Estimation of PM$_{10}$ concentration changes in Shanxi province using MODIS satellite data

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Abstract. In view of the difficulty in monitoring the concentration and distribution of large-scale regional indicators, firstly, this paper uses the deep blue algorithm to invert the aerosol optical thickness of Shanxi province in 2016. Secondly, this paper uses the results of the inversion to establish the correlation regression analysis with the PM$_{10}$ mass concentration data obtained from the monitoring station obtained by the China National Environmental Monitoring Center. Then, by analyzing this model, this paper inverts the concentration and distribution characteristics of PM$_{10}$ in a wide range of regions, and finally obtains the distribution characteristics of PM$_{10}$ concentration in the survey area. The results show that the correlation coefficient of the regression analysis model established in this paper reaches 0.804, and the data shows a good consistency in the trend of change. This model is used to inverse large area PM$_{10}$ concentration. It helps to quickly and efficiently obtain the distribution characteristics of PM$_{10}$ mass concentration in this area. This will provide effective help for related research such as environmental pollution control.

1. Introduction
In recent years, urban pollution has become more and more serious, and severe haze weather has occurred frequently, which seriously affects people's quality of life. According to the urban air quality report provided by the China National Environmental Monitoring Center, the main pollutants affecting China's air quality are atmospheric particulate matter [1]. According to its existence state, atmospheric pollutants can be divided into aerosol pollutants and gaseous pollutants. The multiphase system composed of solid particles and liquid particles suspended in gas clusters and gas carriers is called aerosol, and the dynamics of aerosols. The diameter is 0.001~100 μm [2,3]. Near-surface aerosols, also known as atmospheric particulate matter (PM), can be divided into total suspended particulate matter, respirable particulate matter (PM$_{10}$, kinetic diameter less than or equal to 10 μm) and particulate matter (PM$_{2.5}$, dynamics). If the diameter of the aerosol particles is less than or equal to 2.5 μm, if the amount of aerosol particles exceeds the standard, it will have a great impact on air quality, atmospheric visibility, human health and travel safety. The smog phenomenon is the most direct expression of aerosol particle excess [4]. Aerosol Optical Depth (AOD), one of the most important parameters of aerosols, is an important physical quantity for characterizing atmospheric turbidity [5].
Therefore, accurate acquisition of aerosol optical thickness is used to study the degree of atmospheric pollution and improve air quality is great importance.

Ground-based detection methods and satellite remote sensing methods are the main methods for obtaining AOD. The former mainly uses solar photometers for detection. Relevant institutions at home and abroad have deployed a large number of ground-based observing stations to observe the distribution and variation of aerosols. Although this method can obtain more accurate aerosol information, this method only obtains the data on the observation site, but it can not correctly reflect the spatial and temporal distribution of aerosol in large areas [6]. The latter uses remote sensing technology, which has the advantages of wide coverage, fast, easy access to information, and limited location of site layout. It is faster and more efficient than the first method to obtain atmospheric aerosol information [7,8]. The Moderate-resolution Imaging Spectroradiometer (MODIS) is an important sensor mounted on the National Aeronautics and Space Administration (NASA) Earth Observation System. It has 36 channels of visible light and near-infrared to infrared. The highest resolution of up to 250 m provides an important means of detecting remote sensing of terrestrial aerosols [9].

At present, China has established real-time monitoring stations in many cities to monitor air quality index concentrations such as AQI, PM_{2.5}, and PM_{10}. However, due to the limited number of these stations, it is impossible to monitor the spatial distribution of index concentrations at large regional scales. The satellite optical remote sensing method is used to retrieve the aerosol optical thickness. By establishing the correlation model between the AOD value and the PM_{10} of the monitoring station, the feasibility of estimating the spatial and temporal distribution of PM_{10} in each region is explored.

2. Research area and data source

2.1. General situation of the research area
Shanxi province is rich in coal resources, and the local industrial structure is dominated by heavy industry. The dust generated in the coal area is easily connected to form large-scale pollution. The pollution gas emitted by the industry is seriously exceeded, leading to deterioration of environmental quality and significant climate change. Secondly, Shanxi province is located in the middle of China. The region can represent the vast area of the central and western regions and has a strong representativeness. Therefore, this experiment selected Shanxi province as a research area.

2.2. MODIS data
The MODIS data used in this experiment included Terra/MODIS L1B data (MOD02), geolocation data (MOD03), 500 m surface reflectance 8d synthetic product of MOD 09A1, and two aerosol products of MODIS04. The time span is from January 2016 to December 2016 with a total of 557 scenes.

The preprocessing of MODIS data mainly includes: using the geolocation data set MOD03, and correcting the image geometry by means of MRTSwath (The MODIS Reprojection Tool Swath) software, unifying the two phase images into the same coordinate system, and correcting the radiation of the image, converting the DN (Digital Number) value to the apparent reflectance and the like. The basic flow chart is shown in Figure 1.
2.3. Ground-based monitoring data

The air quality data used in this experiment comes from the National Urban Air Quality Real-Time Publishing Platform of China Environmental Monitoring Center (http://106.37.208.233:20035/). Using forty-nine monitoring points in Shanxi Province, the time resolution is 1h, which is the data recorded every hour. Data types include AQI, PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, O$_3$, and CO. Since the transit time of MODIS is around 10:30 am, the PM$_{10}$ mass concentration data used in this paper is calculated using the 10-point and 11-point mean values.

3. Inversion of aerosol optical thickness

3.1. The basic principle of inverting aerosol optical thickness

For aerosol optical thickness inversion, it is first necessary to assume that the surface observed by the satellite is a uniform Lambertian surface. Considering the influence of the atmosphere, the apparent reflectivity received by the satellite sensor is expressed as [10]:

$$
\rho^* (T_a, \theta_s, \theta_v, \phi) = \rho_a (T_a, \theta_s, \theta_v, \phi) + \frac{\rho}{1 - \rho_s (T_a)} \cdot T(T_a, \theta_s) \cdot T(T_a, \theta_v) \cdot F_d (\theta_s)
$$

In the above formula, $\rho^* (T_a, \theta_s, \theta_v, \phi)$ refers to the apparent reflectance observed by the satellite; $T_a$ is the aerosol optical thickness; $\theta_s$ is the solar zenith angle; $\theta_v$ is the observed zenith angle; $\phi$ is the relative azimuth; $\rho_a (T_a, \theta_s, \theta_v, \phi)$ is the path radiation term, it is the interaction of gas molecules in the atmosphere with aerosol scattering; $\frac{\rho}{1 - \rho_s (T_a)} \cdot T(T_a, \theta_s) \cdot T(T_a, \theta_v) \cdot F_d (\theta_s)$ is the equivalent reflectivity of the surface and atmosphere; $s (T_a)$ is the atmospheric hemisphere
albedo; $\rho$ is the surface reflectivity; $F_d(\theta_s)$ is the downward total radiation; $T(T_o, \theta_s) \cdot T(T_o, \theta_r)$ is the total transmittance from the surface to the satellite sensor.

It can be seen from the above formula (1) that the aerosol optical thickness can be calculated under the conditions of known atmospheric mode, aerosol mode, surface reflectance, apparent reflectance, and related observation geometric information. Since the data observed by the sensor is shared by the atmosphere and the surface, some means must be used to accurately separate the surface contribution from the atmospheric contribution [11]. In the case of known surface reflectivity, a suitable aerosol mode and atmospheric radiation transmission mode can be selected according to different regions, and a look-up table of optical thickness and related parameters can be established to invert the aerosol optical thickness.

3.2. Acquisition of surface reflectance
In this paper, based on the MOD 09A1 500 m surface reflectance 8d synthetic product, the third band surface reflectivity database is constructed. The MOD 09A1 provides a 1-7 band 500 m resolution data product with a sinusoidal projection. Each pixel of MOD 09A1 contains the most effective clear-air observations within 8 days. After cloud detection and atmospheric radiation correction, the product quality has high credibility. The MOD 09A1 product was subjected to geometric correction, data splicing and resampling data processing using ENVI (Environment for Visualizing Images) software to construct a third band (blue band) 1 km resolution surface reflectance database.

3.3. Determination of atmospheric aerosol mode
According to the MODIS image acquisition date and experimental area location, the atmospheric mode and the aerosol type are determined. The experimental data is 557 MODIS images from January to December 2016, so it is uniformly set to the mid-latitude summer atmospheric mode or the mid-latitude winter atmospheric mode, and the aerosol type selects the continental aerosol.

3.4. Construction of the look-up table
The construction of the look-up table is accomplished by using the IDL program to call the 6S program and controlling the model by setting different parameters to perform the radiation transfer calculation. Among them, parameters such as satellite observation geometric parameters, atmospheric aerosol parameters, different observation bands and different surface types need to be considered [12].

The aerosol optical thickness ranges from 0 to 2, with a value of 0 being a pure atmospheric molecule. In this experiment, the optical thickness parameter has a step size of 0.2, and the value range is (0.0001, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8). The center wavelength of the MODIS band used for aerosol optical inversion is 470 nm, 660 nm, and 2120 nm (corresponding to the 42, 44, and 48 band numbers in the 6S software, respectively). The surface parameters include: selecting a uniform Lambertian surface. The land cover type is vegetation.

The look-up table established in this study only considers the value of aerosol optical thickness between 0.0001 and 1.95, and the intermediate values of 0.39, 0.78, 1.17, and 1.56, calculated at six solar zenith angles (0°, 12°, 24°, 36°, 48°, 60°), six observation zenith angles (0°, 12°, 24°, 36°, 48°, 60°), the nine solar incident angles are opposite to the sensor observation angle. The value of the aerosol optical thickness of the azimuthal angles (0°, 24°, 48°, 72°, 96°, 120°, 144°, 168°, 180°) generates a look-up table file.

3.5. Inversion results of aerosol optical thickness
The look-up table was searched and a linear interpolation method was used to calculate the 550 nm aerosol optical thickness. The inversion results are shown in Figure 2, where Figure 2 is the inversion of the aerosol optical thickness in the study area on September 6, 2016.
4. Correlation analysis between AOD and PM$_{10}$ concentration

In this experiment, 118 sets of aerosol optical thickness data and PM$_{10}$ concentration data (in μg/m$^3$) were used for regression analysis. The experiment used coefficient of determination, which measures the difference between actual data and function results[13], select the appropriate regression model, and verify the accuracy of the model.

4.1. Trend analysis of AOD and PM$_{10}$ concentration

This inversion yielded the aerosol optical thickness values of Shanxi province in 49 days of 350 monitoring points. The AOD values of 10 points and 11 points per day of 49 monitoring points were averaged to obtain the average value of AOD in Shanxi province. The average value of ground PM$_{10}$ concentration in 49 stations was combined with AOD as the X axis and PM$_{10}$ concentration as the Y axis. The graph analyzes the relationship between the two [14], and the resulting scatter plot is shown in Figure 3. It can be seen from the figure that the concentrations of AOD and PM$_{10}$ are similar in overall trend.
4.2. Regression analysis of AOD and PM$_{10}$

The linear regression analysis of AOD and PM$_{10}$ concentrations in Excel was carried out [15]. The results are shown in Table 1. As can be seen from the table, the correlation coefficient (R Square) is 0.8042, indicating that the AOD and PM$_{10}$ concentrations are linear. Relationship, in addition to the results of analysis of variance, the statistical F value is 398.4966, the P value is 4.00532E-36, which is less than the confidence level of 0.01, indicating that the results have credibility, that is, AOD is linearly related to PM$_{10}$.

Table 1. AOD and PM$_{10}$ linear regression analysis statistics

| Regression statistics          |        |
|-------------------------------|--------|
| Multiple R                    | 0.896792507 |
| R Square                      | 0.8042368   |
| Adjusted R Square             | 0.793927522 |
| Standard error                | 40.12129624 |
| Observations                  | 118     |

4.3. Evaluation of the relationship model

In order to test the accuracy of the model results after regression, this paper uses the most commonly used ten-fold cross-validation method [16], in the 118 groups of data, select 1, 2, 4, 5, 7, 8, 10, 11. A total of 86 groups of data were used as modeling data in December, and the remaining 32 data in March, June and September were used as verification data. The AOD values of the 86 modeling data were first input into the regression model of the annual AOD and PM$_{10}$ concentrations. Then, the calculated value of PM$_{10}$ is obtained by AOD back calculation, and the absolute error is obtained by using the calculated value and the actual observed value of PM$_{10}$. All errors were averaged with an error of 28.8%. It shows that the model has good precision and can meet the needs of subsequent experiments.

Table 2. Error Analysis Table

| Calculated value | measured value | error (100%) |
|------------------|----------------|--------------|
| 86.996964        | 106            | 0.179273925  |
| 104.014848       | 126            | 0.174485333  |
| 82.639728        | 66             | 0.252117091  |
| 107.837706       | 82             | 0.315093797  |
| 100.726368       | 119            | 0.153599333  |
| 90.162126        | 76             | 0.186343763  |
| 75.158436        | 83             | 0.094476675  |
| 112.606002       | 107            | 0.052392542  |
| 74.665164        | 64             | 0.166643188  |
| 67.71825         | 45             | 0.50485      |
| 88.558992        | 72             | 0.229986     |
| 71.500002        | 78             | 0.083333308  |
| 81.653184        | 87             | 0.061457655  |
| 77.99475         | 79             | 0.012724684  |
| 111.043974       | 92             | 0.206999717  |
| 75.035118        | 60             | 0.2505853    |
| 86.996964        | 106            | 0.179273925  |
| ......            | ......          | ......        |
| ......            | ......          | average error | 0.28769124  |

4.4. Results and analysis
According to the above analysis, the average annual analysis of the inversion PM$_{10}$ concentration combined with the monitoring station PM$_{10}$ concentration is shown in Figure 4. It is found that the highest concentration of PM$_{10}$ in Shanxi Province in 2016 is Yangquan City, and the PM$_{10}$ concentration is as high as 126.0971 $\mu$g/m$^3$. Followed by Linfen City and Taiyuan City, the concentration reached 117 $\mu$g/m$^3$ or more, the lowest average is Datong City, the concentration is 79.76276 $\mu$g/m$^3$, and other urban PM$_{10}$ concentrations are roughly distributed around 100 $\mu$g/m$^3$. It can be seen that Yangquan City, Linfen City and Taiyuan City, which have better economic development, are more polluted than other urban areas, and the pollution level of Datong is relatively low. However, the overall concentration of PM$_{10}$ in Shanxi Province is slightly higher.

Fig.4 Average PM$_{10}$ concentration in each city in 2016

Preliminary analysis of the average monthly PM$_{10}$ concentration [17] changes in each city in 2016 (as shown in Figure 5) shows that Linfen City has the largest PM$_{10}$ concentration in December, reaching 274.2697 $\mu$g/m$^3$, followed by November, reaching 257.513 $\mu$g/m$^3$. Compared with the annual average PM$_{10}$ concentration in Linfen City in 2016, it is 1.33~1.185 times higher. According to the trend analysis of the fold line, it can be seen that the cities are generally in line, and most of them are concentrated between 40 $\mu$g/m$^3$ and 200 $\mu$g/m$^3$. As a whole, there was a significant decrease in PM$_{10}$ concentration from January to February, and then rebounded, reaching a small peak in March. Starting from March, except for Yangquan City, other cities showed a relatively smooth downward trend. In the range of 40 $\mu$g/m$^3$~120 $\mu$g/m$^3$, most of the urban areas reached the lowest value in the year from July to August (below Jincheng reached its lowest point in October) and began to rise slowly. In November, the concentration of PM$_{10}$ increased sharply. The curve suddenly rose, and some urban areas reached their peak in the year. Linfen, Taiyuan, Jinzhou, Yangquan and Xinzhou still had significant changes after November, and other urban areas basically stabilized.

Fig.5 Monthly average change of PM$_{10}$ concentration

From the monthly variation of PM$_{10}$ concentration, the seasonal variation characteristics of PM$_{10}$ mass concentration can be basically seen. After the data is further collated, the statistical graphs of PM$_{10}$ mass concentration changes in each city (as shown in Fig.6) are made, which is more clearly
verified. Characteristics, the concentration of PM$_{10}$ in Taiyuan City in autumn is higher than other seasons in the city. The overall PM$_{10}$ concentration in Datong is low, and the concentration of PM$_{10}$ in spring is the highest. This is similar to Yangquan City and Shuozhou City. Except these urban areas, other urban areas are it is the highest in winter, among which Linfen, Jinzhong, Yuncheng, Xinzhou and Lvliang are the highest in winter, and the concentration of PM$_{10}$ in Changzhi, Linfen, Jinzheng and Yuncheng is significantly higher than that in other seasons, especially in winter. Out of the city 2.6 times in summer. Of course, it is not difficult to see that each city reached the minimum concentration of PM$_{10}$ in summer, which was the lowest in Yuncheng in summer, with a concentration of 49.1 μg/m$^3$. By comparison, the general law is as follows: the PM$_{10}$ mass concentration is relatively high in the spring, the PM$_{10}$ mass concentration is the lowest in the summer, the autumn begins to rise, and reach the peaks in winter. The reasons are as follows: winter heating coal produces a large amount of dust aerosol, in addition to winter rain and snow weather, it is easy to form haze weather, will form a thick inversion layer over the city, air convection activity is reduced, pollutants are not easy diffusion, therefore, although the spring has a small decline compared to winter, it is basically stable in the high range. From summer to autumn, there is a lot of rainfall, which can wash away a lot of suspended particulates in the air. Therefore, the concentration of PM$_{10}$ in urban areas is generally low in summer. Rainwater in the autumn is still abundant, but there is a slight increase in PM$_{10}$ concentration with frequent windy weather [18].

Fig.6 Change of PM$_{10}$ concentration in the four seasons in each city

Fig.7 Diurnal variation characteristics of PM$_{10}$ concentration

Taking Taiyuan City, Shanxi Province and Shuozhou City as March 31, 2016 as an example, the diurnal variation of PM$_{10}$ concentration on the day [19] is comparatively analyzed. As shown in Figure 7, it can be seen that the PM$_{10}$ mass concentration changes with hour. And there are certain rules. At noon, between 10 and 11 o'clock, the PM$_{10}$ concentration in Taiyuan City reached the lowest value of 177 μg/m$^3$ in Taiyuan City. At 14 o’clock, the PM$_{10}$ concentration in Shuozhou City reached the lowest concentration of 144 μg/m$^3$ in that day, and both show a v-curve trend that rises first and then rises,
and both reach the maximum value of the day at 24 o'clock. The v-curve curve of Shuozhou City is more obvious. The PM$_{10}$ concentration in Taiyuan City is greater than the PM$_{10}$ concentration in Shuozhou City from 1 to 21 in one day. After the intersection of 21 points, the PM$_{10}$ concentration in Shuozhou begins to be greater than that in Taiyuan City.

5. Conclusions
In this experiment, the aerosol optical thickness data of Shanxi Province in 2016 was inverted using MODIS image data of 557 scene, and the correlation regression analysis was established by combining PM$_{10}$ mass concentration data. The following conclusions were drawn:

- The inversion method using the dark blue algorithm and the 6S model is applicable in the aerosol optical thickness inversion experiment in Shanxi province. It is better to reverse the aerosol optical thickness value of Shanxi province.
- In this paper, a linear regression model of mass concentration of AOD and PM$_{10}$ in Shanxi province is established to meet the accuracy requirements of subsequent experiments.
- The analysis of the temporal and spatial distribution of AOD distribution characteristics shows that the aerosol is affected by the city and decreases toward the surrounding level with the city as the center. Secondly, it is found that the aerosol optical thickness in the central and southern parts of Shanxi province is significantly higher than that in the northern region, especially in Taiyuan, Yuncheng and Linfen.
- Using the linear model to invert the PM$_{10}$ concentration in Shanxi Province, and obtain the spatio-temporal distribution characteristics of PM$_{10}$ mass concentration, based on this, we can predict the change trend and help the relevant departments to do a good job in prevention and control, and provide reference for people's travel health. It also facilitates other research in relevant departments.

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