Relationship between Air Pollutants and Economic Development of the Provincial Capital Cities in China during the Past Decade

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Abstract

With the economic development of China, air pollutants are also growing rapidly in recent decades, especially in big cities of the country. To understand the relationship between economic condition and air pollutants in big cities, we analysed the socioeconomic indicators such as Gross Regional Product per capita (GRP per capita), the concentration of air pollutants (PM10, SO2, NO2) and the air pollution index (API) from 2003 to 2012 in 31 provincial capitals of mainland China. The three main industries had a quadratic correlation with NO2, but a negative relationship with PM10 and SO2. The concentration of air pollutants per ten thousand yuan decreased with the multiplying of GRP in the provincial cities. The concentration of air pollutants and API in the provincial capital cities showed a declining trend or inverted-U trend with the rise of GRP per capita, which provided a strong evidence for the Environmental Kuznets Curve (EKC), that the environmental quality first declines, then improves, with the income growth. The results of this research improved our understanding of the alteration of atmospheric quality with the increase of social economy and demonstrated the feasibility of sustainable development for China.

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Introduction

China has seen economic soaring in the past three decades, with its gross domestic product (GDP) expanding 140 times during 1978–2012 (National Bureau of Statistics, 2013). However, such economic soaring is accompanied with deterioration of the atmospheric quality. In the first three months of 2013, just like what happened in London in 1952 [1], long-time haze influenced large area of China (Fig S1), which further stimulated the strong demand for improvement of air quality.

Air pollution has significant influence on both climate and human health [2,3]. Oxidising air pollutants like ozone stimulate reactions to produce more greenhouse gases which exacerbate global warming [4]. Besides, decreasing precipitation and increasing dimness [5,6], widening of the tropics [7], weakening of summer monsoon in South Asian [4,8], as well as large-scale ocean circulation and some extreme weather like hurricane [9,10], are all linkd to air pollution. Moreover, anthropogenic air pollutants, especially particulate matter is extremely harmful to human health. According to Silva et al. (2013), more than 2 million premature deaths are associated with PM2.5-related diseases [11]. Research results from Spain and England reported that long-term exposure to air pollution mainly explained heart disease morbidity and mortality [12,13]. Similarly, the heating policy in Northern China was found to cause reduction in life expectancies of Northern residents by about 5.52 years [14]. Given the great influence of air pollution on natural environment and human life, researches are attaching ever greater importance to the causes and effects of air pollution [4,15–17].

Environmental problems result from economic expansion which increases extraction of natural resources and accumulation of waste, in the end exceeding the carrying capacity of the biosphere to the pollutants [18]. From the perspective of the history of human society economy development, the environmental quality is not fixed along a country's development path [19–21]. In the 1990s, scientists found an inverted U-shaped relationship between environmental quality and social income [22–25]. Such relationship was defined as Environmental Kuznets Curve (EKC), showing that the environmental quality would first deteriorate with the increase in revenue, and then it would improve when incomes rise to a certain level [25]. Numerous research results related to developed countries have identified EKC curve between income and air pollutants, especially in the Organization for Economic Co-operation and Development (OECD) countries.
Although some researches studied specific pollutants like SO₂ or indicators like the total amount of atmospheric emission [32–35]. EKC researches in China concentrated on comprehensive economic development of each region is needed [31]. Moreover, country analysis about how particular air pollution is related to economy development paces of different provinces in this big levels of economic development. Considering the disparate focused on econometrics, without relating air pollutants to specific economic development of each region is needed [31]. Moreover, EKC researches in China concentrated on comprehensive indicators like the total amount of atmospheric emission [32–35]. Although some researches studied specific pollutants like SO₂ or PM [36–37], the relationship between the most important three categories of air pollutants and socioeconomic indicators is not adequately reported.

In this study, we aimed to establish regression models to fit the relationship between air pollutants and the three major industries (the primary, secondary and tertiary industries), so as to reveal the relationship between industry and air quality deterioration. We also calculated the ratio of air pollutant concentration to Gross Regional Product (GRP) per capita in order to know the contribution of economic development to air pollution over time. Finally, regression analysis was conducted to verify the existence of EKC in Chinese cities, or to define the otherwise relationship between air pollutants and revenue of Chinese citizens.

Datasets and Methods

1. Study area and data source

Data were collected for 31 provincial capitals in mainland China, which are representative of the general condition of each province (Fig. 2). In order to investigate the relationship between social economy and concentration of environmental pollutants in China, we downloaded data about these two aspects in the database of the National Bureau of Statistics of China (Table S1). The economic data included GRP, population, primary industry output, secondary industry output and tertiary industry output. The pollutant data collected included the concentration of PM₁₀, SO₂, and NO₂ (the three most important air pollutants in China [38]). The air pollution index (API) was calculated with the following formula:

\[ I_j = \frac{I_{\text{high}} - I_{\text{low}}}{C_{\text{high}} - C_{\text{low}}} (C - C_{\text{low}}) + I_{\text{low}} \]

Where:
- \( I \) = (Air pollution) index of one specific pollutant, 
- \( C \) = pollutant concentration, 
- \( C_{\text{low}} \) = the concentration breakpoint \( \leq C \), 
- \( C_{\text{high}} \) = the concentration breakpoint \( \geq C \), 
- \( I_{\text{low}} \) = the index breakpoint corresponding to \( C_{\text{low}} \), 
- \( I_{\text{high}} \) = the index breakpoint corresponding to \( C_{\text{high}} \), 
- \( j \) = Air pollution indicators (PM₁₀, SO₂, NO₂).

\[ API = \max(I_j) \]

The criteria of breakpoints for air pollutants were taken from the website of Ministry of Environment Protection of the People’s Republic of China [39]. All data from 2003 to 2012 used for statistical analyses were retrieved from National Bureau of Statistics of China. As the demographic data for Lhasa during 2003–2006 and 2010 was missing, we did not do analyze the city for these years.

2. Relationship between air pollutants and the three main industries

Linear, quadratic and cubic regression analysis was conducted to examine whether there existed simple positive or negative relationship between the concentration of air pollutants (dependent variables) and the output per capita of the three industries (independent variables) in the provincial capital cities. We chose the best appropriate regression model for each air pollutant and industry and plotted the regression line for those which were significantly correlated.

3. Trend analysis for the ratio of pollutant concentration to industry output

For comparing socioeconomic development level in different regions in China, we classified all the 31 provincial capital cities of mainland China into four economic regions including East Coast (East), Central China (Central), Northeastern China (Northeast), and Western China (West), according to strategies promulgated by the Central People’s Government [40]. The ratio of annual air pollutant concentration to GRP per capita (c PM₁₀/GRP per capita, c SO₂/GRP per capita, and c NO₂/GRP per capita) was calculated year by year for each region. Hereafter, the line trend plots of the ratios were constructed to illustrate the variation of energy efficiency during 2003 to 2012.

4. Analysis associated with EKC

In order to investigate whether EKC exists in China, regression methods were applied to the panel data of GRP per capita and pollutants’ indicators in all provincial capital cities. We also conducted regression fitting for the four economic regions for further information. The relationships between air pollutants and GRP per capita were estimated by the simplified EKC model provided below, which was also described by Agras et al. [41] and Li et al. [42]:

\[ E_{ij} = \gamma_0 + \beta_1 X_{ij} + \beta_2 X_{ij}^2 + \beta_3 X_{ij}^3 \]

Where \( E \) is the concentration of air pollutant; \( X \) is GRP per capita; \( \gamma_0 \) is a fixed effect; \( \epsilon_{ij} \) is a stochastic error term; \( i \) is a region index (region values are “East, Central, Northeast, West and All provincial capital cities”); \( j \) is an air pollutant indicator (PM₁₀, SO₂, NO₂ or API); \( \beta_1, \beta_2, \beta_3 \) are the coefficient for the income variable, for the income squared variable and for the income cubic term, respectively.

5. Statistical analysis

All the regression analysis related to air pollutants and socioeconomic indicators was performed with SPSS for Windows (IBM SPSS statistics; Version 20). The effect of a certain variable was considered statistically significant for \( P < 0.05 \). Annual mean values of data used for trend analysis of energy efficiency between 2003 to 2012 were calculated by Excel 2010.
Table 1. Regression for concentration of PM$_{10}$, SO$_2$, NO$_2$ and the three main industries.

| Described Relationship | Model | n   | $R^2$ | SE  | Sig.  | Independent variable | Constant |
|------------------------|-------|-----|-------|-----|-------|----------------------|----------|
| PM$_{10}$ Linear       | 0.147 | 0.026 | 0.000** | 0.000** | Primary industry |
| & Quadratic            | 0.178 | 0.025 | 0.000** | 0.000** | Primary industry |
| & Quadratic            | 0.163 | 0.020 | 0.000** | 0.000** | Primary industry |
| SO$_2$ Linear          | 0.141 | 0.020 | 0.000** | 0.000** | Primary industry |
| & Quadratic            | 0.163 | 0.020 | 0.000** | 0.000** | Primary industry |
| & Quadratic            | 305   | 0.020 | 0.000** | 0.000** | Primary industry |
| NO$_2$ Linear          | 0.004 | 0.013 | 0.280 |       |                   |
| & Quadratic            | 0.007 | 0.013 | 0.348 |       |                   |
| Primary industry       | 0.016 | 0.013 | 0.172 |       |                   |

* P<0.05; ** P<0.01

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Results

1. Relationship between air pollutants and the three main industries in Chinese cities

Analysis on the provincial capital cities illustrated quadratic relationships between concentration of NO$_2$ and the output per capita of secondary and tertiary industries (Table 1, Fig. 1). The NO$_2$ concentration rose with the increase of the output per capita of the secondary and tertiary industries at the first stage, then began to decrease when the output reached around 45,000 and 70,000 yuan respectively. However, there was no remarkable relationship between that of the primary industry and the NO$_2$ concentration. The results also indicated that all the three industries had significantly negative relationship with the concentration of PM$_{10}$ and SO$_2$.

2. Variation of efficiency ratio in recent years

The ratio of the air pollutant concentration to GRP per capita (cPM$_{10}$/GRP per capita, cSO$_2$/GRP per capita and cNO$_2$/GRP per capita) had a steady declining trend in the four economic regions, especially in the western mainland China, showing a notable enhancement of energy efficiency (Fig. 2). The cPM$_{10}$/GRP per capita ratio fell from 0.103 mg m$^{-3}$ (ten thousand yuan)$^{-1}$ in 2003 to 0.018 in the year of 2012 by 470% in the West, from 0.064 to 0.015 in the Northeast by 320%, from 0.081 to 0.014 in the Central by 470%, and from 0.043 to 0.009 mg m$^{-3}$ (ten thousand yuan)$^{-1}$ in the East by 370%. The ratios of cSO$_2$/GRP per capita and cNO$_2$/GRP per capita also showed analogous disparity among the four regions, with the variation range of efficiency ratio the smallest in the East (Fig. 2).
3. EKC analysis in all the provincial capital cities and the four economic regions

The relationship between air pollutants and GRP per capita in all the provincial capitals is presented in Fig. 3. The concentration of PM\textsubscript{10} and SO\textsubscript{2} or API had a significantly negative linear relationship with GRP per capita; meanwhile the concentration of NO\textsubscript{2} had a quadratic relationship with GRP per capita. However, the relationship between air pollutants and GRP per capita was not the same for the four economic regions (Table 2, 3). The PM\textsubscript{10} concentration was significantly related to GRP per capita only in the Central. Similarly, API was also significantly related to GRP per capita only in the Central. The SO\textsubscript{2} concentration had significant negative linear relationship with GRP per capita in the Central but positive linear relationship in the Northeast. The NO\textsubscript{2} concentration was positively related to the GRP per capita in the Central, West, and quadratic for the East region, but not significantly related to that in the Northeast.

Discussion

1. The relationship between the three main industries and air pollutants

Our results (Fig. 1) showed the quadratic relationship between the secondary and tertiary industries and NO\textsubscript{2} in the provincial capital cities of China. The increase of NO\textsubscript{2} concentration was probably caused by the continuous increase of civil vehicles (The civil vehicles number increased from 1.36 million to 78.0 million according to the National Bureau of Statistics) and the widespread use of transportation in many fields such as tourism. This was in agreement with the point of view ascribing anthropogenic pollution to combustion of fossil fuels [43–44]. Fortunately, the concentration of NO\textsubscript{2} began to descend as the output of secondary and tertiary industries came to a certain level, probably due to the increasing energy efficiency (Fig. 2) and environmental-friendly measurements such as transportation control during traffic peaks [45]. Different from NO\textsubscript{2}, the concentration of PM\textsubscript{10} and SO\textsubscript{2} decreased with the increase of the industry output per capita, which could also be explained by the improved energy efficiency. The negative relationship between the output per capita of tertiary industry and PM\textsubscript{10} and SO\textsubscript{2} might, to a large part, attributable to the rapid development of low-energy-consumption industries such as high-tech industry, though this explanation needed further confirmation. Besides, unadvanced managements such as straw burning were restricted in suburbs with the improved living standard in cities [46], which also helped to decrease the concentration of PM\textsubscript{10} and SO\textsubscript{2}.

2. Variation of energy efficiency in Chinese cities

The results showed that pollutant emissions at every ten thousand yuan fell with sustainable growth of GRP in the provincial capital cities from 2003 to 2012 (Fig. 2), which was coincident with the improvement in energy and technology in Chinese industries [47–48]. Besides, there was a distinct difference between the high income regions and less developed ones: the more developed cities had lower concentration of air pollutants with smaller variation ranges than the less developed cities. This was probably because of the lower energy intensity and more advanced technology [49–50] as well as better-implemented environment-friendly policies [51] in developed cities like Beijing.

3. The EKC in China

The relationship curves of social economy and some air pollution indicators in a period of time present different shape at different stages of development level of the country or state [52]. SO\textsubscript{2} per capita, for instance, seemed to tail off in 12 selected European countries when GRP per capita reached around 10000
dollars. Consequently, the relationship curve of SO\textsubscript{2} per capita and GRP per capita appeared a declining trend [53]. Besides, the relationship curve of one air pollutant varied from another for its particular features. Carbon emissions like CO\textsubscript{2} was found to increase at ever-decreasing rates, with predicted peaks beyond reasonable income level because of its cross-border externalities which result in no sufficient incentives to urge countries to regulate emission [18, 54–55]. These findings remind us to view the relationship of economy and air pollution with consideration of the time period and specific air pollutants [52, 56–57].

In the national scale, our results showed a negative relationship between GRP per capita and PM\textsubscript{10}, SO\textsubscript{2} or API while inverted-U shape relationship with NO\textsubscript{2} (Fig. 3). The EKC did exist for Chinese cities because the concentration of PM\textsubscript{10} and SO\textsubscript{2} stop rising from mid-1990s [58]. However, the turning point of EKC for air pollutants seemed to vary with the place, or, with the economical level. Taking SO\textsubscript{2} as an example, the turning point of EKC was approximately 20 thousand yuan in Changsha-Zhuzhou-Xiangtan Urban Agglomeration [59], but 37 thousand in Beijing [60]. Peng & Bao [61] reported a national EKC knee point of around 36 thousand yuan, close to that of 30 thousand yuan claimed by Li et al [62]. Though we lacked data about SO\textsubscript{2} concentration before 2003, our analysis made an estimated turning point of less than 30 thousand yuan, also consistent with other results.

Such EKC pattern was probably caused by the following: (1) The structure of Chinese economy has changed from energy-intensive heavy industry to a more market-oriented service-based economy [62], which, with its lower environmental damage [25], helped China in ameliorating the environment rather than aggravating pollution. Furthermore, in order to stay competitive, firms are keen on investing new and improved technology to enhance cost effectiveness. One of the most significant consequences of this trend is an improvement in resource use efficiency within industrial sector which cut the industrial energy intensity by 50 percent during 1990s [62]. (2) Citizens’ environmental awareness is improved. As Chinese people get richer and more educated, they become more concerned about the ambient

Figure 3. Regression curves between GRP per capita and air pollutant index (PM\textsubscript{10}, SO\textsubscript{2}, NO\textsubscript{2}, API) in all the provincial capital cities during 2003–2012. The blue line is the regression line and the pink area the 95% confidence limits.
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Table 2. Regression for concentration of PM$_{10}$, SO$_2$, NO$_2$, API and GRP per capita (panel data of all provincial cities).

| Region                  | Relationship | Model summary | Coefficients T test | | | |
|-------------------------|--------------|---------------|---------------------|---|---|---|
| Described              | Regression   | n | R | SE | Sig. | Independent variable | Constant | |
| PM10                   | Linear       | 0.187       | 0.027 | 0.001** | 0.001** | 0.000** | |
|                        | Quadratic    | 305         | 0.187       | 0.027 | 0.005** | 0.267 | 0.000** | |
| GDP per capita         | Cubic        | 0.204       | 0.027 | 0.005** | 0.076 | 0.000** | |
| SO2                    | Linear       | 0.194       | 0.021 | 0.001** | 0.001** | 0.000** | |
|                        | Quadratic    | 305         | 0.194       | 0.022 | 0.003** | 0.439 | 0.000** | |
| All GDP per capita     | Cubic        | 0.213       | 0.021 | 0.003** | 0.084 | 0.000** | |
| Provincial City        | NO2          | Linear       | 0.344       | 0.012 | 0.000** | 0.000** | 0.000** | |
|                        | Quadratic    | 305         | 0.361       | 0.012 | 0.000** | 0.000** | 0.000** | |
| GDP per capita         | Cubic        | 0.363       | 0.012 | 0.000** | 0.361 | 0.000** | |
| API                    | Linear       | 0.155       | 14.327     | 0.007** | 0.007** | 0.000** | |
|                        | Quadratic    | 305         | 0.155       | 14.260 | 0.026* | 0.346 | 0.000** | |
| GDP per capital        | Cubic        | 0.179       | 14.277     | 0.021* | 0.071 | 0.000** | |

* P<0.05; ** P<0.01.

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Table 3. Regression for concentration of PM$_{10}$, SO$_2$, NO$_2$, API and GRP per capita.

| Region          | Relationship | Described | Regression Coefficients | T test | Coefficients | T test | Independent variable | Constant |
|-----------------|--------------|-----------|-------------------------|--------|--------------|--------|----------------------|----------|
| PM$_{10}$       | Linear       | 0.078     | 0.030                   | 0.441  |              |        |                      |          |
|                 | Quadratic    | 100       | 0.192                   | 0.030  | 0.163        |        |                      |          |
| GDP per capita  | Cubic        | 0.192     | 0.030                   | 0.305  |              |        |                      |          |
| SO$_2$          | Linear       | 0.096     | 0.022                   | 0.343  |              |        |                      |          |
|                 | Quadratic    | 100       | 0.228                   | 0.022  | 0.076        |        |                      |          |
| East GDP per capita | Linear     | 0.228     | 0.022                   | 0.161  |              |        |                      |          |
| SO$_2$          | Linear       | 0.096     | 0.022                   | 0.000**| 0.000**      | 0.000**|                      |          |
|                 | Quadratic    | 100       | 0.228                   | 0.022  | 0.076        |        |                      |          |
| GDP per capita  | Cubic        | 0.495     | 0.013                   | 0.000**| 0.016*       | 0.164  |                      |          |
| NO$_2$          | Linear       | 0.383     | 0.014                   | 0.000**| 0.000**      | 0.000**|                      |          |
|                 | Quadratic    | 100       | 0.497                   | 0.013  | 0.076        |        |                      |          |
| GDP per capita  | Cubic        | 0.283     | 6.517                   | 0.129  |              |        |                      |          |
| API             | Linear       | 0.285     | 6.633                   | 0.318  |              |        |                      |          |
|                 | Quadratic    | 100       | 0.285                   | 6.633  | 0.318        |        |                      |          |
| PM$_{10}$       | Linear       | 0.449     | 0.018                   | 0.000**| 0.000**      | 0.000**|                      |          |
|                 | Quadratic    | 60        | 0.465                   | 0.018  | 0.001**      | 0.050* |                      |          |
| GDP per capita  | Cubic        | 0.474     | 0.018                   | 0.002**| 0.070        | 0.000**|                      |          |
| SO$_2$          | Linear       | 0.297     | 0.019                   | 0.021* | 0.021*       | 0.000**|                      |          |
|                 | Quadratic    | 60        | 0.332                   | 0.019  | 0.036*       | 0.063  |                      | 0.000**  |
| Central GDP per capita | Cubic     | 0.391     | 0.019                   | 0.082  |              |        |                      |          |
| NO$_2$          | Linear       | 0.386     | 0.010                   | 0.002**| 0.002**      | 0.000**|                      |          |
|                 | Quadratic    | 60        | 0.386                   | 0.010  | 0.001**      | 0.464  |                      | 0.000**  |
| GDP per capita  | Cubic        | 0.405     | 0.010                   | 0.018* | 0.024        | 0.116  |                      |          |
| API             | Linear       | 0.449     | 9.204                   | 0.000**| 0.000**      | 0.000**|                      |          |
|                 | Quadratic    | 60        | 0.465                   | 9.917  | 0.001**      | 0.050* |                      | 0.000**  |
| GDP per capita  | Cubic        | 0.474     | 9.230                   | 0.002**| 0.871        | 0.000**|                      |          |
| PM$_{10}$       | Linear       | 0.283     | 0.013                   | 0.129  |              |        |                      |          |
|                 | Quadratic    | 30        | 0.285                   | 0.013  | 0.318        |        |                      |          |
| GDP per capita  | Cubic        | 0.296     | 0.013                   | 0.490  |              |        |                      |          |
| SO$_2$          | Linear       | 0.463     | 0.012                   | 0.010**| 0.010**      | 0.000**|                      |          |
|                 | Quadratic    | 30        | 0.463                   | 0.013  | 0.038*       | 0.642  |                      | 0.013*   |
| Northeast GDP per capita | Cubic     | 0.465     | 0.013                   | 0.091  |              |        |                      | 0.000**  |
| NO$_2$          | Linear       | 0.333     | 0.009                   | 0.072  |              |        |                      |          |
| Region          | Relationship | Model    | n   | R    | SE   | Sig. | Independent variable | Constant  |
|-----------------|--------------|----------|-----|------|------|------|----------------------|-----------|
|                 | &            | Quadratic| 30  | 0.334| 0.010| 0.202|                      |           |
| GDP per capita  | Cubic        |          |     |      |      |      |                      |           |
|                 |              |          |     | 0.348| 0.010| 0.332|                      |           |
| API             | Linear       |          |     |      |      |      |                      |           |
|                 |              |          |     | 0.283| 6.517| 0.129|                      |           |
|                 | &            | Quadratic| 30  | 0.285| 6.633| 0.318|                      |           |
| GDP per capita  | Cubic        |          |     |      |      |      |                      |           |
|                 |              |          |     | 0.296| 6.737| 0.490|                      |           |
| PM$_{10}$       | Linear       |          | 115 | 0.149| 0.030| 0.113|                      |           |
|                 |              |          |     |      |      |      |                      |           |
| PM$_{10}$       | Quadratic    |          | 115 | 0.161| 0.031| 0.230|                      |           |
| &               | Cubic        |          |     | 0.184| 0.031| 0.227|                      |           |
| SO$_2$          | Linear       |          |     | 0.169| 0.023| 0.071|                      |           |
|                 | &            | Quadratic| 115 | 0.222| 0.022| 0.059|                      |           |
| West            | GDP per capita| Cubic   |     | 0.225| 0.022| 0.122|                      |           |
| NO$_2$          | Linear       |          |     | 0.211| 0.012| 0.024*| 0.024*                | 0.000**   |
|                 |              |          |     |      |      |      |                      |           |
| NO$_2$          | Quadratic    |          | 115 | 0.233| 0.012| 0.044*| 0.087                | 0.000**   |
| &               | Cubic        |          |     | 0.251| 0.012| 0.065|                      |           |
| API             | Linear       |          |     | 0.152| 15.321| 0.104|                      |           |
| &               | Cubic        |          |     | 0.166| 15.354| 0.208|                      |           |
| GDP per capita  |              |          |     | 0.190| 15.356| 0.250|                      |           |

Only significant P-values of T test are listed.

* P<0.05; ** P<0.01.

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At this time, their behaviors to protect environment and striving for more governmental support to do so contribute to the emergence of EKC [64,66]. For example, a gigantic demonstration against production of p-xylene in Dalian on August 14th, 2011 [67] reflected the strong demand for better living environment. (3) Regulatory policy for environmental protection has been established and effectively implemented, which is another important factor to spur EKC [68-69]. In China, the first law against air pollution took into effect in 1987 and was amended in 1995 and 2000. The environment-friendly measures conducted by the government also provide significant support to air quality. The central government, for example, adopted drastic new pollution control measures for town and village industrial enterprises (TVIEs) and closed 65,000 high-pollution TVIEs in a national campaign in 1996. Therefore, with strict and effective regulatory measures, air pollutants such as SO2, soot and industrial fugitive dust began to decrease since mid-1990s [57]. It’s believed that the environment will continue to improve with Chinese central government policies making efforts to promote ecological progress [70]. However, the rise of the SO2 concentration in the Northeastern China simultaneous with the enhancement of civil revenues in this area (Fig. 4) might be a result of the policy of “revitalizing the old Northeast industry” by the Central Government [71].

The emergence of the knee point of EKC in the developed cities of Eastern China may be a result of well-implemented environmental policies and high investment in pollution control. But in the meantime, the Central and Northeast regions did not show a

Figure 4. Regression curves between GRP per capita and air pollutant index (PM10, SO2, NO2, API) in four economic regions during 2003–2012. The blue line is the regression line and the pink area the 95% confidence limits.

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downward trend of NO$_2$ concentration (Fig. 4), which was probably attributable to the growing impact of vehicular emissions [51,72]. NO$_2$ is one of the dominant components in vehicle exhaust [73]. The ever-increasing civil vehicles, particularly the surge of vehicles in the cities after 2000, probably emit enough NO$_2$ to compensate the decrease of the pollutant from technical advancement of the industries [74]. It would be difficult to decrease NO$_2$ concentration in most cities if civil vehicles continue to increase in the near future, despite the controlling measures already taken [75].

Since API is a simple and generalized indicator, its variation can reflect the general trend of air pollutants. The negative linear trend of API and GRP per capita in the Central region (Fig. 4) was probably attributable to the overall decreasing trend of the three categories of air pollutants (Fig. 3) [76].

It is worth noticing air pollutants were not significantly related to GRP per capita in any of the four economic regions. Since the classification criterion of the four economic regions was not only the economic development level but also including geographical location, variance of economic levels within a region might obscure the relationship between air pollutants and GRP per capita. Some detailed classification is needed to improve the accuracy of analysis.

Comparative qualitative analysis of the world also illustrated the existence of EKC and pointed out the developmental status of China in the world scale (Fig. 5 and Table 4). Two comparative

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**Figure 5. Maps of world PM$_{2.5}$ (µg m$^{-3}$) and GRP per capita ($) during 2001 to 2006.** (a) PM$_{2.5}$, downloaded from NASA website and reproduced with permission from its authors and publisher (van Donkelaar et al., 2010); (b) GRP per capital, derived from the World Development Indicators of the World Bank (http://data.worldbank.org/country). doi:10.1371/journal.pone.0104013.g005
they are still at the very early stage of economic development. Of course there are other factors which bring them seasonal dry, dust-laden winds known as Harmattan [80]. As for the undeveloped countries, most of them have already accomplished the transition of industrialization because of the following two reasons: (1) The developed countries have already accomplished the industrialization which is currently taking place in developing countries like China [77]. (2) The developed countries possess more environment-friendly technology to enhance energy efficiency and reduce pollution [78,79]. Developed countries in the Europe, Oceania and North America, which brings them seasonal dry, dust-laden wind as Harmattan [80]. Of course there are other undeveloped countries with low level of pollutants, simply because they are still at the very early stage of economic development.

Conclusions

The quadratic relationship between the concentration of NO$_2$ and the output per capita of the secondary or tertiary industry, as well as the negative correlation between the concentration of PM$_{10}$, SO$_2$ and industry output per capita, indicate the declining trend of the pollutant concentrations with the improvement of energy efficiency and implementation of environment protection policies. With technology innovation and modulation in industries together with policy implementation from 1990s, ratios of pollutants to GRP in the 31 provincial capitals in mainland China shows a downward trend. Such negative or invert-U quadratic relationship curve between air pollutants and GRP per capita verifies the existence of EKC in China.

Supporting Information

Figure S1 A hazy day (a: January 29, 2013) and a fine day (b: February 1, 2013) in downtown Beijing. (Pictures from http://ndphotos.oeccc.com/album/201302/01/2140.html?id=1).

Table S1 Emission inventories of provincial cities in mainland China.

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Author Contributions

Conceived and designed the experiments: HC YPL QAZ CHP. Analyzed the data: YPL. Contributed reagents/materials/analysis tools: YPL YZY GY. Wrote the paper: YPL GY.

Table 4. Concentration of PM$_{10}$ in cities of different continents.

| Continent | Country (time period) | Mean PM$_{10}$ concentration (mg m$^{-2}$) | Scale | Reference |
|-----------|-----------------------|-------------------------------------------|-------|-----------|
| Asia      | China (2003–2010)     | 0.1056 ± 0.0259                           | National | This study |
|           | Japan (2007–2008)     | 0.0151 ± 0.0078                           | Yokohama | [81]       |
| Africa    | India (1998–1999,2002)| 0.2317 ± 0.0815                           | New Delhi | [82]       |
|           | South Africa (winter of 1997) | 0.0933 ± 0.0188 | National | [83]       |
|           | Tanzania (2005)       | 0.0510 ± 0.0210                           | National | [84]       |
|           | Guinea (2004)         | 0.1453 ± 0.1092                           | Conakry  | [85]       |
| South America | Brazil (2008)     | 0.064 ± 0.0190                           | São Paulo | [86]       |
|           | Argentina (2008)      | 0.0470 ± 0.0120                           | Buenos Aires |         |
|           | Columbia (2008)       | 0.0640 ± 0.0490                           | Bogotá   |           |
| Europe    | (1992–2009)           | 0.0306 ± 0.0084                           | Continental | [87]  |
|           | Netherlands (1985–2008)| 0.0180                                     | Rotterdam | [88]       |
|           | Greece (1999–2000)    | 0.0755 ± 0.0275                           | Athens    | [89]       |
|           | Germany (2002–2005)   | 0.0663 ± 0.0105                           | National  | [90]       |
| North America | US (1992–2009)         | 0.0276 ± 0.0081                           | National  | [87]       |
|           | Canada (1993–2009)    | 0.0155 ± 0.0052                           | National  | [91]       |
| Oceania   | Australia (1998–2001) | 0.0175 ± 0.0018                           | National  | [92]       |
|           | New Zealand (1999–2007)| 0.0299 ± 0.0132                           | National  | [92]       |

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"World Map" in Fig. 5 identified the existence of EKC at the global level. Emerging economics like China and India have the highest concentration of PM$_{2.5}$, PM$_{10}$, S O$_2$ and industry output per capita, indicate the declining relationship curve between air pollutants and GRP per capita together with policy implementation from 1990s, ratios of pollutants to GRP in the 31 provincial capitals in mainland China shows a downward trend. Such negative or invert-U quadratic relationship curve between air pollutants and GRP per capita verifies the existence of EKC in China.
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