

Original Article

Impact of environmental pollution on the retrieval of AOD products from Visible Infrared Imaging Radiometer Suite (VIIRS) over wuhan

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ABSTRACT

Visible Infrared Imaging Radiometer Suite (VIIRS) is a next-generation polar-orbiting operational environmental sensor, and its aerosol optical depth (AOD) data has been widely applied to ground-level PM_{2.5} prediction and air pollution research. However, VIIRS performance affects the accuracy of prediction. In this study, three types of VIIRS AOD products were collected from January 2014 to December 2016 to evaluate their performance under different air quality conditions. Near-surface PM_{2.5} concentrations were determined for the same period to categorize air quality as clean, moderate, or heavily polluted. The performance of three VIIRS AOD products was evaluated from the successful retrieval rate and AOD accuracy aspects. For clean weather days, the AODs obtained from VIIRS intermediate products (IP) had the lowest average absolute bias (0.15 ± 0.15). For the moderate and heavy pollution days, the average absolute deviations of VIIRS environmental data record (EDR) AOD (Quality Flags = 3 and > 1) products were lowest at 0.14 ± 0.14 and 0.2 ± 0.1 respectively. These results suggest that the EDR AOD, Quality Flags > 1 and = 3, products were more suitable for heavy and moderate air pollution, respectively. During clean weather, performance of IP AODs was found to be best. Moreover, seasonal analysis indicated that the EDR AOD (Quality Flags = 3) products were more suitable for spring and autumn and the IP AOD for summer. However, the performance of the EDR AOD products (Quality flags > 1) were best during winter. To ensure accuracy of PM_{2.5} predictions over central China, researchers should carefully balance the needs for successful retrieval rate and accuracy of VIIRS AOD products.

1. Introduction

Aerosols, which are solid or liquid particles suspended in the atmosphere, have a significant influence on environmental pollution and human health (Holben et al., 2001; Kaufman et al., 2002; Pan et al., 2017). Among them, particulate matter with diameter less than 2.5 μm (PM_{2.5}) can remain in the atmosphere for a long time and can be inhaled, resulting in various diseases (Brauer et al., 2015; Liu et al., 2017; Wang et al., 2019a). Therefore, large scale and long-time continuous monitoring for ground-level PM_{2.5} is necessary. Recently, satellite-retrieved aerosol optical depth (AOD) has become an important predictor of ground-level PM_{2.5} and has greatly empowered air pollution research worldwide (Chen et al., 2017; Belle et al., 2016; Wang et al., 2019b).

A variety of satellite sensors, such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging Spectroradiometer (MISR) have been used for long term continuous detection of AOD (Liu et al., 2018a, 2018b; Pan et al., 2018; Belle et al.,

2016). However, these polar-orbital sensors are nearing the end of their lifespans. In order to continue with global Earth observations, the Visible Infrared Imaging Radiometer Suite (VIIRS), a next-generation environmental sensor with a capability for global aerosol observations, was launched on 28 October 2011 (Liu et al., 2014; Cao et al., 2014). The VIIRS AOD products are derived primarily from radiometric channels covering the visible and the short-wave infrared spectral regions (Cao et al., 2013). The products include pixel-level AOD (~750 m), which is considered an intermediate product (IP) to the AOD environmental data record (EDR) at ~6 km resolution (Justice et al., 2013). VIIRS AOD products have also been widely compared and validated with AOD products from other satellite sensors and the Aerosol Robotic Network (AERONET) (Li et al., 2014; Bilal et al., 2017). Huang et al. (2016) estimated the errors of VIIRS AOD and Ångström exponent products by comparing them with observations from AERONET, and indicated that over land, the VIIRS EDR AOD products have an overall global bias of -0.0008 ± 0.12 against AERONET. Xiao et al. (2016)

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assessed VIIRS AOD products by comparing them with sun photometer observations over East Asia, and found that while VIIRS IP 3 km products had positive biases, the VIIRS EDR products could provide the most accurate AOD data. Wang et al. (2017a, 2017b) compared VIIRS IP AOD with sun photometer and MODIS AOD products over central China, and pointed out that VIIRS IP AOD products were underestimated by 5% at Wuhan. He et al. (2018) assessed the VIIRS EDR and MODIS AOD products over Yangtze River Basin, and indicated that the VIIRS EDR AOD products provide an underestimation over regions with a high aerosol loading. Those comparisons provide valuable insights into the application of VIIRS AOD products.

With the increase in anthropogenic emissions and the advancement of urbanization, dust and haze pollution occur frequently over China. Many studies have employed VIIRS AOD products to retrieve surface PM_{2.5} data (Wang et al., 2016; Fu et al., 2018; Ma et al., 2016). Pang et al. (2018) developed a three-dimensional variational data assimilation system to forecast ground-level PM_{2.5} over Eastern China, and pointed out that combining GOCI and VIIRS AOD products can enhance the accuracy of PM_{2.5} prediction. Yao et al. (2018) compared surface PM_{2.5} concentrations retrieved from MODIS and VIIRS AOD over a high aerosol loading region, and indicated that the VIIRS AOD products explained 76% of the total PM_{2.5} variations. These studies show that forecasting the ground PM_{2.5} concentrations requires accurate AOD data and sufficient samples. However, the performance of VIIRS AOD products under the different pollution levels are still unclear. Therefore, it is essential to evaluate the deviation of VIIRS AOD products under different pollution levels, which has significant implications on the application of VIIRS AOD products in research on regional pollution.

In this study, the performance of three VIIRS AOD products from January 2014 to December 2016 was investigated under different air quality conditions. Near-surface PM_{2.5} concentrations were collected to categorize air quality as clean, moderate, and heavily polluted. The performance of the three VIIRS AOD products was evaluated on the basis of successful retrieval rate and AOD accuracy. The organization of this study is as follows: Sections 2–3 show the data and methods. The results and the discussion are described in Sections 4 and 5, respectively. Section 6 provides the conclusions.

2. Materials and data

2.1. Air quality monitoring data

The hourly average PM_{2.5} concentration data were collected from the Ministry of Environmental Protection (MEP) of the People's Republic of China's observation network. According to the MEP requirements, all air quality monitoring stations are required to monitor six key pollutants (PM_{2.5}, PM₁₀, SO₂, NO₂, CO, and O₃) at 1 h intervals (Liu et al., 2018a, 2018b). The nearest air quality monitoring station from the Wuhan monitoring station (114.36°E, 30.52°N), the East Lake pear orchard station (114.38°E, 30.58°N), was selected to obtain the hourly mean PM_{2.5} data. The Wuhan observation station is marked by a white dot in Fig. 1.

2.2. AOD from sun photometer

A Cimel sun photometer, CE-318, was installed at Wuhan University (114.36°E, 30.52°N), Wuhan, Hubei Province, China (Fig. 1) (Zhang et al., 2016, 2017). The sun photometer is a multi-channel, automatic, sun-and-sky-scanning radiometer that measures direct solar irradiance and sky radiance. It performs direct spectral solar radiation measurements at eight bands of 340, 380, 440, 500, 675, 870, 940, and 1020 nm (Che et al., 2009). Detailed instrument calibration and AOD inversion methods have been described in (Tao et al., 2014). This instrument was annually calibrated with the AERONET reference instruments in Beijing to ensure the accuracy and reliability of observation data. The errors of the sun photometer AOD products ranged

approximately from 0.01 to 0.02 (Wang et al., 2015).

2.3. AOD from VIIRS

VIIRS is one of the key environmental remote-sensing instruments onboard the Suomi NPP satellite (Levy et al., 2015). It can provide two types of AOD products: an IP AOD at pixel level resolution (~750 m) and an EDR AOD at ~6 km resolution (Wang et al., 2017a, 2017b). Those products come with corresponding quality flags (QF), which indicates the confidence of the retrievals. The detail division method of quality flags can be seen in the JPSS VIIRS Imagery Products Algorithm Theoretical Basis Document (Baker, 2011). The VIIRS Aerosol team strongly recommends that only the VIIRS EDR AOD with QF = 3, VIIRS EDR AOD with QF = 2, and VIIRS IP AOD with QF = 0 be applied (Jackson et al., 2013). These three VIIRS AOD products (IP_QF = 0 AOD, EDR_QF > 1 AOD, and EDR_QF = 3 AOD) were used in this study to evaluate the performance of VIIRS under different air quality conditions.

3. Comparison of methods

The study was conducted from January 2014 to December 2016. AOD products were employed only when at least 20% of the pixels fell within the ground observation station. Then, the AODs were computed as the average of VIIRS AOD products within a range of 20 km from the ground observation station. Finally, data from the sun photometer was collected within 30 min of the overpass of VIIRS (Liu et al., 2018a, 2018b). Root mean square error and mean absolute difference were calculated from the following equations (Wang et al., 2017a, 2017b):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (AOD_{(satellite)i} - AOD_{(ground)i})^2} \quad (1)$$

$$MAD = \frac{1}{n} \sum_{i=1}^n |AOD_{(satellite)i} - AOD_{(ground)i}| \quad (2)$$

RMSE and MAD represent the root-mean-square error and mean absolute difference, respectively. AOD_{satellite} and AOD_{ground} represent the VIIRS AOD products and mean sun photometer AOD, respectively.

4. Results

4.1. Retrieval statistics under different pollution levels

Observation counts of the PM_{2.5} data, VIIRS_IP AOD, EDR_QF > 1 AOD, EDR_QF = 3 AOD, and sun photometer AOD were conducted. A total of 1092 successful PM_{2.5} observation counts were obtained from January 2014 to December 2016. During this period, the air quality in Wuhan varied widely with PM_{2.5} concentrations ranging from 7 µg/m³ to 287 µg/m³. Meanwhile, the total counts of the VIIRS_IP AOD, EDR_QF > 1 AOD, EDR_QF = 3 AOD, and sun photometer AOD retrievals were approximately 695, 520, 252, and 454, respectively. Fig. 2a shows the retrieval number histograms of the PM_{2.5} data, VIIRS_IP AOD, EDR_QF > 1 AOD, EDR_QF = 3 AOD, and sun photometer AOD under different PM_{2.5} concentrations. The distribution of their retrieval counts is similar as most of the PM_{2.5} data (605), VIIRS_IP AOD (405), EDR_QF > 1 AOD (323), EDR_QF = 3 AOD (144), and sun photometer AOD (268) were concentrated in the range of 50–100 µg/m³. Fig. 2b shows the retrieval number histograms of the VIIRS_IP AOD, EDR_QF > 1 AOD, EDR_QF = 3 AOD, and sun photometer AOD. Most of the retrieval numbers of VIIRS_IP AOD (341), EDR_QF > 1 AOD (247), EDR_QF = 3 AOD (172), and sun photometer AOD (223) were concentrated in the range of 0.2–0.6. Overall, while the PM_{2.5} monitoring data was collected everyday, the AOD retrievals were restricted due to weather conditions and could only be obtained under cloud-free conditions. Among all products, the VIIRS_IP products

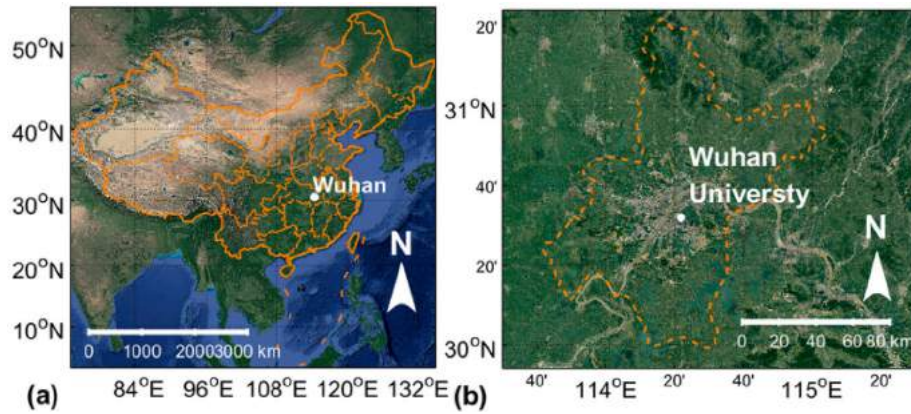


Fig. 1. (a) Geographic location of Wuhan and (b) geographic location of the sun photometer (white dot).

had the largest successful retrievals counts, followed by retrievals of VIIRS_EDR_QF > 1 products, the sun photometer retrievals, and retrievals of the VIIRS_EDR_QF = 3 products.

According to China's latest air quality standards, the air qualities were categorized into three levels: clean (0–75 $\mu\text{g}/\text{m}^3$), moderate pollution (75–150 $\mu\text{g}/\text{m}^3$), and heavy pollution (> 150 $\mu\text{g}/\text{m}^3$). By counting the PM_{2.5} observation data, 5% (58) of these data were from heavy pollution days, 29% (315) from moderate pollution days, and 66% (718) from clean days, which indicates that in Wuhan, approximately 34% of the days were polluted. Due to the effect of rain or clouds, the retrieval counts of AOD should have been less than that of PM_{2.5} observations. Table 1 shows the successful retrievals count (rate) of the VIIRS_IP AOD, EDR_QF > 1 AOD, EDR_QF = 3 AOD, and sun photometer AOD. The successful retrieval rate of the VIIRS_IP AOD was the highest at approximately 61%. The successful retrieval rate of EDR_QF > 1 AOD was approximately 45%, which was similar to the 41% directly derived from the sun photometer observation data. However, the successful retrieval rate for the VIIRS_EDR_QF = 3 AOD was relatively low at approximately 25%. The successful retrieval rates of the EDR_QF = 3 AOD under different air quality standards were approximately 21%, 27%, and 28%, respectively. The successful retrieval count of VIIRS_EDR_QF = 3 AOD during heavy pollution was 16, which is far less than the total number of observations (58). These results indicate that the number of VIIRS_EDR_QF = 3 AOD products may be not enough to reflect the actual air quality situation.

Additionally, retrieval counts of the VIIRS_IP AOD, EDR_QF > 1 AOD, EDR_QF = 3 AOD, and sun photometer AOD during each month were considered. Fig. 3 and Table 2 show the monthly successfully

Table 1

The successful retrievals count of AOD products under different pollution levels.

AOD Products	PM _{2.5} Concentrations ($\mu\text{g}/\text{m}^3$)	Retrieval Counts	Percentage
PM _{2.5}	< 75	718	100%
	75–150	315	100%
	> 150	58	100%
VIIRS_IP	< 75	458	64%
	75–150	206	65%
	> 150	31	54%
VIIRS_EDR_QF > 1	< 75	344	48%
	75–150	152	48%
	> 150	24	41%
VIIRS_EDR_QF = 3	< 75	152	21%
	75–150	84	27%
	> 150	16	28%
Sun_Photometer	< 75	302	42%
	75–150	129	41%
	> 150	23	40%

retrieval counts of the VIIRS_IP AOD, EDR_QF > 1 AOD, EDR_QF = 3 AOD, and sun photometer AOD. More successful retrievals counts were collected in middle of the year (July–September) from VIIRS_IP, VIIRS_EDR_QF > 1, and sun_photometer. However, for the VIIRS_EDR_QF = 3 AOD, more successful retrievals were collected in October and December. For all four AOD products, the fewer successful retrievals in May and June may have been due to the rainy season, while in autumn and winter, less precipitation and fewer clouds may have allowed more AOD retrievals.

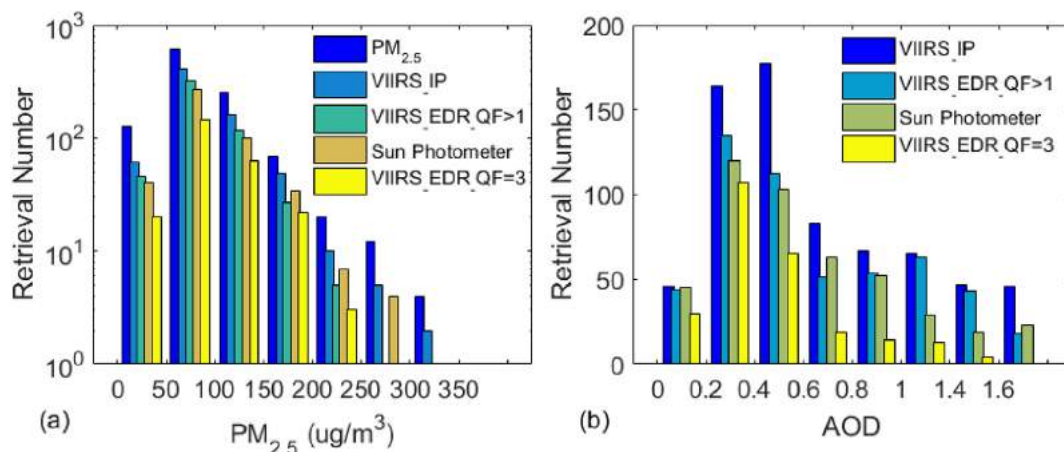


Fig. 2. (a) Retrieval number histograms of the PM_{2.5} data, VIIRS_IP AOD, EDR_QF > 1 AOD, EDR_QF = 3 AOD, and sun photometer AOD under different PM_{2.5} concentration. (b) Retrieval number histograms of the VIIRS_IP AOD, EDR_QF > 1 AOD, EDR_QF = 3 AOD, and Sun photometer AOD.

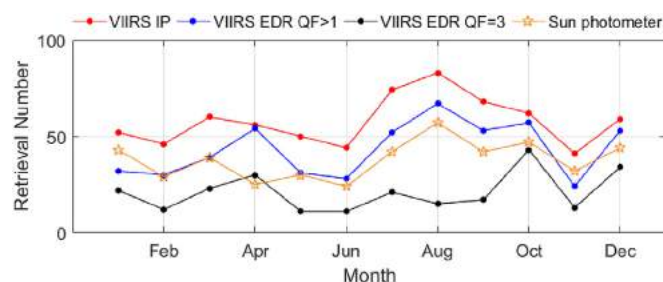


Fig. 3. Monthly successfully retrieval numbers of the VIIRS_IP AOD, EDR_QF > 1 AOD, EDR_QF = 3 AOD, and Sun photometer AOD retrievals. The red, blue, black, and orange line represent the VIIRS_IP, EDR_QF > 1, EDR_QF = 3, and Sun photometer, respectively.

4.2. Deviation of AODs under different pollution levels

To analyse the deviation of AOD products derived from VIIRS_IP, VIIRS_EDR_QF > 1, and VIIRS_EDR_QF = 3, the three AOD products were matched with the sun photometer AOD. After the matching process, the valid matchups cases of VIIRS_IP, VIIRS_EDR_QF > 1, and VIIRS_EDR_QF = 3 were 323, 266, and 187, respectively.

Fig. 4 and Table 3 show the relationship of the AOD products obtained from VIIRS_IP, VIIRS_EDR_QF > 1, VIIRS_EDR_QF = 3, and sun photometer with varying PM_{2.5} levels. Fig. 4a represents correlation of AOD products retrieved from VIIRS_IP and sun photometer, with $R = 0.7$ and RMSE = 0.31. Fig. 4b shows the correlation of AOD products retrieved from VIIRS_EDR_QF > 1 and sun photometer, with $R = 0.72$ and RMSE = 0.32. Fig. 4c shows the correlation of the AOD products retrieved from VIIRS_EDR_QF = 3 and sun photometer, with $R = 0.76$ and RMSE = 0.24. These results indicate that the VIIRS_EDR_QF = 3 AOD products are highly correlated with sun photometer observations. Other evaluation studies have found similar results (Xiao et al., 2016). Moreover, the colour bar indicates that the three VIIRS AOD products were underestimated when the mass concentration of PM_{2.5} was large.

Fig. 5 exhibits the bias in AOD between VIIRS_IP and sun photometer, VIIRS_EDR_QF > 1 and sun photometer, and VIIRS_EDR_QF = 3 and sun photometer with variation in PM_{2.5}. Fig. 5a shows AOD bias of VIIRS_IP products. It suggests that the mean AOD bias between VIIRS_IP and sun photometer increased with an increase in PM_{2.5} concentrations. Mean AOD bias between VIIRS_IP and sun photometer was largest (RMSE = 0.31) when PM_{2.5} concentrations was more than 150 $\mu\text{g}/\text{m}^3$. For the AOD bias of VIIRS_EDR_QF > 1 products (Fig. 5b), the largest AOD bias (RMSE = 0.45) between VIIRS_EDR_QF > 1 and sun photometer was under 60 $\mu\text{g}/\text{m}^3$ < PM_{2.5} < 90 $\mu\text{g}/\text{m}^3$. Fig. 5c represents AOD bias between VIIRS_EDR_QF = 3 and sun photometer. Fig. 5a indicates that VIIRS_IP AODs were overestimated when the PM_{2.5} concentrations was less than 60 $\mu\text{g}/\text{m}^3$, and underestimated when the PM_{2.5} concentrations was more than 90 $\mu\text{g}/\text{m}^3$. The same trend can be seen in Fig. 5b and c. The VIIRS_EDR_QF > 1 and VIIRS_EDR_QF = 3 AODs were also overestimated when PM_{2.5} < 60 $\mu\text{g}/\text{m}^3$, and underestimated when PM_{2.5} > 90 $\mu\text{g}/\text{m}^3$. These results indicate that the performance of the three VIIRS AOD products was affected by a change in PM_{2.5} concentrations.

Table 2
Monthly statistics of observations from January 2014 to December 2016.

AOD Products	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
VIIRS_IP	52	46	60	56	50	44	74	83	68	62	41	59
VIIRS_EDR_QF > 1	32	30	39	54	31	28	52	67	53	57	24	53
VIIRS_EDR_QF = 3	22	12	23	30	11	11	21	15	17	43	13	34
Sun photometer	43	29	39	25	30	24	42	57	42	47	32	44

Fig. 6 and Table 4 show comparisons of AODs derived from the VIIRS_IP, EDR_QF > 1, EDR_QF = 3, and sun photometer under different pollution levels. During clean weather (Fig. 6a), the correlation coefficients (RMSE) between VIIRS_IP, EDR_QF > 1, and EDR_QF = 3 and sun photometer were $R = 0.78$ (0.31), $R = 0.78$ (0.34), and $R = 0.83$ (0.24), respectively. This suggests that AODs derived from VIIRS_IP, EDR_QF > 1, EDR_QF = 3, and sun photometer are consistent under clean weather. Fig. 6b shows the comparison of three AOD products with sun photometer under moderate pollution. The correlation coefficient (RMSE) between three VIIRS AOD products and sun photometer shows a decline, reducing to $R = 0.53$ (0.26), $R = 0.6$ (0.28), and $R = 0.7$ (0.24), respectively. Under heavy air pollution (Fig. 6c), the correlation between VIIRS_IP, EDR_QF > 1 and sun photometer AOD was $R = 0.72$ (0.4), and $R = 0.75$ (0.27), which was better than that between EDR_QF = 3 and sun photometer ($R = 0.58$). These results show that the VIIRS_EDR_QF > 1 AOD were more suitable for heavy air pollution and VIIRS_EDR_QF = 3 AOD were more suitable for moderate pollution.

4.3. Seasonal deviation under different pollution levels

In order to investigate the effect of seasons on VIIRS AOD retrievals, the daily mean VIIRS_IP AOD, EDR_QF > 1 AOD, and EDR_QF = 3 AOD retrieval biases (AODsatellite–AODsunphotometer) were performed for the period of January 2014 to December 2016. Fig. 7 shows the seasonal deviation of VIIRS_IP AOD, EDR_QF > 1 AOD, and EDR_QF = 3 AOD. The red, blue, and black lines show the VIIRS_IP AOD biases, EDR_QF > 1 AOD biases, and EDR_QF = 3 AOD biases, respectively. It indicates that three AOD products have similar seasonal deviation, and the AOD retrievals in summer and in winter were overestimated and underestimated, respectively. This seasonal deviation was similar to Huang's research (2016). The reason may be attributed to changes in the seasonal surface reflectance.

Fig. 8 represents the normalized mean seasonal deviation of VIIRS_IP AOD, EDR_QF > 1 AOD, and EDR_QF = 3 AOD products under different pollution levels. It can be seen that all occurrences of heavy pollution were found in winter. By contrast, there were only clean weather samples during summer. This may be due to frequent haze pollution in winter and rainfall in summer. In the clean air scenario, the normalized mean deviations of three AOD products are positive in spring, autumn, and winter season, and close to 0 in summer season. The standard deviation of VIIRS_IP AOD (0.17) was lowest in summer season. This suggests that VIIRS_IP AOD were more suitable for summer season under clean days. During the moderate pollution period, the normalized mean deviations of three AOD products are similar in spring, autumn, and winter seasons. For the heavy air pollution, the normalized mean deviation of VIIRS_IP AOD, EDR_QF > 1 AOD, and EDR_QF = 3 AOD were -0.14 ± 0.22 , -0.01 ± 0.24 , and -0.19 ± 0.23 in winter season, respectively. This indicates that VIIRS_EDR_QF > 1 AODs were more suitable for the winter season under heavy pollution days.

5. Discussion

The VIIRS aerosol products have been validated with sun photometer in worldwide. The inter-comparison of VIIRS AOD products and

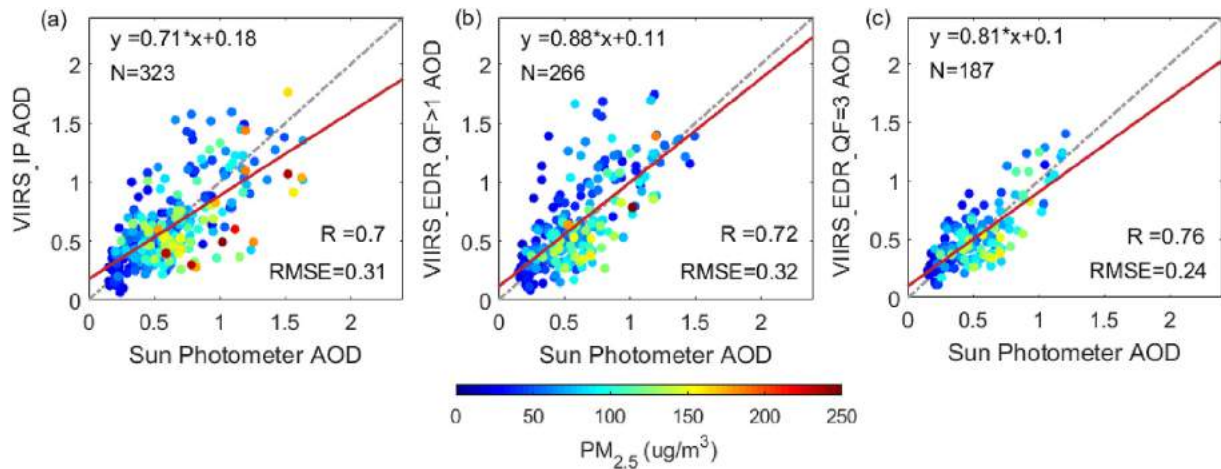


Fig. 4. Comparison of VIIRS AOD products against Sun_photometer AOD during 2014–2016. (a) VIIRS_IP VS. Sun_photometer; (b) VIIRS_EDR_QF > 1 VS. Sun_photometer; (c) VIIRS_EDR_QF = 3 VS. Sun_photometer. Color bars represent the PM_{2.5} concentrations.

Table 3

Comparison of VIIRS AOD products against Sun_photometer AOD at Wuhan during 2014–2016.

AOD Products	N	Slope	y-int	R	RMSE
VIIRS_IP	323	0.71	0.18	0.7	0.31
VIIRS_EDR_QF > 1	266	0.88	0.11	0.72	0.32
VIIRS_EDR_QF = 3	187	0.81	0.1	0.76	0.24

AERONET over land indicated that the VIIRS EDR AOD products have an overall global bias of -0.0008 against AERONET, while the corresponding values of VIIRS IP AOD products were 0.0415 (Huang et al., 2016). However, the validation results may vary from place to place. The validation over east Asia show that 51% of VIIRS EDR AOD, 33% of VIIRS P AOD fell within the reference expected error (EE) envelope ($\pm 0.05 \pm 0.15$ AOD) in Beijing area, but 64% of EDR, 37% of IP fell within the EE in Japan–South Korea region (Xiao et al., 2016). The validations of VIIRS_EDR AOD demonstrated that the high-quality VIIRS_EDR AOD retrievals exhibited poor agreement with the AERONET AOD observations ($R = 0.73$), and the VIIRS_EDR AOD products exhibited positive biases under a high aerosol loading area (He et al., 2018). For Wuhan, the evaluation and comparison of the results showed that the VIIRS IP AODs and sun photometer had a low R^2 of 0.55, with only 52% of retrievals falling within the expected error range established by MODIS over land (Wang et al., 2017a, 2017b). Previous studies have indicated that the accuracy and number of samples of AOD products should be considered when using satellite AOD products to

forecast ground-level PM_{2.5} (Ma et al., 2016; Chen et al., 2017). In this study, the performance of three VIIRS AOD products was evaluated at different pollution levels from the successful retrieval rates and AOD accuracy aspects.

Figs. 6 and 9a show the accuracy of the three VIIRS AOD products under different pollution levels. Under clean weather, the correlation coefficients between VIIRS_IP, EDR_QF > 1, and EDR_QF = 3 and sun photometer were 0.78, 0.78, and 0.83, respectively. Although the correlation coefficients between three VIIRS AOD products and sun photometer was similar, the average absolute bias of AOD between VIIRS_IP, EDR_QF > 1, and EDR_QF = 3 and sun photometer was 0.15 ± 0.15 , 0.17 ± 0.18 , and 0.2 ± 0.2 , respectively. During the moderate days, average absolute bias of AOD between VIIRS_IP, EDR_QF > 1, and EDR_QF = 3 and sun photometer was 0.2 ± 0.16 , 0.2 ± 0.16 , and 0.14 ± 0.14 , respectively. The correlation coefficients between EDR_QF = 3 and sun photometer were the largest ($R = 0.7$). Under heavy air pollution, the average absolute deviation of AOD between VIIRS_IP, EDR_QF > 1, and EDR_QF = 3 and sun photometer was 0.35 ± 0.22 , 0.2 ± 0.1 , and 0.2 ± 0.15 , respectively. Moreover, the EDR_QF > 1 products and sun photometer had the largest correlation coefficients ($R = 0.75$). It was found that the average absolute bias of three AOD products was similar under clean weather and moderate pollution. This is due to fact that the EDR products were aggregated from the finer resolution IP product. For heavy air pollution, the average absolute bias of VIIRS_IP AOD products was more than that of EDR_QF > 1 and EDR_QF = 3 AOD products. There may be two reasons leading to the performance difference of VIIRS AOD products. On the one hand, the larger average absolute bias of VIIRS AODs in

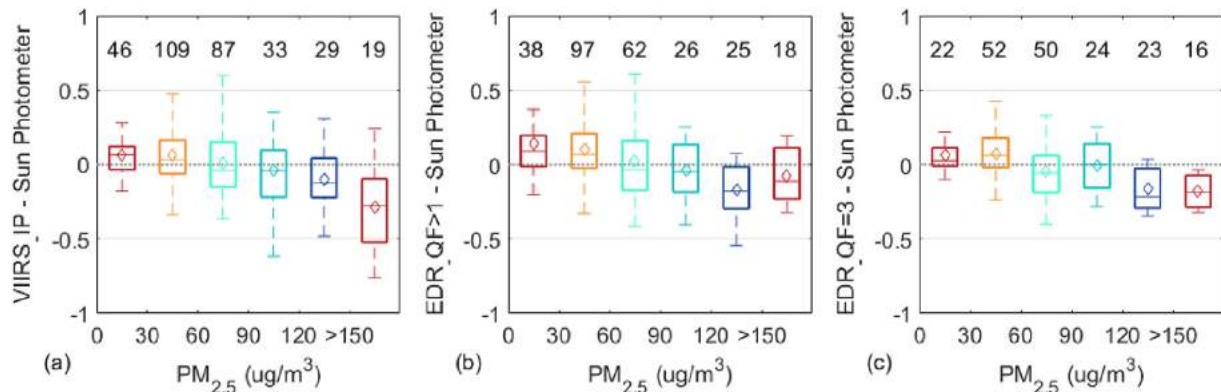


Fig. 5. The AOD bias between (a) VIIRS_IP and sun photometer; (b) VIIRS_EDR_QF > 1 and sun photometer; (c) VIIRS_EDR_QF = 3 and sun photometer with the PM_{2.5} variation. The numbers indicate the sample counts. The middle line and square represent the median and mean value of the AOD bias, respectively.

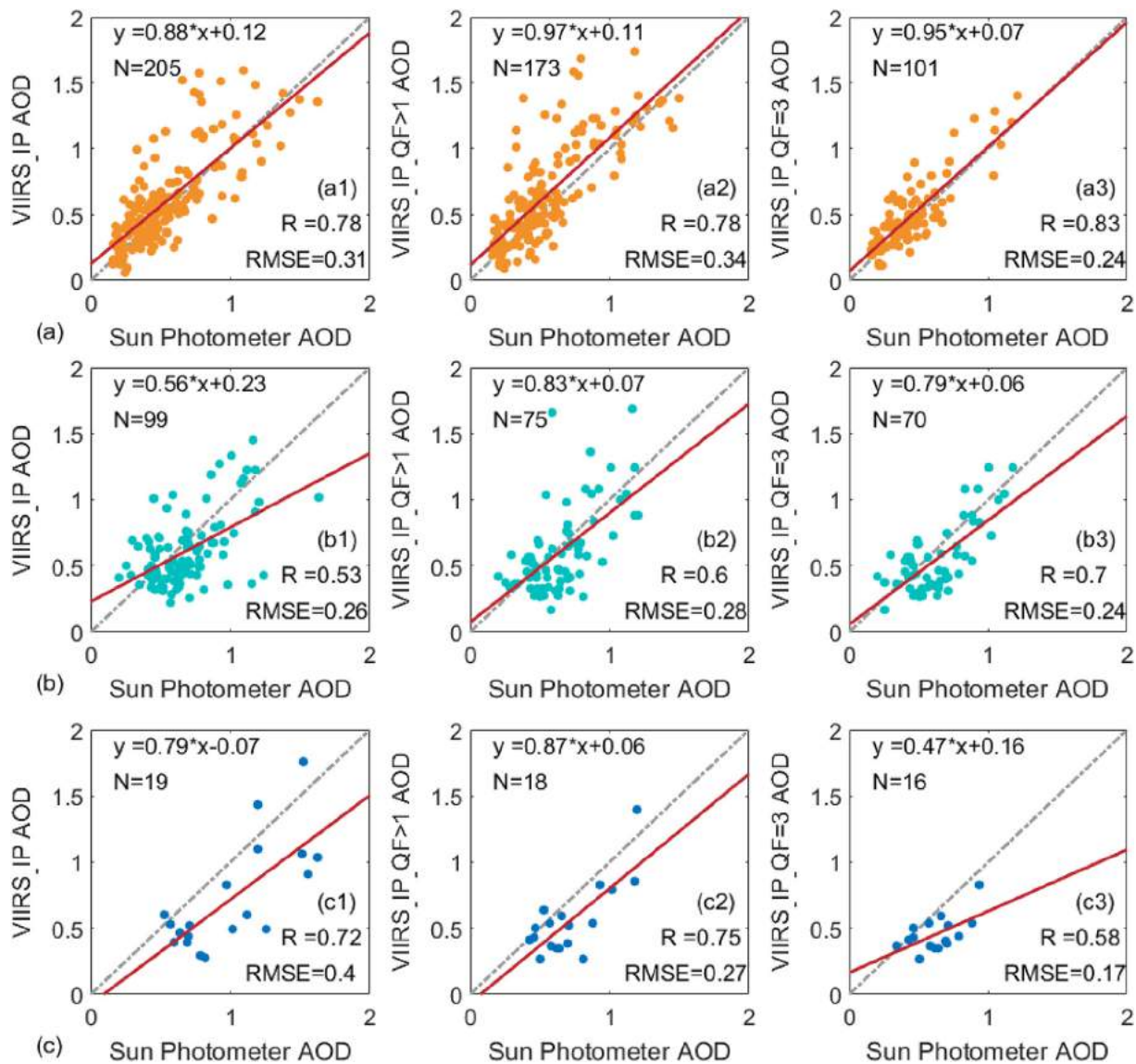


Fig. 6. Scatter plots of AODs derived from the VIIRS_IP, EDR_QF > 1, EDR_QF = 3, and Sun photometer under (a) clean weather, (b) moderate pollution, (c) and heavy pollution.

Table 4

Comparison of VIIRS AOD products against Sun photometer AOD under different air quality during 2014–2016.

AOD Products	Air Quality	N	Slop	y-int	R	RMSE
VIIRS_IP	Clean	205	0.88	0.12	0.78	0.31
	Moderate	99	0.56	0.23	0.53	0.26
	Heavy	19	0.79	0.07	0.72	0.4
VIIRS_EDR_QF > 1	Clean	173	0.97	0.11	0.78	0.34
	Moderate	75	0.83	0.07	0.6	0.28
	Heavy	18	0.87	0.06	0.75	0.27
VIIRS_EDR_QF = 3	Clean	101	0.95	0.07	0.83	0.24
	Moderate	70	0.79	0.06	0.7	0.24
	Heavy	16	0.47	0.16	0.58	0.17

heavy air pollution was attributed to the large bias in surface reflectance estimation, due to sparse vegetation and the large surface brightness of Wuhan in this condition (Wang et al., 2017a, 2017b). On the other hand, it may be related to the successful retrieval counts. The VIIRS_IP AOD products obtained 31 retrieval counts under heavy air pollution, occupying 53% of total heavy pollution days. The retrieval counts of EDR_QF > 1 (24) and EDR_QF = 3 (16) AOD products were

relatively low. Large number of VIIRS_IP AOD retrieval counts increased the average absolute bias. The average absolute bias of EDR_QF > 1 AOD products was similar to that of the EDR_QF = 3 AOD products during heavy air pollution. However, considering the relatively low successful retrieval rates of VIIRS EDR_QF = 3 AOD products, the VIIRS_EDR_QF = 3 AOD were not applicable for the heavy pollution days (Chen et al., 2017). These reasons may lead that the VIIRS AOD products perform differently during different pollution conditions. Overall, these results suggest that the VIIRS_EDR_QF > 1 AOD were more suitable for the heavy air pollution while VIIRS_EDR_QF = 3 AOD were more suitable for the moderate pollution. The performance of VIIRS_IP AODs was best during clean weather.

6. Conclusions

In this study, the VIIRS_IP, EDR_QF > 1 and EDR_QF = 3 AOD products were compared against ground-based sun photometer observations under different air quality periods from January 2014 to December 2016 over central China. The performance of three VIIRS AOD products was evaluated from the successful retrieval rates and AOD accuracy aspects. First, the successful retrieval rate of VIIRS_IP,

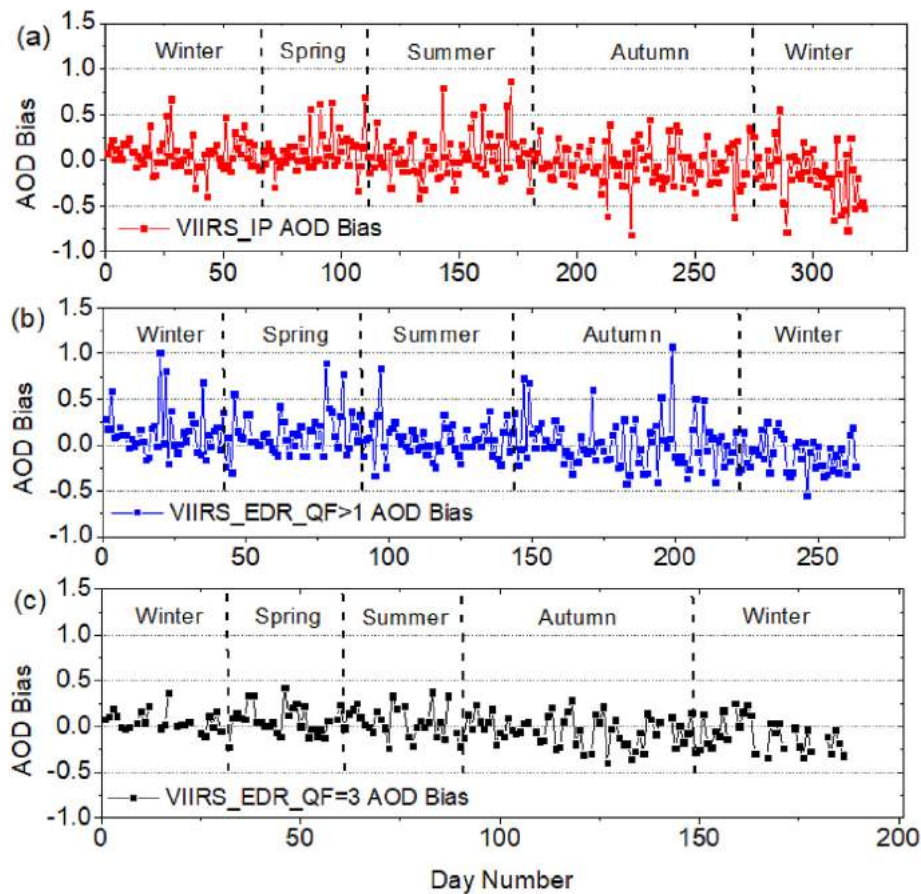


Fig. 7. Seasonal deviation of the (a) VIIRS_IP AOD, (b) EDR_QF > 1 AOD, (c) EDR_QF = 3 AOD. The red, blue, and black lines show the VIIRS_IP AOD biases, EDR_QF > 1 AOD biases, EDR_QF = 3 AOD biases, respectively.

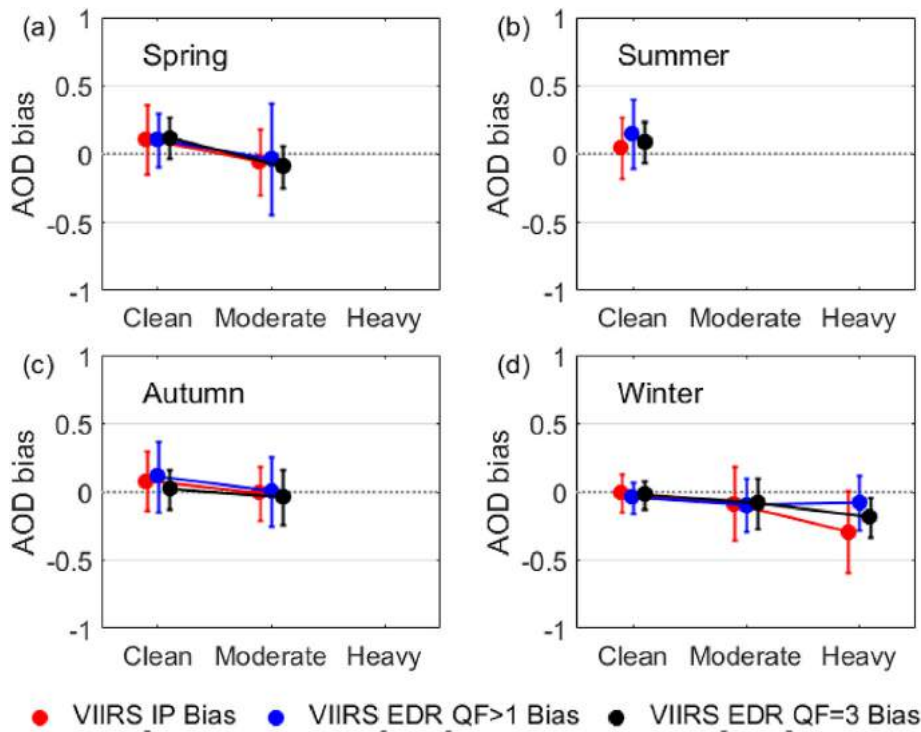


Fig. 8. Normalized mean seasonal bias of AOD under (a) clean weather, (b) moderate pollution, (c) and heavy pollution. The red, blue, and black lines show VIIRS_IP AOD, EDR_QF > 1 AOD, and EDR_QF = 3 AOD bias, respectively. The blank indicates absence of samples.

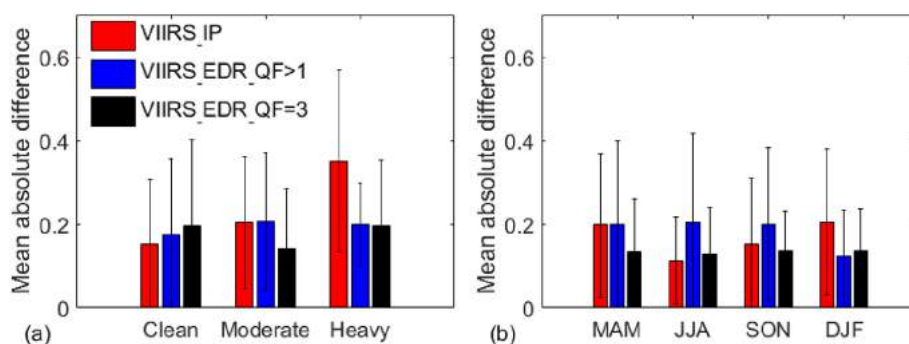


Fig. 9. Average absolute different of AOD products under different periods: (a) clean, moderate, and polluted days; and (b) Spring; Summer; Autumn; and Winter season. Error bars represent standard deviations.

EDR_QF > 1, EDR_QF = 3, and sun photometer AOD was counted under different pollution levels. The VIIRS_IP products had the largest successful retrieval counts, followed by retrievals of VIIRS_EDR_QF > 1 products, the sun photometer retrievals, and retrievals of the VIIRS_EDR_QF = 3 products. During heavily polluted days, the successful retrieval counts of VIIRS EDR_QF = 3 AOD products were relatively low at 18. With respect to the accuracy of three VIIRS AOD products under different pollution levels, the result show that the AODs obtained from VIIRS_IP products have the smallest average absolute bias (0.15 ± 0.15) during clean weather. For the moderate pollution days, the average absolute bias of VIIRS EDR_QF = 3 AOD products was smallest (0.14 ± 0.14). However, under heavy air pollution, the average absolute bias of EDR_QF > 1 AOD products (0.2 ± 0.1) was similar to the EDR_QF = 3 AOD products (0.2 ± 0.15). Considering the successful retrieval rates and AOD bias, the VIIRS_EDR_QF > 1 AODs were found to be more suitable for heavy pollution days. These results suggest that under the heavy air pollution, moderate air pollution, and clean weather, the most suitable products are VIIRS_EDR_QF > 1 AOD, VIIRS_EDR_QF = 3 AOD, and VIIRS_IP AODs, respectively. Finally, the seasonal analyses show that the average absolute deviation of VIIRS_EDR_QF = 3 AOD products was lowest in the spring (0.13 ± 0.13) and autumn (0.14 ± 0.1) seasons. The average absolute bias of VIIRS_IP AOD products was lowest (0.11 ± 0.1) during the summer season and the average absolute bias of EDR_QF > 1 AOD products was lowest (0.12 ± 0.11) in the winter season. This indicates that the VIIRS_EDR_QF = 3 AODs were more suitable for the spring and autumn seasons while VIIRS_IP AODs were suitable for the summer season. However, during the winter season, the performance of VIIRS_EDR_QF > 1 AODs was the best among all products. Therefore, for regions with heavy air pollution events, the VIIRS_EDR_QF > 1 AOD products is recommended as a proxy for air quality monitoring. For the less polluted areas, the VIIRS_IP AOD products may be more suitable for air quality monitoring applications. These results will provide a guide for the researchers to choose a most suitable AOD product in a specific environment.

Author contributions

The study was completed with cooperation between all authors. Yingying Ma and Liu Boming designed the research topic, Ming Zhang and Liu Boming conducted the experiment and wrote the paper, Wei Wang, Yifan Shi and Wei Gong checked the experimental results.

Declaration of competing interest

The authors declare no conflicts of interest.

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