The relationships between PM$_{2.5}$ and aerosol optical depth (AOD) in mainland China: About and behind the spatio-temporal variations

Qianqian Yang a, Qiangqiang Yuan a, b, *, Linwei Yue c, Tongwen Li d, Huanfeng Shen d, Liangpei Zhang e

a School of Geodesy and Geomatics, Wuhan University, Wuhan, Hubei, 430079, China
b Key Laboratory of Geospace Environment and Geodesy, Ministry of Education, Wuhan University, Wuhan, 430079, Hubei, China
c Faculty of Information Engineering, China University of Geosciences, Wuhan, Hubei, 430074, China
d School of Resource and Environmental Sciences, Wuhan University, Wuhan, Hubei, 430079, China
e State Key Laboratory of Information Engineering, Survey Mapping and Remote Sensing, Wuhan University, Wuhan, Hubei, 430079, China

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1. Introduction

Fine particulate matter or PM$_{2.5}$ (particles with aerodynamic diameters of less than 2.5 $\mu$m) has attracted the public’s concern due to its adverse impact on human health (Lelieveld et al., 2015; Ho et al., 2018). The spatially continuous mapping of PM$_{2.5}$ is substantially required for determining the population exposure to PM$_{2.5}$, thus making the use of satellite aerosol optical depth (AOD) product for the retrieval of surface PM$_{2.5}$ popular (Al-Saadi et al., 2005; Zhang et al., 2009; Boys et al., 2014; van Donkelaar et al., 2015a; van Donkelaar et al., 2015b; Jung et al., 2017; Li et al., 2017a; Li et al., 2017b; Shen et al., 2018; Guo et al., 2017b de Hoogh et al., 2018; Xu et al., 2018; Li et al., 2018). An important premise and theoretical foundation for retrieving surface PM$_{2.5}$ concentration with satellite AOD is the strong correlation and connection between PM$_{2.5}$ and AOD (Li et al., 2015). However, the correlation between PM$_{2.5}$ and AOD is not always solid and there are many differences between PM$_{2.5}$ and AOD (Zheng et al., 2017; Zhang and Li, 2015). For example, PM$_{2.5}$ mainly represents the turbidity of the atmosphere near the ground. In contrast, AOD
represents the whole atmospheric column, which extends from the
ground surface to an altitude of several hundred kilometers.
Furthermore, PM$_{2.5}$ mainly represents the dry mass concentration
of fine particulate, which is hardly affected by water and coarse
particles, but the value of AOD includes the influence of water vapor
and coarse particles. Apart from this, in essence, the value of PM$_{2.5}$
represents mass concentration, whereas the AOD value represents
the extinction ability. The connection between mass concentration
and extinction ability can be either strong or weak as the compo-
sition of PM$_{2.5}$ and aerosol varies. Thus, the relationship between
PM$_{2.5}$ and AOD can be affected by many factors like relative hu-
midity, planetary boundary height, aerosol properties etc. (Zheng
et al., 2017; Zhang and Li, 2015). In different conditions, these fac-
tors may affect the relationship to a different degree. Therefore,
before retrieving PM$_{2.5}$ concentration through AOD in a large area
for a long time, it is necessary to explore the relationship between
PM$_{2.5}$ and AOD for the same large spatial and temporal extent, and
to establish the spatial and temporal variations of the relationship
at a fine scale. Only by doing this can we determine whether or not
the foundation is always solid when retrieving PM$_{2.5}$ with AOD in a
large area over a long period of time.
Mainland China has suffered serious PM$_{2.5}$ pollution in recent
decades. The current PM$_{2.5}$-AOD relationship analysis studies for
mainland China are either confined to a small area (Shao et al.,
2017; Ma et al., 2016; Wang et al., 2018a) or have lacked detailed
investigation of the spatial variations though with a large spatial
extent (Guo et al., 2009; Guo et al., 2017a). Besides, the studies of
the temporal variations of the PM$_{2.5}$-AOD relationship have mainly
focused on the seasonal variation (Li et al., 2015; Ma et al., 2016),
and interannual variations have been ignored, which is very worthy
of study because the PM$_{2.5}$ pollution in mainland China has
changed in recent years (Lin et al., 2018). To understand the PM$_{2.5}$-
AOD relationship in mainland China more comprehensively and
thoroughly, the study of a large area for a long time range, with
comparisons for different cities and periods, is needed.
Our study was aimed at comprehensively investigating the rela-
tionships between PM$_{2.5}$ concentration and satellite AOD in
mainland China, with an emphasis on the spatial distribution
pattern and temporal variations, especially interannual variations.
In this study, we explored the PM$_{2.5}$-AOD relationship in 368 cities
and nine urban agglomerations based on a 59-month record of
observations from February 2013 to December 2017, and the rela-
tionships were measured by Pearson correlation coefficient and
the PM$_{2.5}$/AOD ratio. Mainly 3 aspects of work have been done: 1)
spatio-temporal variations of PM$_{2.5}$-AOD relationship were
explored in city, region, month and year scale; 2) the impact of
some of the influencing factors for the PM$_{2.5}$-AOD relationship,
including the aerosol type, relative humidity (RH), topography,
and planetary boundary layer height (PBLH) were discussed; 3) the
impact of the interannual variations of PM$_{2.5}$-AOD relationship on
satellite retrieval accuracy for PM$_{2.5}$ concentration was validated.
The conclusions of this study could provide useful information for
PM$_{2.5}$ retrieval; for example, the spatial and temporal variation
patterns of the PM$_{2.5}$-AOD relationship could provide a reference
for the development of spatially and temporally self-adaptive
retrieval algorithms. Furthermore, the investigation of the influ-
encing factors for the PM$_{2.5}$-AOD relationship could help to
improve our understanding of the formation mechanisms of air
pollution.

2. Data and methods

2.1. Study area and period

The study domain covered 368 cities and nine urban
agglomerations in mainland China, as shown in Fig. 1. The nine
urban agglomerations were the Beijing-Tianjin-Hebei Urban
Agglomeration (BTH), the Yangtze River Delta urban agglomeration
(YRD), the Pearl River Delta urban agglomeration (PRD), the Central
Plain urban agglomeration (CP), Chengyu urban agglomeration
(CY), the Yangtze River Mid-Reaches urban agglomeration (YRM),
the Shandong Peninsula urban agglomeration (SP), the Mid-
Southern Liaoning urban agglomeration (MSL), and the Hachang
urban agglomeration (HC), all of which are regional urban
agglomerations approved by the National Assembly of China. These
nine national urban agglomerations are densely populated and
economically developed areas in mainland China, and have an
important position in the development of national strategy.
Therefore, we chose them to be the objects of the regional-scale
study. The detailed information for the nine urban agglomerations
is listed in Supplementary Table 1. The time range of our study
was from February 2013 to December 2017, i.e., nearly 59 months (5
years) in total.

2.2. Data collection and methodology

Hourly PM$_{2.5}$ concentration data for 2013 to 2017 were down-
loaded from the Data Center of the Ministry of Environmental
Protection of China (http://datacenter.mep.gov.cn/index). The daily
PM$_{2.5}$ concentration was averaged from the hourly values. The
PM$_{2.5}$ concentration is measured by tapered element oscillating
microbalance (TEOM) or beta attenuation monitor.

The satellite AOD product used in this study was the MODIS
level 2 daily AOD data from the Terra MOD04_L2 Collection 6,
which are reported at 10 × 10 km, with uncertainty levels of
±0.05 ± 0.20 × AOD over land (Chu, 2002; Levy et al., 2007; Levy
et al., 2013). In this product, the AOD data over land with low
quality (quality flags = 1.2) has been removed to assure the data
quality. The product was downloaded from the NASA Level-1 and
Atmosphere Archive and Distribution System (LAADS) Distributed
Active Archive Center (DAAC) (https://ladsweb.modaps.eosdis.
nasa.gov/).

Meteorological data including Relative humidity (RH), air tem-
perature (TMP), u-wind (UW), v-wind (VW), and pressure (PS) was
also prepared in our study. They were downloaded from the NCEP/
NCAR Reanalysis 1: Surface data (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html) with a resolution
of 2.5° × 2.5°.

The relationship between daily PM$_{2.5}$ concentration and AOD
was measured by Pearson correlation coefficients ($r$) and the PM$_{2.5}$/
AOD ratio ($\eta$). The ratio between PM$_{2.5}$ concentration and AOD was
first promoted by van Donkelaar et al., in 2010 as a conversion
factor (Van Donkelaar et al., 2010), and the parameter indicates the
dry mass concentration of PM$_{2.5}$/unit aerosol optical thickness.
A previous study proved that the PM$_{2.5}$/AOD ratio is a good
parameter to measure the relationship between PM$_{2.5}$ concentra-
tion and AOD (Zheng et al., 2017). Hence, we introduced this
parameter in our work, in addition to the correlation coefficients,
for a more comprehensive analysis of the PM$_{2.5}$ and AOD
relationship.

3. Results and discussion

3.1. Spatial variations of the relationship

3.1.1. Relationship analysis at the city scale

Fig. 2(a) shows the correlation coefficients between PM$_{2.5}$
concentration and AOD in the 368 cities, where the strong correlation
is mostly concentrated in eastern Sichuan, Chongqing, Yunnan, the
BTH region, and some cities in southern Xinjiang. In contrast, the
correlation in the PRD area, Hainan province, and some cities in the Qinghai-Gansu-Ningxia region (QGN) is quite low. This spatial difference may be the result of aerosol type and properties variations. In the PRD area, Hainan province, and QGN region, the aerosol types are mainly sea salt and dust (Mielonen et al., 2009) with a low fine mode faction (Supplementary Fig. 1), which means the AOD in these regions mainly comes from coarse particles like dust and sea salt. However, the main sources for PM$_{2.5}$ in these regions are secondary particles, coal burning, industrial emissions, and vehicle emissions (Tan et al., 2017; Wang et al., 2006). PM$_{2.5}$ and AOD have different kinds of sources, making the correlation between them low. In comparison, the aerosol type in Sichuan, Chongqing, and the BTH region is mainly the urban-industry type (Che et al., 2015), and the fraction of fine particles is high (Supplementary Fig. 1). Thus, the AOD and PM$_{2.5}$ in these regions tend to share more common sources, making the correlation higher.

In addition to the aerosol type and properties impact, it can be inferred that topography and climate also have a great impact on the PM$_{2.5}$/AOD relationship. For instance, in Sichuan province (marked by cyan boundary in Fig. 2(b)), the correlation is high in the Mideastern Sichuan Basin, but is low in the western Sichuan plateau. The dividing line of the high and low correlation displayed by the dotted cyan line in left of Fig. 2(b) is very close to the topography boundary of Sichuan province marked in the right of Fig. 2(b). In Xinjiang province, the correlation in the south is high and is weaker in the north. The dividing line between high and low correlation is very close to the temperature and climate zone boundary as shown in Fig. 2(c). However, this partitioning does not apply for the whole mainland China, because the PM$_{2.5}$/AOD relationship is simultaneously affected by many factors, in addition to topography and climate. The synthetic impact of all the influencing factors, such as topography, climate, emissions, aerosol optical and physical properties, and even environmental policies, results in the spatial variations found in our study.

Fig. 2(d) shows that the results of the ratio distribution, there is a conspicuous south–north difference in the figure, with higher PM$_{2.5}$/AOD ratios in the north and lower ratios in the south. We find that the distribution of PM$_{2.5}$/AOD ratio is quite similar to the distribution of RH as shown in Fig. 2(e), with high ratio in low RH regions and low ratio in high RH regions. We drew the scatterplot between the ratio and the RH (shown in the inset in Fig. 2(e)), and calculated the Pearson correlation coefficients. The correlation coefficient is −0.45, implying a strong negative correlation between PM$_{2.5}$/AOD ratio and RH. In the southern part of China, the RH is usually higher than in the north. When the environment relative humidity is high, the aerosol would be humidified and the particles tend to contain more water. The AOD represents the extinction ability of aerosol, the water contained in the particles will contribute a lot to AOD and makes the value of AOD larger. However, the concentration of PM$_{2.5}$ is dry mass concentration, where the water contained in the particles is evaporated and contributes little to PM$_{2.5}$ mass concentration in the measurements. That is to say, high humidity makes the particles in the air contain more water, thus making the AOD higher, but the impact on the concentration of PM$_{2.5}$ is relatively weak, resulting in a relatively lower PM$_{2.5}$/AOD ratio in the humid south. On the contrary, in the dry northern China, the relative humidity is low, the extinction ability of aerosol is more contributed by dry particles in the atmosphere, thus, the contribution of PM$_{2.5}$ to AOD is larger, making the ratio larger.

3.1.2. Relationship analysis at the regional scale: the study of nine typical urban agglomerations

The correlation for PM$_{2.5}$ concentration and AOD in the nine urban agglomerations are shown in Fig. 3 through the scatter plot. The Chengyu and Beijing-Tianjin-Hebei urban agglomerations have the highest correlations. Shandong Peninsula has a correlation coefficient of 0.42, following behind the CY and BTH regions. The YRM region has the lowest correlation among the nine urban agglomerations. As for the other urban agglomerations, the correlation coefficients are all between 0.37 and 0.39, which is very close to the average correlation coefficient of all the cities calculated in the last section. We note that the results at the regional scale have a slight difference with the results at the city scale. In the city scale analysis, cities in the PRD region have the lowest correlation, but the correlation is higher in the region-scale analysis, and the YRM urban agglomeration has the lowest correlation. This is because correlation at the regional scale is not a simple averaging of all the cities in the region, and the connections and relevance between these cities can affect the correlation at the regional scale. The fact that the correlation between the PM$_{2.5}$ and AOD of the PRD region is higher than the correlation of the individual cities indicates that cities in the PRD region have very similar pollution conditions. The
correlation between cities is high, making the regional correlation higher than the correlation at the city scale.

The results of the ratio calculation are shown in Fig. 3 as well, where the BTH region holds the highest ratio, followed by the HC and MSL areas, with ratios of 179 and 146, respectively. All three urban agglomerations with a high ratio are in North China, which is consistent with the results at the city scale. The ratios in the YRD, PRD, CY, and YRM areas are all below 100, which is a quite low level. As for the CP and SP areas, the ratio is at a moderate level, with \( h = 139 \) and \( h = 111 \).

To develop a comprehensive understanding of how do topography, aerosol type and meteorology influence the PM2.5-AOD relationship, we made a simple classification of all the cities and the 9 urban agglomerations according to the values of the PM2.5-AOD correlation and ratio, and summarized the features for each type of city and region, the results are shown in Fig. 4. The first type has a high correlation and high PM2.5/AOD ratio, and the representative city and region are Beijing and BTH. The urban-industry type aerosol and dry climate make the correlation and ratio high. The second type includes cities such as Chengdu and Chongqing, which mainly located in or around CY region, and the correlation is high but the ratio low. Compared with BTH region, the climate in CY is more humid, which contributes to the lower ratio. Furthermore, the basin topography in eastern Sichuan also contributes to the high correlation. Features of the third type are low correlation and ratio. Representative cities include Zhuhai, Shenzhen, Haikou etc., which are mostly located in coastal areas in South China. The high proportion of sea salt in aerosol and humid climate result the low ratio and correlation. Representative region of the third type is the YRM, humid climate makes ratio low and the spatial heterogeneity make the correlation low. As for the forth type, cities of this type usually have a dry climate, and the proportion of coarse particles is high, the representative city is Lanzhou in Gansu province and Xining in Qinghai province.

3.2. Temporal variations of the relationship

3.2.1. Monthly variations

Fig. 5 shows the correlation coefficients for each month in the nine urban agglomerations from February 2013 to December 2017.
Because the AOD is commonly missing in winter due to cloud/snow cover or high surface reflectance (Xiao et al., 2017), the correlation coefficients in the cold season are mostly missing (the small number of samples makes the significance test hard to pass). The periodic variations of \( r \) are not obvious. However, we can still find that different regions tend to share similar monthly patterns every year. For example, in 2014 and 2016, the monthly curves are bimodal for most regions, one peak is in May and the other in September. As for 2013, the monthly curve is unimodal for most regions, the high correlation appears in August and September. In 2017, the high correlation tends to appear in September and then reaches a trough in November. The variations of the first half of the year are weak and the curve is nearly flat and smooth. As we can see, the monthly pattern is different for each year, although in the same year, the varying pattern can be different in certain regions. On the whole, the monthly variations of \( r \) are quite complex and we cannot come to an easy conclusion, such as the correlation is high in spring and low in winter. However, in the terms of statistics, there is a higher probability that high correlation will appear in May and September.

We then calculated the ratios in the nine urban agglomerations. The results are shown in Fig. 6. There are obvious periodic variations, in that the ratio is usually lower in warm season and becomes higher in cold season. This difference may result from the seasonal variations of pollution and meteorology. On the one hand, some publications had shown that PM\(_{2.5}\) concentration is high in winter and lower in summer (Li et al., 2017b), and for AOD the reverse (Sogacheva et al., 2018; de Leeuw et al., 2018), therefore, making the ratio high in winter and low in summer. On the other hand, the low PBLH in winter (Supplementary Fig. 2) makes the fine particles mostly concentrate in the lower atmosphere, and thus the surface PM\(_{2.5}\) concentration, which is measured by ground sites and used in our paper, can account for a higher ratio in the PM\(_{2.5}\) concentration for the whole atmospheric column. Hence, the PM\(_{2.5}/\text{AOD}\) ratio can be higher in winter. Similar results were also found in a previous work (Zheng et al., 2017). Furthermore, the RH in winter is usually lower than summer (Supplementary Fig. 3), that may also contribute to the low ratio in summer and high ratio in winter.

3.2.2. Interannual variations

The interannual variations of PM\(_{2.5}\)-AOD correlation are displayed in Fig. 7(a) and Fig. 7(b) (the results for the nine urban

![Fig. 3. Scatter plots for PM\(_{2.5}\) concentration and AOD in the nine urban agglomerations (the unit of PM\(_{2.5}\) concentration is \(\mu g/m^3\)). The number of samples, correlation coefficients and ratios of PM\(_{2.5}\) and AOD are displayed in the upper right corner. The color for dots represents the density of dots. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)](image-url)
agglomerations are shown in two pictures, for a better display of the data). Because the correlation coefficients are often missing in the cold season, and the periodic variations are not obvious, we selected the highest correlation in the warm season (May to October each year) in each year for the nine urban agglomerations to study the interannual variation of the correlation. In most regions, the correlation gets stronger from 2013 to 2014, but starts to decrease after 2014, indicating a weakening of the PM$_{2.5}$-AOD correlation.

Fig. 7(c) and (d) show the interannual variations of the ratio. Overall, there is a decreasing tendency from 2013 to 2017, although with some fluctuations, which indicates that PM$_{2.5}$ is accounting for a smaller part in AOD. To quantitatively evaluate the rate of decrease, we conducted simple linear fitting for the ratios from 2013 to 2017, and represent the rate of decrease with the slope of the fitting line. The linear slope for the BTH area is $\frac{C_0}{16.6}$, and the absolute value is the largest among the nine urban agglomerations. The linear slope for the three urban agglomerations in the north, which have higher ratios than the other regions, are all less than $\frac{C_0}{7}$. However, the slope values for the other regions are all larger than $-5$, representing a slower rate of decrease. Among all the nine urban agglomerations, the Chengyu urban agglomeration is the only region where the ratio is increasing slowly overall, and the slope of the fitting line is 0.73. Combining the results about correlation and ratio, we can infer that the relationship between PM$_{2.5}$ and AOD is getting weaker.

3.3. Discussion

3.3.1. Impacting factors for the PM$_{2.5}$-AOD relationship

In the last section, we compared the spatial and temporal variations of the PM$_{2.5}$-AOD relationship with the spatio-temporal variations of some psychical geographical variables such as aerosol type, topography, RH, and PBLH etc., and through the combined analysis, we developed some understandings on how are these factors influencing the PM$_{2.5}$-AOD relationship, so we simply summarize the impact of these factors here.

1) Aerosol type and properties impact

The high correlation and high FMF in BTH, CY region and the low correlation and low FMF in PRD, QGN shows that the aerosol types and properties can influence the PM$_{2.5}$-AOD correlation. The urban-industry aerosol type, in which sulfates and nitrates are the main species, tends to cause high correlation between PM$_{2.5}$ and AOD. This is because this type of aerosol tends to have low FMF and can share more common sources with PM$_{2.5}$. In contrast, soil dust and sea salt aerosols, in which coarse particles make up a larger proportion and the FMF is small, usually have a different source from PM$_{2.5}$.

2) Topography impact

Topography is a very important influencing factor for PM$_{2.5}$ and the PM$_{2.5}$-AOD relationship, but the study of it is lacking since the quantitative description of complex topography structure is often difficult. In our study, we found that the basin terrain can often result in a high correlation between PM$_{2.5}$ and AOD in local regions. For example, Sichuan Basin and Tarim Basin both have high $r$ values. Therefore, we infer that basin areas tend to form a regional pollution environment, and PM$_{2.5}$ and AOD can share a larger amount of influencing factors, and thus have a higher correlation.
3) Relative humidity (RH) impact

The high consistency between the ratio distribution and RH distribution shows that RH can influence the PM$_{2.5}$-AOD relationship a lot. High humidity represents a high content of water vapor in the environmental atmosphere and in suspended particles. Water vapor in particles can contribute a lot to aerosol extinction ability and make AOD increase. However, the concentration of PM$_{2.5}$ is mainly dry mass concentration, which means that the water vapor in particles will be evaporated, and thus contributes little to PM$_{2.5}$ mass concentration. Hence, high humidity tends to make the ratio between PM$_{2.5}$ concentration and AOD lower.

4) Planetary boundary layer height (PBLH) impact

The seasonal variations of PM$_{2.5}$/AOD ratio takes an opposite trend against PBLH, that means PBLH can have a great impact on PM$_{2.5}$-AOD relationship as well. A high PBLH makes particles able to suspend in a higher vertical space, but the PM$_{2.5}$ concentration measuring instruments are usually located on the ground surface, so only the surface PM$_{2.5}$ is measured. When the PBLH becomes higher, the PM$_{2.5}$ concentration we acquire from in-situ equipment...
will account for a reduced proportion of the total PM$_{2.5}$ in the atmospheric column, thus making the ratio between PM$_{2.5}$ and AOD lower. To verify the impact of PBLH, we conduct a vertical correction (Zhang and Li, 2015) for AOD to see whether the corrected AOD can be more correlated with PM$_{2.5}$; the result is shown in Supplementary Fig. 4, and for most of the regions, correlations are improved after AOD being vertical corrected by PBLH.

### 3.3.2. Implications for PM$_{2.5}$ retrieval through satellite AOD

MODIS AOD has been widely used for PM$_{2.5}$ concentration retrieval. However, as our results show, PM$_{2.5}$ is accounting for a smaller part of AOD, and their correlation has been decreasing since 2014. Therefore, AOD’s prediction ability for PM$_{2.5}$ concentration needs to be further validated. Thus, we conducted a PM$_{2.5}$ retrieval experiment to see how the retrieval performance is varying as the PM$_{2.5}$-AOD relationship gets weaker. The GWR model is a popular regression model proposed by Brunsdon et al., in 1996 (Brunsdon et al., 1996). Recently, it was widely used for retrieving PM$_{2.5}$ concentration from satellite AOD and shows a good performance (Hu et al., 2013; He and Huang, 2018). Therefore, it was used in our experiment (for a more detailed theory of GWR, please refer the Supplementary material). The GWR4 software developed by Tomoki Nakaya et al. (2005) was used to conduct the GWR calculation. AOD and five metrological factors (RH, TMP, UW, VW, PS) were used as independent variables in the model while PM$_{2.5}$ concentration is the dependent variable. The kernel type is adaptive bi-square and the optimal bandwidth is determined by minimizing the corrected Akaike information criterion (AICc). For each year from 2013 to 2017, a GWR model is established. The retrieval $R^2$ and adjusted $R^2$ are listed in Table 1 and the boxplots for the local $R^2$ of each environmental station can be seen in Supplementary Fig. 5. The $R^2$ and adjusted $R^2$ both decrease from 2013 to 2017, indicating that the performance of the GWR model is getting worse.

With time passing by, the PM$_{2.5}$ pollution in mainland China has been reduced (Supplementary Fig. 6). Meanwhile, our results show that the relationship between PM$_{2.5}$ and AOD are getting weaker, and the performance of AOD retrieval is also deteriorating. This implies that with the change of the pollution situation, the relationship between PM$_{2.5}$ and AOD are changing, and the predicting ability of AOD for PM$_{2.5}$ are also getting different. In the long term, we should keep a discreet attitude to the use of AOD product for PM$_{2.5}$ retrieval. In our study, we detected the start of the change. In the future, more studies should be made to capture the full picture and essence of this change.

### 3.3.3. Limitations and future work

We studied the relationship between PM$_{2.5}$ and AOD using the 10 km MODIS AOD product in a large spatial extent and long time series, but there exist several uncertainties. One is the product quality of MODIS AOD. Though only the highest quality of AOD retrievals were used in our analyses, the quality of AOD over complex land surfaces and near water bodies can still be a problem (Wang et al., 2018b). Besides, there are many kinds of AOD product apart from MODIS AOD, such as the 750 m VIIRS AOD product (Jackson et al., 2013) and AOD product from Himawari-8, which have a temporal resolution of 10min (Zang et al., 2018). The differences among these products may also bring uncertainties to the relationship between PM$_{2.5}$ and AOD. In the future, we will pay more attention to the use of AOD product at a higher spatial and temporal resolution. With higher resolution, the PM$_{2.5}$ data and AOD product can match better at temporal and spatial scales. Actually, there are also some possible methods that can improve the PM$_{2.5}$-AOD correlation, such as the introduction of fine mode aerosol or filtering the aloft plumes, but the effect of these methods
in the vast mainland China needs further validation. In the future, we would also like to make more investigations on this problem and explore the PM$_{2.5}$-AOD relationships considering more potential factors like the temporal and spatial scales and the vertical structures of aerosols. At last, though we have explained the spatio-temporal variations of the PM$_{2.5}$-AOD relationship considering multiple kinds of factors, there are still several phenomena that we cannot fully explain, we would also like to make more investigations using more complex methods like model simulation, to explore the inner physical connections between these factors and PM$_{2.5}$-AOD relationship in the future.

4. Conclusions

The PM$_{2.5}$-AOD relationship is the cornerstone for PM$_{2.5}$ satellite retrieval. However, the foundation is not always solid. In this study, we found the PM$_{2.5}$/AOD ratio tends to be higher in dry regions like the drier north China, and the correlation between PM$_{2.5}$ and AOD tends to be larger in places that are serious polluted and where aerosols are fine mode dominated, like the BTH and CY regions. In recent years, the relationships between PM$_{2.5}$ and AOD are getting weaker, and the performance of PM$_{2.5}$ retrieval is getting worse as well. The spatio-temporal variations of the PM$_{2.5}$-AOD relationship are results of the synthetic impact of multiple factors including meteorology, topography and aerosol properties etc. The findings could provide useful instructions and important implications for satellite retrieval of PM$_{2.5}$ concentration, and will help with improving our understanding of the PM$_{2.5}$ pollution situation in China.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.02.071.

References


