

Does vertical environmental protection pressure promote convergence of urban air pollution?



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ABSTRACT

Recent research shows that the annual average concentration and winter average concentration of PM_{2.5} in Chinese cities have exhibited a convergence trend since 2013. However, the urban air situation in China remains far from ideal. For an authoritative government, vertical environmental protection pressure (VEPP) may be an important mechanism to motivate cities with high PM_{2.5} concentration levels to reduce haze pollution more rapidly compared to cities with low PM_{2.5} concentrations. Thus, VEPP could be considered an institutional advantage in China's vertical air pollution allocation strategy. To investigate the impact of the VEPP of Chinese local governments on the convergence of PM_{2.5} concentrations, this study uses the counterfactual distribution dynamics analysis framework, which combines parametric regression analysis with the nonparametric distribution dynamics technique. The results show that the Chinese government can promote the convergence of air pollution in local cities to a "favorable" level by increasing the pressure of environmental protection. However, merely increasing VEPP will not completely solve the problem of air pollution in Chinese cities during winter months. Compared with the central and western regions, the VEPP of local governments in the eastern region can promote the convergence of the average annual and winter PM_{2.5} concentrations.

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Introduction

Countries worldwide are focusing on the coordinated development of their economies and ecological environment (Bustos-Contell, Labatut-Serer, Ribeiro-Navarrete, & Climent-Serrano, 2019; Dabbous & Tarhini, 2021; Lassala, Orero-Blat, & Ribeiro-Navarrete, 2021; Tiago, Gil, Stemberger, & Borges-Tiago, 2021). Air pollution is not only detrimental to people's health but also hampers sustainable economic growth (Saunila, 2020). Thus, curbing air pollution, especially haze pollution, is now a major global challenge, especially in China, where air pollution is severe (Wei, Gu, Wang, Yao, & Wu, 2018; Zhang, Shuai, Bian, Chen, Wu, & Shen, 2019). In 2013, China encountered four extensive and persistent haze episodes, exceeding 100 days and affecting 30 provinces and municipalities, with haze severity reaching its highest historical level. During 2013, 83 percent of China's population was exposed to air pollution, with an annual average PM_{2.5} concentration above 35 μg/m³ (Fan & Xu, 2020;

Liu, Han, Xiao, Zhu, & Zhu, 2016; MEE, 2013). Since 2013, particulate matter with a diameter less than 2.5 μm (PM_{2.5}), which forms the main component of haze, has been the primary air pollutant in China (Zeng, Liu, Feiock, & Li, 2019). This study therefore selected PM_{2.5} as an index to measure air pollution.

Since 2013, China's strategy to combat air pollution has changed. Due to the serious air pollution, especially the increase in the number of days of severe haze pollution, China's State Council promulgated the Air Pollution Prevention and Control Action Plan (APPCAP) in September 2013. This Plan outlined the objectives of China's air pollution prevention and control efforts over the next decade, and proposed ten measures. To successfully realize this Plan, China's Ministry of Environmental Protection (MEP), on behalf of the State Council, signed target responsibility letters with 31 provinces, autonomous regions, and municipalities directly governed by the central government (excluding Hong Kong, Macao, and Taiwan). Consequently, specific requirements and air pollution prevention and control targets and measures came to be included in local government agenda. The provinces, cities, and autonomous regions covered by this Plan have urged local governments under their jurisdiction to issue detailed

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action plans by considering local conditions. These efforts indicate China's determination to control air pollution.

Research based on data prior to 2013 shows that China's central government has established a relatively complete system of environmental laws and regulations. However, local governments have not fully implemented these environmental policies, a key reason for the low efficiency of environmental governance (Cai, Chen, & Gong, 2016; Fraser, Dougill, Mabee, Reed, & McAlpine, 2006; Hong, Yu, & Mao, 2019; Li & Zhou, 2003; Reed et al., 2018). Since 2013, however, local governments have come under intense pressure from the central government to protect China's environment. For an authoritative government, the vertical environmental protection pressure (VEPP) from the central government may be an important mechanism to compel cities with high PM_{2.5} concentration to reduce haze pollution more rapidly compared to cities with low PM_{2.5} concentration, implying that VEPP could be an institutional advantage in China's vertical air pollution allocation strategy. As far as we know, there is little research in this topic. Therefore, this study investigates the impact of the VEPP on the convergence of air pollutants to provide an effective research path for China's national governance strategy on air pollution.

The main contributions of this study are as follows. First, using Chinese cities' annual average PM_{2.5} data from 2015 to 2019, this study uses the counterfactual distribution dynamic analysis framework, combining parametric regression analysis with the nonparametric distribution dynamics technique, to investigate the impact of the VEPP of Chinese local governments on the convergence of PM_{2.5} concentrations. Second, this study investigates the impact of VEPP on the convergence of urban average PM_{2.5} concentration during winter, based on the average PM_{2.5} concentration data from Chinese cities from 2015 to 2018. The average annual index is frequently used as the target in general pollutant concentration convergence studies. However, air pollution in China, particularly PM_{2.5} pollution, is worse during winter than in other seasons. Finally, due to China's vast territory, there are significant differences in economic, cultural, and educational levels, as well as local governments' governance abilities. Accordingly, this study investigates the impact of VEPP on PM_{2.5} distribution dynamics in the Eastern, Central, and Western regions of China.

The remainder of the paper is structured as follows. It starts with a literature review. In the construction of the indicator and model section of the study, distribution dynamic method, variable measurement, counterfactual distribution dynamic frame, and data source are presented. Then, the paper discusses the main results. Finally, conclusions, implications and suggestions for future research are presented.

Literature review

Local governments and air pollution

China's environmental governance is vertical. First, China's highest legislative body, the National People's Congress, promulgates laws to control air pollution. Subsequently, pollution management is delegated to the Ministry of Ecological Environment (MEE, 2013), which is a constituent department of the State Council and is directly responsible for managing national environmental regulations, with jurisdiction over air pollution (Liu & Kong, 2021). The implementing agency is the local Bureau of Ecological Environment (BEE). The provincial Department of Ecological Environments (DEE) links the local BEE with the central MEE to directly supervise and coordinate the implementation of air pollution plans on behalf of the central government. However, when environmental governance is implemented at the local level, it is frequently fraught with difficulties (Zhang et al., 2019).

The local BEE must accept the MEE's guidance, while also recognizing the leadership and financial support of the local government,

which appoints personnel to the local BEE. Therefore, the local government administers environmental management (Liu & Kong, 2021). Under political centralization norms, the central government appoints local governments based on their relative performance. Therefore, some local government officials who are vying for promotions, may neglect their responsibilities toward the environment. The key to China's environmental pollution control, therefore, lies in correcting the behavior of local governments (Caldeira, 2012; Kou & Han, 2021; Xu, 2011; Yang, Liao, & Wei, 2020; Zhao, Liang, & Zhang, 2021).

In this regard, many scholars have conducted relevant research from different perspectives (Jia & Chen, 2019; Kou & Han, 2021; Liu & Kong, 2021; Xu et al., 2021; Zhang, Jin, & Meng, 2020; Zhang, Wang, Yang, Ren, Ran, & Hao, 2021). 2013 is a turning point in China's air pollution control management, and since then, local Chinese governments have been under intense pressure from the central government to protect the environment. Therefore, the question remains—can the central government's VEPP encourage local governments to fulfill their responsibilities actively? A few recent studies focus on the direct impact of VEPP on air pollution. Using provincial data in China from 2003 to 2017, Kou and Han (2021) empirically tested local governments' regulatory behavior regarding sulfur dioxide under the dual pressure of VEPP and fiscal pressure. Their results show that as VEPP increases, local governments will intensify regulation of sulfur dioxide. To the best of our knowledge, few studies have addressed the impact of VEPP on the convergence of air pollutants in China's cities, and this could have significant implications for formulating appropriate environmental policies.

In economic research, the original concept of convergence suggests that underdeveloped economies aspire to draw level with their richer counterparts in per capita income (Solow, 1956). Haze pollution also has a catch-up effect between cities, implying that cities with higher PM_{2.5} concentrations experience higher reductions in haze pollution than those with lower PM_{2.5} concentrations. There are several benefits to be derived from understanding the convergence of different air pollutants. From an international perspective, establishing the presence of convergence in pollution indicators is crucial for the relevant officers in the environment ministries of both developed and developing countries to propose practical environmental blueprints (Payne, 2020; Solarin et al., 2021). From a national perspective, haze pollution convergence can provide a theoretical basis for the rational allocation of haze reduction goals. For instance heavily polluted cities can embark on more haze mitigation measures, and the convergence analysis of haze can be useful for formulating appropriate environmental policies (Fan & Xu, 2020).

In recent years, there have been many studies on the convergence of CO₂ and air pollutants (List, 1999; Apergis & Payne, 2017; Apergis, Payne, & Topcu, 2017; Camarero, Picazo-Tadeo, & Tamarit, 2013; Liu, Hong, Li, & Wang, 2018; Nourry, 2009; Rios & Gianmoena, 2018; Van, 2005). On the research results of the convergence trend of air pollutants in China since 2013, Lin et al.(2021) show that, in the long run, the annual average PM_{2.5} clusters around two levels— $35\mu\text{g}/\text{m}^3$ and $60\mu\text{g}/\text{m}^3$ —while the average PM_{2.5} in winter is concentrated at $100\mu\text{g}/\text{m}^3$, indicating a severe level of pollution. Although APPCAP contributes toward haze reduction to a certain extent, to change China's winter urban pollution, factors affecting the convergence of air pollutants among cities must be examined.

Neoclassical growth theory hypothesizes that market forces promote the free flow of labor and capital. When the capital–labor ratio is balanced in various regions, the per capita income among regions tends to equalize—that is, economic convergence depends more on the "invisible hand" of market allocation (Qian, Yuan, Wang, Zhang, & Gong, 2021; Zhao, 2008). However, as the environment is considered a form of public good, based on the attributes of public goods and the externality of pollution, the environmental Kuznets curve does not suggest a spontaneous transformation between income and

environmental quality, following income growth (Yang & Yang, 2011). In other words, environmental convergence must rely on the "tangible hand" of the government.

For an authoritative government, VEPP from the central government could be an important factor in urging local governments to actively improve air quality (Jia & Chen, 2019). If the VEPP on local governments leads to the convergence of PM2.5 concentration in cities—that is, the VEPP of local governments makes cities with high levels of PM2.5 reduce haze pollution much faster than cities with low PM2.5 concentration—VEPP could be an institutional advantage in China's vertical air pollution allocation strategy. Therefore, this study investigates the impact of the VEPP on the convergence of air pollutants, to provide an effective research direction for China's national governance strategy on air pollution at the city level.

Counterfactual distribution dynamic analysis framework

Previous studies on convergence adopt the parameter regression method, which may lead to Galton's fallacy (Quah, 1993). In order to overcome the "Galton fallacy", Quah (1996 a, b, c; 1997) proposed a nonparametric distribution dynamic method. Compared with the parametric regression method, the nonparametric distribution dynamic research method can provide the shape information of the overall distribution of variables, fully describe the internal liquidity of the distribution evolution process, and intuitively describe the future distribution information of variables with the help of ergodic distribution.

Considering the influence of specific factors on convergence is, however, difficult when studying convergence using the distribution dynamics technique. Quah (1997) was the first to apply the conditional analysis method to study the "spatial" dimension of income distribution dynamics. Based on the conditional analysis method, Wu, Wu, and Cheong (2020) examined the impact of geographical location, capital accumulation, trade openness, and industrial structure on per capita GDP distribution dynamics. Fiaschi, Lavezzi, and Parenti (2009) proposed a counterfactual method combining parametric regression analysis with the distribution dynamics method because the conditional analysis method can only roughly reveal if a factor affects the dynamic distribution. Fiaschi et al. (2009) examined the impact of the European Union's (EU) regional policies on the process of labor productivity convergence across a wide sample of European countries from 1980 to 2002. Using Fiaschi et al.'s (2009) counterfactual framework, Giorgio and Francesco (2019) investigated the role of bank foundations in the distribution dynamics of interprovincial income in Italy. In this study, Fiaschi et al.'s (2009) counterfactual framework is used to quantitatively assess the role of VEPP in the convergence process of PM2.5 concentration levels in Chinese cities.

Construction of the indicator and model

Distribution dynamics method

Quah's analysis framework comprises three steps. The first step involves estimating the probability density of variables. Generally, the kernel density estimation method is used (Lin et al., 2021):

Let X_1, X_2, \dots, X_n be a sample from the probability density $f_t(x)$, where $x \in \chi$, χ is an unbounded support set, and the traditional kernel density estimation reads:

$$\hat{f}_t(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - X_i}{h}\right), \tag{1}$$

where $K(\cdot)$ is the kernel function, and h is the bandwidth $h = 1.06\sigma n^{-1/2}$. The study applies the Gaussian kernel $K(u) = \frac{1}{\sqrt{2\pi}} \exp(-\frac{1}{2}u^2)$.

The second step entails estimating the transition probability $\varphi_\tau(y|x)$: represents time t and time $t + \tau$, respectively. The PM2.5 concentration in China's prefecture-level cities has a cross-sectional distribution density.

Let $f_t(x)$ and $f_{t+\tau}(y)$ represent the cross-sectional distribution density of PM2.5 concentration in China's prefecture-level cities at t and $t + \tau$ respectively, where $\tau > 0$. Assuming that the evolution of the distribution is a time-invariant first-order distribution, future income distribution can be estimated $f_{t+\tau}(y)$ as follows:

$$f_{t+\tau}(y) = \int_0^\infty \varphi_\tau(y|x)f_t(x)dx, \tag{2}$$

where $\varphi_\tau(y|x)$ determines the transition probability of the PM2.5 concentration evolution process.

The transition probability $\varphi_\tau(y|x)$ is estimated as follows (Hyndman, Bashtannyk & Grunwald, 1996):

$$\hat{\varphi}_\tau(y|x) = \frac{\hat{f}_{t,t+\tau}(x,y)}{\hat{f}_t(x)}, \tag{3}$$

where $\hat{f}_t(x)$ is estimated by equation(1) and,

$$\hat{f}_{t,t+\tau}(x,y) = \frac{1}{nh_x h_y} \sum_{i=1}^n K\left(\frac{x - x_i}{h_x}, \frac{y - y_i}{h_y}\right) \tag{4}$$

where the two-dimensional kernel function adopts the product kernel: $K\left(\frac{x-x_i}{h_x}, \frac{y-y_i}{h_y}\right) = K\left(\frac{x-x_i}{h_x}\right) * K\left(\frac{y-y_i}{h_y}\right)$.

The third step in Quah's analysis framework involves estimating the ergodic distribution of continuous state. The ergodic distribution, under the assumption that the transition probability does not change over time, can be used to examine the long-term trend of PM2.5 concentrations in China's prefecture-level cities.

The expression of ergodic distribution of continuous state is to make $t \rightarrow \infty$ at both ends of equation (2):

$$f_\infty(y) = \int_0^\infty \varphi_\tau(y|x)f_\infty(x)dx \tag{5}$$

Lin et al. (2021) used Guo's (2007) iterative algorithm to calculate $f_\infty(y)$. The same algorithm is used in this study.

$f_{t+s}(y)$ must be subject to short-term external shocks; in the long run, however, the ergodic distribution $f_\infty(y)$ is independent of the initial PM2.5 distribution, and can be regarded as the expansion effect of transition probability (for details, see Lin et al., 2021).

Vertical environmental protection pressure indicator

Since VEPP is a fuzzy concept, it is difficult to quantify. However, the author's wishes are often expressed in the text. Meanwhile, the conceptual model and language expression characteristics of the text reflect the author's effective information (Ghose, Ipeirotis, & Li, 2012; Kou & Han, 2021). Therefore, Kou and Han (2021) argued that VEPP from the central government can be measured by the relevant documents issued by the central government, and they refer to the concepts of Chen and Chen (2018) to construct the VEPP index of provincial local governments. The research object of Kou and Han (2021) is the provincial government, while the research object in this study is the municipal local government. The first problem in this study is measuring the VEPP index at the municipal level.

China's central government does not directly manage local governments at the city level, but indirectly manages them through provincial governments. Provincial governments link local governments with the central government and directly supervise and coordinate the implementation of local governments' air pollution plans on behalf of the central government. Simultaneously, China's governmental work report provides a summary of administrative actions

and details regarding implementation of governmental decisions and resolutions. It is a programmatic document guiding the government's work (Chen & Chen, 2018). The annual work report of China's provincial governments not only summarizes the achievements of the provincial government in a particular year, but also proposes the work plan for the next year. Thus, the higher the frequency of environment-related words in the provincial government's annual work report, the greater the pressure on environmental protection for municipal governments in the province. As the provincial government is the local authority that represents the central government, the total number of words related to the environment in the annual work report of the provincial government can be used as a proxy variable for the pressure faced by the local municipal government regarding environmental protection.

(1) Environmental terms include (Chen & Chen, 2018): environmental protection, pollution, energy consumption, emission reduction, sewage, ecology, green, low carbon, air, chemical oxygen demand, sulfur dioxide, carbon dioxide, PM10, and PM2.5.

Figures 1 (a) and (b) show that, from 2008 to 2019, the proportion of words related to the environment in the annual work reports of 31 provincial governments has increased yearly, and local governments at the municipal level have been under increasing pressure to ensure environmental protection. Prior to 2014, several of China's local municipal governments did not disclose PM2.5 data, and reporting of comprehensive data began in 2015. Therefore, the study period for this research is 2015–2019. This study takes the average value of the proportion of environment related words in provincial governments' annual work reports from 2015 to 2019 as a proxy for the VEPP of municipal local governments since the implementation of APPCAP, which is abbreviated as $GWR_j(j=1,2,\dots,31)$.

(1) In the previous step, the environmental protection pressure indicators of China's municipal local governments were constructed using words related to the environment in the work report of provincial governments. However, each city within a province experiences the same pressure of environmental protection, which is

obviously unreasonable. Chen and Chen (2018) believe that the impact of provincial governments' governance on their internal prefecture-level cities varies with the proportion of heavy industries in each city. For cities with a higher proportion of heavy industries, the impact will be higher. Apparently, for cities with a higher proportion of heavy industries, the impact of environmental governance will be much better, and the pressure of environmental protection from provincial governments will be higher. This study draws on the Chen and Chen (2018)'s concept of "variation" and shows that the municipal governments within a province experience different levels of pressure depending on the "proportion of municipal heavy industry" (HIP_i). The proportion of heavy industry in the i -th prefecture-level city is multiplied by the frequency or proportion of environment-related words in the annual work report of the provincial government of the city. Thus, the environmental protection pressure index of the prefecture-level municipal government is obtained: $HIP_i * GWR_j$, where the i -th city is managed by the j -th provincial government.

(2) However, even two cities with a high proportion of heavy industry may have dissimilar levels of pollution. For example, Shizuishan City, a prefecture-level city in the Ningxia Hui Autonomous Region, and Shijiazhuang City in Hebei Province are major industrial cities with a high proportion of heavy industries. However, the former had average annual PM2.5 concentration of $36\mu g/m^3$ in 2019, while the latter has experienced heavy air pollution in recent years, and the pressure of environmental protection is much higher in Shijiazhuang City than in Shizuishan. Clearly, the "proportion of municipal heavy industry" as a variation variable is reasonable, but it still needs to be modified appropriately. Due to varying air pollution conditions, municipal local governments must face different levels of environmental protection pressure. Therefore, the "past" air pollution conditions of local governments can be considered a new variable of variation. Thus, we obtain the vertical environmental protection pressure index of the i -th city during the period 2015–2019: $VEPP_i^{2019} = HIP_i * GWR_j * AQI_i / AQI$, where the i -th city is managed by the j -th provincial government. AQI_i is the city's air quality index level in 2015, AQI is the sample mean of AQI_i .

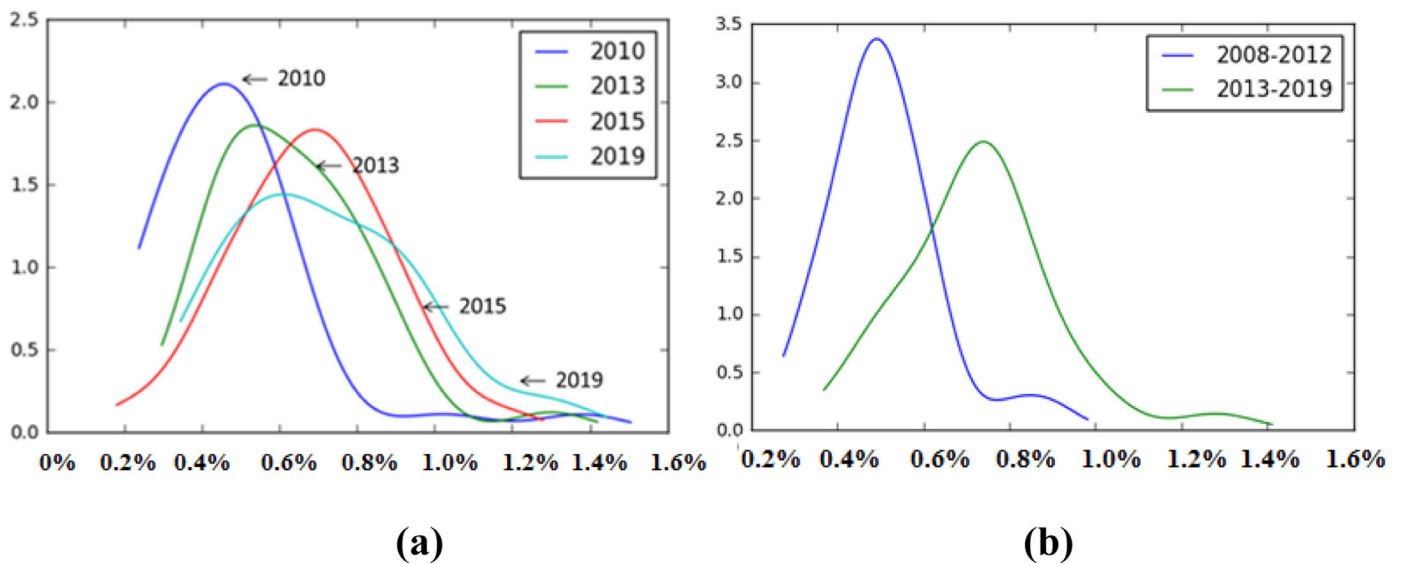


Figure 1. Kernel density of the proportion of environment-related words in government work reports
 Note: (a) Annual kernel density curve of the proportion of environment-related words among all words in the work reports of 31 provinces, autonomous regions, and municipalities in China directly under the central government (excluding Hong Kong, Macao, and Taiwan); (b) Kernel density curve of the proportion of environment-related words in the work reports of 31 provinces, autonomous regions, and municipalities directly under the central government between 2008–2012 and 2013–2019.

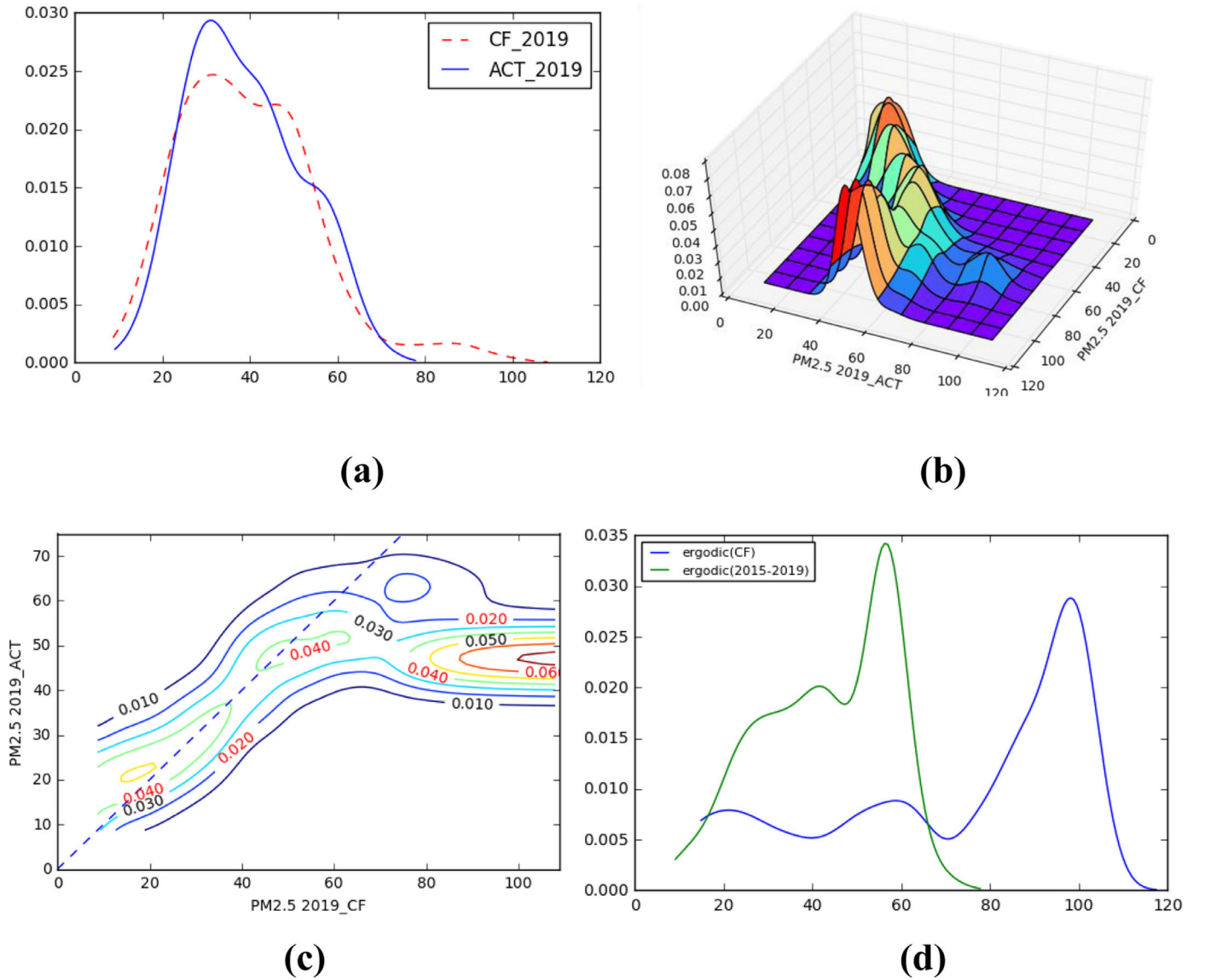


Figure 2. Actual and counterfactual distribution of annual average PM2.5 concentration in Chinese cities
 Note:(a) Actual and counterfactual distribution of annual average PM2.5 in Chinese cities in 2019; (b) Three-dimensional figure of the transfer probability of annual average PM2.5 and its counterfactual value in Chinese cities in 2019; (c) Two-dimensional contour line of the numerical transfer probability of annual average PM2.5 and its counterfactual in Chinese cities in 2019; (d) Actual and counterfactual ergodic distribution of annual average PM2.5 in Chinese cities from 2015 to 2019. The calculation of the counterfactual ergodic distribution in Figure 2 (d) is similar to the actual ergodic distribution, except that the average annual level of PM2.5 in Chinese cities in 2019 is the counterfactual value. The estimate of the counterfactual ergodic distribution of average winter PM2.5 concentrations in Chinese cities in 2018 is also comparable.

Calculation of counterfactual value of urban PM2.5

The influencing factor in this study is the VEPP of local governments ($VEPP_i^{2019}$). Similar to Giorgio and Francesco (2019), the counterfactual level of the annual average PM2.5 concentration at the end of 2019 for the i -th city is:

$$PM2.5_i^{cf,2019} = \exp\left(\ln\left(PM2.5_i^{act,2015}\right) + \hat{g}_i^{cf}\right), \tag{6}$$

where $PM2.5_i^{act,2015}$ is the actual annual average PM2.5 concentration of the i -th city in 2015, \hat{g}_i^{cf} is the counterfactual PM2.5 concentration growth rate in the i -th city. The calculation is as follows:

$$\hat{g}_i^{cf} = g_i^{fit,2019} - \alpha_1\left(VEPP_i^{2019} - VEPP\right), \tag{7}$$

where $g_i^{fit,2019}$ is the fitting value of the PM2.5 concentration growth rate. According to the predicted value of equation (8), α_1 is the

estimated coefficient $VEPP_i^{2019}$ and $VEPP$ is the sample average of $VEPP_i^{2019}$.

According to Fiaschi et al.'s (2009) approach, the regression model should consider the variables of interest, implying that the model should adequately explain the growth rate of PM2.5 in this study. According to Chen and Chen (2018), the regression model developed for urban PM2.5 concentrations in 2015–2019 adds to the government's environmental governance and meteorological element (2018). The following is the established regression model:

$$g_i = \alpha_0 + \alpha_1 VEPP_i^{2019} + \alpha_2 Province_i + \alpha_3 \Delta city_i + \alpha_4 climate_i^{2019} + \varepsilon_i, \tag{8}$$

where g_i is the actual growth rate of PM2.5 concentration in the i -th city from 2015 to 2019. $VEPP_i^{2019}$ represents the VEPP indicator of the i -th city from 2015 to 2019. $Province_i$ is the dummy variable of the

province to which the i -th city belongs. $\Delta city_i$ is the difference between the characteristics of the i -th city at the beginning (2015) and the end (2019), and the characteristics includes per capita GDP, GDP, proportion of secondary industry, loans from financial institutions per capita, proportion of FDI in GDP, per capita financial and scientific and technological expenditure, per capita road construction area, number of Internet users, population per unit area, and proportion of heavy industry in industry (Chen & Chen, 2018), $climate_i^{2019}$ is the average annual wind speed for the i -th city in 2019.

Specifically, the process of calculating the counterfactual value of the average winter PM2.5 concentration in Chinese cities is like the calculation process of the average annual PM2.5 concentration in Chinese cities.

Data source and pretreatment

The urban PM2.5 concentration and China's regional division in this study adopted Lin et al.'s (2021) relevant definitions. The procedures for deriving the urban AQI index value and PM2.5

concentration, are the same. The acquisition and processing instructions for the other main variables are as follows:

- (1) City characteristics: the data for city characteristics for this study were obtained from the China Urban Statistical Yearbook (2016, 2019). The 2016 Yearbook provided data for 2015, and data in the 2019 Yearbook pertain to 2018. Since the China Urban Statistical Yearbook in 2020 had not been published at the time of this study, we retrieved the urban characteristics data from the China Urban Statistical Yearbook in 2019.
- (2) The proportion of heavy industry clusters in the i -th prefecture-level city (HIP_i): when constructing the VEPP value of the i -th city in 2015–2019, the average proportion of heavy industry clusters is required. The data source for the proportion of heavy industry clusters in urban areas is the Economic Profile Systems (EPS) database. However, up to the research of this study, most cities categorized as urban heavy industrial cities in the EPS database appeared only until 2016. Therefore, in this study, the average proportion of

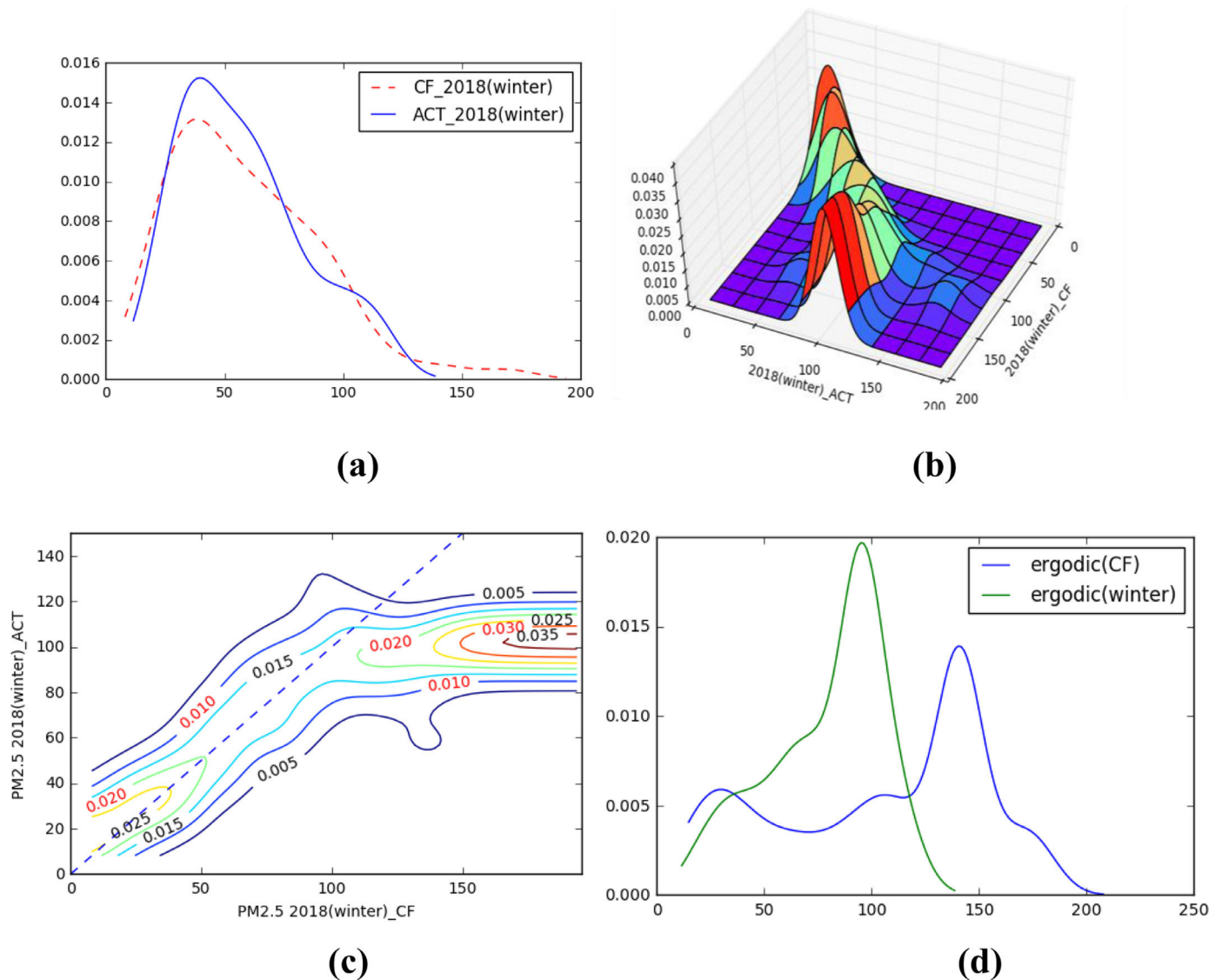


Figure 3. Counterfactual analysis of average PM2.5 concentration distribution in Chinese cities during winter
 Note: (a) Actual and counterfactual distribution of average winter PM2.5 in Chinese cities in 2018; (b) Three-dimensional figure of the value transfer probability of average winter PM2.5 and its counterfactual of Chinese cities in 2018; (c) Two-dimensional contour of the numerical transfer probability of average PM2.5 and its counterfactual of Chinese cities during winter in 2018; (d) Actual and counterfactual ergodic distribution of winter average PM2.5 in Chinese cities from 2015 to 2018.



Figure 4. Eastern, Central, and Western China

Note: This study does not include Hong Kong, Macao, and Taiwan
Source: Lin et al. (2021)

urban heavy industry from 2003 to 2016 was selected as the estimated proportion of urban heavy industry. In the calculation process, the missing data were automatically ignored.

- (3) The provincial government work report: annual government work reports were collected from 31 Chinese provinces (excluding Hong Kong, Macao, and Taiwan) from 2003 to 2019 from the respective provincial official websites. Text was segmented in the government's work reports, the frequency of the environmentally relevant words was counted, and the proportion of these words to total word frequency in the government reports was calculated. We took the annual average of the proportion of environment-related words from 2015 to 2019 as the foundation for the development of proxy variables representing the VEPP of local governments since 2015.
- (4) Meteorological data: meteorological data were captured by the "Worldmet" R package, as developed by Carslaw (2017). The steps involved are as follows: the longitude and latitude of 298 prefecture-level cities were obtained by using Baidu Geocoding API; from the "Worldmet" R package language, hourly weather data of the nearest meteorological station to the city were obtained (Haikou City is missing, so it has been excluded); the hourly wind speed of 297 cities in 2019 is averaged to obtain the 2019 average annual wind speed of the i -th city; the hourly wind speed of 297 cities from November 1, 2008 to February 29, 2019 is averaged to obtain the 2018 winter average wind speed of the i -th city.

Empirical results

Counterfactual distribution analysis of annual average PM_{2.5} concentration in Chinese cities

Figure 2(a) shows the actual distribution and counterfactual distribution of annual average PM_{2.5} concentration in China's prefecture-level cities in 2019. According to Fiaschi et al.'s (2009) framework, the counterfactual value of the annual average PM_{2.5} concentration of the i -th city is obtained when the city's VEPP reaches the national urban average level. In other words, the counterfactual distribution curve of the annual average PM_{2.5} concentration in 2019 is obtained under the assumption that all cities will bear the same environmental protection pressure during 2015–2019. However, the

actual situation shows that during 2015–2019, the environmental protection pressure borne by each city is different, which leads to the difference between the actual distribution curve and the counterfactual distribution curve in Figure 2(a). Compared with the counterfactual distribution curve, the actual distribution curve is more concentrated, the curve kurtosis is steeper, and the left and right sides of the curve "shrink" inward. Overall, this shows that VEPP can significantly encourage cities with high PM_{2.5} concentration to improve their air quality; by contrast, the air quality of cities with low PM_{2.5} concentration, degrades somewhat under the corresponding environmental protection pressure.

Next, we analyzed the conclusion drawn from Figure 2(a) in combination with the transition probability graph between the actual and the counterfactual distributions in Figures 2(b) and (c). In Figure 2(b), the main part of the transfer probability contour line obviously presents a "clockwise" shape. In the high-end part of the horizontal axis, the main part of the contour line is located below the 45 degree diagonal, indicating that if cities with high annual PM_{2.5} concentration bear the same environmental protection pressure between 2015 and 2019, the annual PM_{2.5} concentration of these cities in 2019 will be between $70\mu\text{g}/\text{m}^3$ and $100\mu\text{g}/\text{m}^3$; in practice, however, cities with high annual PM_{2.5} concentration had different environmental protection pressures for the period from 2015 to 2019. The actual annual PM_{2.5} concentration of these cities in 2019 varied between $50\mu\text{g}/\text{m}^3$ and $70\mu\text{g}/\text{m}^3$, which further details that VEPP significantly instigates cities with high PM_{2.5} concentration to improve the air quality. At the lower end of the horizontal axis in Figure 2(b), the main part of the contour line is located above the 45-degree diagonal, indicating that the air quality of cities with low PM_{2.5} concentration is slightly degraded under the corresponding environmental protection pressure.

In summary, it can be concluded that VEPP can promote the convergence of urban average annual PM_{2.5} concentration. Compared with cities with low average annual PM_{2.5} concentration, VEPP has a greater impact on cities with a high average annual PM_{2.5} concentration.

Ergodic distribution is the distribution of PM_{2.5} concentration in Chinese cities when time tends toward infinity under the assumption that the transition probability is constant. Ergodic distribution can reflect the long-term distribution of urban PM_{2.5} concentration and is the expansion effect of transfer probability. Through a comparative analysis of the actual ergodic distribution and the counterfactual ergodic distribution of the urban annual average PM_{2.5} concentration, the long-term impact of VEPP on the urban annual average PM_{2.5} concentration can be obtained.

Figure 2(d) shows that compared with the counterfactual ergodic distribution curve, the actual ergodic distribution shows an obvious shift toward the left, and is more concentrated. This implies that if China's cities experience the same average level of environmental protection pressure from 2015 to 2019, according to the counterfactual traversal distribution curve, the average annual PM_{2.5} concentration of most cities in the future will focus on the serious pollution level of $100\mu\text{g}/\text{m}^3$. In fact, China's cities are under different pressures from environmental protection. According to the actual ergodic distribution curve, the average annual PM_{2.5} of most cities in the future will be between $40\mu\text{g}/\text{m}^3$ and $60\mu\text{g}/\text{m}^3$. This shows that VEPP can have a long-term impact on the urban average annual PM_{2.5} concentration distribution, and promote the distribution of urban PM_{2.5} concentration in the "good" direction.

Counterfactual distribution analysis of average PM_{2.5} concentration in Chinese cities during winter

Figure 3(a) shows the actual and counterfactual distribution curves of average PM_{2.5} in winter 2018 in China's prefecture-level

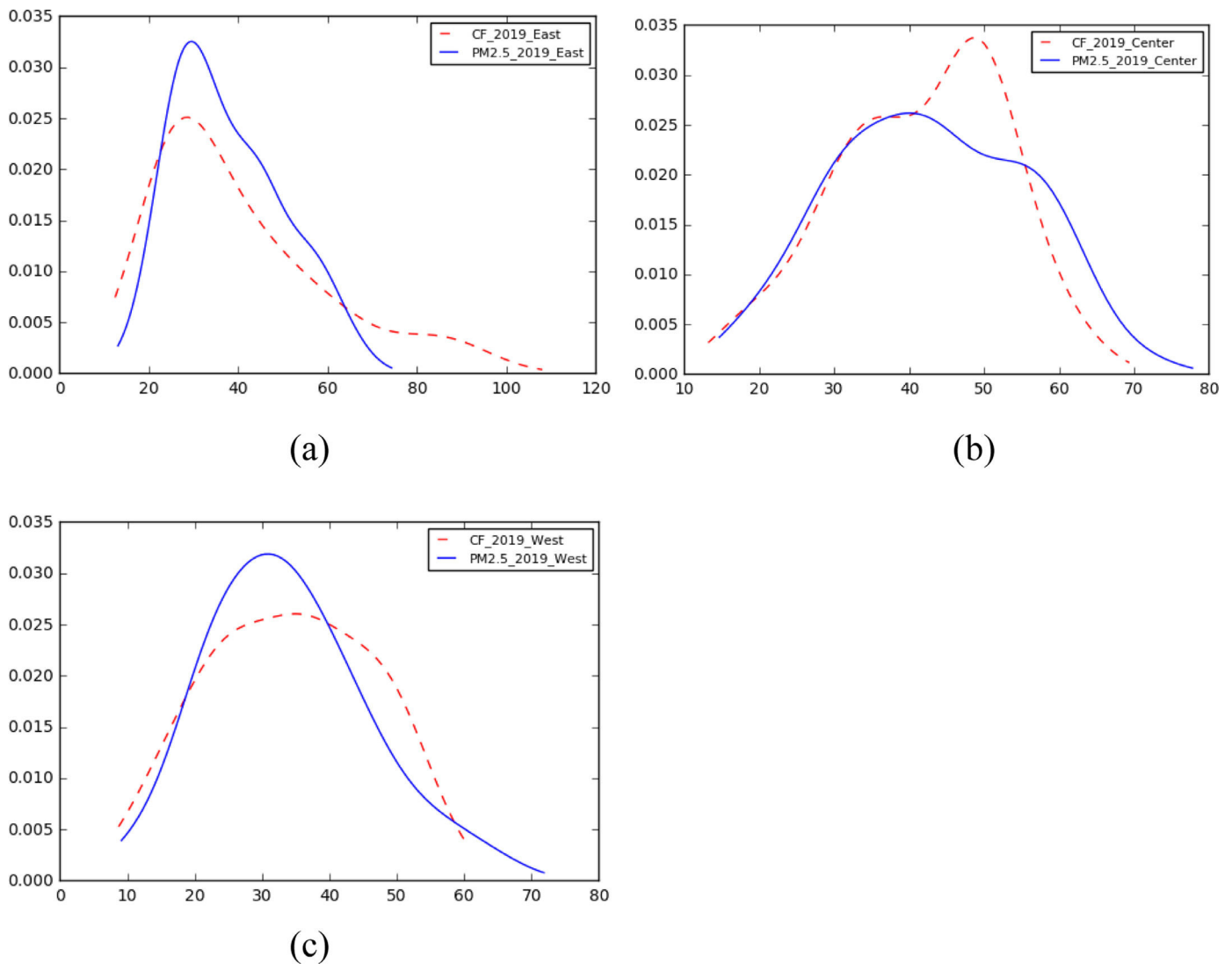


Figure 5. Counterfactual and actual distribution curve of urban annual average PM2.5 concentration in Eastern, Central, and Western China
 Note: Counterfactual and actual distribution curve of urban annual average PM2.5 concentration in 2019 in (a) Eastern China; (b) Central China; (c) Western China.

cities. Like Figure 2(a), compared with the real curve of inverse distribution, the actual distribution curve is more concentrated, the curve kurtosis is steeper, and the left and right sides of the curve "shrink" inward. Combined with Figures 3(b) and (c), similar to the annual situation, VEPP can overall significantly encourage cities with high PM2.5 concentration to improve the air quality; however, the air quality of cities with low PM2.5 concentration degrades slightly under corresponding environmental protection pressure. Therefore, VEPP can also promote the convergence of urban average PM2.5 concentration in winter.

Figure 3(d) shows that in similar annual situations, compared with the counterfactual ergodic distribution curve, the actual ergodic distribution shows an obvious shift toward the left, and is more concentrated. This shows that VEPP can also have a long-term impact on the urban average PM2.5 concentration distribution in winter, and promote the urban PM2.5 concentration distribution in the "good" direction. However, it must be recognized that China's PM2.5 pollution in winter is still at a relatively serious level, from both the counterfactual and actual distribution curves. To some extent, this shows that continuous VEPP will not completely solve the problem of air pollution in winter.

Counterfactual distribution analysis of PM2.5 in sub-regional cities

As illustrated in Figure 4, China was classified into three economic zones during the Seventh Five Year Plan period based on geographical location, economic construction conditions, and regional variances at the real economic and technological level (Lin et al., 2021).

Figure 5 depicts the counterfactual and actual distribution curves of the annual average PM2.5 concentrations in cities in Eastern, Central, and Western China. It should be noted that the counterfactual values of *i*-th city in Figure 5 are the same as those in Figure 2. Similarly, the counterfactual values of *i*-th city in Figure 6 are like those in Figure 3. Figure 5 shows that only the counterfactual curve in the East, notably on the right, extends to both sides when compared to the actual distribution curve. This demonstrates that the VEPP of the local government in the eastern region can promote the convergence of average annual PM2.5 concentrations in eastern cities in a "good" direction. The VEPP of local governments in the central and western regions diverges from the average PM2.5 concentrations.

Figure 6 depicts the winter average counterfactual distribution curve for cities in eastern, central, and western China, and this is similar to the actual distribution curve. Only the counterfactual curve in

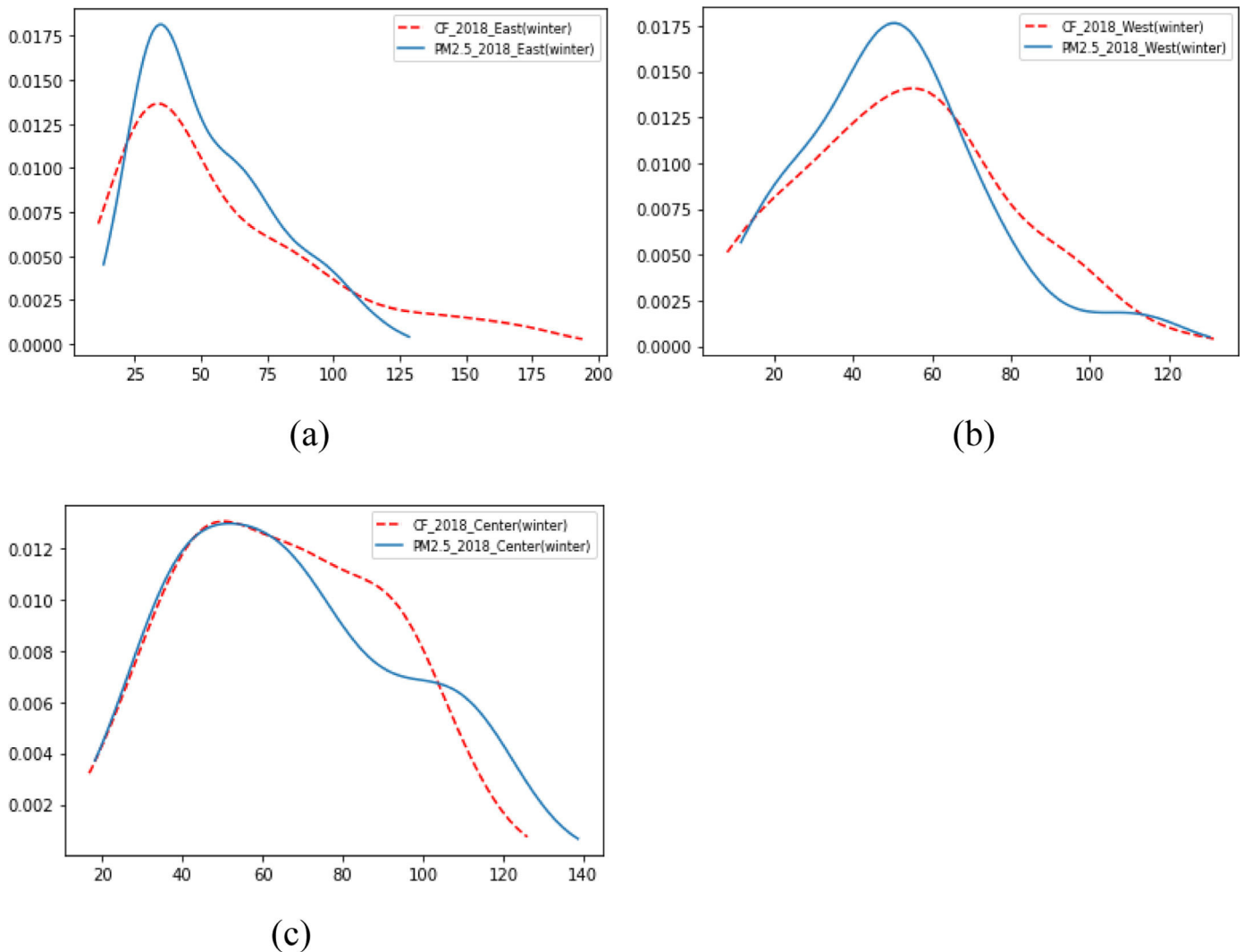


Figure 6. Counterfactual and actual distribution curve of urban average PM2.5 concentration in winter in Eastern, Central, and Western China
 Note:(a) Counterfactual and actual distribution curve of urban average PM2.5 concentration in 2018 winter in (a) Eastern China; (b) Central China; (c) Western China.

the East extends toward both sides when compared to the actual distribution curve in winter. This demonstrates that compared to the central and western regions, the VEPP of the local government in the eastern region can promote the convergence of average PM2.5 concentrations in China’s eastern cities in the "good" direction during winter. The VEPP of local governments in the central and western regions forced the annual average PM2.5 concentrations in winter to diverge.

Discussion

China’s air pollution control reached a tipping point in 2013. According to the existing research, PM2.5 concentration levels in Chinese cities have shown a convergence trend since 2013, both annually and in winter. However, the average winter PM2.5 concentration in Chinese cities converges to the level of serious pollution. Therefore, it is necessary to explore the factors affecting the convergence of urban PM2.5 concentration.

China’s environmental governance mechanism is a vertical governance structure. The relevant central management institutions formulate laws and regulations on environmental protection, while local governments are responsible for implementing specific environmental protection measures. Given that local governments exercise environmental management power, the behavior of local government leaders is crucial to environmental governance. However, local

government leaders tend to focus on local economic development for personal promotion, thus ignoring environmental protection. Scholars believe that for an authoritative government, VEPP from the central government is an important factor to motivate local governments to actively improve air quality (Jia & Chen, 2019). Therefore, this study investigates the impact of VEPP on the convergence of air pollutants, to provide an effective research direction for China’s national governance strategy to address air pollution. Specifically, we developed the VEPP of local government indicators based on the frequency of occurrence of environmental phrases in the provincial work report. Subsequently, we examined the impact of local governments’ VEPP on the distribution dynamics of PM2.5 concentration in Chinese cities using the counterfactual analysis framework, as first proposed by Fiaschi et al. (2009).

The study findings are as follows. (1) The VEPP of local governments can support the convergence of the annual average and winter average PM2.5 concentration in Chinese cities in a "favorable" direction, and the same result can be achieved using a long-term ergodic distribution analysis. (2)The main part of the counterfactual distribution and the real curve both exceed $100\mu\text{g}/\text{m}^3$ in winter, indicating that the increase in VEPP cannot completely solve the problem of air pollution in Chinese cities during winter. (3) Compared to the central and western regions, only the VEPP of local governments in the eastern region promote the convergence of the average annual and

winter PM_{2.5} concentrations in China's eastern cities in a "good" direction.

The study results show that an authoritative government can motivate local governments to combat air pollution and converge to a "favorable" level by increasing the pressure of environmental protection, implying that the central government's VEPP can encourage the implementation of China's urban air pollution classified treatment strategy. That is, the VEPP of local governments makes cities with high PM_{2.5} concentration reduce haze pollution more rapidly than cities with low levels of PM_{2.5} concentrations. Based on the air pollution situation, the central government can exert different types of pressure on local governments, denoting that China's vertical air pollution allocation strategy is effective.

However, improvement in VEPP cannot completely solve the problem of winter air pollution in Chinese cities. Notably, due to weather factors that are not conducive for the diffusion of air pollutants and factors such as coal burning for heating in the north during winter, Chinese cities have been combating more serious air pollution during winter than in other seasons (Xu, Lin, & Taqi, 2020). Local governments must implement more effective measures to promote improved air quality during winter. However, local governments are not only under pressure of environmental protection from the central government but also face the pressure of local economic development (Kou & Han, 2021). Stringent air pollution control measures may hamper the development of the local economy, which is also the main guide for the promotion of local government officials. The empirical analysis conducted in this study shows that notwithstanding serious air pollution in Chinese cities during winter, merely increasing the pressure of central environmental protection may not be a good solution. We must find the path of coordinated economic development and pollution control, that ensures high-quality and sustainable economic development.

Finally, the VEPP of local governments in the central and western regions forced the average PM_{2.5} concentrations in winter to diverge, implying that the VEPP of local governments makes cities with high PM_{2.5} concentration reduce haze pollution much slower than cities with low levels of PM_{2.5} concentration. The central government must reinforce pressure for environmental protection in heavily polluted cities in the central and western regions, implement stringent environmental laws and regulations, and strengthen accountability to promote the convergence of urban air pollution levels in the central and western regions.

Notwithstanding serious air pollution, relying only on the central government's pressure of environmental protection will not urge local governments enough to improve air quality. New factors that can improve the convergence level of urban air pollution must be explored. Seeking new factors such as public participation to make China's urban air pollution converge to a better level is our suggested future research direction.

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