEARPM differences are less than 2 μg m^{-3} for every region and every season except during spring for EPA region 1, where a value of -2.5 μg m^{-3} was calculated because of the high cloud cover in this region.

Figure 3 shows some of the key results from this work using the frequency distribution of ALLPM-CLEARPM as a function of the 10 EPA regions. The overall frequency of ALLPM-CLEARPM is negative, which indicates that the $PM_{2.5}$ calculated during the time of the satellite overpass is missing days with lower daily $PM_{2.5}$ mass concentration, making the differences negative. In general, clear sky conditions are quite often associated with low wind speed, sinking air motion, reduced vertical mixing, and enhanced photochemistry. These conditions result in accumulation of pollutants at the ground, and the reverse is true for cloudy conditions when satellite observations of aerosols are not possible. This explains the negative differences between ALLPM and CLEARPM due to cloud cover. However, during winter at high latitudes, surface snow cover provides another limitation to aerosol retrieval from the satellite observations because the MODIS Collection 5 aerosol retrieval algorithm largely follows the dark target approach.[19] Figure 3 clearly shows that negative ALLPM-CLEARPM differences occurred during the dry and hotter months, whereas positive differences occurred during the colder months. Except for EPA regions 1, 2, and 3, more than 80% of the differences are within ±2.5 μg m^{-3}. These results provide tremendous confidence for using satellite data for assessing $PM_{2.5}$ although cloud/snow cover prohibits measurements nearly 50% of the time. To reiterate, this does not mean that the AOD and $PM_{2.5}$ are well correlated. The authors simply note that for long-term averages from monthly to yearly time scales, cloud/snow cover sampling biases only introduce a mean uncertainty of approximately ±2.5 μg m^{-3}.

CONCLUSIONS

Space-borne sensors can only provide an estimate of $PM_{2.5}$ when there are no clouds obstructing their view, whereas ground monitors measure $PM_{2.5}$ mass concentrations regardless of cloud cover. This study analyzed 1 yr of Terra-MODIS and Aqua-MODIS satellite data in conjunction with nearly 400 ground monitors of $PM_{2.5}$ to answer the following question: What is the difference between $PM_{2.5}$ mass measured by the ground monitor and the $PM_{2.5}$ mass measured at the ground only during the times when there was no cloud cover sensed by the satellite? Quantifying this is important because if satellites are to be used to assess $PM_{2.5}$ near the ground, how much the $PM_{2.5}$ biases are due to missed opportunities because of clouds needs to be known. These results indicate that over 371 ground monitors the mean differences are within 2.5 μg m^{-3}. It is therefore concluded that if the satellite AOD

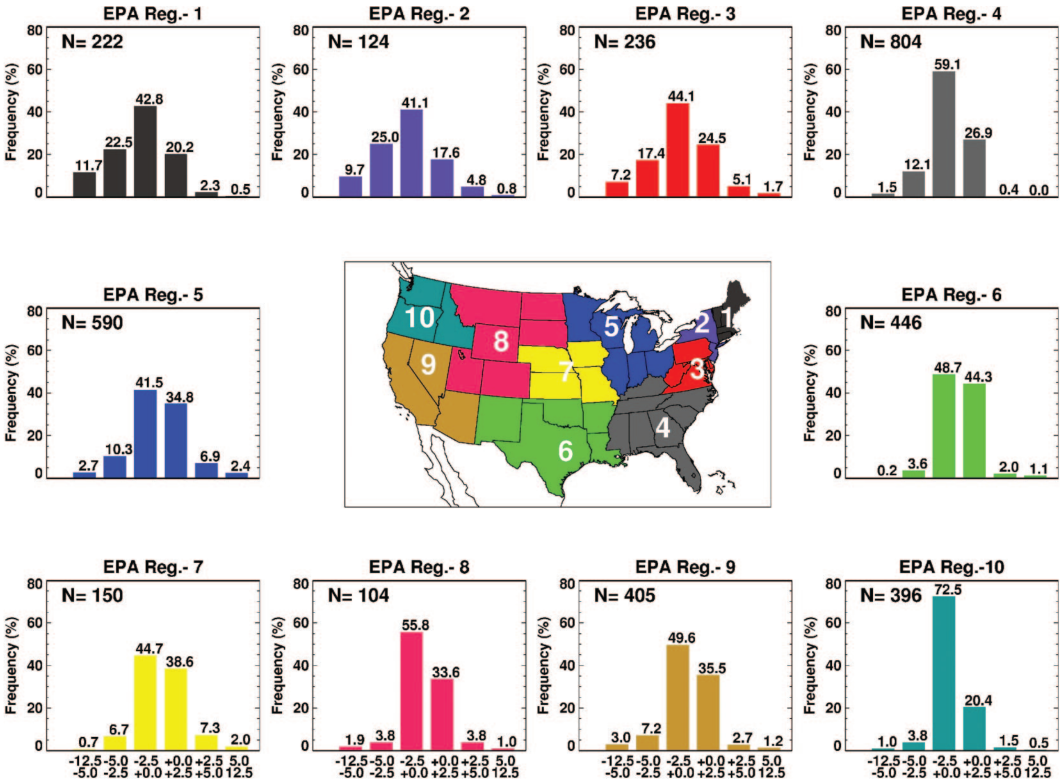

Figure 3. The center of the figure shows the EPA regions in various colors with the EPA regions marked from 1 to 10. The 10 panels surrounding show the frequency distribution of ALLPM-CLEARPM for the 10 EPA zones.

can be appropriately used to estimate $PM_{2.5}$ near the ground, then clouds do not pose a major problem for estimating monthly to yearly $PM_{2.5}$ mass concentrations that are critical for long-term exposure studies.

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REFERENCES

1. Kaufman, Y.J.; Tanre, D.; Boucher, O. A Satellite View of Aerosols in the Climate System; *Nature* **2002**, *419*, 215-223.
2. Pope, C.A., III; Dockery, D.W. Health Effects of Fine Particulate Air Pollution: Lines that Connect; *J. Air & Waste Manage. Assoc.* **2006**, *56*, 709-742.
3. *Ambient Air Monitoring Strategy for State, Local, and Tribal Air Agencies*; U.S. Environmental Protection Agency; Office of Air Quality Planning and Standards: Research Triangle Park, NC, 2008.
4. Lee, J.H.; Hopke, P.K.; Holsen, T.M.; Polissar, A. Evaluation of Continuous and Filter-Based Methods for Measuring $PM_{2.5}$ Mass Concentration; *Aerosol Sci. Technol.* **2005**, *39*, 290-303.
5. Grover, B.D.; Kleinman, M.; Eatough, N.L.; Eatough, D.J.; Hopke, P.K.; Long, R.W.; Wilson, W.E.; Meyer, M.B.; Ambs, J.L. Measurement of Total $PM_{2.5}$ Mass (Nonvolatile Plus Semivolatile) with the Filter Dynamic Measurement System Tapered Element Oscillating Microbalance Monitor; *J. Geophys. Res.* **2005**, *110*, D07S03; doi: 10.1029/2004JD004995.
6. Wang, J.; Christopher, S.A. Intercomparison between Satellite-Derived Aerosol Optical Thickness and $PM_{2.5}$ Mass: Implications for Air Quality Studies; *Geophys. Res. Lett.* **2003**, *30*, 2095; doi: 10.1029/2003GL018174.
7. Al-Saadi, J.; Szykman, J.; Pierce, R.B.; Kittaka, C.; Neil, D.; Chu, D.A.; Remer, L.; Gumley, L.; Prins, E.; Weinstock, L.; Macdonald, C.; Wayland, R.; Dimmick, F.; Fishman, J. Improving National Air Quality Forecasts with Satellite Aerosol Observations; *Bull. Am. Meteorol. Soc.* **2005**, *86*, 1249-1261.
8. Hoff, R.; Christopher, S.A. Remote Sensing of Particulate Matter Air Pollution from Space: Have We Reached the Promised Land; *J. Air & Waste Manage. Assoc.* **2009**, *59*, 645-675; doi: 10.3155/1047-3289.59.6.645.
9. Remer, L.A.; Kaufman, Y.J.; Tanré, D.; Mattoo, S.; Chu, D.A.; Martins, J.V.; Li, R.-R.; Ichoku, C.; Levy, R.C.; Kleidman, R.G.; Eck, T.F.; Vermote, E.; Holben, B.N. The MODIS Aerosol Algorithm, Products and Validation; *J. Atmos. Sci.* **2005**, *62*, 947-973.
10. Gupta, P.; Christopher, S.A. Particulate Matter Air Quality Assessment Using Integrated Surface, Satellite, and Meteorological Products: Multiple Regression Approach; *J. Geophys. Res.* **2009**, *114*, D14205; doi: 10.1029/2008JD011496.
11. Engel-Cox, J.A.; Hoff, R.M.; Rogers, R.; Dimmick, F.; Rush, A.C.; Szykman, J.J.; Al-Saadi, J.; Chu, D.A.; Zell, E.R. Integrating Lidar and Satellite Optical Depth with Ambient Monitoring for 3-Dimensional Particulate Characterization; *Atmos. Environ.* **2006**, *40*, 8056-8067; doi: 10.1016/j.atmosenv.2006.02.039.
12. *Geostationary Coastal and Air Pollution Events*; Workshop Report; National Aeronautics and Space Administration: Chapel Hill, NC, 2008.
13. Gupta, P.; Christopher, S.A. Seven Year Particulate Matter Air Quality Assessment from Surface and Satellite Measurements; *Atmos. Chem. Phys. Discuss.* **2008**, *8*, 3311-3324.
14. Engel-Cox, J.A.; Christopher, H.H.; Coutant, B.W.; Hoff, R.M. Qualitative and Quantitative Evaluation of MODIS Satellite Sensor Data for Regional and Urban Scale Air Quality; *Atmos. Environ.* **2004**, *38*, 2495-2509.
15. Liu, Y.; Park, R.J.; Jacob, D.J.; Li, Q.; Kilaru, V.; Sarnat, J.A. Mapping Surface Concentrations of Fine Particulate Matter Using MISR Satellite Observations of Aerosol Optical Thickness; *J. Geophys. Res.* **2004**, *109*, D22206; doi: 10.1029/2004JD005025.
16. Hidy, G. Introduction to the 2009 Critical Review: Remote Sensing of Particulate Pollution from Space: Have We Reached the Promised Land?; *J. Air & Waste Manage. Assoc.* **2009**, *59*, 642-644; doi: 10.3155/1047-3289.59.6.642.
17. Gupta, P.; Christopher, S.A. An Evaluation of Terra-MODIS Sampling for Monthly and Annual Particulate Matter Air Quality Assessment over the Southeastern United States; *Atmos. Environ.* **2008**, *42*, 6465-6471.
18. Malm, W.C.; Sisler, J.F.; Huffman, D.; Eldred, R.A.; Cahill, T.A. Spatial and Seasonal Trends in Particle Concentration and Optical Extinction in the United States; *J. Geophys. Res.* **1994**, *99*, 1347-1370.
19. Levy, R.C.; Remer, L.A.; Mattoo, S.; Vermote, E.F.; Kaufman, Y.J. Second-Generation Operational Algorithm: Retrieval of Aerosol Properties over Land from Inversion of Moderate Resolution Imaging Spectroradiometer Spectral Reflectance; *J. Geophys. Res.* **2007**, *112*, D13211; doi: 10.1029/2006JD007811.
20. Colarco, P.R.; Schoeberl, M.R.; Doddridge, B.G.; Marufu, L.T.; Torres, O.; Welton, E.J. Transport of Smoke from Canadian Forest Fires to the Surface near Washington, D.C.: Injection Height, Entrainment, and Optical Properties; *J. Geophys. Res.* **2004**, *109*, D06203; doi: 10.1029/2003JD004248.

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