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Co-control of CO_2 and SO_2 Emissions in the Key Environmental Protection Prefectures in China

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Foreword »

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Since its opening-up and reform, China has been in the process of rapid economic development with its people enjoying an increasingly improved standard of life. Meanwhile accompanying this dramatic economic growth is the degradation of environment which has, to some extent, damaged the gains of the opening-up and reform and prevented the economy from a healthy and sustainable development. The Chinese government is increasingly aware of that without addressing the environmental issues it is facing now, will jeopardize its long term goal of the great rejuvenation of the Chinese nation. Given the magnitude and complexity of the environmental issues in China, there is no easy way in addressing them and the solution to them entails an equal priority being given to environmental protection, ecological conservation and economic development or even higher than the latter by mainstreaming the former into the overall socio-economic decision-making process. As a matter of fact, China has been in the struggle against environmental pollution since the very beginning of its economic take-off and trying to explore a pathway that could help address China's environmental issues in the way most suitable to China's specific circumstances.

In recent years, especially since the 12th Five-Year Plan period, the enhanced measures including legislation, policy, regulatory and economic means have been taken by the Chinese government in dealing with environmental problems, of which environmental policies have played an important role in this regard. Corresponding to this situation and in meeting the demand of governments at different levels for environmental policy tools, the environmental policy research projects on topics of a wide range have been conducted by some Chinese environmental research institutions including the Chinese Academy for Environmental Planning (CAEP).

CAEP founded in 2001, is a research advisory body supporting governments in the development of key environmental planning, national environmental policies, and major environmental engineering projects. In the past more than 10 years, CAEP has accomplished the development of the overall planning of national environmental protection for the 10th, 11th and 12th Five-Year Plan periods; water pollution prevention and control planning for key river basins; air pollution prevention and control planning for key regions; soil pollution prevention and control planning; and some regional environmental protection plans. In the same period of time, CAEP also actively engaged in research on such topics as green GDP, environmental taxation, emission trading, ecological compensation, green financing, etc. By so doing, CAEP has become an indispensable advisory body in the environmental decision-making in mainland China. According to *2013 Global Go To Think Tanks Report and Policy Advice* published by University of Pennsylvania, CAEP was ranked 31 in the field of environment in the world. Many of CAEP's research results and project outcomes regarding environmental policies have drawn great attention of decision makers and international institutions, and have been utilized to contribute to the formulation of national environmental policies concerned.

The Chinese Environmental Policy Research Working Paper (CEPRWP) is a new internal publication produced by CAEP for the purpose of facilitating the academic exchange with foreign colleagues in this field, in which the selected research papers on environmental policies from CAEP are set out on the irregular basis. It is expected that this publication will not only make CAEP's research results on environmental policies be known by foreign colleagues but also serve as a catalyst for creating opportunity of international cooperation in the field of environmental policies, and environmental economics in particular, with a view of both the academic research and practical policy needs.

Chinese cities are facing serious environmental issues and climate change challenges at the same time. Because most energy in China is based on coal combustion, almost all air pollutants are related to carbon dioxide (CO_2) emission. Using the Emission Database for Global Atmospheric Research (EDGAR) database and prefecture boundary data, studies comparing CO_2 and sulfur dioxide (SO_2) emissions of 113 key environmental protection cities in China were conducted using statistical analysis. The results showed that significant correlation existed between CO_2 and SO_2 emissions in these cities. Clustering analysis showed that these cities could be categorized into four groups, with 57% of the prefectures emitting low CO_2 and SO_2 emissions. Obviously, clustering was observed in typical prefectures and agglomeration areas, such as the top ten cities for SO_2 emission in China; the CO_2 and SO_2 emissions from these ten cities accounted for 10.71% and 13.15% of the total national emissions, respectively, although these cities took up less than 3% of the country's land area. In the top ten cities of CO_2 emission in China, the CO_2 and SO_2 emissions accounted for 15.30% and 10.45% of the total national emissions, respectively, although these cities took up less than 2% of the country's land area. The implication of these findings for policymakers is that prefectures should be the focus of future strategies designed for the co-control of development, rather than concentrating only on the provinces. Prefectures with low CO_2 and SO_2 emissions or low CO_2/SO_2 ratios should be provided with incentives related to synergistic measures that can be used to achieve the dual control of CO_2 and SO_2 emissions at a lower cost.

Contents

1. INTRODUCTION

China is currently working to improve environmental conditions and develop a low-carbon economy, with the goal of achieving effective control of air pollution and greenhouse gas (GHG) emission. On one hand, after the signing of the Paris Agreement, China identified future action targets with the goal of reaching peak CO_2 emission around 2030 and striving to strengthen the response to climate change, including meeting China's National Independent Contribution (INDC) commitments. On the other hand, air pollution control has become a topic of general concern to communities and the public in China. The central government launched a system of nationwide inspections related to environmental protection, including the 2+26 cities environmental inspection plan and other action programs designed to deal with air pollution and promote environmental improvement.

The fifth assessment report of the United National Intergovernmental Panel on Climate Change (IPCC) noted that climate change mitigation measures had a strong synergistic effect on reduction of pollutant emission. Mitigation measures designed to address the reduction of GHG emission will have a significant effect on reducing pollutant levels, which will create a more obvious synergistic effect, especially in the areas where pollution is relatively severe in developing countries. However, as environmental management improves and environmental standards of developing countries become more stringent, the environmental benefits of mitigating climate change will gradually decrease. The ratio of SO_2 (in kg) to CO_2 (in tons) in Asian countries has fallen from 6.4 in 2000 to 3.9 in 2010. The effect of climate change on pollutant emissions and air quality is closely related to the stringent environmental policies and management plans that have already been implemented. For example, in areas where SO_2 emissions are relatively loosely controlled, the synergistic effects of emission reductions and climate policy would be significant. In areas where SO_2 emissions are very stringently controlled, there is hardly any synergistic effect of climate policies and reduction of SO_2 emission. On a global scale, monetary mitigation of climate change ranges from \$2 to \$420 (2010) per ton of CO_2, and the benefits to developing countries are twice as high as to developed countries. The gap between developing and developed countries mainly occurs because developing countries have lower levels of air pollution control and higher pollutant emissions, thus there is a greater potential to improve environmental conditions in them.

Domestic and foreign scholars studied on the co-control of local air pollutants and CO_2 emission in China and concluded that many climate policies in China had great potential for synergetic reduction. Some scholars assessed the reduction potentials of greenhouse gas and pollutant reduction technologies in the key industries such as steel, power, cement and other industries. Peng et al. studied co-control of air quality and CO_2 emission in different industries in China and evaluated the potential benefits of four sectoral mitigation strategies. All strategies included 80% replacement of small coal power plants with larger more efficient ones, 10% improvement in energy efficiency, replacement of high emitters with average vehicle fleet emissions, and replacement of 20% of coal-based stoves with stoves using liquefied petroleum gas. They found that the improvement of air quality and human health of 10% improvement of energy efficiency was largest and carbon emission reduction was 3 times higher than other strategies. Many researchers studied co-control analysis at provincial level and city level. Mr. Dong and his team predicted the future CO_2 emission and air pollutants (SO_2, NO_x and PM) in all provinces of China in future by using the AIM / CGE model and the GAINS model and found higher co-control air pollutants and CO_2 emission in the provinces with high GDPs or in the energy production base. Cheng et al. studied the effects of different carbon emission reduction policies on four industries, electric power industry, smelting industry, cement industry and iron and steel industry in Guangdong Province through the dynamic Computable General Equilibrium (CGE) model. The research showed that carbon caps policy could reach the goal of emissions reduction and energy savings.

Many researchers in China and abroad have analyzed synergism between CO_2 emission and air pollutants based on the levels of urban pollution and relatively high spatial resolution remote sensing data using spatial grids. Akimoto et al. studied emission-related and hot-spot areas of CO_2 and SO_2 emissions based on 1° × 1° spatial resolution data in Asia. Parrish et al. studied the correlation between GHG emission policies and air quality, suggesting that if GHG control policies, which started in 2005, remained unchanged, the air quality in many parts of the world would decline significantly by 2050. Between 2025 and 2050, concentrations of NO_2, SO_2, and $PM_{2.5}$ in East Asia have been forecasted to reach high levels, and concentrations of O_3 in northern India and the Arabian Gulf have been forecasted to increase significantly. That study used the Multiple Pollutants Index (MPI) to determine that regions with relatively high temperatures may have poor air quality in the future. Although the MPI in the densely populated areas of the northern hemisphere is predicted to be higher, the future air quality in eastern China, northern India, and in the Middle East and North Africa is predicted to be the worst.

Using estimates of domestic pollution, synergistic reductions of GHG emission, and benefit analysis based on an industry point of view, Mao et al. studied the synergistic effects of the reduction of sulfur, nitrogen, and carbon emissions during in an environmental and economic path analysis for China's power industry. Gao et al. studied synergistic emission reduction paths for urban traffic air pollutants and GHGs. The present study tries to use CO_2 emission data on a global 0.1° grid (about 10 km in the middle latitude area) in the EDGAR database to analyze the CO_2 and SO_2 emissions from a statistical point of view. Spatial, economic, and social data were combined from 113 key cities in China, and the spatial characteristics of CO_2 emission in China's urban areas and their correlation with SO_2 emission indicated a synergistic effect of CO_2 and SO_2 emissions in China.

2. DATA AND METHODOLOGY

2.1 Key environmental protection cities

Based on the analysis of the situation related to urban air pollution in 2000, the Chinese government designated a total of 113 key environmental protection cities and targeted them for air pollution control during "the Eleventh Five-Year Plan" period. One principle according to the "People's Republic of China Air Pollution Control Law", article 17 the second paragraph stated that municipalities, provincial cities, coastal open cities, and key tourist cities should be included in the key environmental protection cities targeted for air pollution control and the 43 cities were designated as key environmental protection cities that were targeted for air pollution control. The other principle involves the analysis of the comprehensive economic capacity and environmental pollution status of 338 cities owing atmospheric environmental quality monitoring data and the commitment of the provincial people's government to the 2005 environmental quality standards. They selected special economic zones, prefecture-level cities achieving the goal of "the Tenth Five-Year Plan" of Acid rain and SO_2 pollution control, the cities over-discharged of the current atmospheric environmental quality pollution but reaching the goal in the future and the cultural and tourism cities to strengthen the protection. A total of 70 cities were designated as Key Air Pollution Control Cities (Table 1).

Table 1 113 key environmental protection cities

Provinces	Municipalities directly under the Central Government, Provincial Capitals, Coastal Open Cities, and Key Tourist Cities	Other key environmental protection cities
Municipalities directly under the Central Government	Beijing, Tianjin, Shanghai, Chongqing	/
Hebei	Shijiazhuang, Qinhuangdao	Tangshan, Baoding, Handan
Shanxi	Taiyuan	Changzhi, Linfen, Yangquan, Datong
Inner Mongolia	Hohhot	Baotou, Chifeng
Liaoning	Shenyang, Dalian	Anshan, Fushun, Benxi, Jinzhou
Jilin	Changchun	Jilin
Heilongjiang	Harbin	Mudanjiang, Qiqihar
Jiangsu	Nanjing, Suzhou, Nantong, Lianyungang	Wuxi, Changzhou, Yangzhou, Xuzhou, Zhenjiang
Zhejiang	Hangzhou, Ningbo, Wenzhou	Shaoxing, Huzhou
Anhui	Hefei	Ma'anshan, Wuhu
Fujian	Fuzhou	Quanzhou, Xiamen

Provinces	Municipalities directly under the Central Government, Provincial Capitals, Coastal Open Cities, and Key Tourist Cities	Other key environmental protection cities
Jiangxi	Nanchang	Jiujiang
Shandong	Jinan, Qingdao, Yantai	Zibo, Tai'an, Zaozhuang, Jining, Weifang, Rizhao
Henan	Zhengzhou	Luoyang, Anyang, Jiaozuo, Kaifeng, Pingdingshan, Sanmenxia
Hubei	Wuhan	Jingzhou, Yichang
Hunan	Changsha	Yueyang, Xiangtan, Zhangjiajie, Zhuzhou, Changde
Guangdong	Guangzhou, Zhanjiang	Shaoguan, Shenzhen, Zhuhai, Shantou
Guangxi	Nanning, Guilin, Beihai	Liuzhou
Hainan	Haikou	
Sichuan	Chengdu	Mianyang, Panzhihua, Luzhou, Yibin, Zigong, Deyang, Nanchong
Guizhou	Guiyang	Zunyi
Yunnan	Kunming	Qujing, Yuxi
Tibet	Lhasa	
Shaanxi	Xi'an	Xianyang, Yan'an, Baoji, Tongchuan, Weinan
Gansu	Lanzhou	Jinchang
Qinghai	Xining	
Ningxia	Yinchuan	Shizuishan
Xinjiang	Urumqi	Karamay

2.2 Data sources

The data used in this study were all from public data sources, and all data represented conditions in 2008. These data included CO_2 emission data from the EDGAR database, the city SO_2 emission data from China's 2008 Environmental Statistical Yearbook, and other socio-economic data from China's 2009 Urban Statistical Yearbook.

China's 2008 Environmental Statistical Yearbook provided detailed statistics related to SO_2 emission from the country's 113 key cities, including industrial and residential SO_2 emission. SO_2 emission in key environmental protection cities totaled 11.47 million tons in 2008 and accounted for 49.4% of the total SO_2 emission nationally, including 9.88 and 1.49 million tons of industrial and residential SO_2 emission, respectively.

The EDGAR system is a joint project of the European Commission Joint Research Centre and the Netherlands Environmental Assessment Agency; it provides data of global anthropogenic emission of GHGs. The EDGAR database is currently the dataset available with the highest spatial resolution, including a near 10km spatial resolution CO_2 emission dataset for China. EDGAR calculates CO_2 emission and conforms to the methodology and emission source classification methods of the IPCC guidelines. Emissions for a country are calculated on an annual basis and based on sectors; the calculations are done by multiplying activity data by emission factors. The activity data are from International Energy Agency statistics from Organization for Economic Cooperation and Development (OECD) and non-OECD countries, while the emission factors are from the IPCC guidelines. We only considered the emissions from energy activities and industrial processes (non-combustion).

Emissions were allocated on a spatial grid of 0.1 degree to provide a gridded emission dataset. The EDGAR dataset used point/line emission sources, population density grids, and land use data at various resolutions as spatial proxies to prepare the gridded CO_2 emission data. EDGAR only counted direct CO_2 emission. Therefore, CO_2 emission analysis of prefectures in this article refer to direct CO_2 emission and do not include the indirect emissions that occur outside each prefectures' boundaries because of activities that occur within the prefectures. Extensive studies have been conducted based on the EDGAR database and have proven its value and reliability. Cai (2014) analyzed discrepancies between CO_2 emission data spatially aggregated data from EDGAR database and those calculated from official energy statistical data at the provincial level in China. The EDGAR dataset still has some problems related to uncertainties in spatial accuracy, although many studies have tested its quality and proved its values. Overall, the EDGAR data are quite consistent with China's provincial energy data. The integrity of this dataset provides more consistent and comparable results when applied at the prefecture level. The EDGAR gridded data combined with Chinese prefecture GIS vector data can be used to estimate CO_2 emission of prefectures in China. Based on the GIS spatial analysis platform, the sum of CO_2 emission of all grid cells that fall into each of geographical boundary of prefectures was calculated by the *Zonal Statistics tool* in ArcGIS (ESRI, Redlands, CA, USA). If a particular grid cell spatially overlaid more than one prefecture boundary, its emissions will be assigned to the prefecture that covered the largest part of that grid cell.

2.3 Analytic methods

In this paper, we adopted the spatial autocorrelation analysis method to study the spatial characteristics of CO_2 emission in China and its correlation with the urban spatial distribution. The global spatial autocorrelation index (Global Moran's I) and the local spatial autocorrelation index (Local Moran's I) were used to analyze the range of agglomeration-dispersion space of CO_2 emission in China and detect the hot spots of CO_2 emission. The value of Moran's index was between [-1, 1]. The value of Moran's index was close to 1 and Z-value>2.58 or Moran's index was close to -1 and Z-value<-2.58, which represented clustered similar property of spatial units or cluster different property of spatial units. The value of Moran's index is close to or equal to 0 and

Z-value was between -2.58 and 2.58, which indicated random distribution of the spatial units. Pearson correlation coefficients were adopted to determine the extent to which each prefecture's CO_2 emission were associated with SO_2 emission using SPSS software and t-test was used to test the significance of a correlation coefficient. Clustering analysis was conducted on 113 key environmental protection cities with two variables: CO_2 and SO_2 emissions per capita. The Self-Organizing Feature Maps (SOM) was adopted as the clustering method. The SOMs are trained using unsupervised learning to produce low dimensional data. The SOM method has strong unsupervised learning capability and nonlinear solving capability, which can best meet the clustering principle: i.e., maximize inter-group differences, minimize inter-group differences, and avoid subjectively setting group numbers. The SOM analysis was implemented based on MATLAB software.

3. RESULTS

3.1 Spatial pattern of CO_2 emissions

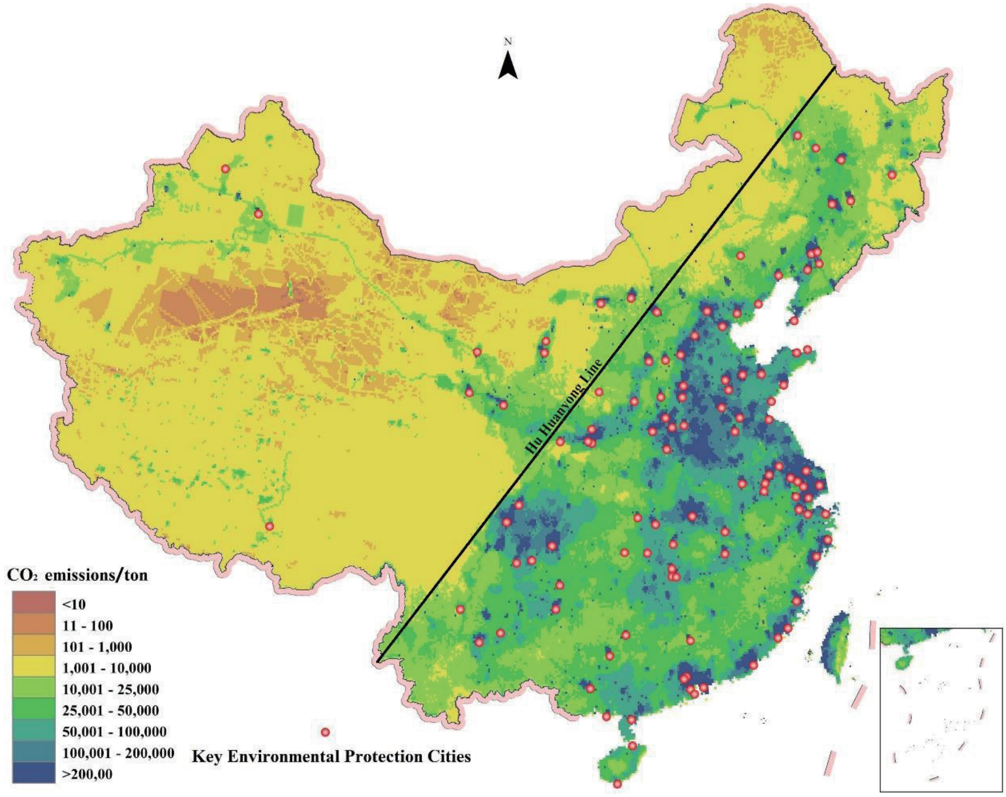
The spatial pattern of CO_2 emission in China was divided into eastern and western sides along Hu Huanyong line. The eastern side of Hu Huanyong line was obviously higher than the western side. Within the eastern side of Hu Huanyong line, the north China plain and the surrounding area of Shanghai was higher than other regions. The high emission grids tended to be concentrated on large cities such as Beijing, Shanghai, Chongqing, Chengdu, Wuhan, Xi'an, Zhengzhou and Guangzhou. The global Moran's index was 0.27 ($Z = 38.57$, $P < 0.01$), indicating that the spatial pattern of CO_2 emission in China had a significant positive correlation with the spatial resolution of 0.1° spatial autocorrelation. In other word, there was a significant spatial agglomeration effect rather than random spurious distribution. The conclusion verified that CO_2 emission in China were spatially clustered in typical cities.

Based on the local Moran index calculation, significant positive spatial correlation of CO_2 emission existed in some regions in China. In other word, CO_2 emissions in some regions were significantly affected by adjacent regions. The positive spatial correlation effect of the regions existed mainly in and around the mega-cities of Beijing, Shanghai, Guangzhou and Zhengzhou. The intense economic activities of these cities had led to the intensity of energy activities in surrounding areas, so CO_2 emission in these regions were higher than other regions. In addition, based on local Moran index, significant negative spatial correlations of CO_2 emission existed in some regions in China, such as southeastern regions of Shanxi Province and southeastern regions of Anhui Province. The former was an important source of energy output in China and the latter had not high energy consumption and high emission industries and did better for ecological conservation. CO_2 emissions in these two regions are in sharp contrast with the surroundings. The conclusion of spatial pattern of the CO_2 emission in the 0.1°resolution is basically the same with spatial pattern analysis of provincial-level carbon dioxide emission, as Xiao et al., Yao et al. and Zhao et al. studied. From the spatial analysis of CO_2 emission, we could find that key cities had substantial influences on CO_2 emission in China, which formed a spatial clustered pattern, while provincial-level cities didn't significantly affect the spatial pattern of CO_2 emission in China.

3.2 Correlation analysis between cities' CO_2 and SO_2 emissions

Based on CO_2 and SO_2 emissions data from the 113 key environmental protection cities, Figure 2 shows the results of correlation analysis between CO_2 and SO_2 emissions among the prefectures of China analyzed here. Both Pearson correlation coefficients passed the test of significance ($p < 0.01$). Based on emission mechanism in these prefectures, China's SO_2 emission were almost entirely from fossil fuel combustion. Similarly, more than 85% of CO_2 emission came from fossil fuel combustion, mainly from limestone calcination of cement kilns and lime kiln combustion processes. Land use changes and forest carbon sink were not considered. Therefore, most of China's SO_2 and CO_2 emissions occurred simultaneously and had the same sources. That is to say,

■ **Figure 1 Spatial distribution of CO_2 emission in China in 2008 with a 0.1° grid resolution**

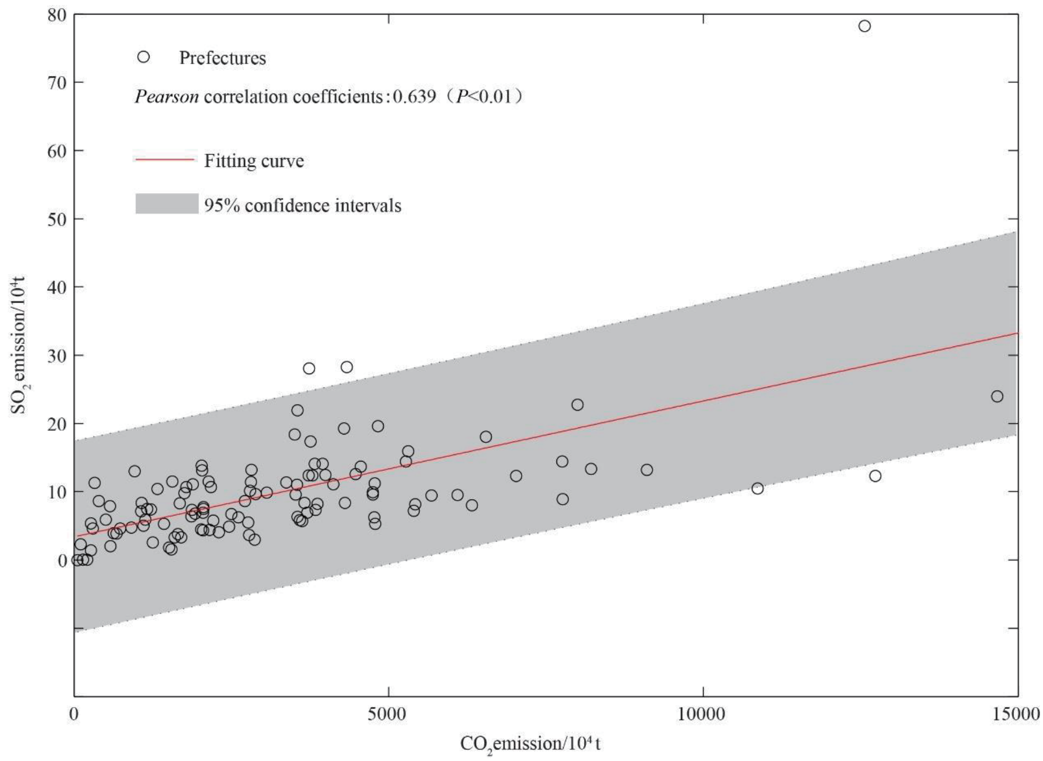


Note: The data are from the EDGAR database.

the mechanisms that led to SO_2 and CO_2 emissions were significantly correlated in China's prefectures.

The average value of the CO_2/SO_2 ratio in the 113 cities analyzed here was 452, which means, 1 ton of SO_2 was discharged for every 452 tons of CO_2 emission. This represents desulfurization related to the use of coal, fuel, and gas energy in the studied prefectures. Obviously, the CO_2/SO_2 ratio was different for each prefecture. Coals produced in China contain 1.1% sulfur and 65% carbon in average. Burning 1 ton of coal will discharge 0.022 tons of SO_2 and 2.347 tons of CO_2. Taking no account of desulfurization, the ratio of CO_2/SO_2 was 107 for one ton of coal, but this ratio reached 452 in the 113 key environmental protection cities. This phenomenon was partly because refined oil, natural gas, and other fossil fuels have a higher CO_2/SO_2 ratio than coal and gasoline. For example, burning 1 ton of gasoline discharges 0.001 tons of SO_2 emission (gasoline contains 500 mg/kg of sulfur) and 3.1 tons of CO_2, therefore, the ratio of CO_2/SO_2 is 3100. Meanwhile, burning 1 ton of diesel has a ratio of 750 since 1 ton of diesel contains 2000 mg/kg of sulfur. In addition, industrial desulfurization has significantly reduced SO_2 emission (in 2008, industrial SO_2 emission were 1,991 million tons, with the removal of 22.86 million tons), thus resulting a significant increase in the CO_2/SO_2 ratio.

■ **Figure 2 CO_2 and SO_2 emissions from 113 key environmental protection prefectures in China**



We analyzed CO_2 and SO_2 emissions in ten selected major prefectures. In Shanghai, Chongqing, Tianjin, and Suzhou, CO_2 and SO_2 emissions were in the top ten among the prefectures with these emissions in China. It shows these areas have a very high level of GHG and pollutant emissions. Comparing the ratio of CO_2/SO_2 in these prefectures, the overall CO_2/SO_2 ratio was low in the prefectures with high SO_2 emission and was high in the prefectures with high CO_2 emission. In addition to the differences in urban energy structure and the sulfur and carbon content of fossil fuels, prefectures with high CO_2 emission are basically developed cities with stronger desulfurization projects and measures, which also had a relatively high per capita GDP. Thus, SO_2 emission has been successfully reduced to a large extent in these cities. However, since the economic development still largely depended on fossil fuels, especially coal, CO_2 emission was still high, which resulted in a high CO_2/SO_2 ratio.

3.3 Clustering analysis on CO_2 and SO_2 emissions of 113 key environmental protection prefectures in China

In the two-dimensional space of CO_2 and SO_2 emissions per capita, the SOM method was used to cluster the prefecture area (Table 2 and Fig. 3), and the characteristics of CO_2 and SO_2 emissions of China's urban areas were identified. The optimal grouping was four. The significance of clustering results is shown in Table 3. The results show that the SOM method achieves the concept that the emission differences are the smaller within one group than the difference between groups. The clustering results were analyzed by an F test ($P < 0.01$).

Table 2 The features of prefecture-groups of SO_2 and CO_2 emissions

Groups	Average CO_2 emission per capita (ton/person)	Average SO_2 emission per capita (ton/person)	Numbers of prefectures	Typical prefectures
High CO_2 emission, high SO_2 emission	17.9	185.5	2	Shizuishan
High CO_2 emission, relatively high SO_2 emission	18.3	43.0	11	Hohhot
Low CO_2 emission, low SO_2 emission	4.1	18.5	64	Shenzhen
Relatively high CO_2 emission, relatively high SO_2 emission	8.6	24.6	36	Hangzhou

Table 3 The significance test of CO_2 and SO_2 emissions clustering in 113 key environmental protection prefectures

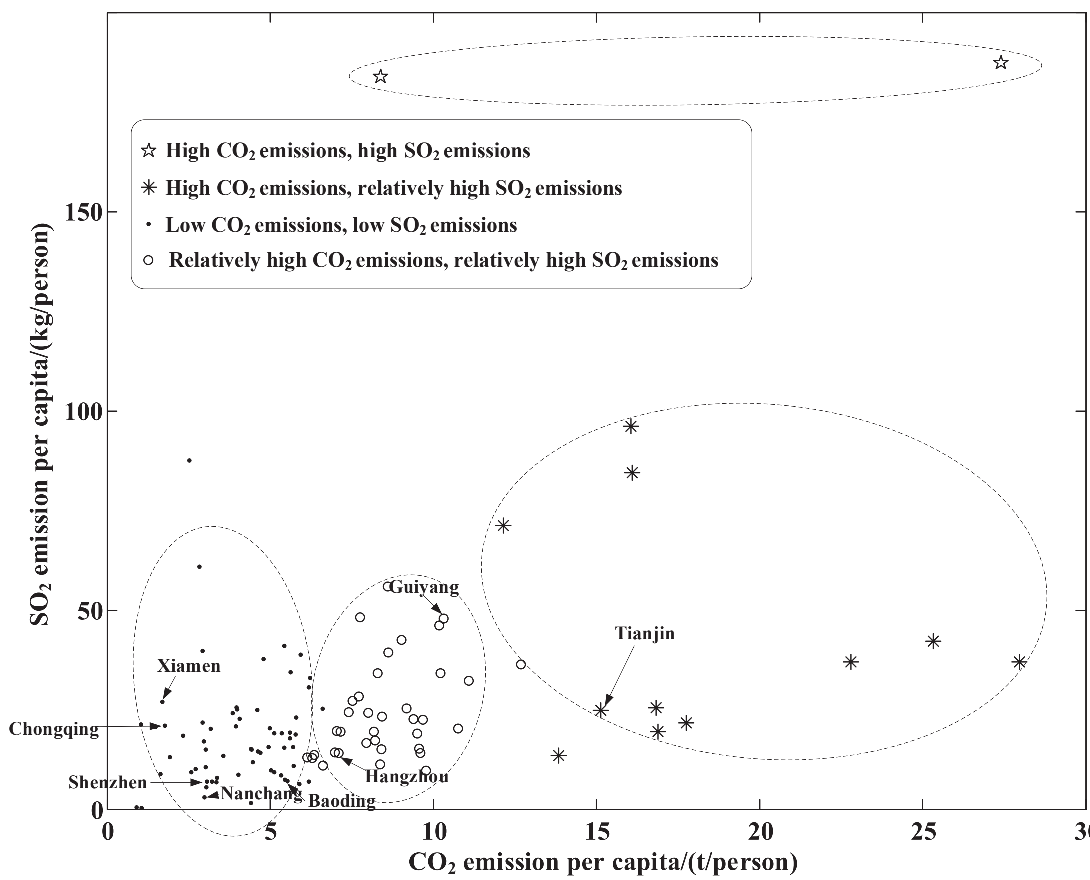
Variables	Classification	Sum of Squares	Degrees of Freedoms	Mean Square	F-test	P-value
CO_2 emission per capita	Between groups	2267.86	3	755.95	127.59	<0.01
	In groups	645.80	109	5.93		
	Total	2913.66	112	/	/	/
SO_2 emission per capita	Between groups	57748.22	3	19249.41	81.42	<0.01
	In groups	25769.38	109	236.42		
	Total	83517.60	112	/	/	/

Note: $P < 0.01$ was considered significant.

The clustering analysis results show that the 113 key environmental protection cities can be divided into four categories: those with high carbon and sulfur emissions, those with high carbon and relatively high sulfur emission, those with relatively high carbon and sulfur emissions, and those with low carbon and sulfur emissions. Shizuishan and Jinchang were the only two cities in the high-carbon emission and high-sulfur emission group; these two were resource-based heavy industrial prefectures in China. Few cities were identified in the high carbon and relatively high sulfur emission group of prefectures. They were basically heavy industrial or resource-based prefectures with Hohhot and Taiyuan as typical representatives. These prefectures have a proportion of heavy industry, and depend heavily on coal, which leads to relatively high per capita CO_2 and SO_2 emissions. In China, 36 prefectures had relatively-high sulfur and carbon emissions with Nanjing, Ningbo, and Hangzhou as relatively typical representatives. These prefectures are striving for active transition by gradually lowering their dependence on coal.

A majority of 64 prefectures are in the low-sulfur–and-carbon emission group, accounting for 57% of 113 key environmental protection prefectures. This group of prefectures can be divided into two categories. The first has a developed economy, a relatively high proportion of tertiary industry, and a dense population, such as Shenzhen, Xiamen and other cities. The second group has a relatively undeveloped economy, such as Yan'an, Jingzhou, and so on. The comparative analysis indicates the uneven development of key prefectures in China and large differences in CO_2 and SO_2 emissions between prefectures.

Figure 3 CO_2 and SO_2 emissions per capita of key environmental protection prefectures in China



Note: The figure was prepared for the National Development and Reform Commission of the first group of low-carbon pilot cities.

It is clear from the spatial pattern of CO_2 emission in China that the hot spots in CO_2 emission are basically concentrated in key environmental protection cities. The results of the global and local Moran indexes also show that the CO_2 emission in the region with key environmental protection cities had a significant positive spatial correlation effect. This shows that these prefectures have a very important effect on national CO_2 emission. In 2010, the National Development and Reform Commission decided to carry out the low-carbon pilot work in five provinces and eight cities, including cities of Baoding, Chongqing, Guiyang, Nanchang, Hangzhou, Shenzhen, Tianjin, and Xiamen (Figure 3). In 2011, the Development and Reform Commission issued an "Emission Trading Pilot Work Notice," and implemented a carbon emission trading pilot project involving the cities of Beijing, Chongqing, Shanghai, Shenzhen and Tianjin, as well as the provinces of Guangdong and Hubei. This shows that the central government of China attaches great importance to the role of cities in developing a low-carbon economy in China.

However, China is not only facing the challenge of developing a low-carbon economy, it's also facing challenges related to controlling the total amount of pollutants released and improving air quality. All air pollutants (SO_2, NOx, PM_{10}, etc.) are associated with CO_2 emission simultaneously, for they have the same sources in the coal-based energy structure of China. China will deal with climate changes and improve the environment quality together by actively taking synergistic measures.

4. CONCLUSIONS AND POLICY IMPLICATIONS

The spatial pattern of CO_2 emission in China indicated that emissions were mainly concentrated in certain key prefectures. Clustering analysis showed the CO_2 and SO_2 emissions of these prefectures could be categorized into four groups, with 57% of the prefectures in the low-CO_2-and-SO_2 emission groups. An obvious clustering was observed in typical groups of prefectures and agglomeration areas, such as the top ten cities with the highest level of SO_2 emission in China, the CO_2 and SO_2 emissions accounted for 10.71% and 13.15%, respectively, of the total national emissions for cities, which covered less than 3% of the land area in China. For the ten cities with the highest level of CO_2 emission with less than 2% of China's land area, the CO_2 and SO_2 emissions accounted for 15.30% and 10.45%, respectively, of the total national emissions for cities.

In the new round of urbanization and development in China, the prefectures need to further adjust and optimize their management systems and policy measures to deal effectively with climate change. Urbanization creates problems related to lack of a sufficient energy supply. It also affects and often exceeds the environmental carrying capacity for pollutants, creating serious pollution problems and other issues. China needs to address the new global challenges brought about by climate change. China covers a very large area, and large differences exist among the provinces. The spatial pattern of CO_2 emission in China is strongly affected by the locations of key cities. As a result, the present study analyzed synergies between CO_2 and other pollutant emissions at the prefecture level rather than at the regional and/or provincial level. At this level, the policy measures can be more flexible and effective. Considering the significant correlation between CO_2 emission of other air pollutants, it is suggested that China should take into account the synergistic effects of CO_2, SO_2, and other pollutants, and focus on controlling GHG and emissions of other pollutants at the prefecture scale. At the same time, prefecture agglomerations can develop renewable energy supply bases that would help to achieve a substantial reduction in CO_2 and SO_2 emissions. Prefectures with low CO_2 and SO_2 emissions or prefectures with low CO_2/SO_2 ratios should be provided with incentives related to synergistic measures that will allow them to achieve the dual control of CO_2 and SO_2 emissions at a lower cost.

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