TRANS-BOUNDARY AIR POLLUTION AND INDUSTRIAL RELOCATION IN CHINA

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This dissertation studies trans-boundary air pollution under China's regionally decentralized environmental management and its influences on non-polluting industries. It consists of three chapters.

In the first chapter, I study whether subnational governments in China have engaged in trans-boundary air pollution. I identify which cities are "downwind" in each of China's provinces and uses difference-in-differences estimations based on wind patterns and a large-scale policy-change. I find that China's provincial governments began locating highly polluting industries in downwind cities near provincial borders after 2003 when the central government introduced stricter environmental policies. These results partly explain why environmental pollution has not been mitigated in certain parts of China.

In the second chapter, I build a model to analyze the effects of policy-induced trans-boundary air pollution on non-polluting industries in China. The patterns of industrial relocation caused by trans-boundary air pollution are characterized in the model. When the central government increases the weight of pollution in its evaluation function, there are more output and employment of polluting industry in the downwind city in each province, which implies more trans-boundary air pollution. This will lead to relatively less output and employment of non-polluting industry in the upwind city, and total welfare of the economy is less than the social planner's solution.

In the third chapter, I empirically estimate the negative externalities of trans-boundary air pollution on non-polluting industries in China. Through a quasi-experimental approach combining regional wind patterns and a large-scale policy-change in the early 2000s, I find that output and employment of existing firms in non-polluting industries are relatively less in cities receiving trans-boundary air pollution from their upwind adjacent provinces. The negative effects are relatively greater for firms of non-polluting industries in cities with higher average wind speed. New firms of non-polluting industries are less likely to be located in cities receiving more trans-boundary air pollution after the policy change.

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PREFACE

I want to thank my advisors Randall Walsh and Daniel Berkowitz for their continuous advice and support. Their encouragement and guidance have contributed a lot to my development as a researcher. I am also thankful for the generous and helpful advice from Douglas Hanley and Ilia Murtazashvili. In addition, I have really enjoyed the years in Pitt. Many people in the economics department have helped me a lot. I want to thank them as well. Finally, I should express my special thanks to my beloved parents. Thank you for supporting and encouraging me throughout the years.

1.0 INTRODUCTION

Trans-boundary spillover is a major issue for pollution control under decentralized environmental management. However, studies on trans-boundary air pollution are limited, as it is difficult to define "downwind" places clearly without detailed information of wind patterns. This dissertation studies trans-boundary air pollution under China's regionally decentralized environmental management through a quasi-experimental approach based on regional wind patterns and a large-scale policy-change. This dissertation consists of three chapters.

The first chapter contributes to the literature on the negative externalities of trans-boundary environmental pollution. One of the major contributions of this study is to identify clearly which cities are "downwind" in each of China's provinces by exploring a recently available dataset of wind patterns. The quasi-experimental approach of this study is also based on a large-scale policy-change. The central government began to introduce stricter environmental regulation in the early 2000s when a long history of using coal as the main energy source had caused severe air pollution in China. However, since subnational governments in China have regionally decentralized economic and environmental management, and subnational leaders are competing for promotion under centrally controlled political governance, they have stronger incentives to dump more air pollution on provincial borders after the policy change. Through difference-in-differences estimations on China's 286 major cities, I find that China's provincial governments began locating more highly polluting industries in downwind cities near provincial borders than in all other types of cities after 2003 when the central government introduced stricter environmental policies. These results provide clear evidence for the negative externalities of trans-boundary air pollution and partly explain why environmental pollution has not been mitigated in certain parts of China.

The second chapter is a straightforward extension of the previous one. I begin to investigate the consequences of policy-induced trans-boundary air pollution across China's provinces. Particularly, my research question is how pollution from one province affects output, the number of firms, and employment in non-polluting industries in its neighboring provinces. In this chapter, I build a model to analyze the effects of trans-boundary air pollution on non-polluting industries in China. Nash equilibrium of provincial leaders' strategic response is solved for this model, and patterns of industrial relocation caused by trans-boundary air pollution are characterized by comparative statics of the equilibrium outcomes. When labor markets are connected within each province, if the central government increases the weight of pollution in its evaluation function, there are more output and employment of polluting industry in the downwind cities, which implies more trans-boundary air pollution. This will lead to relatively less output and employment of non-polluting industry in the upwind cities, and total welfare of the economy is less than the social planner's solution. The predictions from the model are used to guide empirical estimations in the next chapter.

In the third chapter, I empirically study whether non-polluting industries in downwind provinces are affected by increased trans-boundary air pollution due to policy change. The empirical estimations are guided by comparative statics of the model in the previous chapter, and econometric specification is also based on a quasi-experimental approach combining policy-change and regional wind patterns. I figure out which cities are most likely to be affected by trans-boundary air pollution from their neighboring provinces. Difference-in-differences estimations show that trans-boundary air pollution under China's decentralized environmental management has significantly negative effects on non-polluting industries in cities near provincial borders. The output and employment of existing firms in non-polluting industries are relatively less in cities receiving trans-boundary air pollution from their upwind adjacent provinces. The negative effects are relatively larger for clean industries in cities with higher average wind speed. State-owned firms of the clean industries in the receiver cities have more unproductive employment. New firms in clean industries are less likely to be located in the receiver cities. The findings have important contributions to the literature that assesses the economic cost of pollution through estimating the impacts on output and employment of industrial sectors.

2.0 TRANS-BOUNDARY AIR POLLUTION AND REGIONAL DECENTRALIZATION IN CHINA

2.1 INTRODUCTION

Trans-boundary externalities of environmental pollution prove to be major issues when designing and implementing public policies for pollution control. Owing to asymmetric patterns of wind direction, places located downwind suffer more trans-boundary air pollution, generating public concerns in many countries. In the United States, the Environmental Protection Agency (EPA) set Cross-State Air Pollution Rule in 2011, which requires 28 states to reduce trans-boundary air pollution emissions, and the Supreme Court has ruled against electric utilities that opposed this regulation in 2014 (Kendall and Sweet, 2014). In other countries, like China, where air pollution is managed in a decentralized way by provincial and local governments, trans-boundary negative spillover may be more significant. In this chapter, I empirically study trans-boundary air pollution under China's decentralized economic and environmental governance. The main question is whether inefficiencies associated with trans-boundary air pollution have increased after the incentives of local officials changed as a result of a large-scale policy-change of the central government.

While decentralization is good for allowing policies to vary more with the heterogeneity of local preferences and it may induce fewer problems of incomplete information, decentralized environmental management may prove to be costly if a "race to the bottom" in standards of environmental quality occurs when local governments compete for new investment (Cumberland, 1981), or if local governments free ride for trans-boundary negative externalities of pollution (Oates, 1999, 2002). The latter concern of trans-boundary pollution has been considered as a more serious problem when environmental damage is capitalized into local property values (Oates, 1999). There is empirical evidence in the literature for trans-boundary river pollution, showing that polluting activities are generally more significant near downstream jurisdictional borders when environmental management is decentralized (Sigman, 2002, 2005; Helland and Whitford, 2003; Cai et al., 2016; Lipscomb and Mobarak, 2016). However, studies on trans-boundary air pollution are limited, as it is difficult to define "downwind" places clearly without detailed information of wind patterns.

Since wind patterns are crucial for determining the geographical distribution of air-polluting industries, one of the most important contributions of the present research is to define clearly which cities are "downwind" in China's provinces by exploring a dataset of wind patterns from WINDFINDER (2014). This dataset includes dominant wind direction (°) and average wind speed (km/h) over 12 months for each province. Using these data, I calculate the all-time average dominant wind direction in each province, and then define which cities are "downwind" based on this direction. I also measure the intensity of wind by the average wind speed, and measure the stability of wind direction by the standard deviation of wind direction in each province. The details about this dataset and how to define "downwind" cities are discussed in Section 2.2.1. Combining the data of wind patterns and geographical distribution of air-polluting industries, I estimate whether air polluting activities have become more significant in downwind cities near provincial borders after the policy changes of the central government, through difference-in-differences (DID) estimations. I also conduct triple-differences (DDD) estimations in order to analyze whether the effects of trans-boundary air pollution are more significant in places with higher wind speed or with more stable wind direction after the reforms.

This empirical strategy is based on changes to environmental policies made by China's central government in the early 2000s, which have largely affected the incentives of subnational political leaders under China's political system. China's current political system is a combination of centrally controlled political governance and decentralized economic governance (Landry, 2008; Xu, 2011). Subnational governments have overall right and responsibilities in local economic and social governance, including environmental management, while local leaders are appointed from above in a centralized cadre management system. They are motivated to focus on local outcomes in order to satisfy standard and rules set by the central government, and they compete with each other for promotion (Qian et al., 1999; Li and Zhou, 2005). Hence, this political system creates localized incentives for local leaders to free ride on the externalities influencing their neighboring areas. When the central government changed environmental policies in the early 2000s, environmental outcomes became more important for the objectives of local governments, and subnational leaders were given stronger incentives to free ride on trans-boundary environmental pollution.

Reforms of environmental policies were launched by the central government, in order to fight against severe air pollution in China. The annual average ambient concentration of total suspended particles in China's major cities from 1981 to 2001 was more than double the national standard of $200\mu g/m^3$ (Bi et al., 2007), which was itself five times of the level in the United States before the Clean Air Act in 1970 (Chen et al., 2013). The degree of air pollution in modern China is similar to the heavy pollution during the historical period of industrialization in developed countries (Rawski, 2009). Severe air pollution in modern China is highly correlated with the use of coal as the main source of energy. For more than 20 years, China has been the world's largest producer and consumer of coal. In 2015, total production of coal in China was 3.747 billion metric tonnes (47.7% of total global production), and total consumption of coal in China was 3.939 billion metric tonnes (50.0% of total global consumption). Figure 1 shows the production and consumption of coal in China from 1981 to 2015[1]. Severe air pollution has caused huge welfare losses in China. The health losses from air pollution in China are 3.8% of GDP, while the total costs of water and air pollution are 5.8% of GDP according to a survey by World Bank (2007). In order to deal with the environmental crisis, the central government has made major changes to environmental policies since the early 2000s. The new regime of environmental policies includes targets to reduce pollution emissions, stricter laws on monitoring and punishing pollution, and changes to the criteria of evaluating local officials' performances. However, environmental pollution has not been alleviated significantly in China after this policy-change in environmental management. As shown in Figure 1, coal production and consumption continued to grow rapidly during the period from 2001 to 2013. In contrast to the target to reduce total emissions of sulfur dioxide (SO_2) by 10% in the Tenth Five-Year Plan (2001–2005), the actual level of SO_2 emissions

[1]Data source: "BP Statistical Review of World Energy 2016," (British Petroleum, 2016).

increased by 27% during the 5-year period (Cai et al., 2016). The free-riding behavior of local governments for trans-boundary spillover may partly explain the reason that environmental quality is not improving significantly after the regime shift in environmental management. Hence, studies on trans-boundary air pollution may have important policy implications for China's decentralized economic and environmental governance.

In this study, I empirically test the level of trans-boundary air pollution in China through a treatment effects approach, which is based on changes to incentives faced by provincial and local officials after the central government has reformed environmental policies in the early 2000s, as well as patterns of average wind speed and stability of wind direction. According to the definition of "polluting industries" in the *Report on the First National Census of Polluting Sources* (MEP, 2010), I use firm level data from the Annual Survey of Above-Scale Industrial Firms (National Bureau of Statistics, 1998–2007) to calculate the aggregate outputs in polluting industries of four major air pollutants (SO_2, NO_2, dust, and soot) for 286 major cities in China during the period of 1998–2007. These variables are used as measures for intensity of air-polluting activities at city level. From the DID estimations for cities near a provincial border (a distance less than 100 km), I find that outputs of polluting industries for pollutants SO_2, NO_2, and soot are relatively higher in downwind cities after 2003. The DDD estimations further show that the effects of trans-boundary air pollution are stronger in downwind cities with higher average wind speed, and such effects are stronger in downwind cities with more stable wind direction (smaller standard deviation of wind direction). These findings are consistent with the hypothesis that provincial and local governments free ride more on trans-boundary air pollution after the central government reformed environmental policies. Due to this kind of negative trans-boundary externality of environmental pollution, further reforms in political institutions and current decentralized environmental management system are necessary to mitigate air pollution in China effectively.

The remainder of the chapter is organized as follows: Section 2.2 reviews the literature, and introduces the wind patterns and institutions that shape the research design. Section 2.3 reports the data and econometric specifications. Section 2.4 presents the baseline empirical results. Section 2.5 reports the results of the robustness checks. Section 2.6 concludes. Section 2.7 includes the figures and tables.

2.2 WIND PATTERNS, INSTITUTIONS, AND TRANS-BOUNDARY POLLUTION

2.2.1 Wind Patterns and Downwind Cities in China's Provinces

The regime shift in environmental management in the early 2000s provides a chance to study trans-boundary air pollution in China empirically using a difference-in-difference (DID) approach. The incentives faced by local governments have changed since the policy-change, and the localized environmental outcomes have become much more important to local leaders. They are more likely to take advantage of trans-boundary externalities of environmental pollution after the reforms. If the provincial and local governments free ride more on trans-boundary negative externalities, they will relocate air-polluting industries to downwind regions near provincial borders. Since it is difficult to define downwind cities without detailed information about wind patterns in each province, trans-boundary air pollution has not been well studied in previous literature. One of the most important contributions of this study is to define downwind cities clearly in each province according to a recently available dataset of wind patterns. Based on this, I conduct estimations according to dominant wind direction, average wind speed, as well as standard deviation of wind direction.

The provincial data of wind patterns are obtained from WINDFINDER (2014), which provides worldwide wind and weather information, including data of monthly wind patterns in China's 30 provinces[2]. This is an important meteorological dataset currently open to the public for studies on wind in China. It includes dominant wind direction (°) and average wind speed (km/h) over 12 months, showing seasonal changes of wind patterns in each province. Therefore, I can calculate an all-time average dominant wind direction, an average wind speed, and a standard deviation of wind direction for each province according to the dataset. Figure 2 shows the all-time average dominant wind direction for each province of China, and Table 1 presents the summary statistics of wind patterns in each province. "Downwind" cities in each province are defined according to the figure. Here, I take Henan Province, the most populous province in China, as one example of how to define downwind

[2] Mainland China has 31 provinces (including 5 autonomous regions and 4 municipalities), and this dataset covers all provinces except Tibet Autonomous Region.

cities. Figure 3 shows the location of major cities in Henan Province. The average dominant wind direction is 95.3° in this province, which is close to the direction of east. The following cities are defined as downwind cities: Anyang, Hebi, Jiaozuo, Nanyang, Sanmenxia, and Xinyang. Downwind cities in all other provinces are defined in the same way. In addition, I measure wind intensity by average wind speed, and I measure the stability of wind direction by standard deviation of wind direction in each province.

China's wind patterns, including average wind speed and stability of wind direction (measured by standard deviation of wind direction), are comparable to other big countries with large population size (e.g. the United States, India, and Brazil). There is quite large variation in both wind speed and stability of wind direction, across different regions in China. Therefore, China is a good example for studying trans-boundary air pollution using a quasi-experimental approach based on wind patterns.

2.2.2 Institutions: Decentralization, Changes of Environmental Policy, and Incentives of Local Officials in China

The empirical strategy in this chapter is motivated by some important features of the fundamental institutions of China's political economy, which shape the incentives of local governments when they are faced with changes of the central government's environmental policies. In this subsection, I briefly introduce background facts about institutions, beginning with China's regional decentralization.

China's political system since the reforms starting in 1978 has been characterized as a regionally decentralized authoritarian (RDA) regime[3] by some scholars. This regime is a combination of centrally controlled political governance and decentralized economic governance (Landry, 2008; Xu, 2011); while local leaders are appointed from above in a centralized cadre management system, the governance of national economy is delegated to subnational governments, and subnational governments have overall responsibility for developing local economic policies, providing public services, and designing and enforcing laws Xu (2011).

[3] The term RDA regime is suggested by Xu (2011) to characterize the political system in modern China for interpreting the political economy of China's rapid economic growth in recent decades, which is different from both federalism under democracy and a centrally-planned economy.

Currently, there are five vertical hierarchies in China's governance structure: the nation, province, prefecture, county and township. The governments at hierarchies from province to township are generally called local (subnational) governments, and the governments at provincial and prefectural levels are the most powerful in developing local economic policies and implementing environmental regulation. In China's political system, local governments are motivated to fulfill the targets and tasks set by the upper-level government, and "yardstick competition" takes place among provincial and local governments for political promotion (Qian et al., 1999). In 1980s and 1990s, China's central government used GDP growth as a major indicator to evaluate performance of provincial and local governments; Li and Zhou (2005) find that there was a significant effect of GDP growth on the probability of provincial governors being promoted in China from 1979 to 2002. This kind of GDP competition was not able to provide enough incentives for local governments to pursue long-run sustainable development and environmental protection.

However, there have been major changes to environmental policies in the period of the Tenth Five-Year Plan (2001–2005). The incentives of the central government to initiate this regime shift in environmental management include concerns about legitimacy when environmental pollution has caused social unrest and international pressure (Wang, 2013), as well as increasing demand for better environmental quality of the growing urban middle class in China (Zheng and Kahn, 2013). The Tenth Five-Year Plan adopted in 2000 set specific targets to reduce major water and air pollutants for the first time in history. Furthermore, laws to monitor and punish offenders for environmental pollution were amended and became effective in the middle of 2003, requiring stricter environmental compliance. Moreover, there have been more indicators of environmental quality in the explicit performance criteria of provincial and local officials, including air pollution level (Landry, 2008). The central government also uses preferential fiscal transfers as a way to encourage local governments to pursue environmental goals (Liu and Zhang, 2011), as a large proportion of local public expenditure in China relies on fiscal transfers from the central government under China's current tax revenue-sharing system[4]. Hence, provincial and local governments may have much stronger incentives to free ride on trans-boundary environmental pollution after the policy-change, as

[4]The share of fiscal transfer in local public expenditure was 43.8% in 2010.

they compete with each other to fulfill the targets of the central government under centrally controlled personnel governance. Their intention can be realized by influencing the location choices of firms by urban planning and land sales as basic policy tools (Zheng and Kahn, 2013), as land supply in China is totally controlled by governments, and the state-owned enterprises controlled by local governments own a large share of local output. Zheng et al. (2014) find that energy intensity and air pollution affect the promotion probability of mayors in 86 Chinese cities. However, there are still questions on how environmental pollution really matter for the promotion of local officials, as other factors, like corruption and connections with central leaders, may affect the relationship between pollution and promotion of local officials (Jia, 2017). The observed patterns of trans-boundary air pollution in the empirical results of this chapter may be helpful to infer whether environmental pollution really matter for the incentives facing provincial and local officials after the regime shift in environmental management undertaken by the central government.

2.2.3 Trans-boundary Pollution and Empirical Strategy

Trans-boundary pollution has become an important research question in environmental economics as it affects the efficiency of decentralized environmental management. Since it is easier to define "upstream" and "downstream" for river than air, and water pollution is under decentralized management while air pollution is managed in a relatively more centralized systems in countries like the United States, previous studies mainly focus on trans-boundary river pollution. Early studies using traditional multivariate regression have found that river pollution is generally higher in places near jurisdictional borders. Sigman (2002) uses data from 291 river monitoring stations of the UN's Global Emissions Monitoring System in 49 countries from 1979 to 1996, and finds that places just upstream of international borders have higher levels of Biochemical Oxygen Demand than other places do. Helland and Whitford (2003) use Toxic Release Inventory (TRI) data in the United States from 1987 to 1996 to find that toxic chemical releases are higher in counties near state border. However, there may be potential endogeneity problems when we observe correlation of having more pollution and being nearer to jurisdictional border in these traditional multivariate regression analysis, because places near borders may differ in many dimensions from interior regions. Hence, identification strategies based on treatment effects have been adopted in later studies on trans-boundary river pollution.

More recent studies use DID methodology to estimate the effects of trans-boundary river pollution under decentralized environmental management. Sigman (2005) uses the variation in the time of U.S. states being authorized to manage river pollution via the Clean Water Act to study whether trans-boundary pollution is higher when the states received authorization to the act, and she finds a 4% degradation of water quality downstream of authorized states. The natural experiment in this research is changes in the degree of decentralization. Changes of jurisdictional borders are also used in some studies on trans-boundary river pollution. Lipscomb and Mobarak (2016) use changes of county boundaries in each electoral cycle in Brazil to find empirical evidence for the following hypotheses: pollution should increase at an increasing rate as a river approaches a downstream exit border; there should be a structural break in the slope of the pollution function at border; and a larger number of managing jurisdictions should increase negative externalities. Different from both Sigman (2005) and Lipscomb and Mobarak (2016), Cai et al. (2016) use changes to incentives facing local governments when the central government changed environmental policy, in order to study trans-boundary pollution in China's 24 longest rivers. They find that after the policy changes in the Tenth Five-Year Plan period (2001–2005), output in polluting industries [5] is much higher in the most downstream counties in each province along the 24 rivers. I use similar methods to define and calculate outputs in polluting industries for air pollutants, and my empirical strategy is also based on changes of incentives facing local governments.

Since I am able to define downwind cities clearly based on a provincial dataset of wind patterns, while China's air pollution is under decentralized management and provincial and local governments have significant flexibility to develop policies to deal with air pollution, my research focuses on trans-boundary air pollution. I provide empirical evidence for whether there has been more trans-boundary air pollution after the central government changed environmental policies in China. Although it is difficult to define "upstream" and "downstream"

[5] The *Report on the First National Census of Polluting Sources* (MEP, 2010) defines seven industries as polluting rivers.

for air as clearly as for rivers, I define which cities in each province are "downwind" for air pollution according to the patterns of wind direction, as discussed in Section 2.2.1. I use DID estimations to explore whether the outputs in air-polluting industries are higher in downwind cities near provincial borders after the reforms. Moreover, the additional information of wind speed and standard deviation of wind direction leads to DDD estimations for whether the effects of trans-boundary air pollution are more significant in downwind cities with higher wind speed, or whether those effects are higher in downwind cities with more stable wind direction (smaller standard deviation of wind direction).

2.3 DATA SOURCE AND ECONOMETRIC SPECIFICATION

The empirical analysis in this chapter answers the following question. After the central government changed environmental policies, are local governments dumping more air pollutants in downwind cities near the provincial border? If inefficiencies associated with trans-boundary pollution have increased after the policy changes, the following predictions can be tested in my empirical analysis. (1) Outputs in air-polluting industries are relatively higher in downwind cities near the provincial border after 2003. (2) This effect is more significant in downwind cities with higher wind speed. (3) This effect is more significant in downwind cities with more stable wind direction (smaller standard deviation of wind direction). (4) For non-polluting industries, this effect does not exist, or moves in the opposite direction.

I use total production output in polluting industries, aggregated from a firm-level dataset, in order to measure the size of polluting activities in each city. This approach follows Cai et al. (2016)'s empirical study on trans-boundary river pollution in China. According to their introduction to the institutional background of China's environmental management system, the monitoring technology for pollutant discharges adopted by China's central government during the sample period (1998–2007) was very crude in that the pollutant discharges were not measured directly. Instead, pollution discharges were estimated from output in polluting industries. Industrial air pollution was estimated in the same way as water pollution, using output data. In this chapter, owing to data limitations, I use the aggregated output data of polluting industries to measure the intensity of polluting activities, following the approach of Cai et al. (2016) to estimate river pollution.

The city-level measures of the intensity of air-polluting activities are aggregate outputs in the polluting industries of four major air pollutants (SO_2, NO_2, dust, and soot). These variables are calculated using the dataset of the Annual Survey of Above-Scale Industrial Firms (National Bureau of Statistics, 1998–2007). An above-scale industrial firm is that with annual revenue above 5 million RMB (approximately 0.76 million U.S. dollars). The survey covers all such firms and all other state-owned firms located in 286 major cities from 1998 to 2007. Similar to the definition of polluting industries for river pollution in Cai et al. (2016), I define polluting industries for each kind of air pollutant according to the *Report on the First National Census of Polluting Sources* (MEP, 2010). The four kinds of air pollutants listed in this report are SO_2, NO_2, dust, and soot. Table 2 summarizes the two-digit polluting industries for each kind of air pollutant according to MEP (2010). I calculate the aggregate outputs in the polluting industries of those four major air pollutants in each city and in each year during the period 1998–2007.

Different from previous studies on trans-boundary pollution, like the empirical works of Sigman (2002, 2005) and Lipscomb and Mobarak (2016) on river pollution, which estimated changes to pollutant level on the boundary, I instead consider industrial location choice when subnational governments in China have more incentives to free ride on trans-boundary air pollution. China's provincial governments began locating more highly polluting industries in downwind cities near provincial borders than in all other types of cities, after the central government changed its environmental policy in 2003. I test this change to industrial location directly through estimation of the output of polluting industries in downwind cities near provincial borders, using a DID approach. There could be more outputs in air polluting industries in downwind cities near provincial borders, there could be more outputs in downwind cities with higher wind speed, and there could be more outputs in downwind cities with more stable wind direction (smaller standard deviation of wind direction).

First, for cities near a provincial border (distance of less than 100 km), I estimate the effects on downwind cities after the policy changes in environmental management through

DID estimation. The baseline estimation equation is shown in Equation (2.1) as follows.

$$Pollution_{it} = \beta_0 + \beta_1 \cdot Downwind_i \times Post_t + \mathbf{X}\theta + \alpha_i + \gamma_t + \varepsilon_{it} \tag{2.1}$$

The subscript i in Equation (2.1) denotes city, while t denotes year. $Pollution_{it}$ denotes city level air pollution intensity. The interaction term between $Post_t$ and $Downwind_i$ is the key explanatory variable for estimating the treatment effects of the policy changes in environmental management. $Post_t$ is a dummy variable indicating time of the policy changes. $Downwind_i$ is a dummy variable indicating whether the city i is in a downwind part of the province, according to the wind patterns in Figure 2. I test whether β_1, the coefficient of interaction term between $Downwind_i$ and $Post_t$ is significantly positive, which is the parameter of interest that indicates whether provincial governments dump more air-polluting industries to downwind cities near provincial border after the policy changes. X is a set of other control variables, which are the city level socio-economic characteristics that may affect air pollution, including population size, size of industrial output, population density, GDP per capita[6], industrial structure, percentage of government expenditure, and share of foreign investment. The data sources for control variables are from every year's *China Urban Statistical Yearbook*. α_i is the city fixed effects. γ_t is the year fixed effects. ε_{it} is the random error term.

Second, wind speed is added to the estimation to show whether outputs of air polluting activities are higher in downwind cities with higher average wind speed. A DDD estimation is shown in Equation (2.2) as follows.

$$\begin{aligned} Pollution_{it} &= \beta_0 + \beta_1 \cdot Downwind_i \times Post_t + \beta_2 \cdot Wind\ Speed_i \times Post_t \\ &+ \beta_3 \cdot Downwind_i \times Wind\ Speed_i \times Post_t + \mathbf{X}\theta + \alpha_i + \gamma_t + \varepsilon_{it} \end{aligned} \tag{2.2}$$

$Wind\ Speed_i$ is average wind speed. The coefficient of the interaction term $Downwind_i \times Wind\ Speed_i \times Post_t$ is the DDD estimator for whether intensity of air-polluting activities is higher after the policy changes in downwind cities with higher average wind speed. The hypothetical trans-boundary air pollution after policy changes predicts a positive sign for β_3, which is the parameters of interest in Equation (2.2).

[6]I also include its square term to control for possible environmental Kuznets curve effects.

Third, standard deviation of wind direction is added to the estimation to show whether outputs of air-polluting activities are higher in downwind cities with more stable wind direction (smaller standard deviation of wind direction). A DDD estimation is shown in Equation (2.3) as follows.

$$\begin{aligned} Pollution_{it} &= \beta_0 + \beta_1 \cdot Downwind_i \times Post_t + \beta_2 \cdot Direction\ Std_i \times Post_t \\ &+ \beta_3 \cdot Downwind_i \times Direction\ Std_i \times Post_t + \mathbf{X}\theta + \alpha_i + \gamma_t + \varepsilon_{it} \end{aligned} \tag{2.3}$$

$Direction\ Std_i$ is the standard deviation of wind direction. The coefficient of the interaction term $Downwind_i \times Direction\ Std_i \times Post_t$ is the DDD estimator for whether intensity of air-polluting activities is higher after the policy changes in downwind cities with more stable wind direction (smaller standard deviation of wind direction). The hypothetical trans-boundary air pollution after policy changes predicts a positive sign for β_2 and negative sign for β_3, which are the parameters of interest in Equation 2.3.

Next, for a sample of all cities, a DDD estimation is based on whether the city is near a provincial border, whether the city is downwind, and time of the reforms. The estimation equation is shown in Equation (2.4) as follows.

$$\begin{aligned} Pollution_{it} &= \beta_0 + \beta_1 \cdot Border_i \times Post_t + \beta_2 \cdot Downwind_i \times Post_t \\ &+ \beta_3 \cdot Border_i \times Downwind_i \times Post_t + \mathbf{X}\theta + \alpha_i + \gamma_t + \varepsilon_{it} \end{aligned} \tag{2.4}$$

The coefficient of the interaction term $Border_i \times Downwind_i \times Post_t$ is the DDD estimator for whether intensity of air-polluting activities is higher after the policy changes in cities near a provincial border and in a downwind part of the province. The hypothetical trans-boundary air pollution after policy changes predicts a positive sign for β_3, which is the parameter of interest in Equation (2.4).

Finally, a DDD estimation is based on distance to provincial border, whether the city is downwind, and time of the reforms. The estimation equation is shown in Equation 2.5 as follows.

$$\begin{aligned} Pollution_{it} &= \beta_0 + \beta_1 \cdot Distance\ Border_i \times Post_t + \beta_2 \cdot Downwind_i \times Post_t \\ &+ \beta_3 \cdot Distance\ Border_i \times Downwind_i \times Post_t + \mathbf{X}\theta + \alpha_i + \gamma_t + \varepsilon_{it} \end{aligned} \tag{2.5}$$

$Distance\ Border_i$ is the city's distance to a provincial border. For the estimations on all cities, distance to provincial border should be controlled, because the effects of trans-boundary pollution may be significant only in cities located not too far from a provincial border, and the effects may be larger in cities closer to a provincial border. The coefficient of the interaction term $Distance\ Border_i \times Downwind_i \times Post_t$ is the DDD estimator for whether intensity of air-polluting activities is higher after the policy changes in cities closer to a provincial border and in a downwind part of the province. The hypothetical trans-boundary air pollution after policy changes predicts a positive sign for β_2 and a negative sign for β_3, which are the parameters of interest in this regression equation. Table 3 shows the summary statistics of variables used in the empirical analysis.

2.4 ESTIMATION RESULTS

2.4.1 Difference-in-differences Estimations for Cities near Border

First, I report the results for DID estimations based on Equation (2.1) in Table 4, which uses interaction terms between $Distance\ Border$ and year dummies $Post2000$ and $Post2003$. Since the years 2000 and 2003 were the time of major policy changes, $Post2000$ ($Post2003$) is a dummy variable that equals 1 after year 2000 (2003), and 0 otherwise. The dependent variables in all columns of Table 4 are annual outputs in polluting industries for each kind of pollutant according to the definition in Table 2. Columns (1) to (3) are estimation results for pollutant SO_2. The specification in Column (1) is without any control variable, and the parameters of interest are not statistically significant. In Column (2), when population size and total output of industrial firms are controlled, the coefficient of the interaction term $Downwind \times Post2003$ is significantly positive (2.526), which implies that annual output in polluting industries of SO_2 is higher by 2.526 billion RMB (approximately 382 million U.S. dollars) in downwind cities after 2003. The coefficient of the interaction term $Downwind \times Post2000$ is not statistically significant, which implies that the effect did not exist at the beginning. In Column (3), when a set of other control variables is controlled, the coefficient of the interaction term $Downwind \times Post2003$ is also significantly positive (3.245), which implies that annual output in polluting industries of SO_2 is higher by 3.245 billion RMB (approximately 490 million U.S. dollars) in downwind cities after 2003. The coefficient of the interaction term $Downwind \times Post2000$ is not statistically significant, which implies that the effect did not exist at the beginning. Columns (4) to (6) are the estimation results for pollutant NO_2. The general patterns of the results are very similar to those for SO_2. In Column (6), when all the control variables are included, the coefficient of the interaction term $Downwind \times Post2003$ is significantly positive (2.908), which implies that annual output in polluting industries of NO_2 is higher by 2.908 billion RMB (approximately 435 million U.S. dollars) in downwind cities after 2003. The coefficient of the interaction term $Downwind \times Post2000$ is not statistically significant, which implies that the effect did not exist at the beginning. Figure 4 shows trends before and after the policy changes in the two groups of cities.

The results in Table 5 are also based on the specification of Equation (2.2), with different dependent variables. Columns (1) to (3) are the estimation results for pollutant *Soot*. The specification in Column (1) is without any control variable, and the parameters of interest are not statistically significant. In Column (2), when population size and total output of industrial firms are controlled, the coefficient of the interaction term $Downwind \times Post2000$ is significantly positive (1.033), which implies that the annual output in polluting industries of *Soot* is higher by 1.033 billion RMB (approximately 156 million U.S. dollars) in downwind cities after 2000. The coefficient of the interaction term $Downwind \times Post2003$ is also significantly positive (3.356), which implies that annual output in polluting industries of *Soot* is higher by 3.356 billion RMB (approximately 507 million U.S. dollars) in downwind cities after 2003. In Column (3), when a set of other control variables is controlled, the coefficient of the interaction term $Downwind \times Post2000$ is still significantly positive (1.340), which implies that annual output in polluting industries of *Soot* is higher by 1.340 billion RMB (approximately 202 million U.S. dollars) in downwind cities after 2000. The coefficient of the interaction term $Downwind \times Post2003$ is also significantly positive (4.117), which implies that annual output in polluting industries of *Soot* is higher by 4.117 billion RMB (approximately 622 million U.S. dollars) in downwind cities after 2003. Columns (4) to (6) are the estimation results for pollutant $Dust$. In Column (5) and (6), when control variables are included, neither $Downwind \times Post2000$ nor $Downwind \times Post2003$ is statistically significant, which implies that the effects on downwind cities for SO_2, NO_2 and $Soot$ are insignificant for pollutant $Dust$. Figure 5 shows trends before and after the policy changes in the two groups of cities. Figure 6 shows that the share of polluting industries in downwind cities is higher after the policy changes.

2.4.2 Triple-differences Estimations for More Wind Patterns and More Cities

Table 6 reports the results for the DDD estimations using average wind speed, based on the specification in Equation (2.2). All columns are estimated using fixed-effect models, in which I also include control variables of socio-economic characteristics and dummy variables for year fixed effects. Column (1) shows the estimation result for pollutant SO_2. While the interaction terms with $Post2000$ are not statistically significant, the DDD interaction term $Downwind \times Wind\ Speed \times Post2003$ is significantly positive (0.523), and the interaction term $Downwind \times Post2003$ is negative (-2.640) but not statistically significant. This result implies that the effects of trans-boundary air pollution are stronger in downwind cities with higher average wind speed. I also calculate the estimated marginal effects of $Downwind$ at different percentiles of $WindSpeed$, which shows that the effect at the 90th percentile of $Wind\ Speed$ (15.5 km/h) is 5.46, and the effect at the 25th percentile of $Wind\ Speed$ (10.3 km/h) is 2.75. Column (2) shows the estimation result for pollutant NO_2. While both $Downwind \times Wind\ Speed \times Post2003$ and $Downwind \times Post2003$ are positive but insignificant, the estimated marginal effects of $Downwind$ at different percentiles of $Wind\ Speed$ are significantly positive. The effect at the 90th percentile of $Wind\ Speed$ (15.5 km/h) is 3.82, and the effect at the 25th percentile of $Wind\ Speed$ (10.3 km/h) is 2.62. Column (3) shows the estimation result for pollutant $Soot$. The general patterns of the estimated coefficients are very similar to those in Column (1), and the marginal effect at the 90th percentile of $Wind\ Speed$ (15.5 km/h) is 7.29, while the effect at the 25th percentile of $Wind\ Speed$ (10.3 km/h) is 3.73. Column (4) shows the estimation result for pollutant $Dust$, and the parameters of interest are not statistically significant.

Table 7 reports the results for the DDD estimations using standard deviation of wind direction, based on the specification in Equation (2.3). All columns are estimated using fixed-effect models, in which I also include the control variables of socio-economic characteristics and dummy variables for year fixed effects. Column (1) shows the estimation result for pollutant SO_2. While the DDD interaction term $Downwind \times Direction\ Std \times Post2000$ is not statistically significant, the DDD interaction term $Downwind \times Direction\ Std \times Post2003$ is significantly negative (-0.0753), and the interaction term $Downwind \times Post_2 003$ is significantly positive (7.618). This finding implies that the effects of trans-boundary air pollution are stronger in downwind cities with more stable wind direction (smaller standard deviation of wind direction). I also calculate the estimated marginal effects of $Downwind$ at different percentiles of $Direction\ Std$, which shows that the effect at the 10th percentile of $Direction\ Std$ (42.9) is 4.39, and the effect at the 50th percentile of $Direction\ Std$ (68.4) is 2.47. The effect becomes statistically insignificant at the 75th percentile of $Direction\ Std$ (88.4). Column (2) shows the estimation result for pollutant NO_2. While $Downwind \times Direction\ Std \times Post2003$ is negative but not statistically significant, $Downwind \times Post2003$ is still significantly positive (6.725). The marginal effect at the 10th percentile of $Direction\ Std$ (42.9) is 3.87, and the effect at the 50th percentile of $Direction\ Std$ (68.4) is 2.10. The effect becomes statistically insignificant at the 75th percentile of $Direction\ Std$ (88.4). Column (3) shows the estimation result for pollutant $Soot$. The general patterns of estimated coefficients are very similar to those in Column (2), and the marginal effect at the 10th percentile of $Direction\ Std$ (42.9) is 5.48, while the effect at the 50th percentile of $Direction\ Std$ (68.4) is 3.59. The effect becomes statistically insignificant at the 75th percentile of $Direction\ Std$ (88.4). Column (4) shows the estimation result for pollutant $Dust$, and the parameters of interest are not statistically significant.

Next, I estimate Equation (2.4) for the sample of all cities and report the results in Table 8. This is a DDD estimation based on whether the city is near a provincial border, whether the city is downwind, and time of the reforms. All columns are estimated using fixed-effect models, in which I also include the control variables of socio-economic characteristics and dummy variables for year fixed effects. Columns (1) shows the estimation results for pollutant SO_2. The DDD interaction term $Border \times Downwind \times Post2003$ is significantly positive (8.332), while the interaction terms $Downwind \times Post2003$ and $Border \times Post2003$ are negative (-5.190 and -1.114, respectively). This result implies that the aggregate effect on annual output of polluting industries for pollutant SO_2 is 2.028 billion RMB higher in an average downwind city near a provincial border. Columns (2) shows the estimation result for pollutant NO_2. The DDD interaction term $Border \times Downwind \times Post2003$ is significantly positive (8.422), while the interaction terms $Downwind \times Post2003$ and $Border \times Post2003$ are negative (-5.369 and -1.609 respectively). This result implies that the aggregate effect on the annual output of polluting industries for pollutant NO_2 is 1.444 billion RMB higher in an average downwind city near provincial border. Columns (3) shows the estimation results for pollutant *Soot*. The DDD interaction term $Border \times Downwind \times Post2003$ is significantly positive (6.063), while the interaction terms $Downwind \times Post2003$ and $Border \times Post2003$ are negative (-2.068 and -3.374, respectively). This result implies that the aggregate effect on the annual output of polluting industries for pollutant *Soot* is 0.621 billion RMB higher in an average downwind city near a provincial border.

Finally, I estimate Equation (2.5) for the sample of all cities and report the results in Table 9. This is a DDD estimation based on distance to provincial border, whether the city is downwind, and time of the reforms. All columns are estimated using fixed-eefect models, in which I also include the control variables of socio-economic characteristics and dummy variables for year fixed effects. Column (1) shows the estimation results for pollutant SO_2, and Column (2) shows the estimation results for pollutant NO_2. The parameters of interest in these two columns are not statistically significant, but the signs of $Distance\ Border \times Downwind \times Post2003$ are negative and the signs of $Downwind \times Post2003$ are positive, which is consistent with the findings in Table 4. Column (3) shows the estimation results for pollutant *Soot*. $Distance\ Border \times Downwind \times Post2003$ is significantly negative and $Downwind \times Post2003$ is significantly positive, which is consistent with the findings in Table 5. I also calculate the estimated marginal effects of *Downwind* at different percentiles of *Distance Border*, which shows that the effect at the 5th percentile of *Distance Border* (14km) is 5.55, and the effect at the 50th percentile of *Distance Border* (62km) is 3.03. This result implies that the output in polluting industries of soot is relatively higher in the most downwind regions after the policy changes, and the effect decreases with greater distance from the province border. Column (4) shows the estimation result for pollutant *Dust*; the parameters of interest are not statistically significant, with different signs.

2.4.3 The Effects of Neighboring Highly Populated Cities

One interesting aspect to study is whether provincial leaders care about the risk of polluting highly populated neighboring cities arising from potential exposure by media or other pressures, when they take advantage of trans-boundary pollution in downwind cities close to a provincial border. There are two main reasons that provincial and local governments might not be willing to pollute neighboring megacities. First, the politicians of big cities have higher probability of being promoted and of becoming future leaders of provincial and central government. Landry (2008) finds that the probability of being promoted is higher for the mayors of cities with higher population, higher GDP per capita, and higher economic growth. Moreover, Landry (2008) shows that there are 10 megacities among the top 15 cities in 2000 based on economic progress since city mayors of the time were appointed, and economic performance is the most important indicator in determining the outcomes of promotion competition among provincial and local politicians (Li and Zhou, 2005; Xu, 2011). Megacities are the most important places for the competition of promotion. Second, under a state-controlled media system with limited freedom of press, megacities with more political significance have greater influence on news media. Nearly all influential news media in China (newspapers, radio, and television stations) are located in major big cities, and they are either controlled or censored by the government (Latham, 2000; Stockmann and Gallagher, 2011). Meanwhile, economic reforms toward a market economy has resulted in most media institutions in China financing themselves via advertising revenues, instead of relying on state subsidies (Stockmann and Gallagher, 2011). The larger market potential in megacities encourages most news media to focus on events occurring in those cities. Therefore, pollution in neighboring megacities is more likely to be exposed by news media, and this may be of concern to provincial governments when they decide where to locate air-polluting industries.

Table 10 shows descriptive statistics for the effects of being neighboring to highly populated big cities on the share of air-polluting industries. All cities in Table 10 are downwind cities, and Panel A shows the sub-sample of downwind cities located close to highly populated megacities (urban population greater than 1 million) in the downwind direction, while Panel B shows the subsample of downwind cities that are not located close to any megacities in the downwind direction. The results clearly suggest that the increase in the share of air-polluting industries for each air pollutant after 2003 is larger and more significant in downwind cities that are not located close to any megacities in the downwind direction. This result implies that when provincial governments began to dump more air pollution to downwind cities after the policy changes in 2003, they were more likely to increase the share of polluting industries in downwind cities that were not located close to any megacities in the downwind direction. As there is a much higher risk of polluting highly populated neighboring cities arising from potential exposure by media or other pressures in the cities close to megacities in the downwind direction, provincial leaders may strategically respond to this risk when they take advantage of trans-boundary pollution in the downwind cities close to provincial border.

Tables 11–13 present some regression results to confirm the above mentioned findings. In Tables 11 and 12, I add a dummy variable *Near Megacity*, which takes the value of 1 when a city is close to a highly populated megacity (urban population greater than 1 million) in the downwind direction, and its interaction terms with time dummies $Post2000$ and $Post2003$ in the regression equations. Although *Near Megacity* is positive, the interaction terms $Near\ Megacity \times Post2000$ and $NearMegacity \times Post2003$ are negative, and the overall effects of *Near Megacity* become negative after 2003, which means that the share of air-polluting industries is lower in cities located close to highly populated megacities in the downwind direction. In Table 11, the model specification is according to Equation (2.4), and patterns of other variables are similar to the findings in Table 8. In Table 12, the model specification is according to Equation (2.5), and patterns of other variables are similar to the findings in Table 9. Meanwhile, the interaction term $Downwind \times Post2003$ becomes significantly positive, and interaction term $Distance\ Border \times Downwind \times Post2003$ becomes significantly negative for pollutant SO_2 and NO_2 in this regression, which is consistent with the pattern of more trans-boundary pollution after 2003. Table 13 reports the estimation results for regressions, including the term *Near Initial Megacity*, which is a dummy variable for whether the city is located close to megacities in the downwind direction before 2000. The significantly negative coefficient of the interaction term $Near\ Initial\ Megacity \times Post2003$ implies that when a city is located close to highly populated megacities in the downwind direction before 2000, the share of air polluting industries is relatively lower after 2003 than that of other cities not located close to any megacities in the downwind direction. This result is consistent with the hypothesis that provincial governors may care about the risk of polluting highly populated neighboring cities arising from potential exposure by news media or other pressures.

2.5 ROBUSTNESS CHECKS

In this section, I perform several robustness checks for the estimation results. The first group is shown in Table 14, in which I replace the dependent variables of outputs in polluting industries in Table 9 with aggregated outputs in several groups of non-polluting industries defined in Table 2. The dependent variable in Column (1) is aggregated outputs in all non-polluting industries for air pollution. The dependent variable in Column (2) is aggregated outputs for the combination of two-digit industries of food production (14), beverage production (15), textile (17), garments manufacture (18), and leather, furs, feather and related products (19). The dependent variable in Column (3) is aggregated outputs for the combination of two-digit industries of furniture manufacturing (21), printing (23), Cultural and sports appliances (24), medical and pharmaceutical products (27), and rubber products (29). The dependent variable in Column (4) is aggregated outputs for the combination of two-digit industries of plastic products (30), metal products (34), general appliances manufacturing (35), special appliances manufacturing (36), transportation appliances manufacturing (37), and electric appliances manufacturing (39). The dependent variable in Column (5) is aggregated outputs for the combination of two-digit industries of electronic appliances manufacturing (40), office appliances manufacturing (41), handicrafts manufacturing (42), cooking gas production (45), and water production (46). None of the five columns resembles the estimation results using the outputs in polluting industries for the four kinds of air pollutants SO_2, NO_2, $Dust$, and

Soot in Table 9. Hence, the effects of trans-boundary air pollution found in Table 9 for the polluting industries do not exist for those non-polluting industries.

Tables 15–17 replicate the estimations in Tables 4–7, with a smaller sample of cities that have a distance to provincial border of less than 80 km. There are no major changes in these results from the previous findings, and therefore, the main results of more trans-boundary pollution in downwind cities after the policy changes still hold. Tables 18–20 further restrict the sample cities to a smaller group that have a distance to provincial border of less than 60 km, and the main results are still robust.

2.6 CONCLUSION

Trans-boundary pollution is one of the major potential disadvantages of decentralized environmental management. Owing to asymmetric patterns of wind direction, places located downwind may suffer more trans-boundary air pollution. In this chapter, I empirically analyze trans-boundary air pollution under China's regionally decentralized environmental management, and find some evidence that polluting activities are relatively higher in the most downwind cities near provincial borders after the incentives of provincial and local officials were changed by the policies of the central government. From the DID estimations for the cities near a provincial border (a distance of less than 100 km), I find that the outputs of polluting industries for pollutants SO_2, NO_2, and soot are relatively higher in downwind cities after 2003. The DDD estimations further show that the effects of trans-boundary air pollution are stronger in the downwind cities with higher average wind speed, and the effects are also stronger in the downwind cities with more stable wind direction (smaller standard deviation of wind direction). These findings are consistent with the hypothesis that subnational governments free ride more on trans-boundary air pollution after the central government implemented stricter environmental standards, and this kind of free-riding behavior at least partly explains the reason that environmental pollution has not been mitigated in China even after the policy-change in environmental management initiated by the central government since the early 2000s.

The RDA regime has been considered as the fundamental institution behind China's rapid economic growth in the past several decades. However, the competition among local officials for promotion under the RDA regime is not able to provide enough incentives for local governments to pursue long-run sustainable development and environmental protection. When the central government begins to pursue environmental goals, distorted incentives facing local officials are likely to have caused more significant trans-boundary environmental pollution, which greatly reduces the efficiency of decentralized environmental management. Given the existence of negative trans-boundary externalities, reforms in political institutions and decentralized environmental management system are necessary to mitigate air pollution in China effectively.

2.7 FIGURES AND TABLES

Figure 1: Production and Consumption of Coal in China (Unit: Million Metric Tonnes)

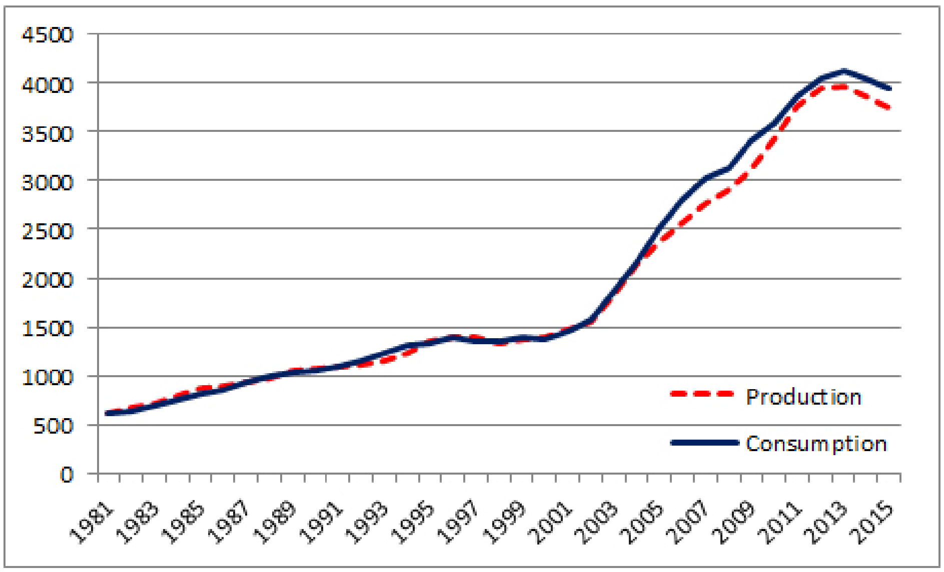


Figure 2: Dominant Wind Directions in China

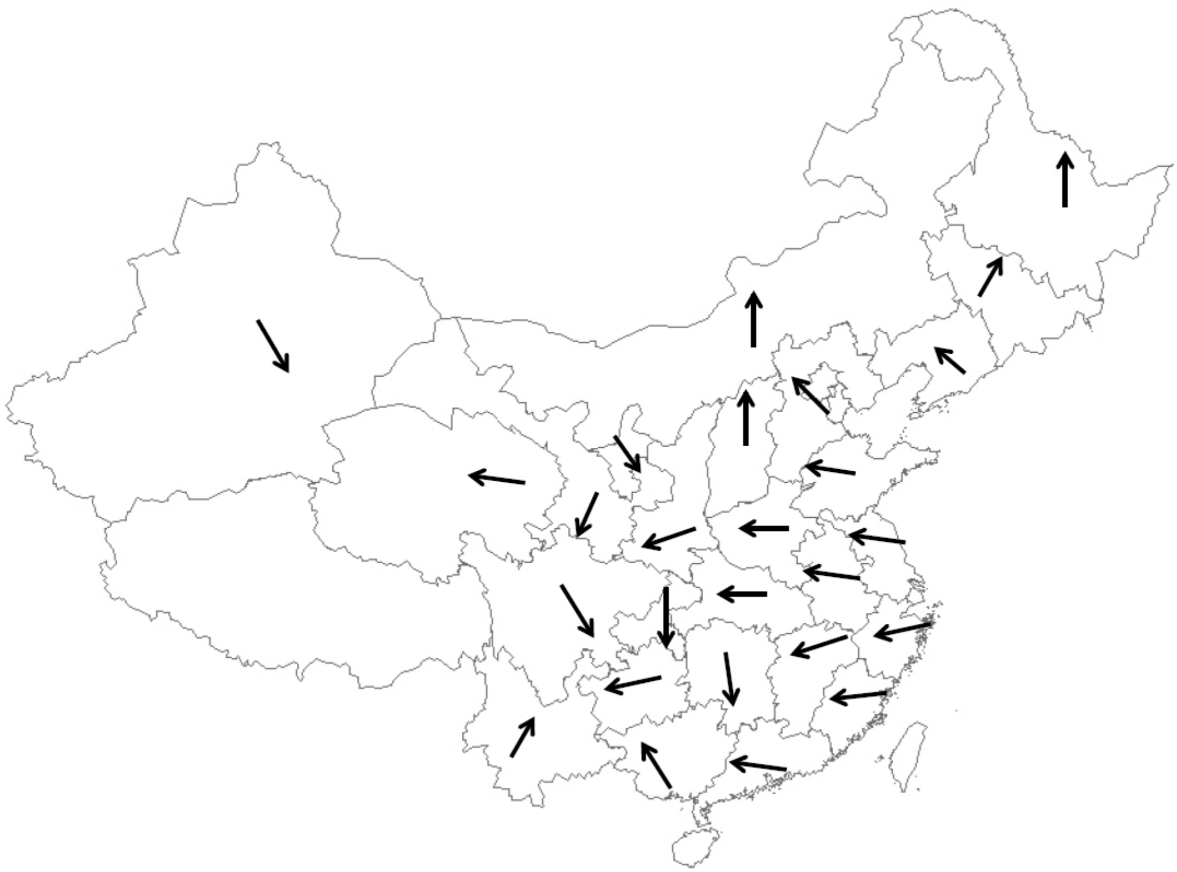


Figure 3: Downwind and Upwind Cities in Henan Province

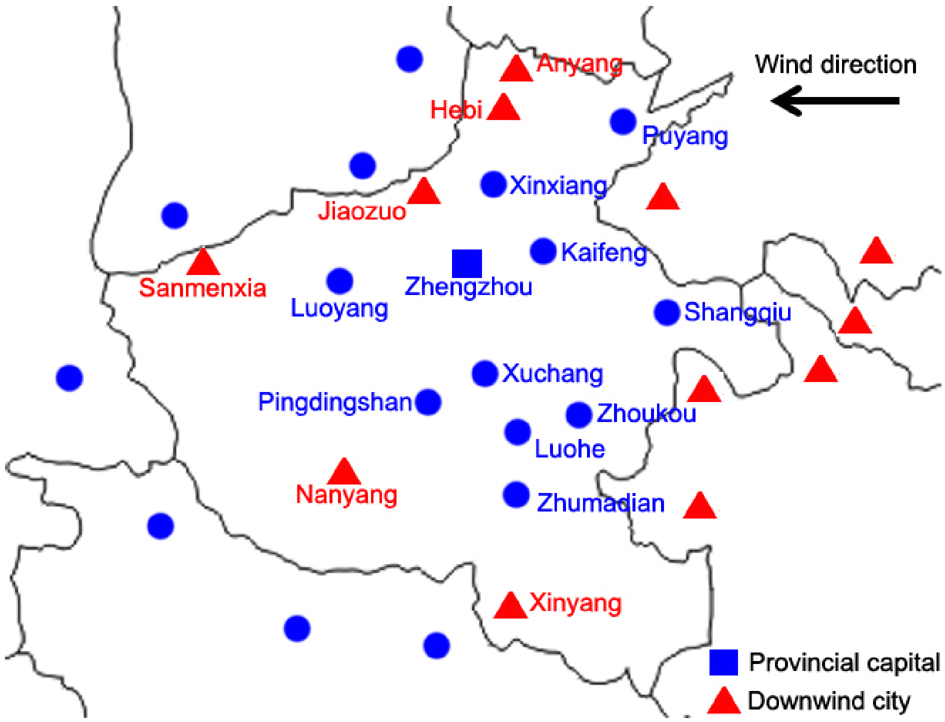


Figure 4: Trends of Polluting Industries (SO_2 and NO_2)

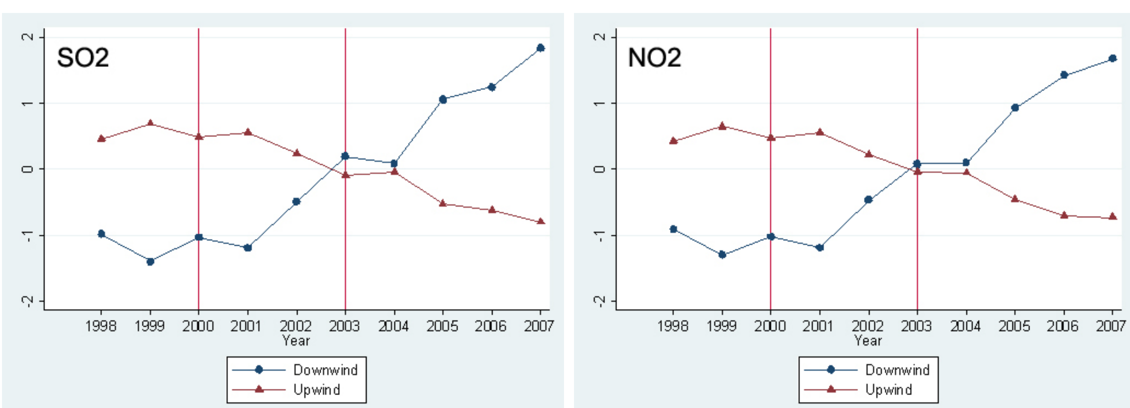


Figure 5: Trends of Polluting Industries (*Soot* and *Dust*)

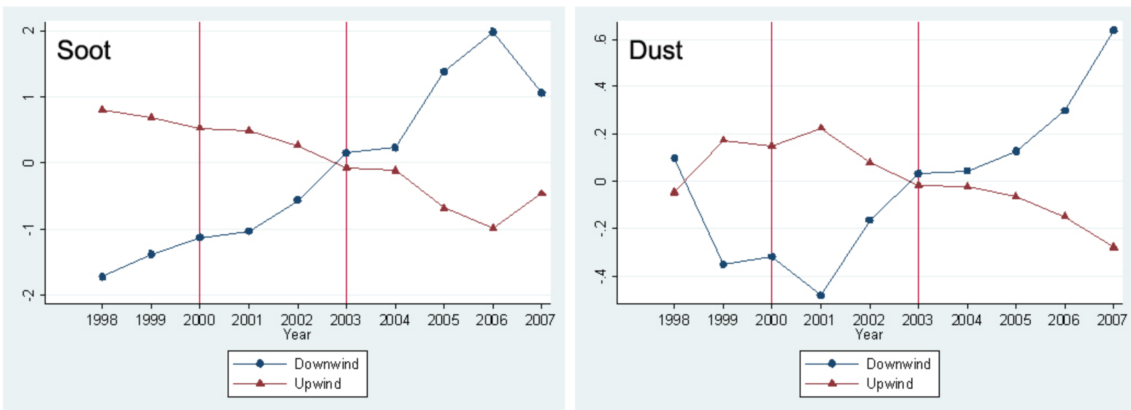


Figure 6: Share of Polluting Industries in Downwind Cities

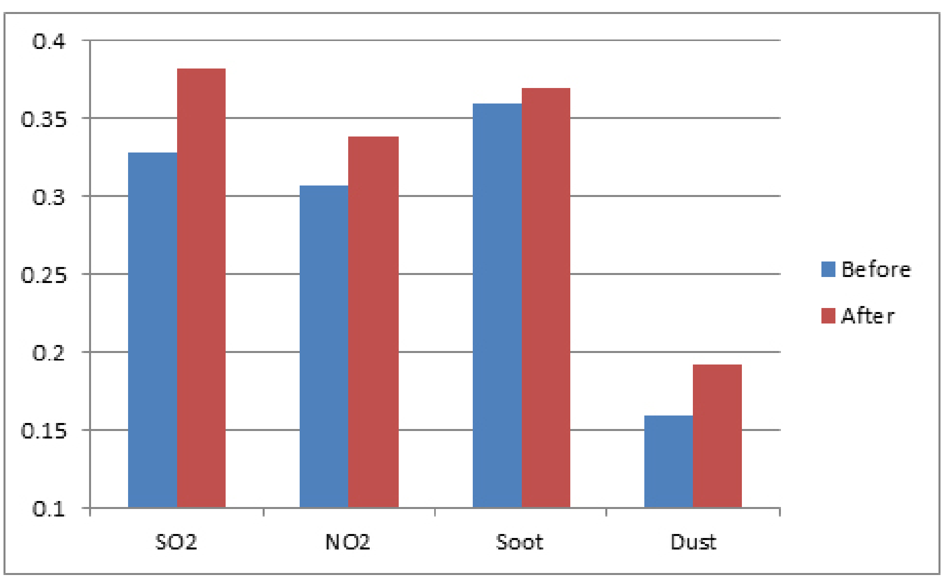


Table 1: Wind Patterns in China's Provinces

Province (Provincial capital)	Average wind speed (km/h)	Average wind direction (∘)	Standard deviation of wind direction (∘)
Hebei (Shijiazhuang)	7.6	140.5 (SE)	9.9
Shanxi (Taiyuan)	11.2	183.5 (S)	75.9
Inner Mongolia (Hohhot)	12.5	172.3 (S)	82.8
Liaoning (Shenyang)	13.5	134.8 (SE)	88.4
Jilin (Changchun)	14.2	219.3 (SW)	39.7
Heilongjiang (Harbin)	15.5	174.2 (S)	42.9
Jiangsu (Nanjing)	12.8	112.0 (ESE)	47.0
Zhejiang (Hangzhou)	11.5	54.3 (NE)	68.4
Anhui (Hefei)	11.8	117.8 (ESE)	69.3
Fujian (Fuzhou)	18.9	74.8 (ENE)	68.8
Jiangxi (Nanchang)	6.7	61.7 (ENE)	53.6
Shandong (Jinan)	10.5	134.8 (SE)	55.2
Henan (Zhengzhou)	11.8	95.3 (E)	77.6
Hubei (Wuhan)	11.2	82.3 (E)	55.3
Hunan (Changsha)	10.3	318.4 (NW)	10.3
Guangdong (Guangzhou)	11.3	117.8 (ESE)	111.9
Guangxi (Nanning)	11.0	155.3 (SSE)	95.1
Hainan (Haikou)	15.8	106.4 (ESE)	71.8
Sichuan (Chengdu)	8.0	307.0 (NW)	92.7
Guizhou (Guiyang)	10.7	50.2 (NE)	66.0
Yunnan (Kunming)	21.1	221.2 (SW)	9.0
Shaanxi (Xian)	11.3	44.8 (NE)	43.8
Gansu (Lanzhou)	10.7	39.0 (NE)	65.3
Qinghai (Xining)	6.3	121.4 (ESE)	88.7
Ningxia (Yinchuan)	7.5	305.2 (NW)	95.1
Xinjiang (Urumqi)	8.9	325.9 (NW)	59.5

Table 2: The Polluting and Non-polluting Industries for Air Pollutants

Pollutant	Two-digit Industry
SO_2	Petroleum and nuclear fuel processing (25), Chemical materials and products (26), Non-metal mineral products (31), Ferrous metals smelting and pressing (32), Non-ferrous metals smelting and pressing (33), Power production (44)
NO_2	Petroleum and nuclear fuel processing (25), Chemical materials and products (26), Non-metal mineral products (31), Ferrous metals smelting and pressing (32), Power production (44)
Soot	Agricultural products and byproducts (13), Pulp and paper production (22), Chemical materials and products (26), Non-metal mineral products (31), Ferrous metals smelting and pressing (32), Power production (44)
Dust	Processing of wood, bamboo, and straw (20), Petroleum and nuclear fuel processing (25), Non-metal mineral products (31), Ferrous metals smelting and pressing (32)
Other water polluting industries	Beverage production (15), Textile (17), Metal products (34), General appliances manufacturing (35), Transportation appliances manufacturing (37)
Non-polluting industries	Food production (14), Garments manufacture (18), Leather, furs, feather and related products (19), Furniture manufacturing (21), Printing (23), Cultural and sports appliances (24), Medical and pharmaceutical products (27),Rubber products (29), Plastic products (30), Special appliances manufacturing (36), Electric appliances manufacturing (39), Electronic appliances manufacturing (40), Office appliances manufacturing (41), Handicrafts manufacturing (42), Cooking gas production (45), Water production (46)

Note: According to *Report on the First National Census of Polluting Sources* (MEP, 2010), two-digit codes in parentheses.

Table 3: Summary Statistics of Polluting Industries

Variable	Observations	Mean	Standard Deviation	Min.	Max.
Dependent variables					
Output in polluting industries:					
Output SO_2 (unit: 1 billion RMB)	2727	20.14	40.628	0.002	577.223
Output NO_2 (unit: 1 billion RMB)	2727	18.067	37.591	0.002	534.178
Output Dust (unit: 1 billion RMB)	2727	10.59	22.929	0	307.935
Output Soot (unit: 1 billion RMB)	2727	16.237	29.532	0.002	370.139
Independent variables					
Average wind speed: *Wind Speed* (unit: km/h)	2860	11.139	3.387	3.5	21.1
Standard deviation of wind direction: *Direction Std* (unit: $\circ$)	2860	66.518	25.241	9	111.9
Distance to provincial border: *Distance Border* (unit: 10 km)	2860	7.622	5.32	0.1	36.8
Distance to provincial capital: *Distance Capital* (unit: 10 km)	2860	17.795	14.087	0	112.3
Population size: *Population* (unit: 10,000 persons)	2698	119.432	146.124	14.08	1526.02
Total output of industrial firms: *Industrial Output* (unit: 1 billion RMB)	2727	62.828	137.742	0.002	2225.147
Population density: *Population Density* (unit: 10,000 /km^2)	2672	0.097	0.052	0.001	1.094
GDP per capita: *GDP* (unit: 10,000 RMB)	2691	2.001	2.043	0.184	32.025
Percentage of secondary industry in GDP: *Secondary Industry*	2726	49.578	12.946	8.05	92.3
Percentage of tertiary industry in GDP: *Tertiary Industry*	2726	41.046	10.259	7.3	81

Table 3 (continued).

Total number of above-scale firms: *Firm number*	2691	765.155	1306.484	1	15520
Percentage of government expenditure in GDP: *Government Expenditure*	2676	11.175	9.443	0	195.922
Percentage of FDI in GDP: *FDI*	2860	3.435	5.296	0	134.592

Table 4: Air-polluting Industries in Cities near Provincial Borders (SO_2 and NO_2)

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	*Output* SO_2	*Output* SO_2	*Output* SO_2	*Output* NO_2	*Output* NO_2	*Output* NO_2
$Downwind \times Post2000$	-1.239	0.830	1.080	-1.052	0.846	0.907
	(0.811)	(0.505)	(0.678)	(0.795)	(0.546)	(0.686)
$Downwind \times Post2003$	-3.959	2.526*	3.245**	-3.352	2.596*	2.908**
	(3.297)	(1.276)	(1.279)	(2.980)	(1.340)	(1.202)
Population		0.0595	0.0719*		0.0573	0.0676
		(0.0414)	(0.0414)		(0.0434)	(0.0454)
Industrial Output		0.346***	0.331***		0.314***	0.303***
		(0.0179)	(0.0202)		(0.0188)	(0.0213)
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Other control variables	No	No	Yes	No	No	Yes
Observations	1,970	1,714	1,696	1,970	1,714	1,696
R-squared	0.263	0.858	0.865	0.239	0.840	0.845
Number of cities	209	209	209	209	209	209

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 5: Air-polluting Industries in Cities near Provincial Borders (*Soot* and *Dust*)

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable:	*Output Soot*	*Output Soot*	*Output Soot*	*Output Dust*	*Output Dust*	*Output Dust*
$Downwind \times Post2000$	-0.109	1.033***	1.340**	-1.136**	-0.131	-0.0665
	(0.554)	(0.370)	(0.518)	(0.483)	(0.348)	(0.432)
$Downwind \times Post2003$	-0.692	3.356*	4.117***	-2.504	0.815	0.281
	(3.028)	(1.827)	(1.352)	(1.915)	(1.109)	(0.857)
Population		0.0505*	0.0611***		0.0164	0.0218
		(0.0257)	(0.0213)		(0.0222)	(0.0245)
Industrial Output		0.214***	0.204***		0.180***	0.175***
		(0.0158)	(0.0155)		(0.0173)	(0.0212)
Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Other control variables	No	No	Yes	No	No	Yes
Observations	1,970	1,714	1,696	1,970	1,714	1,696
R-squared	0.311	0.818	0.830	0.228	0.728	0.735
Number of cities	209	209	209	209	209	209

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 6: Triple-differences Estimation with Wind Speed

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
Downwind × *Wind Speed* × *Post*2000	0.158	0.0244	0.326**	-0.135
	(0.163)	(0.174)	(0.152)	(0.121)
Downwind × *Post*2000	-0.647	0.656	-2.248	1.435
	(1.608)	(1.725)	(1.585)	(1.316)
Wind Speed × *Post*2000	-0.117	-0.0324	-0.120	-0.0114
	(0.146)	(0.146)	(0.120)	(0.123)
Downwind × *Wind Speed* × *Post*2003	0.523**	0.232	0.685***	-0.208
	(0.235)	(0.221)	(0.247)	(0.248)
Downwind × *Post*2003	-2.640	0.224	-3.320	2.341
	(2.222)	(2.231)	(2.539)	(2.667)
Wind Speed × *Post*2003	-0.695	-0.468	-0.292*	-0.365
	(0.516)	(0.571)	(0.153)	(0.557)
Population	0.0725*	0.0682	0.0603***	0.0231
	(0.0423)	(0.0463)	(0.0207)	(0.0260)
Industrial Output	0.333***	0.305***	0.205***	0.175***
	(0.0205)	(0.0219)	(0.0152)	(0.0218)
Est. Marginal effect of Downwind at:				
90th Pctile of *Wind Speed* (15.5)	5.46**	3.82*	7.29***	-0.88
	(2.02)	(1.90)	(1.98)	(1.61)
75th Pctile of *Wind Speed* (11.8)	3.53**	2.96**	4.76***	-0.11
	(1.36)	(1.34)	(1.36)	(1.00)
50th Pctile of *Wind Speed* (11.2)	3.22**	2.82**	4.35***	0.01
	(1.28)	(1.28)	(1.30)	(0.95)
25th Pctile of *Wind Speed* (10.3)	2.75**	2.62**	3.73***	0.20
	(1.18)	(1.20)	(1.22)	(0.91)
Year dummies	Yes	Yes	Yes	Yes

Table 6 (continued).

Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	1,696	1,696	1,696	1,696
R-squared	0.866	0.846	0.831	0.737
Number of cities	209	209	209	209

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 7: Triple-differences Estimation with Standard Deviation of Wind Direction

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
Downwind × *Direction Std* × *Post*2000	-0.0205	-0.0228	-0.00857	-0.0134
	(0.0211)	(0.0207)	(0.0187)	(0.0129)
Downwind × *Post*2000	2.365*	2.333	1.853	0.788
	(1.376)	(1.465)	(1.345)	(0.745)
Direction Std × *Post*2000	0.00391	0.00198	0.00154	-0.00133
	(0.0150)	(0.0143)	(0.0122)	(0.00928)
Downwind × *Direction Std* × *Post*2003	-0.0753*	-0.0665	-0.0739	-0.0285
	(0.0424)	(0.0400)	(0.0447)	(0.0341)
Downwind × *Post*2003	7.618*	6.725*	8.648**	1.766
	(3.785)	(3.588)	(3.390)	(2.311)
Direction Std × *Post*2003	-0.0497	-0.0564	0.0223	-0.0688
	(0.0757)	(0.0814)	(0.0325)	(0.0761)
Population	0.0701*	0.0657	0.0606***	0.0201
	(0.0405)	(0.0445)	(0.0212)	(0.0237)
Industrial Output	0.331***	0.303***	0.204***	0.175***
	(0.0197)	(0.0210)	(0.0156)	(0.0209)
Est. Marginal effect of Downwind at:				
10th Pctile of *Direction Std* (42.9)	4.39**	3.87*	5.48***	0.54
	(2.13)	(2.01)	(1.74)	(1.24)
25th Pctile of *Direction Std* (47)	4.08**	3.60*	5.18***	0.43
	(1.99)	(1.88)	(1.61)	(1.18)
50th Pctile of *Direction Std* (68.4)	2.47*	2.18*	3.59***	-0.18
	(1.37)	(1.27)	(1.21)	(1.14)
75th Pctile of *Direction Std* (88.4)	0.96	0.85	2.12	-0.75
	(1.19)	(1.07)	(1.43)	(1.47)
Year dummies	Yes	Yes	Yes	Yes

Table 7 (continued).

Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	1,696	1,696	1,696	1,696
R-squared	0.866	0.847	0.831	0.739
Number of cities	209	209	209	209

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 8: Triple-differences Estimation for All Cities

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
Border × *Downwind* × *Post*2000	3.002	2.659	2.754**	1.121
	(1.855)	(1.761)	(1.286)	(1.273)
Downwind × *Post*2000	-1.879	-1.726	-1.352	-1.181
	(1.734)	(1.569)	(1.261)	(1.056)
Border × *Post*2000	0.510	0.404	-0.225	0.241
	(0.703)	(0.659)	(0.576)	(0.638)
Border × *Downwind* × *Post*2003	8.332**	8.422**	6.063**	3.662
	(3.360)	(3.431)	(2.648)	(3.210)
Downwind × *Post*2003	-5.190	-5.369	-2.068	-3.110
	(3.416)	(3.265)	(1.985)	(2.748)
Border × *Post*2003	-1.114	-1.609	-3.374	-0.164
	(1.736)	(1.759)	(2.382)	(2.441)
Population	0.0426	0.0356	0.0480**	0.00619
	(0.0286)	(0.0311)	(0.0176)	(0.0143)
Industrial Output	0.346***	0.316***	0.235***	0.166***
	(0.0270)	(0.0270)	(0.0304)	(0.0154)
Year Dummies	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes
Observations	2,356	2,356	2,356	2,356
R-squared	0.847	0.821	0.803	0.711
Number of cities	286	286	286	286

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 9: Triple-differences Estimation for All Cities (with Distance to Border)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
Distance Border × *Downwind* × *Post*2000	-0.189	-0.144	-0.240**	-0.00396
	(0.117)	(0.114)	(0.0981)	(0.0758)
Downwind × *Post*2000	1.572	1.203	2.307***	-0.295
	(0.933)	(0.978)	(0.690)	(0.602)
Distance Border × *Post*2000	-0.0515	-0.0465	0.0507	-0.0504
	(0.0485)	(0.0406)	(0.0471)	(0.0452)
Distance Border × *Downwind* × *Post*2003	-0.578	-0.552	-0.525*	-0.0361
	(0.372)	(0.354)	(0.287)	(0.260)
Downwind × *Post*2003	4.406	4.188	6.289**	-0.408
	(2.713)	(2.711)	(2.540)	(1.856)
Distance Border × *Post*2003	-0.0872	-0.0600	0.322*	-0.186
	(0.182)	(0.184)	(0.169)	(0.213)
Population	0.0425	0.0355	0.0476**	0.00612
	(0.0288)	(0.0313)	(0.0177)	(0.0144)
Industrial Output	0.346***	0.315***	0.235***	0.165***
	(0.0270)	(0.0271)	(0.0300)	(0.0153)
Est. Marginal effect of Downwind at:				
5th Pctile of *Distance Border* (14km)	3.60	3.42	5.55**	-0.46
	(2.28)	(2.29)	(2.17)	(1.54)
10th Pctile of *Distance Border* (21km)	3.19	3.03	5.19**	-0.48
	(2.08)	(2.09)	(2.00)	(1.40)
25th Pctile of *Distance Border* (37km)	2.27	2.15	4.35**	-0.54
	(1.68)	(1.69)	(1.61)	(1.10)
50th Pctile of *Distance Border* (62km)	0.83	0.77	3.03**	-0.63
	(1.39)	(1.34)	(1.13)	(1.87)
Year Dummies	Yes	Yes	Yes	Yes

Table 9 (continued).

Fixed Effects	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes
Observations	2,356	2,356	2,356	2,356
R-squared	0.847	0.821	0.804	0.712
Number of cities	286	286	286	286

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 10: Share of Air Polluting Industries in Downwind Cities

Panel A: Near Megacity (Population > 1 million) in Downwind Direction

	SO_2 Share	*NO_2 Share*	*Soot Share*	*Dust Share*
Before 2000	0.335	0.321	0.378	0.163
(Std. Dev.)	(0.179)	(0.173)	(0.173)	(0.175)
After 2003	0.365	0.336	0.354	0.186
(Std. Dev.)	(0.184)	(0.180)	(0.164)	(0.154)
Difference	0.030	0.015	-0.025	0.022
(Std. Err.)	(0.022)	(0.021)	(0.020)	(0.019)

Panel B: No Megacity (Population > 1 million) Near in Downwind Direction

	SO_2 Share	*NO_2 Share*	*Soot Share*	*Dust Share*
Before 2000	0.323	0.295	0.344	0.155
(Std. Dev.)	(0.167)	(0.159)	(0.137)	(0.133)
After 2003	0.398	0.340	0.384	0.198
(Std. Dev.)	(0.182)	(0.171)	(0.169)	(0.172)
Difference	0.075**	0.045**	0.040**	0.043**
(Std. Err.)	(0.019)	(0.018)	(0.017)	(0.018)

Table 11: The Effects of Neighboring Megacities

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
$Border \times Downwind \times Post2000$	3.828**	3.470**	3.110**	1.536
	(1.694)	(1.687)	(1.160)	(1.383)
$Downwind \times Post2000$	-2.610*	-2.448*	-1.656	-1.553
	(1.531)	(1.405)	(1.147)	(1.117)
$Border \times Post2000$	0.767	0.632	-0.0531	0.345
	(0.739)	(0.695)	(0.661)	(0.607)
$Border \times Downwind \times Post2003$	9.108***	9.079**	6.499**	3.985
	(3.254)	(3.427)	(2.758)	(3.309)
$Downwind \times Post2003$	-5.888*	-5.961*	-2.428	-3.410
	(3.106)	(3.048)	(2.146)	(2.720)
$Border \times Post2003$	-1.123	-1.618	-3.347	-0.177
	(1.573)	(1.607)	(2.424)	(2.355)
Near Megacity	4.092**	3.709**	2.599	1.718
	(1.642)	(1.667)	(1.790)	(1.546)
Near Megacity $\times$ $Post2000$	-0.610	-0.808	0.171	-0.498
	(0.800)	(0.801)	(0.728)	(0.503)
Near Megacity $\times$ $Post2003$	-4.035**	-3.437	-2.023*	-1.757
	(1.973)	(2.025)	(1.072)	(1.516)
Year Dummies	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes
Observations	2,356	2,356	2,356	2,356
R-squared	0.849	0.822	0.804	0.712
Number of cities	286	286	286	286

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 12: The Effects of Neighboring Megacities (with Distance to Border)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
Distance Border × *Downwind* × *Post*2000	-0.223*	-0.184	-0.247**	-0.0249
	(0.117)	(0.121)	(0.0953)	(0.0820)
Downwind × *Post*2000	1.705	1.368	2.317***	-0.207
	(1.115)	(1.162)	(0.764)	(0.675)
Distance Border × *Post*2000	-0.0708	-0.0621	0.0343	-0.0565
	(0.0526)	(0.0449)	(0.0535)	(0.0444)
Distance Border × *Downwind* × *Post*2003	-0.688*	-0.645*	-0.597*	-0.0780
	(0.352)	(0.348)	(0.310)	(0.266)
Downwind × *Post*2003	5.006*	4.696*	6.699**	-0.186
	(2.668)	(2.698)	(2.534)	(1.927)
Distance Border × *Post*2003	-0.0638	-0.0400	0.334*	-0.176
	(0.169)	(0.173)	(0.174)	(0.208)
Near Megacity	4.087**	3.718**	2.664	1.647
	(1.721)	(1.753)	(1.745)	(1.508)
Near Megacity × *Post*2000	-0.434	-0.645	0.221	-0.392
	(0.832)	(0.821)	(0.726)	(0.497)
Near Megacity × *Post*2003	-4.003*	-3.410	-2.189*	-1.631
	(1.998)	(2.059)	(1.078)	(1.518)
Year Dummies	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes
Observations	2,356	2,356	2,356	2,356
R-squared	0.849	0.822	0.805	0.713
Number of cities	286	286	286	286

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 13: The Effects of Neighboring Megacities Before 2000 (with Distance to Border)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
Distance Border × *Downwind* × *Post*2000	-0.206*	-0.163	-0.247**	-0.0146
	(0.115)	(0.115)	(0.0984)	(0.0757)
Downwind × *Post*2000	1.635*	1.269	2.334***	-0.258
	(0.960)	(1.006)	(0.700)	(0.615)
Distance Border × *Post*2000	-0.0525	-0.0477	0.0504	-0.0511
	(0.0478)	(0.0393)	(0.0480)	(0.0451)
Distance Border × *Downwind* × *Post*2003	-0.680*	-0.647*	-0.595*	-0.0802
	(0.368)	(0.363)	(0.305)	(0.274)
Downwind × *Post*2003	4.727	4.489	6.507**	-0.269
	(2.861)	(2.861)	(2.493)	(1.951)
Distance Border × *Post*2003	-0.104	-0.0754	0.311*	-0.193
	(0.165)	(0.168)	(0.177)	(0.208)
Near Initial Megacity × *Post*2000	-0.694	-0.732	-0.284	-0.418
	(0.462)	(0.449)	(0.418)	(0.344)
Near Initial Megacity × *Post*2003	-4.274**	-4.004**	-2.906**	-1.853
	(1.846)	(1.843)	(1.257)	(1.576)
Year Dummies	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes
Observations	2,356	2,356	2,356	2,356
R-squared	0.849	0.822	0.805	0.713
Number of cities	286	286	286	286

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 14: Estimations on the Output in Polluting Industries of Air Pollutants (with Non-polluting Industries for Robustness Check)

	(1)	(2)	(3)	(4)	(5)
Dependent variable:	*Output Non*	*Output Non1*	*Output Non2*	*Output Non3*	*Output Non4*
$Distance\ Border \times Downwind \times Post2000$	0.0458	0.144	0.0150	-0.128	0.0140
	(0.252)	(0.163)	(0.0205)	(0.0914)	(0.110)
$Downwind \times Post2000$	-1.060	-0.657	-0.0726	0.458	-0.788
	(1.442)	(0.692)	(0.139)	(0.835)	(0.739)
$Distance\ Border \times Post2000$	0.0927	-0.00505	0.0136	0.0608	0.0233
	(0.103)	(0.0347)	(0.0128)	(0.0400)	(0.0999)
$Distance\ Border \times Downwind \times Post2003$	0.443	0.917	-0.00525	-0.392	-0.0768
	(0.520)	(0.602)	(0.0481)	(0.361)	(0.228)
$Downwind \times Post2003$	-4.478	-3.096	0.303	-0.489	-1.195
	(4.554)	(2.961)	(0.448)	(2.462)	(1.738)
$Distance\ Border \times Post2003$	0.153	0.00900	0.0747	0.240	-0.171
	(0.361)	(0.133)	(0.0442)	(0.167)	(0.248)
Control variables	Yes	Yes	Yes	Yes	Yes
Year Dummies	Yes	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes	Yes
Observations	2,356	2,356	2,356	2,356	2,356
R-squared	0.940	0.596	0.787	0.871	0.863
Number of cities	286	286	286	286	286

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 15: Robustness Checks (Distance to Border < 80km)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
$Downwind \times Post2000$	1.249	1.150	1.246*	0.141
	(0.849)	(0.855)	(0.635)	(0.581)
$Downwind \times Post2003$	3.056**	2.788**	4.161***	0.103
	(1.403)	(1.334)	(1.427)	(0.819)
Population	0.0737*	0.0692	0.0616***	0.0219
	(0.0416)	(0.0464)	(0.0207)	(0.0262)
Industrial Output	0.337***	0.313***	0.199***	0.184***
	(0.0207)	(0.0229)	(0.0156)	(0.0234)
Year effects	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	1,440	1,440	1,440	1,440
R-squared	0.869	0.854	0.825	0.745
Number of cities	177	177	177	177

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 16: Triple-differences Estimation with Wind Speed (Distance to Border < 80km)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
$Downwind \times Wind\ Speed \times Post2000$	0.106	0.0100	0.252	-0.120
	(0.158)	(0.166)	(0.176)	(0.132)
$Downwind \times Post2000$	0.111	1.065	-1.508	1.470
	(1.464)	(1.574)	(1.796)	(1.350)
$Wind\ Speed \times Post2000$	-0.0565	-0.00481	-0.0384	-0.0197
	(0.138)	(0.145)	(0.120)	(0.136)
$Downwind \times Wind\ Speed \times Post2003$	0.752**	0.434	0.903***	-0.177
	(0.311)	(0.319)	(0.280)	(0.327)
$Downwind \times Post2003$	-5.347	-2.108	-5.679**	1.836
	(3.224)	(3.573)	(2.627)	(3.723)
$Wind\ Speed \times Post2003$	-0.897	-0.645	-0.491**	-0.381
	(0.580)	(0.675)	(0.182)	(0.659)
Population	0.0737*	0.0694	0.0605***	0.0229
	(0.0424)	(0.0472)	(0.0201)	(0.0274)
Industrial Output	0.339***	0.315***	0.201***	0.185***
	(0.0211)	(0.0236)	(0.0151)	(0.0242)
Year dummies	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	1,440	1,440	1,440	1,440
R-squared	0.870	0.854	0.827	0.747
Number of cities	177	177	177	177

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 17: Triple-differences Estimation with Standard Deviation of Wind Direction (Distance to Border < 80km)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
$Downwind \times Direction\ Std \times Post2000$	-0.0189	-0.0231	-0.0102	-0.0141
	(0.0224)	(0.0219)	(0.0182)	(0.0136)
$Downwind \times Post2000$	2.423	2.574	1.859	1.018
	(1.441)	(1.547)	(1.357)	(0.844)
$Direction\ Std \times Post2000$	0.00395	0.00400	5.26e-05	0.000939
	(0.0147)	(0.0142)	(0.0111)	(0.00862)
$Downwind \times Direction\ Std \times Post2003$	-0.0710	-0.0659	-0.0762	-0.0177
	(0.0489)	(0.0474)	(0.0526)	(0.0392)
$Downwind \times Post2003$	7.179	6.595	8.852**	0.925
	(4.261)	(4.127)	(4.035)	(2.615)
$Direction\ Std \times Post2003$	-0.0485	-0.0518	0.0319	-0.0774
	(0.0862)	(0.0926)	(0.0405)	(0.0806)
Population	0.0720*	0.0675	0.0615***	0.0200
	(0.0408)	(0.0456)	(0.0205)	(0.0253)
Industrial Output	0.337***	0.313***	0.199***	0.184***
	(0.0203)	(0.0226)	(0.0157)	(0.0231)
Year dummies	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	1,440	1,440	1,440	1,440
R-squared	0.871	0.856	0.826	0.749
Number of cities	177	177	177	177

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 18: Robustness Checks (Distance to Border < 60km)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
$Downwind \times Post2000$	1.397	1.086	1.640*	0.0398
	(0.942)	(0.955)	(0.816)	(0.567)
$Downwind \times Post2003$	4.011**	3.668*	4.208**	0.756
	(1.859)	(1.794)	(1.919)	(0.909)
Population	0.0956	0.0886	0.0682**	0.0339
	(0.0568)	(0.0627)	(0.0323)	(0.0344)
Industrial Output	0.333***	0.311***	0.188***	0.188***
	(0.0216)	(0.0243)	(0.0118)	(0.0253)
Year effects	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	1,102	1,102	1,102	1,102
R-squared	0.881	0.862	0.858	0.762
Number of cities	135	135	135	135

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 19: Triple-differences Estimation with Wind Speed (Distance to Border < 60km)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
$Downwind \times Wind\ Speed \times Post2000$	0.279	0.201	0.352	-0.0726
	(0.237)	(0.244)	(0.222)	(0.153)
$Downwind \times Post2000$	-1.559	-1.032	-2.084	0.800
	(2.106)	(2.141)	(2.022)	(1.397)
$Wind\ Speed \times Post2000$	-0.163	-0.111	-0.127	-0.0372
	(0.188)	(0.200)	(0.121)	(0.164)
$Downwind \times Wind\ Speed \times Post2003$	1.039**	0.577	1.108**	-0.118
	(0.379)	(0.477)	(0.412)	(0.498)
$Downwind \times Post2003$	-7.389**	-2.805	-7.569**	1.641
	(3.503)	(5.041)	(3.577)	(5.386)
$Wind\ Speed \times Post2003$	-1.078	-0.837	-0.513**	-0.572
	(0.752)	(0.877)	(0.247)	(0.857)
Population	0.0946	0.0883	0.0666**	0.0347
	(0.0573)	(0.0635)	(0.0313)	(0.0353)
Industrial Output	0.337***	0.314***	0.190***	0.190***
	(0.0225)	(0.0256)	(0.0114)	(0.0265)
Year dummies	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	1,102	1,102	1,102	1,102
R-squared	0.883	0.863	0.860	0.765
Number of cities	135	135	135	135

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

Table 20: Triple-differences Estimation with Standard Deviation of Wind Direction (Distance to Border < 60km)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output* SO_2	*Output* NO_2	*Output Soot*	*Output Dust*
Downwind × *Direction Std* × *Post*2000	-0.0216	-0.0266	-0.0118	-0.0110
	(0.0248)	(0.0229)	(0.0255)	(0.0179)
Downwind × *Post*2000	2.595	2.564	2.299	0.611
	(1.552)	(1.556)	(1.828)	(1.078)
Direction Std × *Post*2000	-0.00332	-0.00371	0.000485	-0.00843
	(0.0166)	(0.0162)	(0.0135)	(0.0104)
Downwind × *Direction Std* × *Post*2003	-0.0331	-0.0350	-0.0558	0.0128
	(0.0629)	(0.0640)	(0.0490)	(0.0549)
Downwind × *Post*2003	5.332	5.102	7.425*	-0.656
	(4.874)	(5.140)	(3.758)	(3.553)
Direction Std × *Post*2003	-0.108	-0.107	-0.00291	-0.121
	(0.101)	(0.115)	(0.0314)	(0.106)
Population	0.0942	0.0872	0.0680**	0.0326
	(0.0560)	(0.0622)	(0.0319)	(0.0341)
Industrial Output	0.332***	0.310***	0.187***	0.187***
	(0.0209)	(0.0236)	(0.0118)	(0.0248)
Year dummies	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	1,102	1,102	1,102	1,102
R-squared	0.884	0.866	0.859	0.769
Number of cities	135	135	135	135

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at province level. (4) *Population* and *Industrial Output* are lagged by 1 year to control endogeneity. (5) Other control variables include: population density, per capita GDP, share of secondary industry, share of tertiary industry, government expenditure, and FDI.

3.0 TRANS-BOUNDARY AIR POLLUTION AND INDUSTRIAL RELOCATION: A MODEL FOR THE EFFECTS ON NON-POLLUTING INDUSTRIES

3.1 INTRODUCTION

China's large-scale policy-change of environmental regulation in the early 2000s has caused a severe problem of trans-boundary pollution under its decentralized environmental management system. China's provincial capitals began locating more highly polluting industries in downwind cities near provincial borders than in other cities after the central government began to implement stricter environmental regulation in 2003. This type of policy-induced trans-boundary air pollution is associated with negative influences on health, employment, and output in cities near provincial borders. These effects are exogenous to the non-polluting industrial sectors in cities near the upwind side of provincial borders, where more likely to receive air pollution from its upwind neighboring province. Therefore, it provides an opportunity to study the cost of air pollution, through estimating the effects of policy-induced trans-boundary air pollution on non-polluting industries in cities near provincial borders. In this chapter, I analyze the effect of policy-induced trans-boundary air pollution on industrial relocation in a model, and predictions from the comparative statics in this model will become the foundation for empirical analysis in next chapter.

The fast growth of highly polluting industries in China during the period of economic take-off has caused severe air pollution problems (Bi et al., 2007). Higher pollution is associated with higher mortality, worse health, and lower output (Matus et al., 2012; Chen et al., 2013), and the total monetary value of health losses caused by air pollution in China is estimated at 3.8% of GDP according to a survey by World Bank (2007). China's inability to effectively control pollution stems in part from its decentralized regulatory structure: pollution in China is not regulated by a single, federal authority, but rather by a multitude of provincial governments (Cai et al., 2016)). Provincial governments under-provide pollution abatement because they do not bear the full cost of pollution generated within their borders. When subnational governments are by law required to reduce pollution in their territory, they have incentives to dump pollution on their neighbors, causing the problem of trans-boundary pollution (Oates, 1999, 2002). Specifically for the case air-pollution, subnational governments have incentives to set up factories and enterprises downwind from where their constituents live and on borders with neighboring jurisdictions. Through free riding on trans-boundary air pollution, they can enjoy more employment and economic growth from polluting industries, while dumping pollution on their downwind neighbors.

The problem of trans-boundary pollution has become much more significant since China's central government began to implement stricter environmental regulation when there had been fierce political competition among provincial leaders under a combination of centrally controlled political governance and decentralized socio-economic governance in modern China. China's central government has launched a large-scale policy-change to fight against environmental pollution since the early 2000s. This new regime of environmental policies includes targets to reduce pollution emissions, stricter laws on monitoring and punishing polluters, and changes to the criteria of evaluating local officials' performances (Landry, 2008; Cai et al., 2016). However, since China's current political system is a combination of centrally controlled political governance and decentralized economic governance, provincial and local governors are motivated to focus on their local outcomes and to compete with each other for promotion (Qian et al., 1999; Li and Zhou, 2005; Xu, 2011). It is high-level government officials in the provincial capital that shape industrial location policy in each province, and they are affected by the policy change. When central government's policy-change made local environmental quality more important to the promotion of officials, those local leaders received stronger incentives to free ride on trans-boundary environmental pollution, and the polluting industries have thus increased in downwind cities near provincial borders. Therefore, much of the cost of pollution in a given province, say province A, is borne by the residents of adjacent provinces that are downwind of polluting industry sites in province A.

While the introduction of polluting industries in province A creates more employment and growth in A, it also increases trans-boundary air pollution, which in turn generates adverse health, employment, and output effects in non-polluting industries in neighboring provinces.

In this chapter, I use a theoretical model to analyze the strategic responses of provincial leaders given the central government's policy change. Each province in this model has two cities with a constant wind direction, and provincial government allocates output levels of polluting and non-polluting industries across the two cities. Cost of production in the non-polluting industry in each city is affected by the amount of pollution from its upwind neighbor. There is a central government that decides political promotion of provincial leaders, and it evaluates performances of provincial leaders according to a weighted sum of total economic surplus and total environmental pollution. This evaluation function becomes the objective function in provincial leaders' decision problem, and Nash equilibrium of political leaders' competition is solved in the model. The patterns of industrial relocation caused by trans-boundary air pollution are characterized by comparative statics of the model. When labor markets are connected across cities within each province, if the central government increases the weight of pollution in its evaluation function, the policy-change will cause more output and employment of polluting industry in the downwind city in each province, which implies there is more trans-boundary pollution. This will lead to less output and employment of non-polluting industry in the upwind city, and more of which in downwind city in each province. Total social welfare of the economy is less than the social planner's solution. The distortions are greater when the central government cares more about environmental pollution and imposes greater regulatory pressures. The predictions from the model will guide empirical analysis in the next chapter about the costs of policy-induced trans-boundary air pollution in China.

The remainder of the chapter is organized as follows: Section 3.2 introduces the assumptions and model settings. Section 3.3 reports the equilibrium results and implications of the model. Section 3.4 reports the analysis of the model that labor is mobile across cities. Section 3.5 concludes. Section 3.6 includes the figures.

3.2 ASSUMPTIONS AND MODEL SETTINGS

The analytical framework is a model for a province with two cities (*up*, *down*). The province is located in a circle of many provinces, with a constant wind direction as shown in Figure 7. Since all provinces are identical, the analysis will focus on one representative province. Each province has 2 cities *up* and *down*, and industrial production can take place in both cities. City *up* is located near the upwind side of the provincial border, while city *down* is located near the downwind side. The provincial government will decide output levels of industrial production in both cities. There are two types of industries: "dirty" and "clean", and the amount of pollution emission in each city is associated with the output level of dirty industry. There is a central government that decides political turnover of provincial leaders, according to an objective function consisting of both levels of industrial output and environmental pollution, and the relative weights of output and pollution can be different when the central government implements different policies. Given the central government's policy (characterized by parameters in objective function), provincial leaders will make decisions to maximize their probability of being promoted, and their competition leads to a Nash equilibrium in the model. I will solve comparative statics for equilibria under different policies of central government. In this section, I will introduce and discuss the setting and assumptions of the model at first.

3.2.1 Production Function and Cost Function

There are two different sectors or industries in this economy. One sector has air pollution emission, and it is called "dirty" industry (denoted as a superscript "d"). The level of air pollution is a function of output in dirty industry. The other sector does not pollute the air, and it is called "clean" industry (denoted as a superscript "c"). Production functions are different for the two sectors. I assume that only productivity of clean industry is affected by pollution, because impact from pollution is relatively larger for clean industries like food and beverage production, medical and pharmaceutical products, and electronic appliances manufacturing, compared with dirty sectors like power production, petroleum fuel processing, and metals smelting and pressing. For simplicity, I assume that the production function of clean industry has a term of negative effects from pollution. This term can be considered as a relative measure for the effect of pollution on the productivity of clean industry, being normalized by the relatively small effect of pollution on dirty industry. Here I assume a production function that has only one factor of production called "labor", and this Ricardian form of production function will make the cost of production become a function of output level. Hence, the decision variables in the provincial government's maximization problem will be output levels in different sectors and cities only, which are convenient for characterizing and analyzing decisions of provincial governments on industrial production. I assume production functions to be constant return to scale. The production function for the dirty industry in city i is assumed to be:

$$q_i^d = L_i^d$$

Assume unit wage is w_i^d, from the cost minimization problem shown in Appendix A.1, the cost function for the dirty industry in city i is derived as:

$$c^d(q_i^d) = w_i^d q_i^d$$

The production function for the clean industry in city i is:

$$q_i^c = \frac{L_i^c}{\gamma P_{-i} + 1}$$

where P_{-i} is pollution from upwind city $-i$, and $\gamma \geq 0$ represents negative production externalities. When $\gamma = 0$ or $P_{-i} = 0$, we have $q_i^c = L_i^c$. This result means that when $\gamma = 0$, production of clean industry is not affected by air pollution. When γ is larger, the negative effects of air pollution on the production of clean industry is larger. From the cost minimization problem shown in Appendix A.1, the cost function for the clean industry in city i is derived as:

$$c^c(q_i^c) = w_i^c(\gamma P_{-i} + 1)q_i^c$$

It is increasing in negative externality of pollution from the upwind city $-i$.

3.2.2 Assumptions: Trans-boundary Pollution and Labor Markets

In order to characterize trans-boundary air pollution and its consequences, I assume that pollution externalities can only affect the next city in downwind direction, so production in city *down* is affected by pollution in city *up* (P_{up}), and production in city *up* is affected by pollution in city *down* of the upwind province ($P_{down(-i)}$). For simplicity, I also assume that the amount of pollution is equal to the amount of output in the dirty industry.

Assumption 1.

$$P_{down(-i)} = q^d_{down(-i)}$$

$$P_{up} = q^d_{up}$$

Under this assumption, the cost functions for the clean industry in cities *up* and *down* will become:

$$c^c(q^c_{up}) = w^c_{up}(\gamma q^d_{down(-i)} + 1)q^c_{up}$$

$$c^c(q^c_{down}) = w^c_{down}(\gamma q^d_{up} + 1)q^c_{down}$$

The negative externalities of air pollution are characterized as increasing cost of production in the clean industry. When there are negative production externalities ($\gamma > 0$), the cost of production of the clean industry in city *up* is increasing in pollution from city $down(-i)$, and the cost of production in the clean industry in city *down* is increasing in city *up*.

For labor markets, I have the following important assumptions:

Assumption 2. Labor markets are monopsonistic and labor supply functions are linear in wage:

$$L^d_{up} = w^d_{up},\ L^d_{down} = w^d_{down}$$

$$L^c_{up} = w^c_{up},\ L^c_{down} = w^c_{down}$$

Assumption 3. Labor markets are segmented in each city and each industry.

This assumption is for the baseline analysis. There are four segmented labor markets in each province: dirty industry in city *up*, dirty industry in city *down*, clean industry in city *up*, and clean industry in city *down*. In the monopsonistic labor market equilibrium, wage of the dirty industry is determined by:

$$w^d_{up} = L^d_{up} = q^d_{up},\quad w^d_{down} = L^d_{down} = q^d_{down}$$

Wage for the clean industry is determined by:

$$w^c_{up} = L^c_{up} = (\gamma q^d_{down(-i)} + 1)q^c_{up}, \quad w^c_{down} = L^c_{down} = (\gamma q^d_{up} + 1)q^c_{down}$$

Therefore, cost functions for both industries and cities become:

$$c^d(q^d_{up}) = w^d_{up} L^d_{up} = (q^d_{up})^2$$

$$c^d(q^d_{down}) = w^d_{down} L^d_{down} = (q^d_{down})^2$$

$$c^c(q^c_{up}) = w^c_{up} L^c_{up} = (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2$$

$$c^c(q^c_{down}) = w^c_{down} L^c_{down} = (\gamma q^d_{up} + 1)^2 (q^c_{down})^2$$

The comparative statics of the model under this assumption will be solved and discussed in Section 3.3. In Section 3.4, this assumption will be relaxed and I will consider an alternative assumption that labor market is connected between cities within a province.

In order to calculate economic surplus in each province, I have the following important assumption:

Assumption 4. Product markets are competitive and prices of "dirty" product (p^d) and "clean" product (p^d) are exogenously determined in global markets.

This assumption is a reasonable assumption because China has been an export-oriented economy since the economic reforms beginning in the late 1970s.

3.2.3 Decision Problem of Provincial Government

The decision problem of provincial government is according to the objective function that central government uses to evaluate performances of provincial leaders. It is a weighted sum of total economic surplus and environmental pollution being monitored in each province. The provincial government will choose quantities of output q^d_{up}, q^c_{up}, q^d_{down}, and q^c_{down} to maximize their probability of being promoted, which is according to the evaluation function. The relative weights of economic surplus and environmental pollution are set by the central government, and the decision problem of provincial government can be considered as in the following two different cases.

Case 1: Negative production externalities ($\gamma \geq 0$), but no regulatory pressure ($\phi = 0$).

In this case, central government does not care about environmental pollution, which is similar to the situation during periods of China's early economic development from the late 1970s to 1990s. The central government used GDP growth as a major indicator for evaluating the performances of provincial leaders, and provincial leaders competed in GDP growth for being promoted at that time (Qian et al., 1999; Li and Zhou, 2005). This type of GDP competition is modeled as the following objective function of a provincial government, which is the sum of economic surplus in two industries and two cities in that province. Employment is not directly included in the objective function, but it is highly correlated with economic output because the production functions are Ricardian in this model. In reality, subnational governments in China can achieve more employment by using the revenue from GDP growth to hire more workers in the state-owned sectors[1].

$$
\begin{aligned}
&\max p^d q^d_{up} - c^d(q^d_{up}) + p^c q^c_{up} - c^c(q^c_{up}) + p^d q^d_{down} - c^d(q^d_{down}) + p^c q^c_{down} - c^c(q^c_{down}) \\
&= p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2 \\
&+ p^d q^d_{down} - (q^d_{down})^2 + p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2
\end{aligned}
$$

Given the value of parameter γ, and other provinces' strategy $q^d_{down(-i)}$, best response functions of provincial government are solved by the first-order conditions of this decision problem in Appendix A.3.1.

Case 2: Negative production externalities ($\gamma > 0$), and positive regulatory pressures ($\phi > 0$).

In this case, the central government includes environmental pollution when evaluating performances of provincial leaders, and $\phi > 0$ becomes the regulatory pressures for provincial governments. The promotion of provincial leaders depends on both economic growth (aggregate surplus) and environmental pollution. This is similar to the situation after policy changes that central government began to implement stricter environmental regulation in the early 2000s. The Tenth Five-Year Plan adopted in 2000 set specific targets to reduce major water and air pollutants for the first time in history, and the laws to monitor and punish offenders for environmental pollution were amended and became effective in the middle of 2003, which has since required stricter environmental regulations. Moreover, there have been

[1] A more flexible setting of the objective functions, for analysis of employment and wage, will be considered in the future research.

more indicators of environmental quality in the explicit performance criteria of provincial and local officials, including air pollution level (Landry, 2008). Under this new regime of environmental policies, central government uses both GDP growth and environmental quality to evaluate performances of provincial leaders and determine their promotion. Therefore, the objective function becomes the following one, which includes $\phi \geq 0$ as the regulatory pressures.

$$\begin{aligned}
&\max p^d q^d_{up} - c^d(q^d_{up}) + p^c q^c_{up} - c^c(q^c_{up}) + p^d q^d_{down} - c^d(q^d_{down}) + p^c q^c_{down} - c^c(q^c_{down}) \\
&-\phi(\gamma q^d_{down(-i)} + \gamma q^d_{up}) \\
&= p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2 + p^d q^d_{down} - (q^d_{down})^2 + p^c q^c_{down} \\
&-(\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - \phi(\gamma q^d_{down(-i)} + \gamma q^d_{up})
\end{aligned}$$

Given the value of parameter γ, and other provinces' strategy $q^d_{down(-i)}$, the best responses of a provincial government are solved by the first-order conditions of this decision problem in Appendix A.4.1.

3.3 EQUILIBRIUM RESULTS AND IMPLICATIONS OF THE MODEL

The equilibrium condition comes from the symmetric pattern that every province is located in a circle of identical provinces, with a constant wind direction as shown in Figure 7. Since all provinces are identical, the equilibrium output level q^d_{down} should be equal for all provinces. Therefore, we have the following condition for solving equilibrium:

Proposition 1. The symmetric Nash equilibrium of trans-boundary pollution satisfies

$$q^d_{down} = q^d_{down(-i)}$$

for all provinces.

This proposition shows the condition for solving the Nash equilibrium in both cases of the model. For Case 1, the system of equations solving equilibrium outputs q^{d*}_{up}, q^{d*}_{down}, q^{c*}_{up}, and q^{c*}_{down} are derived in Appendix A.3.2, through combining this equilibrium condition and first-order conditions in Appendix A.3.1. We can also solve for the social planner's solutions

(q_{up}^{ds}, q_{down}^{ds}, q_{up}^{cs}, and q_{down}^{cs}) by the system of equations derived in Appendix A.3.3, as the social planner's problem can be defined as including $q_{down(-i)}^{d} = q_{down}^{d}$ in objective function of representative province. The comparative statics with respect to parameter γ are then summarized in the following propositions. When there is negative effect of pollution on productivity ($\gamma \geq 0$), but the central government does not care about pollution ($\phi = 0$), we have the following results.

Proposition 2. When the central government does not care about environmental pollution ($\phi = 0$), we have:

(i) If there is no negative production externality ($\gamma = 0$), the equilibrium outputs and employments in both industries and cities are all equal to the social planner's solutions.

(ii) If $\gamma > 0$, the upwind equilibrium output and employment of the dirty industry are always equal to the social planner's solutions, and downwind equilibrium output and employment of the clean industry are also always equal to the social planner's solutions.

(iii) If $\gamma > 0$, the downwind equilibrium output and employment of the dirty industry are always greater than the social planner's solutions.

(iv) If $\gamma > 0$, the upwind equilibrium output and employment of the clean industry are always less than the social planner's solutions.

Proposition 3. When the central government does not care about environmental pollution ($\phi = 0$), and if negative production externality (γ) is increasing:

(i) Dirty industries: The upwind equilibrium output and employment are decreasing, and the downwind equilibrium output and employment are constant. The gaps between equilibrium and social planner's solutions are increasing in the downwind city.

(ii) Clean industries: The upwind equilibrium output and employment are decreasing, and the downwind equilibrium output and employment are also decreasing. The gaps between equilibrium and social planner's solutions are increasing in the upwind city.

These propositions imply that without intervention from the central government, provincial leaders will have stronger incentives to free ride on trans-boundary air pollution when the negative effect of pollution on productivity is stronger. While the gap between q_{down}^{d*} and its social planner's solution is increasing in γ, which means there is more trans-boundary air pollution relative to the social planner's solution when γ is larger, employment and output of clean industry in the upwind city are decreasing in γ: negative impact of trans-boundary pollution on employment and output in non-polluting sector is stronger when γ is larger. Meanwhile, although q^{c*}_{down} is also decreasing in γ, it does not deviate from its social planner's solution. Combined with the pattern that q^{c*}_{up} is below its social planner's solution when $\gamma > 0$ and the gap is larger when γ is larger, these results imply that clean industry is more likely to move from the upwind city to the downwind city when trans-boundary air pollution is larger as γ is larger. Figures 8 and 9 illustrate the results of Propositions 2 and 3. The dashed lines are the social planner's solutions, and the solid lines are equilibrium solutions.

For Case 2, the objective function includes a parameter $\phi \geq 0$, which is the weight that central government set for environmental pollution when evaluating the performance of provincial leaders. ϕ represents the regulatory pressures for provincial leaders. The large-scale policy change from 2003, which is used as a natural experiment in empirical analysis, is modeled as a sharp increase of ϕ. Therefore, the empirical analysis in the next chapter will be guided by the predictions from the comparative statics with respect to parameter ϕ. The system of equations solving equilibrium outputs q^{d*}_{up}, q^{d*}_{down}, q^{c*}_{up}, and q^{c*}_{down} in this case are derived in Appendix A.4. When there is negative production externality ($\gamma > 0$), and there regulatory pressures ($\phi > 0$) , we have the following results.

Proposition 4. Provincial government (equilibrium) versus social planner's outcomes for segmented labor markets.

If there are negative production externalities ($\gamma > 0$) and regulatory pressures ($\phi > 0$), then:

(i) Dirty industries: The upwind equilibrium employment and output are the same as the social planner's solution. However, the downwind equilibrium employment and output are greater.

(ii) Clean industries: The upwind equilibrium employment and output are less than the social planner's solution. However, the downwind levels are the same.

Proposition 5. The impact of regulatory pressures in segmented labor markets.

If $\gamma > 0$ and $\phi > 0$, then as regulatory pressures increase, the economy becomes more distorted for two reasons:

(i) The gaps between the equilibrium outputs (employments) for the provincial governments versus social planner increase in the downwind city for the dirty industry.

(ii) These gaps in absolute terms increase in the upwind city for the clean industry.

The results in Propositions 4(i) and 5(i) are consistent with my findings of policy-induced trans-boundary air pollution in Chapter 2. China's provincial capitals began locating more highly-polluting industries in downwind cities near provincial borders than in all other types of cities, after the central government began to implement stricter environmental regulation in 2003. The results in Propositions 4(ii) and 5(ii) have important implications for the empirical analysis of the impact of trans-boundary pollution on non-polluting industries. When regulatory pressures (ϕ) are largely increased by central government's policy change, the model predicts that the output and employment of the clean industry in the upwind city will be less than the social planner's solutions, and the gaps are larger. Figures 10 and 11 illustrate numerical results for Propositions 4 and 5 when assuming $\gamma = 0.5$. The dashed lines are the social planner's solutions, and the solid lines are equilibrium solutions.

Next, the following proposition conclude losses of social welfare for the whole economy due to policy-induced trans-boundary pollution.

Proposition 6. When there are negative production externalities ($\gamma > 0$), and if the regulatory pressures (ϕ) are increasing: the total welfare of this economy is less than the social planner's solution, and the gap increases.

This proposition predicts economic and welfare losses from the policy-induced trans-boundary air pollution under China's regionally decentralized environmental management. When environmental regulation is stricter, distortion from free-riding on trans-boundary pollution is larger, and losses of social welfare are larger. This is an explanation for the fact in China that environmental pollution is still getting worse when the central government has implemented stricter environmental regulation in recent years. Figures 12 illustrates numerical results for Propositions 6 when assuming $\gamma = 0.5$. The dashed lines are the social planner's solutions, and the solid lines are equilibrium solutions.

3.4 ANALYSIS OF THE MODEL THAT LABOR MARKETS ARE CONNECTED

In the alternative model setting, I assume that labor markets are connected within each industry. There are now two labor markets: industry "dirty" and "clean". Wage is increasing in total labor demand in each labor market.

In the monopsonistic labor market equilibrium, wage for industry "dirty" is now given by:

$$w^d_{up} = L^d_{up} + \alpha L^d_{down} = q^d_{up} + \alpha q^d_{down}$$

$$w^d_{down} = \alpha L^d_{up} + L^d_{down} = \alpha q^d_{up} + q^d_{down}$$

The parameter α represents the degree of mobility of labor across two cities ($0 < \alpha < 1$). Wage for industry "clean" is given by:

$$w^c_{up} = L^c_{up} + \alpha L^c_{down} = (\gamma q^d_{down(-i)} + 1) q^c_{up} + \alpha(\gamma q^d_{up} + 1) q^c_{down}$$

$$w^c_{down} = \alpha L^c_{up} + L^c_{down} = \alpha(\gamma q^d_{down(-i)} + 1) q^c_{up} + \alpha(\gamma q^d_{up} + 1) q^c_{down}$$

Therefore, cost functions for both industries and cities are:

$$c^d(q^d_{up}) = w_{up} L^d_{up} = (q^d_{up})^2 + \alpha q^d_{down} q^d_{up}$$

$$c^d(q^d_{down}) = w_{down} L^d_{down} = (q^d_{down})^2 + \alpha q^d_{down} q^d_{up}$$

$$c^c(q^c_{up}) = w_{up} L^c_{up} = (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2 + \alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down}$$

$$c^c(q^c_{down}) = w_{down} L^c_{down} = (\gamma q^d_{up} + 1)^2 (q^c_{down})^2 + (\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down}$$

The decision problem of provincial governments will become the following one under the above assumptions:

$$\begin{aligned}
&\max p^d q^d_{up} - (q^d_{up})^2 - \alpha q^d_{down} q^d_{up} + p^c q^c_{up} - (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2 \\
&-\alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down} + p^d q^d_{down} - (q^d_{down})^2 - \alpha q^d_{down} q^d_{up} \\
&+p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - \alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down} \\
&-\phi(\gamma q^d_{down(-i)} + \gamma q^d_{up})
\end{aligned}$$

The model is solved in Appendix B, and the following propositions summarize the findings in this model.

Proposition 7. Provincial government (equilibrium) versus social planner's outcomes for connected labor markets.

If $\gamma > 0$ and $\phi > 0$, then:

(i) Dirty industries: The upwind equilibrium employment and output are less than the social planner's solution. And, the downwind equilibrium employment and output are greater.

(ii) Clean industries: The upwind equilibrium employment and output are less than the social planner's solution. And, the downwind levels are greater.

Proposition 8. The impact of regulatory pressures in connected labor markets.

If $\gamma > 0$ and $\phi > 0$, then as regulatory pressures increase:

(i) Dirty industries: The downwind equilibrium output and employment of the dirty industry are increasing in ϕ.

(ii) Clean industries: The upwind equilibrium output and employment of the clean industry are decreasing in ϕ.

(iii) The economy becomes more distorted because all gaps for outputs (employments) between equilibrium and social planner's solutions increase in absolute terms.

The results in Proposition 7(i) are consistent with my findings of policy-induced trans-boundary air pollution in the empirical analysis of Chapter 2. When labor markets are connected across cities, the results in Propositions 7(ii) and 8 have important implications for empirical analysis about the impact of trans-boundary pollution on the non-polluting industries. When labor markets are connected, if regulatory pressures (ϕ) are largely increased by central government's policy change, the model predicts that the output and employment of clean industry in the upwind city will be less, and which in the downwind city will be greater. Policy-induced trans-boundary air pollution has negative effects on the non-polluting sector in the upwind city, and non-polluting industries are more likely to move from the upwind city to the downwind city after the policy change. These results are different from the segmented labor markets in Section 3.3 and suggest that there are more distortions of trans-boundary pollution when labor markets are connected. Since the economic reforms began in the late 1970s, labor mobility within province has been less restricted in China. Labor mobility is freer within each province, especially for the urban population. The prediction of Proposition 8 is that clean industries in the cities receiving trans-boundary pollution will have less output and employment after the policy change. For the empirical analysis of next chapter, I will use a difference-in-differences (DID) approach to test whether output, number of firms, and employment of non-polluting industries in upwind cities near provincial borders are negatively affected by the policy-induced trans-boundary pollution. Figures 13 and 14 illustrate numerical results for Propositions 7 and 8 when assuming $\gamma = 0.5$ and $\alpha = 0.3$. The dashed lines are the social planner's solutions, and the solid lines are equilibrium solutions.

Finally, the following proposition concludes losses of social welfare for the whole economy due to policy-induced trans-boundary pollution:

Proposition 9. When labor markets are connected across cities within a province, and there are negative production externalities ($\gamma > 0$), if the regulatory pressures (ϕ) are increasing: the total welfare of this economy is less than the social planner's solution, and the gap increases.

This proposition does not change the findings in Proposition 6 for which labor markets are assumed to be segmented. Figure 15 illustrates numerical results for Propositions 9 when assuming $\gamma = 0.5$ and $\alpha = 0.3$. The dashed lines are the social planner's solutions, and the solid lines are equilibrium solutions.

3.5 CONCLUSION

The patterns of industrial relocation caused by policy-induced trans-boundary air pollution in China are characterized by the comparative statics of the model in this chapter. When the central government increases the weight of pollution in its evaluation function, there is more output and employment of polluting industry in downwind city in each province, which implies more trans-boundary air pollution. This will lead to relatively less output and employment of non-polluting industry in the upwind city. The total social welfare of the economy is below the social planner's solution, and gaps are larger when the central government imposes greater regulatory pressures. The results are consistent with the fact that trans-boundary air pollution has become worse since the large-scale policy changes made by the central government in the early 2000s.

The wind patterns and institutional features in modern China provide a unique quasi-experimental setting for studying the impacts of trans-boundary air pollution. The theoretical model in this chapter will become the foundation for analyzing the costs of trans-boundary air pollution in China, and the predictions from the model will guide empirical analysis in the next chapter. I will empirically test whether non-polluting industries in downwind provinces are harmed by the increased trans-boundary pollution from upwind provinces due to the policy changes of 2003. Specifically, I will test the effects of policy-induced trans-boundary pollution on output, number of firms, and employment in non-polluting industries in cities near other provinces to the upwind direction. The empirical analysis guided by the model predictions will contribute to the literature about estimating the economic costs of environmental pollution. The findings will also have implications for designing and improving public policies of reducing environmental pollution in China effectively.

3.6 FIGURES

Figure 7: A Circle of Provinces

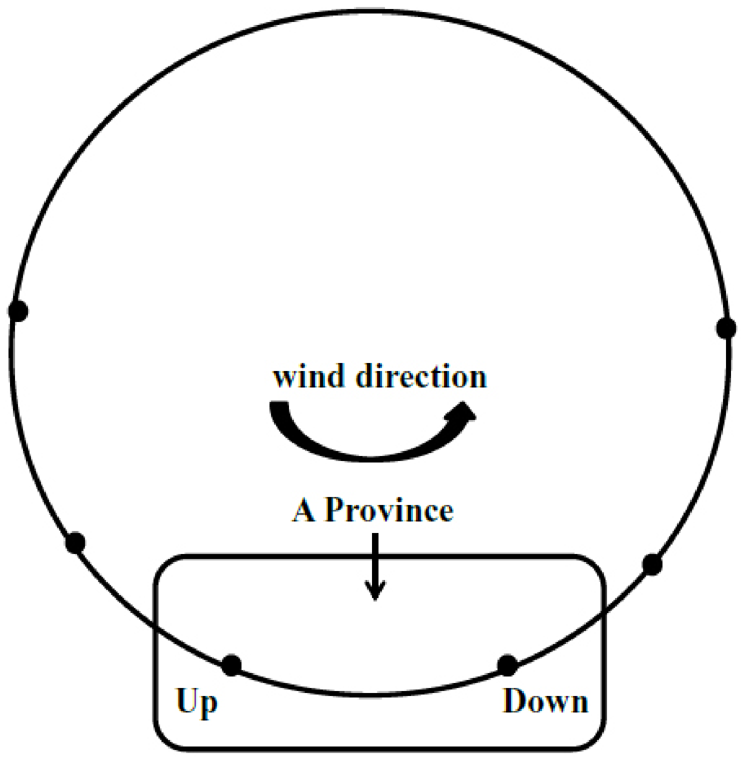


Figure 8: Comparative Statics of Equilibrium Outputs with Parameter γ (Model 1)

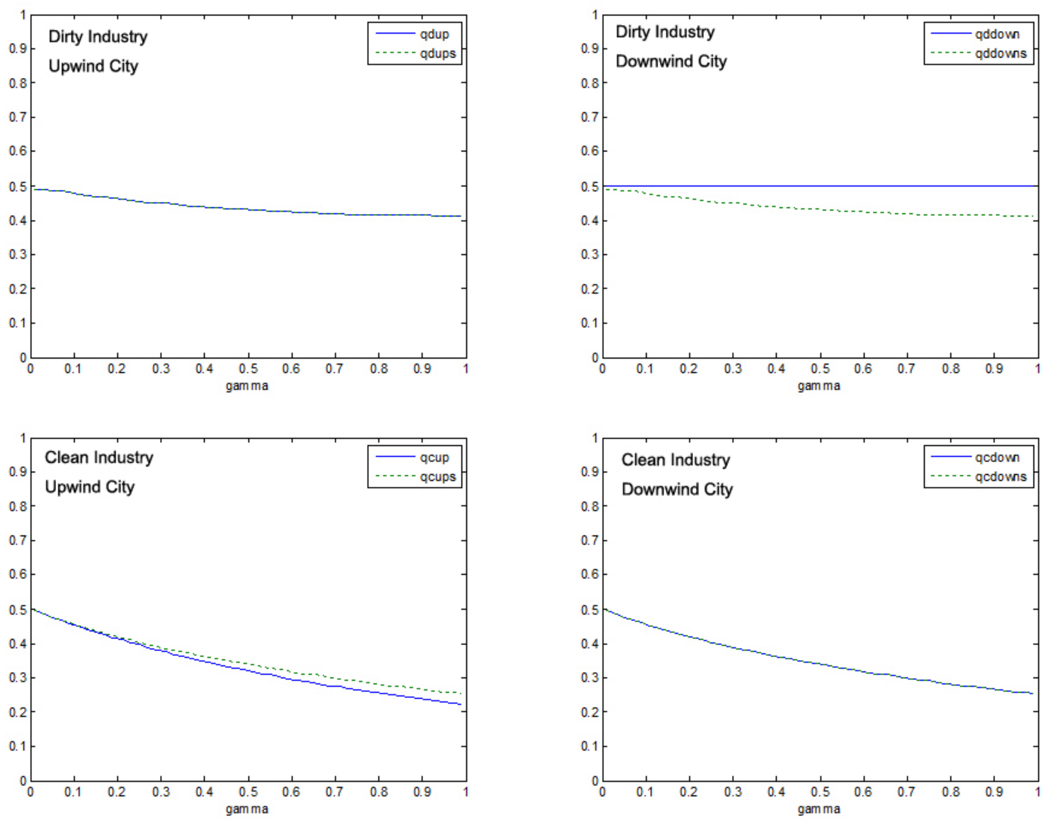


Figure 9: Comparative Statics of Equilibrium Employments with Parameter γ (Model 1)

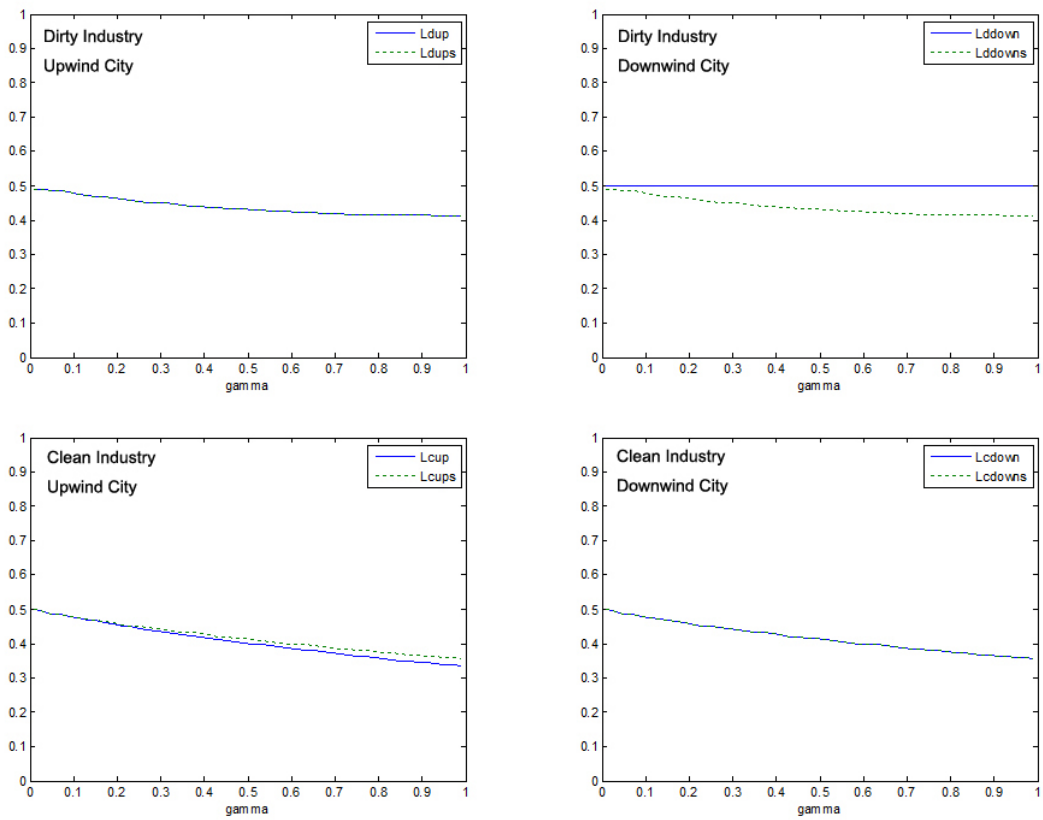


Figure 10: Comparative Statics of Equilibrium Outputs with Parameter ϕ (Model 1)

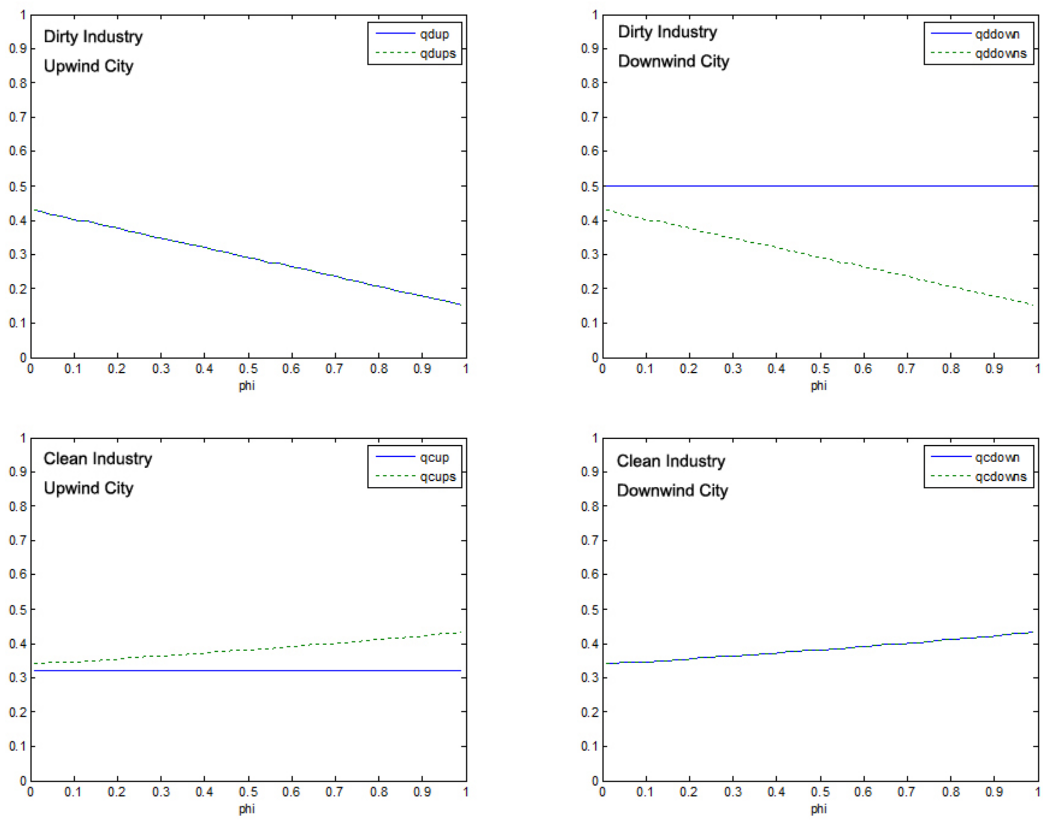


Figure 11: Comparative Statics of Equilibrium Employments with Parameter ϕ (Model 1)

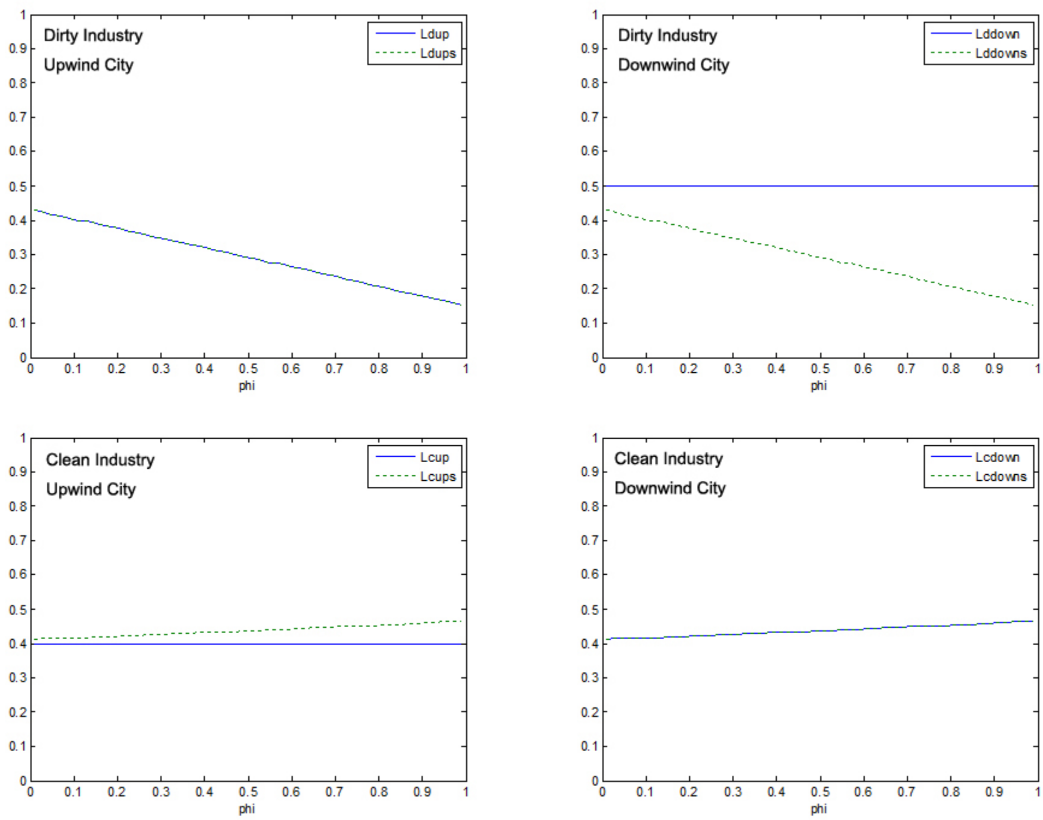


Figure 12: Comparative Statics of Equilibrium Social Welfare with Parameter ϕ (Model 1)

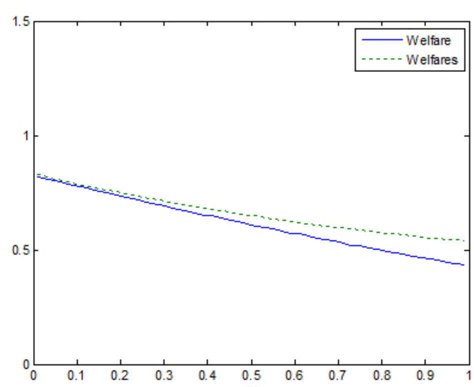


Figure 13: Comparative Statics of Equilibrium Outputs with Parameter ϕ (Model 2)

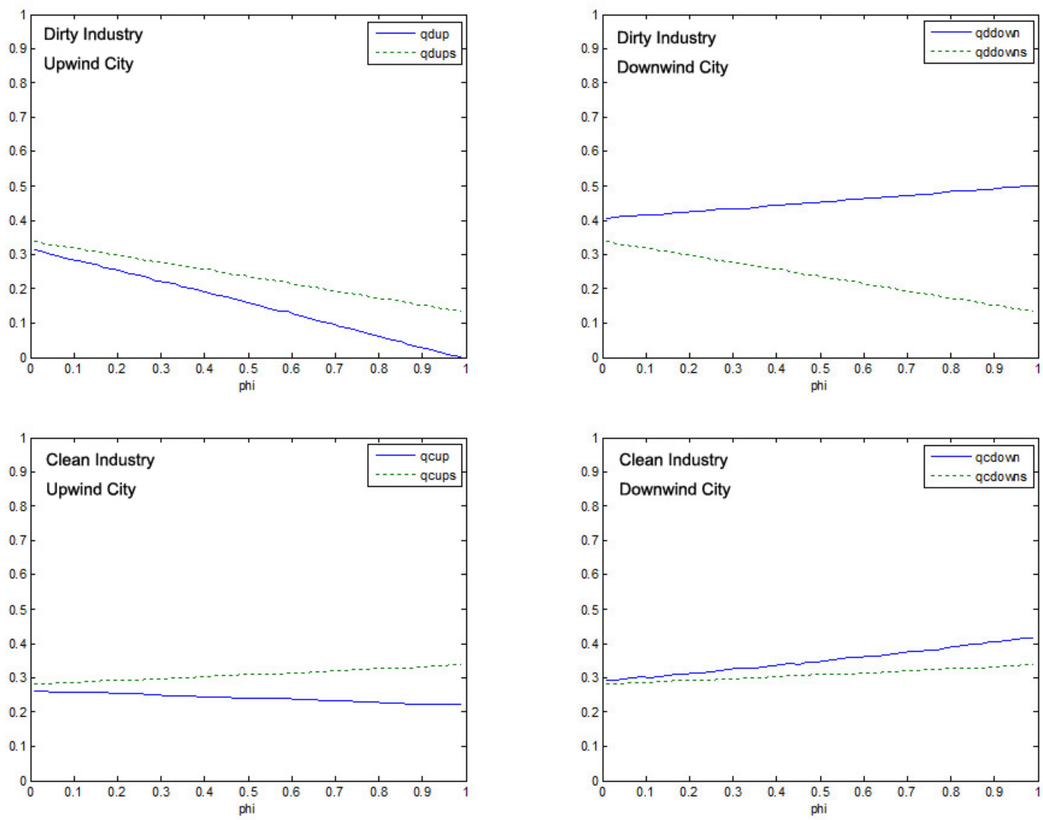


Figure 14: Comparative Statics of Equilibrium Employments with Parameter ϕ (Model 2)

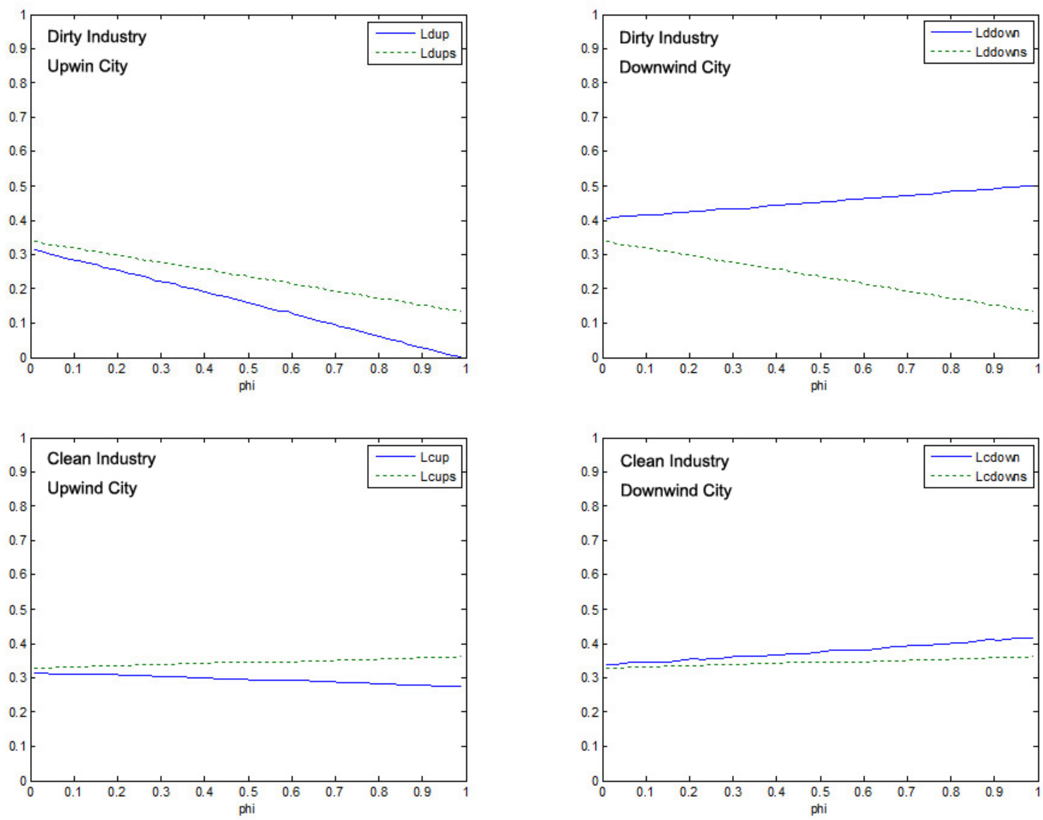
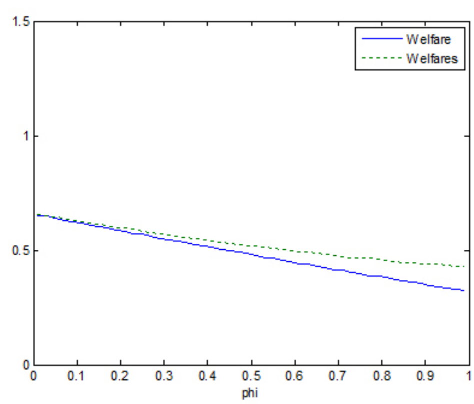


Figure 15: Comparative Statics of Equilibrium Social Welfare with Parameter ϕ (Model 2)



4.0 THE CONSEQUENCES OF TRANS-BOUNDARY AIR POLLUTION IN CHINA: EMPIRICAL EVIDENCE FOR THE NEGATIVE EFFECTS ON NON-POLLUTING INDUSTRIES

4.1 INTRODUCTION

Trans-boundary air pollution is a major inefficiency of decentralized environmental management. However, it is difficult to assess the exact cost of trans-boundary pollution, as geographic distribution of polluting industries and intensity of pollution emissions are endogenous to local social and economic characteristics. The policy-induced trans-boundary air pollution in modern China provides an opportunity to estimate the cost of trans-boundary air pollution in a scientific way. Since the 1990s, severe air pollution has become a lasting and challenging social problem in China, as the growing economy of this country is heavily based on consumption of fossil fuels like coal and oil (Bi et al., 2007; Rawski, 2009; Chen et al., 2013). As discussed in Chapter 2, the central government of China launched a large-scale policy-change in the early 2000s in order to implement stricter environmental regulation, but it has caused a dramatic increase of trans-boundary air pollution across provincial borders, due to the decentralized environmental management in China. This increase of trans-boundary air pollution is exogenous to non-polluting industrial sectors ("clean industries") in cities near provincial borders, which are more likely to be affected by air pollution from its upwind adjacent province. In this chapter, I will empirically study the consequences of policy-induced trans-boundary air pollution across China's provinces. I will particularly focus on how air pollution from one province affects output, employment, and number of firms in clean industries in its downwind adjacent provinces.

The institutional features in modern China lead to a unique quasi-experimental setting for studying the incidence and impacts of trans-boundary air pollution. China's inability to effectively control pollution stems in part from its decentralized regulatory structure. Pollution in China is not regulated by a single federal authority, but rather by a multitude of provincial governments (Landry, 2008; Cai et al., 2016). Provincial governments under-provide pollution abatement because they do not bear the full cost of pollution generated within their borders. When subnational governments are by law required to reduce pollution in their territory, they have incentives to dump pollution on their neighbors, causing the problem of trans-boundary pollution (Oates, 1999). In the case of air pollution, it is well documented that subnational governments set up more polluting industries downwind from where their constituents live and on borders with neighboring jurisdictions. Through difference-in-differences estimation using regional wind patterns and a large-scale policy-change, I have found that China's provincial capitals began locating more highly-polluting industries in downwind cities near provincial borders than in all other types of cities after 2003. Therefore, much of the cost of pollution in a given province, say province A, is borne by the residents of adjacent provinces that are downwind of polluting industry sites in province A. Put another way, while the introduction of polluting industries in province A creates more employment and growth in A, it also increases trans-boundary air pollution, which in turn generates adverse health, employment, and output effects in clean industries in adjacent provinces.

The empirical analysis in this chapter is guided by the theoretical model in Chapter 3, which has predicted adverse employment and output effects of trans-boundary pollution across China's provinces. Strategic responses of provincial leaders under central government's policy-change are solved in the model, and patterns of industrial relocation caused by trans-boundary air pollution are well characterized in the comparative statics. I have the following testable predictions: when labor markets are connected within each province, if the central government increases the weight of pollution in its evaluation function for imposing greater regulatory pressures, there are more output and employment of polluting industry in the downwind city in each province, which implies more trans-boundary air pollution. This will lead to less output and employment of clean industry in the upwind city, and the total welfare of the economy is below the social planner's solution. The gas are larger when the central government implements stricter environmental regulation.

The empirical strategy is also based on wind patterns of China. From the dataset of WINDFINDER (2014), I have calculated all-time average dominant wind direction in each province, and then define which cities are "downwind" according to this. Therefore, downwind cities close to provincial borders are "senders" of trans-boundary air pollution. For analyzing the effects on clean industry, I also figure out which cities are most likely to be affected by trans-boundary air pollution from their upwind neighboring provinces. Those cities are "receivers" of trans-boundary air pollution. I empirically estimate whether output and employment of clean industry firms in "receiver" cities are negatively affected by the policy-induced trans-boundary pollution, through a difference-in-differences (DID) estimation. I will also estimate whether new firms in clean industries are less likely to locate in "receiver" cities affected by trans-boundary air pollution.

Through empirical estimations based on the large-scale policy-change and wind patterns, I provide evidence-based results for the negative effects of policy-induced trans-boundary air pollution on clean industries. The DID estimations show that trans-boundary air pollution under China's decentralized environmental management has significantly negative effects on clean industries in cities near provincial borders. After 2003, output and employment of existing firms in clean industries are relatively less in cities receiving trans-boundary air pollution from neighboring provinces. For all existing firms in the receiver cities, the total negative effect on output is about 37.3 billion RMB (approximately 5.64 billion U.S. dollars). The negative effects are relatively larger for the clean industries in cities with higher average wind speed. State-owned firms of the clean industries in the receiver cities have more unproductive employment. New firms in clean industries are less likely to be located in the receiver cities. The probability of new firms in clean industries to be located in cities receiving trans-boundary air pollution is about 1.4% to 1.9% lower after 2003.

My empirical findings also contribute to the literature on estimating the economic costs of environmental pollution. Hedonic regressions on housing prices have been a typical method to assess impact and cost of pollution, following the idea and framework in Roback (1982). For example, Chay and Greenstone (2005) find significantly negative effects of TSP concentrations on housing prices through an instrument variable of "nonattainment" counties under the Clean Air Act. However, hedonic regressions may not be appropriate for inter-city comparison of housing prices, if the differences in labor markets and migration across cities are not well addressed in the analytical framework (Albouy, 2009, 2016). Another approach to assess the cost of pollution is to directly test "voting with feet" of migration. Banzhaf and Walsh (2008) directly test the theoretical prediction of "voting with feet" and find evidence for migration resulted from changing environmental quality. Bayer et al. (2009) estimate the effects of environmental pollution on household location decision. More recently, some literature is trying to directly test the effects of pollution on industrial productivity. Hanna and Oliva (2015) find that work hours were increased after air pollution was reduced in Mexico City. Hanlon (2016) finds that employment growth of British cities was significantly reduced by local industrial coal use after the Industrial Revolution. Chang et al. (2016) estimate the negative effects of air pollution on the productivity of pear packers as indoor workers. In this chapter, empirical estimation is guided by a model of labor market across cities, and I focus on output and employment to directly test the economic cost of trans-boundary air pollution on clean industries. The quasi-experimental approach based on large-scale policy-change and wind patterns provide convincing estimation for the negative effects of trans-boundary air pollution on clean industries. My findings also contribute to the analysis of unintended consequences of environmental regulation in China. The negative effects of trans-boundary air pollution on clean industries in the upwind cities are unintended consequences for the central government's regulation policy, as the large-scale policy changes were aimed at increasing the regulatory pressures. Moreover, the less restricted labor markets in modern China further strengthened the negative spillover effects.

The remainder of the chapter is organized as follows: Section 4.2 introduces the wind patterns and institutions in shaping the research design. Section 4.3 reports the data and econometric specifications. Section 4.4 presents the empirical results. Section 4.5 concludes. Section 4.6 includes the figures and tables.

4.2 INSTITUTIONS, WIND PATTERNS, AND EMPIRICAL STRATEGY

The large-scale policy-change in the early 2000s provides an opportunity to empirically study the effects of trans-boundary air pollution on clean industries through a difference-in-difference (DID) approach. The central government has initiated a new regime of environmental management, including targets for reducing pollution emissions, stricter laws on monitoring and punishing pollution, and changes to the criteria of evaluating local officials' performances (Landry, 2008; Chen et al., 2013). However, fierce political competition for promotion always exists among provincial leaders in China, as they are under a combination of centrally controlled political governance and decentralized socio-economic governance (Qian et al., 1999; Li and Zhou, 2005; Xu, 2011). High-level government officials in provincial capital shape industrial location decision in each province, and they are motivated to free ride on trans-boundary pollution after the policy change. From comparative statics of the model in Chapter 3, I have the following testable predictions for the effects of policy-induced trans-boundary air pollution on clean industries (as shown in Figures 13 and 14).

When labor markets are connected within a province and there are negative production externality for clean industries, if the central government imposes greater regulatory pressures (parameter ϕ is increasing):

(i) The equilibrium output and employment of the dirty industry in the upwind city are decreasing, and which in the downwind city are increasing. The gaps between equilibrium and social planner's solutions increase.

(ii) The equilibrium output and employment of the clean industry in the upwind city are decreasing, and which in the downwind city are increasing. The gaps between equilibrium and socially optimal levels are larger.

I will empirically test this prediction, through an identification strategy is based on wind patterns. I have clearly identified which cities are "downwind" in each of China's provinces, from exploring the WINDFINDER (2014) dataset of wind patterns. It provides worldwide wind and weather information, which includes data on monthly wind patterns in China's 30 provinces. I have calculated an all-time average dominant wind direction, an average wind speed, and a standard deviation of wind direction for each province according to the dataset. Figure 2 in Chapter 2 has shown the all-time average dominant wind direction in every province of China.

"Downwind" cities located close to provincial borders in each province are defined according to this figure, and they are the "senders" of trans-boundary air pollution after policy-change. For analyzing the effects on clean industry, I also figure out which cities are most likely to be affected by the trans-boundary air pollution from their neighboring provinces. Those cities are "receivers" of trans-boundary air pollution. Here I take Henan Province, the most populous province in China, as one example showing how to define sender and receiver cities for trans-boundary air pollution. Figure 16 shows the location of major cities in Henan Province. The average dominant wind direction is 95.3° in this province, which is close to the direction of east. The following cities are defined as "sender" (downwind) cities: Anyang, Hebi, Jiaozuo, Nanyang, Sanmenxia, and Xinyang. The following cities are defined as "receiver" cities: Puyang, Shangqiu, and Zhoukou. "Sender" and "receiver" cities in all other provinces are also defined in the same way.

4.3 DATA SOURCE AND ECONOMETRIC SPECIFICATION

The empirical analysis in this chapter answers the following question. Has policy-induced trans-boundary air pollution in modern China negatively affected clean industries in cities located close to provincial borders? If the inefficiencies for clean industries associated with trans-boundary pollution have increased after the policy changes, the following predictions can be tested in my empirical analysis. (1) Output and employment in clean industries are relatively less in cities receiving trans-boundary air pollution from upwind provinces. (2) New firms in clean industries are less likely to locate in cities receiving more trans-boundary air pollution.

The main data source for industrial output is the firm-level dataset of Annual Survey of Above-Scale Industrial Firms (National Bureau of Statistics, 1998–2007). Above-scale industrial firms are those with annual revenues above 5 million RMB (approximately 0.76 million U.S. dollars), and the survey covers all such firms located in 286 major cities from

1998 to 2007. Similar to the definition of polluting industries for river pollution in Cai et al. (2016), I define air-polluting industries for each kind of air pollutant according to *Report on the First National Census of Polluting Sources* (MEP, 2010). The four kinds of air pollutants listed in this report are SO_2, NO_2, dust, and soot. After defining the polluting industries for those four pollutants, the non-polluting (clean) industries are also defined. Table 2 in Chapter 2 has summarized the polluting and clean industries.

In my previous analysis about the incidence of trans-boundary air pollution in Chapter 2, empirical estimation is based on the city-level aggregate measure of polluting intensity. When the firm-level analysis is available in this chapter, it provides an opportunity to distinguish the two possible channels of increasing trans-boundary pollution: increasing size of existing firms in polluting industries, or increasing new firms of polluting industries in downwind cities. Therefore, as a prelude to the analysis of clean industries, I will estimate the firm-level outcomes for polluting industries. First, it is an estimation for existing firms in polluting industries.

$$Polluting_{it} = \beta_0 + \beta_1 \ Downwind_i \times Post_t + \mathbf{X}\theta + \alpha_i + \gamma_t + \varepsilon_{it} \tag{4.1}$$

The subscript i in Equation (4.1) denotes firm, while t denotes year. $Polluting_{it}$ denotes the output of an existing firm in polluting industry. The interaction term between $Post_t$ and $Downwind_i$ is the key explanatory variable for estimating the incidence of trans-boundary pollution. $Post_t$ is a dummy variable indicating the time of policy-change. $Downwind_i$ is a dummy variable indicating whether city i is in downwind cities. If the size of polluting industry firms are increasing in downwind cities after the policy change, the coefficient β_1 of the interaction term $Downwind_i \times Post_t$ is predicted to be positive. X is a set of other control variables including socioeconomic characteristics that may affect air pollution (population size, size of industrial output, population density, GDP per capita, industrial structure, the percentage of government expenditure, and share of foreign investment). The data sources for control variables are from every year's *China Urban Statistical Yearbook*. α_i is the firm fixed effects. γ_t is the year fixed effects. ε_{it} is the random error term.

The other possible channel for increasing trans-boundary pollution is that new firms of polluting industries are more likely to choose locations in downwind cities. Therefore, next I estimate the effects on new firms of polluting industries as follows:

$$Prob(Downwind)_{it} = \beta_0 + \beta_1 \ Polluting_i \times Post_t + \mathbf{X}\theta + \gamma_t + \varepsilon_{it} \tag{4.2}$$

Dependent variable $Prob(Downwind)_{it}$ is the probability of choosing to locate a new firm in a downwind city. $Polluting_i$ is a dummy variable indicating whether the firm is in a polluting industry. If the free-riding incentives affect location choice of new firms, the coefficient of the interaction term $Polluting_i \times Post_t$ is predicted to be positive.

Similar to the above two channels of increasing trans-boundary pollution, the effects of trans-boundary air pollution on clean industries are also through both outcomes of existing firms and location choices of new firms starting after the policy-change. In order to estimate the effects through those two different channels, empirical estimations will be conducted for both the sub-samples of existing firms and new firms. For existing firms, I will estimate the effects through a DID estimation. The baseline estimation equation is shown in Equation (4.3) as follows.

$$Nonpolluting_{it} = \beta_0 + \beta_1 \ Receiver_i \times Post_t + \beta_2 \ Sender_i \times Post_t + \mathbf{X}\theta + \alpha_i + \gamma_t + \varepsilon_{it} \tag{4.3}$$

The subscript i in Equation (4.3) denotes firm, while t denotes year. $Nonpolluting_{it}$ denotes the outcomes of an existing firm in clean industries. The dependent variable can be output or employment of a firm in the clean industry. The interaction term between $Post_t$ and $Receiver_i$ is the key explanatory variable for estimating the effects of trans-boundary pollution on clean industries. I will test whether β_1 is significantly negative. $Post_t$ is a dummy variable indicating the time of policy-change. $Receiver_i$ is a dummy variable indicating whether city i is affected by trans-boundary air pollution from upwind provinces, i.e. whether city i is a "receiver" city of trans-boundary air pollution. $Sender_i$ is a dummy variable indicating whether city i is in downwind cities, i.e. whether city i is a 'sender" city of trans-boundary air pollution.

Since wind speed is an important factor affecting trans-boundary air pollution, average wind speed is added into the estimation to show whether output and employment of clean industries are lower in "receiver" cities with higher average wind speed. A DDD estimation is shown in Equation (4.4) as follows.

$$
\begin{aligned}
&Nonpolluting_{it} = \beta_0 + \beta_1\ Receiver_i \times Post_t + \beta_2\ Wind\ Speed_i \times Post_t \\
&+\beta_3\ Receiver_i \times Wind\ Speed_i \times Post_t + \beta_4\ Sender_i \times Post_t + \mathbf{X}\theta + \alpha_i + \gamma_t + \varepsilon_{it}
\end{aligned} \tag{4.4}
$$

$Wind\ Speed_i$ is average wind speed. The coefficient of interaction term $Receiver_i \times Wind\ Speed_i \times Post_t$ is the DDD estimator for whether negative effect of trans-boundary pollution is larger in cities with higher wind speed. The hypothetical trans-boundary air pollution after policy-change predicts a negative sign for β_3, which is the parameters of interest in this regression equation.

Since state-owned enterprises (SOEs) in China are more likely to be influenced by preferences and decisions of government, and foreign-invested firms are much less likely to be influenced by government, I will include dummy variables indicating ownership of firms in Equation (4.5) as follows:

$$
\begin{aligned}
&Nonpolluting_{it} = \beta_0 + \beta_1\ Receiver_i \times Post_t + \beta_2\ State_i \times Post_t \\
&+\beta_3\ Receiver_i \times State_i \times Post_t + \beta_4\ Foreign_i \times Post_t \\
&+\beta_5\ Receiver_i \times Foreign_i \times Post_t + \beta_6\ Sender_i \times Post_t + \mathbf{X}\theta + \alpha_i + \gamma_t + \varepsilon_{it}
\end{aligned} \tag{4.5}
$$

$State_i$ is a dummy variable indicating whether the firm is a state-owned enterprise, and $Foreign_i$ is a dummy variable indicating whether the firm is foreign-invested. Triple-differences estimators $Affected_i \times State_i \times Post_t$ and $Affected_i \times Foreign_i \times Post_t$ are of interest. Since the state-owned firms are less free to adjust their decision when receiving more trans-boundary air pollution, the coefficient of $Affected_i \times State_i \times Post_t$ is predicted to be small or even with a different sign than $Affected_i \times Post_t$. On the other hand, foreign-invested firms are much freer to adjust their decision when receiving more trans-boundary air pollution, the coefficient of $Affected_i \times Foreign_i \times Post_t$ is predicted to be larger.

The policy-induced trans-boundary air pollution can also affect the location choice of new firms in clean industry. When some cities close to provincial borders are receiving more air pollution from upwind neighbor province, new firms will be less likely to locate in such cities. I will empirically test the effects of trans-boundary air pollution on location choice of new firms through the following linear probability model in Equation (4.6):

$$Prob(Receiver)_{it} = \beta_0 + \beta_1 \, Clean_i \times Post_t + \mathbf{X}\theta + \gamma_t + \varepsilon_{it} \tag{4.6}$$

The dependent variable $Prob(Receiver)_{it}$ is the probability of a new firm being located in a city receiving trans-boundary air pollution from upwind province, i.e. a receiver city. $Clean_i$ is a dummy variable indicating whether the firm is in a clean industry. If the negative effects of trans-boundary air pollution affect location choice of new firms, the coefficient of interaction term $Clean_i \times Post_t$ is predicted to be negative. The variables indicating ownership will be included in Equation (4.7):

$$\begin{aligned} Prob(Receiver)_{it} &= \beta_0 + \beta_1 \, Clean_i \times Post_t + \beta_2 \, State_i \times Post_t \\ &+ \beta_3 \, Clean_i \times State_i \times Post_t + \beta_4 \, Foreign_i \times Post_t \\ &+ \beta_5 \, Clean_i \times Foreign_i \times Post_t + \mathbf{X}\theta + \gamma_t + \varepsilon_{it} \end{aligned} \tag{4.7}$$

Table 21 shows the summary statistics for variables used in the empirical analysis.

4.4 ESTIMATION RESULTS

4.4.1 Firm-level Analysis of the Polluting Industries

First, I report the results for the air-polluting industries at the firm level. In my previous city-level analysis in Chapter 2, I have found that the output of polluting industries is more in downwind cities closer to provincial borders after 2003. The possible mechanisms of increasing polluting industries in those downwind cities include expansion of existing firms and increasing new firms. Firm-level analysis can help us examine whether and how those different channels have contributed to the increase of trans-boundary air pollution. This analysis is a prelude for estimating the effects on clean industries, as those effects are also through the two possible channels of changing the size of existing firms and affecting the location choice of new firms.

Table 22 reports the regression results for the output of existing firms in polluting industries, based on the econometric specification of Equation (4.1). Since the years 2000 and 2003 were the time of major policy changes, the interaction terms between *Downwind* and year dummies *Post*2000 and *Post*2003 are the key explanatory variables. Column (1) is for the subsample of all air-polluting industries. $Downwind \times Post2000$ is positive but not statistically significant, and $Downwind \times Post2003$ is significantly positive. After 2003, the average output of existing firms in air-polluting industries has been higher by 5.748 million RMB (approximately 0.868 million U.S. dollars) in downwind cities. Column (2) is for the subsample of polluting industries of pollutant $SO2$. $Downwind \times Post2000$ is positive but not statistically significant, and $Downwind \times Post2003$ is significantly positive. After 2003, the average output of existing firms in polluting industries of $SO2$ has been higher by 7.230 million RMB (approximately 1.092 million U.S. dollars) in downwind cities. Column (3) is for the subsample of polluting industries of pollutant $NO2$. $Downwind \times Post2000$ is negative but not statistically significant, and $Downwind \times Post2003$ is significantly positive. After 2003, the average output of existing firms in polluting industries of $NO2$ has been higher by 6.120 million RMB (approximately 0.925 million U.S. dollars) in downwind cities. Column (4) is for the subsample of polluting industries of pollutant *Soot*. $Downwind \times Post2000$ is positive but not statistically significant, and $Downwind \times Post2003$ is significantly positive. After 2003, the average output of existing firms in polluting industries of *Soot* has been higher by 5.586 million RMB (approximately 0.844 million U.S. dollars) in downwind cities. The above results conclude that existing firms of air-polluting industries in downwind cities have more output after the policy- change, which has contributed to the increase of trans-boundary air pollution after 2003.

Table 23 reports the effects of state ownership on polluting industries. State-owned enterprises are more likely to be influenced by government, and one hypothesis to test is that the effects of policy-induced trans-boundary pollution are larger for state-owned enterprises. I include the interaction terms $State \times Post_t$ and $Downwind \times State \times Post_t$ in the regressions to test this hypothesis by a DDD estimation. When these interaction terms are included, the estimated coefficients of $Downwind \times Post2000$ and $Downwind \times Post2003$ are nearly the same as in Table 22. $Downwind \times Post2003$ is still significantly positive. The results of increasing trans-boundary air pollution after policy-change are robust. For all four columns, the DDD estimator $Downwind \times State \times Post2003$ is positive but not significant.

Table 24 further includes variable indicating whether a firm is foreign-invested. When these interaction terms are included, the estimated coefficients of $Downwind \times Post2000$ and $Downwind \times Post2003$ are nearly the same as in Table 22. $Downwind \times Post2003$ is still significantly positive. The results of increasing trans-boundary air pollution after policy-change are robust. The DDD interaction term $Downwind \times Foreign \times Post2003$ is negative and not significant for all four columns, and the combined marginal effects for foreign-invested firms are not significant.

Table 25 reports the estimation results for the location choice of new firms in polluting industries, based on the econometric specification of Equation (4.2). The sample is all new firms starting after 1998. In all four columns, $Polluting \times Post2003$ is significantly positive, which implies that the probability of new firms in clean industries to be located in downwind cities is about 2.0% to 3.4% higher after 2003. When including variables indicating state ownership, the interaction term $Polluting \times State \times Post2003$ is positive but not significant. When including variables indicating foreign ownership, the interaction term $Polluting \times State \times Post2000$ is positive but not significant, and $Polluting \times State \times Post2003$ is negative but not significant.

4.4.2 Firm-level Analysis for the Clean Industries

Table 26 reports the estimation results for the outcomes of existing firms in clean industries, based on the econometric specification of Equation (4.3). The dependent variables of Columns (1) and (2) are the output of clean industry firms, and which of Columns (3) and (4) are the employment of clean industry firms. $Receiver \times Post2000$ and $Receiver \times Post2003$ are both significantly negative, which imply that trans-boundary air pollution has significant negative effects on the output and employment of clean industries. In Column (2), when control variables are included in regression, $Receiver \times Post2000$ is -4.738 and $Receiver \times Post2000$ is -7.690. These results imply that the average output of an existing clean industry firm in cities receiving trans-boundary air pollution has decreased by 4.290

million RMB (approximately 0.648 million U.S. dollars) after 2000 and has decreased by 7.690 million RMB (approximately 1.162 million U.S. dollars) after 2003. Since there are a total of 3127 existing clean industry firms in cities receiving trans-boundary air pollution, the total negative effect on the annual output of existing firms of clean industries in receiver cities is about 37.5 billion RMB (approximately 5.67 billion U.S. dollars). In Column (4), when control variables are included in regression, $Receiver \times Post2000$ is -37.31 and $Receiver \times Post2000$ is -15.26. These results imply that the average employment of an existing clean industry firm in receiver city has decreased by about 37 persons after 2000 and has decreased by about 15 persons after 2003. The total negative effect on the employment of existing firms of clean industries in receiver cities is about 164 thousand. Figure 17 shows trends before and after policy-change in the two groups of cities. Since the economic reforms began in the late 1970s, labor mobility within province has been less restricted in China. Labor mobility for urban population across cities apply within each province. Therefore, my empirical findings are consistent with the prediction of the model in Section 3.4 that distortion caused by trans-boundary pollution is greater when labor markets are connected. The estimated negative effects of trans-boundary pollution on clean industries are not only from the negative productivity externalities, but also from the labor competition effects that labor is leaving from the clean industries in the upwind cities receiving trans-boundary pollution.

Table 27 reports the estimation results for the outcomes of existing firms in clean industry firms when there are more control variables $Sender \times Post2000$ and $Sender \times Post2003$. Like in Table 26, the dependent variables of Columns (1) and (2) are the output of a clean industry firm, while which of Columns (3) and (4) are the employment of a clean industry firm. The estimation results are very similar as in Table 26: $Receiver \times Post2000$ and $Receiver \times Post2003$ are both significantly negative, which imply that trans-boundary air pollution has significant negative effects on the output and employment of clean industries. In Column (2), $Receiver \times Post2000$ is -4.009 and $Receiver \times Post2000$ is -7.928. These results imply that the average output of an existing clean industry firm in receiver cities has decreased by 4.009 million RMB (approximately 0.606 million U.S. dollars) after 2000 and has decreased by 7.928 million RMB (approximately 1.198 million U.S. dollars) after 2003. Since there are a total of 3127 existing firms of clean industries in those cities, the total negative effect on the annual output of existing firms of clean industries in receiver cities is about 37.3 billion RMB (approximately 5.64 billion U.S. dollars). The negative effects of trans-boundary air pollution on the output of clean industries are robust as being found in Table 7. In Column (4), $Receiver \times Post2000$ is -38.10 and $Receiver \times Post2000$ is -15.43. These results imply that the average employment of an existing clean industry firm in receiver city has decreased by about 38 persons after 2000 and has decreased by about 15 persons after 2003. The total negative effect on the employment of existing firms of clean industries in receiver cities is about 167 thousand. The negative effects of trans-boundary air pollution on employment of clean industries are also robust.

Table 28 reports the results for DDD estimations using average wind speed, based on the econometric specification of Equation (4.4). Like in Table 26, dependent variables of Columns (1) and (2) are the output of a clean industry firm, while which of Columns (3) and (4) are the employment of a clean industry firm. Column (2) is the regression for output with all control variables. The DDD interaction term $Receiver \times Wind\ Speed \times Post2003$ is significantly negative (-1.319), and the interaction term $Receiver \times Post2003$ is positive (6.552) but not statistically significant. This implies that the negative effects of trans-boundary air pollution are stronger in receiver cities with higher average wind speed. I also calculate the estimated marginal effects of $Receiver$ at different percentiles of $WindSpeed$, which shows that the effect at the 90th percentile of $Wind\ Speed$ (15.5 km/h) is -13.90, and the effect at the 25th percentile of $Wind\ Speed$ (10.3 km/h) is -7.04. Column (4) is the regression for employment with all control variables. The DDD interaction term $Receiver \times Wind\ Speed \times Post2003$ is significantly negative (-6.396), and the interaction term $Receiver \times Post2003$ is significantly positive (58.74). The estimated marginal effects of $Receiver$ at different percentiles of $Wind\ Speed$ are negative. The effect at the 90th percentile of $Wind\ Speed$ (15.5 km/h) is -40.40, and the effect at the 25th percentile of $Wind\ Speed$ (10.3 km/h) is -7.14. Negative effects are larger in cities with higher average wind speed.

Table 29 reports the results for regressions including state and foreign ownership, based on the econometric specification of Equation (4.5). Columns (1) and (2) have the output of existing firms in clean industries as the dependent variable, and Columns (3) and (4) have the employment of existing firms in clean industries as the dependent variable. In Column (1), when dummy variables indicating state ownership are included in the regression, $Receiver \times Post2000$ is still negative but not significant, and $Receiver \times Post2003$ is still significantly negative (-5.025). The DDD estimator $Receiver \times State \times Post2003$ is not significant, which implies that the negative effects on state-owned firms are not significantly different from other firms. In Column (2), when dummy variables indicating foreign-invested firms are also included, $Receiver \times State \times Post2003$ is negative but still not statistically significant. Meanwhile, $Receiver \times Foreign \times Post2003$ is significantly negative (-33.37), which implies that the negative effects on foreign-invested firms are stronger than on other firms. When comparing with the estimation results for employment in Columns (3) and (4), we can find that employment of existing state-owned clean industry firms is significantly more than other existing clean industry firms in receiver cities after 2003, while the negative effects on output of existing state-owned clean industry firms are not significantly different from other firms. These results suggest that state-owned clean industry firms under control or influences of provincial governments have increased their employment after the policy change when their productivity is negatively affected by trans-boundary pollution. The state-owned firms of clean industries in the receiver cities hire more unproductive workers after policy change, which is a distortion that reduces the efficiency of the economy. For the foreign-invested clean industry firms, they are freer to adjust their decisions, so both output and employment have decreased after receiving more trans-boundary air pollution. The combined marginal effects of interaction terms $Receiver \times Post2003$ and $Receiver \times Foreign \times Post2003$ is a reduction of 36.19 million RMB (approximately 5.468 million U.S. dollars) for the output of an existing foreign-invested firm of clean industries in cities receiving trans-boundary air pollution.

Table 30 reports the estimation results for the location choice of new firms in clean industries, based on the econometric specification of Equations (4.6) and (4.7). In all four columns, $Clean \times Post2003$ is significantly negative, which implies that the probability of new firms in clean industries to be located in cities receiving trans-boundary air pollution is about 1.4% to 1.9% lower after 2003. When including variables indicating state ownership, the interaction term $Clean \times State \times Post2000$" has a large and significantly negative coefficient (around -0.07) in Columns (3) and (4). However, $Clean \times Post2000$ and $Clean \times Post2003$ in Columns (3) and (4) are not very different from the regressions in Columns (1) and (2) without the triple-differences interaction term of state ownership. Since decisions for setting up new state-owned firms are made by local governments themselves and their actions are earlier than private and foreign firms, the negative effect for state-owned new firms is significant after 2000. Meanwhile, there were 69,896 new firms being setup during the period 1998 to 2007, and 2,094 of which were state-owned new firms. The number of state-owned new firms was only 3% of the total number of new firms. When economic reforms toward market economy took place in China in the 1990s and 2000s, there was a rule of "grasping the large and letting the small go" to downsize the state sector. Therefore, state-owned firms did not possess a large share in the new firms during that period, and the large and significantly negative coefficient of the triple-differences interaction term $Clean \times State \times Post2000$ does not affect the coefficients of $Clean \times Post2000$ and $Clean \times Post2003$. When including variables indicating foreign ownership, the interaction term $Clean \times State \times Post2000$ and $Clean \times State \times Post2003$ are neither significant.

4.4.3 City-level Analysis for the Clean Industries

In order to estimate the aggregate negative effects on clean industries, I also perform regressions at the city level. Table 31 reports the estimation results for regressions with the interaction terms $Receiver \times Post_t$. The dependent variable of Column (1) is the total employment of firms in clean industries without polluting the air, and which of Column (2) is the total employment of firms in clean industries without polluting air or water. The estimated coefficient of $Receiver \times Post2000$ are not statistically significant for either column, but $Receiver \times Post2003$ are both significantly negative. These results imply that total employment of firms in clean industries without polluting air is relatively lower by about 26.65 thousand in an average receiver city after the policy change, and total employment of firms in clean industries without polluting air or water is relatively lower by about 16.79 thousand in an average receiver city after the policy-change. The dependent variable of Column (3) is the number of firms in clean industries without polluting air, and which of Column (4) is the number of firms in clean industries without polluting air or water. The estimated coefficient of $Receiver \times Post2000$ are not statistically significant for either column, but $Receiver \times Post2003$ are both significantly negative. These results imply that the number of firms in clean industries without polluting air is relatively lower by about 161 in an average receiver city after the policy change, and the total number of firms in clean industries without polluting air or water is relatively lower by about 85 in an average receiver city after the policy change. Figure 18 shows trends before and after policy-change in the two groups of cities.

Table 32 reports the estimation results for regressions further including the interaction term $Sender \times Post_t$. The same as in Table 31, the dependent variable of Column (1) is the total employment of firms in clean industries without polluting the air, and which of Column (2) is the total employment of firms in clean industries without polluting air or water. The estimated coefficient of $Receiver \times Post2000$ are not statistically significant for either column, but $Receiver \times Post2003$ are both significantly negative and very similar to the results in Table 31. These results imply that total employment of firms in clean industries without polluting air is relatively lower by about 26.44 thousand in an average receiver city after the policy change, and total employment of firms in clean industries without polluting air or water is relatively lower by about 16.67 thousand in an average receiver city after the policy change. The dependent variable of Column (3) is the number of firms in clean industries without polluting air, and which of Column (4) is the number of firms in clean industries without polluting air or water. The estimated coefficient of $Receiver \times Post2000$ are not statistically significant for either column, but $Receiver \times Post2003$ are both significantly negative. These results imply that the number of firms in clean industries without polluting air is relatively lower by about 159 in an average receiver city after the policy-change, and the total number of firms in clean industries without polluting air or water is relatively lower by about 85 in an average receiver city after the policy change.

4.5 CONCLUSION

China's inability to control pollution in an effective way stems in part from its decentralized regulatory structure. Trans-boundary pollution is one of the major potential disadvantages of decentralized environmental management. In this chapter, I figure out which cities are most likely to receive trans-boundary air pollution from their upwind adjacent provinces. Through a quasi-experimental approach combining large-scale policy-change and regional wind patterns, my findings provide convincing evidence for the negative effects of policy-induced trans-boundary air pollution on clean industries. The DID estimations show that trans-boundary air pollution under China's regionally decentralized environmental management has significantly negative effects on non-polluting industries in cities near provincial borders. The output and employment of existing firms in clean industries are relatively less in cities receiving trans-boundary air pollution from neighboring provinces after 2003. For all existing firms in the receiver cities, the total negative effect on output is about 37.3 billion RMB (approximately 5.64 billion U.S. dollars). The negative effects are relatively larger for clean industries in cities with higher average wind speed. State-owned firms of the clean industries in the receiver cities have more unproductive employment. New firms in clean industries are less likely to be located in the receiver cities. The probability of new firms in clean industries to be located in receiver cities is about 1.4% to 1.9% lower after 2003.

The quasi-experimental approach based on large-scale policy-change and regional wind pattern provide convincing evidence for the adverse effects of trans-boundary air pollution on output and employment of clean industries. These findings contribute to the literature about estimating the negative effects of environmental pollution on industrial output. The negative effects of policy-induced trans-boundary air pollution on output and location choice of clean industries are unintended consequences of environmental regulation in China. When clean industries are leaving cities receiving more trans-boundary air pollution, it reduces economic opportunities in those cities and thus increases inequality across regions. The negative consequences of trans-boundary air pollution greatly reduce the efficiency of decentralized environmental management, and reforms in the environmental management system are necessary to mitigate air pollution in China effectively.

4.6 FIGURES AND TABLES

Figure 16: Receiver Cities in Henan Province

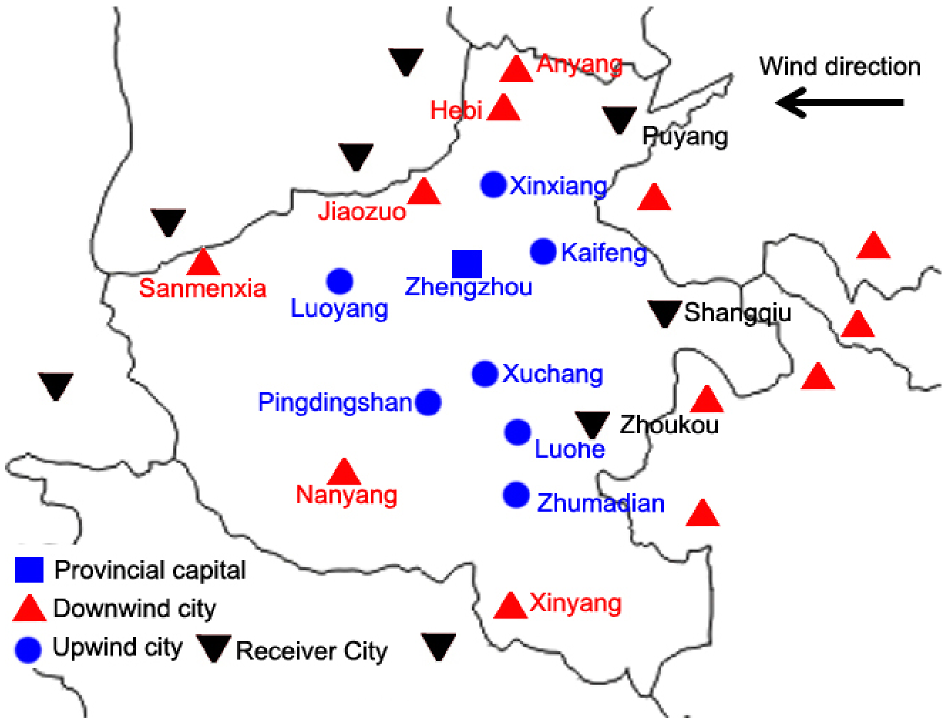


Figure 17: Trends of Output and Employment of Clean Industries

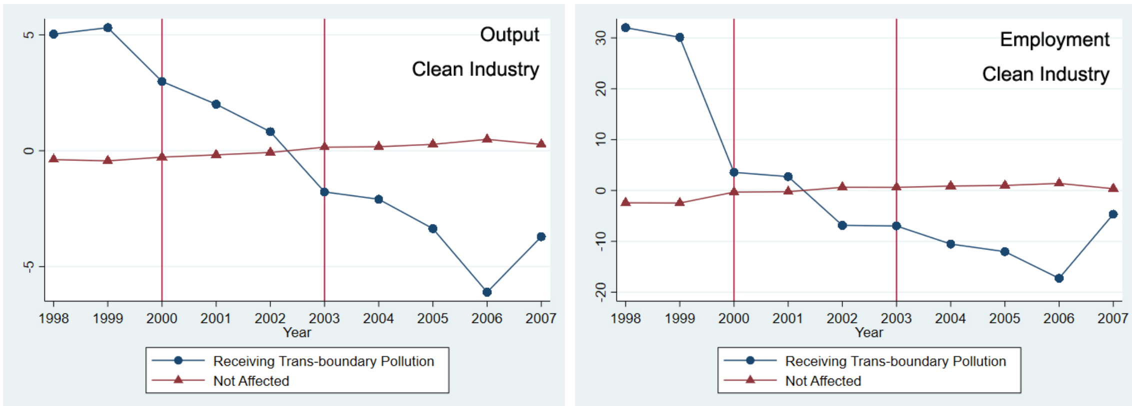


Figure 18: Trends of Employment and Number of Firms of Clean Industries

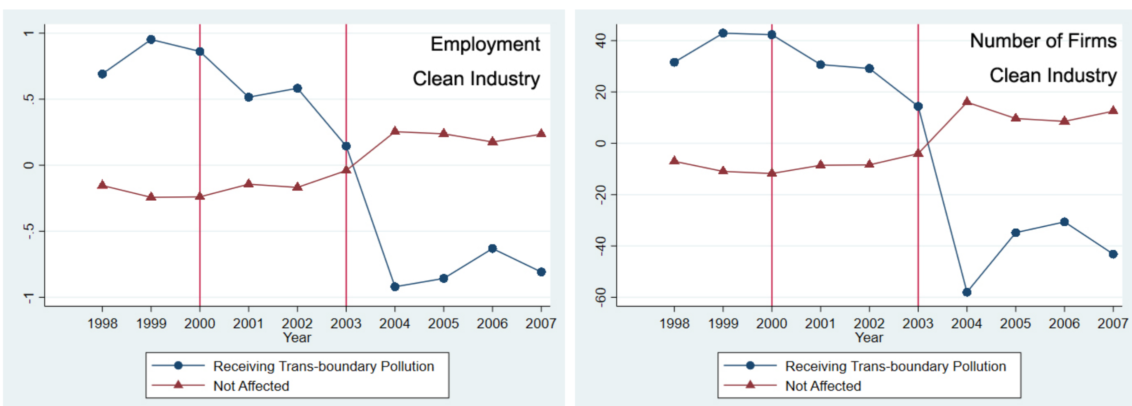


Table 21: Summary Statistics (City and Firm Level)

Variable	Observations	Mean	Standard Deviation	Min.	Max.
Firm-level variables					
Firms in polluting industries:					
Output Polluting (unit: 1 million RMB)	208,651	57.379	102.643	0.001	1148.078
Output SO_2 (unit: 1 million RMB)	148,209	59.157	107.239	0.001	1145.889
Output NO_2 (unit: 1 million RMB)	139,204	57.541	105.324	0.001	1145.889
Output Soot (unit: 1 million RMB)	187,449	56.119	100.178	0.001	1148.078
Firms in non-polluting industries:					
Ouput Clean (unit: 1 million RMB)	286,434	62.774	143.274	0.001	2489.780
Employment Clean (unit: person)	284,630	332.472	609.507	1.000	25733
City-level variables					
Average wind speed: *Wind Speed* (unit: km/h)	2860	11.139	3.387	3.500	21.100
Population size: *Population* (unit: 10,000 persons)	2698	119.432	146.124	14.080	1526.020
Total output of industrial firms: *Industrial Output* (unit: 1 billion RMB)	2727	62.828	137.742	0.002	2225.147
Population density: *Population Density* (unit: 10,000 /km2)	2672	0.097	0.052	0.001	1.094
GDP per capita: *GDP* (unit: 10,000 RMB)	2691	2.001	2.043	0.184	32.025
Percentage of secondary industry in GDP: *Secondary Industry*	2726	49.578	12.946	8.050	92.300
Percentage of tertiary industry in GDP: *Tertiary Industry*	2726	41.046	10.259	7.300	81.000
Total number of above-scale firms: *Firm number*	2691	765.155	1306.484	1.000	15520
Percentage of government expenditure in GDP: *Government Expenditure*	2676	11.175	9.443	0.000	195.922

Table 21 (continued).

Percentage of FDI in GDP: FDI	2860	3.435		5.296	0.000	134.592

Table 22: The Effects on Dirty Industries (Existing Firms)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output Polluting*	*Output* SO_2	*Output* NO_2	*Output Soot*
$Downwind \times Post2000$	-0.221	0.162	-0.225	-0.680
	(0.701)	(0.825)	(0.816)	(0.699)
$Downwind \times Post2003$	5.748***	7.230***	6.120***	5.586***
	(1.355)	(1.700)	(1.682)	(1.368)
Year effects	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	171,973	122,649	115,274	154,745
R-squared	0.135	0.147	0.142	0.136
Number of firms	28,192	19,858	18,704	25,364

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at firm level. (4) Other control variables include city characteristics.

Table 23: The Effects of State Ownership on Dirty Industries (Existing Firms)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output Polluting*	*Output* SO_2	*Output* NO_2	*Output Soot*
$Downwind \times Post2000$	0.445	1.067	1.005	-0.0862
	(0.942)	(1.161)	(1.171)	(0.952)
$State \times Post2000$	-3.992***	-5.083***	-4.243***	-3.499***
	(1.007)	(1.247)	(1.157)	(1.000)
$Downwind \times State \times Post2000$	-1.522	-1.697	-2.863	-1.236
	(1.996)	(2.531)	(2.508)	(1.951)
$Downwind \times Post2003$	4.827***	5.871***	4.564***	4.672***
	(1.421)	(1.770)	(1.719)	(1.414)
$State \times Post2003$	7.393***	12.01***	13.44***	9.709***
	(2.030)	(2.472)	(2.518)	(2.037)
$Downwind \times State \times Post2003$	3.039	3.598	4.030	2.748
	(3.703)	(4.477)	(4.474)	(3.762)
Est. Marginal Effect:				
$Downwind \times Post2003 + Downwind \times State \times Post2003$	7.865**	9.469**	8.594**	7.420**
	(3.458)	(4.165)	(4.184)	(3.525)
Year effects	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	171,973	122,649	115,274	154,745
R-squared	0.135	0.148	0.145	0.137
Number of firms	28,192	19,858	18,704	25,364

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at firm level. (4) Other control variables include city characteristics.

Table 24: The Effects of State and Foreign Ownership on Dirty Industries (Existing Firms)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output Polluting*	*Output* SO_2	*Output* NO_2	*Output Soot*
$Downwind \times Post2000$	0.319	0.763	0.738	-0.0719
	(0.944)	(1.158)	(1.166)	(0.961)
$State \times Post2000$	-4.070***	-5.349***	-4.514***	-3.532***
	(1.008)	(1.250)	(1.160)	(1.001)
$Downwind \times State \times Post2000$	-1.369	-1.393	-2.561	-1.157
	(1.999)	(2.534)	(2.511)	(1.953)
$Foreign \times Post2000$	7.409*	1.318	1.521	9.411**
	(3.785)	(5.333)	(5.462)	(3.972)
$Downwind \times Foreign \times Post2000$	12.24	21.34	16.32	3.808
	(9.682)	(15.01)	(15.55)	(9.342)
$Downwind \times Post2003$	5.051***	6.130***	4.899***	4.978***
	(1.429)	(1.773)	(1.720)	(1.421)
$State \times Post2003$	7.981***	12.78***	14.24***	10.28***
	(2.032)	(2.473)	(2.519)	(2.038)
$Downwind \times State \times Post2003$	2.717	3.201	3.554	2.349
	(3.705)	(4.477)	(4.472)	(3.764)
$Foreign \times Post2003$	15.08***	26.46***	26.58***	14.08***
	(4.299)	(6.298)	(6.402)	(4.300)
$Downwind \times Foreign \times Post2003$	-5.479	-10.00	-9.405	-6.925
	(10.19)	(16.35)	(16.72)	(10.97)
Est. Marginal Effect:				
$Downwind \times Post2003 + Downwind \times State \times Post2003$	7.768**	9.332**	8.453**	7.327**
	(3.459)	(4.165)	(4.184)	(3.525)
$Downwind \times Post2003 + Downwind \times Foreign \times Post2003$	-0.428	-3.871	-4.505	-1.947
	(10.09)	(16.25)	(16.63)	(10.88)
Year effects	Yes	Yes	Yes	Yes

Table 24 (continued).

Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	171,973	122,649	115,274	154,745
R-squared	0.135	0.147	0.142	0.136
Number of firms	28,192	19,858	18,704	25,364

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at firm level. (4) Other control variables include city characteristics.

Table 25: The Effects of State and Foreign Ownership on Dirty Industries (Existing Firms)

	(1)	(2)	(3)	(4)
Dependent variable:	$Prob(Downwind)$	$Prob(Downwind)$	$Prob(Downwind)$	$Prob(Downwind)$
$Polluting \times Post2000$	0.00551	-0.00279	-0.00204	-0.000992
	(0.00829)	(0.00799)	(0.00820)	(0.00830)
$State \times Post2000$			0.0155	0.0162
			(0.0253)	(0.0253)
$Polluting \times State \times Post2000$			-0.0173	-0.0181
			(0.0366)	(0.0366)
$Foreign \times Post2000$				0.00963
				(0.0264)
$Polluting \times Foreign \times Post2000$				-0.0332
				(0.0570)
$Polluting \times Post2003$	0.0344***	0.0208**	0.0200**	0.0197**
	(0.00904)	(0.00877)	(0.00897)	(0.00909)
$State \times Post2003$			-0.00731	-0.00894
			(0.0347)	(0.0348)
$Polluting \times State \times Post2003$			0.0235	0.0236
			(0.0510)	(0.0510)
$Foreign \times Post2003$				-0.0354
				(0.0281)
$Polluting \times Foreign \times Post2003$				-0.0232
				(0.0610)
Year effects	Yes	Yes	Yes	Yes
Province Fixed effects	Yes	Yes	Yes	Yes
Other control variables	No	Yes	Yes	Yes
Observations	69,896	65,570	65,570	65,570
R-squared	0.161	0.200	0.200	0.200

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Other control variables include city characteristics.

Table 26: The Effects on Clean Industries (Existing Firms)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output Clean*	*Output Clean*	*Employment Clean*	*Employment Clean*
$Receiver \times Post2000$	-4.738***	-4.290***	-35.67***	-37.31***
	(1.047)	(1.051)	(10.76)	(10.73)
$Receiver \times Post2003$	-9.232***	-7.690***	-20.49***	-15.26**
	(1.795)	(1.780)	(6.656)	(6.594)
Year effects	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	No	Yes	No	Yes
Observations	241,961	238,576	241,959	238,574
R-squared	0.080	0.078	0.005	0.007
Number of firms	38,241	38,241	38,241	38,241

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at firm level. (4) Other control variables include city characteristics.

Table 27: The Effects on Clean Industries (Existing Firms)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output Clean*	*Output Clean*	*Employment Clean*	*Employment Clean*
$Receiver \times Post2000$	-4.437***	-4.009***	-36.41***	-38.10***
	(1.056)	(1.060)	(10.89)	(10.85)
$Receiver \times Post2003$	-9.477***	-7.928***	-20.24***	-15.43**
	(1.802)	(1.787)	(6.713)	(6.646)
$Sender \times Post2000$	-2.049**	-1.780*	5.139	5.771
	(0.958)	(0.948)	(5.902)	(5.896)
$Sender \times Post2003$	2.366	2.691	-2.066	3.447
	(1.787)	(1.737)	(6.127)	(6.198)
Year effects	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	No	Yes	No	Yes
Observations	241,961	238,576	241,959	238,574
R-squared	0.080	0.078	0.005	0.007
Number of firms	38,241	38,241	38,241	38,241

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at firm level. (4) Other control variables include city characteristics.

Table 28: Triple-differences Estimation with Wind Speed (Clean Industry)

	(1)	(2)	(3)	(4)
Dependent variable:	*Output Clean*	*Output Clean*	*Employment Clean*	*Employment Clean*
$Receiver \times Wind\ Speed \times Post2000$	-0.935***	-1.367***	-5.698**	-5.778***
	(0.360)	(0.371)	(2.238)	(2.205)
$Receiver \times Post2000$	5.523	11.10***	29.48	28.05
	(4.084)	(4.221)	(23.93)	(23.80)
$Wind\ Speed \times Post2000$	-0.0323	0.0506	2.523***	2.715***
	(0.121)	(0.123)	(0.656)	(0.660)
$Receiver \times Wind\ Speed \times Post2003$	-1.277**	-1.319**	-5.107*	-6.396**
	(0.613)	(0.616)	(2.647)	(2.629)
$Receiver \times Post2003$	4.667	6.552	37.25	58.74**
	(7.192)	(7.236)	(27.80)	(27.68)
$Wind\ Speed \times Post2003$	-0.165	-0.0245	3.084***	4.494***
	(0.217)	(0.212)	(0.723)	(0.681)
Est. Marginal effect of Downwind at:				
90th Pctile of $Wind\ Speed$ (15.5)	-15.12***	-13.90***	-41.91***	-40.40***
	(3.11)	(3.10)	(15.35)	(15.18)
75th Pctile of $Wind\ Speed$ (11.8)	-10.40***	-9.02***	-23.01***	-16.73**
	(1.81)	(1.80)	(7.60)	(7.52)
50th Pctile of $Wind\ Speed$ (11.2)	-9.63***	-8.23***	-19.95***	-12.89*
	(1.79)	(1.79)	(6.86)	(6.80)
25th Pctile of $Wind\ Speed$ (10.3)	-8.48***	-7.04***	-15.35**	-7.14
	(1.90)	(1.91)	(6.36)	(6.32)
Year dummies	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	No	Yes	No	Yes
Observations	241,961	238,576	241,959	238,574
R-squared	0.080	0.079	0.005	0.008

Table 28 (continued).

Number of cities	38,241	38,241	38,241	38,241

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Other control variables include city characteristics.

Table 29: The Effects of State and Foreign Ownership on Clean Industries

	(1)	(2)	(3)	(4)
Dependent variable:	*Output Clean*	*Output Clean*	*Employment Clean*	*Employment Clean*
$Receiver \times Post2000$	-3.572	-3.326	-37.95***	-39.86***
	(2.209)	(2.239)	(13.54)	(13.61)
$State \times Post2000$	-3.103***	-3.629***	2.691	-1.117
	(1.128)	(1.139)	(4.617)	(4.620)
$Receiver \times State \times Post2000$	0.495	1.003	1.526	6.192
	(4.472)	(4.485)	(15.96)	(15.92)
$Foreign \times Post2000$		5.539*		16.29
		(3.366)		(10.68)
$Receiver \times Foreign \times Post2000$		-12.57		-45.17
		(13.17)		(37.89)
$Receiver \times Post2003$	-5.025**	-2.822	-18.94**	-10.71
	(2.352)	(2.388)	(7.653)	(7.620)
$State \times Post2003$	-18.38***	-16.04***	-103.3***	-90.84***
	(1.428)	(1.428)	(5.613)	(5.524)
$Receiver \times State \times Post2003$	0.0567	-2.540	50.39***	40.55***
	(2.917)	(2.943)	(13.67)	(13.67)
$Foreign \times Post2003$		26.15***		75.69***
		(3.456)		(10.51)
$Receiver \times Foreign \times Post2003$		-33.37***		-12.96
		(10.02)		(51.00)
Est. Marginal Effect:				
$Receiver \times Post2003 +$				
$Receiver \times State \times Post2003$	-4.968***	-5.362***	31.45***	29.84**
	(1.862)	(1.861)	(11.90)	(11.93)
$Receiver \times Post2003 +$				
$Receiver \times Foreign \times Post2003$		-36.19***		-23.68
		(9.81)		(50.40)

Table 29 (continued).

Year effects	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	238,576	238,576	241,959	238,574
R-squared	0.080	0.083	0.009	0.013
Number of firms	38,241	38,241	38,241	38,241

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Other control variables include city characteristics.

Table 30: Location Choice of New Firms (Clean Industries)

	(1)	(2)	(3)	(4)
Dependent variable:	*Prob*(*Receiver*)	*Prob*(*Receiver*)	*Prob*(*Receiver*)	*Prob*(*Receiver*)
$Clean \times Post2000$	0.00114	0.00270	0.00564	0.00577
	(0.00689)	(0.00680)	(0.00693)	(0.00708)
$State \times Post2000$			0.0248	0.0247
			(0.0175)	(0.0175)
$Clean \times State \times Post2000$			-0.0747**	-0.0751**
			(0.0355)	(0.0355)
$Foreign \times Post2000$				-0.0175
				(0.0317)
$Clean \times Foreign \times Post2000$				0.00506
				(0.0402)
$Clean \times Post2003$	-0.0189**	-0.0138*	-0.0168**	-0.0170**
	(0.00752)	(0.00747)	(0.00760)	(0.00777)
$State \times Post2003$			-0.0221	-0.0226
			(0.0244)	(0.0244)
$Clean \times State \times Post2003$			0.0763	0.0765
			(0.0488)	(0.0488)
$Foreign \times Post2003$				-0.0102
				(0.0335)
$Clean \times Foreign \times Post2003$				0.00903
				(0.0427)
Year effects	Yes	Yes	Yes	Yes
Province Fixed effects	Yes	Yes	Yes	Yes
Other control variables	No	Yes	Yes	Yes
Observations	69,896	65,570	65,570	65,570
R-squared	0.183	0.197	0.197	0.197

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Other control variables include city characteristics.

Table 31: The Effects on Clean Industries (City-level)

	(1)	(2)	(3)	(4)
Dependent variable:	*Employment Clean*1	*Employment Clean*2	*Firm Clean*1	*Firm Clean*2
$Receiver \times Post2000$	-0.247	-0.275	-14.42	-6.831
	(1.042)	(0.689)	(37.18)	(21.91)
$Receiver \times Post2003$	-2.665**	-1.679**	-160.5**	-85.27***
	(1.104)	(0.682)	(61.84)	(30.66)
Year effects	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Other control variables	Yes	Yes	Yes	Yes
Observations	2,648	2,648	2,648	2,648
R-squared	0.501	0.564	0.386	0.430
Number of cities	286	286	286	286

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at city level. (4) Other control variables include city characteristics.

Table 32: The Effects on Clean Industries (City-level, with More Control Variables)

	(1)	(2)	(3)	(4)
Dependent variable:	*Employment Clean*1	*Employment Clean*2	*Firm Clean*1	*Firm Clean*2
Receiver × *Post*2000	-0.323	-0.331	-13.80	-6.320
	(1.068)	(0.710)	(37.59)	(22.19)
Receiver × *Post*2003	-2.644**	-1.666**	-158.6**	-84.62***
	(1.096)	(0.684)	(61.25)	(30.51)
Sender × *Post*2000	0.940	0.680	-1.421	-3.887
	(0.939)	(0.730)	(20.30)	(12.85)
Sender × *Post*2003	-0.324	-0.178	-41.53	-14.94
	(1.107)	(0.881)	(38.03)	(23.89)
Other control variables	Yes	Yes	Yes	Yes
Year effects	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
Observations	2,648	2,648	2,648	2,648
R-squared	0.501	0.565	0.386	0.430
Number of cities	286	286	286	286

Notes: (1) Standard error in parentheses. (2) *** denotes significance at the 1% level, ** at the 5% level, and * at the 10% level. (3) Standard errors are clustered at city level. (4) Other control variables include city characteristics.

APPENDIX A

SOLVING THE MODEL WITH SEPARATED LABOR MARKETS

A.1 PRODUCTION FUNCTION AND COST FUNCTION

I assume production functions to be constant return to scale. The production function for "dirty" industry in city i is

$$q_i^d = L_i^d$$

The cost minimization problem is

$$\min w_i^d L_i^d$$

$$s.t.\ L_i^d = q_i^d$$

Therefore, the cost function for "dirty" industry in city i is

$$c^d(q_i^d) = w_i^d q_i^d$$

The production function for "clean" industry in city i is

$$q_i^c = \frac{L_i^c}{\gamma P_{-i} + 1}$$

where P_{-i} is the negative externality of pollution from upwind city $-i$, and $\gamma \geq 0$.

The cost minimization problem is

$$\min w_i^c L_i^c$$

$$s.t.\ \frac{L_i^c}{\gamma P_{-i}+1} = q_i^c$$

Therefore, the cost function for "clean" industry in city i is

$$c^c(q_i^c) = w_i^c(\gamma P_{-i}+1)q_i^c$$

A.2 TRANS-BOUNDARY POLLUTION

I assume that pollution can only affect the next city in downwind direction, so productivity in city *down* is affected by pollution in city *up* (P_{up}), and productivity in city *up* is affected by pollution in city *down* of the upwind province ($P_{down(-i)}$).

For simplicity, I assume that negative effect of pollution is a function of output in dirty industry:

$$P_{down(-i)} = q^d_{down(-i)}$$

$$P_{up} = q^d_{up}$$

Therefore, the cost functions for "clean" industry in cities *up* and *down* are:

$$c^c(q^c_{up}) = w^c_{up}(\gamma q^d_{down(-i)}+1)q^c_{up}$$

$$c^c(q^c_{down}) = w^c_{down}(\gamma q^d_{up}+1)q^c_{down}$$

A.3 CASE 1: NEGATIVE PRODUCTION EXTERNALITIES ($\gamma > 0$), BUT NO REGULATORY PRESSURE ($\phi = 0$)

In this setting, there is negative effects of pollution on productivity ($\gamma > 0$):

$$\begin{aligned}
&\max p^d q^d_{up} - c^d(q^d_{up}) + p^c q^c_{up} - c^c(q^c_{up}) + p^d q^d_{down} - c^d(q^d_{down}) + p^c q^c_{down} - c^c(q^c_{down}) \\
&= p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{down(-i)}+1)^2 (q^c_{up})^2 \\
&+ p^d q^d_{down} - (q^d_{down})^2 + p^c q^c_{down} - (\gamma q^d_{up}+1)^2 (q^c_{down})^2
\end{aligned}$$

Let the objective function be

$$L = p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2$$
$$+ p^d q^d_{down} - (q^d_{down})^2 + p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2$$

A.3.1 Case 1: Solution

First order conditions:

$$\frac{\partial L}{\partial q^d_{up}} = 0 \Rightarrow p^d - 2q^d_{up} - 2\gamma^2 (q^c_{down})^2 q^d_{up} - 2\gamma (q^c_{down})^2 = 0 \tag{A.1}$$

$$\frac{\partial L}{\partial q^c_{up}} = 0 \Rightarrow p^c - 2(\gamma q^d_{down(-i)} + 1)^2 q^c_{up} = 0 \tag{A.2}$$

$$\frac{\partial L}{\partial q^d_{down}} = 0 \Rightarrow p^d - 2q^d_{down} = 0 \tag{A.3}$$

$$\frac{\partial L}{\partial q^c_{down}} = 0 \Rightarrow p^c - 2(\gamma q^d_{up} + 1)^2 q^c_{down} = 0 \tag{A.4}$$

From Equation (A.2):

$$q^{c*}_{up} = \frac{p^c}{2(\gamma q^d_{down(-i)} + 1)^2}$$

From Equation (A.3):

$$q^{d*}_{down} = \frac{p^d}{2}$$

Equations (A.1) and (A.4) will solve optimal q^{d*}_{up} and q^{c*}_{down}. From Equation (A.4) I get:

$$q^c_{down} = \frac{p^c}{2(\gamma q^d_{up} + 1)^2} \tag{A.5}$$

From Equation (A.1) I get:

$$q^c_{down} = \sqrt{\frac{p^d - 2q^d_{up}}{2\gamma^2 q^d_{up} + 2\gamma}} \tag{A.6}$$

A.3.2 Case 1: Symmetric Nash Equilibrium

The symmetric pattern of the model implies that the Nash equilibrium of trans-boundary pollution will satisfy:

$$q^d_{down(-i)} = q^d_{down}$$

Therefore, equilibrium q^{d*}_{down} and q^{c*}_{up} are

$$q^{d*}_{down} = \frac{p^d}{2}$$

$$q^{c*}_{up} = \frac{p^c}{2(\gamma q^d_{down(-i)} + 1)^2} = \frac{p^c}{2(\frac{\gamma p^d}{2} + 1)^2}$$

Equilibrium q^{c*}_{down} and q^{d*}_{up} are solved by Equations (A.5) and (A.6).

A.3.3 Case 1: Social Planner's Solution

Here is the social planner's problem of this case. There is $q^d_{down(-i)} = q^d_{down}$ in the objective function of a social planner, which is different from the objective function of competitive provincial governments.

$$L = p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{down} + 1)^2 (q^c_{up})^2 + p^d q^d_{down} - (q^d_{down})^2 + p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2$$

Since the spatial structure is totally symmetric, there will be no difference between cities *up* and *down* for the social planner. Therefore, we have the following conditions:

$$q^d_{up} = q^d_{down}$$

$$q^c_{up} = q^c_{down}$$

Using these conditions, the social planner's problem becomes

$$L = p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{up} + 1)^2 (q^c_{up})^2$$

First order conditions:

$$\frac{\partial L}{\partial q^d_{up}} = 0 \Rightarrow p^d - 2q^d_{up} - 2\gamma^2 (q^c_{up})^2 q^d_{up} - 2\gamma (q^c_{up})^2 = 0 \tag{A.7}$$

$$\frac{\partial L}{\partial q^c_{up}} = 0 \Rightarrow p^c - 2(\gamma q^d_{up} + 1)^2 q^c_{up} = 0 \tag{A.8}$$

This is a two-equation system that solves the social planner's solutions.

From Equation (A.7):

$$q^c_{up} = \sqrt{\frac{p^d - 2q^d_{up}}{2\gamma^2 q^d_{up} + 2\gamma}}$$

From Equation (A.8):

$$q^c_{up} = \frac{p^c}{2(\gamma q^d_{up} + 1)^2}$$

A.4 CASE 2: NEGATIVE PRODUCTION EXTERNALITIES ($\gamma > 0$), AND POSITIVE REGULATORY PRESSURES ($\phi > 0$)

In this setting, central government includes environmental pollution when evaluating performances of provincial leaders ($\phi > 0$). The promotion of provincial leaders depends on both economic growth (aggregate surplus) and environmental pollution.

Therefore, the decision problem becomes:

$$\begin{aligned}
&\max p^d q^d_{up} - c^d(q^d_{up}) + p^c q^c_{up} - c^c(q^c_{up}) + p^d q^d_{down} - c^d(q^d_{down}) + p^c q^c_{down} - c^c(q^c_{down}) \\
&-\phi(\gamma q^d_{down(-i)} + \gamma q^d_{up}) \\
&= p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2 + p^d q^d_{down} - (q^d_{down})^2 \\
&+p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - \phi(\gamma q^d_{down(-i)} + \gamma q^d_{up})
\end{aligned}$$

Let the objective function be

$$\begin{aligned}
L &= p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2 + p^d q^d_{down} - (q^d_{down})^2 \\
&+p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - \phi(\gamma q^d_{down(-i)} + \gamma q^d_{up})
\end{aligned}$$

A.4.1 Case 2: Solution

First order conditions:

$$\frac{\partial L}{\partial q^d_{up}} = 0 \Rightarrow p^d - 2q^d_{up} - 2\gamma^2(q^c_{down})^2 q^d_{up} - 2\gamma(q^c_{down})^2 - \phi\gamma = 0 \tag{A.9}$$

$$\frac{\partial L}{\partial q^c_{up}} = 0 \Rightarrow p^c - 2(\gamma q^d_{down(-i)} + 1)^2 q^c_{up} = 0 \tag{A.10}$$

$$\frac{\partial L}{\partial q^d_{down}} = 0 \Rightarrow p^d - 2q^d_{down} = 0 \tag{A.11}$$

$$\frac{\partial L}{\partial q^c_{down}} = 0 \Rightarrow p^c - 2(\gamma q^d_{up} + 1)^2 q^c_{down} = 0 \tag{A.12}$$

From Equation (A.10):

$$q^{c*}_{up} = \frac{p^c}{2(\gamma q^d_{down(-i)} + 1)^2}$$

From Equation (A.11):

$$q^{d*}_{down} = \frac{p^d}{2}$$

Equations (A.9) and (A.12) will solve optimal q^{d*}_{up} and q^{c*}_{down}. From Equation (A.12) I get:

$$q^c_{down} = \frac{p^c}{2(\gamma q^d_{up} + 1)^2} \tag{A.13}$$

From Equation (A.9) I get:

$$q^c_{down} = \sqrt{\frac{p^d - 2q^d_{up} - \phi\gamma}{2\gamma^2 q^d_{up} + 2\gamma}} \tag{A.14}$$

A.4.2 Case 2: Symmetric Nash Equilibrium

The symmetric pattern of the model implies that the Nash equilibrium of trans-boundary pollution will satisfy:

$$q^d_{down(-i)} = q^d_{down}$$

Therefore, equilibrium q^{d*}_{down} and q^{c*}_{up} are

$$q^{d*}_{down} = \frac{p^d}{2}$$

$$q^{c*}_{up} = \frac{p^c}{2(\gamma q^d_{down(-i)} + 1)^2} = \frac{p^c}{2(\frac{\gamma p^d}{2} + 1)^2}$$

Equilibrium q^{c*}_{down} and q^{d*}_{up} are solved by Equations (A.13) and (A.14).

A.4.3 Case 2: Social Planner's Solution

Here is the social planner's problem of this case. There is $q^d_{down(-i)} = q^d_{down}$ in the objective function of a social planner, which is different from the objective function of competitive provincial governments.

$$L = p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{down} + 1)^2 (q^c_{up})^2 + p^d q^d_{down} - (q^d_{down})^2$$
$$+ p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - \phi(\gamma q^d_{down} + \gamma q^d_{up})$$

Since we have the following conditions for a social planner:

$$q^d_{up} = q^d_{down}$$

$$q^c_{up} = q^c_{down}$$

Using these conditions, the social planner's problem becomes

$$L = p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{up} + 1)^2 (q^c_{up})^2 - \phi\gamma q^d_{up}$$

First order conditions:

$$\frac{\partial L}{\partial q^d_{up}} = 0 \Rightarrow p^d - 2q^d_{up} - 2\gamma^2 (q^c_{up})^2 q^d_{up} - 2\gamma (q^c_{up})^2 - \phi\gamma = 0 \tag{A.15}$$

$$\frac{\partial L}{\partial q_{up}^c} = 0 \Rightarrow p^c - 2(\gamma q_{up}^d + 1)^2 q_{up}^c = 0 \tag{A.16}$$

This is a two-equation system that solves the social planner's solutions.

From Equation (A.15):

$$q_{up}^c = \sqrt{\frac{p^d - 2q_{up}^d - \phi\gamma}{2\gamma^2 q_{up}^d + 2\gamma}}$$

From Equation (A.16):

$$q_{up}^c = \frac{p^c}{2(\gamma q_{up}^d + 1)^2}$$

APPENDIX B

SOLVING THE MODEL THAT LABOR MARKETS ARE CONNECTED WITHIN EACH INDUSTRY

In the second model, I assume that labor markets are connected within each industry in each province. There are now two labor markets: industry "dirty" and "clean". Wage is increasing in total labor demand in each labor market.

B.1 CASE 1: NEGATIVE PRODUCTION EXTERNALITIES ($\gamma > 0$), BUT NO REGULATORY PRESSURE ($\phi = 0$)

$$
\begin{aligned}
&\max p^d q^d_{up} - c^d(q^d_{up}) + p^c q^c_{up} - c^c(q^c_{up}) + p^d q^d_{down} - c^d(q^d_{down}) + p^c q^c_{down} - c^c(q^c_{down}) \\
&= p^d q^d_{up} - (q^d_{up})^2 - \alpha q^d_{down} q^d_{up} + p^c q^c_{up} - (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2 \\
&-\alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down} + p^d q^d_{down} - (q^d_{down})^2 \\
&-\alpha q^d_{down} q^d_{up} + p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - \alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down}
\end{aligned}
$$

Let the objective function be

$$
\begin{aligned}
&L = p^d q^d_{up} - (q^d_{up})^2 - \alpha q^d_{down} q^d_{up} + p^c q^c_{up} - (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2 \\
&-\alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down} + p^d q^d_{down} - (q^d_{down})^2 - \alpha q^d_{down} q^d_{up} \\
&+p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - \alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down} \\
&= p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2 + p^d q^d_{down} - (q^d_{down})^2 \\
&+p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - 2\alpha q^d_{down} q^d_{up} - 2\alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down}
\end{aligned}
$$

B.1.1 Case 1: Solution

First order conditions:

$$\frac{\partial L}{\partial q^d_{up}} = 0 \Rightarrow p^d - 2q^d_{up} - 2\gamma(q^c_{down})^2(\gamma q^d_{up} + 1) - 2\alpha q^d_{down} - 2\alpha\gamma(\gamma q^d_{down(-i)} + 1)q^c_{up}q^c_{down} = 0 \quad \text{(B.1)}$$

$$\frac{\partial L}{\partial q^c_{up}} = 0 \Rightarrow p^c - 2(\gamma q^d_{down(-i)} + 1)^2 q^c_{up} - 2\alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1)q^c_{down} = 0 \quad \text{(B.2)}$$

$$\frac{\partial L}{\partial q^d_{down}} = 0 \Rightarrow p^d - 2q^d_{down} - 2\alpha q^d_{up} = 0 \quad \text{(B.3)}$$

$$\frac{\partial L}{\partial q^c_{down}} = 0 \Rightarrow p^c - 2(\gamma q^d_{up} + 1)^2 q^c_{down} - 2\alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1)q^c_{up} = 0 \quad \text{(B.4)}$$

B.1.2 Case 1: Symmetric Nash Equilibrium

The symmetric pattern of the model implies that the Nash equilibrium of trans-boundary pollution will satisfy:

$$q^d_{down(-i)} = q^d_{down}$$

Hence Equations (B.1), (B.2) and (B.4) will become:

$$p^d - 2q^d_{up} - 2\gamma(q^c_{down})^2(\gamma q^d_{up} + 1) - 2\alpha q^d_{down} - 2\alpha\gamma(\gamma q^d_{down} + 1)q^c_{up}q^c_{down} = 0 \quad \text{(B.5)}$$

$$p^c - 2(\gamma q^d_{down} + 1)^2 q^c_{up} - 2\alpha(\gamma q^d_{down} + 1)(\gamma q^d_{up} + 1)q^c_{down} = 0 \quad \text{(B.6)}$$

$$p^c - 2(\gamma q^d_{up} + 1)^2 q^c_{down} - 2\alpha(\gamma q^d_{down} + 1)(\gamma q^d_{up} + 1)q^c_{up} = 0 \quad \text{(B.7)}$$

The equilibrium solutions are solved by the system of Equations (B.3), (B.5), (B.6), and (B.7).

From Equation (B.3), I get

$$q^d_{down} = \frac{p^d - 2\alpha q^d_{up}}{2}$$

From Equation (B.6), I get

$$q^c_{down} = \frac{p^c - 2(\gamma q^d_{down} + 1)^2 q^c_{up}}{2\alpha(\gamma q^d_{down} + 1)(\gamma q^d_{up} + 1)} = \frac{p^c - 2(\frac{\gamma(p^d - 2\alpha q^d_{up})}{2} + 1)^2 q^c_{up}}{2\alpha(\frac{\gamma(p^d - 2\alpha q^d_{up})}{2} + 1)(\gamma q^d_{up} + 1)}$$

Substituting them into Equation (B.5) and (B.6), then it will become a 2-equation system with 2 variables that will be used for numerical analysis of comparative statics.

B.1.3 Social Planner's Solution

Here is the social planner's problem of this case. There is $q^d_{down(-i)} = q^d_{down}$ in the objective function of a social planner.

$$\begin{aligned}
&L = p^d q^d_{up} - (q^d_{up})^2 - \alpha q^d_{down} q^d_{up} + p^c q^c_{up} - (\gamma q^d_{down} + 1)^2 (q^c_{up})^2 \\
&-\alpha(\gamma q^d_{down} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down} + p^d q^d_{down} - (q^d_{down})^2 - \alpha q^d_{down} q^d_{up} + p^c q^c_{down} \\
&-(\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - \alpha(\gamma q^d_{down} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down}
\end{aligned}$$

Since the spatial structure is totally symmetric, there will be no difference between cities *up* and *down* for the social planner. Therefore, we have the following conditions:

$$q^d_{up} = q^d_{down}$$

$$q^c_{up} = q^c_{down}$$

Using these conditions, the social planner's problem becomes:

$$L = p^d q^d_{up} - (1 + \alpha)(q^d_{up})^2 + p^c q^c_{up} - (1 + \alpha)(\gamma q^d_{up} + 1)^2 (q^c_{up})^2$$

First order conditions:

$$\frac{\partial L}{\partial q^d_{up}} = 0 \Rightarrow p^d - 2(1 + \alpha) q^d_{up} - 2(1 + \alpha)\gamma (q^c_{up})^2 (\gamma q^d_{up} + 1) = 0 \tag{B.8}$$

$$\frac{\partial L}{\partial q^c_{up}} = 0 \Rightarrow p^c - 2(1 + \alpha)(\gamma q^d_{up} + 1)^2 q^c_{up} = 0 \tag{B.9}$$

B.2 CASE 2: NEGATIVE PRODUCTION EXTERNALITIES ($\gamma > 0$), AND POSITIVE REGULATORY PRESSURE ($\phi > 0$)

In this setting, central government includes environmental pollution when evaluating performances of provincial leaders ($\phi > 0$). The promotion of provincial leaders depends on both economic growth (aggregate surplus) and environmental pollution.

Therefore, the decision problem becomes:

$$\begin{aligned}
&\max p^d q^d_{up} - c^d(q^d_{up}) + p^c q^c_{up} - c^c(q^c_{up}) + p^d q^d_{down} - c^d(q^d_{down}) + p^c q^c_{down} - c^c(q^c_{down}) \\
&-\phi(\gamma q^d_{down(-i)} + \gamma q^d_{up}) \\
&= p^d q^d_{up} - (q^d_{up})^2 - \alpha q^d_{down} q^d_{up} + p^c q^c_{up} - (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2 \\
&-\alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down} + p^d q^d_{down} - (q^d_{down})^2 - \alpha q^d_{down} q^d_{up} + p^c q^c_{down} \\
&-(\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - \alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down} - \phi(\gamma q^d_{down(-i)} + \gamma q^d_{up})
\end{aligned}$$

Let the objective function be

$$\begin{aligned}
&L = p^d q^d_{up} - (q^d_{up})^2 + p^c q^c_{up} - (\gamma q^d_{down(-i)} + 1)^2 (q^c_{up})^2 + p^d q^d_{down} - (q^d_{down})^2 \\
&+p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - 2\alpha q^d_{down} q^d_{up} - 2\alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down} \\
&-\phi(\gamma q^d_{down(-i)} + \gamma q^d_{up})
\end{aligned}$$

B.2.1 Case 2: Solution

First order conditions:

$$\frac{\partial L}{\partial q^d_{up}} = 0 \Rightarrow p^d - 2q^d_{up} - 2\gamma(q^c_{down})^2(\gamma q^d_{up} + 1) - 2\alpha q^d_{down} - 2\alpha\gamma(\gamma q^d_{down(-i)} + 1) q^c_{up} q^c_{down} - \phi\gamma = 0 \tag{B.10}$$

$$\frac{\partial L}{\partial q^c_{up}} = 0 \Rightarrow p^c - 2(\gamma q^d_{down(-i)} + 1)^2 q^c_{up} - 2\alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{down} = 0 \tag{B.11}$$

$$\frac{\partial L}{\partial q^d_{down}} = 0 \Rightarrow p^d - 2q^d_{down} - 2\alpha q^d_{up} = 0 \tag{B.12}$$

$$\frac{\partial L}{\partial q^c_{down}} = 0 \Rightarrow p^c - 2(\gamma q^d_{up} + 1)^2 q^c_{down} - 2\alpha(\gamma q^d_{down(-i)} + 1)(\gamma q^d_{up} + 1) q^c_{up} = 0 \tag{B.13}$$

B.2.2 Case 2: Symmetric Nash Equilibrium

The symmetric pattern of the model implies that the Nash equilibrium of trans-boundary pollution will satisfy:

$$q^d_{down(-i)} = q^d_{down}$$

Hence Equations (B.10), (B.11) and (B.13) will become:

$$p^d - 2q^d_{up} - 2\gamma(q^c_{down})^2(\gamma q^d_{up} + 1) - 2\alpha q^d_{down} - 2\alpha\gamma(\gamma q^d_{down} + 1)q^c_{up}q^c_{down} - \phi\gamma = 0 \quad \text{(B.14)}$$

$$p^c - 2(\gamma q^d_{down} + 1)^2 q^c_{up} - 2\alpha(\gamma q^d_{down} + 1)(\gamma q^d_{up} + 1)q^c_{down} = 0 \quad \text{(B.15)}$$

$$p^c - 2(\gamma q^d_{up} + 1)^2 q^c_{down} - 2\alpha(\gamma q^d_{down} + 1)(\gamma q^d_{up} + 1)q^c_{up} = 0 \quad \text{(B.16)}$$

The equilibrium solutions are solved by the system of Equations (B.12), (B.14), (B.15), and (B.16).

From Equation (B.12), I get

$$q^d_{down} = \frac{p^d - 2\alpha q^d_{up}}{2}$$

From Equation (B.15), I get

$$q^c_{down} = \frac{p^c - 2(\gamma q^d_{down} + 1)^2 q^c_{up}}{2\alpha(\gamma q^d_{down} + 1)(\gamma q^d_{up} + 1)} = \frac{p^c - 2(\frac{\gamma(p^d - 2\alpha q^d_{up})}{2} + 1)^2 q^c_{up}}{2\alpha(\frac{\gamma(p^d - 2\alpha q^d_{up})}{2} + 1)(\gamma q^d_{up} + 1)}$$

Substituting them into Equation (B.14) and (B.16), then it will become a 2-equation system with 2 variables that will be used for numerical analysis of comparative statics.

B.2.3 Social Planner's Solution

Here is the social planner's problem of this case. There is $q^d_{down(-i)} = q^d_{down}$ in the objective function of a social planner.

$$
\begin{aligned}
&L = p^d q^d_{up} - (q^d_{up})^2 - \alpha q^d_{down} q^d_{up} + p^c q^c_{up} - (\gamma q^d_{down} + 1)^2 (q^c_{up})^2 \\
&-\alpha(\gamma q^d_{down} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down} + p^d q^d_{down} - (q^d_{down})^2 - \alpha q^d_{down} q^d_{up} \\
&+p^c q^c_{down} - (\gamma q^d_{up} + 1)^2 (q^c_{down})^2 - \alpha(\gamma q^d_{down} + 1)(\gamma q^d_{up} + 1) q^c_{up} q^c_{down} - \phi(\gamma q^d_{down} + \gamma q^d_{up})
\end{aligned}
$$

Since the spatial structure is totally symmetric, there will be no difference between cities *up* and *down* for the social planner. Therefore, we have the following conditions:

$$q^d_{up} = q^d_{down}$$

$$q^c_{up} = q^c_{down}$$

Using these conditions, the social planner's problem becomes:

$$L = p^d q^d_{up} - (1+\alpha)(q^d_{up})^2 + p^c q^c_{up} - (1+\alpha)(\gamma q^d_{up} + 1)^2 (q^c_{up})^2 - \phi \gamma q^d_{up}$$

First order conditions:

$$\frac{\partial L}{\partial q^d_{up}} = 0 \Rightarrow p^d - 2(1+\alpha) q^d_{up} - 2(1+\alpha)\gamma (q^c_{up})^2 (\gamma q^d_{up} + 1) - \phi\gamma = 0 \tag{B.17}$$

$$\frac{\partial L}{\partial q^c_{up}} = 0 \Rightarrow p^c - 2(1+\alpha)(\gamma q^d_{up} + 1)^2 q^c_{up} = 0 \tag{B.18}$$

BIBLIOGRAPHY

Albouy, David, "What are Cities Worth? Land Rents, Local Productivity, and the Capitalization of Amenity Values," NBER Working Paper No. 14981, 2009.

_ , "What are Cities Worth? Land Rents, Local Productivity, and the Total Value of Amenities," *Review of Economics and Statistics*, 2016, *98* (3), 477–487.

Banzhaf, H. Spencer and Randall P. Walsh, "Do People Vote with Their Feet? An Empirical Test of Tiebout," *American Economic Review*, 2008, *98* (3), 843–63.

Bayer, Patrick, Nathaniel Keohane, and Christopher Timmins, "Migration and Hedonic Valuation: The Case of Air Quality," *Journal of Environmental Economics and Management*, 2009, *58* (1), 1–14.

Bi, Xiaohui, Yinchang Feng, Jianhui Wu, Yuqiu Wang, and Tan Zhu, "Source Apportionment of PM10 in Six Cities of Northern China," *Atmospheric Environment*, 2007, *41* (5), 903–912.

British Petroleum, "BP Statistical Review of World Energy 2016," 2016.

Cai, Hongbin, Yuyu Chen, and Qing Gong, "Polluting Thy Neighbor: Unintended Consequences of China's Pollution Reduction Mandates," *Journal of Environmental Economics and Management*, 2016, *76*, 86–104.

Chang, Tom, Joshua Graff Zivin, Tal Gross, and Matthew Neidell, "Particulate Pollution and the Productivity of Pear Packers," *American Economic Journal: Economic Policy*, 2016, *8* (3), 141–69.

Chay, Kenneth Y. and Michael Greenstone, "Does Air Quality Matter? Evidence from the Housing Market," *Journal of political Economy*, 2005, *113* (2), 376–424.

Chen, Yuyu, Avraham Ebenstein, Michael Greenstone, and Hongbin Li, "Evidence on the Impact of Sustained Exposure to Air Pollution on Life Expectancy from China's Huai River Policy," *Proceedings of the National Academy of Sciences*, 2013, *110* (32), 12936–12941.

Cumberland, John H., "Efficiency and Equity in Interregional Environmental Management," *Review of Regional Studies*, 1981, *2* (1), 1–9.

Hanlon, W. Walker, "Coal Smoke and the Costs of the Industrial Revolution," Working Paper, 2016.

Hanna, Rema and Paulina Oliva, "The Effect of Pollution on Labor Supply: Evidence from a Natural Experiment in Mexico City," *Journal of Public Economics*, 2015, *122*, 68–79.

Helland, Eric and Andrew B. Whitford, "Pollution Incidence and Political Jurisdiction: Evidence from the TRI," *Journal of Environmental Economics and management*, 2003, *46* (3), 403–424.

Jia, Ruixue, "Pollution for Promotion," Working Paper, 2017.

Kendall, B. and C. Sweet, "Supreme Court Revives EPA Rule on Air Pollution Across State Lines," *The Wall Street Journal*, April 30, 2014.

Landry, Pierre Francois, *Decentralized Authoritarianism in China: the Communist Party's Control of Local Elites in the Post-Mao Era*, Cambridge, U.K.: Cambridge University Press, 2008.

Latham, Kevin, "Nothing but the Truth: News Media, Power and Hegemony in South China," *The China Quarterly*, 2000, *163*, 633–654.

Li, Hongbin and Li-An Zhou, "Political turnover and economic performance: the incentive role of personnel control in China," *Journal of public economics*, 2005, *89* (9-10), 1743–1762.

Lipscomb, Molly and Ahmed Mushfiq Mobarak, "Decentralization and Pollution Spillovers: Evidence from the Re-drawing of County Borders in Brazil," *Review of Economic Studies*, 2016, *84* (1), 464–502.

Liu, Antung A. and Junjie Zhang, "Fiscal Incentives and Infrastructure: The Case of Sewage Treatment in China," Working Paper, 2011.

Matus, Kira, Kyung-Min Nam, Noelle E. Selin, Lok N. Lamsal, John M. Reilly, and Sergey Paltsev, "Health Damages from Air Pollution in China," *Global environmental change*, 2012, *22* (1), 55–66.

MEP, *Report on the First National Census of Polluting Sources*, Ministry of Environmental Protection of the People's Republic of China (MEP), 2010. (in Chinese).

National Bureau of Statistics, "Annual Survey of Above-Scale Industrial Firms," National Bureau of Statistics of China, 1998–2007.

Oates, Wallace E., "An Essay on Fiscal Federalism," *Journal of Economic Literature*, 1999, *37* (3), 1120–1149.

_ , "A Reconsideration of Environmental Federalism," in J. A. List and A. de Zeeuw, eds., *Recent Advances in Environmental Economics*, Cheltenham, U.K.: Edward Elgar, 2002.

Qian, Yingyi, Gerard Roland, and Chenggang Xu, "Why is China Different from Eastern Europe? Perspectives from Organization Theory," *European Economic Review*, 1999, *43* (4-6), 1085–1094.

Rawski, Thomas G., "Urban Air Quality in China: Historical and Comparative Perspectives," in Nazrul Islam, ed., *Resurgent China: Issues for the Future*, Houndmills and New York: Palgrave-Macmillan, 2009, pp. 353–370.

Roback, Jennifer, "Wages, Rents, and the Quality of Life," *Journal of political Economy*, 1982, *90* (6), 1257–1278.

Sigman, Hilary, "International Spillovers and Water Quality in Rivers: Do Countries Free Ride?," *American Economic Review*, 2002, *92* (4), 1152–1159.

_ , "Transboundary Spillovers and Decentralization of Environmental Policies," *Journal of Environmental Economics and Management*, 2005, *50* (1), 82–101.

Stockmann, Daniela and Mary E. Gallagher, "Remote Control: How the Media Sustain Authoritarian Rule in China," *Comparative Political Studies*, 2011, *44* (4), 436–467.

Wang, Alex L., "The Search for Sustainable Legitimacy: Environmental Law and Bureaucracy in China," *Harvard Environmental Law Review*, 2013, *37*, 365–440.

WINDFINDER, "WINDFINDER - Wind, Wave and Weather Reports, Forecasts and Statistics," URL: https://www.windfinder.com/ , 2014.

World Bank, *Cost of Pollution in China*, World Bank, 2007.

Xu, Chenggang, "The Fundamental Institutions of China's Reforms and Development," *Journal of Economic Literature*, 2011, *49* (4), 1076–1151.

Zheng, Siqi and Matthew E. Kahn, "Understanding China's Urban Pollution Dynamics," *Journal of Economic Literature*, 2013, *51* (3), 731–72.

_ , _ , Weizeng Sun, and Danglun Luo, "Incentives for China's Urban Mayors to Mitigate Pollution Externalities: The Role of the Central Government and Public Environmentalism," *Regional Science and Urban Economics*, 2014, *47*, 61–71.