Long-term Variation of Absorption and Total Aerosol Optical Properties over Typical Provinces of China from Satellite Observations

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Abstract. Increase of atmospheric aerosols has a profound impact on the Earth’s climate. It’s also one of the crucial factors that caused more frequent air pollution events in China. Monthly average Aerosol Optical Depth (AOD) from MODIS and UltraViolet Absorbing aerosol Index (UVAI) from OMI during 2011 to 2019 are used to analyse the trend of absorption and total aerosol optical properties over three typical provinces of China, namely Shandong, Gansu and Guangdong provinces. The results show the average annual AOD of the three provinces are all decreasing while UVAI rises during this period. In addition, the monthly variation of AOD and UVAI are also obviously different over these provinces. In particular, the peak value of AOD appeared in July and the trough appeared in December over Shandong Province. And the peak appeared in April over Gansu Province, but AOD decrease slower then over Shandong Province. And there were two peaks in April and August over Guangdong Province. For UVAI, the peaks over Shandong and Gansu provinces both occur in January, while that over Guangdong Province appears in March. Above mentioned differences in the long-term trend and monthly variation of AOD and UVAI might be closely related to the meteorological conditions and aerosol emission of these three provinces.

1. Introduction
Aerosols refer to solid or liquid particles that are uniformly distributed in a system of finely divided state, such as the atmosphere of the Earth. Aerosol particles with diameters in the range of 0.001 to 100μm[1] could last in the atmosphere for a short period of time. Though they are only a small part of the earth’s atmosphere, their composition, concentration and distribution are quite different in time and space[2]. Aerosols play an important role in air pollution and climate[1,3]. Absorbing aerosols, black carbon in particular, can attenuate solar radiation through both scattering and absorption. These effects lead to a significant heating to the atmosphere and cooling to the surface. Thus the combined forcing of absorbing aerosols to the Earth-atmosphere system might be more complex and introduces uncertainty in climate projections, as emphasised in IPCC AR5[4].

Satellite aerosol observation data is one of the important data sources for studying aerosols and their meteorological effects due to their advantage in global observation[5]. Aerosol Optical Depth (AOD) is the measure of aerosols distributed within a column of air, and an important parameter to characterize the total amount of aerosols [6]. For example, the AOD products retrieved by the Moderate Resolution Imaging Spectroradiometer (MODIS) demonstrate better applicability in China; and the correlation coefficient between the C6 version and the AERONET ground station observation data in China is 0.94...
The analysis of the trend and influencing factors of AOD in China by use of MODIS AOD products [6,7,9,10] reveals that since 2000, the average AOD in China has generally shown a decreasing trend [7], while the AOD in Pearl River Delta and Yangtze River Delta regions (2001-2018) showed a trend of rising first and then falling [6, 9, 10].

Ultraviolet Absorbing Aerosol Index (UVAI) is a parameter of backscattered radiation observed by satellites at the ultraviolet band. UVAI is the measure of ultraviolet absorbing effect of aerosol, and an important parameter reflecting the total amount of absorbing aerosols [11]. The OMI (Ozone Monitoring Instrument) UVAI product on the AURA satellite has higher accuracy [12]. Observations of OMI has better spatial and temporal continuity, which can be used to analyze the variation and transmission trend of absorbing aerosols [13]. Recent studies in northwest China revealed that UVAI value in the area showed an upward trend with fluctuations, and that these changes might be affected by temperature, precipitation, terrain, wind direction and human activities [5,14,15,16]. Moreover, studies have shown that the UVAI value in northern China demonstrated an overall increasing trend from 2009 to 2018 [17].

China’s economy has rapidly developed in the past decades, meanwhile human activities (including industrial emissions, urban traffic, living stoves, heating boilers and other energy consumption) have become one of the main reasons for the increase in aerosol emissions. Statistics show that the proportion of coal energy supply in northern China is as high as 70%-80% [18]. In particular, coal-fired heating in winter lead to larger emissions of smoke and sulfur dioxide, which might be one of the major factors of more frequent haze events in winter. However, the characteristics of aerosol emission variation in southern China are different from those in the north [7] due to the difference of meteorological and energy consumption. Years after implementation of “a ten-point list of measures” for controlling air pollution and promulgation of "Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution each", the atmospheric environment has improved with enhanced governance efforts.

In this paper, AOD from MODIS and UVAI from OMI during year of 2011 to 2019 have been used to analyze the temporal variation characteristics of aerosols in three typical regions (Shandong Province, Gansu Province and Guangdong Province). Section 2 described data and methodology, section 3 reported results and discussion, and section 4 summarized all the findings.

2. Data and Methodology

2.1. Regions of Interest

The three typical regions are Shandong Province in northeastern China, Gansu Province in northwestern China, Guangdong Province in southern China.

Shandong Province (34°23’-38°24.01’N, 114°48’-122°42’E) has a total land area of 157,900 square kilometers. The terrain of Shandong is mainly flat, arable land accounts for 73.61% of the total land area in Shandong. Shandong Province is the most populous province in the north, whose permanent population ranks second in the world. Shandong’s GDP has reached 7312.90 billion yuan (2020), whose industry has been developing rapidly in the past. Its total industrial output value and industrial added value has ranked among the top three provinces in China. As a result, a large number of aerosols are produced in Shandong. Meanwhile, coal is needed for heating in cold winter in Shandong, which also causes a large amount of aerosol emissions.

Gansu Province (32°11’-42°57’N, 92°13’-108°46’E) is in the northwestern part of China, with a total land area of 425,800 square kilometers. The terrain in this province is relatively complex, as it is located at the intersection of the three plateaus of the Loess, Qinghai-Tibet and Inner Mongolia Plateaus. There are many mountains with large terrain height difference. The overall terrain tilts from southeast to northwest. Gansu is affected by different meteorological systems. Precipitation concentrated in summer over Gansu was caused by east Asian monsoon. Economy of Gansu has grewed rapidly due to development of its industries, that also caused increase of aerosol emission. Not to mention that fossil fuel consumption for heating rises in winter, and dust storms in spring, which also aggravated increase of aerosol emission.
Guangdong Province (20°13’-25°31’N, 109°39’-117°19’E) is a coastal province in southern China with a total area of 179,725 square kilometers. There lie mountains across the northeast to southwest of Guangdong Province. Guangdong is located in the region affected by East Asian monsoon, and its annual average temperature is around 22.3 °C. Guangdong’s GDP has reached 11076.094 billion RMB in 2020, which is the highest of the three provinces and ranked 1st in China. Also GDP of its industry accounts for 39.2% of the total number. Since the industrial structure and climatic conditions of Guangdong Province are different from the other two province of the northern China, there must be differences in the types and temporal and spatial distribution of aerosols.

2.2. Data Set and Method

2.2.1 MODIS MYD08 Data. MODIS is the remote sensing instrument equipped on the satellites Terra and Aqua, which provides observation data at 36 channels cover visible, near-infrared and infrared. With a scan width of 2330 km, it provides high-resolution image on the features of land, ocean, atmosphere, aerosols, and clouds. At present, the MODIS data service provides level 3(L3) aerosol products with 1 degree resolution [9]. Our paper selected monthly average AOD products with 1°×1° resolution from MODIS/Aqua(MYD08_M3 v6.1). There are two AOD datasets produced by dark blue (DB) and dark target (DT) algorithms. The DB algorithm is suitable for bright surfaces, while the other one is suitable for darker surfaces with higher vegetation coverage. Vegetation coverage of some areas significantly reduce in winter over provinces of northern China, such as Shandong and Gansu. So the AOD products using only the one dataset may cause value missing or overestimation [10]. Thus monthly average aerosol dataset “Dark Target and Deep Blue AOD at 0.55 micron for land and ocean” combined results from both algorithms are used in this study. The acquired aerosol data is monthly average data. Annual AOD data was aggregated from monthly AOD data for analysis of its inter-annual variation.

2.2.2 OMI UVAl Data. The Aura is a satellite monitoring air pollution in the orbit of 705 kilometers. The OMI is a new generation of atmospheric composition sensor onboard Aura. OMI is a high-resolution spectrometer covers bands from 270–500nm(ultraviolet and visible) with a spectral resolution of 0.5nm[19]. Its spatial resolution is 13km×2km, and the scan width is 2600km allowing daily coverage of the globe. OMI is sensitive to the amount of atmospheric absorbing aerosols, thereby UVAl derived from OMI could be used to analyze the variation of absorbing aerosol. Generally, UVAl>0 proves that the gas has strong absorption of ultraviolet radiation; the UVAl of clouds or non-absorbable aerosols with larger particle diameters (DP≥0. 2 μm) is generally 0±0.2. When UVAl<0, it refers to non-absorbable aerosols with a smaller particle size (DP <0.2 μm); and an absorbing aerosol with a larger contribution to UVAl usually has a particle size of 0.2 μm<DP<0. 6 μm [5]. The monthly L3 product of OMI (Aura_OMI_Level 3/OMAERUVd.003) with a spatial resolution of 1°×1° for the same period of time. Annual UVAl data was aggregated from monthly UVAl data for analysis of its inter-annual variation.

2.2.3 Mann-Kendall Method. Mann-Kendall method [20] was used to analyze the trend of annual AOD and UVAl. This method mainly adopts the cumulative calculation method, which can reveal long-term trend and separate anomaly from natural fluctuations. The cumulative calculation make some outliers have no significant impact on the results, so it is widely used in non-parametric tests [20]. The calculation formula of the change trend function $S$ is as follows:

$$ S = \sum_{k=1}^{n-1} \sum_{j=K+1}^{n-1} \text{Sgn}(X_k - X_j) $$
\[ Sg(X_k - X_j) = \begin{cases} 
+1 & (X_k - X_j) < 0 \\
0 & (X_k - X_j) = 0 \\
-1 & (X_k - X_j) > 0 
\end{cases} \]

Where \( n \) represents the number of years, and \( X_k \) and \( X_j \) represent the data of the year \( k \) and the year \( j \) respectively. As for the function \( S \), \( S>0 \) indicates an increasing trend; \( S=0 \) indicates that the parameter has no significant change; and \( S<0 \) indicates a decreasing trend.

3. Results and Discussion

3.1. Average AOD and UVAI Distribution over China

The average AOD and UVAI from 2011 to 2019 are shown in Figure 1. And ROIs was outlined, red for Guangdong Province, green for Shandong Province and blue for Gansu Province.

![Figure 1](image-url)

**Figure 1.** The spatial distribution of China’s average AOD and UVAI from 2011 to 2019

As illustrated in fig. 1a, AOD are relatively high in the east and southeast China. And northwest China have higher UVAI according to fig. 1b. Distribution of AOD and UVAI are much different from each other, that may be caused by different local emissions or meteorological conditions. Shandong Province has higher average AOD (0.81) but lower UVAI(0.61), yet Gansu Province is the opposite case, lower AOD(0.21) but higher UVAI(0.48). In Guangdong Province it is the same as in Shandong Province, but value of AOD and UVAI are relatively lower, which are 0.51 and 0.36 respectively.
3.2. Trend of Annual Average AOD and UVAI

Figure 2. Statistics of monthly average AOD and UVAI from 2011 to 2019: Shandong Province (a. monthly average AOD trend change graph, b. monthly average UVAI trend change graph); Gansu Province (c. monthly average AOD trend change graph, d. monthly average UVAI trend change graph); Guangdong Province (e. monthly average AOD trend change graph, f. monthly average UVAI trend change graph).

Fig.2 illustrated trends of monthly AOD and UVAI over three ROIs. AOD and UVAI in the three provinces have similar seasonal variation. The slopes of AOD and UVAI trend from 2011 to 2019 over Shandong Province are -0.0043 and 0.0044 respectively. The slopes over Gansu Province are -0.0009
and 0.0048, and those over Guangdong Province are -0.0022 and 0.0041. It revealed a consistent trend of decreasing AOD and increasing UVAI over the three ROIs. It might indicate a probably co-variation of AOD and UVAI, and trend of absorbing aerosols is opposite to the trend of total aerosols. Therefore, in order to further clarify their relationship, annual average variation of AOD and UVAI is further analyzed as in fig. 3.

Figure 3. Statistics of annual average AOD and UVAI of Shandong Province (a), Gansu Province (b), and Guangdong Province (c) from 2011 to 2019

Annual average AOD and UVAl of these three ROIs are almost the same, that AOD is decreasing and UVAI is increasing. In particular, AOD is highest in Shandong and the trend is flatted since 2017, as shown in fig. 2a. However, AOD of Guangdong Province is turning around at 2017 in fig. 2c. As for Gansu Province, AOD is much lower than the other two provinces. UVAI of the three ROIs shown same trend, slowly increase since 2011, but rapidly increase since 2017, and the their trends turn around for a few years at some point near 2013.

Similarly, the annual average AOD of Shandong Province (see fig. 3a) decreased in all other years except for a slight increase in 2014, and decreased slowly from 2011 to 2013 and from 2017 to 2019. The maximum and minimum values were reached in 2011 and 2019 respectively. Meanwhile, in addition to the slight decrease in the three years from 2013 to 2016, the UVAI index of Shandong Province increased significantly in the other six years. Contrary to AOD, the maximum and minimum annual UVAI were in 2019 and 2011 respectively. In general, the annual average AOD of Shandong Province showed a decreasing trend, while the annual average UVAI in Shandong Province had an increasing trend opposite to its annual average AOD. Although the change in AOD in Gansu Province (see Figure 3b) was not particularly obvious, it is not difficult to see that, except for a slight increase in individual annuals, the overall trend was also decreasing. It reached the maximum in 2011 and the minimum in 2017. In contrast, the UVAI in Gansu Province, except for a decrease from 2014 to 2016, had an increasing trend in other years. Like Shandong Province, its annual average UVAI reached the maximum and minimum in 2011 and 2019. The changes in the two annual average aerosol indexes in Guangdong Province (see Figure 3c) were similar to those in Shandong Province. The average annual AOD values decreased except for the obvious growth in 2014 and in 2019. This made it reach the minimum in 2018 and the maximum in 2014. Except for the slow decrease in the average annual UVAI trend in 2013 and from 2014 to 2017, relatively high increase can be seen in the other years. Although the average annual UVAI of Guangdong Province is different from that of the previous two provinces in nine years, they all reach the minimum and maximum in 2011 and 2019 respectively.

The Mann-Kendall change trend function S was calculated using the annual average data of AOD and UVAI in the above three provinces, as shown in Table 1. It can be seen from Table 1 that the change trends of AOD and UVAI values in the three provinces from 2011 to 2019 are generally opposite. Among them, the average AOD change trend function S of the entire region of Shandong Province reached -33, indicating that Shandong Province had reduced AOD more obviously than Gansu and
Guangdong. In contrast, the change trend function S of UVAI in Shandong reached 22, showing an increasing trend. The average AOD change trend function S of the entire region of Gansu Province reached -14, which was the smallest of the three provinces; and the decreasing trend of AOD was also relatively small. In addition, the change trend function S of UVAI in Gansu Province was the most obvious to reach 26. The average AOD change trend function S of the entire area of Guangdong Province reached -22, showing a decreasing trend; and the change trend function S of UVAI in Guangdong Province reached 18, which was the slowest increase. Analysis of the above results and the trend line slopes of AOD and UVAI values in the three provinces reveals that the relationship between the AOD value and the UVAI value of the three provinces is the same as the slope of the trend lines and that the sign is the same, which better verifies the accuracy of the change trends of AOD and UVAI in the three provinces.

Previous studies has shown that the reasons for the reduction of AOD over China may be related to the implementation of air pollution prevention and control leading by Chinese government [22]. However, factors like population, car ownership, thermal power generation, energy consumption and the improvement of living standards may contribute to the increase of UVAI [5,17].

Table 1. Trend analysis results using Mann Kendall method

| Province     | S value of annual change in AOD | S value of UVAI annual change |
|--------------|---------------------------------|------------------------------|
| Shandong     | -33                              | 22                           |
| Gansu        | -14                              | 26                           |
| Guangdong    | -22                              | 18                           |

3.3. Seasonal Variation of AOD and UVAI

Seasonal trends of AOD and UVAI over the three ROIs are shown in fig. 4.

As for Shandong Province (fig. 4a), the monthly variation of AOD show a pattern of increase in spring and summer then decrease in autumn and winter. The peak value of AOD over Shandong Province is in July, and valley value is in December. However, the UVAI decreased in winter and spring but increase mainly in autumn. Thus minimum of UVAI is in June while maximum of UVAI is in January. The results reveal that opposite trend of the monthly variation of AOD and UVAI, and the minimum and maximum of AOD is roughly corresponded to the maximum and minimum of UVAI respectively. The seasonal variation of AOD may be affected by meteorological conditions, for example, high temperature and lavish water vapor in summer might be the main factors that causes high AOD in summer [22-23]. As one of the main wheat producing areas, there might be straw burning events in the summertime over Shandong Province, that may also lead to increase of AOD [24]. Because diffusion
condition is poorer in winter, the concentration of pollutants near the ground increases and the vertical distribution is uneven. However secondary aerosols might be much less in the winter, which makes the AOD of the Northern Plains lower in winter. The temperature rises but dry that the soil becomes loose after thawing, and the scarcity of surface vegetation leads to frequent dust storms, might contributed greatly to peak of UVAI in spring. In winter, consumption for coal for heating which lead to emission of absorbing aerosols, may be the reason that UVAI increases significantly.

Compared with Shandong Province, trend of AOD over Gansu Province (see Figure 4b) was relatively stable; and its annual average was lower than 0.4. And its AOD increased in spring and winter with the peak being in April and decreased in summer and autumn with the valley value being in October. UVAI over Gansu Province was similar to Shandong, which decreased in spring and summer with the valley value being in June, but increased in autumn and winter with the peak being in January. Smaller anomaly of AOD may be related to the less aerosol emission [25]. UVAI was higher in spring and winter but lower in summer, because absorbing aerosols increased due to dust storm in spring and energy consumption for heating in winter[5]. In addition, as regional GDP and industrial output value are correlated with AOD and UVAI to some extent [21], it can be reflected that the economic level of Gansu Province is lower than that of Shandong Province.

As illustrated in fig. 4c, AOD over Guangdong Province increased in winter and spring with the peak being in April then decreased in summer and autumn with the valley value being in November. Its UVAI increased in autumn and winter with the peak being in March, and decreased in spring and summer with the valley value being in June. It seems relative to the stable atmospheric conditions in March and April, which is suitable for formation of secondary aerosol but not for pollutant diffusion[21]. In spring, the variation of AOD and UVAI was quite similar. It is possible that the increase of absorbable aerosols contributes greatly to the increase of total aerosols in spring, which is related to the transportation of biomass combustion emissions in Southeast Asia [26]. Southerly airflow prevails in spring and summer, which is conducive to the diffusion of pollutants, resulting in the decline of AOD and UVAI [17]. Air humidity increase in summer, thus the hygroscopic growth of aerosol particles lead to the increase of AOD in summer[27]. And the valley value of AOD is in November, because strong wind accompanying the cold air southward is conducive to the diffusion of pollutants lead to decrease of AOD [28].

4. Conclusion
This article mainly uses MODIS AOD data and OMI UVAI data from 2011 to 2019 to study the temporal distribution characteristics of total aerosols and absorbing aerosols in Shandong, Gansu and Guangdong provinces. Meanwhile, it analyzes the change trends of two indexes and discusses the reasons for these changes.

In terms of annual variation, the AOD of the three typical regions (Shandong, Gansu and Guangdong) showed a downward trend from 2011 to 2019, however their decline rates were different. The AOD of Shandong, Gansu and Guangdong provinces reached the peak in 2011, 2011 and 2014 respectively and hit the valley value in 2019, 2017, and 2018 respectively. On the contrary, UVAI of the three ROI generally rose during this period of time. Besides, it can be seen from the line chart of the monthly average over the nine years that AOD and UVAI exhibited periodicity in the measure of years. As for seasonal variation, AOD over Shandong province increased in spring and winter with the peak being in July, then decreased in summer and autumn with the valley value being in December. However, UVAI over Shandong Province decreased in winter, spring and summer with the peak being in June, and increased from autumn with the valley value being in January. The monthly changes over Gansu Province were relatively stable compared to Shandong on the whole. The monthly variation of its AOD increased in spring and winter with the peak being in April, however decreased in summer and autumn.
with the valley value being in October. Trend of UVAI was similar to that of Shandong, with the peak being in June and the valley value being in January. The AOD of Guangdong Province increased in winter and spring with the peak being in April, and decreased in summer and autumn with the valley value being in November; while its UVAI increased in autumn and winter with the valley value being in June, and decreased in spring and summer with the valley value being in March.

From the analysis of AOD and UVAI in this article and the findings of other studies, it is inferred that AOD and UVAI will be affected by the same factors and that some factors have different or even opposite effects on the two indexes. In terms of vegetation coverage, it can be seen that too scarce vegetation may cause the missing of AOD data, and that vegetation has a purifying effect for UVAI. In terms of temperature and precipitation, the change of AOD may be caused by the high temperature and rich water vapor content in summer, which are more prone to photochemical reaction and thus result in the increase of AOD. However, summer precipitation is conducive to the sediment of UVAI and thus causes a decrease in UVAI. In the coldest and dry winter, AOD is the lowest throughout the year while UVAI is the highest throughout the year, which indicates that temperature and precipitation exert different effects on AOD and UVAI.

In addition, some factors have the same effect on AOD and UVAI. Taking Shandong and Gansu provinces which have similar climate conditions as an example. In terms of The AOD and UVAI of Shandong Province are higher than those of Gansu Province as Shandong has more population and more developed economy than Gansu Province. In terms of biomass combustion, a lot of straw combustion and forest fire accidents will release a large number of aerosols, which is one of the reasons for the high aerosol index in summer and spring. In terms of wind influence, wind can not only guide the direction of aerosol propagation, but also cause dust storms.

Moreover, since aerosols include absorbing aerosols, AOD and UVAI have opposite trends, which indicates that there are other types of aerosols that affect the changes in AOD and that UVAI is only a part of them. Meanwhile, the changes in AOD and UVAI reflect that the proportion of UVAI in the total aerosols is changing, meaning that the content inside aerosols is constantly changing.

5. References
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