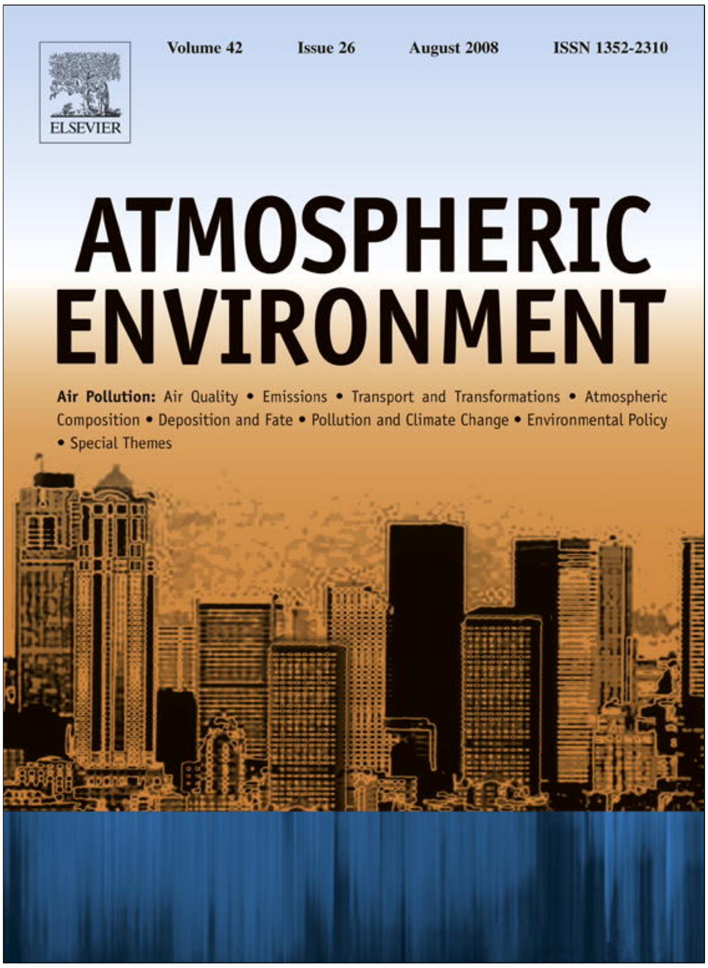

Volume 42 Issue 26 August 2008 ISSN 1352-2310

ELSEVIER

ATMOSPHERIC ENVIRONMENT

Air Pollution: Air Quality • Emissions • Transport and Transformations • Atmospheric Composition • Deposition and Fate • Pollution and Climate Change • Environmental Policy • Special Themes

Atmospheric Environment 42 (2008) 6465–6471

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

An evaluation of Terra-MODIS sampling for monthly and annual particulate matter air quality assessment over the Southeastern United States

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ARTICLE INFO

Article history:
Received 3 October 2007
Received in revised form 14 April 2008
Accepted 17 April 2008

Keywords:
Air quality
Satellite remote sensing
Particulate matter

ABSTRACT

Although satellites provide reliable and repeated measurements on a global basis, particulate matter air quality information can be derived from satellites only when clouds are absent and when surface conditions are favorable. However, ground measurements provide particulate matter information irrespective of cloud cover and surface conditions. Therefore there could be a sampling bias when using satellite data for air quality research. To examine this issue, we calculate particulate matter (PM2.5) mass concentration from daily ground-based measurements (ALLPM) on monthly to yearly time scales and compare these against the same ground measurements for only those days when satellite data is available (SATPM). To accomplish this, we use six years of PM2.5 mass concentration data from 38 stations along with Terra-MODIS satellite data over the Southeastern United States. Our results indicate that satellite data are generally available less than 50% of the time over these locations, although the interregional variability of data availability is between 32% and 57%. However, the mean differences between the ALLPM and SATPM, over monthly to yearly time scales over the Southeastern United States, is less than 2 μgm^{-3} indicating that low sampling from satellites due to cloud cover and other reasons is not a major problem for studies that require long term PM2.5 data sets. These results have important implications for satellite studies especially over areas where ground-based measurements are not available.

1. Introduction

Particulate matter (PM) is a mixture of both solid and liquid particles suspended in air and is usually classified as fine (PM2.5, $d < 2.5$ μm) and coarse (PM10, $2.5 < d < 10$ μm), where d is the aerodynamic diameter. In this paper, we are primarily concerned with PM2.5 that could be from various sources including dust, vehicle and industrial emissions, forest and agricultural fires. PM2.5 air quality continues to degrade throughout the world due to increasing pressures of urbanization that has serious implications for health, climate, visibility, and hydrology (Kaufman et al., 2002). Although some countries have a dense network of PM2.5 monitoring stations (Al-Saadi et al., 2005), worldwide, there are limited ground measurements thereby creating a challenge for monitoring and studying air pollution. With the launch of Terra and Aqua polar orbiting satellites, there has been an increased emphasis for using satellite data to study PM2.5 to alleviate some of the problems due to the unavailability of ground measurements (Al-Saadi et al., 2005). While satellites can provide reliable, repeated measurements from space, monitoring surface level air pollution continues to be a challenge since most satellite measurements are column-integrated quantities. However, several studies have shown that satellite data can be a good surrogate for

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doi:10.1016/j.atmosenv.2008.04.044

ground measurements provided appropriate adjustments are made for converting columnar quantities to surface values (van Donkelaar et al., 2006; Liu et al., 2004). With new satellites that can now provide vertical distribution of aerosols and clouds, we are poised to make significant advances in using satellite data for particulate matter air quality research (Engel-Cox et al., 2006).

The link between PM exposure and adverse health recently prompted the United States Environmental Protection Agency (EPA) to tighten its 24-h fine particle standard from 65 μgm^{-3} to 35 μgm^{-3} (Federal Register, 2006). Studies show that long term particulate matter exposures are associated with death due to heart failure, and cardiac arrest (Pope et al., 2002). However, it is difficult to obtain long term estimates in large spatial scales from the limited number of ground measurements and therefore the use of satellite data could be beneficial.

Several research papers have outlined the methods by which satellite data can be used to obtain surface PM2.5 (e.g. Wang and Christopher, 2003; Engel-Cox et al., 2006; Hutchison et al., 2005; Gupta et al., 2006; Liu et al., 2004; van Donkelaar et al., 2006). In summary, first the columnar satellite-derived aerosol optical depth (AOD) values are related to surface PM2.5 mass measurements. Then this AOD-PM2.5 relationship can be used to convert the satellite measurements to air quality indices based on EPA guidelines. These values are then color coded for dissemination to the public where Green is for Good air quality and Orange and Red are poor quality. A good example of this can be seen at http://alg.umbc.edu/usaq/.

Given the links between PM2.5 and health, and the scarcity of monitoring stations throughout the world, satellite remote sensing appears to be the only viable method to monitor PM2.5 air pollution over large spatial scales. However, satellite retrievals of AOD rely on cloud-free conditions and favorable surface conditions to obtain PM2.5 air quality thereby limiting the number of days where satellite data can be used over a certain location. Also satellite retrievals are sometimes not available due to various retrieval issues such as bright surface backgrounds and data dropouts. What the satellite retrievals lose in terms of cloud cover limitations, it makes up in terms of the wide spatial coverage that is often useful for assessing how the pollution plumes move from one area to another (Hoff et al., 2005). Even with these limitations, satellite data sets due to their global coverage are a valuable asset for monitoring PM2.5 air quality (Gupta et al., 2007).

In contrast, ground measurements of PM2.5 are available regardless of cloud cover and depending upon the location, measurements are made available every hour or as 24-h averages. While this is extremely useful, ground measurements are limited due to lack of spatial coverage or unavailability. Since continuous monitoring of PM2.5 is essential and monthly and annual averages of PM2.5 air quality is vital for assessing global air quality, it is important to assess whether satellite data can provide the sampling necessary to monitor air quality over these time scales. We assume that satellite data sets are good surrogate for monitoring surface PM2.5 air quality while recognizing that there are indeed some research limitations that are currently being addressed using new satellite data, meteorology, and other tools (e.g. Engel-Cox et al., 2006).

Since PM2.5 mass is measured from the ground irrespective of cloud cover while satellite data only provide AOD information during cloud-free and favorable retrieval conditions, we ask the following questions,

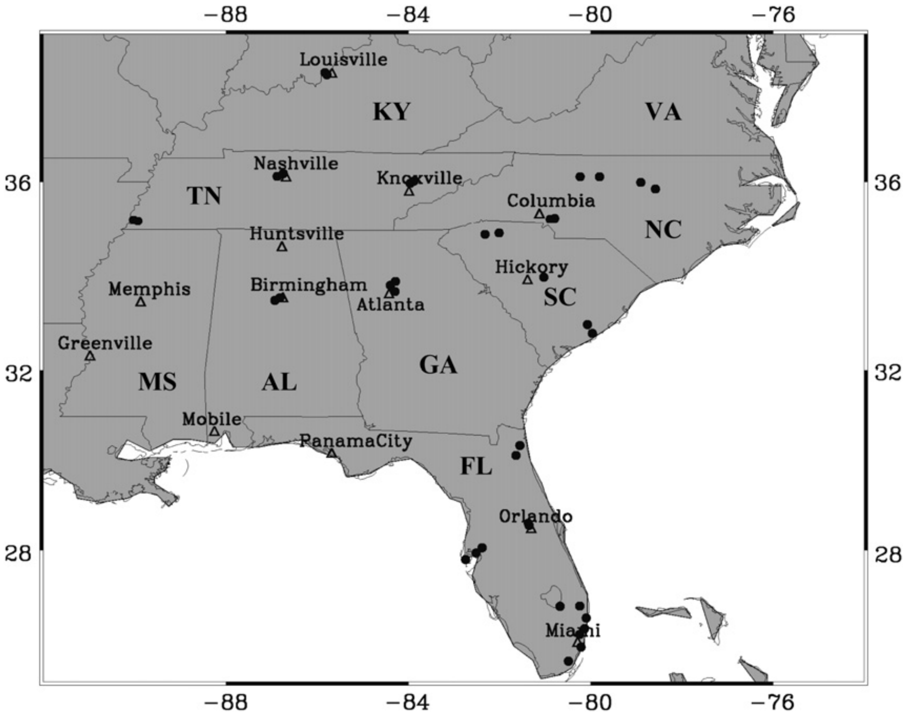

Fig. 1. Area of study and location of PM2.5 measuring stations in the South Eastern United States.

Table 1
Detailed information on surface locations of PM2.5 mass measurements along with mean values of PM2.5, MODIS AOT and available number of days

Station #	City, State	Lat.	Lon.	Months	ALL	PM2.5	SAT DAYS	AOT
1	Birmingham 1, AL	33.55	−86.82	71	2161	18.9	991	0.20
2	Birmingham 2, AL	33.50	−86.92	71	2161	17.4	987	0.19
3	Davie, FL	26.08	−80.24	70	2111	8.3	672	0.27
4	Pompano Beach, FL	26.22	−80.13	66	1982	8.3	713	0.24
5	Jacksonville 1, FL	30.14	−81.63	58	1712	10.3	751	0.19
6	Jacksonville 2, FL	30.36	−81.55	49	1435	10.6	612	0.23
7	Tampa 1, FL	27.93	−82.51	69	2076	11.5	753	0.21
8	Tampa 2, FL	28.05	−82.38	47	1415	11.4	552	0.20
9	Miami, FL	25.79	−80.21	67	2025	9.7	635	0.21
10	Miami, FL	25.47	−80.48	58	1765	7.8	613	0.29
11	Orlando, FL	28.55	−81.35	68	2047	10.3	762	0.21
12	Winter Park, FL	28.60	−81.36	67	1997	10.2	734	0.21
13	Belle Glade, FL	26.72	−80.67	54	1645	7.7	741	0.21
14	Royal Palm Beach, FL	26.73	−80.23	71	2161	7.9	727	0.24
15	Delray Beach, FL	26.46	−80.09	54	1645	7.4	618	0.23
16	Saint Petersburg, FL	27.79	−82.74	71	2140	10.6	728	0.19
17	Decatur, GA	33.69	−84.29	71	2152	15.9	989	0.22
18	Doraville, GA	33.90	−84.28	71	2156	16.6	979	0.23
19	Atlanta, GA	33.82	−84.39	71	2145	16.7	978	0.22
20	Louisville 1, KT	38.23	−85.82	62	1875	16.3	815	0.20
21	Louisville 2, KT	38.19	−85.78	71	2150	16.2	950	0.20
22	Durham, NC	35.99	−78.90	71	2159	14.1	1151	0.20
23	Winston-Salem, NC	36.11	−80.23	68	2061	15.1	1071	0.21
24	Greensboro, NC	36.11	−79.80	48	1461	13.8	797	0.19
25	Charlotte 1, NC	35.22	−80.88	71	2161	15.6	1127	0.21
26	Charlotte 2, NC	35.24	−80.79	71	2161	14.9	1127	0.21
27	Raleigh, NC	35.86	−78.57	68	2069	14.0	1143	0.20
28	North Charleston, SC	32.98	−80.07	71	2161	12.4	1162	0.21
29	Charleston, SC	32.79	−79.96	70	2131	11.9	1152	0.22
30	Taylors, SC	34.90	−82.31	71	2161	14.9	1210	0.19
31	Columbia, SC	33.99	−81.02	48	1461	14.0	792	0.19
32	WEST VIEW, SC	34.93	−82.00	71	2161	14.3	1156	0.19
33	Nashville 1, TN	36.18	−86.74	71	2161	15.2	993	0.20
34	Nashville 2, TN	36.12	−86.87	71	2161	13.3	1007	0.19
35	Knoxville 1, TN	35.97	−83.95	71	2161	16.9	1091	0.22
36	Knoxville 2, TN	36.02	−83.87	71	2161	16.2	1082	0.22
37	Memphis 1, TN	35.18	−89.93	71	2158	13.9	1070	0.20
38	Memphis 2, TN	35.21	−90.03	71	2156	14.3	1061	0.21

Lat: latitude, Lon: longitude, ALL is number of days of data available between 08/2000 and 12/2005, PM2.5 is the mean PM2.5 mass concentration (μgm^{-3}) for all days, SAT is the number of days when Terra-MODIS AOT is available, and AOT is mean aerosol optical thickness at 550 nm for SAT.

'What is the difference between ground-based PM2.5 (ALLPM) and the PM2.5 for only those days where satellite data are available (SATPM) on monthly and yearly time scales?' How many days of satellite data are available due to cloud cover contamination and other limitations for PM2.5 air quality research? Understanding these differences are important to address the utility of satellite data in mapping PM2.5 air quality over monthly and yearly time scales especially since long term exposure studies require global data sets on yearly time scales (Pope and Dockery, 2006). Note that we are not using the satellite-derived AOT in this paper, rather we simply examine the PM2.5 during the time of the satellite overpass. To examine this issue, we selected the EPA region 4 in Southeast United States (Fig. 1) where previous research has shown that satellite data is indeed a robust surrogate for PM2.5 estimation (Wang and Christopher, 2003). This region was also selected due to the numerous ground-based PM2.5 measurements that are available to address the aforementioned questions.

2. Data and methods

We obtained 24-h PM2.5 mass concentration values from 38 ground monitoring stations in Southeastern United States from February 24, 2000 to December 31, 2005 covering eight states in EPA region 4. Fig. 1 shows the location of air quality stations used in the current study. We used these PM2.5 values to calculate monthly, seasonal and yearly averages (ALLPM). We then obtained six years of the MODIS satellite data [MODO4, V005] (Levy et al., 2007) that contain AOD and other geophysical parameters in 10 km^2 grid resolution. MODIS AOD is retrieved for cloud-free conditions and 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 2.1 μm channel reflectance is more than 0.25 (Levy et al., 2007). For each one of the 38 PM2.5 stations, a 5 × 5 group of the 10 km^2 pixels centered on the ground station are examined. This method of using 5 × 5 pixels is often the standard practice when comparing ground-based with satellite

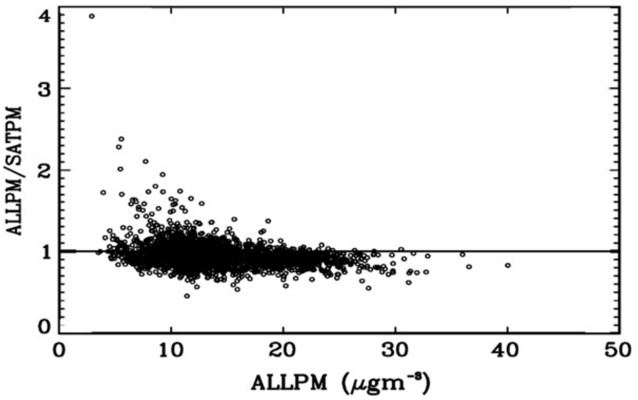

Fig. 2. Scatter plot of the ratio of the monthly mean ground PM2.5 mass concentration from all measurements (ALLPM) to the monthly mean ground PM2.5 mass concentration from only when satellite retrieval of AOD is available (SATPM) as a function of monthly mean value of ALLPM. Data from all 38 stations and 71 months is shown.

measurements (e.g. Ichoku et al., 2002). If MODIS retrieved AOD is present on any given day, over the ground location, then the PM2.5 value from the ground was included in computing monthly, seasonal, and yearly values of PM2.5 mass. Note that the satellite-derived AOD values are not used in the calculations. We only use the satellite data to check if AOD retrievals are available for the 5 × 5 pixels grid. Even if one of the pixels in the 5 × 5 grid had a reported AOD value, the ground-based PM2.5 for these days are tagged and labeled as SATPM, since this is what the Terra-MODIS will sample over time. In this way, we measure the difference between mean PM2.5 values from the all ground measurements (ALLPM) and PM2.5 values from the only those ground measurements when the satellite-derived AOD values are available (SATPM). We also track the number of days when satellite data are available in a given month, season, or year which is called SAT DAYS through out 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. However, during the 6-year period, only 32–57% of data (SAT DAYS) is available over the various locations (Fig. 3). Many stations in Florida and North Carolina are located near the coast and therefore fewer SAT DAYS are available due to MODIS AOD retrieval limitations in coastal regions (Remer et al., 2005). For all of the following analysis we set 85% thresholds on data availability from the surface data, to maintain uniformity across all locations. For annual analysis, we used data from all locations if they had greater than 310 out of 365 days of data, for seasonal analysis 75 out of 90, and for monthly analysis 25 days of 30 corresponding to about 85% for each case. A total of 74 876 data points from the surface and 33 211 data points from the satellite are used. Table 1 provides geographical locations and other detailed information such as ALL DAY, SAT DAY, mean PM2.5 mass concentration and mean AOD value for each station. Daily mean values are averaged over the entire study period.

3. Results and discussion

We first examine the ratio of ALLPM to SATPM for 71 months. In ideal conditions, ALLPM/SATPM for every ALLPM value should be a straight line centered at 1.0. Any deviation from this 1.0 value will represent a bias due to the low sampling by MODIS. A scatter plot of the ratio between ALLPM and SATPM as a function of ALLPM is shown in Fig. 2. The mean and standard deviation in the ratio of ALLPM to SATPM is 0.96 ± 0.15 with very few points (28) having ratios greater than 1.5 indicating that 99% of the time the SATPM has similar PM2.5 values as ALLPM, with small overestimation (<1%) by SATPM. It is also important to note that high ALLPM/SATPM values correspond to ALLPM values less than 10 μgm^{-3}. Further analysis reveals that all these high ratio values correspond to 13 different

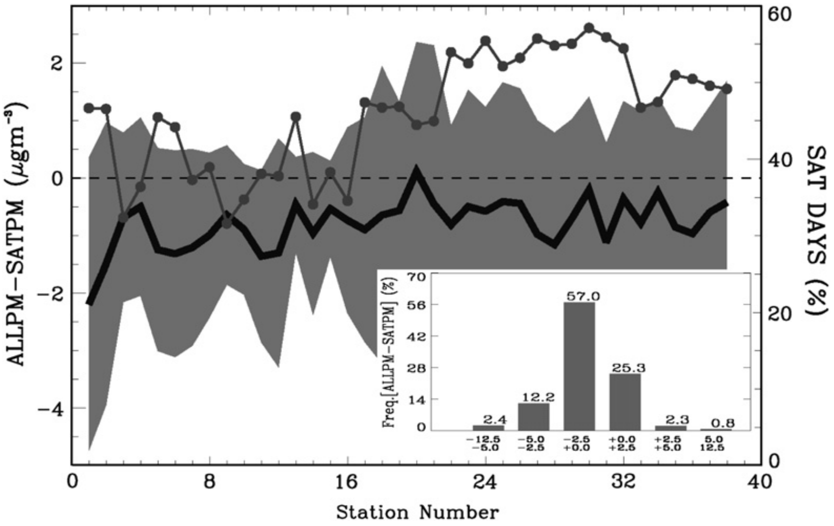

Fig. 3. Difference between PM2.5 mass from all ground-based measurements (ALLPM) and only when MODIS reports cloud-free conditions (SATPM) for 38 locations. Also shown is the data availability for each station in percent. The inset shows the frequency distribution of the difference between ALLPM and SATPM. The shaded area shows the standard deviation in difference.

Table 2
Annual mean statistics from 2000 to 2005 for ALLPM, SATPM and ALLPM–SATPM denoted as ALL–SAT

Year	Parameter	Min	Max	Mean	STD	#Station	Total days
2000	ALLPM	9.38	22.12	15.32	3.30	31	11169
	SATPM	9.56	25.10	16.28	3.67	31	4362
	ALL–SAT	−4.87	1.05	−1.25	1.11	31	
2001	ALLPM	7.66	19.01	13.73	3.39	31	11132
	SATPM	9.12	22.02	14.42	3.24	31	5376
	ALL–SAT	−8.28	1.62	−1.23	1.91	31	
2002	ALLPM	6.94	17.38	12.49	3.15	37	13323
	SATPM	8.09	19.51	13.68	3.27	37	5933
	ALL–SAT	−3.68	0.57	−1.73	0.95	37	
2003	ALLPM	7.24	17.33	12.14	3.01	37	13441
	SATPM	8.01	19.87	12.88	3.15	37	5691
	ALL–SAT	−2.78	0.86	−1.04	0.89	37	
2004	ALLPM	7.51	17.68	12.60	2.87	36	13,110
	SATPM	8.03	20.16	13.22	2.73	36	5794
	ALL–SAT	−4.36	1.20	−0.94	1.18	36	
2005	ALLPM	7.21	19.67	12.74	3.33	35	12,701
	SATPM	7.79	22.60	13.91	3.72	35	6055
	ALL–SAT	−4.91	0.24	−1.72	1.16	35	

stations during 2000, which could be due to partial or full data loss during MODIS initial phase of data collection. The highest value (3.9) of this ratio occurred in May 2000 when satellite data only exist 7 out of 31 days for that particular station. To examine these differences in detail, both ALLPM and SATPM are calculated for each station separately.

Fig. 3 shows the difference between ALLPM and SATPM for each station averaged for the entire 6-year period. The differences in mean values over all 71 months for each station are connected by the solid line and the gray shaded area represent the standard deviations. Also shown for each station is the percent number of days that data is available (SAT DAYS). Recall that ALLPM denotes all the values averaged for the entire 6-year period from ground measurements, and SATPM are also values obtained from the ground measurements only when satellite retrievals were available. Several conclusions can be gleaned from Fig. 3. First, note that some stations have only 32% data availability over a 71-month period whereas the maximum data availability is only 57%. The lack of data availability is largely due to cloud contamination and the mean SATPM is higher than ALLPM over all the stations except one, indicating that the PM2.5 values obtained during the times when satellite data is available is larger. This suggests that if we aggregate the PM2.5 values when satellite retrievals are available, it overestimates the PM2.5 by nearly 2 μgm^{-3}. This may be due to missing low PM2.5 values and sampling the higher PM2.5 values when satellite data is available. Other factors such as cloud cover, rainfall and secondary organics production may also be responsible for these differences that are difficult to unravel with only the data sets used in this study. In contrast, the ALLPM values have nearly a 100% data sampling rate, but have a high proportion of small PM2.5 values that reduces the mean values below the SATPM values. The inset of Fig. 3 presents the frequency distribution of ALLPM–SATPM and it shows that nearly 72% of the values have higher SATPM when compared to ALLPM and the remaining 28% have lower SATPM than ALLPM. The differences are between 0.0 and $-2.5\ \mu gm^{-3}$ for 57% of the data and between 0.0 and $2.5\ \mu gm^{-3}$ for about 25% of the data. Only less than 18% data points show greater ($> \pm 2.5$) differences. Our analysis therefore indicates when averaged over monthly and yearly time scales, the surface (ALLPM) and satellite (SATPM) do not show large differences even though the satellite samples these locations less than 50% of the time. We therefore conclude that the satellite data sampling does not pose major problems for capturing PM2.5 air quality. However, we are not saying that the satellite data is a perfect surrogate for monitoring PM2.5 air quality, since it also depends upon other factors such as conversion of columnar satellite to surface values, cloud cover, relative humidity and satellite retrieval issues. Our analysis only indicates that assuming satellite is indeed a good surrogate for PM2.5 air quality, the sampling from satellites due to cloud cover and other issues does not present a major problem for studying particulate matter air quality over monthly and annual scales.

We next examine the ALLPM–SATPM differences as a function of various months, seasons and years averaged over all stations, which is a good indicator of a large spatial area analysis (Table 2 and Fig. 4). The differences range from -2.8 to $4.9\ \mu gm^{-3}$ with mean value of $-0.8 \pm 1.1\ \mu gm^{-3}$. The upper range ($4.9\ \mu gm^{-3}$) of the difference corresponds to February 2000 when Terra-MODIS satellite started providing data and only 12% of data were available in this initial phase. The positive differences occurred in the winter and spring months, when SAT DAYS are the highest (>50%). Analysis for each month (averaged over all years) separately shows that July has a maximum difference of $2.0\ \mu gm^{-3}$, whereas January shows minimum difference of $-0.07\ \mu gm^{-3}$. In terms of

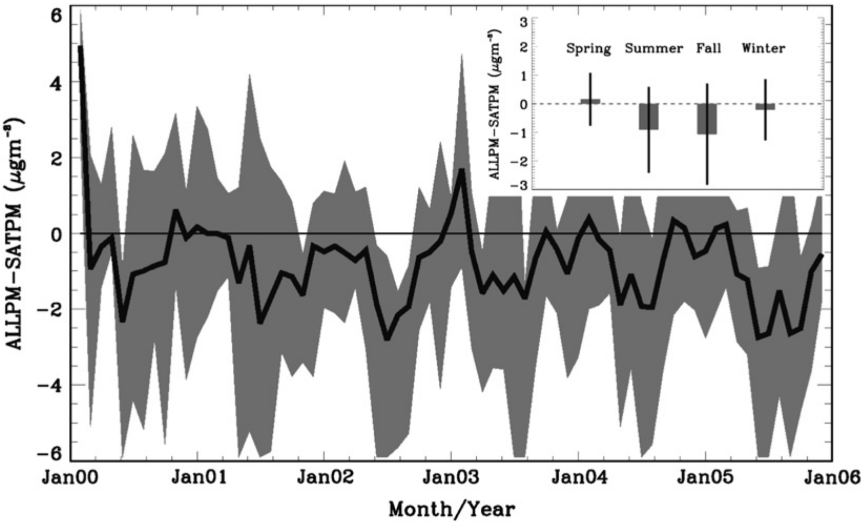

Fig. 4. Same as Fig. 2 except that the data is shown for all stations as a function of each month. The inset shows the ALLPM–SATMP differences as a function of seasons and the standard deviations are shown is vertical lines. Shaded area shows the standard deviation in the difference.

available SAT DAYS, November has maximum values (55%) and July has minimum values (39%). ALLPM values are smaller than SATPM values for most months except February when ALLPM are higher by 1.1 μgm^{-3} than SATPM. Going from monthly to seasonal analysis, the maximum differences occur during summer (-0.91 μgm^{-3}) and fall (-1.1 μgm^{-3}) when PM2.5 values are generally larger in this area (e.g. Wang and Christopher, 2003). Terra-MODIS day time cloud fraction values are also high during summer and fall month in the entire study area, thereby reducing SAT DAYS and producing these large differences. Differences in winter values are negative but very small (-0.21 μgm^{-3}) compared to fall and summer seasons, which is due to higher number of SAT DAYS in this season. The spring season shows SATPM values lower than ALLPM values with positive difference of 0.16 μgm^{-3}. Monthly and seasonal variations are also dependent on the variability in PM2.5 mass concentration within the month and season. Months with high variability in PM2.5 will tend to show large differences compared to those with low variability. Averaged over all stations, the mean ALLPM–SATPM differences are on the order of 2 μgm^{-3} indicating that satellite data does not have major sampling issues averaged over all stations. However, there may be large day-to-day variations in PM2.5 that cannot be captured by satellites if there is cloud cover.

Note that it is difficult to extrapolate these results to a global context without having PM2.5 data from the ground since the differences between the ALLPM and SATPM depend upon various factors including meteorology, pollution sources, transport, vertical distribution of aerosols, clouds and other factors. For example it is possible that in a highly polluted area the PM2.5 values from the ground may be high but due to persistent cloud cover, the satellite will not have an AOD retrieval. Furthermore, regions with high day to variability in PM2.5 mass will tend to produce larger differences compared to areas with less variability. Therefore it is difficult to estimate this sampling bias for global areas without further research.

4. Summary and conclusions

Polar orbiting satellites increasingly are being used for studying surface PM2.5 air pollution. The typical strategy in most studies is to develop a regression relationship between hourly or daily PM2.5 mass concentration from the ground stations and coincident satellite-derived AOD. These relationships can then be applied to larger spatial scales for determining air quality indices that range from good to unhealthy categories. While there are obvious advantages and disadvantages when using satellite data to estimate PM2.5 as outlined in this paper, one of the fundamental limitations of satellite data is the unavailability of air pollution observations when clouds obstruct the satellite sensors field of view. This poses the question then as to how well do the satellites represent PM2.5 air quality if a location is not being sampled due to cloud cover and other reasons such as high reflectivity surfaces such as urban areas and when snow/ice conditions prevail. To examine this issue, we used 6-years of data over 38 locations in Southeastern United States and aggregated all PM2.5 values from the ground (ALLPM) over monthly, seasonal and yearly time scales. For these stations, we used 5 × 5 boxes grid cells centered on the PM2.5 location and obtained PM2.5 values from the ground when the satellite retrieval of AOD is available (SATPM). The difference between ALLPM and SATPM provides a measure of the sampling issue when satellites are used. We reiterate that we are not focusing on the robustness of columnar AOD to obtain surface PM2.5 mass that has been addressed in previous studies. We merely address the issue of whether satellite data can adequately sample the PM2.5 over monthly to yearly time scales. Our results indicate that over monthly and yearly time scales, whether for individual stations or area averages, the difference is between the ALLPM and SATPM is less than 2 μgm^{-3} indicating that the loss of data due to nonretrieval conditions such as cloud cover, and surface type not a major problem. However, we note that these results cannot be extrapolated to global areas without further research.

Acknowledgements

This research is supported by NOAA grants NA06NES4400008 and NA07NES4280005. Pawan Gupta was supported by NASA Headquarters under the Earth and Space Science Fellowship (NESSF) Grant. MODIS data were obtained from the Level 1 and Atmosphere Archive and Distribution System (LAADS) at Goddard Space Flight Center (GSFC). PM2.5 data were obtained from EPA's Air Quality System (AQS).

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