



Validation and Analysis of MAIAC AOD Aerosol Products in East Asia from 2011 to 2020

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Abstract: East Asia is one of the most important sources of aerosols in the world. The distribution of aerosols varies across time and space. Accurate aerosol data is crucial to identify its spatiotemporal dynamics; thus, it is of great significance to obtain and verify new aerosol data for this region. Based on the Aerosol Optical Depth (AOD) data of the Aerosol Robotic Network (AERONET) program for 17 stations from 2011 to 2020, this study comprehensively verified the accuracy and applicability of the Multi-Angle Implementation of Atmospheric Correction (MAIAC) AOD 1 km products among different seasons, elevations, and climate zones over entire East Asia. The results showed that: (1) The overall accuracy of MAIAC AOD was high in East Asia, and the accuracy of Terra was slightly better than that of Aqua. MAIAC AOD showed significant heterogeneity among sites. MAIAC AOD performed well in areas with high vegetation cover and flat terrain, while the inversion accuracy was relatively low in areas with low vegetation cover and high terrain. (2) In general, MAIAC AOD and AERONET AOD showed good agreement in different seasons, presenting as winter > spring > autumn > summer. Yet the accuracy and consistency of Terra AOD product were better than Aqua product. (3) MAIAC AOD showed different accuracy at different elevations and climate zones. It had a high correlation and best inversion accuracy with AERONET AOD at low and medium elevations. MAIAC AOD had better inversion accuracy in the arid and warm temperate zones than that in the equatorial and cold temperate zones. (4) AOD distribution and its trend showed significant spatial differences in East Asia. The high AOD values were dominant in the Sichuan basin and the eastern plains of China, as well as in India and Bangladesh, while the relatively low AOD values were distributed in southwestern China and the areas north of 40°N. AOD in most parts of East Asia showed a negative trend, indicating a great improvement in air quality in these regions.

Keywords: MAIAC AOD; AERONET; Eastern Asia; validation



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1. Introduction

Atmospheric aerosols are stable mixed systems of solid and liquid particles uniformly dispersed in the atmosphere, and the aerodynamic diameter of the particles ranges from 0.001 to 100 μm [1]. Aerosol sources and formation mechanisms are complex. The main sources can be divided into anthropogenic sources (e.g., industrial emissions, straw burning, vehicle exhaust, and construction) and natural sources (e.g., sea salt particles, forest wildfires, volcanic eruptions, and wind and sand dust) [2]. Due to the combination of local sources and long-range transport, aerosol aging [3,4] and interactions between different types of aerosols can lead to the formation of various mixed states (i.e., internal and external) of aerosols [5]. Different types of atmospheric aerosols directly affect the Earth's climate system by scattering and absorbing solar radiation [6–8] and also impact visibility [9], air quality [10,11], and human health [12,13]. Thus, a better understanding of the distribution and variation of aerosols across different regions is essential to improve the quality of human life. Aerosol Optical Depth (AOD) is one of the important optical

parameters to characterize aerosol properties. The physical meaning of AOD is the total weakening intensity of solar radiation by aerosol absorption and scattering per unit cross-section along the radiation transmission path, which is mainly used to describe the light attenuation effect of aerosols [14]. AOD, which reflects regional atmospheric pollution level and ground-level air quality, has been widely used for quantitative assessment of air quality [15]. Detailed, reliable, and continuous AOD monitoring is essential for air quality management and protection of human health.

AOD acquisition methods mainly include ground-based observation and satellite remote sensing [16]. Because of the small number and uneven distribution of ground-based observation stations, it is difficult to characterize and analyze the spatial and temporal distribution of AOD. Unlike ground-based observations, satellite remote sensing has largely compensated for the lack of aerosol observations and uneven distribution in the spatial dimension. It has been used widely to quantify and monitor aerosol distribution over a large area.

However, there are some differences between ground and remote sensing AOD due to topography, different inversion methods, and instrument degradation [17]. Validation of remotely sensed AOD is essential for surface characterization and atmospheric correction of air quality [18]. The Aerosol Robotic Network (AERONET) is a ground-based aerosol observation network jointly established by NASA and LOAPHOTONS (CNRS), providing high-quality data for major regions of the world. The data from AERONET has been used to verify satellite remote-sensing aerosol products [19]. For example, Che et al. [20] used AERONET and CARSNET data in China to evaluate the accuracy and adaptability of Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua C 6 and C 6.1 dark target (DT) AOD products with a resolution of 10 km at different scales and sub-surfaces for the period of 2002–2014. Similarly, Aldabash et al. [21] used AERONET observations to verify the accuracy of MODIS C 6.1 and Modern-ERA Retrospective Analysis for Research and Application (MERRA-2) AOD in Turkey. They found that MODIS AOD accuracy was better, and the number of daily, monthly, and quarterly available AOD values increased significantly when MODIS Terra and Aqua observations were combined. Anoruo [22] used AERONET observations to validate the MODIS AOD and its characteristics over Italy during the monsoon season. The results have quantified an advancement to characterize trends in MODIS and AERONET AODs in monsoon periods in Italy. It was found that there were some differences between MODIS and AERONET AODs in monsoon periods. Therefore, it is quite important for validating AOD data among different seasons.

The MCD19A2 data is a Multi-Angle Implementation of Atmospheric Correction (MAIAC) terrestrial AOD gridded level 2 product with a spatial resolution of 1 km. The MCD19A2 data, combined with MODIS Terra and Aqua [23], performs well across the globe, such as in South America [24], South Asia [25], and Europe [26,27]. A number of studies have assessed the accuracy of MAIAC AOD data. Chen et al. [28] examined the applicability and distribution characteristics of MAIAC AOD in Central Asia based on the AOD data from remote sensing (i.e., MYD04_L2) and ground-based observations (i.e., AERONET and Microtop II). With the information entropy method, they showed that MAIAC AOD had strong applicability in describing the local fine-scale features and large interannual variability in most of the Central Asian regions over the past 20 years. Further, Falah et al. [29] comparatively explored the effects of different environments on MAIAC AOD inversions across North Africa, California, and Germany and suggested that the AOD inversions obtained in areas with higher vegetation cover (i.e., lower surface reflectance) were more accurate than those obtained in arid areas. They further demonstrated that the inversion accuracy had a large deviation between MAIAC and AERONET AOD at high aerosol loadings of coarse particles. Wu et al. [30] investigated the spatial distribution, interannual variation, and occurrence frequency of atmospheric aerosol optical properties at the regional scale in the city of Tianjin, China, from 2001 to 2020 using MAIAC AOD data. They revealed significant long-term variations of atmospheric aerosol optical properties in coastal areas. In summary, MAIAC AOD has great advantages and is more suitable

for studies that aim to show comprehensive or spatial details, compared to the AOD inversion products generated by the DT and Deep Blue algorithms (DB) [25,31]. If the data inversion results prove to be reliable over a certain region, its high spatial resolution is a great advantage, making it possible to conduct AOD-related studies at a finer scale. It may also make the integration with other satellite data more convenient.

East Asia is one of the largest sources of aerosols and their precursors, which are mostly a complex mixture of coarse and fine particles [32]. As the most populous and fastest-growing region in the world, anthropogenic aerosol emissions are rapidly increasing [33], and aerosol composition and spatial distribution are rapidly changing [34,35]. This has exacerbated the impact of aerosols on human life and the climatic environment. As a result of increased pollutant emissions, the frequency of severe haze events in East Asia has increased substantially, especially under stagnant meteorological conditions that favor secondary aerosol formation and accumulation [36,37]. Therefore, it is important to investigate the spatial and temporal distribution patterns of aerosols in East Asia for the protection of the atmospheric environment and the health of life in the region. Yet there are relatively few studies using long-term time series data of MAIAC AOD in this region. One possible reason is due to a lack of accurate information on MAIAC AOD data in East Asia. To address this gap, this study assessed the applicability and accuracy of MCD19A2 AOD data based on AERONET AOD data, providing reliable data for subsequent atmospheric studies in East Asia.

2. Data and Methods

2.1. Study Area

The aim of this study is to investigate the accuracy and applicability of MAIAC AOD in East Asia from 2011 to 2020, including eastern and central China, Mongolia, North Korea, South Korea, Laos, Cambodia, the Philippines, Thailand, and Vietnam, and some regions in Myanmar, Japan, and Malaysia, as shown in Figure 1.

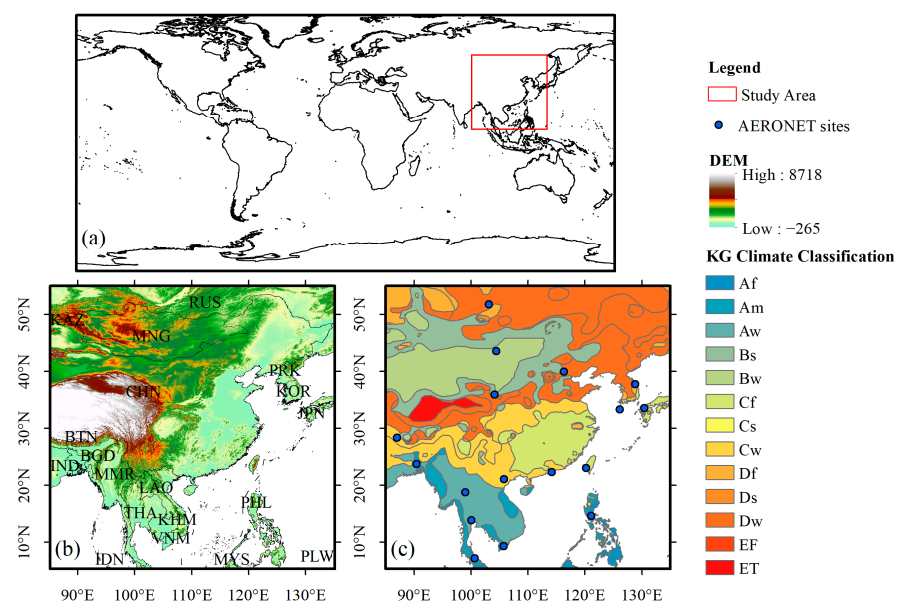


Figure 1. (a) Location of the study area in a global map; (b) Relevant topography and major countries within the study area (RUS KAZ MNG CHN PRK KOR JPN BTN BGD IND MMR LAO THA KHM VNM PHL MYS PLW); and (c) Distribution of climate types and AERONET sites within the study area (Af: Tropical rainforest climate Aw: Tropical open forest climate Am: Tropical monsoon climate BS: Steppe climate BW: Desert climate Cf: Normally humid and warm climate Cs: Dry summer and warm climate Cw: Dry and warm climate in winter Df: Normally humid and cold temperature climate Ds: Subarctic continental climate Dw: Sub-frigid monsoon climate EF: Tundra climate ET: Ice climate).

2.2. Data

2.2.1. MAIAC AOD

MCD19A2 (2011–2020) Collection 6 (MAIAC aerosol product) was obtained from the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (<https://earthdata.nasa.gov/>, accessed on 7 June 2021). This data with 1 km spatial resolution is a daily terrestrial atmospheric aerosol product generated by MODIS AOD product and a multi-angle atmospheric correction algorithm [38]. Compared with AOD products provided by other satellites, MCD19A2 has relatively better quality, wider coverage, and higher spatial and temporal resolutions [39].

2.2.2. Ground-Based AOD

AERONET (<https://aeronet.gsfc.nasa.gov/>, accessed on 20 June 2021) is a global ground-based aerosol observation network organized by NASA and CNRS. AERONET version 3 provides optical and physical properties of aerosols and publishes aerosol observations at three quality levels, including daily monitoring data at level 2 with high accuracy (error $\pm 0.01\sim 0.02$). This can well reflect local aerosol characteristics and variations and thus is a good ground-based aerosol calibration data set. This study selected 17 ground-based AERONET stations, which are evenly distributed in the study area (Figure 1c and Table 1).

Table 1. Information of AOD ground-based observation sites.

Name of Station	Longitude (°E)	Latitude (°N)	Time Span	Elevation (m)
Bac_Lieu	105.73	9.28	2011–2019	<50
Chen-Kung_Univ	120.205	22.993	2011–2020	
Dhaka_University	90.398	23.728	2012–2020	
Fukuoka	130.475	33.524	2012–2020	
Gangneung_WNU	128.867	37.771	2012–2020	
Gosan_SNU	126.162	33.292	2011–2016	
Hong_Kong_PolyU	114.18	22.303	2011–2017	
NGHIA_DO	105.8	21.048	2011–2016, 2018–2019	
Silpakorn_Univ	100.041	13.819	2011–2020	
Songkhla_Met_Sta	100.605	7.184	2011–2020	50–200
Beijing-CAMS	116.317	39.933	2012–2020	
Manila_Observatory	121.078	14.635	2011–2020	
Chiang_Mai_Met_Sta	98.972	18.771	2011–2020	200–500
Irkutsk	103.087	51.8	2011–2020	500–1000
Dalanzadgad	104.419	43.577	2011–2020	1000–2000
SACOL	104.137	35.946	2011–2013	
QOMS_CAS	86.948	28.365	2011–2017	

The AERONET instrument collects data at multiple wavelengths, and AERONET does not directly provide observations at 550 nm, which is slightly different from the MODIS channel (550 nm). Therefore, the AOD at 550 nm was obtained by interpolating the Ångström index (α) at 440 nm to 870 nm, as defined in Equations (1) and (2).

$$\alpha = -\frac{\ln(\tau_{440}/\tau_{870})}{\ln(440/870)} \quad (1)$$

$$\tau_{550} = \tau_{550}(550/870)^{-\alpha} \quad (2)$$

2.2.3. Auxiliary Data

The Digital Elevation Model (DEM) data used in this study is the Global Multi-resolution Terrain Elevation Data (GMTED) in 2010 with 200 m spatial resolution. We downloaded the data from the USGS and the NGA of the United States National Geological and Geographic Information Service (https://topotools.cr.usgs.gov/gmted_viewer/viewer.htm, accessed on 15 May 2021).

We also used the Köppen climate zones, the most widely used climate classification. It divides the world continent into five major climate zones (A, B, C, D, and E) based on vegetation distribution considering seasonal variations in monthly and annual temperature and rainfall in each zone (Table 2 and Figure 1c) [40]. Since the number of matchable point pairs at polar zone sites is small and discontinuous, AERONET sites in four different climatic zones (i.e., A, B, C, and D) were selected for this study to evaluate the accuracy of MAIAC AOD values in different climatic zones. The distribution of climate zones is shown in Figure 1c.

2.3. Evaluation Methods

AERONET provides repeated measurements at a fixed point, while the satellite provides measurements in a certain area at regular intervals. In order to match AERONET AOD and MAIAC AOD in space and time, the spatial average of MODIS AOD data within $25 \text{ km} \times 25 \text{ km}$ centered at AERONET site and the temporal average of AERONET ground-based data before and after 30 min of satellite transit were selected in this study [24].

Table 2. Division and definition criteria of the Köppen climate zone *.

Climatic Zone	Climatic Type	Climate Subtype	Characteristic
A: Equatorial zone			$T_{cold} \geq 18$
	Af (Tropical rainforest climate)		$P_{dry} \geq 60 \text{ mm}$
	Aw (Tropical open forest climate)		$P_{dry} \leq 60 \text{ mm}$ and $P_{dry} \geq (100 - MAP/25) \text{ mm}$
	Am (Tropical monsoon climate)		$P_{dry} \leq 60 \text{ mm}$ and $P_{dry} \leq (100 - MAP/25) \text{ mm}$
B: Arid zone			$MAP < 10 P_{th}$
	BS (Steppe climate)		$MAP \geq 5 P_{th}$
	BW (Desert climate)		$MAP < 5 P_{th}$
C: Warm zone		h	$MAT \geq 18^\circ \text{C}$
		k	$MAT < 18^\circ \text{C}$
			$Thot > 10^\circ \text{C}$ and $0^\circ \text{C} < T_{cold} < 18^\circ \text{C}$
	Cs (Dry summer and warm climate)		$P_{sdry} < 40 \text{ mm}$ and $P_{sdry} < P_{wwet}/3$
	Cw (Dry and warm climate in winter)		$P_{wdry} < P_{swet}/10$
	Cf (Normally humid and warm climate)		Neither Cw nor Cf
		a	$Thot \geq 22^\circ \text{C}$
D: Cold temperate zone		b	$Thot < 22^\circ \text{C}$ and count ($T_{mon} > 10^\circ \text{C}$) ≥ 4
		c	$T_{cold} \geq -38^\circ \text{C}$ and count ($T_{mon} > 10^\circ \text{C}$) < 4
			$Thot > 10^\circ \text{C}$ and $T_{cold} \leq 0^\circ \text{C}$
	Ds (Subarctic continental climate)		$P_{sdry} < 40 \text{ mm}$ and $P_{sdry} < P_{wwet}/3$
	Dw (Sub-frigid monsoon climate)		$P_{wdry} < P_{swet}/10$
	Df (Normally humid and cold temperature climate)		Neither Ds nor Dw
		a	$Thot \geq 22^\circ \text{C}$
		b	$Thot < 22^\circ \text{C}$ and count ($T_{mon} > 10^\circ \text{C}$) ≥ 4
		c	$T_{cold} \geq -38^\circ \text{C}$ and count ($T_{mon} > 10^\circ \text{C}$) < 4
		d	$T_{cold} < -38^\circ \text{C}$

Table 2. Cont.

Climatic Zone	Climatic Type	Climate Subtype	Characteristic
E: Polar zone			Thot < 10 °C
	ET (Tundra climate)		Thot > 0 °C
	EF (Frost climate)		Thot ≤ 0 °C

* Note: Tcold = the average temperature of the coldest month, Thot = the average temperature of the hottest month, Pdry = the driest monthly precipitation, Psdry = the driest monthly precipitation in summer (April to September), Pwdry = the driest monthly precipitation in winter (October to March), Pswet = the wettest monthly precipitation in summer, Pwwet = the wettest monthly precipitation in winter. MAP = the annual precipitation, MAT = the annual average temperature, Pth = if the regional summer precipitation is greater than or equal to 70% of MAP, then Pth = 2 × (MAT + 14) mm; if the regional winter precipitation is greater than or equal to 70% of the annual precipitation, then Pth = 2 × MAT mm; if it is less than the above proportion, then Pth = 2 × (MAT + 7) mm.

The study explored the correlation between MAIAC AOD products and AERONET AOD data by conducting multiple statistical analyses. We assessed the quality of MAIAC AOD products using the expected error (EE), which was calculated as $EE = \pm(0.05 + 0.15 \times AOD)$. The accuracy of MAIAC AOD products is verified quantitatively using four other metrics: Pearson correlation coefficient (R), relative mean deviation (RMB), mean absolute error (MAE), and root mean square error ($RMSE$) [41].

(1) Pearson correlation coefficient (R)

R is used to measure the degree of linear correlation between the inverse and true value, and a larger value of $|R|$ indicates a higher correlation and more accurate inversion results. The calculation of R is shown in Equation (3).

$$R = \frac{\sum_{i=1}^n (y_i - \bar{y})(x_i - \bar{x})}{\sqrt{\sum_{i=1}^n (y_i - \bar{y})^2 \sum_{i=1}^n (x_i - \bar{x})^2}} \quad (3)$$

(2) Relative Mean Deviation (RMB)

RMB is used to evaluate the degree of deviation between the inverse value and the true value, and the closer RMB is to 1, the smaller the deviation is and the more accurate the inverse result is. The RMB is calculated as Equation (4).

$$E_{RMB} = \frac{1}{n} \sum_{i=1}^n \frac{y_i}{x_i} \quad (4)$$

(3) Mean Absolute Error (MAE)

MAE indicates the average value of the absolute error between the inversion value and the measured value (Equation (5)). It is used to measure the overall magnitude of the absolute error of the inversion results; a smaller MAE indicates that the inversion results are more accurate.

$$E_{MAE} = \frac{1}{n} \sum_{i=1}^n |y_i - x_i| \quad (5)$$

(4) Root Mean Square Error ($RMSE$)

$RMSE$ represents the sample standard deviation of the difference (called residual) between the inverse and true value (Equation (6)). It is used to measure the deviation between the inverse and true value; a smaller $RMSE$ indicates a more accurate inversion result.

$$E_{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - x_i)^2} \quad (6)$$

A regression relationship was further established with AOD of AERONET as the independent variable and AOD of MCD19A2 as the dependent variable using a linear regression

model ($y = kx + b$). The aerosol inversion expectation error (EE) was used to analyze the overall distribution between the inversion results and the true values (Equation (7)).

$$EE = \pm(0.05 + 0.15 \times x_i) \quad (7)$$

The value of k close to 1 indicates that the inversion value is more accurate, and the value of b close to 0 represents the deviation of the inversion value is smaller. The percentage of AOD inversion results within, above, and below the expected error EE is indicated by $=$, $>$, and $<EE$, respectively. The larger percentage of $AOD = EE$ and the smaller percentage of $AOD >$ or $<EE$ indicate that the consistency of inversion results with the true value is better, and the inversion results are more accurate.

In Equations (3)–(7), x and y denote the AERONET true value and MCD19A2 inverse value, respectively. n denotes the number of validation groups. i is the selected validation point pair number. $\bar{x}$ and $\bar{y}$ denote the average of the observed and inverse values, respectively.

It is noteworthy that Pearson's correlation coefficient is prone to be affected by isolated extreme data points, and as such, the linear regression may be of limited representativeness [29]. This study thus proposed an evaluation approach by combining R , RMB , MAE , and $RMSE$ to determine the accuracy of the MAIAC AOD at all sites. This combination can intuitively show the difference in accuracy between sites in the study area (Table 3).

Table 3. The division of evaluation indicators and accuracy, including R , RMB , MAE , $RMSE$, and Matching accuracy.

R	RMB	MAE	$RMSE$	Reclassification
<0.5	<0.8/>1.2	>0.15	>0.2	1
0.5–0.8	0.8–0.9/1.1–1.2	0.1–0.15	0.15–0.2	2
0.8–0.9	0.9–1.1	0.08–0.1	0.1–0.15	3
>0.9		0.05–0.08	0.05–0.1	4
		<0.05	<0.05	5
Summation of reclassification				Accuracy
>12				Excellent
9–12				Very good
7–9				Good
<7				Poor

3. Results

Based on the statistical assessment methods, this study validated the accuracy of MAIAC AOD in different seasons, at different altitudes, and in different climate zones. The seasons were divided into spring (March to May), summer (June to August), autumn (September to November), and winter (December to February).

3.1. Overall Comparison between MAIAC and AERONET AOD at 550 nm

Figure 2 shows the correlation between MAIAC and AERONET AOD at 17 sites from 2011 to 2020. Both MAIAC's Terra and Aqua products have a good correlation with AERONET site observations, with an R value larger than 0.85. RMB is 1.008 and 1.005, respectively, which are only 0.8% and 0.5% overestimated than AERONET AOD. This indicates that MAIAC AOD has better accuracy than many other AOD products [42]. In terms of MAE and $RMSE$, the inversion accuracy of the MAIAC product is relatively high, especially for the Terra product ($RMSE = 0.137$, $MAE = 0.080$). Around 71.53% of the data are within EE , which is slightly higher than that of Aqua (69.83%). The overall $Bias$ was only 0.002 and 0.001 for Terra and Aqua. In summary, MAIAC AOD products demonstrate a high degree of accuracy and applicability in the eastern region of Asia.

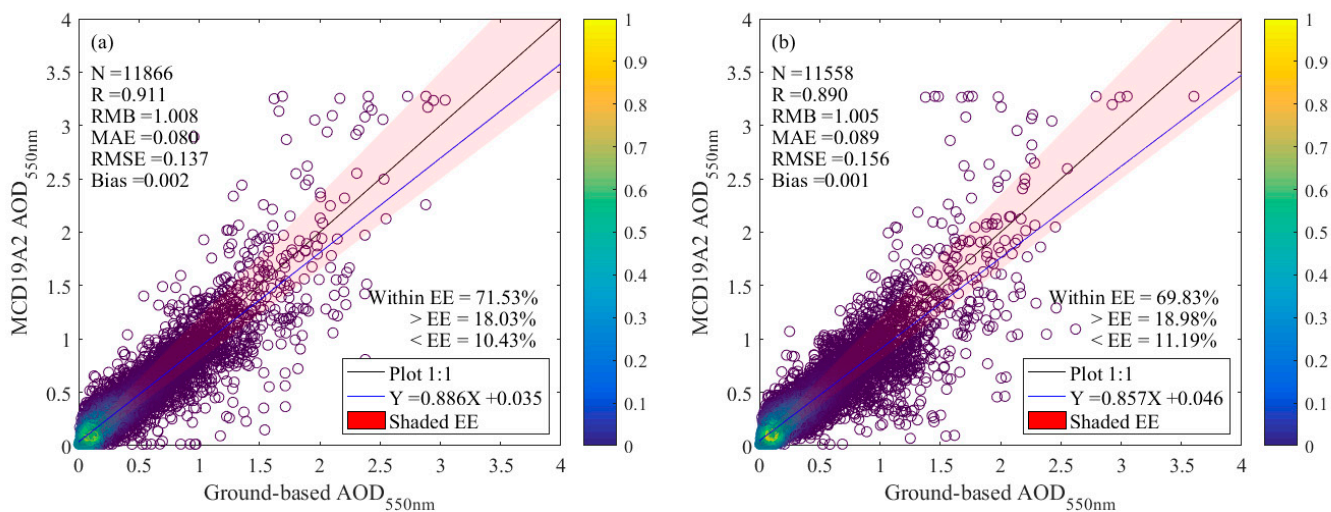


Figure 2. Overall accuracy of MAIAC AOD. (a) MAIAC Terra vs. AERONET, (b) MAIAC Aqua vs. AERONET.

As shown in Figure 3a–j, the inversion accuracy of Terra and Aqua products are different, but both MAIAC AOD products are highly correlated with AERONET AOD and have good inversion accuracy overall. Both Terra and Aqua AOD products have more than 58% of sites with R greater than 0.8, more than 76% of sites with MAE less than 0.1, more than half of sites with RMB between 0.9 and 1.1, and more than 64% of sites with $RMSE$ less than 0.15. In general, the percentages of sites with good matching accuracy performance for both products are more than 82%. It denotes that MAIAC AOD products have good applicability in the study area and can meet the accuracy requirements for most applications.

3.2. Comparison of MAIAC and AERONET AOD at 550 nm in Different Seasons

Figure 4a–h shows the quality of MAIAC AOD in East Asia for all seasons in the last decade. It is found that the number of matching points between MAIAC Terra and Aqua products and AERONET data is high in four seasons. The number of effective matching points is highest in spring, followed by winter, and lowest in summer. Nevertheless, both MAIAC AOD products and ground measurements show good agreement. The R value of MAIAC's Terra product is above 0.9 in all four seasons, and the R value of the Aqua product is above 0.8 in all seasons. For MAIAC's Terra products, the R -values for all seasons show winter = spring > summer > autumn (R : 0.922 = 0.922 > 0.905 > 0.903), while the R value for summer is almost the same compared to that for autumn, which is only 0.002 higher. Terra products have more than 70% of sites within the EE in four seasons, while the Aqua product has good accuracy in all seasons, except for the summer when the proportion of samples within the EE is below 66%. Overall, the inversion results of both products are reliable and usable, although the accuracy and consistency of the AOD between the Terra product and AERONET AOD are better than those of the Aqua product.

MAE and $RMSE$ are lower in autumn and winter, indicating the inversion results are more accurate during these two seasons. In summer, MAE and $RMSE$ are larger. RMB is larger than 1, the proportion of sample points within EE is smaller, and the proportion of overestimation reaches 26.82% and 34.54%, respectively. $Bias$ is less than 0 in winter and spring and greater than 0 in summer and autumn. During four seasons, MAIAC retrievals have an absolute $Bias$ lower than 0.05. Especially for Terra product, their quality is better in the autumn than in summer according to values of RMB , MAE , $RMSE$, $Bias$, and Within EE . Collectively, the accuracy of MAIAC AOD in all seasons is as follows: winter > spring > autumn > summer.

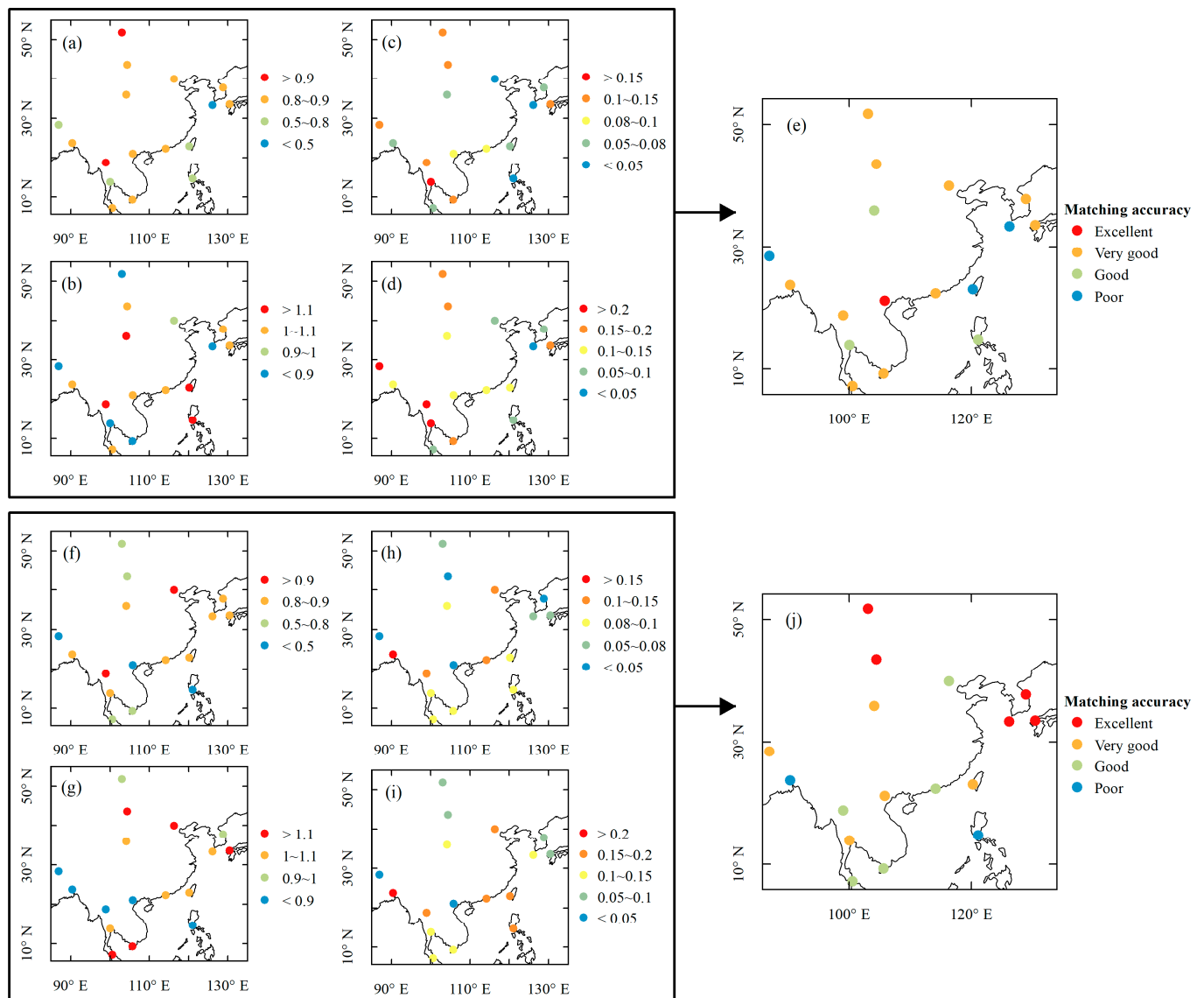


Figure 3. Accuracy of AOD observations for MAIAC Terra (a–e) and Aqua (f–j) against AERONET measurements at each site. (a,f) R ; (b,g) RMB; (c,h) MAE; (d,i) RMSE; (e,j) Matching accuracy.

3.3. Comparison of MAIAC and AERONET 550 nm AOD at Different Elevations

To explore the inversion accuracy and availability of MAIAC AOD at different elevations in complex terrain in East Asia, we validated MAIAC Terra and Aqua AOD with AERONET AOD at different elevation intervals from 2011 to 2020 (Figure 5). As the elevation increases, the values of R and RMB of Terra and Aqua AOD products consistently show a trend of raising–decreasing–raising–decreasing, and the values of MAE and RMSE both show a trend of increasing first and then decreasing.

The R and RMB values of Terra and Aqua AOD products are close to 1 when the elevation is less than 2000 m. The R is especially high in the interval of 50–200 m and 200–500 m, and both are above 0.9. Terra AOD product has the least deviation in the interval of below 50 m and 200–500 m, and Aqua has the least deviation in the interval of below 50 m and 500–1000 m. MAE and RMSE values are between 0 and 0.1 at elevations greater than 500 m, indicating that the inversion results are more accurate at the elevations. When the elevation is greater than 2000 m, MAE and RMSE have better accuracy, while R and RMB show poor values. Overall, MAIAC AOD shows different accuracy at different elevations. MAIAC AOD is highly correlated with AERONET AOD at low and medium elevations and thus has the best inversion accuracy in these elevations.

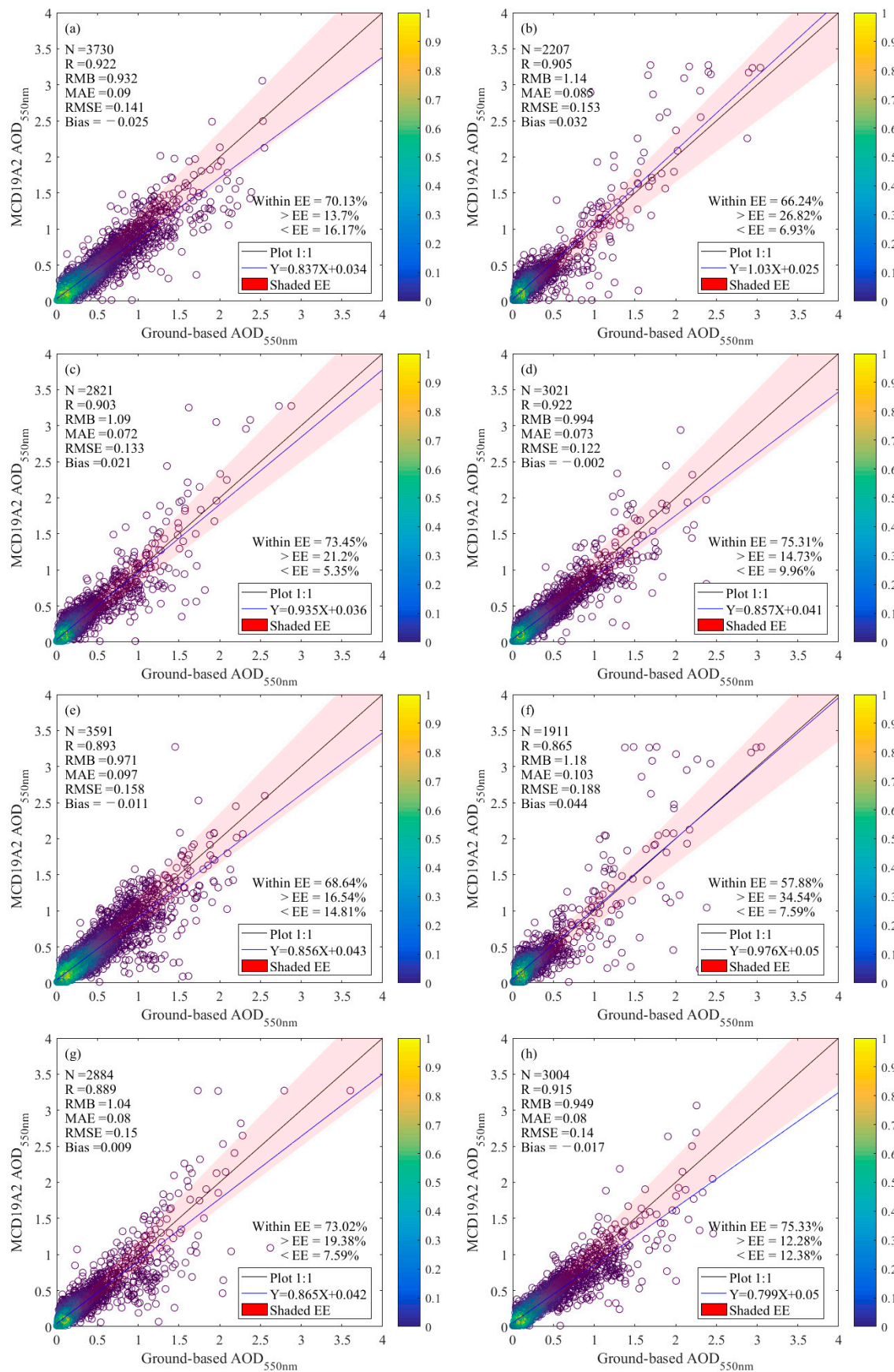


Figure 4. Comparison of the accuracy of AOD observations for MAIAC Terra (a–d) and Aqua (e–h) against AERONET measurements in (a,e) spring; (b,f) summer; (c,g) autumn and (d,h) winter.

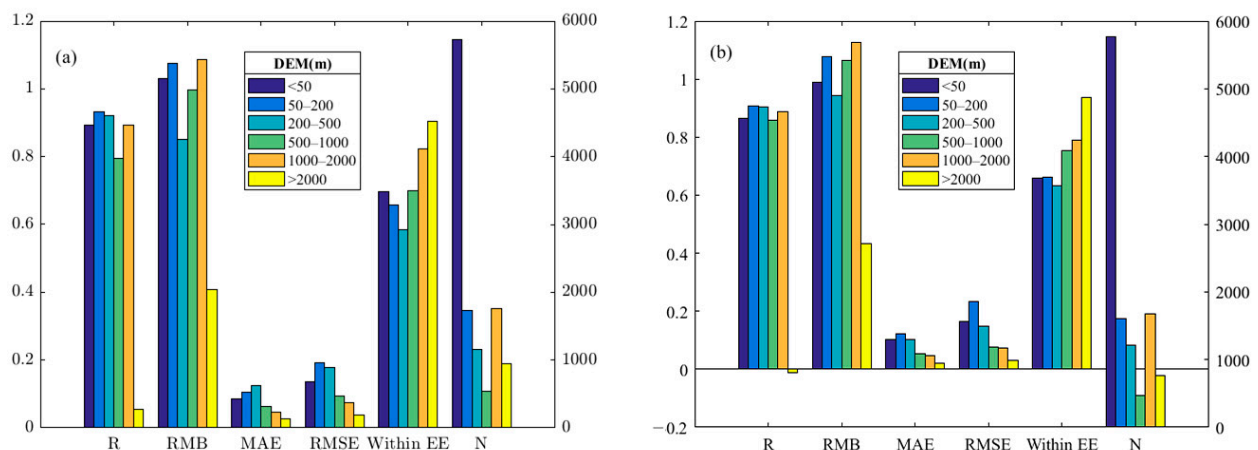


Figure 5. Comparison of the accuracy of AOD observations for MAIAC Terra (a) and Aqua (b) against AERONET measurements at different elevations.

3.4. Comparison of MAIAC and AERONET 550 nm AOD in Different Climate Zones

Figure 6 shows the validation results of the MAIAC AOD for different climatic zones. Among the four climate types, Terra and Aqua AOD products have the best *EE* percentages in the arid zone, 82.21% and 79.09%, respectively, and poorer *EE* percentages in the equatorial zone with 61.52% and 60.03%, respectively. The *R* values are above 0.864, with the best one occurring in the cold temperate zone with 0.947 and 0.935, respectively. *RMB* is close to 1, with small deviations, and the best values occur in the warm temperate zone with 1.02 and 1, respectively. *MAE* and *RMSE* are much closer to 0 in the arid zone and warm temperate zone, with a small deviation. Overall, the inversion accuracy of MAIAC AOD in the arid zone and the warm temperate zone is better than that in the equatorial zone and cold temperate zone.

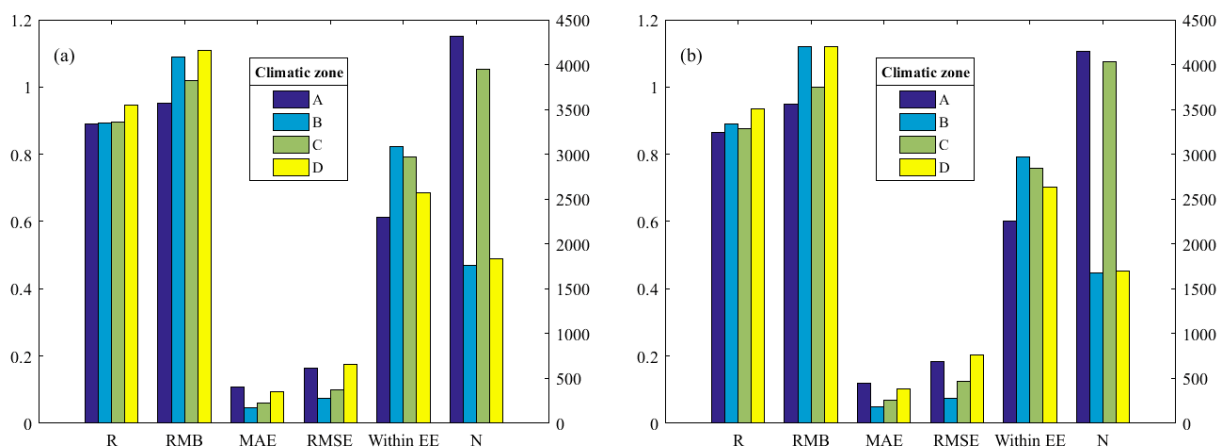


Figure 6. Comparison of accuracy of AOD observations for MAIAC Terra (a) and Aqua (b) against AERONET measurements in different climate zones.

3.5. Spatial Patterns of MAIAC AOD

Figure 7 shows the spatial distribution and change rates of the average AOD values from 2011 to 2020. The results indicate that aerosols show significant regional differences in the distribution and trends in East Asia. High values of AOD are dominant in the Sichuan basin and eastern plains of China, as well as in India and Bangladesh. The relatively low AOD values are widely distributed in southwestern China and the areas north of 40°N. Most of the AOD in East Asia showed a significant negative trend. The improvement is most significant in central and eastern China. Southeast Asian regions such as India, Bangladesh, and Thailand show an increasing trend of AOD.

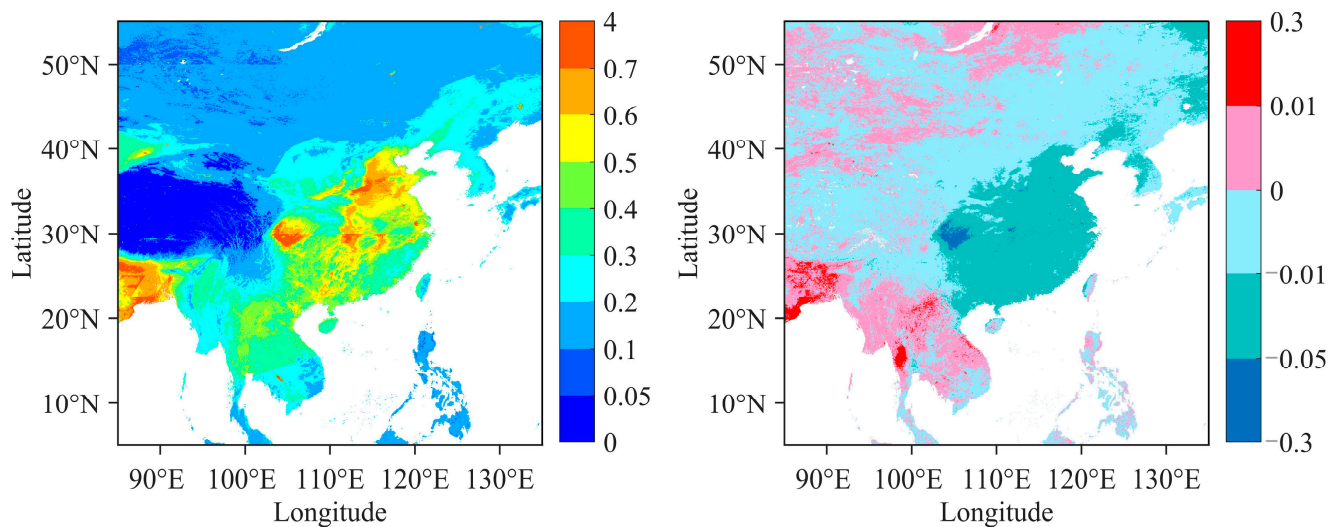


Figure 7. Spatial distribution and change rate of MAIAC AOD from 2011 to 2020.

4. Discussion

The validation results in Figure 2 show that MAIAC AOD products demonstrate a high degree of accuracy and applicability in East Asia. What is worth mentioning is that the inversion accuracy of MAIAC's Terra products is higher than that of the Aqua products. This may be due to the fact that the study area is located in the northern hemisphere, and Terra passes the equator from north to south and transits at 10:30 a.m. Considering the solar perspective, the satellite data acquired by Terra has a better spectral effect compared with Aqua, which makes the Terra product slightly better than Aqua in terms of inversion accuracy. Nevertheless, the points falling within the *EE* exceed 66% for both products, indicating both versions are reliable [43]. This is reinforced by Mhawish et al. [25], who confirmed that both terra and aqua of MAIAC provided good accuracy in South Asia, with Terra slightly outperforming Aqua.

To further examine the reliability of MAIAC AOD products, we compared and analyzed the accuracy at different sites. The results in Figure 3 indicate significant heterogeneity in MAIAC AOD inversion. In general, MAIAC AOD products perform well in Mongolia, Japan and Korea, northern China, and Southeast Asian countries such as Laos. Those regions are mostly covered by dark surfaces and dense vegetation that favor aerosol inversion. In contrast, the accuracy of MAIAC AOD inversion in southwest China, India, and the Philippines is relatively low. Southwest China is a plateau with thin air and glaciers all over, and India has many desert areas with bright surfaces. The sensitivity of top-of-atmosphere reflectivity (TOA) to aerosol changes under bright surfaces is low, resulting in high uncertainty in satellite monitoring [44]. The weather conditions in the Philippines, which are rainy and typhoon prone all year round, cause the uncertainty of satellite signals, resulting in slightly poor matching accuracy. On the contrary, the high cloudiness makes the aerosol inversion values easy to be overestimated due to the topography and airflow in the central as well as the eastern coastal regions of China.

The accuracy of MAIAC AOD varies in different seasons. Collectively, the accuracy of MAIAC AOD in all seasons is as follows: winter > spring > autumn > summer. *RMB* is slightly less than 1, and *Bias* is below 0 in spring and winter. This is mainly due to high winds, snow, and ice melting in that season, resulting in a very small portion of the satellite monitoring being underestimated. However, this is a great improvement compared with other data [45,46]. The percentage of points falling within the *EE* is low in both spring and summer, which may be because of the fact that more material burning and forest fires occur in that season, increasing the uncertainty of AOD fluctuations [47,48]. In addition, summer has the largest positive bias. This could be due to the cloudy and rainy summer season in East Asia. Among the eight different scenarios, the higher correlation *R*-values

and lower error values in winter suggest that MAIAC AOD products perform better in winter. This is consistent with the results of previous studies [49]. With low temperatures, high winds, and low humidity in winter, the hygroscopic nature of aerosols has less impact on the accuracy of satellite monitoring.

The results shown in Figure 5 indicate that the retrieval performance of MAIAC AOD is closely related to altitude, in agreement with previous studies [49]. Both MAIAC's Terra and Aqua products have the best correlation at low and medium elevations. However, the higher altitudes, mainly above 2000 m, the lower correlation R values. This reflects that MAIAC AOD has different advantages at different elevations. Moreover, due to the small number of matched point pairs in this interval, as well as sparse population, thin air, and low AOD values, there are some errors in the accuracy assessment at this elevation. Shi et al. [50] also found that complex surface features were able to produce a high AOD bias in the data.

Comparing the inversion accuracy of MAIAC Terra and Aqua products in different climate zones, we found that they shared similar characteristics. The arid and the warm temperate zones have the most percentages of AOD within EE , and the values of MAE and $RMSE$ are closer to 0 with good accuracy. Lee et al. [51] found similar conclusions in their study. The clear weather makes the warm temperate zone better monitored, with RMB closest to 1 and the least bias. This is followed by the arid zone, where bright surfaces cause satellite monitoring to be prone to overestimation. The cold temperate zone has the best correlation, indicating that MAIAC AOD is still well-adapted in this region. This is possibly due to the relatively low temperature and humidity, which made the satellite monitoring less affected. With the above analyses, we conclude that MAIAC AOD has good applicability in East Asia.

Atmospheric aerosols are highly variable [52]. Together with Figure 1b, it is found that the AOD distribution is significantly influenced by topographic features. Because the plains of eastern and central China are economically developed, low-lying, and densely populated, those regions have large anthropogenic aerosol emissions. India and Bangladesh have high sources of aerosol precursor emissions due to industrial development, agricultural burning, large deserts, and dense population. In fact, India has become one of the most serious regions for aerosol pollution [53]. Mongolia and Russia have low AOD values due to their high latitude, alpine terrain, and sparse population under both small natural and anthropogenic influences. Qinghai Province and Tibet Autonomous Region are located in the Qinghai–Tibet Plateau with high altitude, low human activities, and thin atmosphere [54], thus the AOD values are extremely low. Most of the AOD in East Asia show a significant negative trend, indicating that aerosol pollution has reduced. In addition, the improvement is most significant in central and eastern China, due to high levels of original AOD, and measures of energy conservation and emission reduction [55]. Aerosol pollution has increased due to the large population base and economic development in Southeast Asian regions such as India, Bangladesh, and Thailand. It may also be influenced by coastal environments and extreme climates. It can be concluded that the variation characteristics of AOD in East Asia deserve an in-depth analysis, given its influencing factors and mechanisms varying across space and time. In the future study, we will comprehensively address this question.

5. Conclusions

(1) From the validation results of ground-based sites from 2011 to 2020, the overall accuracy of MAIAC AOD products showed high accuracy and applicability in East Asia. The inversion accuracy of Terra AOD was slightly better than that of Aqua. MAIAC and AERONET AOD were highly correlated and had good inversion accuracy overall, but MAIAC Terra and Aqua products had different inversions and showed significant heterogeneity among sites. Additionally, MAIAC AOD products performed well in areas with high vegetation cover and flat terrain, while the inversion accuracy was relatively low in areas with low vegetation cover and high terrain.

(2) MAIAC and AERONET AOD showed good agreement in different seasons. The accuracy of MAIAC AOD had the character of winter > spring > autumn > summer. The MAIAC Terra and Aqua products showed reliable inversion results and strong usability in general, although the accuracy and consistency of the AOD of the Terra product were better than that of the Aqua product.

(3) MAIAC AOD indicated different accuracy at different elevations. MAIAC and AERONET AOD were highly correlated and had the best inversion accuracy at low and medium elevations. The accuracy of MAIAC AOD was also influenced by different climate zones. The inversion accuracy of MAIAC AOD in the arid zone and the warm temperate zone was better than that in the equatorial zone and cold temperate zone.

(4) The patterns and trends of AOD in East Asia showed obvious regional differences. High AOD values were mainly distributed in the Sichuan basin and eastern plains of China as well as India and Bangladesh, while relatively low AOD values were distributed in southwestern China and the areas north of 40°N. Most AODs in East Asia showed a negative growth trend, with the most significant improvement in the central and eastern regions of China. India, Bangladesh, Thailand, and other Southeast Asian regions showed a positive growth trend in AOD; therefore, aerosol pollution has increased.

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Data Availability Statement: Datasets analyzed during the current study mainly include MCD19A2, Ground-based AOD, GMTED, and Köppen climate zones. The MCD19A2 dataset is available at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (<https://earthdata.nasa.gov/>, accessed on 7 June 2021). Ground-based AOD is available in the AERONET established by NASA and PHOTONS (<https://aeronet.gsfc.nasa.gov/>, accessed on 20 June 2021). GMTED in 2010 is available in the USGS and the NGA of the United States National Geological and Geographic Information Service (https://topotools.cr.usgs.gov/gmted_viewer/viewer.htm, accessed on 15 May 2021). Köppen climate zones dataset can be obtained from National Earth System Science Data Center, National Science & Technology Infrastructure of China (<http://www.geodata.cn>, accessed on 23 May 2021).

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