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Spatiotemporal Trend Analysis of $PM_{2.5}$ Concentration in China, 1999–2016

Jianghua Zhao [1,2,3], Xuezhi Wang [1], Hongqing Song [3,4], Yi Du [1,2], Wenjuan Cui [1] and Yuanchun Zhou [1,3,*]

1 Computer Network Information Center, Chinese Academy of Sciences, Beijing 100190, China
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 National & Local Joint Engineering Lab for Big Data Analysis and Computing Technology, Beijing 100190, China
4 School of Energy and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China
* Correspondence: zyc@cnic.cn

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Abstract: China is experiencing severe $PM_{2.5}$ (fine particles with a diameter of 2.5 µg or smaller) pollution problem. Little is known, however, about how the increasing concentration trend is spatially distributed, nor whether there are some areas that experience a stable or decreasing concentration trend. Managers and policymakers require such information to make strategic decisions and monitor progress towards management objectives. Here, we present a pixel-based linear trend analysis of annual $PM_{2.5}$ concentration variation in China during the period 1999–2016, and our results provide guidance about where to prioritize management efforts and affirm the importance of controlling coal energy consumption. We show that 87.9% of the whole China area had an increasing trend. The drastic increasing trends of $PM_{2.5}$ concentration during the last 18 years in the Beijing–Tianjin–Hebei region, Shandong province, and the Three Northeastern Provinces are discussed. Furthermore, by exploring regional $PM_{2.5}$ pollution, we find that Tarim Basin endures a high $PM_{2.5}$ concentration, and this should have some relationship with oil exploration. The relationship between $PM_{2.5}$ pollution and energy consumption is also discussed. Not only energy structure reconstruction should be repeatedly emphasized, the amount of coal burned should be strictly controlled.

Keywords: $PM_{2.5}$ pollution; spatiotemporal trend analysis; energy consumption; pixel-based linear trend analysis

1. Introduction

Fine particles with a diameter of 2.5 µg or smaller ($PM_{2.5}$) contain toxic substances which affect the respiratory and circulatory systems. A meta-analysis conducted by Huang et al. indicated that there was a strong association between exposure to $PM_{2.5}$ and lung cancer incidence and mortality [1]. $PM_{2.5}$ also leads to a sharp decrease in visibility, which indirectly affects economic activities [2]. Moreover, by reflecting or absorbing incoming solar radiations, particulate matter can also influence the climate [3]. In addition to weather conditions, human activities can play the most important factors for $PM_{2.5}$ [4–6]. Increasing populations, local economic growth, and urban expansion are the three main driving forces impacting $PM_{2.5}$ concentrations [7–9], and major sources include road traffic, dust, industry, biomass burning, coal combustion and so on [3,10,11]. In China, economic development is prioritized to reduce poverty, one of the global tasks on sustainable development, and is heavily dependent on energy-intensive industries [12]. As a result, China is experiencing a severe $PM_{2.5}$ pollution problem [13].

Understanding the spatial and temporal patterns in $PM_{2.5}$ concentrations in China can provide a foundation for government decisions. A lot of $PM_{2.5}$ concentrations in China have been studied at regional and national scales. Studies examining the spatiotemporal patterns of $PM_{2.5}$ from global scales found that the highest threat of $PM_{2.5}$ concentrations was located in Eastern China [13]. By conducting studies on the spatio-temporal distribution features of $PM_{2.5}$, Luo et al. found that the concentration of $PM_{2.5}$ in China had increased while the spatial patterns from 1998 to 2012 were very similar, showing an increasing trend from west to east [14]. Yan et al. applied network analysis on $PM_{2.5}$ emission data to study spatial and temporal characteristics [11]. At regional levels, many studies have focused on heavily polluted cities such as Beijing [15–18], Shanghai [19], Shandong [20] and Xi'an [21] etc. Moreover, the major focus has been given to the relation between $PM_{2.5}$ and emission sources. Sun et al. conducted a study about the relationship between air pollution and the economic boom in China, and gave suggestions of adjusting energy and industrial structures [12]. However, up till now, little is known by reseacrhers about how the trend of $PM_{2.5}$ change is spatially distributed.

Knowing the $PM_{2.5}$ concentration trend for all specific areas can fill the gap of understanding pollution control effects across the country. Managers and policymakers require such information to make strategic decisions and monitor progress towards management objectives. Change detection approaches, especially long time-series analysis, are often used to obtain such results. Hansen et al. used an ordinary least squares slope of the regression of annual loss versus year to derive trends in annual forest loss [22]. Vogelmann et al. describe the use of linear regression relationships on a pixel by pixel basis between time (x variable) and the vegetation index value (y variable) for selected pixels [23]. Unlike bi-temporal change detection, long time-series analysis can identify a large disturbance occurring in a single year from regional to national areas over time.

Based on annual $PM_{2.5}$ time series, linear regression can make better use of the temporal depth of the data to reconstruct $PM_{2.5}$ disturbance histories with annual resolution and to map trends, such as $PM_{2.5}$ rise and fall. Here, for the first time, we perform a pixel-based linear trend analysis on the recently available satellite-derived annual $PM_{2.5}$ data [24] to characterize spatio-temporal patterns of $PM_{2.5}$ concentration changes. Not only the spatial changes of the $PM_{2.5}$ concentration are discussed, but also temporal context of changes are considered. Moreover, we have studied the relationship between $PM_{2.5}$ concentration and energy consumption and new suggestions on controlling coal consumption are reported in the discussion.

2. Materials and Methods

2.1. $PM_{2.5}$ Concentration Data

Satellite-retrieved data are very suitable for studying spatiotemporally continuous distribution characteristics of $PM_{2.5}$ concentrations. The $PM_{2.5}$ datasets we use in this paper were inversed by van Donkelaar et al. based on multiple satellite data (MISR, MODIS and SeaWiFS), simulation model (GEOS-Chem) and ground-based sun photometer (AERONET) observations. The resultant global 10-km resolution $PM_{2.5}$ estimates have a long time span, from 1999 to 2016, and have been effectively applied on national and regional scales [8,12,14,25,26]. The dataset can be downloaded from Battelle Memorial Institute and the Center for International Earth Science Information Network (CIESIN)/Columbia University (http://beta.sedac.ciesin.columbia.edu/data/set/sdei-global-annual-gwr-pm2-5-modis-misr-seawifs-aod). Data for China are extracted from the global dataset using the open-source Geospatial Data Abstraction Library (GDAL).

2.2. Pixel Based Trend Analysis

The $PM_{2.5}$ concentration data are in in a geospatial raster format. Trend analysis of $PM_{2.5}$ concentration in China from 1999 to 2016 would form a large amount of calculation for personal computers. To facilitate raster data processing, all raster files are segmented based on a grid tessellation. The grid tessellation has the same coordinate system as the $PM_{2.5}$ data, and segments in each grid are

1000 × 1300 raster arrays. Then, pixel-based trend analysis of segments of all years at the same grid location are processed in a three-step procedure.

First, extract pixel values of all years at the same location.

Then, linear least-squares regression is calculated using scipy. Among it, x is the vector of years in order, y is a vector of corresponding $PM_{2.5}$ values for each year. Slope, intercept, rvalue, pvalue and stderr are calculated for each pixel location.

At last, results for each pixel size location are spatially aggregated into an array, and are stored as a raster file with coordinate system information.

After linear regression was calculated for segments in all grids, all segments of slope, intercept, rvalue, pvalue and stderr were recombined, respectively, to form complete raster data for the Chinese region. All maps in this paper are generated in ArcGIS10.2, URL: http://www.esrichina-bj.cn/softwareproduct/ArcGIS/.

3. Results and Discussion

3.1. Trend Analysis of $PM_{2.5}$ Concentrations during 1999–2016

For the 18-year study period, the $PM_{2.5}$ levels in China have increased by 48%, and area percentage with $PM_{2.5}$ < 10 μg/m^3 decreased from 56.4% to 39.4% (Figure 1). The annual average concentrations of $PM_{2.5}$ had the highest of 18.68 μg/m^3 in 2007 and the lowest of 11.48 μg/m^3 in 2000, showing a general increase in recent years.

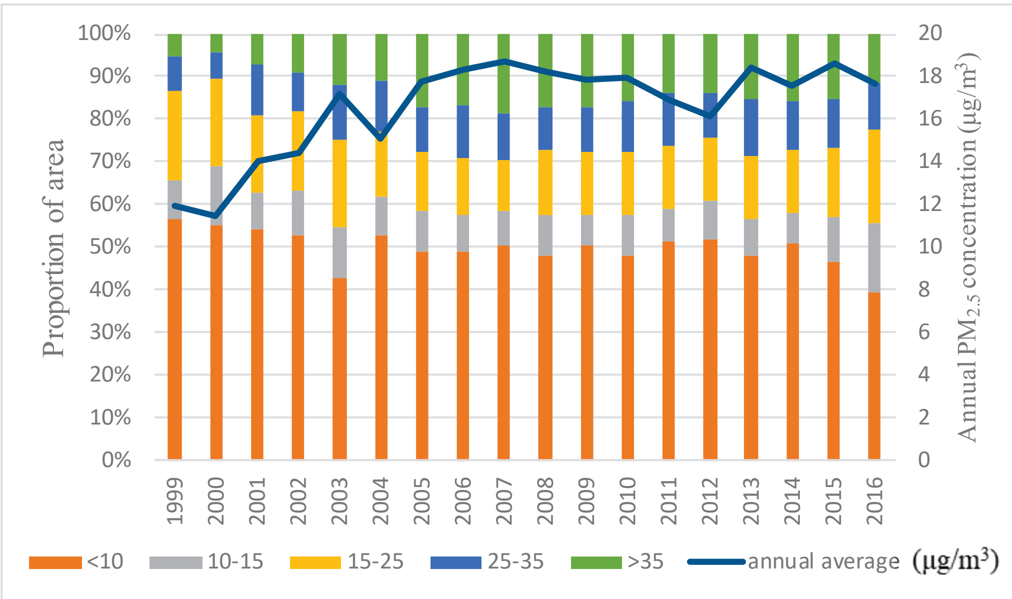


Figure 1. Trend analysis of annual average $PM_{2.5}$ concentrations during 1999–2016 for China. In order to make the analysis straightforward, annual mean $PM_{2.5}$ concentrations were categorized sequentially into five grades according to WHO air quality guidelines. WHO air quality guidelines have four standards, including one air quality guideline (<10 μg/m^3) and three interim targets, which are 10–15 μg/m^3, 15–25 μg/m^3, 25–35 μg/m^3 respectively. In this paper, we add another guideline, of which $PM_{2.5}$ concentration values are larger than 35 μg/m^3. The cumulative proportion of areas of each concentration range were calculated).

The whole time period can be divided into three phases in light of the distinctive characteristics in the $PM_{2.5}$ concentration trend. The years 2007 and 2012 are the turning points. In the first phase (from 1999 to 2007, designated as Phase I), the annual average concentrations increased at an annual change of 7.10% per year. The severe particulate matter (PM) pollution increase problem is probably closely linked to rapid economic growth in China. In contrast, the second phase (from 2007 to 2012, named as Phase II), displayed a distinct decreasing concentration trend with a rate of −2.75%. In this period, the 29th Olympic Games were held in Beijing in 2008, and this may have led to some air pollution control measures to be implemented [27]. During the third phase (from 2012 to 2016, named as Phase III), the annual concentrations showed a fluctuation trend (Figure 1). As air pollution in China has become particularly serious, it caused a great deal of attention of both the government and local residents. On 29 February 2012, China issued a newly revised "Environmental Air Quality Standard", which increased the monitoring index of fine particulate matter ($PM_{2.5}$). In addition, a nationwide monitoring network was established in January 2013.

3.2. Spatial Distribution Analysis of $PM_{2.5}$ Concentration Trend

In order to understand the spatial distribution of the temporal trend of $PM_{2.5}$ concentration across China, pixel-based ordinary least squares regression was performed, where the dependent variable y was the value of annual $PM_{2.5}$, and independent variable in the model was the time. The slope of the regression function is represented in Figure 2.

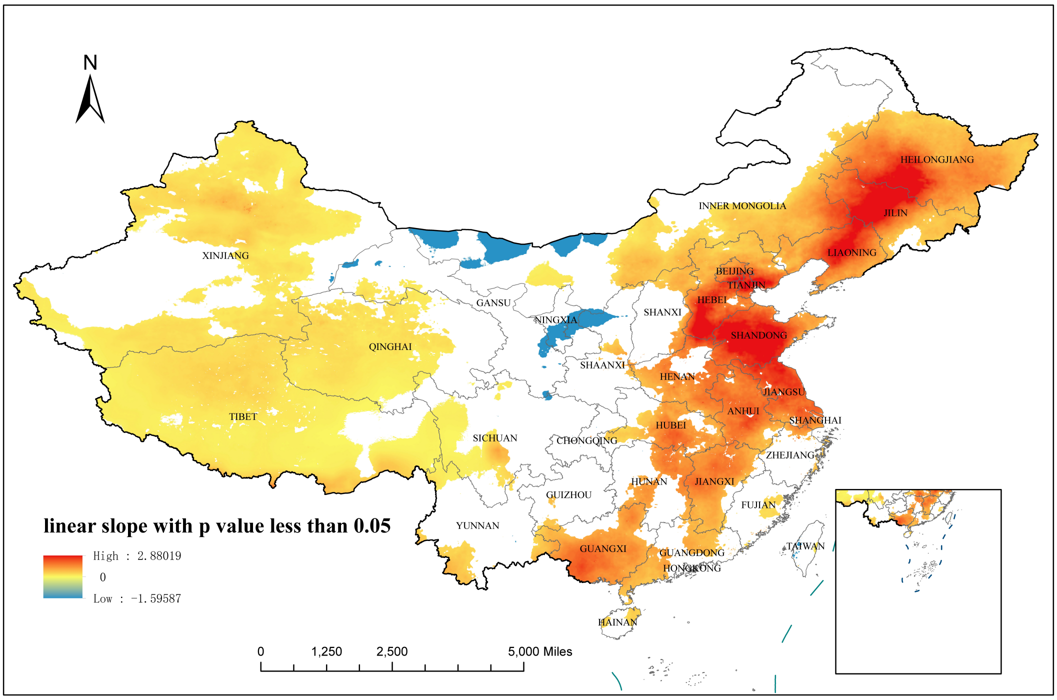
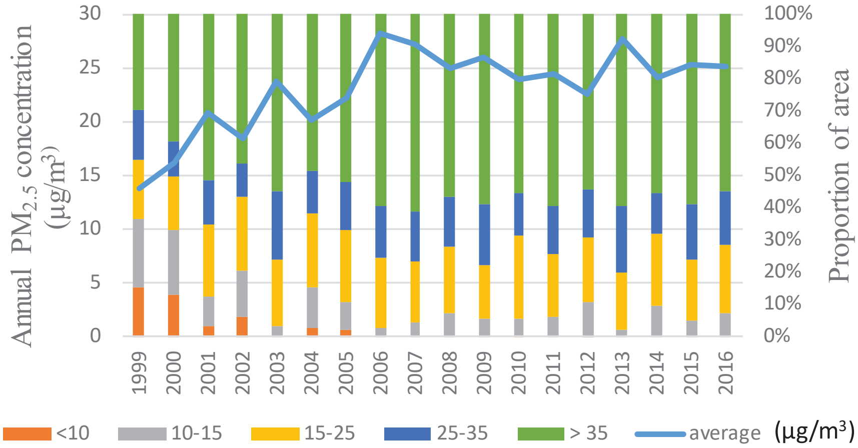


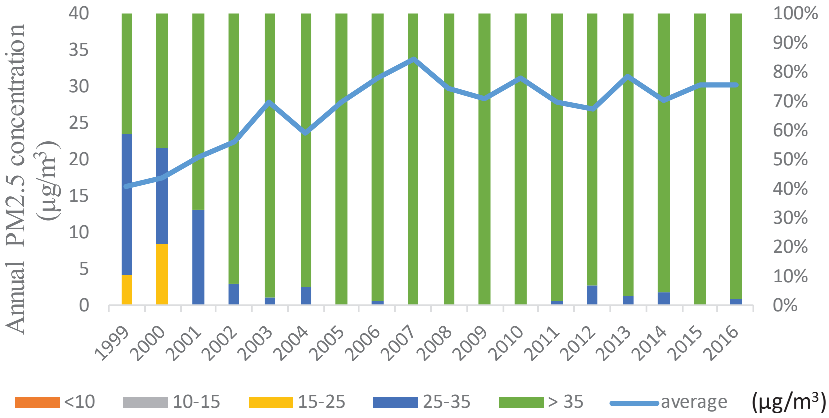
Figure 2. Geographic distribution of trend analysis of $PM_{2.5}$ concentration in China during 1999–2016 (areas of increasing trend in red, and decreasing trend in blue).

Areas with positive values of slope are considered as contributing to $PM_{2.5}$ increase and they account for about 87.9% of the entire country. Among them, marked upward $PM_{2.5}$ concentration trends are evidenced in the eastern parts of the country, including the southern part of the Beijing–Tianjin–Hebei region, the western part of the Shandong province, and the Three Northeastern Provinces, which includes the Heilongjiang, Jilin and Liaoning provinces.

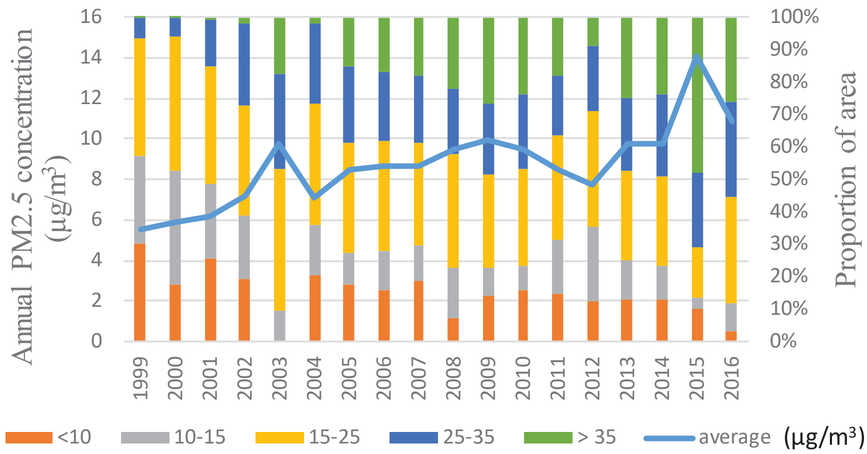
For the Beijing–Tianjin–Hebei region, the $PM_{2.5}$ concentrations of more than 45% of the area are larger than 35 $\mu g/m^3$ since 2001. It had experienced a great increase up to 2006 (Figure 3a). Heavy industries are the main $PM_{2.5}$ sources, and the Taihang mountains in the west of the Hebei province inhibit pollutant dispersion, leading to pollutant accumulation in this area [28]. Coupled with unfavorable topographic conditions and prevailing wind directions [16], this region is also affected by air masses from the Gobi desert approximately 400 km to the northwest, particularly in the spring [3].



(**a**) Beijing–Tianjin–Hebei region



(**b**) Shandong province



(**c**) Three Northeastern Provinces

Figure 3. Trend analysis of annual average $PM_{2.5}$ concentrations during 1999–2016 for regions ((**a**) Beijing–Tianjin–Hebei region. (**b**) Shandong province. (**c**) Three Northeastern Provinces.)

The Shandong province has a more serious situation. Almost the entire province endured annual $PM_{2.5}$ concentrations larger than 35 $\mu g/m^3$ from 2002 to 2016 (Figure 3b). On one hand, local pollution sources and imperfect urban pollution control mechanisms lead to heavy air pollution; on the other hand, external pollution sources also become a cause of serious pollution in the western part of the Shandong Province. Most of the cities with the worst air quality in China are located in the Hebei

Province [29]. Since the northern part of the Shandong province is bordered by the Hebei Province, the Shandong province is affected by pollution source transmission and diffusion [30].

The Three Northeastern Provinces, including Heilongjiang, Jilin and Liaoning provinces, are primarily highly dependent on heavy industries, such as iron and steel factories and cement production, which are typical sources for emissions of $PM_{2.5}$ [3]. In 2003, almost the entire region had $PM_{2.5}$ values greater than 10 μg/m^3. The mean value of $PM_{2.5}$ concentration in this region peaked in 2015, with more than 70% of the total area experiencing $PM_{2.5}$ larger than 25 μg/m^3, the limit recommended by WHO (Figure 3c). Though heavy industries have dropped since the reform era in this area, the municipal coal fired heating system is still used [31]. Moreover, since China's implementation of the exhaust gas purification equipment, investment in waste gas treatment and disposal capacity are not good enough, there is still a lot of dust generated [32].

As areas with negative values of slope had low values of t-statistics, annual $PM_{2.5}$ concentration values were plotted against time for the five main regions. Figure 4 illustrates the results, from which we can notice that all these regions had much lower annual $PM_{2.5}$ concentrations than national average values. In addition, there is a slightly decreasing pattern in the central region, which is mainly located in the southern Loess Plateau. This phenomenon may have a relationship with the effort known as the Loess Plateau Watershed Rehabilitation Project, which was launched in 1994.

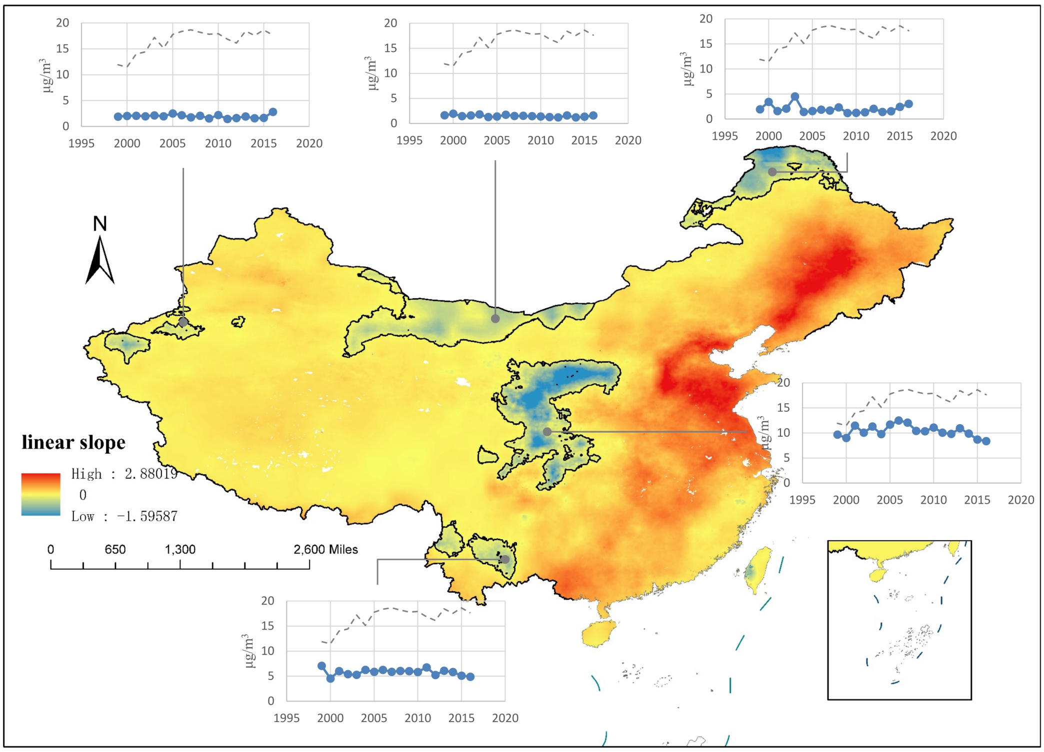


Figure 4. Trajectories of annual $PM_{2.5}$ concentration values over regions of the negative trend (the gray dashed lines are national annual average $PM_{2.5}$ concentration values, and the blue lines are annual average $PM_{2.5}$ concentration values for the corresponding regions).

Another phenomenon to be stressed is that the Tarim basin may experience dust events. Figure 5 illustrates the $PM_{2.5}$ concentration in 2016 for the Tarim region, where areas with $PM_{2.5}$ concentrations larger than 25 μg/m^3 are represented with shades of yellow. The high $PM_{2.5}$ concentration in the Tarim basin may be mainly caused by oil exploitation processes. All stages of oil management beginning from exploration and production and ending with the use of petroleum products are accompanied by strong air pollution problems, and a large volume of dust including $PM_{2.5}$ is produced in the oil exploration working site, shown in Figure 5. In addition, located at the heart of the Eurasian Continent, the Tarim Basin is one of the driest areas on earth [33]. As a consequence, it is easy to produce dust during transportation. To develop western provinces in a sustainable way, the government can use certain incentives to speed up technological breakthroughs and innovations to study how to reduce emissions.

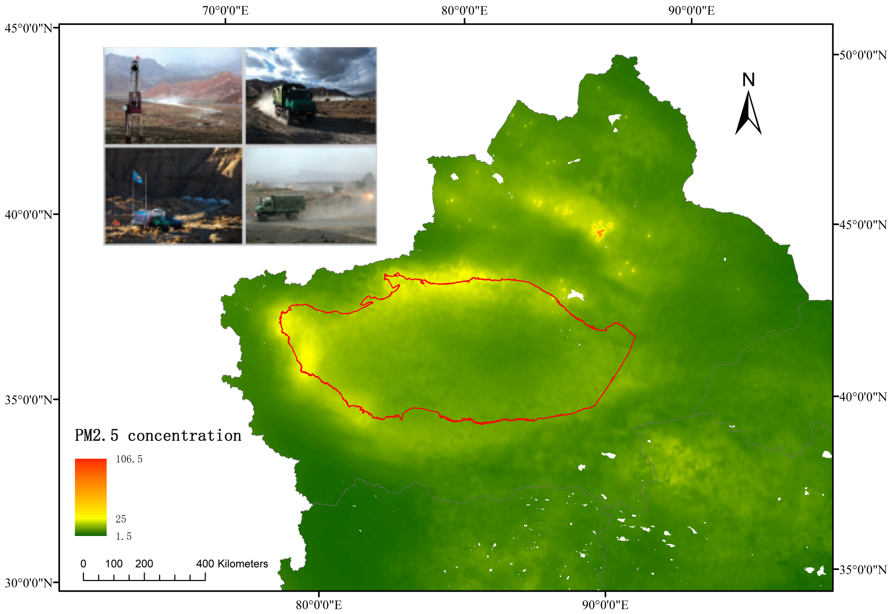


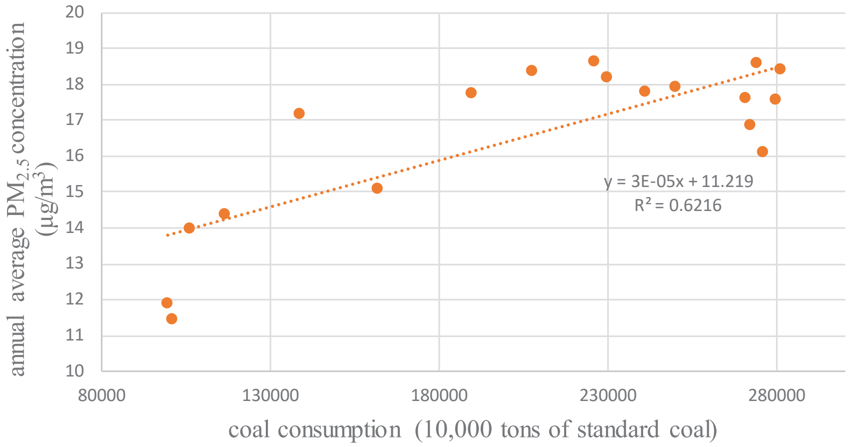
Figure 5. $PM_{2.5}$ concentration in 2016 and oil exploration in Tarim regions.

3.3. Relationship with Energy Consumption

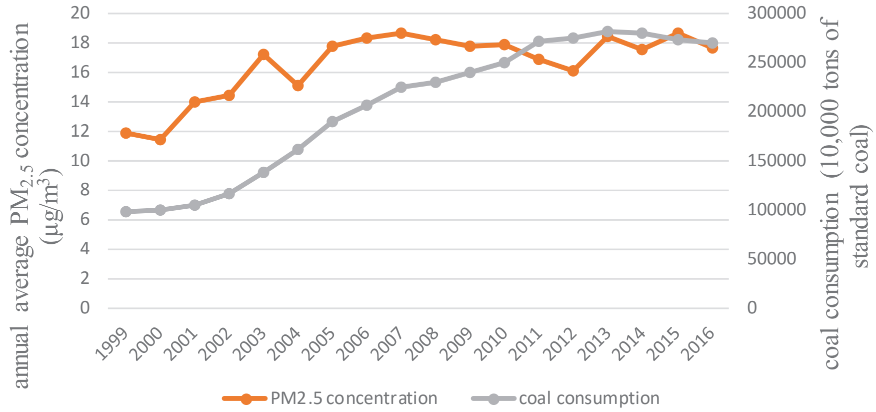
We all know that human activity can be a main reason for generating $PM_{2.5}$. In general, high $PM_{2.5}$ concentration has been attributed to socio-demographic factors, such as population growth, economy and specific exploitation activities like commercial coal exploration [34].

Being a proxy for air pollution emission from anthropogenic sources, energy consumption, especially coal combustion, could be considered one of predictors that may be used to explain variations of $PM_{2.5}$ concentrations across Mainland China. So, in order to analyze the possible relationship of the ambient air pollution with the emission patterns, a short evaluation of the National Bureau of Statistics of China is presented here.

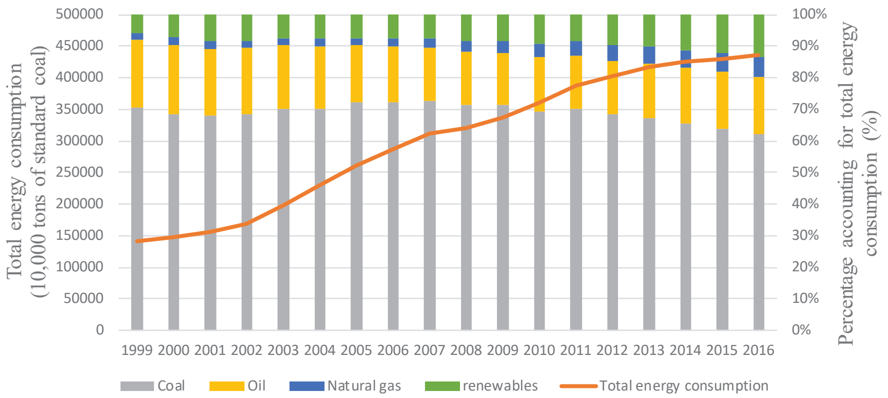
From Figure 6a, we can see that $PM_{2.5}$ concentration has a positive relationship with coal consumption (r = 0.78, p = 0.0001). Figure 6b shows the time variation of coal consumption and annual $PM_{2.5}$ concentration. From it, we can see that coal consumption had a stable increase during 1999 and 2013, and decreased slightly since 2013. While from 2007 there was no obvious increase in $PM_{2.5}$ concentration, but a fluctuation status was exhibited. This was accompanied by a huge energy structure reconstruction effort. As shown in Figure 6c, the percentage of natural gas and renewables accounting for the total energy consumption began to increase. From 2011, the increased speed became faster, up to 1.34%/year (during 2011–2016). However, only cutting down the proportion of coal in energy consumption is not enough. We should reduce energy consumption and improve the efficiency of coal utilization, such as developing coal to substitute the natural gas (coal-to-SNG) industry [35].



(**a**) Annual average $PM_{2.5}$ concentration versus coal consumption



(**b**) Time series



(**c**) Total energy consumption and composition

Figure 6. Relationship of annual average $PM_{2.5}$ concentration to coal consumption. ((**a**) Scatterplot of annual average $PM_{2.5}$ concentration versus annual coal consumption with linear regression lines. (**b**) Time series of average $PM_{2.5}$ concentration and coal consumption for each year. (**c**) Total energy consumption and composition of China from 1999 to 2016 [36]).

4. Conclusions

We used recently updated annual average $PM_{2.5}$ gridded data to study the spatial and temporal trend at 1 km^2 resolution from 1999 to 2016. $PM_{2.5}$ concentrations throughout most areas of Mainland China have increased during the period 1999–2016, but there are still some areas where $PM_{2.5}$

concentration levels are stable or showing a downward trend. Such trends are analyzed to inform air quality management and policies. Mitigation efforts need to be strengthened in areas where $PM_{2.5}$ concentrations are strongly increasing, including the Beijing–Tianjin–Hebei region, Shandong province, and the Three Northeastern Provinces. Oil exploitation work should take emission control and dust prevention measures in Tarim. For the energy control measures, not only energy structure reconstruction should be repeatedly emphasized, the amount of coal burned also should be strictly controlled.

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Conflicts of Interest: The authors declare no conflict of interest.

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