Aerosol and Air Quality Research, 15 1347–1356, 2015

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2015.01.0009

Estimating Ground-Level $PM_{2.5}$ Using Fine-Resolution Satellite Data in the Megacity of Beijing, China

Rong Li[1,2], Jianhua Gong[1,3*], Liangfu Chen[1], Zifeng Wang[1]

[1] *State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth of Chinese Academy of Sciences, Beijing 100101, China*
[2] *University of Chinese Academy of Sciences, Beijing 100049, China*
[3] *Zhejiang-CAS Application Center for Geoinformatics, Jiaxing 314100, China*

ABSTRACT

Estimating ground-level $PM_{2.5}$ in urban areas from satellite-retrieved AOD data is limited because of the coarse resolution of the data. The spatial resolution of recent MODIS Collection 6 aerosol data has increased from 10 km to 3 km. Taking advantage of this new AOD dataset, we used a mixed effects model to calibrate the day-to-day relationship between satellite AOD and ground-level $PM_{2.5}$ concentrations. Regional daily $PM_{2.5}$ concentrations were estimated by the AOD from March 1, 2013, to February 28, 2014, in the megacity of Beijing. Compared with the simple linear regression model, the accuracy of the $PM_{2.5}$ prediction improved significantly, with an R^2 of 0.796 and a root mean squared error of 16.04 $\mu g/m^3$. The results showed high $PM_{2.5}$ concentrations in the intra-urban region of Beijing because of local emissions. The $PM_{2.5}$ concentrations were relatively low in the northern rural area but high in the southern rural area, which was close to the industrial sector in Hebei Province. We found that the 3 km AOD produces detailed spatial variability in the Beijing area but introduces somewhat large biases due to missing AOD pixels.

Key words: Particulate matter; Satellite remote sensing; Statistical models; Air quality.

INTRODUCTION

$PM_{2.5}$ is defined as particle matter with an aerodynamic diameter of less than 2.5 μm. A large number of epidemiological studies have shown that exposure to fine particles can increase the incidence of heart disease, cardiovascular disease and lung cancer (Pope, 2000; Peters *et al.*, 2001; Zanobetti, 2005; Hu, 2009). Ground-based measurements provide continuous and accurate data for epidemiologic studies and air quality assessments. However, ground sites are usually sparse or unavailable in many developing areas; thus, the corresponding research has large uncertainties.

Previous studies found that the satellite-derived aerosol optical depth (AOD) is closely related to the surface $PM_{2.5}$ concentration, which can be used to predict $PM_{2.5}$ at the regional scale (Chu *et al.*, 2003; Engel-Cox *et al.*, 2004; Gupta *et al.*, 2006; Van Donkelaar *et al.*, 2010). Because AOD denotes the integrated amount of particle extinction over the entire vertical column and $PM_{2.5}$ is the mass concentration of dry particles measured near the surface, the AOD-$PM_{2.5}$ relationship is impacted by several factors, such as the vertical distribution of the aerosols, aerosol components, and the hygroscopic growth of particles (Gupta *et al.*, 2009a). Numerous studies have been conducted to obtain reliable AOD-$PM_{2.5}$ relationships by eliminating these influences (Toth *et al.*, 2014; Wang *et al.*, 2010). However, it is usually difficult to obtain observational parameters, such as the aerosol vertical distribution, that regulate the AOD-$PM_{2.5}$ relationship, particularly at the regional scale. Thus, statistical models and atmospheric chemistry models have been widely used to eliminate these influences and to obtain a more accurate AOD-$PM_{2.5}$ relationship (Liu *et al.*, 2004).

Early research mostly focused on establishing the AOD-$PM_{2.5}$ relationship by simple linear regression (Liu *et al.*, 2005). Meteorological and environmental parameters were then incorporated to improve the correlation between AOD and $PM_{2.5}$ (Pelletier *et al.*, 2007; Gupta *et al.*, 2009a). Recently, several advanced statistical models, such as artificial neural networks (Gupta *et al.*, 2009b), general additive models (Liu *et al.*, 2009; Strawa *et al.*, 2013), and geographically weighted regression (Hu *et al.*, 2013, Ma *et al.*, 2014), were developed to improve the satellite-based $PM_{2.5}$ predictions. However, these models did not adequately consider the time-varying property between the satellite AOD and ground $PM_{2.5}$ measurements. Lee *et al.* (2011)

* Corresponding author.
Tel.: 86-10-13701081095
E-mail address: gongjh@radi.ac.cn

developed a mixed effect model to establish a daily specific AOD-$PM_{2.5}$ relationship with an R^2 = 0.62. Yap *et al.* (2013) expanded this model by establishing the monthly AOD-PM_{10} relationship to improve the predictive power of the MODIS AOD. To establish a reliable AOD-$PM_{2.5}$ relationship, these models require abundant ground $PM_{2.5}$ measurements. With rapid economic development, Beijing, the capital of China, has been experiencing severe air pollution (Yu *et al.*, 2011; Tao *et al.*, 2012, 2014b). So far, there is limited research on satellite $PM_{2.5}$ prediction in Beijing due to the lack of ground monitoring networks (Wang *et al.*, 2010; Guo *et al.*, 2014). The Environmental Protection Agency (EPA) of China began to monitor $PM_{2.5}$ (i.e., particle pollution) in major cities in January, 2013.

Most $PM_{2.5}$ estimation studies have used the AOD from the MODerate Resolution Imaging Spectroradiometer (MODIS) because of its daily global coverage and consistent accuracy. However, the 10 km resolution of the conventional Collection 5.1 (C5.1) MODIS AOD is coarse for predicting $PM_{2.5}$ at the urban scale (Chudnovsky *et al.*, 2013). The spatial resolution of the recent C6 MODIS AOD has increased to 3 km for resolving fine-scale AOD gradients and point sources (Munchak *et al.*, 2013). In this paper, we assessed the ability of the MODIS 3 km AOD to predict $PM_{2.5}$ in the typical megacity of China using satellite observations and ground measurements in 2013. The $PM_{2.5}$ estimation was conducted in a relatively limited temporal scope of only one year. When longer ground observations were available, further analyses, such as the seasonality of the AOD-$PM_{2.5}$ relationship, can be conducted. In this study, the correlations of the 3 km and 10 km MODIS AOD with $PM_{2.5}$ were compared. We used the mixed effects model to calibrate the day-to-day AOD-$PM_{2.5}$ relationship. The uncertainties in the $PM_{2.5}$ prediction were also evaluated. This paper provides the first study of $PM_{2.5}$ estimations using the C6 3 km AOD in urban areas of China.

METHOD

Ground-Level $PM_{2.5}$ Data

The EPA of China began to publish real-time hourly pollutant concentrations in January 2013. There are 35 $PM_{2.5}$ monitoring sites in the Beijing area (Fig. 1). To determine the particle pollution in different areas, the $PM_{2.5}$ monitoring sites are located near busy roads, urban regions, suburbs, and rural background regions. The monitoring sites are mainly located in urban areas, whereas rural areas have little coverage. The ground $PM_{2.5}$ concentration is measured by the tapered element oscillating microbalance method (TEOM) or beta-attenuation method within the Chinese National Ambient Air Quality Standard (GB3095-2012, http://kjs.mep.gov.cn/). Daily average $PM_{2.5}$ measurements in Beijing from March 1, 2013, to February 28, 2014, were collected from the EPA of China for this study.

MODIS-Derived AOD

The MODIS sensors on the Terra and Aqua satellites provide daily global information of the Earth-atmosphere

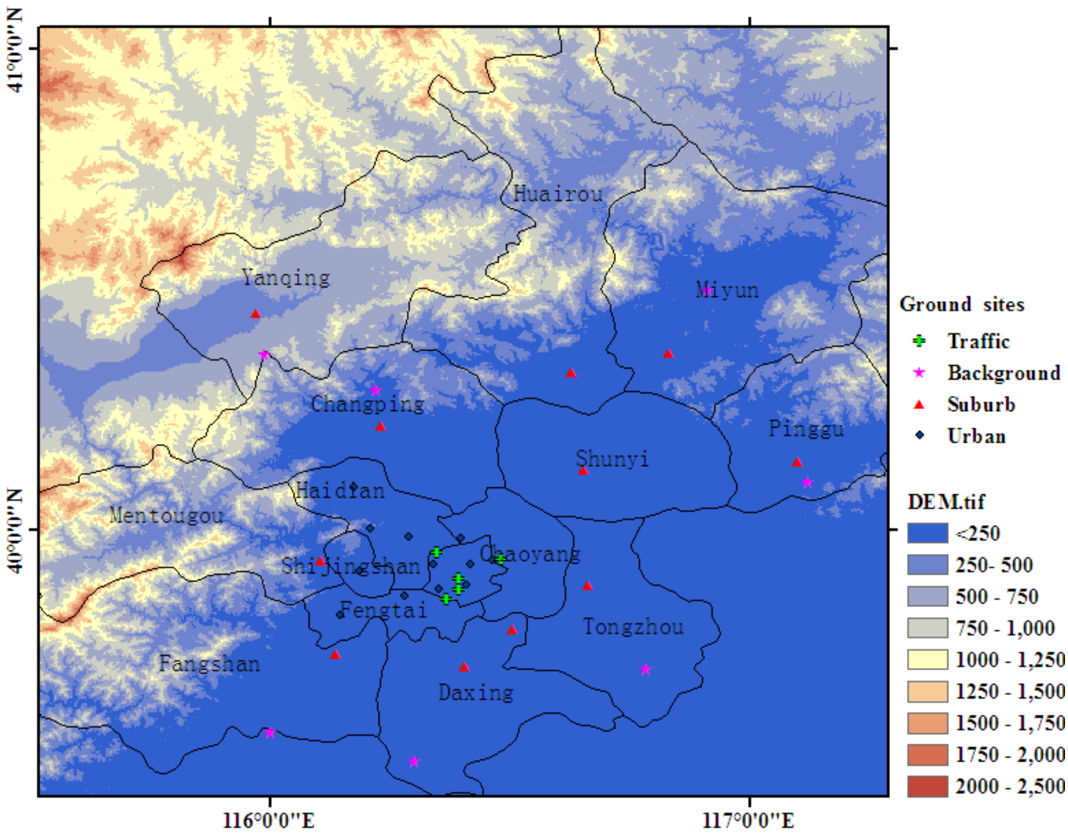

Fig. 1. Spatial distribution of the 35 $PM_{2.5}$ monitoring sites in Beijing area.

system in 36 spectral bands (0.4–14 μm) with a swath width of ~2330 km. The C5.1 AOD is retrieved by a dark-target algorithm with an accuracy of ± (0.05 + 15%) over land (Levy *et al.*, 2010). AOD values are often missing due to the high surface reflectance and cloud cover. The 3 km AOD is retrieved by the same dark-target algorithm, but it can better resolve aerosol gradients and pixels closer to clouds, coastlines and small water bodies, although the accuracy is slightly lower ± (0.05 + 20%) over land (Levy *et al.*, 2013; Munchak *et al.*, 2013; Remer *et al.*, 2013). Because the 3 km AOD is not available for Terra MODIS data, the C5.1 AOD (MYD04) and C6 (MYD04_3K) aerosol data were used to analyze the relationship between the AOD and $PM_{2.5}$. Details on the MODIS AOD retrieval were reported by Levy *et al.* (2013) and Remer *et al.* (2013). To minimize the influence of the AOD inaccuracy, only the MODIS AOD with the best quality (quality flag = 3) was used.

Data Processing and Analysis

The 3 km AOD was collocated with ground $PM_{2.5}$ measurements by averaging the AOD values within a 3 × 3 pixel window centered on the ground monitoring site. Because diffusion of particle pollution usually occurs within a particular distance over a short time (Gupta *et al.*, 2007, 2009a), the satellite AOD exhibited a close relationship with the daily $PM_{2.5}$ (Lee *et al.*, 2011; Hu *et al.*, 2014). Here, we correlated the satellite AOD with the daily averaged $PM_{2.5}$. To match the 3 km AOD pixel box, corresponding 10 km AOD data were selected. Invalid $PM_{2.5}$ or AOD was not considered. There were 2,777 pairs of $PM_{2.5}$ and 10 km AOD values in Beijing (35 sites and 364 days) and 3,098 pairs of values for the 3 km AOD. For comparison, we selected the 3 km and 10 km AOD-$PM_{2.5}$ pairs for the same days and locations. Afterward, 2,147 pairs of AOD-$PM_{2.5}$ points were retained.

Statistical Model and Validation

Although statistical models do not need to consider particular physical processes, the AOD-$PM_{2.5}$ relationship is influenced by a combination of daily changes in the wind, relative humidity and boundary layer height. Lee *et al.* (2011) developed a mixed effects statistical model that considered time-varying changes by calculating the daily AOD-$PM_{2.5}$ relationship separately by assuming that they have little spatial variability in the study region. Yap *et al.* (2013) expanded this model to calibrate the AOD-PM_{10} relationship in the Malaysian Peninsula by changing the daily parameter to a monthly parameter. Particle pollution and emission sources in China are very different from those in the United States and other countries (Philip *et al.*, 2014). We investigated the AOD-$PM_{2.5}$ relationship using a mixed effects model with the 3 km MODIS AOD (MYD04_3K) in our study region. The model is described by the following equations:

$$PM_{mn} = (\alpha + \mu_m) + (\beta + \nu_m) \times AOD_{mn} + s_n + \varepsilon_{mn} \quad (1)$$

PM_{mn} is the 24 h $PM_{2.5}$ average concentration on day m and at site n. AOD_{mn} denotes the MODIS AOD value at the corresponding site on day m; α and β are the fixed intercept and slope, respectively; these values explain the effect of the long-term AOD on the $PM_{2.5}$ for all days; μ_m and ν_m are the random intercept and slope, which adjust the fixed intercept and slope each day. These values explain the daily variation in the relationship between $PM_{2.5}$ and AOD; s_n is the random intercept at site n; ε_{mn} denotes the random error on day m and at site n. Details on the model were reported by Lee *et al.* (2011).

The performance of the model was tested by cross validation (CV). We selected one of the 35 $PM_{2.5}$ monitoring sites as a test site, and the mixed effects model was fitted by the remaining sites. This model was also used to predict the $PM_{2.5}$ concentrations for the test site. Finally, we repeated the process for each monitoring site. The root mean square error (RMSE) was calculated for every cross validation.

$$RMSE = \sqrt{\frac{1}{n}\sum_{j=1}^{n}[Z(s_j,t_j) - \hat{Z}(s_j,t_j)]^2} \quad (2)$$

RESULTS AND DISCUSSION

Comparison between MODIS 10 km and 3 km AOD

In this section, we assessed the ability of the 3 km AOD data to predict $PM_{2.5}$ in the Beijing area. Fig. 2 shows two $PM_{2.5}$ monitoring sites in traffic roads (sites YDMN and QM) and one urban $PM_{2.5}$ monitoring site (site TT) within one 10 km AOD pixel but different 3 km AOD pixels. The 3 km AOD data can capture finer spatially variability than the 10 km AOD. The 10 km and 3 km AOD showed different details, although they revealed similar aerosol trends at the large scale (Munchak *et al.*, 2013). Because the 10 km AOD was derived from 30% of the dark pixels with moderate values in a 20 × 20 500 m window (Levy *et al.*, 2007), it can smooth both high and low values and thus miss fine features. However, there is a slight decrease in the spatial coverage of the 3 km AOD because the 10 km AOD may also include 3 km cloudy pixels.

Fig. 3 shows the linear regression of the AOD-$PM_{2.5}$ relationship. The R^2 of the AOD-$PM_{2.5}$ relationship was 0.361 for the 10 km AOD and 0.3613 for the 3 km AOD. Both the 3 km and 10 km AOD appear to exhibit a direct correlation with the ground-level $PM_{2.5}$ concentration. The correlation is nearly the same for both the 10 km and 3 km AOD. Note that the dots are scattered, and there is a large offset in the AOD-$PM_{2.5}$ relationship that may be caused by the vertical distribution of the aerosols and hygroscopic growth. To obtain a high accuracy in the estimation of the regional $PM_{2.5}$, effort should be made to eliminate these effects.

Descriptive Statistics

Table 1 shows the mean $PM_{2.5}$ concentration measured at the 35 $PM_{2.5}$ monitoring sites from March 1, 2013, to February 28, 2014. The mean $PM_{2.5}$ concentration ranged from 62.08 μg/m^3 to 116.67 μg/m^3. The annual mean $PM_{2.5}$ concentration at the two sites (sites BDL and MYSQ) in

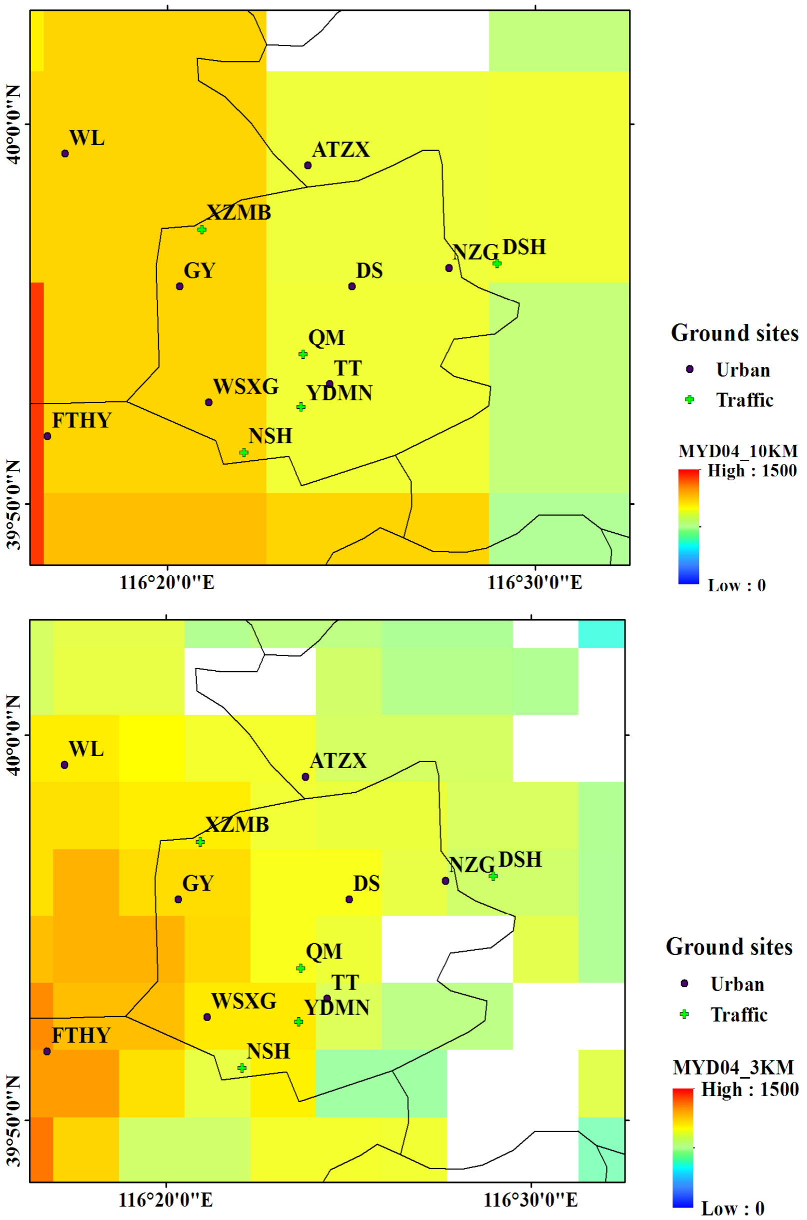

Fig. 2. MODIS 10 km (left) and 3 km (right) AOD data in Beijing area on 3 June 2013.

northern rural Beijing were below 70 µg/m^3. The $PM_{2.5}$ concentration in urban regions was obviously higher than that in the northern rural areas but was mostly lower than that in the southern rural areas. The average concentration in the southern suburb adjacent to the industrial regions in Hebei was much higher than that in the northern suburbs, indicating that the southerly transport of industrial pollutants from Hebei Province significantly influenced the air quality in Beijing (Tao *et al.*, 2014). The $PM_{2.5}$ concentration at 10 sites exceeded 100 µg/m^3; most of the sites are located in the southern suburbs and rural areas. Three of the sites are located in urban Beijing, with one site in the south and the other two near busy roads.

Model Fitting and $PM_{2.5}$ Prediction

The mixed effects model generated 188 daily AOD-$PM_{2.5}$ relationships for the 3 km AOD. The fixed intercept and slope of the model were 46.967 (SE = 2.886) and 34.111 (SE = 4.808), respectively. The p-value was less than 0.0001, suggesting statistical significance. The random effects of the intercept and slope of the AOD varied daily. We compared the fitted $PM_{2.5}$ concentration with the observed $PM_{2.5}$ values at the 35 monitoring sites. The result is shown in Fig. 4 (R^2 = 0.8466; slope = 0.831; RMSE = 13.88 µg/m^3) and is much larger than that obtained by simple linear regression (Fig. 3). The slope was close to 1, indicating that the predicted $PM_{2.5}$ concentration by the mixed effects model was highly consistent with the observed values. Furthermore, we compared the $PM_{2.5}$ obtained from the CV procedure with the ground measurements (R^2 = 0.796; slope = 0.807; RMSE = 16.04 µg/m^3). The CV test also indicated that the result is reliable, although the model slightly overfits the data.

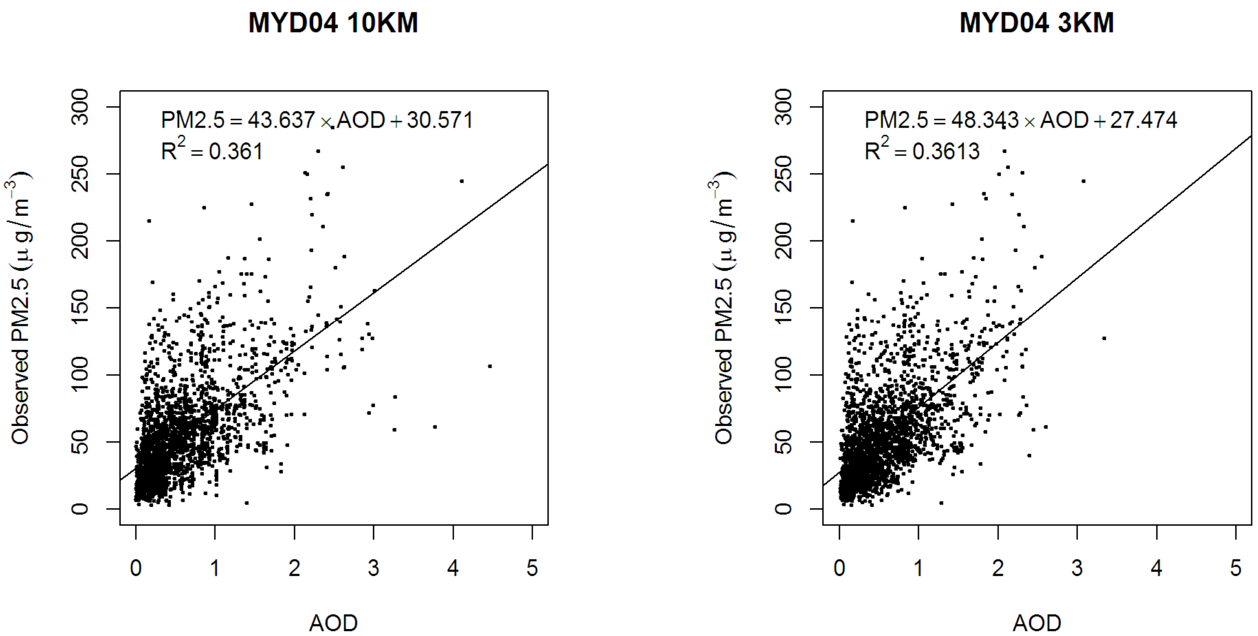

Fig. 3. Comparison of the AOD-$PM_{2.5}$ correlation between MODIS 10 km (left) and 3 km (right) AOD when 10 km, 3 km AOD and $PM_{2.5}$ measurement are all available.

Table 1. $PM_{2.5}$ concentration (μg/m^3) observed at the 35 monitoring sites in the whole year.

SITE	LON	LAT	N	MEAN	MAX	MIN	STD
ATZX	116.397	39.982	359	89.50	402.25	5.54	69.98
BDL	115.988	40.365	357	65.42	330.06	6.00	57.42
BBXQ	116.174	40.09	359	85.96	391.00	4.50	69.16
CP	116.23	40.217	353	78.90	335.63	3.00	64.79
DX	116.404	39.718	358	106.19	462.38	7.25	81.48
DL	116.22	40.292	357	73.02	373.50	4.58	66.22
DGC	117.12	40.1	358	81.87	377.29	5.04	65.00
DS	116.417	39.929	297	88.10	330.29	5.92	62.91
DSH	116.483	39.939	359	97.45	406.17	5.65	74.14
FS	116.136	39.742	355	104.10	448.13	3.00	77.62
FTHY	116.279	39.863	355	103.01	457.58	7.33	79.32
GC	116.184	39.914	353	91.65	399.13	5.33	69.53
GY	116.339	39.929	357	89.58	396.00	6.42	69.33
HR	116.628	40.328	350	77.28	435.07	3.21	64.08
LLH	116	39.58	350	116.67	448.04	9.42	79.00
MTG	116.106	39.937	310	81.72	343.63	5.58	64.41
MY	116.832	40.37	359	74.28	400.00	4.13	62.06
MYSK	116.911	40.499	358	62.08	294.21	3.46	56.40
NSH	116.368	39.856	353	108.16	446.63	5.92	76.23
NZG	116.461	39.937	355	91.72	437.96	6.67	73.24
PG	117.1	40.143	353	80.85	444.27	3.14	69.39
QM	116.395	39.899	359	103.24	443.29	3.00	76.72
SY	116.655	40.127	351	86.46	455.00	5.00	70.06
TT	116.407	39.886	359	89.88	407.46	5.50	69.25
TZ	116.663	39.886	358	106.32	474.25	7.57	50.13
WL	116.287	39.987	356	99.84	417.88	5.67	55.79
WSXG	116.352	39.878	356	93.42	437.58	5.33	52.85
XZMB	116.349	39.954	359	95.06	389.42	7.33	52.45
YQ	115.972	40.453	359	73.16	360.25	4.28	42.22
YZ	116.506	39.795	358	104.10	459.54	5.58	49.75
YDMN	116.394	39.876	358	96.88	413.83	5.00	54.69
YLD	116.783	39.712	359	113.67	510.50	3.71	52.72

Table 1. *(continued).*

SITE	LON	LAT	N	MEAN	MAX	MIN	STD
YF	116.3	39.52	352	110.50	470.46	7.00	50.09
YG	116.146	39.824	359	91.75	407.17	5.83	49.40
ZWY	116.207	40.002	358	77.26	353.25	4.12	51.19

N: Number of samples days.
STD: Stand deviation.

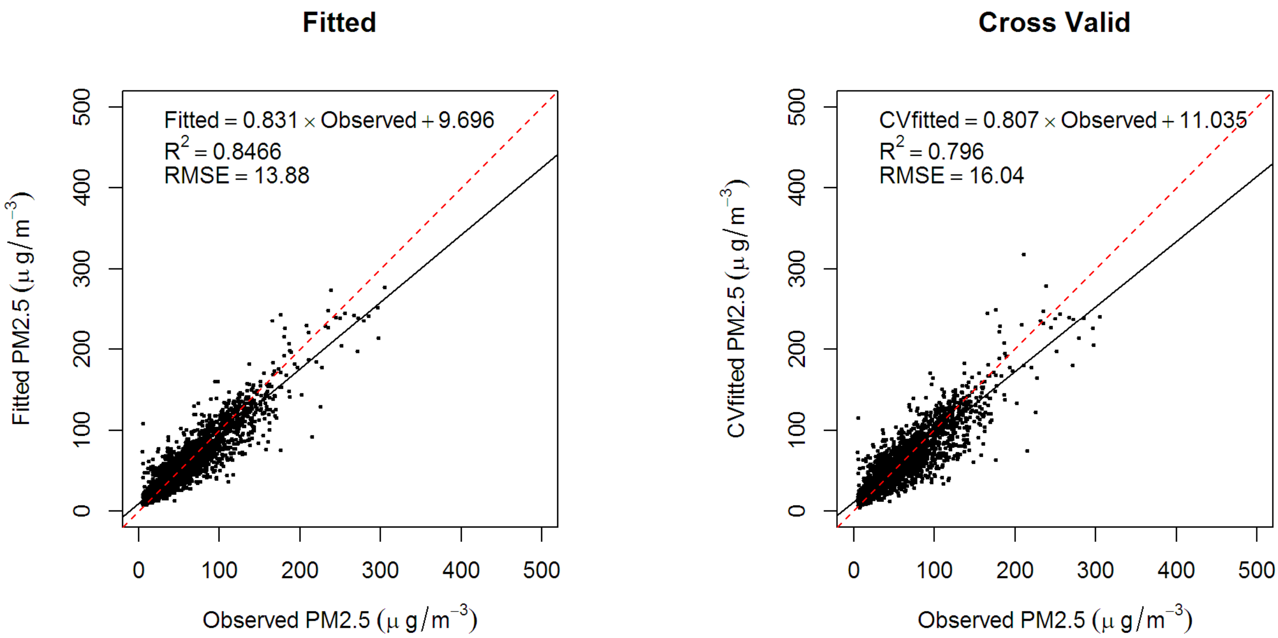

Fig. 4. Comparison of predicted $PM_{2.5}$ and ground measurements by mixed effects model (left) and CV mixed effects model (right).

Fig. 5 shows the yearly mean AOD-derived $PM_{2.5}$ in the Beijing area in 2013. The mean $PM_{2.5}$ ranged from 40–60 µg/m^3 in the northern and western rural mountain areas to 60–80 µg/m^3 in most of the urban, southern and eastern regions. High-level $PM_{2.5}$ in the southern urban region and in the rural towns can be clearly seen, indicating the existence of local emission sources. In contrast, the air quality was relatively better in the northern rural areas. The distribution of the high $PM_{2.5}$ concentration was consistent with the ring roads in the urban region, which could be associated with the intense vehicle emissions in Beijing (Yu *et al.*, 2011, 2013).

Generally, the regional $PM_{2.5}$ was within a reasonable range and was strongly correlated with the ground measurements. The distinct differences in the $PM_{2.5}$ in Beijing indicate that the 3 km AOD reveals fine-scale gradients of the exposure levels in urban regions. The satellite-estimated $PM_{2.5}$ was slightly lower than that of the ground measurements, partly because the satellite-derived $PM_{2.5}$ denotes the average values at the 3 × 3 km scale.

Analysis of the Satellite Estimation Errors

The RMSE of the $PM_{2.5}$ estimation in Beijing was 16.04 µg/m^3, which is much higher than that in the United States (~5 µg/m^3) (Lee *et al.*, 2011; Hu *et al.*, 2014). However, the RMSE of our estimation was much lower than that for the results for China overall (32.98 µg/m^3) (Ma *et al.*, 2014), mainly due to the much denser ground sites in the Beijing area. The high RMSE in Beijing can be explained by several factors. First, the AOD-$PM_{2.5}$ relationship was negative on some days due to the dense aerosol layers aloft (high AOD) with low $PM_{2.5}$ or very low boundary layers (low AOD) with high $PM_{2.5}$, which sometimes appeared in northern China (Tao *et al.*, 2014a). Second, the $PM_{2.5}$ ranged from 3 to 510 µg/m^3 in our study region; these values were much higher than those in the United States. The large variations in the $PM_{2.5}$ may be overlooked due to the missing satellite AOD. The model may underestimate the $PM_{2.5}$ concentrations at high concentrations. In addition, the complicated aerosol sources and location of the ground sites may also contribute to the high RMSE (Lee *et al.*, 2011).

To evaluate the influence of the sampling frequency of the satellite AOD, we calculated the mean $PM_{2.5}$ of all of the ground measurements ("ALL" hereafter), the $PM_{2.5}$ values when AOD values were available ("SAT") and the mean predicted $PM_{2.5}$ by the CV mixed effects model ("CV"). Fig. 6 shows that there were high biases between the mean $PM_{2.5}$ on all days and the value when the satellite AOD is available. The biases ranged from 15 to 40 µg/m^3, most of which exceeded 25 µg/m^3. The high biases demonstrate that many days with high $PM_{2.5}$ values were excluded because

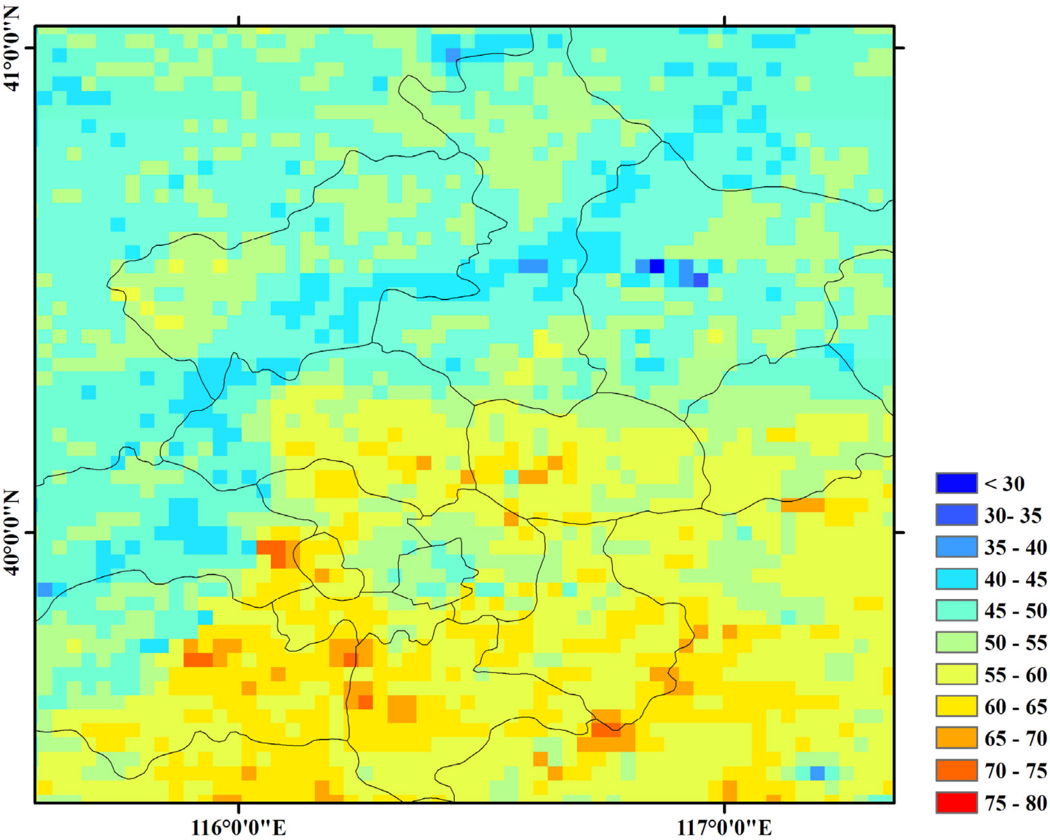

Fig. 5. The annual mean AOD-derived $PM_{2.5}$ of Beijing area from March 1, 2013 to February 28, 2014.

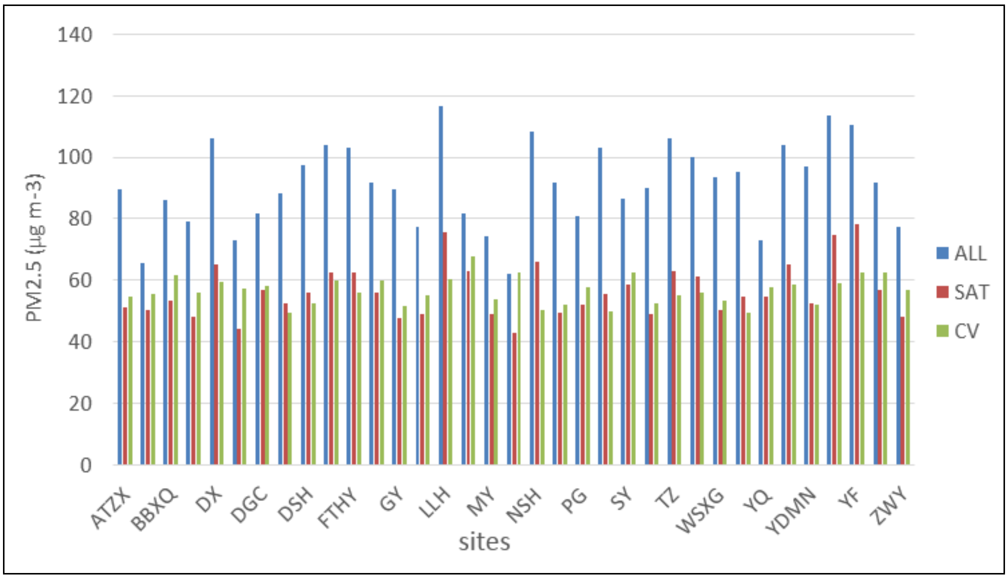

Fig. 6. The mean $PM_{2.5}$ values from all ground measurements (ALL), the ground measurements when AOD values are available (SAT) and mean $PM_{2.5}$ predicted by CV mixed effects model (CV).

of missing AOD values. The MODIS dark-target aerosol retrieval is not valid for heavy haze pollution and bright surfaces in winter (Tao *et al.*, 2012), when high $PM_{2.5}$ usually occur. Missing satellite retrievals on these polluted days could significantly contribute to the underestimation of the AOD-derived $PM_{2.5}$.

Our finding is significantly different from the result presented by Gupta *et al.* (2008), who argued that the low sampling from satellites is not a major problem for $PM_{2.5}$ predictions, with a bias of less than 2 $\mu g/m^3$ in the southeastern United States. As shown in Fig. 6, the missing AOD values can lead to large deviations in the $PM_{2.5}$

estimation. The mean $PM_{2.5}$ in China, where heavy pollution is frequent, is much higher than that in the United States. The $PM_{2.5}$ concentration in northern China ranges from several to hundreds µg/m^3 within 1–2 days (Tao *et al.*, 2014a, b); this range causes large deviations from the mean value when the AOD is unavailable. As shown in Table 2, the available MODIS 3 km AODs did not span more than one-third of the entire year at nearly all the sites; thus, many episodes may have been missed.

Table 2 shows the annual mean $PM_{2.5}$ concentrations from the measured and CV-predicted values when the satellite AOD was available. The bias between the CV-predicted and measured values ranged from 0 to 20 µg/m^3. All monitoring sites except DL, LLH, MYSK, NSH, YF and YLD had a bias below 10 µg/m^3. The large positive biases at the DL and MYSK sites in the northern rural areas may be due to the high AOD value but low $PM_{2.5}$ concentration on particular days. In contrast, the satellite-estimated $PM_{2.5}$ exhibited obvious negative biases near busy roads and southern rural areas, indicating an underestimation of heavy particle pollution.

Generally, $PM_{2.5}$ in the Beijing area can be predicted by the 3 km AOD at fine scales and low relative deviations. However, the satellite AOD should be used cautiously in $PM_{2.5}$ estimations over Beijing due to the missing samples in heavy pollution cases. As more $PM_{2.5}$ data in the network becomes available in the future, further studies should consider additional factors to obtain higher accuracies.

CONCLUSIONS

Satellite AODs have been widely used in predicting regional $PM_{2.5}$ concentrations. However, the coarse resolution

Table 2. The measured $PM_{2.5}$ and CV predicted $PM_{2.5}$ concentrations for 35 $PM_{2.5}$ monitoring sites.

Site Name	N_SAT	Frequency	CV	SAT	Bias
ATZX	79	22.01	54.77	51.35	3.42
BDL	113	31.65	55.72	50.42	5.30
BBXQ	100	27.86	61.51	53.40	8.11
CP	90	25.50	55.98	48.12	7.86
DX	94	26.26	59.43	65.22	-5.79
DL	108	30.25	57.50	44.39	13.11
DGC	131	36.59	58.14	56.85	1.29
DS	64	21.55	49.28	52.29	-3.01
DSH	77	21.45	52.36	56.11	-3.75
FS	93	26.20	59.70	62.70	-3.00
FTHY	78	21.97	55.92	62.36	-6.44
GC	83	23.51	59.96	56.14	3.82
GY	67	18.77	51.61	47.78	3.83
HR	70	20.00	55.04	49.16	5.88
LLH	111	31.71	60.26	75.78	-15.52
MTG	58	18.71	67.87	63.08	4.79
MY	103	28.69	53.80	48.91	4.89
MYSK	70	19.55	62.55	43.00	19.55
NSH	64	18.13	50.10	66.05	-15.95
NZG	72	20.28	52.19	49.34	2.85
PG	117	33.14	57.87	51.91	5.96
QM	62	17.27	49.77	55.71	-5.94
SY	81	23.08	62.35	58.48	3.87
TT	62	17.27	52.32	49.06	3.26
TZ	84	23.46	55.00	63.00	-8.00
WL	79	22.19	56.19	61.32	-5.13
WSXG	68	19.10	53.34	50.10	3.24
XZMB	69	19.22	49.37	54.51	-5.14
YQ	104	28.97	57.76	54.86	2.90
YZ	71	19.83	58.58	65.30	-6.72
YDMN	68	18.99	52.01	52.65	-0.64
YLD	121	33.70	58.85	74.65	-15.8
YF	115	32.67	62.63	78.15	-15.52
YG	104	28.97	62.36	56.97	5.39
ZWY	97	27.09	56.80	48.21	8.59

N_SAT: The number of days with both measured $PM_{2.5}$ and satellite AOD are available.
Frequency: The frequency of available AOD for each station in percent.
SAT: The mean $PM_{2.5}$ concentrations of ground $PM_{2.5}$ when AOD values are available.
CV: The mean predicted $PM_{2.5}$ by CV mixed effects model.

(~10 km) of the conventional MODIS AOD usually limits research in urban areas. In this study, we estimated the regional distribution of $PM_{2.5}$ over the Beijing area using one year of C6 3 km MODIS AOD data in 2013. The 3 km AOD exhibited nearly the same correlation with the $PM_{2.5}$ as the 10 km AOD, but it could reveal finer spatial characteristics. A mixed effects model was used to calibrate the 3 km AOD for the $PM_{2.5}$ estimation in the Beijing area, where heavy particle pollution is common. The AOD-$PM_{2.5}$ relationship significantly improved when day-to-day variability was considered; the results had a much higher accuracy (R^2 = 0.846) than the simple linear regression results (R^2 = 0.361) in $PM_{2.5}$ prediction. The mean $PM_{2.5}$ concentration in Beijing was 60–80 µg/m^3 in the southern and eastern areas and 40–60 µg/m^3 in the western and northern regions. In contrast to clean-air regions, such as the Unites States, large deviations can be introduced into the $PM_{2.5}$ over eastern China when the sampling frequency of the satellite AOD is low.

ACKNOWLEGEMENT

This study was supported by the science and technology of major project (Grant No. 2014ZX10003002), Type B Leading Special Project of CAS (XDB05020100), National Science Foundation of China (Grant No. 41201333). We thank the MODIS team for the data used in our work.

REFERENCES

Chu, D.A., Kaufman, Y.J., Zibordi, G., Chern, J.D., Mao, J., Li, C. and Holben, B.N. (2003). Global Monitoring of Air Pollution over Land from the Earth Observing System-Terra Moderate Resolution Imaging Spectroradiometer (Modis). *J. Geophys. Res.* 108: 4661, doi: 10.1029/2002JD003179.

Chudnovsky, A., Tang, C., Lyapustin, A., Wang, Y., Schwartz, J. and Koutrakis, P. (2013). A Critical Assessment of High-Resolution Aerosol Optical Depth Retrievals for Fine Particulate Matter Predictions. *Atmos. Chem. Phys.* 13: 10907–10917.

Engel-Cox, J.A., Holloman, C.H., Coutant, B.W. and Hoff, R.M. (2004). Qualitative and Quantitative Evaluation of MODIS Satellite Sensor Data for Regional and Urban Scale Air Quality. *Atmos. Environ.* 38: 2495–2509.

Guo, Y., Feng, N., Christopher, S.A., Kang, P., Zhan, F.B. and Hong, S. (2014). Satellite Remote Sensing of Fine Particulate Matter ($PM_{2.5}$) Air Quality over Beijing Using Modis. *Int. J. Remote Sens.* 35: 6522–6544, doi: 10.1080/01431161.2014.958245.

Gupta, P., Christopher, S.A., Wang, J., Gehrig, R., Lee, Y. and Kumar, N. (2006). Satellite Remote Sensing of Particulate Matter and Air Quality Assessment over Global Cities. *Atmos. Environ.* 40: 5880–5892.

Gupta, P. and Christopher, S.A. (2008). An Evaluation of Terra-MODIS Sampling for Monthly and Annual Particulate Matter Air Quality Assessment over the Southeastern United States. *Atmos. Environ.* 42: 6465–6471.

Gupta, P. and Christopher, S.A. (2009a). Particulate matter Air Quality Assessment Using Integrated Surface, Satellite, and Meteorological Products: Multiple Regression Approach. *J. Geophys. Res.*114: D14205.

Gupta, P. and Christopher, S.A. (2009b). Particulate Matter Air Quality Assessment Using Integrated Surface, Satellite, and Meteorological Products: A Neural Network Approach. *J. Geophys. Res.* 114: D20205.

Hu, X., Waller, L.A., Al-Hamdan, M.Z., Crosson, W.L., Estes, M.G., Jr., Estes, S.M., Quattrochi, D.A., Sarnat, J.A. and Liu, Y. (2013). Estimating Ground-Level $PM_{2.5}$ Concentrations in the Southeastern U.S. Using Geographically Weighted Regression. *Environ. Res*. 121: 1–10.

Hu, X., Waller, L.A., Lyapustin, A., Wang, Y., Al-Hamdan, M.Z., Crosson, W.L., Estes, M.G., Estes, S.M., Quattrochi, D.A., Puttaswamy, S.J. and Liu, Y. (2014). Estimating Ground-Level $PM_{2.5}$ Concentrations in the Southeastern United States Using Maiac Aod Retrievals and a Two-Stage Model. *Remote Sens. Environ.* 140: 220–232.

Hu, Z. (2009). Spatial Analysis of MODIS Aerosol Optical Depth $PM_{2.5}$ and Chronic Coronary Heart Disease. *Int. J. Health Geographics* 8: 27, doi: 10.1186/1476-072X-8-27.

Lee, H.J., Liu, Y., Coull, B.A., Schwartz, J. and Koutrakis, P. (2011). A Novel Calibration Approach of Modis Aod Data to Predict $PM_{2.5}$ Concentrations. *Atmos. Chem. Phys.* 11: 7991–8002.

Levy, R.C., Remer, L.A., Mattoo, S., Vermote, E.F. and Kaufman, Y.J. (2007). Second-Generation Operational Algorithm: Retrieval of Aerosol Properties over Land from Inversion of Moderate Resolution Imaging Spectroradiometer Spectral Reflectance. *J. Geophys. Res.* 112: D13211, doi: 10.1029/2006JD007811.

Levy, R.C., Remer, L.A., Kleidman, R.G., Mattoo, S., Ichoku, C., Kahn, R. and Eck, T.F. (2010). Global Evaluation of the Collection 5 Modis Dark-Target Aerosol Products over Land. *Atmos. Chem. Phys.* 10: 10399–10420.

Levy, R.C., Mattoo, S., Munchak, L.A., Remer, L.A., Sayer, A.M., Patadia, F. and Hsu, N.C. (2013). The Collection 6 Modis Aerosol Products over Land and Ocean. *Atmos. Meas. Tech.* 6: 2989–3034.

Liu, Y., Park, R.J., Jacob, D.J., Li, Q., Kilaru, V. and Sarnat, J.A. (2004). Mapping Annual Mean Ground-Level $PM_{2.5}$ Concentrations Using Multiangle Imaging Spectroradiometer Aerosol Optical Thickness over the Contiguous United States. *J. Geophys. Res.* 109: D22206.

Liu, Y., Sarnat, J.A., Kilaru, V., Jacob, D.J. and Koutrakis, P. (2005). Estimating Ground-Level $PM_{2.5}$ in the Eastern United States Using Satellite Remote Sensing. *Environ. Sci. Technol.* 39: 3269–3278.

Liu, Y., Paciorek, C.J. and Koutrakis, P. (2009). Estimating Regional Spatial and Temporal Variability of $PM_{2.5}$ Concentrations Using Satellite Data, Meteorology, and Land Use Information. *Environ. Health Perspect.* 117: 886–892.

Ma, Z., Hu, X., Huang, L., Bi, J. and Liu, Y. (2014). Estimating Ground-Level $PM_{2.5}$ in China Using Satellite Remote Sensing. *Environ. Sci. Technol.* 48: 7436–7444.

Munchak, L.A., Levy, R.C., Mattoo, S., Remer, L.A., Holben, B.N., Schafer, J.S., Hostetler, C.A. and Ferrare, R.A. (2013). Modis 3 Km Aerosol Product: Applications over Land in an Urban/Suburban Region. *Atmos. Meas. Tech.* 6: 1747–1759, doi: 10.5194/amt-6-1747-2013.

Peters, A., Dockery, D.W., Muller, J.E. and Mittleman, M.A. (2001). Increased Particulate Air Pollution and the Triggering of Myocardial infarction. *Circulation* 103: 2810–2815.

Philip, S., Martin, R.V., van Donkelaar, A., Lo, J.W., Wang, Y., Chen, D., Zhang, L., Kasibhatla, P.S., Wang, S., Zhang, Q., Lu, Z., Streets, D.G., Bittman, S. and Macdonald, D.J. (2014). Global Chemical Composition of Ambient Fine Particulate Matter for Exposure Assessment. *Environ. Sci. Technol.* 48: 13060–13068.

Pope, C.A. III. (2000). Epidemiology of Fine Particulate Air Pollution and Human Health: Biologic Mechanisms and Who's at Risk? *Environ. Health Perspect.* 108: 713–723.

Remer, L.A., Mattoo, S., Levy, R.C. and Munchak, L.A. (2013). MODIS 3 km Aerosol Product: Algorithm and Global Perspective. *Atmos. Meas. Tech.* 6: 1829–1844, doi: 10.5194/amt-6-1829-2013.

Strawa, A.W., Chatfield, R.B., Legg, M., Scarnato, B. and Esswein, R. (2013). Improving Retrievals of Regional Fine Particulate Matter Concentrations from Moderate Resolution Imaging Spectroradiometer (MODIS) and Ozone Monitoring Instrument (OMI) Multisatellite Observations. *J. Air Waste Manage. Assoc.* 63: 1434–1446.

Tao, M., Chen, L., Su, L. and Tao, J. (2012). Satellite Observation of Regional Haze Pollution over the North China Plain. *J. Geophys. Res.* 117: D12203.

Tao, M., Chen, L. and Wang, Z. (2014a). A Study of Urban Pollution and Haze Clouds over Northern China during the Dusty Season Based on Satellite and Surface Observation. *Atmos. Environ.* 82: 183–192.

Tao, M., Chen, L., Xiong, X., Zhang, M., Ma, P., Tao, J. and Wang, Z. (2014b). Formation Process of the Widespread Extreme Haze Pollution over Northern China in January 2013: Implications for Regional Air Quality and Climate. *Atmos. Environ*. 98: 417–425.

Toth, T.D., Zhang, J., Campbell, J.R., Hyer, E.J., Reid, J.S., Shi, Y. and Westphal, D.L. (2014). Impact of Data Quality and Surface-to-Column Representativeness on the $PM_{2.5}$/Satellite Aod Relationship for the Contiguous United States *Atmos. Chem. Phys.* 14: 6049–6062, doi: 10.5194/acp-14-6049-2014.

Van Donkelaar, A., Martin, R.V., Brauer, M., Kahn, R., Levy, R., Verduzco, C. and Villeneuve, P.J. (2010). Global Estimates of Ambient Fine Particulate Matter Concentrations from Satellite-Based Aerosol Optical Depth: Development and Application. *Environ. Health Perspect.* 118: 847–855.

Wang, Z., Chen, L., Tao, J., Zhang, Y. and Su, L. (2010). Satellite-Based Estimation of Regional Particulate Matter (PM) in Beijing Using Vertical-and-Rh Correcting Method. *Remote Sens. Environ.* 114: 50–63.

Yap, X.Q. and Hashim, M. (2013). A Robust Calibration Approach for PM_{10} Predction from MODIS Aerosol Optical Depth. *Atmos. Chem. Phys.* 13: 3517–3526.

Yu, L., Wang, G., Zhang, R., Zhang, L., Song, Y., Wu, B., Li, X., An, K. and Chu, J. (2013).. Characterization and Source Apportionment of $PM_{2.5}$ in an Urban Environment in Beijing. *Aerosol Air Qual. Res.* 13: 574–583.

Yu, Y., Schleicher, N., Norra, S., Fricker, M., Dietze, V., Kaminski, U., Cen, K. and Stuben, D. (2011). Dynamics and Origin of $PM_{2.5}$ during a Three-year Sampling Period in Beijing, China. *J. Environ. Monit.* 13: 334–346.

Zhao, X., Zhang, X., Xu, X., Xu, J., Meng, W. and Pu, W. (2009). Seasonal and Diurnal Variations of Ambient $PM_{2.5}$ Concentration in Urban and Rural Environments in Beijing. *Atmos. Environ.* 43: 2893–2900.

Received for review, January 5, 2015
Revised, March 2, 2015
Accepted, April 3, 2015