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Study on long-term aerosol distribution over central plains economic region using MODIS data

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Abstract. The long-term (2000-2013) Moderate Resolution Imaging (MODIS) level 2 aerosol products were used to study the spatial and temporal distributions of both aerosol optical depths (AOD) over Central Plains Economic Region (CPER), which is critical for a thorough understanding of its formation, transport and accumulation in the atmosphere. The results indicate that the spatial distribution of AOD with higher values locate in Xinxiang city, Kaifeng city, Zhengzhou city and Jiaozuo city. The lower ones locate in the south of Shanxi province and the west of Henan province, which are all mountainous regions. Spring and summer are the two seasons with the lowest AOD in a year. The minimum AOD in CPER occurred in winter. In the Central Plains Urban Agglomeration (CPUA), Kaifeng city, Xinxiang city and Zhengzhou city are the areas with the worst air pollution of particulate matter. The AOD over CPER significantly reduce during the period from 2011 to 2013. In the long term, however, the condition of particulate matter pollution has not been improved.

1. Introduction
In recent years, with the rapid expansion of city scope, the rapid development of industry, and the increase of urban population and vehicles, accompanied urban atmospheric pollution problems, especially the particulate pollution is getting worse, air quality continues to deteriorate become the main problems of the harm to human health, restricting urban development, and harm to harmonious society construction. In 2014, the World Health Organization released a report that each year about 700 million people died of air pollution of the world; Air pollution has become the world’s largest single environmental health risks [1]. Therefore, how to accurately obtain the space-time distribution, source and transmission path of aerosol has become one of the world’s hot spots; meanwhile, it is also an important guarantee for weighting particulate pollution effect, formulating particulate reduction, prevention and control policies.

Presently, aerosol’s remote sensing measurement methods are mainly included satellite remote sensing and ground-based remote sensing. Although ground monitoring instruments have a number of advantages in routine particle monitoring, it can only be carried out on limited ground stations, and the station is rarely in vast rural and underdevelopment areas. Satellite remote sensing has advantages of wide coverage, provide macroscopic change information, and reflect large scale and regional scale
transportation of pollutions, which can make up for the shortage of spatial distribution of ground monitoring stations [2].

In recent years, at home and abroad have a lot of new results about air pollution research using satellite remote sensing data. Using the NASA’s Level2 aerosol optical thickness of 10 km, Chu et al. [3] demonstrated the very significant application values of MODIS data in the monitoring of global, regional and local air pollution. Engel-Cox et al. studied the application of AOD in research of air pollution by using the MODIS true color image and the aerosol optical thickness data, respectively in qualitatively and quantitatively. Through comparing the satellite remote sensing data with the ground pollutant concentration, it was found that those in the United States, the center region and eastern region have high correlation than the western region [4]. In the aspect of long time series data analysis, Zhai Tianyong used the aerosol optical depth data of Terra MODIS from 2000 to 2013 to analyze the spatial and temporal characteristics of AOD in the Yangtze River Delta and the influence of meteorological factors on its distribution [5]. Wang Zhao et al. used the MODIS C5 aerosol product from 2000 to 2010 to analyze the multi-year variation of aerosol optical thickness and small particle aerosol contribution to total optical thickness in the Central Plains basin [6]. Although there are many studies on the spatial and temporal distribution of aerosols in the major cities such as Beijing-Tianjin-Hebei, the Pearl River Delta and the Yangtze River Delta, few studies have been done on the Central Plains urban agglomeration, which is one of China's seven national-level urban agglomerations.

2. Study area and data

2.1. Overview of the study area

In this paper, the Central Plains Economic Zone (CPER), which takes the Zheng-Bian-Luo urban area as the core, the Central Plains city group as the support, covering all Henan province and surrounding areas of the economic area, located in the center of China, latitude and longitude range of roughly 32 ° N ~ 38 ° N, 110 ° E ~ 118 ° E (as shown in Figure 1). The Central Plains Economic Zone consists of 28 prefecture-level cities (18 prefecture-level cities and 10 provincial-level cities and counties) in Henan, and 12 prefecture-level cities and three prefecture-level cities around Shandong, Hebei, Anhui and Shanxi, those with a total area of about 289,000 square kilometers. This area is relatively flat terrain, plain, and it is a temperate monsoon climate, the weather characters is high temperature and rainy in summer, cold and dry in winter.

The Central Plains urban agglomeration as the core of the Central Plains Economic Zone, it takes Zhengzhou as the center, and Luoyang as deputy center, including Kaifeng, Xinxiang, Jiaozuo, Xuchang, Luohe, Pingdingshan, Jiyuan, those nine regional central cities for the nodes constitute a close ties. In recent years, with the continuous and rapid development of economy in the Central Plains region, especially the Central Plains urban agglomerations, the region’s air pollution problem is increasingly prominent. Recently, Henan Province Environmental Quality Bulletin shows that the Central Plains urban agglomerations atmospheric environment pollutants are mainly respirable particulate matters. Therefore, through study the pollution level and longtime spatiotemporal variation characteristics of aerosol particles in the region, it can provides scientific basis for government decision-making, which is of great practical significance to realize the sustainable development of the Central Plains Economic Zone.

2.2. Satellite data sources and data processing

Terra and Aqua satellites are part of NASA’s Earth Observing System (EOS) program, which was launched on 18 December 1999 and 4 May 2002, respectively, transit time is for daily locations at 10:30 am and 13:30 pm, which are known as AM and PM satellites, they are all equipped with a Moderate Resolution Imaging Spectroradiometer sensor. In this paper, Using the MODIS / Terra 10 km aerosol optical depth data (MOD04) to analysis the aerosol long time series of the Central Plains Economic Zone, with accuracy of ± 0.05 ± 0.15τ and ± 0.03 ± 0.05τ on the land and sea respectively [7], those data can be obtained directly from NASA’s MODIS website.
Figure 1. The location and terrain of CPER.

Figure 2. The distribution of AOD over CPER averaged from MOD04 products in the period of 2000–2013. (http://ladsweb.nascom.nasa.gov/data/search.html). The MOD04 aerosol optical thickness of the product is currently one of the most widely used and the highest reliability of the AOT data. In this paper, we validate the MOD04 data from February 2000 to December 2013 by pixel-by-pixel and then combine the mean values to obtain the monthly and annual mean distributions.

3. Retrieval Algorithm of Aerosol Remote Sensing

The physical meaning of the aerosol optical thickness AOD is the integral of the extinction coefficient along the radiation propagation direction.

$$\tau_{\lambda} = \int_{0}^{\infty} \delta_{\lambda} N(z)dz$$  \hspace{1cm} (1)

Among them, $\tau_{\lambda}$ means the aerosol optical thickness, $\lambda$ means the wavelength, $\delta_{\lambda}$ means the aerosol extinction cross section, $N(z)$ means the aerosol particle number density vertical distribution.

The MODIS 10 km resolution aerosol products currently used in the mainstream algorithm for dark pixel inversion algorithm, and the algorithm theory as follows: According to the vegetation - intensive and low albedo of the surface ground (dark pixels), there is a good linear correlation between near-infrared channel reflectance and red-blue channel reflectance. The effect of aerosols is 15 to 30 times smaller in the short-wave infrared band than in the visible band, thus it can be ignored. Therefore, the surface reflectivity of the red-blue band can be obtained from the apparent reflectivity of the short-wave infrared band, and then remove the surface contribution from the apparent reflectivity of the red-blue band, obtain the hemispheric reflectivity of the lower atmosphere, the equivalent reflectance of radiation term in the atmosphere and other atmospheric parameters, then get the aerosol optical thickness.

In order to increase the applicability of the dark pixel inversion algorithm, the new inversion algorithm of MOD04 C005 product uses a new inversion idea: In the dark target region, the relationship between the visible red bands and near infrared band is a function of the scattering angle and the vegetation index, and there is a fixed linear relationship between the visible red band and the blue band surface reflectivity. At the same time, MOD04C005 product inversion algorithm updated the aerosol model based on geographical distribution [8]. Based on the results of Dubovik et al., the MOD04 C005 product identified five aerosol models, namely continental, dust, no absorbable, moderately absorbing and severely absorbing, and these aerosol patterns varied with the season and geographical Change [9].

4. Result Analysis
Figure 2 shows the multi-year mean distribution of AOD in the CPER from 2000 to 2013. In Figure 2, the results indicate that the spatial distribution of AOD with higher values locate in Xinxiang, Kaifeng, the north of Zhengzhou and the south of Jiaozuo, which are relatively densely populated and economically developed urban areas. Locating in the southern foot of Taihang Mountains, the dominant wind direction of these regions is northeast and southwest, and sub-dominant wind direction is northwest wind. The high atmospheric stability of these areas leads to high static wind frequency. The topography and meteorological conditions aren’t conducive to the dilution and diffusion of air pollutants, causing heavily polluted weather. In addition, the energy structures of these areas mainly dominated by coal. The irrational energy structure and lagging environmental infrastructure increased the pressure of atmospheric environmental quality improvement from the source. On the contrary, the
In terms of interannual variation trend, from 2000 to 2013, the CPER experienced three fluctuations (Figure 3): the first fluctuation from 2000 to 2004, the second from 2004 to 2009, and the last from 2009 to 2013. Among these fluctuations, the peak value of AOD respectively appeared in 2003, 2006 and 2011. In addition, the mean annual AOD and the area of high AOD region (AOD>0.7) in the CPER experienced the process of first increase and then decrease during each fluctuation. It’s important to note that the degree of particulate pollution in CPER is obviously reduced relative to the previous fluctuating period (2006–2008), which except for affected by meteorological elements, but also is closely relate to the policies of adjustment of industrial structure and strict supervision of air pollution in Henan province, and even in the entire Central Plains in recent years.

4.2. The interannual trend of AOD means for key cities of Central Plains Urban Agglomeration during 2000-2013

The nine key cities (Zhengzhou, Xinxiang, Kaifeng, Jiaozuo, Xuchang, Luoye, Pingdingshan and Jiyuan) of Central Plains Urban Agglomeration are not only representing the economic core of CPER, but also represent the region of serious particulate pollution. In this paper, we specialize in conducting a statistical analysis of the annual variability of AOD within its administrative area of these nine key cities (Figure 4). As shown in Figure 4, from 2000 to 2013, we find that the three cities with the highest mean of AOD in Central Urban Agglomeration are Kaifeng, Xinxiang and Zhengzhou. Relatively, the three cities with the lowest mean are Luoyang, Jiyuan and Pingdingshan. Among them, the mean value of AOD in Kaifeng, as the city with highest level of particulate pollution reaches 0.74, and the value of Luoyang is only 0.412. In addition, many cities such as Kaifeng, Xinxiang etc. also experienced three obvious fluctuations as referred in 3.1 section. Meanwhile, from 2000 to 2013, except Jiyuan, the AOD’s average value of the other eight key cities shows the trend of slow increase or constant during each fluctuation. But in the period of 2011~2013, the mean value of each city appears the trend of significant downward. Therefore, we conclude that the annual average of AOD in Central Plains Urban Agglomeration and CPER always has been in the fluctuations of continuous improvement and rebound. In the short term, the level of particulate pollution in the whole region truly shows the trend of decreasing year by year after 2011. But in the long term, both Central Plains Urban Agglomeration and CPER, the particulate pollution level has not been significantly improved, or even deteriorated after 2000.

4.3. The temporal and spatial distribution of seasonal AOD over CPER during 2000-2013

To analyze the seasonal variation of CPER, we calculated the monthly mean AOD and its standard deviation from 2000 to 2013. As shown in Figure 5, the seasonal trend of CPER is significant, spring and summer are the two seasons with the lowest AOD, while the value of summer and winter are lower relatively. Throughout the year, the highest value of AOD generally appears in the June of summer (AOD years mean = 0.704), the lowest value often exists in the December of winter (AOD years mean = 0.358). In the same year, the difference of AOD in different months can be as high as 0.97. In this paper, we only present the spatial distribution of the seasonal mean of AOD in 2013 because the spatial and temporal distribution of AOD in CPER has good consistency and regularity (Figure 6). The results of the above analysis are different from the case of low visibility events in autumn and winter. Because the AOD represents the extinction effect of the vertical layer aerosol, while ground visibility represents the horizontal extinction effect of the aerosol on the ground surface. In spring, the long-distance transport of coarse dust particles from Inner Mongolia and other places is one of the main reasons for the increase of AOD in the CPER. In summer, the relative humidity in the atmosphere is too high to leads the phenomenon of aerosol particle’s hygroscopic growth becomes more obvious. Therefore, AOD also changes bigger relatively.
Figure 4. The trend of annual mean AOD for nine cities of Central Plains Urban Agglomeration in the period of 2000–2013.

Figure 5. The temporal variations of monthly mean AOD over CPER from 2000 to 2013. The error-bars represent the standard deviations.

Figure 6. The distributions of seasonal mean AOD over CPER during 2013.

5. Conclusion and discussion
Central Plains Economic Zone as one of the seven state-level urban agglomeration, the air pollution problem has been caused increasing importance attention of the Ministry of Environmental Protection and other departments. Based on MOD04 aerosol product data from 2000 to 2013, this paper analyzes the temporal and spatial variation characteristics of AOD in the Central Plains Economic Zone, and focuses on the nine key cities in the Central Plains urban agglomeration. Research indicates:
1) The AOD high-value areas of Central Plains Economic Zone appear in Xinxiang, Kaifeng, northern Zhengzhou and southern Jiaozuo. The low-value areas are mainly mountainous areas in western Henan and southern Shanxi.

2) From 2000 to 2013, AOD of Central Plains Economic Zone experienced three wave periods, the peak of which was 2003, 2006 and 2011 respectively.

3) The highest value of AOD in the Central Plains Economic Zone usually occurs in spring, summer, and autumn followed, and winter is the smallest in the region.

4) The three cities with the most serious level of particulate pollution are Kaifeng, Xinxiang and Zhengzhou, the lightest three cities are Luoyang, Jiyuan and Pingdingshan.

5) In the short term, after 2011, the particulate pollution level of the Central Plains Economic Zone has obviously decreased year by year, but in the long run, after 2000, neither the Central Plains urban agglomeration nor all the Central Plains Economic Zone, the pollution level of the particulate matter has not been significantly improved; Industrial structure adjustment, air pollution’s prevention and control, and other measures still need to strictly enforce.

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