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EFFECTIVENESS AND COST OF AIR POLLUTION CONTROL IN CHINA[*]

Thomas Stoerk[†]

31 August 2018

Abstract

I evaluate the effectiveness and cost of China's first serious air pollution control policy. Using both official, misreporting-prone data as well as NASA satellite data in a differences-in-differences strategy that exploits variation in reduction targets, I find that the policy reduced air pollution by 11% as intended. Compliance was initially rhetorical but later real, and did not differ by level of enforcement. I construct marginal abatement cost curves for SO_2 for each province in China to calculate the cost of a counterfactual market-based policy instrument compared to the command-and-control policy that China used. I find that the market-based policy instrument would increase average (marginal) efficiency by 25% (49%). I further provide cost estimates for the total cost of a one unit decrease in $PM_{2.5}$ concentrations in China to complement recent WTP estimates.

JEL Codes: Q52, Q53, H11

Keywords: Air pollution, China, abatement cost, instrument choice

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1 Introduction

Effective design and implementation of environmental regulation is crucial for correcting environmental externalities. Traditionally, economists have analyzed environmental regulation in developed countries where technical expertise, appropriate monitoring of pollution and rule of law often allowed successful cost-effective implementation of regulation. Recently, attention has turned to environmental regulation in developing countries and how the cost of regulation interacts with imperfect institutions (Duflo et al., 2013; Oliva, 2015). This shift in research focus is timely, as developing countries are often more severely affected by the most important environmental externalities such as air pollution (Greenstone and Jack, 2015). According to the latest WHO estimates, air pollution is responsible for one in eight global deaths, or 7 million deaths a year (WHO, 2014). One country which is particularly struck by air pollution is China. As development has soared, so has air pollution. Recent air pollution levels in Northern China are as severe as those in London at the height of the Industrial Revolution[1].

This study provides the first empirical evaluation of China's first serious air pollution control policy, a total emissions control target in the 11th Five-Year Plan (FYP) from 2006 to 2010. In an effort to bring down air pollution, the Chinese government decided to limit the total emissions of sulphur dioxide (SO_2) by 10% relative to 2005 baseline levels. The national limit was later assigned by command-and-control into widely varying reduction targets for each province. This research uses a combination of unique datasets, microeconometrics, and detailed marginal abatement cost curves to provide a comprehensive evaluation of the SO_2 reduction policy along three margins: First, did the policy improve SO_2 pollution outcomes? Second, how did the regulated provincial governments comply? Third, how costly was the policy and how efficient was it compared to a counterfactual market-based policy instrument?

The 11th FYP marks a turning point in environmental policy-making in China; it is considered 'the most environmentally ambitious document in the history of the Communist Party' (Watts, 2011). When the policy was passed in 2005, China's regulatory agency was the weak State Environmental Protection Administration (SEPA). SEPA did not have access to reliable SO_2 pollution data in 2005 and had to implement the regulation based on limited information from SO_2 emission statistics. This situation changed drastically in 2008, when the central government upgraded SEPA to become the Ministry of Environmental Protection (MEP), gave it high-level political backing and allowed it to track SO_2 pollution at the source and independent of provincial governments (State Council, 2007).

This empirical setting is insightful for several reasons. My setting is unique because of the availability of real pollution data in the period before the Chinese government could monitor it. This is due to coincidence: in late 2004, just before the start of the policy, NASA launched the *EOS-Aura* satellite that provides an independent and reliable data source for SO_2 pollution in China. Moreover, rich outcome variables are available for China to track the behaviour of provincial governments along multiple margins, including quantified political statements about current and past political priorities at the province-year level. My setting also allows to study the cost of the policy in detail due to the availability of micro-level data on the cost of SO_2 abatement in each province. I use these data to construct marginal abatement cost curves at the province level, allowing me to construct a counterfactual market-based policy instrument.

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[1] The level of total suspended particles (TSP) in London in 1890 was just beyond 600 $\mu g/m^3$ (see Figure 3 in Fouquet, 2011). Similarly, TSP levels North of China's Huai River were just beyond 600 $\mu g/m^3$ up until 1980 (see Figure 2 in Chen, Ebenstein, et al., 2013).

Firstly, I evaluate whether the SO_2 control policy improved pollution outcomes despite the lack of regulatory capacity at the start of the 11th FYP. Exploiting variation across provinces in a differences-in-differences (DID) specification, I recover the causal effect of the SO_2 control policy on both reported pollution, using the official indicator, and on real pollution, measured through NASA satellite data. I then study whether the effect of the SO_2 reduction target differs at the county level according to the initial distribution of pollution within the province. Finally, I investigate the timing of the effects of the policy to study compliance over time.

I find that the policy was a success according to the official SO_2 emissions indicator: a one-standard deviation increase in the stringency of the reduction target leads to a statistically significant 6% decrease in SO_2 emissions. The effect is similar based on the SO_2 NASA satellite data at an effect size of 11% per standard deviation. Within a province, the estimated effect is stronger for counties that were initially more polluted. However, the timing of the estimated differs when comparing the official and the satellite data: according to the satellite data, SO_2 pollution in provinces with higher targets only started to decrease in 2008, after the government gained the ability to monitor SO_2 pollution. A plausible reason for these differences in timing is misreporting due to moral hazard. Combining a subsample of hand-collected prefecture-level data covering one third of China with data on the number of environmental enforcement officials, I find no evidence for heterogeneous treatment effects by level of enforcement.

Next, I evaluate the mechanisms through which the regulated agents comply with the policy. I study their reactions along two margins: rhetorical and real compliance. Given the initial period of moral hazard when the Chinese government could not monitor SO_2, I first ask whether provincial governments reacted to the SO_2 reduction targets by changing their political rhetoric. I construct a unique province-year dataset of political statements by the governments of each province in China. These statements discuss the political priorities of each provincial government, both for the preceding year and the year to come.

This allows me to study not only the content of the provincial governments' rhetoric but also the timing. I use these statements to quantify the importance of air pollution in a province's political rhetoric. To study real compliance, I collect data on the two most economic measures to reduce SO_2 at the province level. These are the installation of desulfurization equipment (scrubbers) in power plants and industrial facilities, and the shutdown of small, inefficient power plants.

I find that provincial governments strongly adjusted their rhetoric to the political goals from the center: a one-standard deviation increase in the province's SO_2 reduction target leads to a 30% increase in political statements on air pollution, mainly driven by mentions of sulfur. A placebo test using other goals from the 11th FYP shows that provinces specifically adapt their rhetoric to the SO_2 targets. Regarding the timing of the political statements, I find that the increase in political statements is most pronounced in statements that praise past work on air pollution. This is particularly visible for the period just before the government could monitor air pollution. In light of the difference between the official and the satellite SO_2 data, this provides further suggestive evidence for strategic misreporting. Ultimately, however, the SO_2 reduction policy worked, and compliance became real. Among the abatement measures available to provinces, I find that real compliance for provinces with higher SO_2 reduction targets relied less on the installation of desulfurization equipment, or on an earlier installation of this equipment. Instead, I find that the main driver for bringing down SO_2 pollution was the shutdown of small, inefficient power plants.

The second part of this research provides detailed evidence on the cost of air pollution control in China. To study the efficiency of the policy design and quantify the gains from trade across different policy instruments, I compute detailed SO_2 marginal abatement cost (MAC) curves for each province in China. These curves show the large heterogeneity in SO_2 abatement cost across the provinces of China. Based on the MAC curves, I find that command-and-control policy did not equate marginal abatement cost across space. Instead, the Chinese government favored reductions in coastal provinces in the East where abatement costs are higher. This is consistent with a tale-of-two-cities story, in which China would develop amenity-based consumer cities along the coast, while maintaining a base of polluting manufacturing in its interior (Kahn, 2006; Zheng and Kahn, 2013). Using the MAC curves, I construct the counterfactual market-based allocation of SO_2 reduction targets across provinces needed to achieve the 10% SO_2 reduction target. This allows me to study the gains from trade from moving from a command-and-control regulation to the allocation of SO_2 reduction targets that would result from a stylised emissions trading scheme across provinces. I find that the market-based allocation would increase efficiency by 25%, lowering the average abatement cost from \$437/tSO_2 to \$323/tSO_2. At the margin, efficiency would rise by 49%, lowering marginal abatement cost from \$816/tSO_2 to \$419/tSO_2. Combining my empirical and cost findings with an ex ante study in atmospheric science (Wang, Jang, et al., 2010b), I find that the cost of a 1 $\mu g/m^3$ reduction in $PM_{2.5}$ concentrations is \$217,100, or 25% lower at \$161,997 using a market-based policy.

As a robustness check, I quantify how sensitive my estimates are to the inclusion of a measure for the marginal benefits of reducing air pollution. I use the back-of-the-envelope method employed by Oliva (2015) to construct a measure for the marginal abatement benefits of reducing SO_2 emissions at the province level. This method proceeds in 3 steps: (i) how does the SO_2 control policy change pollutant concentrations?, (ii) what health effects do the changes in pollutant concentrations cause?, and (iii) what is the monetary value of those health effects? I find that the gains from trade from moving to the market-based allocation are robust to including the benefits of air pollution abatement: at the margin, welfare increases are 45%, a similar magnitude as the cost-based efficiency increases.

The paper is organised as follows: Section 2 discusses the related literature. Section 3 describes the setting and discusses environmental governance in China as well as the 2008 changes in the SO_2 monitoring. Section 4 explains my data sources, while Section 5 contains the empirical analysis. Section 6 constructs detailed marginal abatement cost curves at the province level to assess the cost of air pollution control and to compute the gains from trade across different policy instruments. Section 7 concludes.

2 Related literature

The two main reasons to study air pollution in China are the magnitude of the problem and the possibility to alleviate it through policy. Air pollution in China causes enormous health costs as shown by literatures in both economics and health. Chen, Ebenstein, et al. (2013), for instance, use a natural experiment to find that one coal-subsidy alone led to the loss of 2.5 billion life-years in Northern China. Epidemiological studies summarized in Yang et al. (2013) give the same sense of magnitude: they find air pollution to be the fourth most important health burden in China. In monetized terms, the health cost amount to 1.2 to 3.8% of GDP (World Bank and State Environmental Protection Administration, 2007). Air pollution furthermore induces losses in productivity Chang et al. (2016), Fu, Viard, and Zhang (2018), and He, Liu, and Salvo (2018) and cognitive performance (Zhang, Chen, and Zhang, 2018). At the same time, Jia (2014) has shown in a convincing causal setting that pollution is a side effect of political incentives. A large literature in urban economics, political economy and environmental law backs this conclusion (Almond et al., 2009; Wang, 2013; Zheng and Kahn, 2013; Zheng, Sun, et al., 2014). It therefore seems possible to mitigate air pollution through the right combination of policies and incentives.

My study is the first to provide a causal empirical evaluation of the total emissions control policy in the 11th FYP. Despite the huge burden from air pollution in China, there has been no empirical evaluation of China's flagship air pollution control policy. Evaluation so far has come in one of two guises: through detailed narrative accounts of the changes (Cao, Garbaccio, and Ho, 2009; Hao et al., 2007; Schreifels, Fu, and Wilson, 2012) or through model-based studies in atmospheric science (Lu et al., 2010; Wang, Jang, et al., 2010a,b). Additionally, I am amongst the first to evaluate any environmental policy in China. The main other study I am aware of is Kahn, Li, and Zhao (2015), who analyze water pollution regulation. Their findings complement the empirical part of my research and allow for a richer interpretation of the role of pollution monitoring.

This research also contributes to three distinct literatures in environmental economics. The first is a nascent empirical literature that evaluates the design and implementation of environmental policies in imperfect settings, the second literature studies the efficiency of the design of regulation through comparison of different policy instrument, and the third literature provides willingness to pay (WTP) for clean air estimates.

In the first literature, Duflo et al. (2013) study how the emissions of regulated industrial firms in India respond to changes in effective monitoring. Using a field experiment, they find that improved auditing leads regulated firms to reduce pollution, most notably through water pollution. Relatedly, Oliva (2015) provides a static snapshot of an air pollution regulation gone wrong. She documents the ineffectiveness of emissions regulation for private cars in Mexico City. Using a statistical test to detect misreporting, she shows that car owners often fail to comply and instead pay a bribe to circumvent regulation, leading to a private benefit to car owners at great damage to the public. Hansman, Hjort, and Leon (2015), by contrast, study the design of a reform aimed at preserving fish stock in Peru. They show that the piecemeal nature of the reform led to unforeseen side effects for air pollution outcomes.

This paper sheds light on whether a simple command-and-control policy can be effective in a setting in which the government has a very low regulatory capacity initially. Due to the availability of independent satellite data on pollution throughout, I can study the behaviour of regulated agents in terms of different pollution outcomes, and in terms of rhetorical compliance both before and after the Chinese government gains the ability to monitor pollution in 2008. Understanding how the affected agents comply with an environmental regulation under moral hazard is central to policy implementation and thus of great importance for contexts beyond China. The analysis of a command-and-control regulation in an emerging country such as China contributes furthermore to the existing literature on the effectiveness of air pollution control, which has focused almost exclusively on developed countries such as the U.S. (Auffhammer and Kellogg, 2011; Chay and

Greenstone, 2005; Chay, Dobkin, and Greenstone, 2003; Henderson, 1996)[2]. Additionally, while research on air pollution regulation has led to clear findings for pollutants such as TSP, the results for SO_2 are more mixed (Greenstone, 2004; Greenstone and Hanna, 2014).

The second literature to which I contribute studies the design of environmental regulation and the use of different policy instruments. This line of research compares the efficiency of different policy instruments such as command-and-control and market-based policies. Most contributions come from analyses of air pollution control regulation in the U.S., most notably through the U.S. SO_2 mitigation efforts (Ellerman et al., 2000; Keohane, 2003, 2006; Schmalensee et al., 1998; Stavins, 1998), but a small number of studies exist from other countries such as Chile (Montero, Sanchez, and Katz, 2000). My work relates most closely to Carlson et al. (2000), Ellerman et al. (2000), Keohane (2003) and Oates, Portney, and McGartland (1989), all of which compare the efficiency differences of market-based and command-and-control policy instruments empirically.

Carlson et al. (2000) compute marginal abatement cost curves for SO_2 for the electricity sector in the U.S. to quantify the efficiency gains from trade of moving from command-and-control regulation to SO_2 emissions trading. While those cost savings are large, at a 43% efficiency gain from trading, they are surprisingly lower than anticipated ex ante. Ellerman et al. (2000) find efficiency gains of 50%, while Keohane (2003) finds lower gains at 16% to 25%. Another closely related paper is Oates, Portney, and McGartland (1989), who compare the efficiency of incentive-based regulation against command-and-control regulation to control air pollution in Baltimore. They find that a well designed command-and-control regulation can deliver pollution reductions at a welfare cost that can be lower than a comparable incentive-based regulation. This conclusion, however, only applies when that command-and-control regulation is informed by the marginal cost of abatement rather than by political considerations. Taken together, these studies show that while moving from a command-and-control regulation to a market-based regulation is generally seen as increasing the efficiency of the regulation (Schultze, 1977), whether this is so is an empirical question that depends on the particular case of the regulation under consideration. In particular, it will depend on whether the cost of abatement was taken into account when designing the the command-and-control allocation of targets[3].

I estimate detailed marginal abatement cost curves for SO_2 for each province in China in 2005, contributing to the few studies that estimate full marginal abatement cost curves in environmental economics in general (Gollop and Roberts, 1985; Carlson et al., 2000 and Abito, 2012)[4]. In particular, this study is the first to derive comprehensive marginal abatement cost curves at the province level in China. Two earlier contributions by Tu and Shen (2014) and Li, Wu, and Zhang (2015) provide interesting analysis in this direction but both studies rely on modelling in addition to microdata and only compute partial snapshots rather than full MAC curves. I use the marginal abatement cost curves to predict the counterfactual allocation of SO_2 reduction targets across provinces in China that would result from an emissions trading scheme across provinces. This allows me to quantify the efficiency gains from trade from moving from the actual command-and-control allocation of SO_2 reduction targets to a market-based allocation. Furthermore, I investigate the robustness of this quantification to the inclusion of a measure for the marginal abatement benefits. Overall, I contribute by studying whether the design of air pollution control regulation in a developing country such as China differs from the experience of developed countries like the U.S., and by providing detailed data on the cost of air pollution control in China.

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[2] One exception are Greenstone and Hanna (2014), who investigate the effect of regulation on air and water pollution in India.

[3] Further related studies are Newell and Stavins (2003), who propose a simple way of calculating the efficiency gains from market-based policies in situations with limited data, and show an application to NO_x control in the U.S., and Antle et al. (2003), who investigate spatial heterogeneity in the abatement cost for carbon sequestration in the U.S. and show that different policy instruments vary in efficiency by a factor of 5.

My research lastly complements recent research that estimates the willingness to pay (WTP) for clean air in China. WTP estimates for environmental quality have traditionally focused on the U.S. (Chay and Greenstone, 2005; Deschenes, Greenstone, and Shapiro, 2017). Recently, the focus of WTP for clean air research has shifted to China. Ito and Zhang (2016) exploit a policy discontinuity across space to recover WTP estimates for clean air from defensive investments in air purifiers. Freeman et al. (2017), by contrast, use an instrumental variable strategy to recover WTP estimates through a residential sorting model. Lastly, Barwick et al. (2018) recover a lower bound for consumer WTP for clean air in China based on healthcare spending, while Mu and Zhang (2017) estimate a lower bound based on defensive investment in facemasks. Greenstone and Jack (2015) hypothesize that one of the reasons environmental quality in developing countries is low is the high cost of improvements in environmental quality at the margin. My research provides crucial data to test this conjecture. By providing data on the cost of air pollution control, my research combines with the WTP estimates to allow for credible cost-benefit analysis of air pollution control in China.

3 The SO_2 reduction policy in context

This section provides the context around the 11th Five-Year Plan (FYP) and China's flagship air pollution control policy that is the focus of this research. Environmental governance in China has undergone a rapid transformation in the last two decades. Until 2005, economic growth was the defining development paradigm. Environmental policies, where they existed, were paper tigers: they lacked political support from the central government and were rarely enforced. 2005 marks the turning point with a Five-Year Plan that 'was the most environmentally ambitious document in the history of the Communist Party' (Watts, 2011). The following paragraphs sketch how this change can best be seen as a change in political will rather than a change in formal laws.

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[4] Partial estimates of marginal abatement cost curves for compliance with air pollution control regulation are further reported in Hartman, Wheeler, and Singh (1997), Becker and Henderson (2001), Keller and Levinson (2002) and Becker (2005).

Before the policy Laws regulating SO_2 emissions have existed in China since 1998, when the State Council approved the establishment of the 'Two Control Zones', a policy to address acid rain and SO_2 emissions (McElwee, 2011). Enforcement of this policy was intensified in 2000, but has remained constant since. Implementation of SO_2 policies, however, still encountered great difficulties (Gao et al., 2009), as China's overall development strategy remained firmly rooted in economic growth. Existing environmental policies overall, for instance on energy efficiency, were left underfunded by the central government (Gao et al., 2009; Lin, 2007). And while the 10th Five-Year Plan included a nationwide goal to reduce SO_2 emissions by 10%, it did not have political backing, and failed to induce SO_2 emissions reductions (Schreifels, Fu, and Wilson, 2012), possibly because of a lack of incentives for meeting the targets (Wang, 2013).

First change in the political outlook of the central government came in 2003, when President Hu - a hydroengineer - and Prime Minister Wen - a geologist - took power. The 'scientific development' paradigm, which emphasized environmental protection alongside economic growth, started to substitute for economic growth. Environmental governance, however, was still weak.

2005: The 11th Five-Year Plan (2006-2010) Amidst the increasing political will to implement and enforce environmental policies, the general directions of the 11th FYP started being discussed as early as mid-2003, and probably ended by 2004 (Xu, 2011). During the National People's Congress in March 2006, the 11th FYP was presented in its final form and included emissions control targets for air pollution (SO_2) and water pollution (chemical oxygen demand, or COD) as well as a target on energy efficiency. Concurrently, environmental governance started being taken seriously, when the once powerless SEPA successfully stopped hundreds of billions of Yuan of industrial investment on environmental grounds at the beginning of of 2005. This radical action came as a surprise to Chinese society (Gao et al., 2009). In March 2008, the SEPA's new political authority was formalized when SEPA obtained full rank in the State Council and received ministry status as the MEP (McElwee, 2011). This is the period that I analyze in this research.

The air pollution control target consisted of a 10% SO_2 emissions control target for

China as a whole. This reduction target was handed down to the provinces in May 2006 at the latest, when SEPA - with high-level political backing - signed formal, binding reduction targets with the provincial governments (Gao et al., 2009; Xu, 2011)[5]. These reduction targets were given the highest political priority, paralleled only by mandates on growth, social stability and the one-child policy (Wang, 2013). Compliance with environmental targets entered the performance evaluation of local leaders (Moser, 2013). Provincial SO_2 reduction targets, in particular, were made a veto target: failure to comply would nullify all other performance achievements of a provincial leader (Kahn, Li, and Zhao, 2015; Xu, 2011). The reduction targets specified reductions in SO_2 emissions from 2006 to 2010 with 2005 as the baseline. These are the reduction targets that I use in this study. Figure 1 shows that these targets vary considerably, mandating reductions from 0% to more than 25%.

[INSERT FIGURE 1 ABOUT HERE]

SO_2 emissions data in China in 2005 were of bad quality, and misreporting-prone. A province's SO_2 emissions were calculated by aggregating the physical quantity of coal used in a province in a given year, and by then multiplying this quantity with SO_2 emissions factors depending on the sulfur-intensity of the type of coal used. The political authority to compile these data rested with the provincial governments. While this procedure yields only coarse aggregate data at best (Guan et al., 2012), it can also be corrupted to produce the desired data. Anecdotal evidence and extensive field work in several provinces confirm that misreporting of SO_2 emissions data was prevalent in the first 2 years of the SO_2 control policy (Song et al., 2015). The likely reason why the central government decided to use emissions rather than other pollution data is that the network of *in situ* measurement stations was not of sufficiently high quality and quantity in 2005 to track SO_2 pollution outcomes on the ground.

Up to 2005, provincial governments in China had little incentive to control air pollution. A province in China is governed by a pair of provincial leaders, the governor and the party secretary. Provincial leaders are career officials who are appointed in a top-down manner. As career officials, they are often positioned outside their native provinces and move frequently as a results of promotion or demotion. Cadre regulations stipulate a maximum term length of 5 years for both governors and party secretaries (Kahn, Li, and Zhao, 2015). This rule is mostly respected: on average, provincial leaders have held office for just two years, with only a small number exceeding a tenure of 5 years. As a consequence of these frequent changes, provincial leaders are mainly concerned with furthering their own career in the short period that they hold office. Following the regulations in the past, this meant relying on pollution-intensive, quick-and-dirty GDP growth (Chen, Li, and Zhou, 2005; Jia, 2014; Li and Zhou, 2005). Incentives for provincial leaders to fix air pollution are further weakened by vested interests in polluting enterprises, of which local governments are often major shareholders (Gao et al., 2009). As provincial leaders got promoted to posts elsewhere, air pollution therefore remained unfixed.

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[5] The 31 province-level administrative units include the four municipalities directly under the central government (Beijing, Chongqing, Shanghai and Tianjin) and the five autonomous regions (Guangxi, Neimongol, Ningxia, Tibet and Xinjiang).

2008: Changes to SO_2 monitoring In 2007, the State Council passed a law that fundamentally changed the regulator's capacity to monitor SO_2 pollution (the law is known as the 'Reduction of the Three Ways'). The core of the law was twofold: to change the politics of SO_2 data collection to avoid tampering with data at the political level, and to install appropriate monitoring equipment and ensure frequent statistical inspections on the ground (State Council, 2007).

On the political side, reporting was taken from provincial governments and put directly under the political control of the MEP. The MEP, in turn, directly reports to the State Council. On the ground, SO_2 measurement stations were build in pollution hotspots and the number of environmental monitoring officials was increased by 17% (Song et al., 2015). Key industrial polluters for each prefecture had their SO_2 emissions tracked on site. By May 2008, uninterrupted automatic monitoring devices with data feeds directly into the local environmental agency were used for this purpose (McElwee, 2011; MEP, 2008a,b). All changes became effective in July 2008 at the latest (Song et al., 2015). These changes mark a landslide for environmental governance in China: a nearly powerless agency was upgraded into a powerful ministry. A ministry given the tools to ensure it was going to be a force to be reckoned with.

The 2008 changes naturally divide the analysis into three periods: (i) before the policy; (ii) SO_2 reduction targets, but little monitoring; (iii) SO_2 reduction targets, and comprehensive monitoring. These periods will guide my subsequent empirical estimations to evaluate the policy.

4 Data

I compile a unique dataset that allows me to study the effect of the SO_2 control policy along two margins: First, to evaluate the effect of the policy on pollution outcomes, I use two different data sources: (i) the official, misreporting prone SO_2emissions indicator and (ii) independent satellite data from NASA. Second, I evaluate the reactions by the regulated provincial governments. I divide these reactions into rhetorical compliance and real compliance. To measure rhetorical compliance, I build a novel dataset of political reports, which I quantify. Behaviour related to real compliance is based on official data sources on SO_2 abatement measures. Finally, I add data on the number of enforcement officials per province to measure the effect of enforcement. I first describe the pollution data, then the data related to the behaviour of the regulated provincial governments, and finally the enforcement official data.

4.1 Data on pollution outcomes

Official SO_2 data The SO_2 control policy relies on SO_2 *emissions* as the official indicator. Note that this is a proxy indicator for the ultimate goal of reducing pollutant *concentrations*. It is likely that the central government chose this indicator due to a combination of a legacy of state-planning that focused on total emissions control and a lack of suitable SO_2 concentrations data from *in situ* measurement stations. I use the data reported in the *China Energy Databook* (Fridley, Romankiewicz, and Fino-Chen, 2013), who compile the official SO_2 emissions data from the statistical yearbooks.

The official SO_2 emissions data gives at best a noisy picture of true SO_2 emissions (Guan et al., 2012), and anecdotal evidence and research based on fieldwork suggest that the incentives before the 2008 policy changes led to severe misreporting (Song et al., 2015). The literature more generally has also noted misreporting of air pollution data (Andrews, 2008; Chen, Jin, et al., 2012; Ghanem and Zhang, 2014). However, this kind of misreporting consists of relabeling around the politically sensitive *Blue Sky Day* threshold in air pollution index data. It is thus tangential to misreporting in SO_2 emissions data, affects the mean of the data very little, and there are signs that this particular kind of misreporting has come to an end with the introduction of $PM_{2.5}$ measurements from 2012 onwards (Stoerk, 2016). The potential source of misreporting was therefore removed after the MEP started collecting SO_2 pollution data directly in 2008.

SO_2 satellite data To measure real SO_2 pollution, I make use of the uniqueness of my empirical setting. In August 2004 - just before the start of the SO2 control policy - NASA launched a satellite with the Ozone Monitoring Instrument (OMI). In lay terms, OMI is an instrument that captures images of Earth from space at different wavelengths. Post-processing trough extraction algorithms produces SO_2 vertical columns of high precision that became available in 2014[6]. It is unlikely that the Chinese government would have had access to the satellite data during the policy, an these data were not used in the official evaluation of the policy. Dates with cloud cover can lead to missing values over individual pixels, but this is not generally considered a first-order problem (Krotkov et al.,

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[6] The new algorithm significantly improved the precision of the extracted vertical column densities and removed a number of biases compared to the earlier data product that was available from OMI (Krotkov et al., 2016). Note further that the OMI data itself have a detection threshold that is two magnitudes smaller than earlier satellite data and can thus enable the detection of SO_2 pollution from human activity in the lowest part of the atmosphere (NASA, 2014).

2016)[7]. All in all, the NASA SO_2 satellite data are a very good proxy for ground-level SO_2 emissions. To illustrate, Figure 2 shows the cross-section in January 2006.

[INSERT FIGURE 2 ABOUT HERE]

Relation between both data sources SO_2 emissions decay in a span of 4-36 hours (Fioletov et al., 2015; He, 2012). Since the satellite data capture Earth daily, they represent a snapshot of SO_2 pollution on that day. Given the quick decay, this prevents leakage from confounding the outcome and allows me to capture local rather than transported SO_2 emissions. NASA's retrieval algorithm produces four different data products, each of which corresponds to SO_2 pollution at different levels of altitude in the atmosphere (NASA, 2014). For this analysis, I use the lowest level at an altitude of 900m above ground, for two reasons: first, because this is the best proxy for anthropogenic emissions sources, and secondly, because a lower altitude further minimizes transportation. Second, the precision of the satellite images is high enough to identify individual sources of pollution that produce as little as 30kt of SO_2 anually (Fioletov et al., 2015). I aggregate these daily cross-sections to the province-month and the province-year levels. Annual changes in the SO_2 satellite data can therefore be expected to be mimicked closely in the official statistics[8].

4.2 Data on reactions by the regulated provincial governments

This section describes the data sources that I use to study the reactions of the provincial governments along two margins: (i) rhetorical compliance and (ii) real compliance.

Rhetorical compliance I build a comprehensive dataset of political statements by each provincial government to study whether the regulated provincial governments respond to the SO_2 reduction targets by mimicking the central government's rhetoric. In China, each provincial government has the obligation to issue a government work report every year. This report is publicly delivered by one of the two highest ranked officials in the province, the party secretary or the governor. Each report contains information on the provincial government's activities and achievements. These reports are divided into two parts: Part 1 discusses the provincial government's work and achievements in the preceding period, while Part 2 discusses the work in the period to come. This unique setting allows me not only to investigate political rhetoric in general, but to also specifically investigate rhetorical responses relating to past and future achievements in response to the SO_2 reduction targets. Figure 7 shows an example of a government work report from Liaoning province in 2003, delivered by then-governor Bo Xilai.

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[7] Furthermore, I aggregate daily values to at least monthly, and pixels of not bigger than 0.25 degrees by 0.25 degrees latitude-longitude to counties and provinces, further reducing the magnitude of the potential problem due to clouds.

[8] A cross-check of known ground-level emission sources with SO_2 OMI satellite data revealed a correlation of 0.91 (Fioletov et al., 2015).

[INSERT FIGURE 7 ABOUT HERE]

To measure the provincial government's political attention towards air pollution for a given province-year, I scan each province's government work report for the years 2002-2010 and construct a variable that is equal to the number of occurrences of keywords related to air pollution[9]. Keywords were chosen from a technical document on urban air pollution in developing countries (GTZ, 2009) as well as from China-specific air pollution articles, webpage entries and blog posts in March 2014 from *China Daily*, *Global Times*, *Beijing Review* and *Jinyang Yangcheng Evening News*. To further rule out cherry-picking of keywords, I have defined the list of keywords as widely as possible. Figure 8 contains the raw count of keywords over time, offering two take-aways. First, there is a distinct increase in air pollution related keywords: Mentions of air pollution increase by more than 400% during the 11th Five-Year Plan (2006-2010). Second, one keyword drives this increase: the specific keyword 'sulfur'. This keyword is directly related to the provincial SO_2 reduction targets from the 11th Five-Year Plan. The outcome variable therefore appears to capture relevant political statements[10].

[INSERT FIGURE 8 ABOUT HERE]

Real compliance Based on my own calculations of the marginal cost of SO_2 emissions abatement (see Section 6), the installation of desulfurization devices in existing industrial and power plants (scrubbers), fuel-switching to better quality coal and the shutdown of small, inefficient thermal units are the main margins by which the provincial governments could reduce SO_2 emissions over the relatively short time horizon of 5 years. I collect data on both the timing and the quantity of installation of desulfurization devices at the province level during the 11th Five-Year Plan (2006-2010). Furthermore, I compute the number and capacity of small thermal units that were shut down by 2010 in each province. The latter are based on a planning document from 18th January 2008, in which the MEP asked the provincial governments to submit a concrete proposal for the thermal units to be shut down over the following two years. All data were compiled from sources available through the data center of the MEP (datacenter.mep.gov.cn). I do not analyze the sulfur content of coal used at the province-year level since reliable data is unavailable.

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[9] 6 reports are missing in 2002 and 1 report is missing in 2003.

[10] One valid concern with the raw count of air pollution keywords is that the length of the government work reports might have changed over time or across provinces. This could introduce a bias in my measure. To show that this is not the case, Figure A.6 in the Appendix divides the number of keywords by the length of the report and finds a very similar pattern. I prefer to use raw data because of its clearer interpretation. All regressions results are robust to using the adjusted number of keywords. These results are available upon request.

4.3 Data on the number of environmental enforcement officials in a province

This section describes the data on the number of enforcement officials for each province in China. The dataset comes from an NGO that has trained 34,887 enforcement officials since 2006 for the Ministry of Environmental Protection (since rename to Ministry of Ecological Environment). Overall, this represents 44% of the China total. Since further information on the province of the remaining enforcement officials is unavailable, I assume that the enforcement official data I have is an accurate proxy for the number of enforcement officials in a province at a given time. This assumption is reasonable in practice because the NGO knew the total number of officials in a province and used this criterion to avoid unduly influencing the cross-province distribution of officials. My data show that training of enforcement officials was scarce in 2006 and 2007, and picked up from 2008 on, concurrent with the upgrade of the Ministry and the rollout of monitoring technology to measure SO_2.

Given the large differences in the size of China's provinces, I compute a normalized number of enforcement officials by dividing the number of officials by the province area to account for the time cost of travelling. This density of enforcement officials is my main measure for enforcement[11].

5 Empirical analysis

5.1 Empirical strategy

Baseline specification I use the following difference-in-differences model to investigate whether a higher SO_2 reduction target led to a relatively stronger decrease in SO_2 emissions:

$$y_{pt} = \beta_0 + \beta_1 Reductiontarget_p \times D(Post)_t + \beta_2 Reductiontarget_p + \sum_{t=1}^{T} \beta_{3t}\gamma_t + \alpha_p + u_{pt} \quad (1)$$

The outcome y_{pt} for province p at time period t is either the official SO_2 emissions data that was used by the central government to assess the policy or the independent satellite SO_2 data. The variable $Reductiontarget_p$ is the provincial SO_2 reduction target and captures the cross-sectional variation shown in Figure 1. Policy variation over time is captured in the indicator $D(Post)$ that takes on the value of 1 from 2006 onwards. α_p are province fixed effects. The estimate for β_1 gives the causal effect of an increase in the target stringency by one unit for the whole period of the 11th Five-Year Plan, from 2006 to 2010.

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[11] Other density measures are possible, such as the number of enforcement officials per unit tonne of SO_2 emissions. The measure correlates strongly with area, and yields similar results.

Identification The DID specification exploits cross-province variation in the stringency of the SO_2 reduction target to estimate the causal effect of the pollution control policy. Identification relies on a combination of three factors: (i) common trends in the outcome variables prior to the SO_2 control policy, (ii) a sharp deviation from those trends following the policy changes, and (iii) the absence of forward-looking considerations that would also explain SO_2 abatement efforts by the provincial governments in 2006.

Provincial governments can rely on three main channels to bring down pollution. All of which are quick to implement, in particular for a country like China: fuel-switching to higher quality coal with a lower sulfur content, installation of desulfurisation devices, and the shutdown of small, inefficient thermal units. It is therefore reasonable to expect an immediate effect of the SO_2 reduction policy on pollution outcomes. Lu et al. (2010) provide evidence that abatement measures started immediately: power plants already started to switch to better quality coal in 2005 (with a sulfur content reduced by about 20% compared to the preceding year), and flue-gas desulfurization technology doubled from below 10% to more than 20% of all operating power plant capacity.

Common pre-trends and the timing of effects are empirically testable, and I show below that these conditions are fulfilled. Consideration (iii) is not directly testable, but supporting evidence shows that it is likely fulfilled. While the exact algorithm used by the Chinese government to allocate the targets is unknown, and it is unlikely that the targets were distributed randomly, random allocation is not needed for my identification. Instead, I only need that the allocation of SO_2 reduction targets across provinces was independent of forward-looking considerations that would explain SO_2 pollution reductions by a province independent of the SO_2 reduction targets.

The official statement by the State Council on how the target distribution would have taken place mentions a whole array of factors that were used to determine the allocation of targets for a province (State Council, 2006): (i) environmental quality and environmental capacity, (ii) current pollution levels, (iii) level of economic development, (iv) SO_2 mitigation capabilities and (v) regional differentiation (Eastern, Central, Western). Xu (2011) finds that the allocation of targets does not correlate with either of those factors (barring a correlation of non-power SO_2 emissions divided by the area of a province). Therefore, there is no evidence that any of these factors drove the target allocation, which suggests that the allocation of targets followed guidelines orthogonal to changes in SO_2 emissions at the turn of the 11th FYP. I also rule out the possibility that the allocation of SO_2 reduction targets followed the cost of abatement, both by itself and net of benefits. If that were the case, my empirical strategy would pick up the compound effect of an SO_2 reduction target and a cost advantage. In Section 6, I derive detailed marginal abatement cost (MAC) curves and combine those with a measure of marginal abatement benefits. I find that neither the MAC nor the marginal welfare impacts correlate with the target allocation, lending further credibility to my empirical strategy. Appendix A.1 validates this claim in more detail.

Inference I follow Bertrand, Duflo, and Mullainathan (2004) and compute standard errors that are heteroskedasticity-robust and clustered at the province level. Statistical inference based on these standard errors, however, could still be incorrect if the number of clusters is too small, as the required asymptotic results might not apply. China has 31 provinces, yielding substantially fewer than 50 clusters, the usual rule of thumb. While reporting the clustered standard errors, I therefore base my statistical inference on p-values derived from the wild bootstrap method described in Cameron, Gelbach, and Miller (2008). This is common practice in applied research on China (e.g., Martinez-Bravo et al., 2017).

5.2 The effect of the SO_2 control policy on SO_2 pollution

Baseline results Table 1 provides the summary statistics for my sample. The first two columns of Table 2 show the results from estimation Equation (1) for the effect of the policy for the full 11th FYP. A first glance reveals that the policy had a different effect depending on the indicator used for evaluation. According to the official SO_2 emissions data, the policy was a success: SO_2 emissions decrease in response to the target, with the estimated magnitude being a 5.8% decrease for a one-standard deviation increase in target stringency. The satellite data, by contrast, do not show a significant relationship between the targets and the SO_2 pollution outcomes. The sign of the estimated coefficient is in the same direction as with the official indicator, and the estimated magnitude is even higher, but it is not statistically different from zero.

To improve the precision of the estimates, I increase statistical power by focussing on polluted cities only. Given the same amount of noise in the data, a higher absolute effect can be expected to be more easily detected in this sample. The sample of polluted cities is built by taking the location of each *in situ* measurement stations run by the MEP[12]. The point estimate for the effects of a higher reduction target is nearly identical to the overall sample in percentage terms, but the coefficient turns significant because the higher absolute effect in the polluted sample increases statistical power (Table 2). All baseline estimates taken together, I find that that the SO_2 control policy was effective in reducing air pollution over the whole sample period.

Dynamic treatment effects To take a closer look at what might explain these differing findings, I estimate yearly versions of the above DID specification. Instead of collapsing the time periods into before and after the policy as in Equation (1), I interact a dummy for each time period with the reduction target. This yields the following equation:

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[12] I select the 25 nearest pixels up to a distance of at most 25 kilometers around the city centroids, and compute the province-level observations only based on those pixels. Results from this sample are robust to changes in the 25 kilometers cutoff, as most pixels are closer than 15 kilometers from the city centroid.

$$y_{pt} = \beta_0 + \sum_{t=1}^{T} \beta_{1t} Reductiontarget_p \times \gamma_t + \beta_2 Reductiontarget_p + \sum_{t=1}^{T} \beta_{3t}\gamma_t + \alpha_p + u_{pt} \quad (2)$$

As before, y_{pt} are the SO_2 pollution outcomes for province p in time period t. In this specification, the SO_2 reduction targets are interacted with each time period γ_t to estimate the differential trajectory of SO_2 pollution for provinces with different SO_2 reduction targets. These effects are captured in the point estimates for β_{1t} for periods 2 through T, where T is the last observation for 2010.

Figures 3 and 4 plot the estimate of the interaction coefficients $\sum_{t=1}^{T} \beta_{1t}$ in equation (2) and show that the identifying assumption of common pre-trends is satisfied. Both indicators are on a common trend before the start of the policy in 2006. However, there is only one year of satellite data before the start of the policy, because NASA only launched the satellite in late 2004. Figure 5 zooms in on the satellite data and plots the estimates for $\sum_{t=1}^{T} \beta_{1t}$ estimated on monthly satellite data. While there is more noise in the monthly data, there are common pre-trends before the start of the policy, as illustrated through the vertical grey lines.

[INSERT FIGURES 3, 4 and 5 ABOUT HERE]

The official SO_2 emissions data also show a clear deviation from the pre-trend at the start of the policy, lending further support to the identification. SO_2 emissions decrease immediately and linearly until the end of the 11th FYP. On the other hand, a look at the SO_2 satellite data paints a different picture: SO_2 pollution does not go down for provinces with a higher reduction target when the central government cannot monitor SO_2. After 2008, the satellite data show a distinct drop in SO_2 pollution. Taken together, I find the following: (i) there is possible misreporting of SO_2 emissions during the first two years of the 11th FYP when the Chinese government lacks the ability to properly monitor SO_2 emissions (ii) once the government gains the ability to monitor, rhetorical compliance turns into real compliance and SO_2 pollution is reduced. Ultimately, the policy worked.

The empirical findings in context. My findings suggest the importance of the government's monitoring to achieve compliance with the pollution control regulation. A comparison to findings from contemporaneous research strengthens this conclusion: Kahn, Li, and Zhao (2015) study water pollution control in China during the 11th Five-Year Plan (2006-2010). That is, they estimate the effect of a pollution control policy for the same country, time period and institutional setting. Their setting differs in one crucial aspect, however: the central government had access to high-quality monitoring data for water pollution from the start. A comparison to their findings can thus shed light onto the effect of monitoring on compliance.

In Table 4 (Panel A), Kahn, Li, and Zhao (2015) estimate yearly treatment effects for the effect of the water pollution control policy. Their findings show a pattern that is very different from my findings along two characteristics: (i) real compliance is immediate and statistically different from zero for all years (excepting 2009) and (ii) the yearly effects are of a similar magnitude throughout. Given that the salient difference to my setting is the government's ability to monitor pollution already in 2006 and 2007, this comparison provides further evidence that information is the likely channel that explains the behaviour by the provincial governments until 2008 and the lack of real compliance[13].

Heterogeneous treatment effects based on initial pollution levels Where do the improvements in air pollution take place? Figure 2 shows a large heterogeneity in the location of SO_2 pollution across provinces. Sichuan, for instance, suffers from a pollution hotspot towards the East, and enjoys comparatively lesser pollution in the Western part of the province. The NASA satellite data allow me to exploit this heterogeneity to ask whether the effect of the SO_2 pollution reduction target in the province differs depending on the initial level of pollution. To answer this question, I map the SO_2 satellite data to the county-level, yielding 2,638 cross-sectional units. For each county, I measure its mean SO_2 pollution for 2005 relative to all other counties within the same province. This information is captured in a variable that takes the value of 1 for counties in the lowest quartile of initial pollution within their province, up to a value of 4 for counties that have the highest initial pollution. I then re-estimate the DID specification from Equation (1) at the county-yearmonth level on each subsample along the distribution of initial pollution. $\sum_{t=1}^{T} \gamma_t$ therefore are year-month fixed effects in this subsample. As above, statistical inference relies on heteroskedasticity standard errors at the province-level and t-statistics from a wild bootstrap procedure with 1000 repetitions. I expect to find no effects for the lowest quartile, because initial pollution in these counties is below 0.2 Dobson Units on average, making further air quality improvements unlikely. Furthermore, for the same precision of data, a nominally smaller effect is harder to detect statistically, making it more likely to find a significant effect the higher the initial level of pollution.

The results in Table 4 confirm that this is the case. As expected, SO_2 reductions in response to the targets mainly take place in the higher two quartiles of the initial distribution, though only the most polluted quartile is statistically significant. This reproduces the baseline results, where the effect only turned statistically significant for the sample of polluted cities due to noise. The effect size for the two highest quartiles is a 9.4% and 9.9% decrease in SO_2 pollution per one standard-deviation increase in the stringency of the reduction target, respectively.

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[13] Relatedly, Stavins (1998) mentions that 'the SO_2 program has also brought home the importance of monitoring and enforcement provisions' in the U.S. experience of SO_2 pollution control, lending further support to the monitoring interpretation of empirical findings.

5.3 The effect of enforcement

Figure 3 showed that the effect of the targets sets in from 2008 on, after the Central Government gained the ability to accurately track pollution. Research from the U.S. has shown that enforcement can have an important influence on how polluters respond to air pollution limits (Blundell, 2017). In this section, I therefore ask whether the effect of a reduction target on pollution outcomes depends on the level of enforcement in a province. In other words, I estimate heterogeneous treatment effects by level of enforcement.

Selection of the prefecture subsample To overcome the low number of cross-sectional units in my province-level sample, I estimate the role of enforcement amplifying the effects of the target in a new sample at the prefecture level. The prefecture is China's second administrative level after the province. Compared to the province level with its 31 units, the prefecture level features 334 units.

My sample contains hand-collected reduction targets for 123 different prefectures, a little over a third of China's prefectures. This sample was collected from a variety of sources such as provincial government webpages through a significant data collection effort[14]. I am confident that this sample is as comprehensive as can be collected: The four municipalities directly under the Central Government do not report prefecture-level targets. Additionally, five of China's provinces containing another 124 prefectures were given a reduction target of zero (Gansu, Hainan, Qinghai, Tibet, Xinjiang), and therefore did not use prefecture-level targets. Figure 6 shows the full prefecture-level sample.

To gauge how representative this sample is of the general sample, it is useful to ask: what are the incentives to report a prefecture-level target publicly? This depends on who reports the target: the prefecture itself would likely self-select to publicize its target only if it has been able to comply. A province, on the other hand, would publicize the targets of all its constituent prefectures simply to show the Central Government and the public that it is taking air pollution seriously. Luckily, the large majority of my subsample data comes from province-wide lists, and is thus unlikely to involve a selection issue.

To substantiate this claim, I compare the distribution at the prefecture level to the distribution of the province-level targets. Both distributions are very similar in shape, as well as quantitatively: the subsample has a mean reduction target of 14.43 (SD: 10.90) compared to the full sample's mean reduction target of 9.65 (SD: 6.71). The reason for the slightly higher mean in the subsample is that some prefectures received targets up to 53.6% compared to at most 25.9% for a province (see Figure A.3 in the Appendix for a plot of both histograms). Both distributions, therefore, are very similar[15]. Figure A.4 in the Appendix further shows that the prefecture subsample covers areas of different air pollution levels that are representative of the main sample.

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[14] A full list of primary sources is available upon request.

Estimation To analyze the effect of enforcement, I use the density of enforcement officials for each province in the subsample shown in Figure A.5 in the Appendix. I then split the prefecture-level sample into quartiles according to the enforcement official density. As can be seen from the distribution, the upper quartile shows a comparatively large standard deviation of enforcement official density while the lower three quartiles are more homogeneous in their enforcement official density.

The rollout of SO_2 monitoring devices and the large-scale employment of enforcement officials started at the same time, from 2008 on. I exploit the timing of this change together with the cross-sectional variation in the number of enforcement officials (normalized by province area). In this way, I can study heterogeneous treatment effects depending on the number of enforcement officials in a province. For each quartile, I re-estimate a prefecture-level version of equation 1:

$$\begin{aligned} y_{ipt} = \beta_0 + \beta_1 Reductiontarget_i \times D(Post1)_t + \beta_2 Reductiontarget_i \times D(Post2)_t \\ + \beta_3 Reductiontarget_i + \sum_{t=1}^{T} \beta_{4t}\gamma_t + \alpha_i + u_{it} \end{aligned} \tag{3}$$

where i denotes a prefecture in province p in year t. $D(Post1)_t$ is a dummy for the beginning of the 11th Five-Year Plan, 2006 to 2007, whereas $D(Post2)_t$ is a dummy that captures the rollout of monitoring devices and enforcement officials from 2008 onwards. Apart from these ex ante considerations, the reason to study the effect of enforcement officials separately from 2008 onwards are my dynamic estimates of the effects of the targets. As shown in table 3, the effect of the reduction target on pollution outcomes sets in only from 2008 onwards. To study how the presence of enforcement officials influences the effect of a reduction target on pollution outcomes, it is thus useful to study the compliance period by itself.

Results Table 5 shows the results from estimating equation 3. Overall, the evidence is mixed. The prior on enforcement officials is that they are useful. That is, ex ante one would expect that the higher the density of enforcement officials, the larger the reduction effect of a target. The point estimates for the compliance period for the lower three quartiles point in this direction: the effect size for the prefectures with the lowest enforcement density is 0.5% of the pre-treatment mean, or close to zero. The point estimates for the second and third quartiles are −6.4% and −8.4%, respectively. Only the estimate for the third quartile is statistically different from zero. The results for the fourth quartile show the opposite, with a 7.6% increase in pollution, with the point estimate marginally significant. Overall, I can find no evidence for heterogeneous treatment effects by differences in enforcement.

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[15] Estimating 1 on the prefecture-level subsample also reproduces my main findings at the prefecture level, further indicating that the subsample is informative about the aggregate.

5.4 Reactions by the regulated agents in response to the targets

This subsection provides evidence into the responses by the regulated agents. Two facts stand out from the empirical analysis above. On the one hand, regulated provincial governments likely misreport the desired emissions data when the central government cannot monitor them. On the other hand, my analysis shows that the SO_2 reduction control policy was ultimately successful in reducing air pollution. Provincial governments thus reacted along two margins. They appeared to bring down air pollution through *rhetorical compliance* initially, and switched to *real compliance* towards the end of the policy.

Rhetorical compliance As shown above in Table 3, the effect of the reduction targets has a different sign when comparing the official SO_2 emissions data and the NASA SO_2 satellite data before 2008. Given that the SO_2 satellite data move closely with real SO_2 emissions (see Section 4), this suggests initial misreporting of data. This subsection investigates whether this misreporting was accompanied by further political rhetoric by the provincial governments. In particular, I test whether the provincial governments changed their political rhetoric in response to the SO_2 reduction control targets. To do so, I estimate versions of Equation (2), using different counts of keywords as outcome variables. First, I use the overall number of keywords related to air pollution in each government work report. Figure 9 plots the estimates for the yearly interaction coefficients β_{1t}. It shows that provinces that received a higher SO_2 reduction target show a distinct increase in their political rhetoric on air pollution.

[INSERT FIGURE 9 ABOUT HERE]

Next, I zoom in and split political statements into those on work done in the preceding year and those related to projects for the year to come. Figure 10 shows that the increase is most pronounced in the period before the central government had the capacity to monitor. Provincial governments that received a higher SO_2 reduction target claim past work on projects related to air pollution in 2007, thus exploiting the central government's inability to monitor SO_2 initially. That is, a higher SO_2 reduction target induces provinces to claim work on air pollution in 2006. Political statements relative to future work on air pollution also increase with the SO_2 reduction targets, although the evidence is less stark (Figure 11). Finally, Table 6 summarizes these results based on estimating Equation (1) on the political attention variables to find that: (i) political attention to air pollution increases with target stringency, and (ii) statements about past work on air pollution peak in the period in which the government could not monitor SO_2[16]. As shown through the comparison of results from the official SO_2 emissions indicator and NASA satellite data, however, SO_2 pollution during that period did not improve.

[INSERT FIGURES 10 and 11 ABOUT HERE]

Taken together, my empirical findings suggest that the provincial governments exploit the central government's inability to monitor along two margins: they likely misreport the desired SO_2 emissions data, and they back up the misreporting through rhetorical compliance in their public political statements.

Real compliance As shown above, the SO_2 reduction targets worked in reducing SO_2 pollution significantly from 2008 onwards. Based on my own calculations of the marginal cost of SO_2 emissions abatement (see Section 6), the installation of desulfurization devices in existing industrial and power plants, fuel-switching to better quality coal, and the shutdown of small, inefficient thermal units are the main margins by which the provincial governments could reduce SO_2 emissions over relatively short time horizon of 5 years. I provide evidence on the last two channels.

The data on the *installation of scrubbers* include both the capacity of the desulfurization equipment as well as the timing of its installation in each province. Figure 12 shows that while provinces with a higher SO_2 reduction targets installed more desulfurization devices on average, that effect is not statistically different from zero. Figure 13 computes the skewness of the timing of the installation of the scrubbers between the years 2006 and

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[16] Table 6 includes a robustness check to further show that my estimates on rhetorical compliance are meaningful. This test involves estimating the effect of the SO_2 reduction targets on closely related, yet different placebo outcomes that should not be affected by the SO_2 reduction targets. The 11th Five-Year Plan (2006-2010) included goals to increase China's forest cover from 18.2% to 20% and to extend the coverage of rural medical care from 23.5% to 80%. To measure the political attention towards these policies, I use the count of 'forest' and of 'medical care' in the government work reports as dependent variables for the falsification test. Results based on these outcomes using the specification in Equation (1) are reported in the columns 'Placebo Outcomes' in Table 6. As in the case of the keywords related to air pollution, both keywords are mentioned more often during the 11th Five-Year Plan (2006-2010) than before. Provinces that received a higher SO_2 reduction target, however, do not talk more about either topic. This strongly suggests that governments of provinces with higher reduction targets do not mimic the Central government's political agenda in their own statements in general. Instead, they specifically change their political communications in response to the SO_2 reduction targets.

2010 and correlates it to the SO_2 reduction targets at the province level. As can be seen, provinces with a higher SO_2 reduction target did not install scrubbers earlier than other provinces. The data on the *shutdown of small, inefficient thermal units* shows a much clearer picture. Figure 14 shows that the higher the reduction target, the higher the capacity of small thermal units shut down by 2010. Shanghai and Beijing are the exception to this rule, most likely because they already shut down inefficient plants in the past.

[INSERT FIGURES 12, 13 and 14 ABOUT HERE]

6 Instrument choice and gains from trade

In this section I evaluate two questions of policy design for the SO_2 reduction targets in the 11th FYP: what allocation of targets across provinces would a market-based policy instrument have created? And: what are efficiency gains from trade associated with moving from the command-and-control allocation to the counterfactual market-based policy?

Both questions bear enormous policy importance for China. SO_2 trading was initially discussed as an alternative to a command-and-control policy in the 11th FYP. Though ultimately discarded, China has now embraced emissions trading for CO_2 in its 8 pilot markets and in the upcoming national carbon market (Stoerk, Dudek, and Yang, 2018).

Moreover, both types of questions have been studied for the U.S. (Carlson et al., 2000; Oates, Portney, and McGartland, 1989). This research has shown that the efficiency of different policy instruments is an empirical question. It will depend, among other things, on whether the command-and-control regulation is designed in an enlightened way that takes the cost of pollution abatement into account. Whether the efficiency of China's flagship air pollution control regulation could have been increased through the use of a different policy instrument is therefore of academic interest.

In this section, I construct detailed marginal abatement cost (MAC) curves for SO_2 at the province level for China. I use these SO_2 MAC curves to predict the counterfactual market-based allocation. In this way, I can assess whether the actual command-and-control regulation was enlightened and took into account the cost of abatement. Furthermore, I can quantify the efficiency gains from trade from moving from the command-and-control allocation of reduction targets compared to the market-based allocation. As noted by Stavins (2003), cost might be the best measure to assess policy efficiency. Finally, I compute a back-of-the-envelope measure for the marginal benefits of SO_2 abatement at the province level to study whether the gains from trade based on cost alone are driven by omitting the benefits of reducing air pollution.

6.1 Construction of the marginal abatement cost curves

Data I use a rich set of micro data on SO_2 emissions and abatement costs in each province in China at a very detailed level. These data are compiled by the IIASA research institute for use as input into their GAINS model for China (on the model, see IIASA, 2010a, IIASA, 2010b, Klimont et al., 2009). The data rely on a variety of sources of two kinds: *common data*, that are used across different countries and rely on the assumption of free international markets in abatement equipment, and *country-specific data*. Common data include the unit investment cost for technologies, fixed costs of operation, and the amount of input factors needed for some of the variable cost components. These data have been compiled and updated by IIASA for several decades on the basis of expert meetings at the UN (AP EnvEcon, 2010).

Country-specific data, on the other hand, include a detailed breakdown of China's industrial structure: the type and size of polluting installations, the facility operating conditions, national fuel consumption data, local input prices (labour, electricity, fuel cost) as well as unabated emission factors and removal efficiencies (AP EnvEcon, 2010). The local data are compiled by IIASA experts in collaboration with local experts from the Chinese Energy Research Institute in Beijing and Tsinghua (Purohit et al., 2010). These data are combined into unit cost estimates per technology, as well as abatement potential[17].

The data give a detailed breakdown of all SO_2 emission sources for each province, split into different sectors (such as the combustion of coal) that use different fuels (such as gas or low-sulfur coal) and each of which has different abatement technologies at its disposal (such as limestone injection). Overall, the dataset contains 2170 distinct sector-fuel combinations, and 5680 different abatement technologies. Each of the abatement technologies is characterised by a unit cost of abatement (in \$/tSO_2)[18] and its abatement potential (i.e. how much would the emissions factor of the current sector-fuel combination be lowered when switching to the abatement technology). To illustrate, one abatement technology would be the use of limestone-injection (*abatement technology*) in a modern coal-fired power plant (*fuel* and *sector*) at the cost of \$639.07/tSO_2 (*unitcost of abatement*).

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[17] While the data on the cost of abatement are ex ante cost estimates for China, they are not pure engineering estimates. Instead, the common part of the abatement cost data rely on the ex post experience of other countries. The data are likely to be an upper bound for the ex post abatement cost: cheaper local inputs and China's capacity for scale likely allowed for cheaper abatement abatement in practice. The use of identified ex post MAC estimates from revealed-preference settings such as Meng (2017) and Gosnell, List, and Metcalfe (2016) would be desirable, but no such estimates are available for China or at the required level of comprehensiveness. My ex ante estimates, by contrast, are consistent across provinces and thus allow for cross-province comparisons. To err on the conservative side for abatement cost estimates also has a second advantage: it avoids underestimating the cost side in the cost-benefit calculus for the overall regulation. Regulatory practice, such as the EPA's subsequent assessments of the Clean Power Plan, supports this.

[18] The original datasource is in €, which I convert into \$ at the contemporaneous exchange rate of 1.24.

My data also allow me to look at sectors individually. The main SO_2-emitting sectors are power plants (63.4% of China's SO_2 emissions), industry (24.8%) and the residential sector (12.2%). The power sector, in particular, is of interest because it allows for an additional robustness check for the quality of the abatement cost data. Figure A.7 in the Appendix depicts the power sector's MAC curve in China to show that over 90.8% of the SO_2 emissions from China's power sector can be abated before cost become prohibitive. This level of possible abatement, as well as the general shape of the MAC curve, reflect the earlier SO_2 abatement experience in the U.S. (Ellerman et al., 2000, Figure 9.1).

Construction of the MAC curves I first construct two simplified versions of the full MAC curve: a MAC curve that only uses the least cost abatement technology per province, fuel and sector (*least cost*), and a MAC curve that solely relies on the abatement technology per province, fuel and sector that offers the largest emissions abatement (*highest abatement*). To construct the *least cost* MAC curve for one province, I follow a two-step procedure. First, I rank each abatement option by the unit cost of abatement within each sector and fuel. Second, I abate SO_2 emissions within each sector and fuel in increasing cost order across the province. I follow an analogous procedure to construct the *highest abatement* MAC curve.

In principle, construction of the full MAC curve for a given province requires an optimization that trades off both dimensions (see Appendix A.2). In practice, the difference between just using the least cost MAC and the optimised MAC is negligible for the comparatively low levels of abatement that were part of the 11th Five-Year Plan. I therefore take a computational shortcut to draw the full MACs: I construct it as the lower envelope of the *least cost* and the *highest abatement* curves. For low levels of abatement, the least cost curve dominates, whereas higher levels of abatement can be reached using the highest abatement technologies.

Figure 15 shows two examples for full MAC curves, Gansu and Sichuan, to illustrate the large heterogeneity in marginal abatement cost across provinces (Appendix A.4 contains the full MAC curves for each province). In contrast to many MAC studies, I do not rely on a top-down model but base the cost estimates entirely on data, and I am the first to provide complete MAC curves on Chinese provinces in this way.

[INSERT FIGURE 15 ABOUT HERE]

Consistency checks To check that my data represent the official Chinese data well, Figure 16 shows the average ratio between the GAINS SO_2 emissions and the official

MEP SO_2 emissions as a function of the province's level of emissions: the overall fit between my data and the MEP data is good (correlation: 85.9%) and fairly stable across provinces, except for two outliers with very low emissions: Tibet and Hainan. Overall, the GAINS data report higher emissions for all provinces than do the official data. This is in line with the literature in atmospheric science that has found that GAINS data tend to be more comprehensive and slightly overpredict official SO_2 data sources, which is possibly due to differing assumptions on the distribution of fuel consumption across sectors (Klimont et al., 2009) and the fact that official MEP statistics lack rural pollution sources and biofuels (Lu et al., 2010).

[INSERT FIGURE 16 ABOUT HERE]

To gauge whether my abatement cost data accurate, I compare my dataset to a firm-level analysis from China in 2005. It turns out that the use of scrubbers in the power sector, for instance, cost between \$84 and \$916 per ton of abated SO_2 in 2005, depending on the quality of the coal used Wang, Pan, and Peng (2005). This is in line with abatement cost estimates for the U.S. from Ellerman et al. (2000), who find an average cost of scrubbing of \$265 per ton of abated SO_2. It is certainly possible that the cost of abatement came down over the course of the 11th Five-Year Plan through innovation and economies of scale from wider deployment. The magnitude of my ex ante cost curves, however, reflects the reality on the ground.

Additionally, there is a drawback in using detailed SO_2 emissions data at the microlevel: the detailed breakdown across sectors does not allow me to compute the cost of moving activity across sectors (such as moving electricity generation from coal-fired power plants to wind turbines). In other words, these data limitations make it necessary to assume scrappage cost and imperfect substitution across sectors in the short run. Given the 5-year horizon of the policy, however, I feel that this is a reasonable assumption to make.

6.2 The counterfactual market-based allocation of SO_2 reduction targets

In this subsection, I compute the counterfactual allocation of SO_2 reduction targets across provinces for the market-based policy. I compute the market-based policy-instrument as the cost-optimal allocation of targets to provinces given the national target. The market-based policy instrument thus represents a simplified emissions trading scheme in which provinces trade emissions allowances until their marginal abatement cost are equalized. To compute the counterfactual allocation for the market-based policy instrument, I pool the province-level microdata and construct the SO_2 marginal abatement cost curve at the national level for China. As shown in Figure 17, marginal abatement cost is relatively flat until an abatement level of 35% of 2005 SO_2 emissions. Up until this abatement level, the cost of SO_2 abatement at the margin is less than \$500/tSO_2. Beyond ca. 70% of 2005 SO_2 emissions, however, the picture changes and the cost of abatement rises rapidly. Beyond 75%, abatement becomes prohibitively costly.

[INSERT FIGURE 17 ABOUT HERE]

Figure 17 also shows the counterfactual marginal abatement cost for the national SO_2 reduction target of 10%, given by the intersection between the vertical line at 10% and the MAC curve. At an abatement level of 10%, the market-based allocation of SO_2 reduction targets would have led to a marginal abatement cost of \$419/tSO_2. This Figure is the counterfactual marginal cost of the Chinese government's SO_2 emissions control strategy had the central government distributed the provincial reduction targets in a cost-optimal way.

The intersection of the marginal abatement cost curve for China as a whole with the 10% national abatement level also produces the market-based allocation of SO_2 reduction targets across provinces. Figure 18 shows that this allocation is far more skewed than the distribution of targets that was actually used in the 11th FYP. The command-and-control allocation already ranges from targets of 0% to 25.9%, but is approximately uniformly distributed within this range. The market-based allocation, by contrast, is more unequal. A small number of provinces would bear most of the reductions. These provinces are Sichuan, Shandong, and Zhejiang. The industrial structure of these provinces allows for comparatively cheap installation of wet flue-gas desulfurisation in industry and power plants and the use of more efficient combustion processes in refineries and steel sintering.

[INSERT FIGURE 18 ABOUT HERE]

Based on the MAC curves, I find that the Chinese government did not equate marginal abatement cost across space. Instead, the reduction targets targeted coastal provinces in the East even though abatement coasts are higher at the margin. These results are shown in Table 7 and Figure A.8 in the Appendix. The actual command-and-control allocation is consistent with a tale-of-two-cities story, in which China would develop amenity-based consumer cities along the coast, while maintaining a base of polluting manufacturing in its interior (Kahn, 2006; Zheng and Kahn, 2013). Shanghai is a prime example for this: under the cost-efficient allocation, Shanghai would have received an SO_2 reduction target of 6.2% on 2005 levels. Under command-and-control, however, Shanghai received a reduction target of 25.9%, or more than four times the cost-efficient target.

My findings show that actual command-and-control regulation that China used to control SO_2 pollution in the 11th FYP was not cost-optimal. As suggested by Oates, Portney, and McGartland (1989), command-and-control regulation will only be efficient if it is designed in an enlightened fashion by keeping an eye on the cost of abatement. Figure 19 shows that this was not done by the Chinese government in 2005. There is no statistically significant relationship between the SO_2 reduction target a province received under the 11th FYP and its abatement cost at the margin.

[INSERT FIGURE 19 ABOUT HERE]

6.3 A measure for marginal abatement benefits

Because China's provinces differ markedly with respect to income levels, population densities and initial pollution, I include a measure for the benefits of air pollution abatement as a robustness check. I use the method employed by Oliva (2015) to construct a back-of-the-envelope measure for the marginal abatement benefits of reducing SO_2 pollution at the province level. This method proceeds in 3 steps: (i) how does the SO_2 control policy change pollutant concentrations?, (ii) what health effects do the changes in pollutant concentrations cause? and (iii) what is the monetary value of those health effects?

(i) Changes in pollutant concentrations I use the results from Wang, Jang, et al. (2010b), who use the CMAP modelling system (maintained by the U.S. Environmental Protection Agency) to simulate the effects of the 11th FYP's SO_2 reduction policy on concentrations of SO_2 and $PM_{2.5}$ under the assumption of full compliance. My empirical analysis shows that this assumption is well-founded. The measurements from Wang, Jang, et al. (2010b) allow me to attribute changes in pollutant concentrations of SO_2 and $PM_{2.5}$ to the SO_2 emissions reduction target of each province. Their estimates are net of spatial spillovers.

(ii) Health effects To convert the changes pollutant concentrations to changes in health outcomes, I use dose-response estimates for $PM_{2.5}$ and SO_2 from Bombardini and Li (2016). They estimate an elasticity of infant mortality rates of 0.9 to SO_2 and of 2.2 for $PM_{2.5}$. I combine those estimates with data on SO_2 and $PM_{2.5}$ levels in 2005 from MEP and the *China Energy Databook* (Fridley, Romankiewicz, and Fino-Chen, 2013) to approximate a linear dose-response function for each pollutant.

I use the estimates from Bombardini and Li (2016) for two reasons: first, they use an instrumental strategy approach to estimate a dose-response function for the health effects of air pollution, thus correcting downward bias from OLS estimates (due to migration, income effects and avoidance behaviour). Additionally, their study is from China, from a recent period, and includes consistent estimates for both SO_2 and $PM_{2.5}$, which are the main pollutants that are affected by the SO_2 reduction policy. The downside is that this restricts my focus on infant mortality when calculating the benefits from reducing air pollution.

Infant mortality, however, is likely to capture a first-order welfare effect. Matus et al. (2012) calculate that 71.4% of all air pollution costs in China are health costs, and that mortality captures over 85% of those health costs. Chen, Ebenstein, et al. (2013), in turn, show that mortality impacts from TSP are strongest in infants. Evidence from Indonesian wildfires in 1997 also points to large infant mortality effects from exposure to particulates, mostly driven by prenatal exposure (Jayachandran, 2009). Greenstone and Hanna (2014) also focus on infant mortality to evaluate the effect of pollution. Furthermore, data on infant mortality is of high quality and available for all regions of China, allowing me to answer questions of allocative efficiency across space[19].

(iii) Valuation To convert the health damages into monetary values, I use a baseline value of a statistical life (VSL) of 1 million yuan from World Bank and State Environmental Protection Administration (2007). This value is a midpoint between the VSL estimates from the reviewed studies ranging from 0.24 to 1.7 million yuan[20]. Following Hammitt and Robinson (2011), I account for the income heterogeneity across Chinese provinces by adjusting the central VSL estimate according to the income level in each province using an income elasticity of VSL of one. This yields VSL estimates from 360,000 yuan (Guizhou) to 3,000,000 yuan (Shanghai).

Taking into account the reductions in concentrations of both SO_2 and $PM_{2.5}$, I multiply these VSL estimates by the mortality numbers to compute the benefit of reducing SO_2 emissions by 1kt for each province. Since I employ a linear approximation, the marginal benefits of abatement is constant[21].

Then, in a similar vein to the MAC data, I can use the combined data on both marginal cost and benefit to construct marginal welfare impact curves. I combine the marginal abatement benefit data with the marginal abatement cost data by dividing the marginal abatement cost by the marginal abatement benefit to obtain a measure of the marginal welfare impact of abatement. When this ratio is below one, benefits are larger than cost.

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[19] Many more benefits exist to reducing air pollution, e.g. reduced adult morbidity and mortality (Barwick et al., 2018), increased productivity (Chang et al., 2016; Fu, Viard, and Zhang, 2018; He, Liu, and Salvo, 2018), as well as improvements in cognitive performance (Zhang, Chen, and Zhang, 2018) and mental health (Chen, Oliva, and Zhang, 2018). The literature is active, however, and the verdict on the full social cost of air pollution is still out. To be able to make statements about the optimal allocation of reduction targets across space, however, data on the full benefits is not needed. A shortcut is to assume that the damages from air pollution are proportional to population, which is an acceptable simplifying assumption.

[20] VSL estimates for China are available for more recent periods (Ito and Zhang, 2016), but to evaluate a policy from 2005 I prefer to use estimates from that period.

[21] For those provinces with a reduction target of zero, I find that the benefits are 0 or nearly 0, too. This is due to low initial pollution, low VSL estimates, and low population numbers. The exception is Gansu, for which I compute the marginal benefits as the average of its 5 nearest neighbours with respect to initial pollution, VSL estimates, and population numbers.

Once this ratio exceeds one, costs are higher than benefits. Figure 20 pools the province-level data to obtain the marginal welfare impacts for China as a whole, where the cost of abatement is normalized by the benefits within each province before pooling the data. The vertical dashed line at 0.1 marks the 10% national SO_2 emissions control target of the 11th FYP. The marginal benefits of abatement exceed the marginal cost of abatement by 12 times at this abatement level, and this calculus abstracts from a number of benefits from reductions in air pollution[22].

Caveats I rely on an overly conservative measure of benefits by including only infant mortality which may underestimate the true benefits and lead to an underestimation of the welfare-optimizing level of SO_2 abatement for China. However, this concern is muted in practice since even my lower bound benefit measure suggests SO_2 abatement up until the prohibitive marginal abatement cost ranges. Additional abatement benefits at the margin would thus only have a negligible effect on the welfare-optimizing abatement level. The advantage is that the dose-response functions used are more precise for infants because low migration translates into better knowledge of lifetime exposure to pollution, improving the consistency of estimates *across* provinces.

6.4 Gains from trade

Finally, I study the gains from trade across the two different policy instruments. Gains from trade will be possible if the actual command-and-control regulation used to allocate the SO_2 reduction targets in the 11th FYP was not done optimally with respect to the cost of abatement. As I have shown above, this is the case. This subsection quantifies these efficiency gains in terms of cost-efficiency. To further take into account the heterogeneities across Chinese provinces, I construct a back-of-the-envelope measure for the marginal benefits of air pollution abatement to study the robustness of the findings based on pure cost-efficiency.

Table 8 shows the gains from trade that are possible. Firstly, I follow the literature (e.g.Stavins, 2003) and assess the gains from trade using the cost efficiency measure. I find that moving from the command-and-control allocation to the market-based allocation would decrease abatement cost by 49% at the margin (\$816/tSO_2 to \$419/tSO_2). Secondly, I find that this conclusion is robust to taking into account the benefit side. Adding the benefit measure, I find efficiency improvements of 45% (from a welfare ratio of 2.19 to a welfare ratio of 1.2).

Overall efficiency would increase by 25%, lowering average abatement cost from \$437 per ton of SO_2 for the command-and-control policy to \$323 per ton of $SO_2$for the market-based policy. Efficiency gains of 25% might seem low compared to the literature from the U.S. that finds efficiency gains up to 50% (Carlson et al., 2000; Ellerman et al., 2000; Keohane, 2003). However, a crucial difference in the analyses is that my market-based policy instrument focuses on the province rather than the firm level. The potential inefficiency compared to using plant-level data is therefore lower, and a 25% efficiency gain considerable.

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[22] Assuming that the calculus contains all benefits, it is also possible to ask the normative question of what would have been the optimal national SO_2 reduction target for China in 2005. These results are available upon request.

6.5 Abatement cost expressed per unit of pollution

For policy, the cost of achieving a certain pollution outcome rather than a change in pollution inputs often matter. This indicator is particularly useful to compare the cost of reducing air pollution to willingness to pay (WTP) estimates. The WTP for clean air in China, in particular, is an active research topic, with important contributions by Ito and Zhang (2016), Freeman et al. (2017) and Barwick et al. (2018) and Mu and Zhang (2017). These estimates are typically expressed as a per unit decline in concentrations of particulate matter.

This indicator reflects the typical policy goal, to reduce *concentrations* of pollutants rather than their *emissions*. To go from reductions in emissions to reductions in concentrations, I combine my empirical findings with an ex ante study in atmospheric science (Wang, Jang, et al., 2010b). Assuming full compliance with the 11th FYP's SO_2 reduction targets, Wang, Jang, et al. (2010b) use an atmospheric science model from the U.S. EPA to compute the resulting improvements in pollutant concentrations across China, net of transport and spatial spillovers. Given that I find near universal compliance in my empirical evaluation, their estimates are likely to reflect the true reduction in pollutant concentrations as a result of the SO_2 reduction policy I analyze in this research.

Wang, Jang, et al. (2010b) find that the policy reduced $PM_{2.5}$ concentrations by 3 to 15 $\mu g/m^3$, or 9 $\mu g/m^3$ on average. These changes are calculated for the most populated areas in China. Based on my MAC curves, the total cost of the SO_2 abatement in the 11th FYP was \$1,953,898. The cost of a 1 $\mu g/m^3$ reduction in $PM_{2.5}$ concentrations is, therefore, \$217,100. Note that these figures abstract from co-benefits such as lowered concentrations in pollutants other than particulate matter. Had China used a market-based policy instrument with a total cost of \$1,457,971, the cost of a 1 $\mu g/m^3$ reduction in $PM_{2.5}$ concentrations would have been 161,997, or 25% lower. These figures can be used directly to address whether environmental quality in developing countries is low because of high marginal cost for improvements, as posited by Greenstone and Jack (2015).

7 Concluding remarks

This research evaluates China's main air pollution control policy. In 2005, China decided on a 10% SO_2 emissions reduction goal as part of the 11th Five-Year Plan (2006-2010). To study the effect of this policy on pollution outcomes, I use both official, misreporting-prone indicator and independent NASA SO_2 satellite data in a differences-in-differences strategy that exploits variation in target stringency at the province level. Overall, my empirical findings show that SO_2 pollution control in the 11th Five-Year Plan (2006-2010) was a success. SO_2 pollution, as measured by independent satellite data, decreased by more than 10% as a result of the policy, most notably through the shutdown of inefficient and small thermal units. Compliance, however, only started when the central government upgraded its pollution monitoring capacity in 2008. Combining a subsample of hand-collected prefecture-level data covering one third of China with data on the number of environmental enforcement officials, I find no evidence for heterogeneous treatment effects by level of enforcement. Further research in the spirit of Duflo et al. (2013) would be needed to clarify the role of environmental enforcement in China.

To analyze the cost and efficiency of the chosen command-and-control regulation, I construct detailed marginal abatement cost curves for each province in China and show the large heterogeneity across provinces in marginal abatement cost. Based on these cost curves, I can quantify the efficiency gain of moving from the actual command-and-control regulation to a counterfactual market-based policy instruments such as a cost-based SO_2 emissions trading scheme. I find that the market-based allocation would increase efficiency by 25%, lowering the average abatement cost from \$437/tSO_2 to \$323/tSO_2. At the margin, efficiency would rise by 49%. This finding is robust to the inclusion of a back-of-the-envelope measure of marginal abatement benefits. I further estimate the cost of a 1 $\mu g/m^3$ reduction in $PM_{2.5}$ concentrations for China at \$217,100, or 25% less using a market-based policy instrument. Such cost estimates are crucial for complementing the recent literature on WTP for clean air in China (Ito and Zhang, 2016; Freeman et al., 2017; Barwick et al., 2018).

My analysis, then, suggests that China faces similar problems in its air pollution control as more developed countries did in the past. Air pollution control is initially plagued by monitoring difficulties, and works in general, though it is not initially cost-efficient. In analyzing environmental policy in China during the 11th Five-Year Plan (2006-2010), I zoom in on a period in recent Chinese history that saw the turning point in environmental governance with the creation of the Ministry of Environmental Protection in 2008. This change in governance coincides with a change in China's dynamics of pollution and economic growth. My research can thus be seen as a detailed account of how and at what cost China achieved the turning point on its environmental Kuznets curve (Grossman and

Krueger, 1995). Understanding China's ongoing transition from the planet's biggest dirty industrial powerhouse to a cleaner consumer economy is crucial for China, but also for other countries in the process of development (Greenstone and Jack, 2015). As its biggest environmental policy ambition to date, China has now started to build a national carbon market. Abatement cost loom amongst the biggest concerns in practice.

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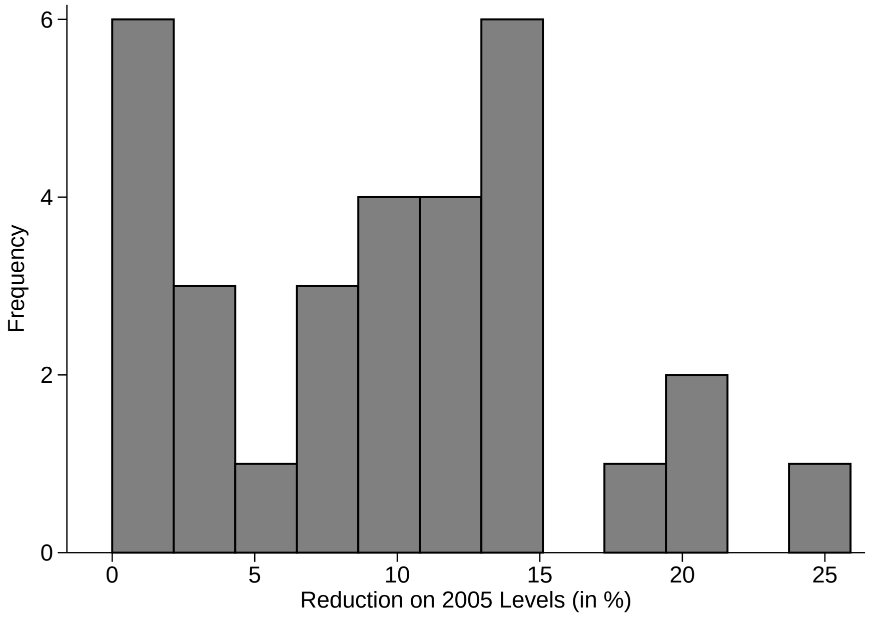
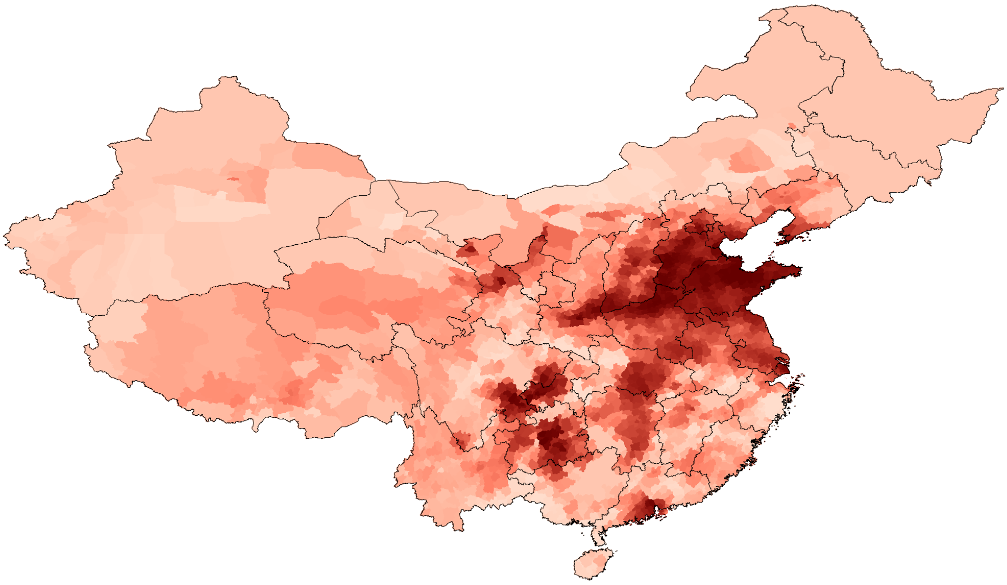
Figures

Figure 1: The SO_2 emission control targets



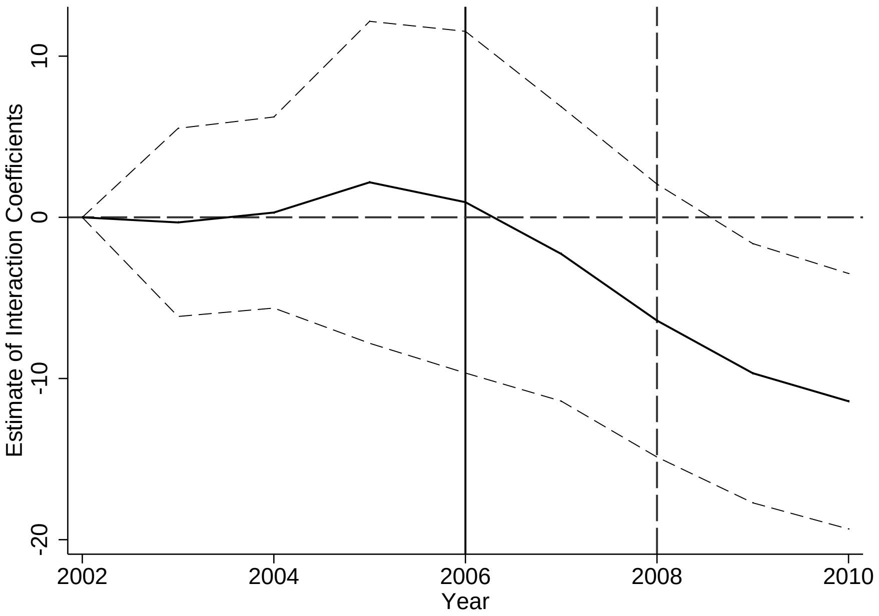
Notes: This figure shows the variation in the SO_2 emissions reduction targets across the 31 provinces. Targets are shown as percentage reduction on 2005 SO_2 emission baselines. The mean of the distribution is 9.4% and the standard deviation is 6.8 percentage points. Data source: State Council (2006).

Figure 2: SO_2 POLLUTION IN CHINA IN JANUARY 2006 BASED ON NASA SATELLITE DATA



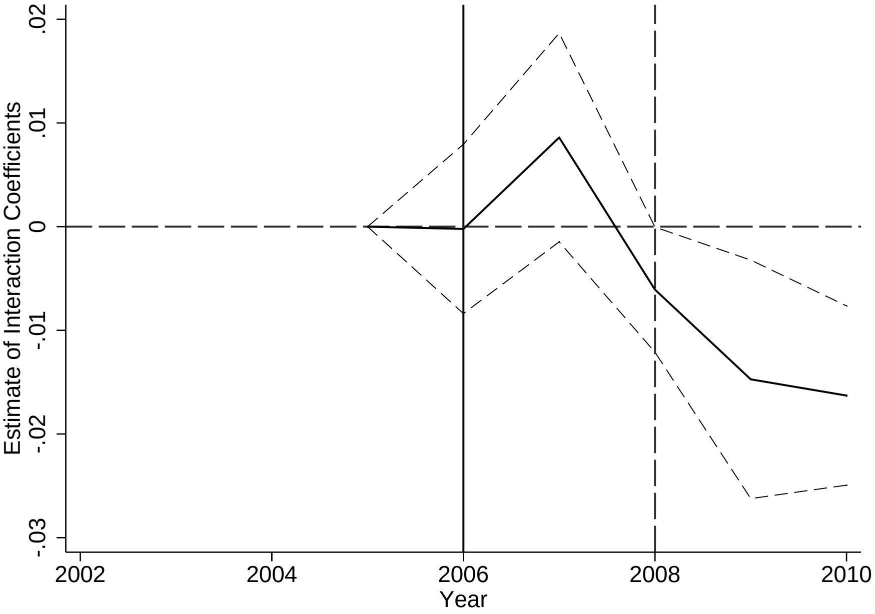
Notes: This figure shows the cross-section of the SO_2 satellite data based on the NASA OMI SO_2 data product for January 2006 mapped to the county-level.

Figure 3: Dynamic treatment effects: Official SO_2 emissions



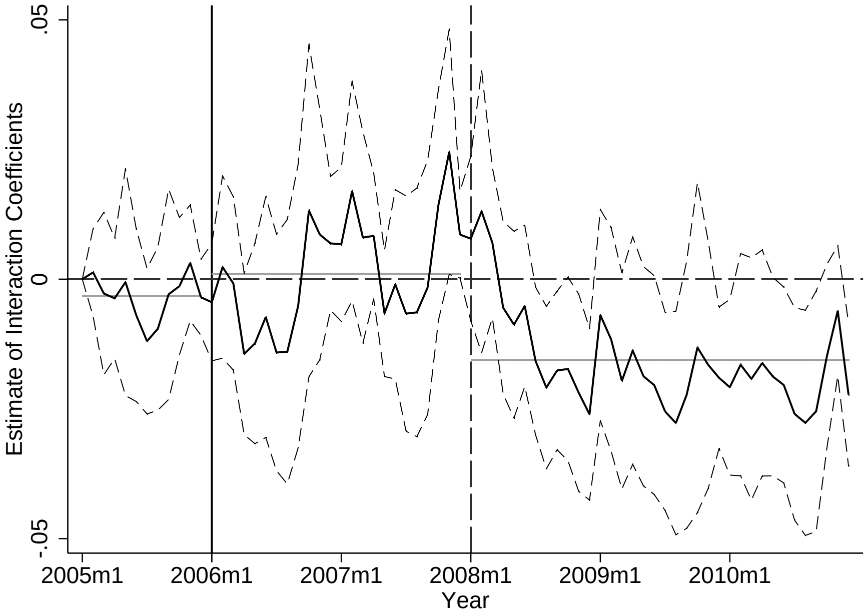
Notes: The solid line plots the point estimate for yearly coefficient estimates of the interaction coefficients $\sum_{t=1}^{T} \beta_{1t}$ in Equation (2) for the official SO_2 emissions data. The dashed lines show the 95% confidence bands, based on heteroskedasticity-robust standard errors clustered at the province-level. The excluded time period $t = 1$ is the year 2002. The vertical line before 2006 marks the start of the policy and the vertical line before 2008 marks the start of SO_2 monitoring.

Figure 4: Dynamic treatment effects: SO_2 satellite data



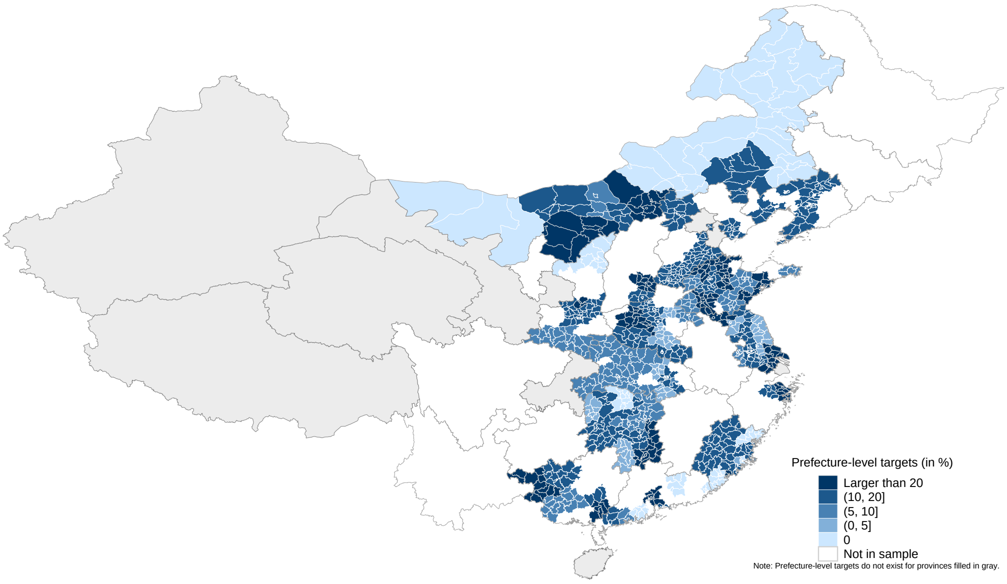
Notes: The solid line plots the point estimate for yearly coefficient estimates of the interaction coefficients $\sum_{t=1}^{T} \beta_{1t}$ in Equation (2) for the NASA SO_2 satellite data. The dashed lines show the 95% confidence bands, based on heteroskedasticity-robust standard errors clustered at the province-level. The excluded time period $t = 1$ is the year 2005. The vertical line at 2006 marks the start of the policy and the vertical line at 2008 marks the start of SO_2 monitoring.

Figure 5: Dynamic treatment effects: SO_2 satellite data (Monthly)



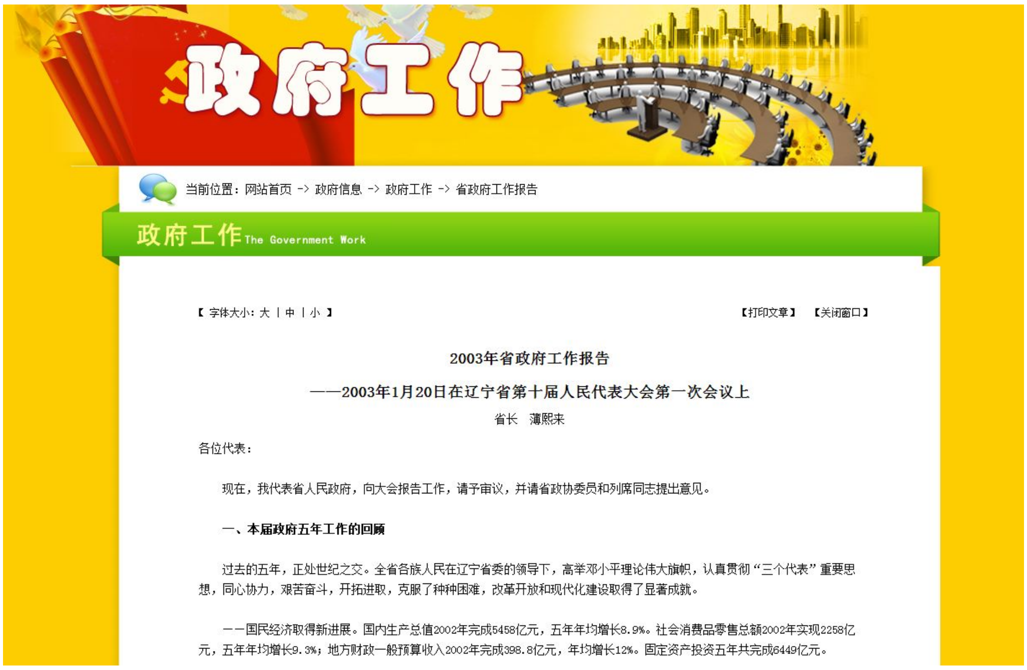
Notes: The solid line plots the point estimate for monthly coefficient estimates of the interaction coefficients $\sum_{t=1}^{T} \beta_{1t}$ in Equation (2) for the NASA SO_2 satellite data. The dashed lines show the 95% confidence bands, based on heteroskedasticity-robust standard errors clustered at the province-level. The horizontal grey lines plot the average of the point estimates of the interaction coefficient in the pre-period (2005), the period without monitoring (2006-2007) and the period with monitoring (2008-2010). The excluded time period $t = 1$ is January 2005. The vertical line at 2006 marks the start of the policy and the vertical line at 2008 marks the start of SO_2 monitoring.

Figure 6: Sample of prefecture-level reduction targets


Prefecture-level targets (in %)
Larger than 20
(10, 20]
(5, 10]
(0, 5]
0
Not in sample
Note: Prefecture-level targets do not exist for provinces filled in gray.

Notes: The graph shows the sample of prefecture-level SO_2 reduction targets used to estimate heterogeneous treatment effects. Provinces filled in gray do not report prefecture-level targets.

Figure 7: Example of a Government Work Report


政府工作
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政府工作 The Government Work
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【打印文章】
【关闭窗口】

2003年省政府工作报告

——2003年1月20日在辽宁省第十届人民代表大会第一次会议上

省长　薄熙来

各位代表：

现在，我代表省人民政府，向大会报告工作，请予审议，并请省政协委员和列席同志提出意见。

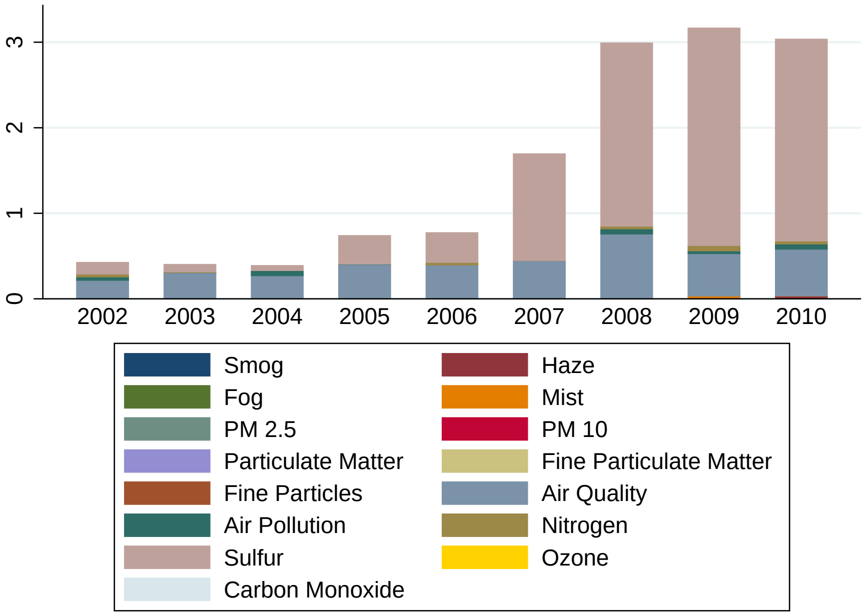
一、本届政府五年工作的回顾

过去的五年，正处世纪之交。全省各族人民在辽宁省委的领导下，高举邓小平理论伟大旗帜，认真贯彻“三个代表”重要思想，同心协力，艰苦奋斗，开拓进取，克服了种种困难，改革开放和现代化建设取得了显著成就。

——国民经济取得新进展。国内生产总值2002年完成5458亿元，五年年均增长8.9%。社会消费品零售总额2002年实现2258亿元，五年年均增长9.3%；地方财政一般预算收入2002年完成398.8亿元，年均增长12%。固定资产投资五年共完成6449亿元。

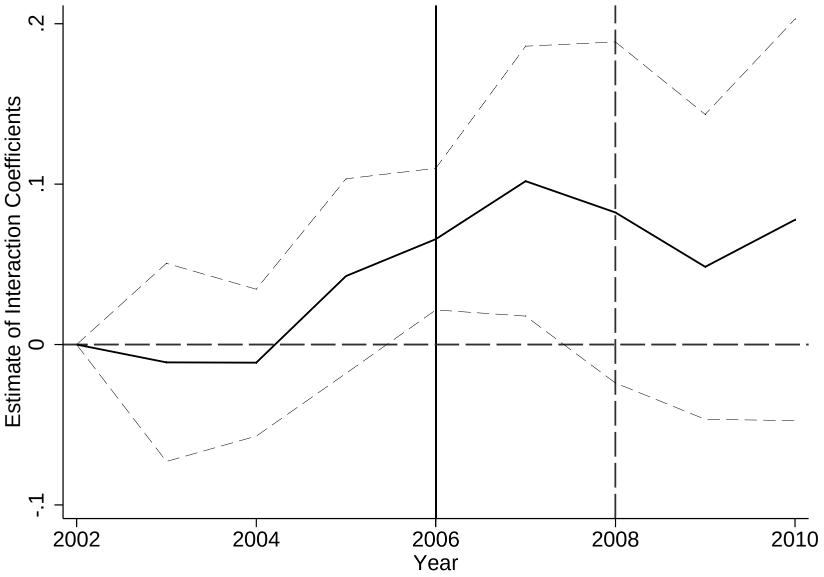
Notes: The graph shows the beginning of the government work report for Liaoning province in 2003. It was delivered by then-governor Bo Xilai.

Figure 8: POLITICAL ATTENTION TO AIR POLLUTION OVER TIME



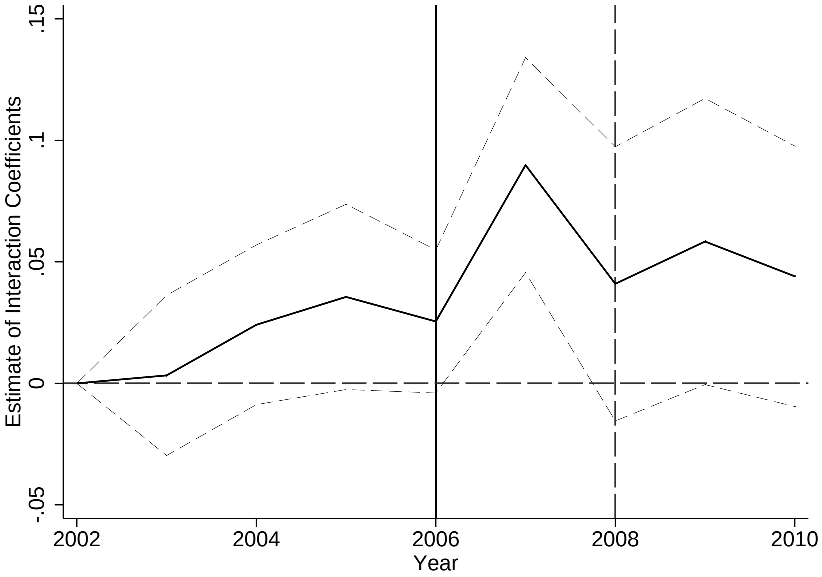
Notes: The graph shows the mean count of keywords related to air pollution for all provincial government work reports in a given year from 2002 to 2010.

Figure 9: DYNAMIC TREATMENT EFFECTS: RHETORICAL COMPLIANCE



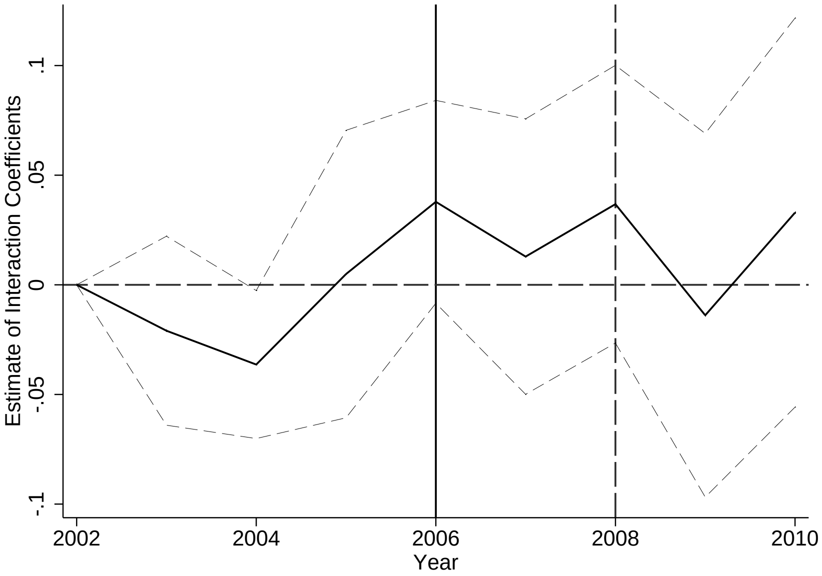
Notes: The solid line plots the point estimate for yearly coefficient estimates of the interaction coefficients $\sum_{t=1}^{T} \beta_{1t}$ in Equation (2) for the number of keywords related to air pollution in a province-year government work report. The dashed lines show the 95% confidence bands, based on heteroskedasticity-robust standard errors clustered at the province-level. The excluded time period $t = 1$ is the year 2002. The vertical line at 2006 marks the start of the policy and the vertical line at 2008 marks the start of SO_2 monitoring.

Figure 10: DYNAMIC TREATMENT EFFECTS: RHETORICAL COMPLIANCE (PRECEDING PERIOD)



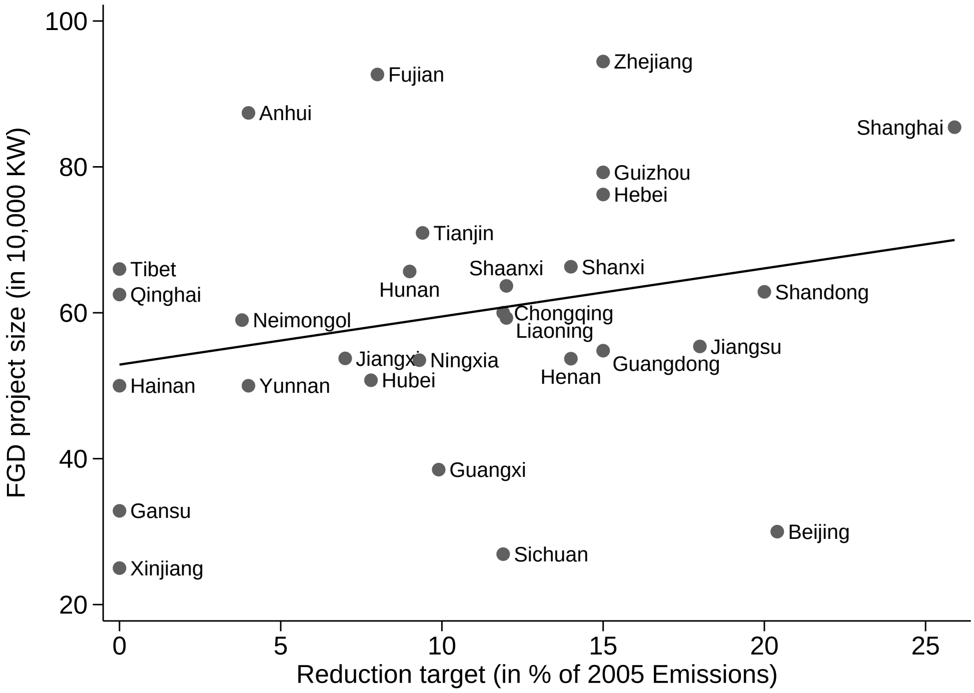
Notes: The solid line plots the point estimate for yearly coefficient estimates of the interaction coefficients $\sum_{t=1}^{T} \beta_{1t}$ in Equation (2) for the number of keywords related to air pollution in a province-year government work report *for work done in period preceding the report.* The dashed lines show the 95% confidence bands, based on heteroskedasticity-robust standard errors clustered at the province-level. The excluded time period $t = 1$ is the year 2002. The vertical line at 2006 marks the start of the policy and the vertical line at 2008 marks the start of SO_2 monitoring.

Figure 11: Dynamic treatment effects: rhetorical compliance (subsequent period)



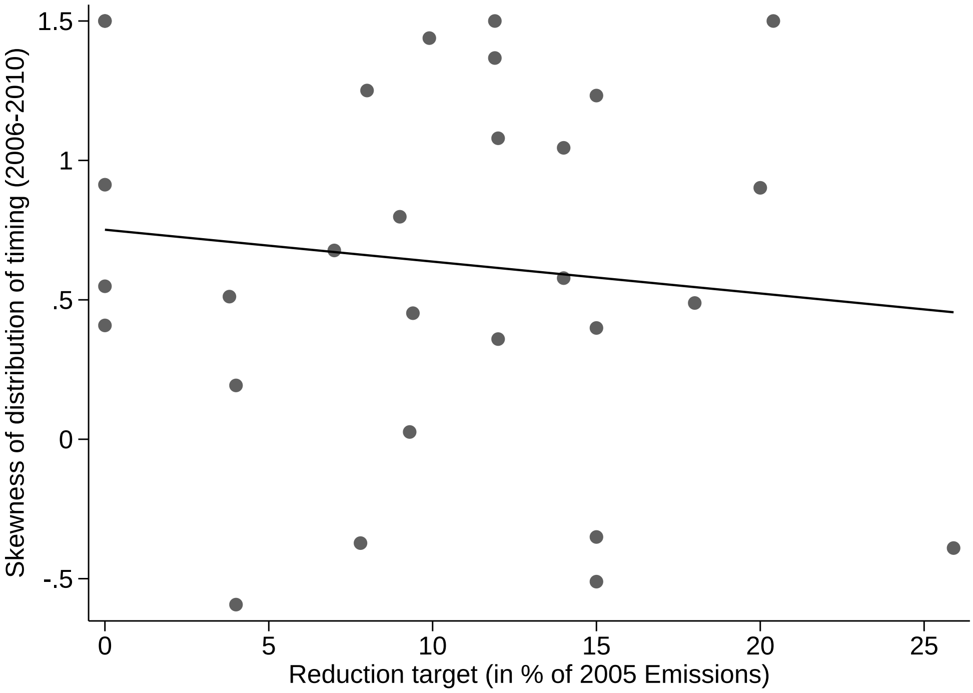
Notes: The solid line plots the point estimate for yearly coefficient estimates of the interaction coefficients $\sum_{t=1}^{T} \beta_{1t}$ in Equation (2) for the number of keywords related to air pollution in a province-year government work report *for work announced for the period following the report.* The dashed lines show the 95% confidence bands, based on heteroskedasticity-robust standard errors clustered at the province-level. The excluded time period $t = 1$ is the year 2002. The vertical line at 2006 marks the start of the policy and the vertical line at 2008 marks the start of SO_2 monitoring.

Figure 12: Real compliance: Installation of desulfurization devices



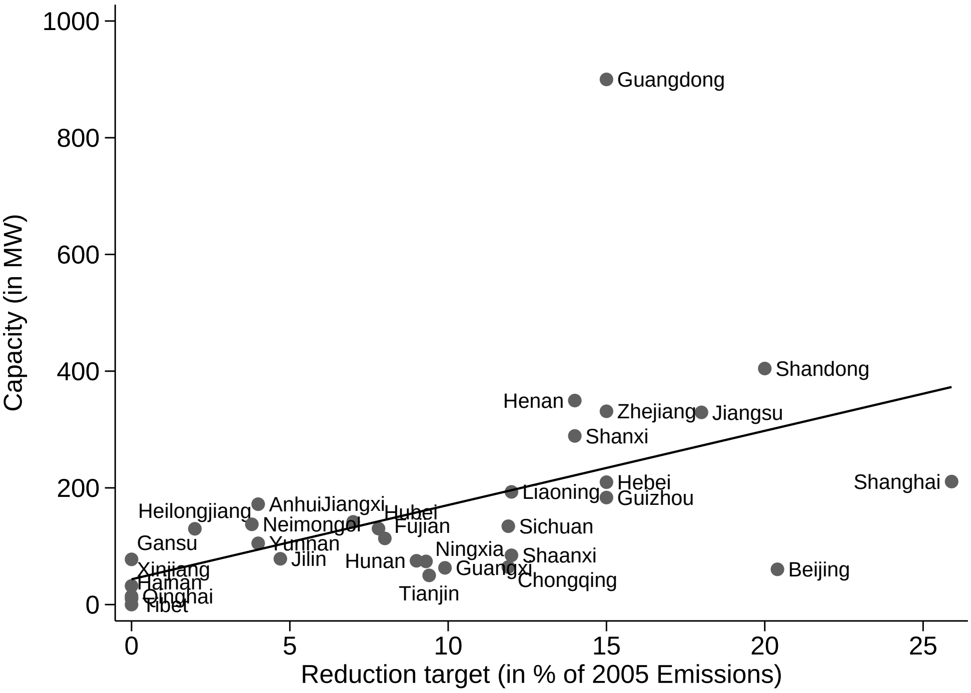
Notes: This graph plots the relationship between the SO_2 reduction target and the planned installation of desulfurization devices at the province level. The solid line fits a linear regression with slope parameter b=0.66 and p=022 computed from standard errors clustered at the province level.

Figure 13: Real compliance: Installation of desulfurization devices



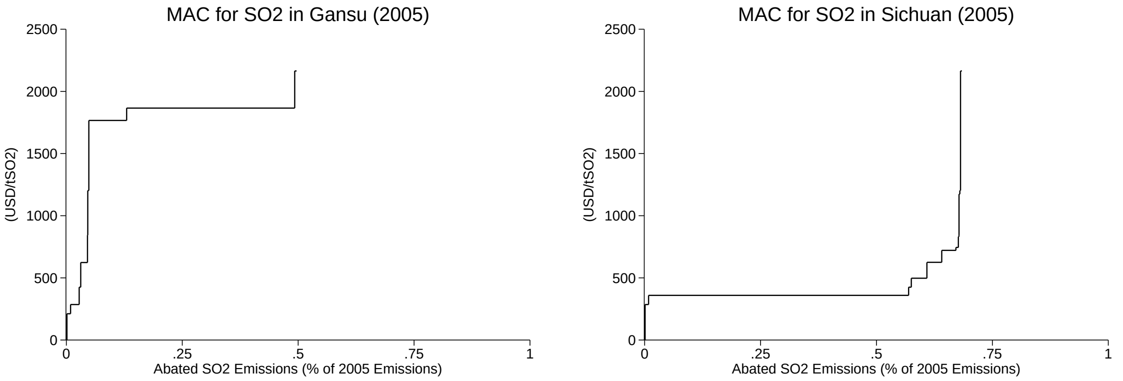
Notes: This graph tests whether provinces with a higher reduction target installed the planned desulfurization devices earlier. The vertical axis shows the skewness for each province of the 5 yearly observations from 2006-2010, where the weight is the capacity (in 10,000 KW) of planned desulfurization devices in each year. The solid line fits a linear regression with slope parameter b=-0.01 and p=0.56 computed from standard errors clustered at the province level.

Figure 14: Real compliance: Shutdown of small thermal units



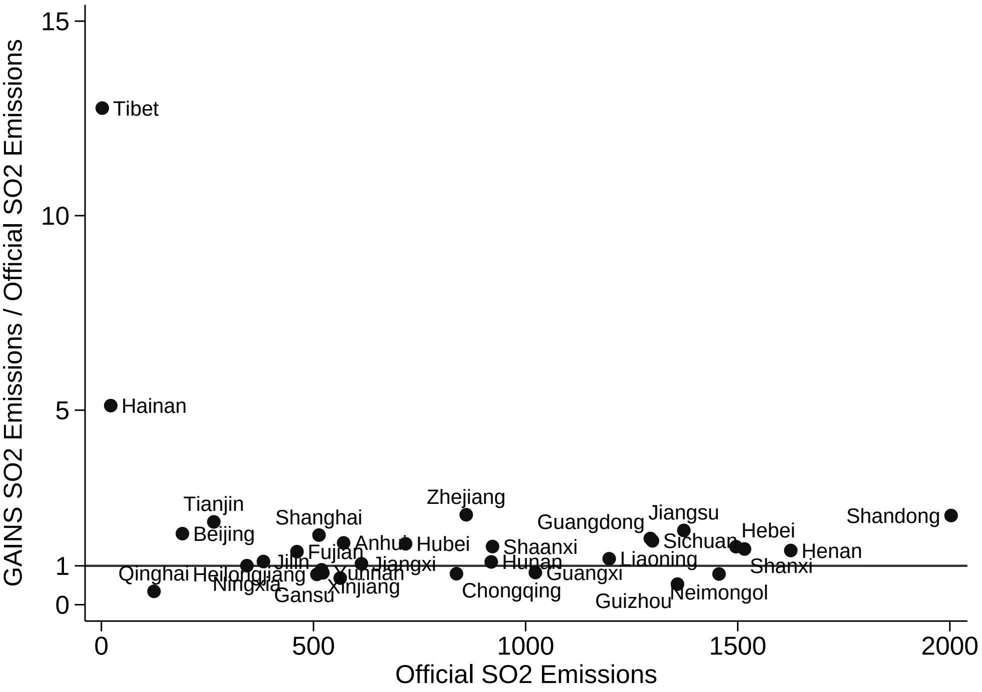
Notes: This graph plots the relationship between the SO_2 reduction target and the decommissioning of small thermal units at the province level. The solid line fits a linear regression with slope parameter b=12.72*** and p=0.004 computed from standard errors clustered at the province level.

Figure 15: Marginal abatement cost curve examples



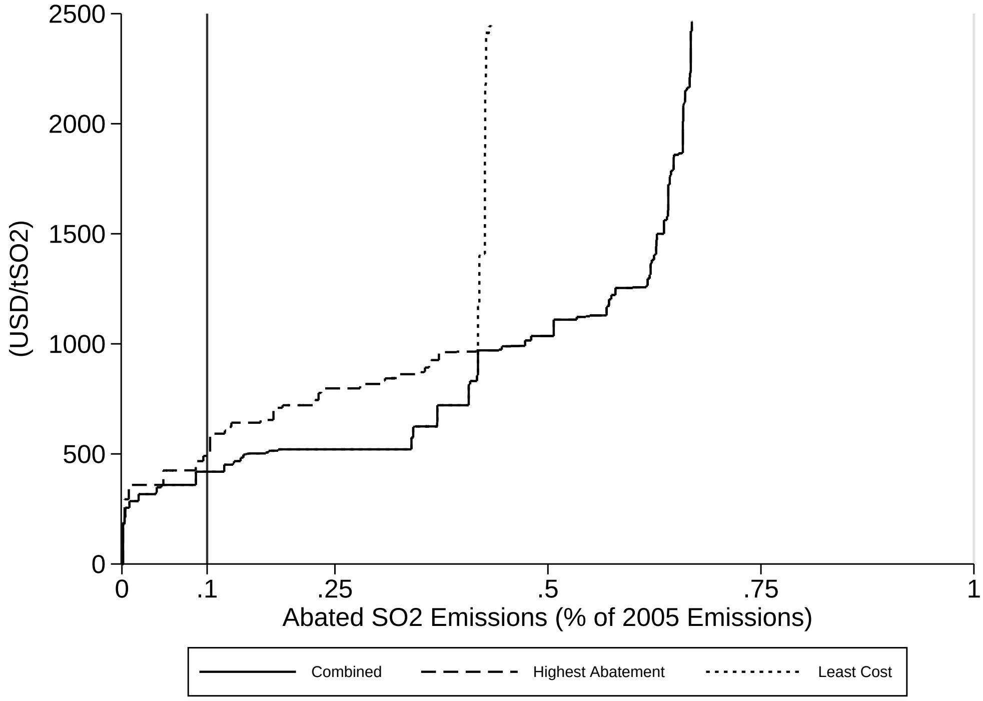
Notes: This graph shows the marginal SO_2 abatement cost curves for Gansu and Sichuan in 2005. The horizontal axis lists the abatement intensity relative to the 2005 SO_2 emissions level.

Figure 16: Consistency of SO_2 marginal abatement cost data and official data



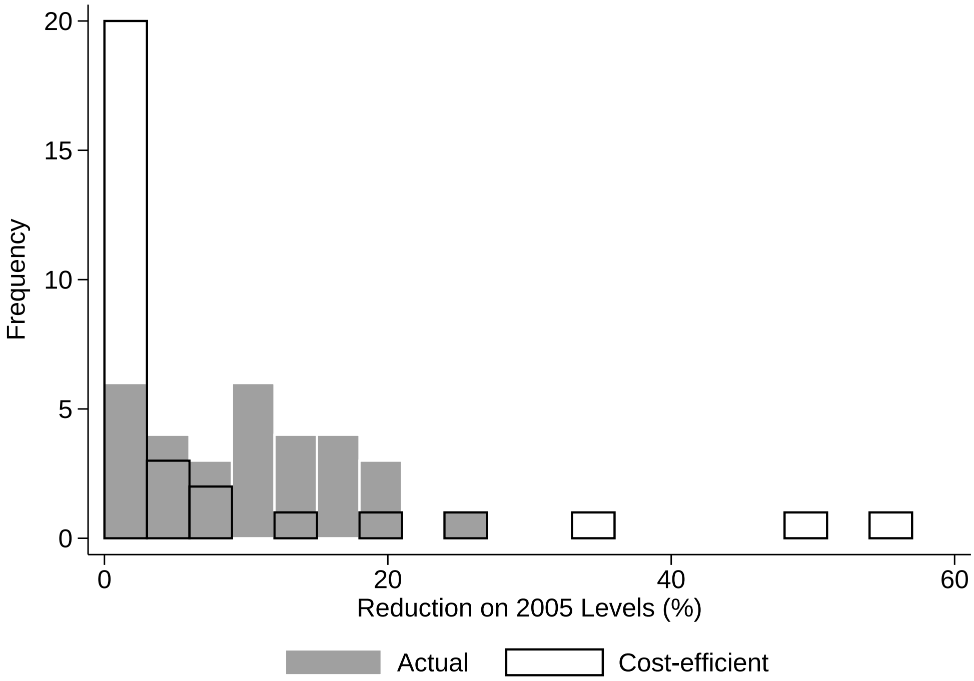
Notes: This graph shows the ratio of the SO_2 emissions data underlying the construction of the marginal abatement cost curve (from IIASA's GAINS model) and the official SO_2 emissions data from the Ministry of Environmental Protection for the year 2005 on the vertical axis. The datapoints are ordered according to the official SO_2 emissions level on the horizontal axis. The raw correlation between both data sources is 85.9%.

Figure 17: SO_2 MARGINAL ABATEMENT COST CURVE FOR CHINA



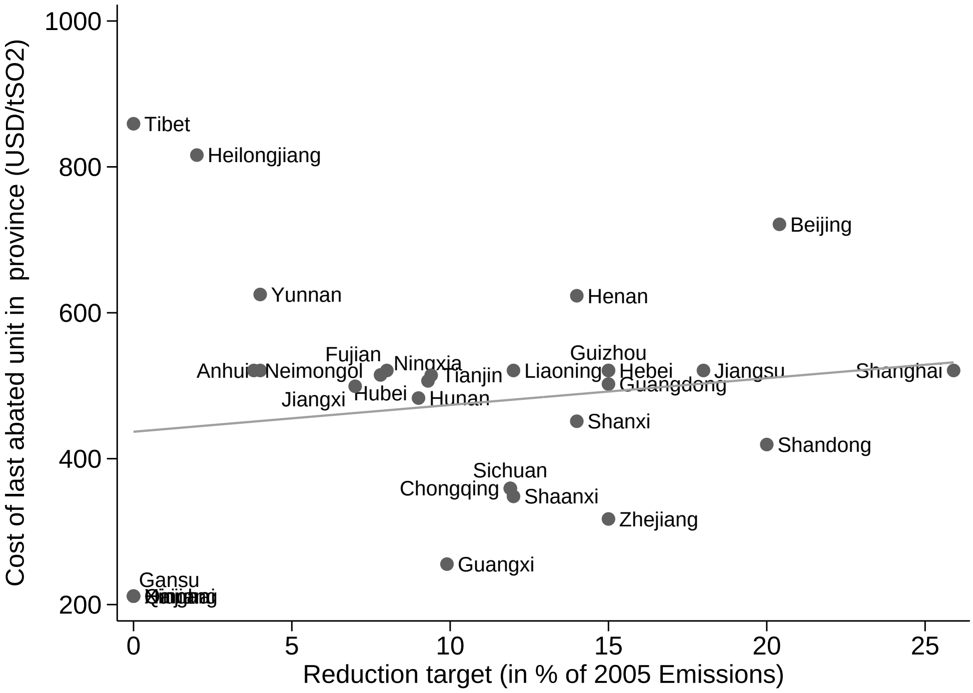
Notes: This graph shows the marginal SO_2 abatement cost curve for China in 2005. The horizontal axis plots the abatement intensity relative to the 2005 SO_2 emissions level. The vertical line at an abatement level of 10% illustrates the 10% national SO_2 emissions control target for China as a whole. Its intersection with the marginal abatement cost curves shows that the counterfactual marginal abatement cost for this abatement level is \$419/tSO_2.

Figure 18: THE COST-EFFICIENT ALLOCATION OF SO_2 REDUCTION TARGETS



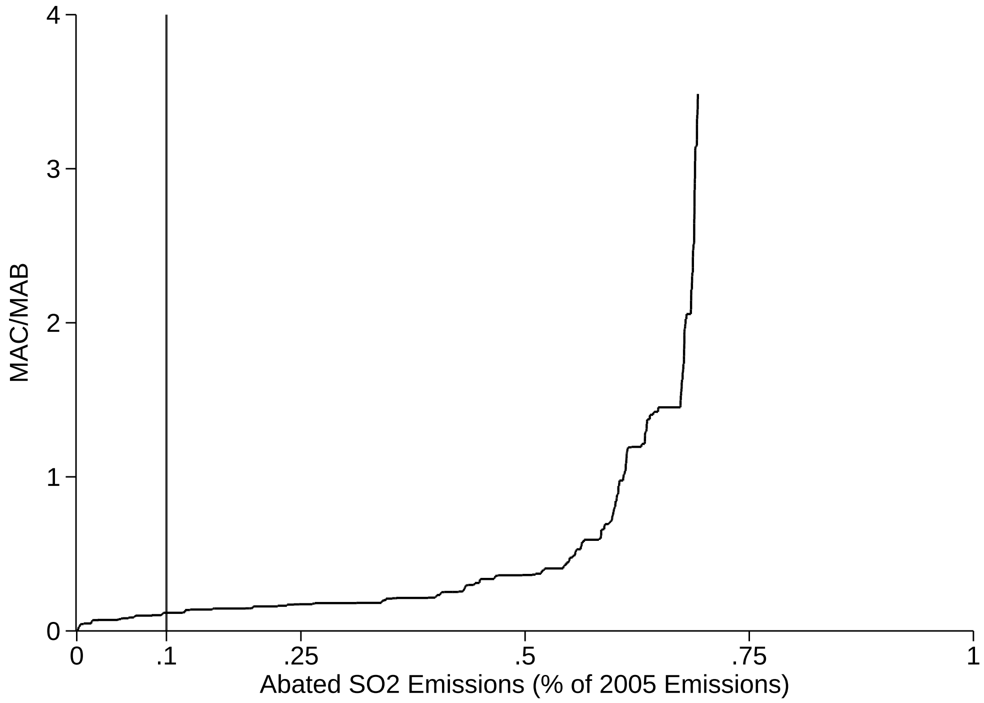
Notes: This graph shows the counterfactual market-based allocation of SO_2 reduction targets under the 10% SO_2 total control target of the 11th Five-Year Plan (2006-2010), shown in white boxes. These targets are based on equating MAC across provinces. The three provinces with the highest targets under the counterfactual market-based allocation are Sichuan, Shandong and Zhejiang. Solid grey boxes show the actual command-and-control allocation of reduction targets in comparison.

Figure 19: RELATION BETWEEN MAC AND SO_2 REDUCTION TARGETS



Notes: This graph shows the lack of correlation between a province's command-and-control SO_2 reduction target in the 11th Five-Year Plan (2006-2010) and its marginal abatement cost at the level of the target. The solid line fits a linear regression with slope parameter b=2.96 and p=0.54 computed from standard errors clustered at the province level.

Figure 20: Marginal welfare impact and SO_2 reduction targets



Notes: This graph shows the ratio of marginal abatement cost to marginal abatement benefits for SO_2 for China in 2005. The horizontal axis plots the abatement intensity relative to the 2005 SO_2 emissions level. The horizontal, longdashed line at 1 marks the welfare-optimal level of SO_2 abatement (40.3%). The vertical, shortdashed line at 0.1 marks the ratio of marginal abatement cost to marginal abatement benefit for the 10% SO_2 reduction target (0.07). Prohibitive cost ranges beyond a MAC/MAB ratio of 3.5 not shown.

Tables

Table 1: Summary statistics for main variables

	Mean	Std. Dev.	Min.	Max.	Time Period
SO2 Emissions (kt)	739	471	1	2003	2002-2010
SO2 Satellite (DU)	0.37	0.39	-0.02	1.93	2005-2010
Selected SO2 Sat. (DU)	0.72	0.53	-0.03	2.57	2005-2010
SO2 Reduction Target (% on 2005 Baseline)	9.65	6.71	0	25.9	-

Note: Satellite data is measured in Dobson Units (DU). Selected SO_2 Sat. is the sample of polluted cities. Satellite SO_2 measurements below 0.2 Dobson Units are generally considered as clean air and negative values are likely noise from measurement error. Replacing negative values as either 0s or missing does not change the subsequent results.

Table 2: THE EFFECT OF THE POLICY FOR THE WHOLE PERIOD (2006-2010)

	SO2 Emissions (Kt)	Satellite SO2 (Dobson Units)	Selected Sat. SO2 (Dobson Units)
Reductiontarget	-6.30***	-0.0057	-0.0115**
× D(Post)	(2.22)	(0.0040)	(0.0048)
	[0.00]	[0.24]	[0.05]
Reductiontarget	0.36	0.0214***	0.0251***
	(1.23)	(0.0034)	(0.0040)
	[0.81]	[0.00]	[0.00]
Year FE	✓	✓	✓
Province FE	✓	✓	✓
Effect size (% of mean/σ)	-5.8%	-10.5%	-10.9%
Observations	279	186	186
Provinces	31	31	31
R^2	0.98	0.94	0.91

Note: Heteroskedasticity-robust standard errors clustered at the province level are shown in parentheses. Wild bootstrap p-values from 1000 repetitions clustered at the province level are shown in square brackets. The effect size gives the estimated coefficient of the interaction term β_1 in Equation (1) as percentage of the mean of the dependent variable for a one standard deviation(σ)-increase in the SO_2 reduction target. $***p < 0.01$, $**p < 0.05$, $*p < 0.1$.

Table 3: THE EFFECT OF THE POLICY FOR EACH YEAR OF THE 11TH FIVE-YEAR PLAN (2006-2010)

	SO2 Emissions (Kt)	Satellite SO2 (Dobson Units)	Selected Sat. SO2 (Dobson Units)
2002× Reductiontarget	Excluded	-	-
2003× Reductiontarget	-0.32 (3.93) [0.93]	-	-
2004× Reductiontarget	0.30 (3.64) [0.93]	-	-
2005× Reductiontarget	2.17 (4.04) [0.66]	Excluded	Excluded
2006× Reductiontarget	0.94 (4.08) [0.86]	-0.00 (0.00) [0.93]	0.00 (0.01) [0.94]
2007× Reductiontarget	-2.27 (3.70) [0.62]	0.01 (0.00) [0.21]	0.01 (0.01) [0.29]
2008× Reductiontarget	-6.40 (3.69) [0.14]	-0.01 (0.00) [0.11]	-0.01*** (0.01) [0.00]
2009× Reductiontarget	-9.67** (3.79) [0.02]	-0.01** (0.00) [0.02]	-0.02** (0.00) [0.01]
2010× Reductiontarget	-11.41*** (3.89) [0.00]	-0.02*** (0.00) [0.00]	-0.03*** (0.00) [0.00]
Year FE	✓	✓	✓
Province FE	✓	✓	✓
Mean dep. var.	739	0.37	0.72
Observations	279	186	186
Provinces	31	31	31
R^2	0.98	0.96	0.93

Note: Heteroskedasticity-robust standard errors clustered at the province level are shown in parentheses. Wild bootstrap p-values from 1000 repetitions clustered at the province level are shown in square brackets. The yearly interaction coefficients are estimates for $\sum_{t=1}^{T} \beta_{1t}$ in Equation (2), while 'Excluded' is the omitted time period. Note that the SO_2 reduction started in 2006 while government monitoring of SO_2 pollution became effective in 2008. $***p < 0.01$, $**p < 0.05$, $*p < 0.1$.

Table 4: HETEROGENEOUS TREATMENT EFFECTS DEPENDING ON INITIAL POLLUTION LEVELS

	SO2 Satellite Data			
	Quartile 1	Quartile 2	Quartile 3	Quartile 4
Reductiontarget × D(Post)	0.0004 (0.0028) [0.93]	-0.0032 (0.0030) [0.41]	-0.0082 (0.0055) [0.26]	-0.0119* (0.0053) [0.07]
Reductiontarget	0.0311*** (0.0023) [0.00]	0.0248*** (0.0025) [0.00]	0.0224*** (0.0046) [0.00]	0.0210*** (0.0044) [0.00]
Year-Month FE	✓	✓	✓	✓
Province FE	✓	✓	✓	✓
Effect size (% of mean/σ)	1.5%	-5.8%	-9.9%	-9.4%
Observations	47,376	47,592	47,016	48,096
Provinces	31	31	31	31
R^2	0.59	0.66	0.66	0.67

Note: The table reports estimates for Equation (1) at the county-yearmonth level for different subsamples. Quartile marks the quartile of initial pollution based on its 2005 SO_2 pollution, calculated from SO_2 satellite data, relative to the mean SO_2 pollution within the same province. Heteroskedasticity-robust standard errors clustered at the province level are shown in parentheses. Wild bootstrap p-values from 1000 repetitions clustered at the province level are shown in square brackets. $***p < 0.01$, $**p < 0.05$, $*p < 0.1$.

Table 5: THE EFFECT OF ENFORCEMENT

	SO2 Satellite Data			
	Enforcement officials density			
	Quartile 1	Quartile 2	Quartile 3	Quartile 4
Reductiontarget	0.1855	0.1153	0.1068	1.2713
× D(Post1)	(0.1367)	(0.2392)	(0.1640)	(0.6337)
	[0.20]	[0.66]	[0.58]	[0.15]
Reductiontarget	0.0429	-0.3351	-0.4061***	1.0497*
× D(Post2)	(0.1405)	(0.2232)	(0.1408)	(0.4632)
	[0.68]	[0.14]	[0.006]	[0.09]
Year FE	✓	✓	✓	✓
Prefecture FE	✓	✓	✓	✓
Effect size (% of mean/σ)	0.5%	-6.4%	-8.4%	7.6%
Observations	2,016	2,088	2,448	2,304
Prefectures	28	29	34	32
R^2	0.80	0.73	0.57	0.58

Note: The table shows the results from estimating equation 3 at the prefecture level. Quartile marks the quartile of the number of enforcement officials per area at the end of the 11th Five-Year Plan. Heteroskedasticity-robust standard errors clustered at the prefecture level are shown in parentheses. Wild bootstrap p-values from 1000 repetitions clustered at the prefecture level are shown in square brackets. Effect size expresses the point estimate for the period in which there was enforcement (Reductiontarget× D(Post2)) as per cent change in pollution per standard deviation increase in reduction target stringency relative to each subsample's 2005 mean of SO2 pollution. $***p < 0.01$, $**p < 0.05$, $*p < 0.1$.

Table 6: Reactions by the regulated agents in response to the targets

	Political attention to air pollution			Placebo outcomes	
	All statements	Past period	Future period	'Forest'	'Medical care'
Reductiontarget × D(Post)	0.07**	0.03**	0.04**	-0.12	0.02
	(0.03)	(0.01)	(0.02)	(0.12)	(0.09)
	[0.02]	[0.02]	[0.03]	[0.36]	[0.73]
Reductiontarget	-0.01	-0.00	-0.00	-0.07	0.34***
	(0.02)	(0.01)	(0.01)	(0.07)	(0.05)
	[0.75]	[0.70]	[0.69]	[0.34]	[0.00]
Year FE	✓	✓	✓	✓	✓
Province FE	✓	✓	✓	✓	✓
Effect size (% of mean/σ)	30.9%	29.6%	31.5%	-7.2%	1.2%
Observations	274	273	273	274	274
Provinces	31	31	31	31	31
R^2	0.66	0.64	0.54	0.72	0.58

Note: Heteroskedasticity-robust standard errors clustered at the province level are shown in parentheses. Wild bootstrap p-values from 1000 repetitions clustered at the province level are shown in square brackets. The effect size gives the estimated coefficient of the interaction term β_1 in Equation (1) as percentage of the mean of the dependent variable for a one standard deviation(σ)-increase in the SO_2 reduction target. $***p < 0.01$, $**p < 0.05$, $*p < 0.1$.

Table 7: Actual and counterfactual SO_2 target allocations

	SO2 reduction target under different allocations (in % of 2005 emissions)		Difference between target allocations (in percentage points)
	Market-based	Actual	Actual - Market-based
Anhui	1.5	4	2.5
Beijing	7.3	20.4	13.1
Chongqing	50.5	11.9	-38.6
Fujian	0.7	8	7.3
Gansu	2.5	0	-2.5
Guangdong	0.7	15	14.3
Guangxi	20	9.9	-10.1
Guizhou	5.8	15	9.2
Hainan	0	0	0
Hebei	1.7	15	13.3
Heilongjiang	1.7	2	0.3
Henan	0.6	14	13.4
Hubei	2.5	7.8	5.3
Hunan	1	9	8
Jiangsu	0.9	18	17.1
Jiangxi	1.6	7	5.4
Jilin	1.6	4.7	3.1
Liaoning	4.2	12	7.8
Neimongol	1.1	3.8	2.7
Ningxia	0.1	9.3	9.2
Qinghai	3.5	0	-3.5
Shaanxi	13.9	12	-1.9
Shandong	25.5	20	-5.5
Shanghai	6.2	25.9	19.7
Shanxi	0.6	14	13.4
Sichuan	56.2	11.9	-44.3
Tianjin	2.2	9.4	7.2
Tibet	0	0	0
Xinjiang	1.6	0	-1.6
Yunnan	1.3	4	2.7
Zhejiang	35.4	15	-20.4

Note: This table shows the SO_2 emissions reduction targets under each policy regime. 'Market-based' are the counterfactual targets for achieving the counterfactual market-based allocation given the national 10% SO_2 reduction target, 'Optimal' are the counterfactual targets for achieving the welfare-optimizing allocation given the national 10% SO_2 reduction target and 'Actual' are the actual command-and-control provincial reduction targets used in the 11th Five-Year Plan (2006-2010).

Table 8: Efficiency gains from trade

Allocation	Efficiency measure Average abatement cost (in \$/tSO_2)	Marginal abatement cost (in \$/tSO_2)	Marginal welfare impact (MAC/MAB)
Command-and-control	436.78	816.2	2.2
Cost-efficient	323.45	419.4	1.2

Note: The average abatement cost measure reports the total cost divided by the total number of abated units of SO_2 for the actual command-and-control allocation from the 11th Five-Year Plan (2006-2010) and the counterfactual market-based allocation reported in Table 7. The marginal efficiency measures report the highest cost of all last abated units across provinces for either allocation. Estimates for the cost of the actual allocation exclude outliers. The welfare impact at the margin is the ratio between marginal abatement cost and marginal abatement benefits.

Appendix

A.1 Further robustness checks for identification

This section further substantiates my identification strategy by showing that neither the cost nor the benefit of reducing air pollution nor the Great Recession correlates with the SO_2 reduction targets. Firstly, I show that the neither the cost nor the welfare impact at the margin correlates with the SO_2 reduction targets, using the following empirical specification:

$$\begin{aligned} y_{pt} = \beta_0 + \beta_1 Reductiontarget_p \times D(Post)_t + \beta_2 X_p \times D(Post)_t \\ + \beta_3 Reductiontarget_p + \beta_4 X_p + \sum_{t=1}^{T} \beta_{5t}\gamma_t + \alpha_p + u_{pt} \end{aligned} \tag{4}$$

where X_p is either a province-level measure of (i) the marginal abatement cost or (ii) the ratio of marginal abatement benefits to marginal abatement cost. Specific details for the construction of those measures are provided in Section 6. In a nutshell, my approach is this: I compute detailed marginal abatement cost curves for SO_2 for each province in China, based on a reliable set of micro data on the cost and abatement potential of fine-grained polluting activities. The marginal benefits from reducing air pollution are based on a back-of-the-envelope calculation that follows Oliva (2015) and evaluates health improvements based on the value of a statistical life.

Table A.1 shows that the estimates for β_2 are 0 and that the estimates for β_1 are nearly identical to those in Table 2.

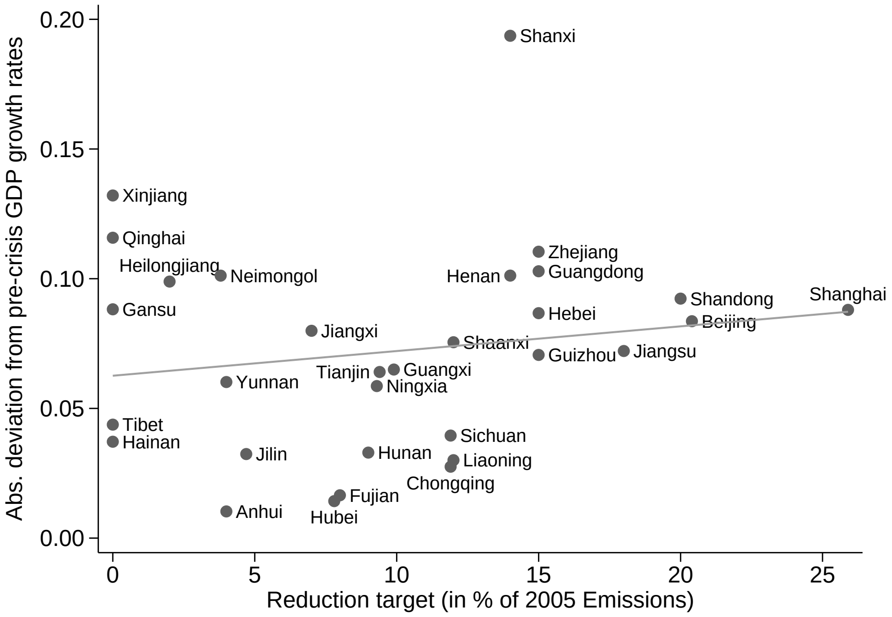
Secondly, I find that there is no relationship between the economic downturn in the Great Recession and the stringency of a province's SO_2 reduction targets. If this were the case, my results could be confounded because a slowdown in economic activity could go hand in hand with a reduction in SO_2 pollution. It is important to note that even though China experienced a slowdown in growth in 2009, the slowdown was comparatively mild. Even in 2009, there are only 3 provinces with a growth rate below 5%, and the growth rate for those provinces is still positive. I compute the magnitude of the downturn as the deviation in the average of the growth rates for 2002-2007 for each province. I find that there is no relationship between the magnitude of the recession and the reduction targets in a province. This is because different provinces with similar reduction targets experienced rather different deviations from their long term growth rates in 2009, and overall there is no statistically significant correlation between SO_2 reduction targets and the downturn. As shown in Figure A.1, a linear regression with standard errors clustered at the province level finds a best fit with a p-value of 0.31. The Great Recession can therefore not explain the decrease in SO_2 pollution from 2008 onwards.

Table A.1: Controlling for marginal abatement cost and marginal welfare impact

	SO2 Emissions (Kt)		SO2 Satellite (Dobson Units)		Sel. Satellite SO2 (Dobson Units)	
Reductiontarget	-6.26***	-6.15***	-0.0057	-0.0058	-0.0116**	-0.0117*
× D(Post)	(2.23)	(2.22)	(0.0040)	(0.0041)	(0.0048)	(0.0048)
	[0.01]	[0.00]	[0.20]	[0.27]	[0.05]	[0.05]
Reductiontarget	0.33	1.33	0.0214***	0.0364***	0.0252***	0.0461***
	(1.24)	(1.23)	(0.0034)	(0.0034)	(0.0040)	(0.0040)
	[0.80]	[0.28]	[0.00]	[0.00]	[0.00]	[0.00]
MAC	0.17		-0.0000		-0.0000	
× D(Post)	(0.026)		(0.0000)		(0.0000)	
	[0.45]		[0.87]		[0.20]	
MAC	-0.12***		-0.0003***		-0.0003***	
	(0.014)		(0.0000)		(0.000)	
	[0.00]		[0.00]		[0.00]	
MAC/MAB		-0.59		0.0001		0.0009
× D(Post)		(0.76)		(0.0013)		(0.0011)
		[0.43]		[0.90]		[0.34]
MAC/MAB		0.71*		0.0053***		0.0068***
		(0.42)		(0.0010)		(0.0009)
		[0.09]		[0.00]		[0.00]
Year FE	✓	✓	✓	✓	✓	✓
Province FE	✓	✓	✓	✓	✓	✓
Observations	279	279	186	186	186	186
Provinces	31	31	31	31	31	31
R^2	0.98	0.98	0.94	0.94	0.91	0.91

Note: Heteroskedasticity-robust standard errors clustered at the province level are shown in parentheses. Wild bootstrap p-values from 1000 repetitions clustered at the province level are shown in square brackets. The table reports the results from estimating Equation (4). MAC refers to the marginal abatement cost given the actual command-and-control SO_2 reduction target and MAC/MAB is the ratio of the marginal abatement benefits to the marginal abatement cost. $***p < 0.01$, $**p < 0.05$, $*p < 0.1$.

Figure A.1: The Great Recession and SO_2 reduction targets



Notes: This graph plots the SO_2 reduction targets on the horizontal axis against the absolute deviation from the pre-crisis (2002-2007) GDP growth rate for each province in China in 2009, the year China was struck by the Great Recession. The solid line fits a linear regression with slope parameter b=0.001 and p=0.305 computed from standard errors clustered at the province level.

A.2 Construction of optimized marginal abatement cost curves

In principle, construction of the full MAC curve for a given province requires an optimization that trades off the unitcost and the abatement potential of different abatement technologies to reach a given abatement level $\bar{x}$. Figure A.2 illustrates this point: for most of the lower abatement levels, up to ca. 40%, the *least cost* MAC would be picked as the optimal MAC (black line). At one point, however, the *least cost* crosses the *highest abatement* curves (dashed line), offering the chance for cheaper abatement by switching to the *highest abatement* cost curve.

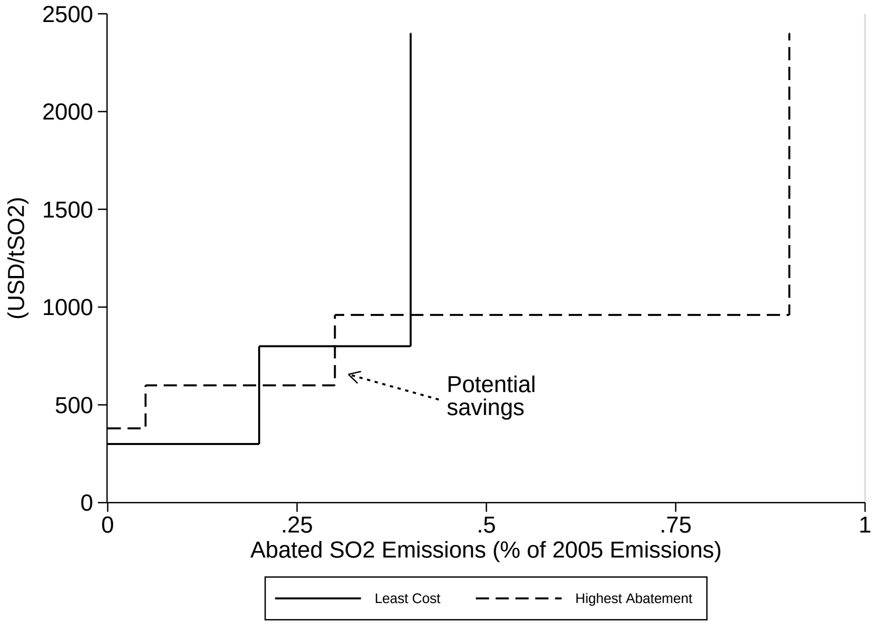
[INSERT FIGURE A.2 ABOUT HERE]

For example, pick $\bar{x}$ to be an abatement level of 25% of the baseline, or 0.25. Here, the last unit of abatement would be cheaper than on the least cost curve. However, to be able to use the highest abatement technology at that point, one would have to forego the use of cheaper abatement technologies from the least curve for earlier units. To calculate the marginal abatement cost for abatement level $\bar{x}$, one would therefore have to compute the total abatement cost for abatement level $\bar{x} - \epsilon$ for both the least cost and the highest abatement MACs plus the cost of the marginal unit along each curve. In other words, the cost for abatement at the margin depends on the history of abatement for units that were abated earlier.

The following algorithm would be required fully calculate the optimized MAC: (i) Compute all possible combinations of abatement technologies for each province, (ii) for each discrete abatement level $\bar{x}$, $\bar{x} \in (0, 100)$, calculate the total cost of abatement along all combinations of abatement technologies, (iii) record the cost at the margin for abatement level $\bar{x}$ by substracting the same cost for abatement level $\bar{x} - \epsilon$. Do this calculation for infinitesimally small $\Delta\bar{x}$.

Computational considerations make these calculations overly costly for my application. More importantly, however, they are not needed: for the relatively low levels of reduction considered in this research, the least cost MAC is nearly always below the highest abatement MAC. In the relevant range, the fully optimized MAC would be nearly identical to the least cost MAC .

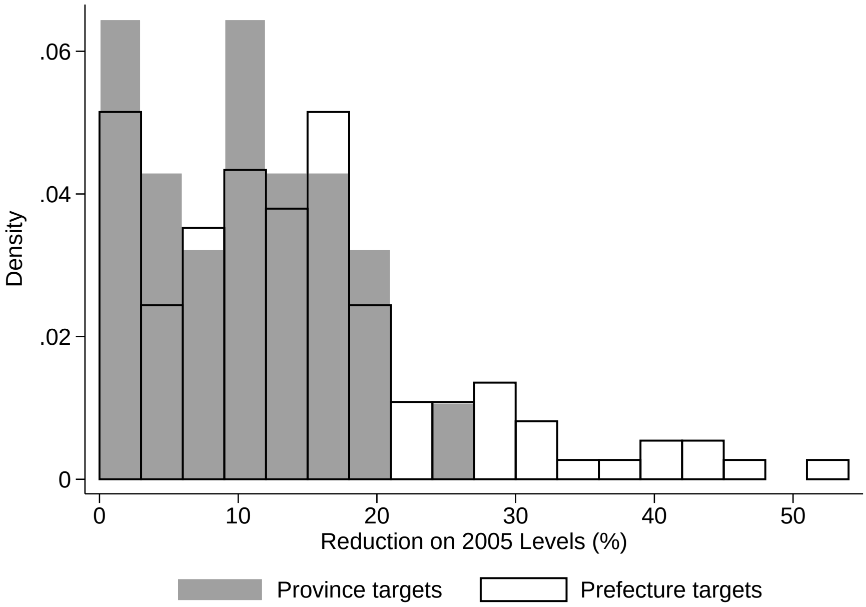
Figure A.2: Example to illustrate MAC curve construction



Notes: This graph is an example for illustrative purposes, based on simulated data. It shows that the *least cost* MAC curve could, in principle, overestimate the cost of abatement for the abatement levels for which the *highest abatement* MAC offers lower cost (area marked as 'Potential savings').

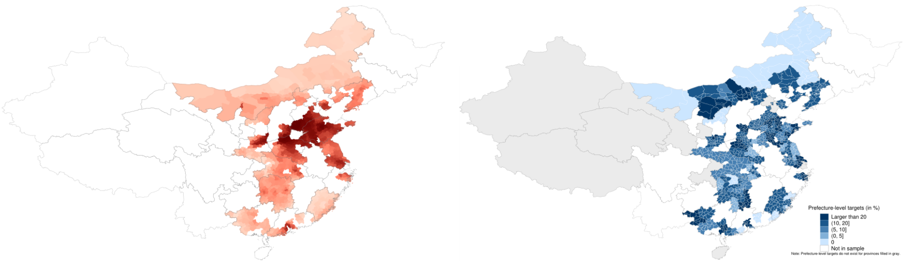
A.3 Additional Figures and Tables

Figure A.3: Representativeness of the prefecture subsample



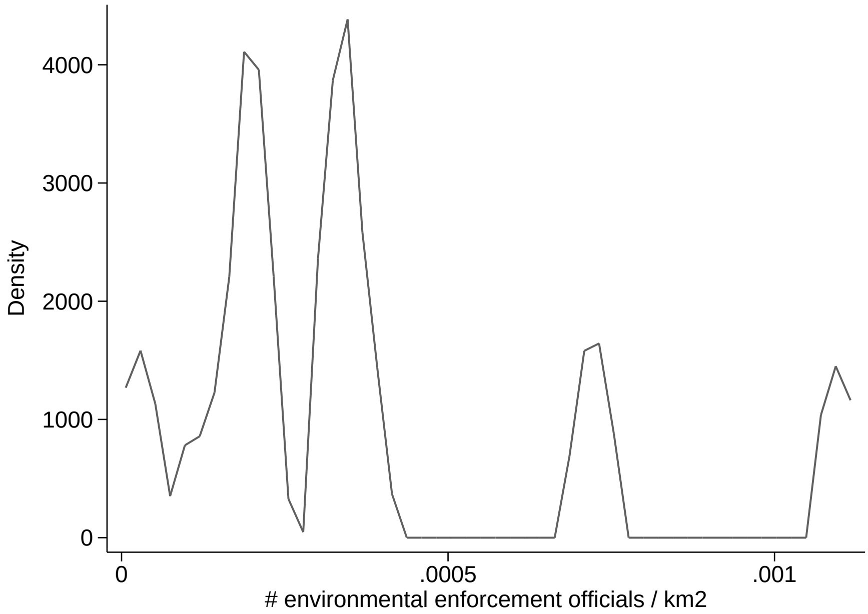
Notes: This graph overlays the SO_2 reduction targets for the provinces and the prefectures in the subsample used to study the effect of enforcement. The province targets have a mean of 9.65 (standard deviation: 6.71) while the prefecture targets have a mean of 14.43 (standard deviation: 10.90).

Figure A.4: SO_2 levels and reduction targets for the prefecture subsample


Prefecture-level targets (in %)
Larger than 20
(10, 20]
(5, 10]
(0, 5]
0
Not in sample
Note: Prefecture-level targets do not exist for provinces filled in gray.

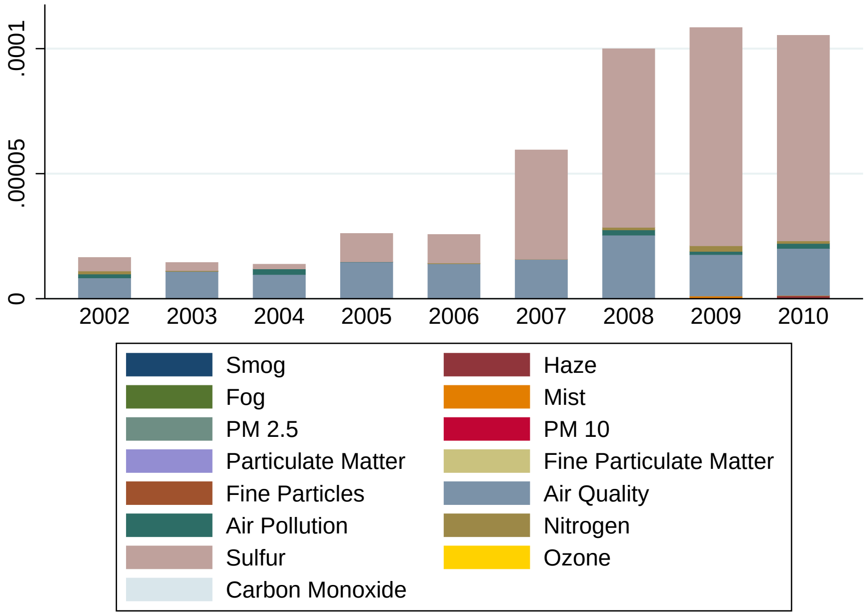
Notes: The left panel shows SO_2 pollution at the beginning of the 11th Five-Year Plan for those prefecture that are in the prefecture subsample. The right panel shows the corresponding prefecture-level SO_2 reduction targets.

Figure A.5: DISTRIBUTION OF ENFORCEMENT OFFICIAL DENSITY



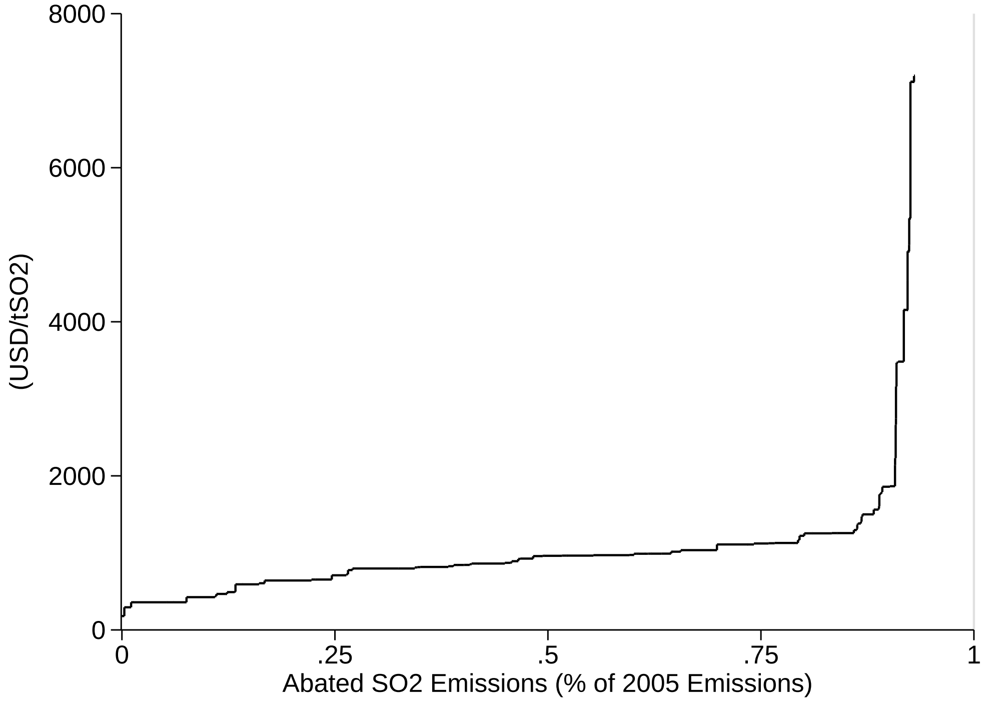
Notes: The figure shows the kernel density measure for the number of environmental enforcement officials per square kilometer for the provinces in my prefecture-level sample (Fujian, Guangdong, Guangxi, Hebei, Henan, Hubei, Hunan, Jiangsu, Liaoning, Neimenggu, Shaanxi, Shandong, Shanxi and Zhejiang). The kernel function is an Epanechnikov kernel with half-width $2.064e-05$.

Figure A.6: Political attention to air pollution over time (normalized by report length)



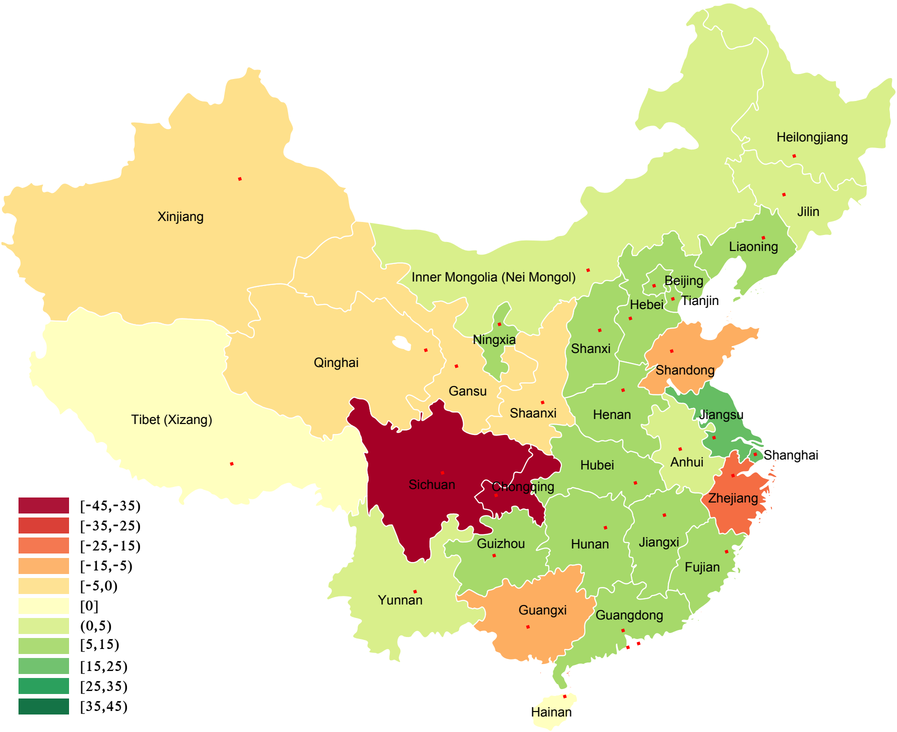
Notes: The graph shows the mean count of keywords related to air pollution for all provincial government work reports in a given year from 2002 to 2010. The count of keywords is normalized by the length of each government work report.

Figure A.7: SO_2 MAC in China's power sector



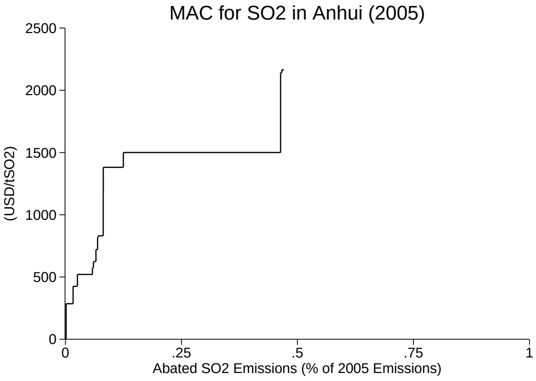
Notes: This graph shows the marginal abatement cost curve for SO_2 abatement in China's power sector in 2005. The curve is constructed by using the abatement options that offer the highest level of abatement.

Figure A.8: Difference between cost-efficient and actual allocation

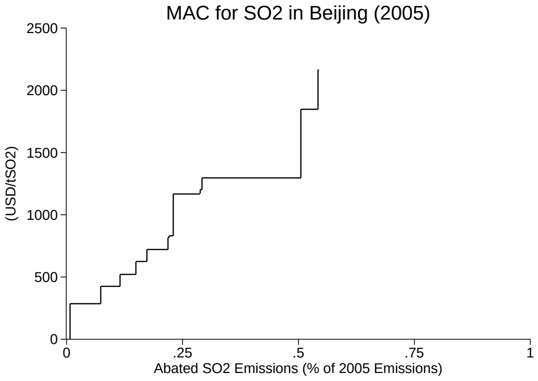

Heilongjiang
Xinjiang
Jilin
Liaoning
Inner Mongolia (Nei Mongol)
Beijing
Hebei
Tianjin
Ningxia
Shanxi
Qinghai
Shandong
Gansu
Tibet (Xizang)
Shaanxi
Henan
Jiangsu
Shanghai
Hubei
Anhui
Sichuan
Chongqing
Zhejiang
Guizhou
Hunan
Jiangxi
Fujian
Yunnan
Guangxi
Guangdong
Hainan
[-45,-35)
[-35,-25)
[-25,-15)
[-15,-5)
[-5,0)
[0]
(0,5)
[5,15)
[15,25)
[25,35)
[35,45)

Notes: The graph shows the difference in percentage points between the SO_2 reduction target of each province under the command and control minus the market-based allocation (data from Table 7).

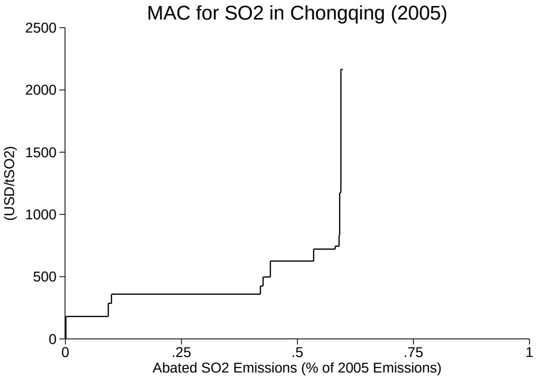
A.4 Marginal SO_2 abatement cost curves for all provinces in China



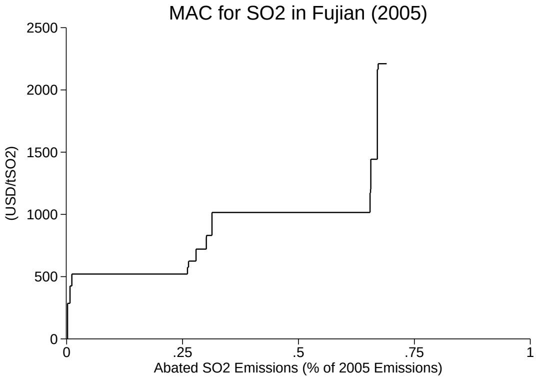
MAC for SO2 in Anhui (2005)



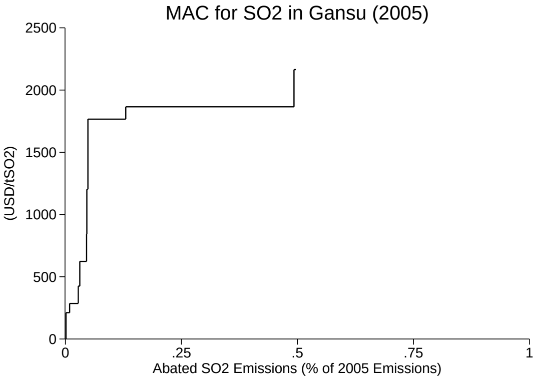
MAC for SO2 in Beijing (2005)



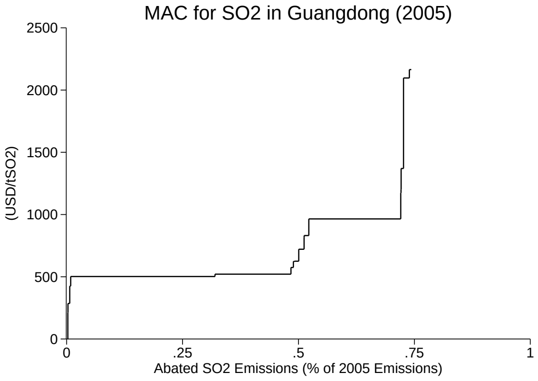
MAC for SO2 in Chongqing (2005)



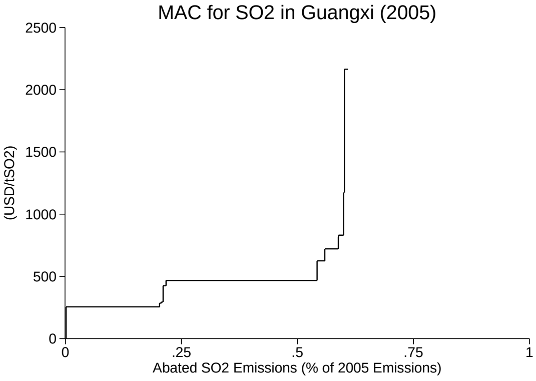
MAC for SO2 in Fujian (2005)



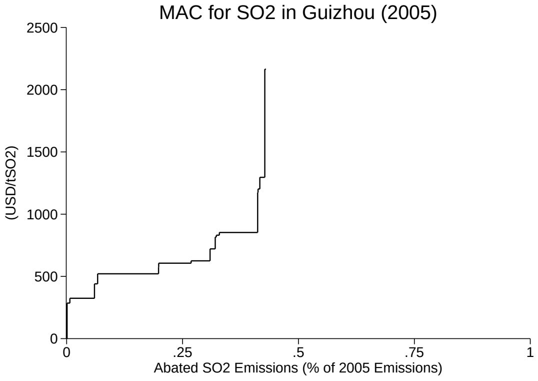
MAC for SO2 in Gansu (2005)



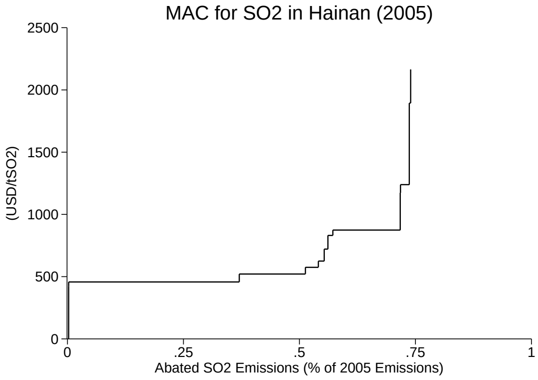
MAC for SO2 in Guangdong (2005)

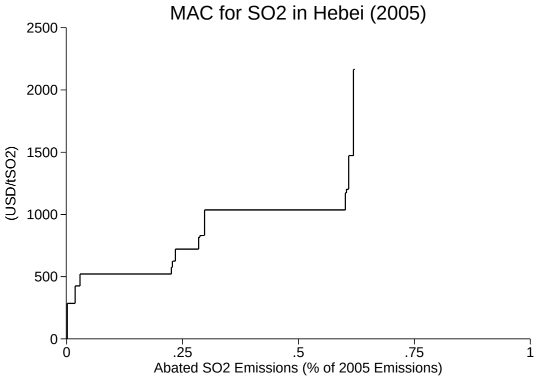


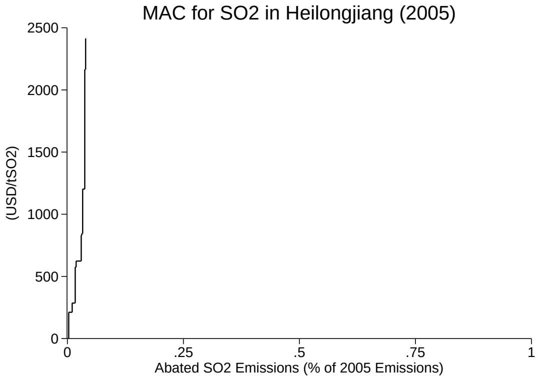
MAC for SO2 in Guangxi (2005)

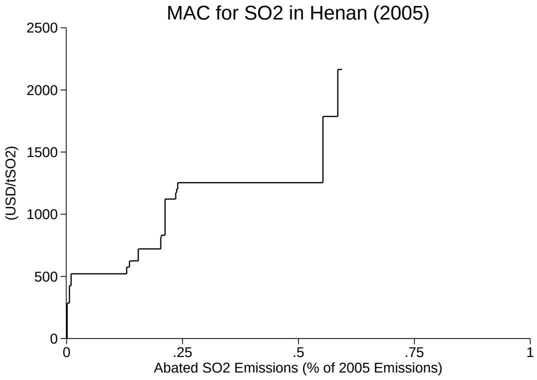


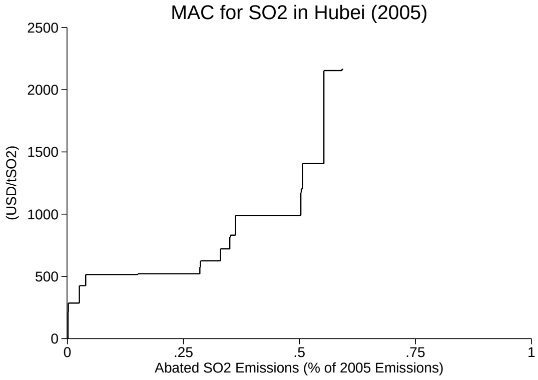
MAC for SO2 in Guizhou (2005)

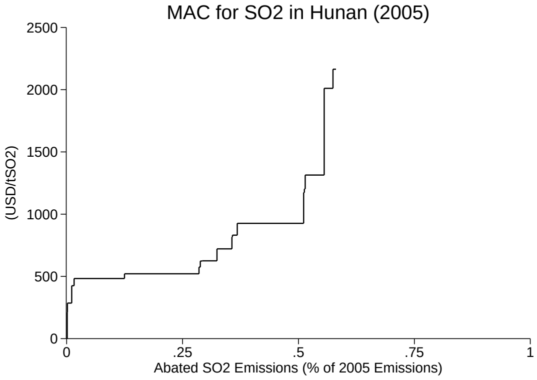

MAC for SO2 in Hainan (2005)

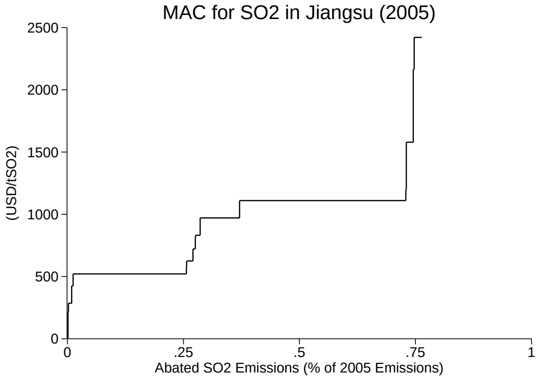

MAC for SO2 in Hebei (2005)

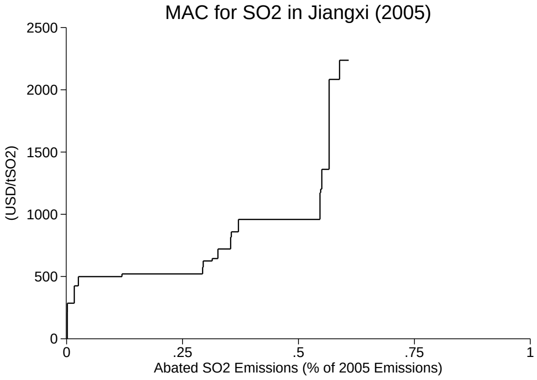

MAC for SO2 in Heilongjiang (2005)

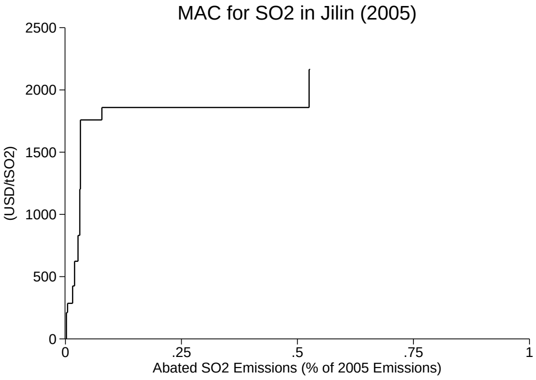

MAC for SO2 in Henan (2005)


MAC for SO2 in Hubei (2005)

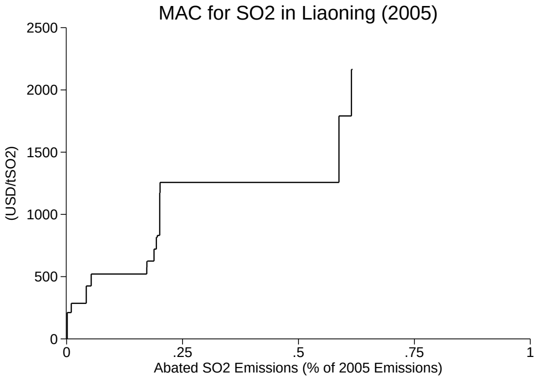

MAC for SO2 in Hunan (2005)


MAC for SO2 in Jiangsu (2005)

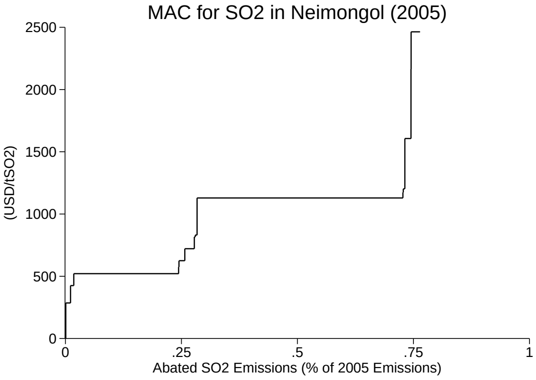

MAC for SO2 in Jiangxi (2005)



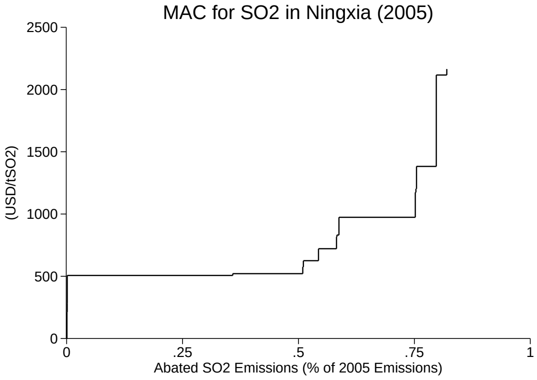
MAC for SO2 in Jilin (2005)



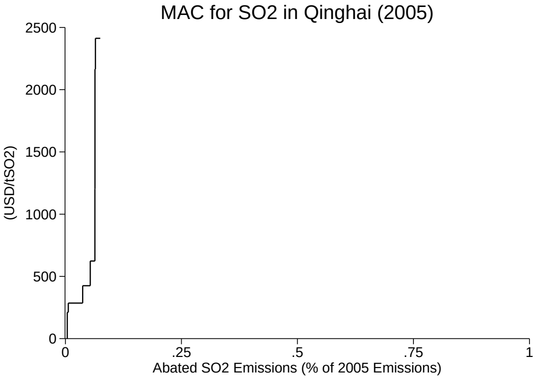
MAC for SO2 in Liaoning (2005)



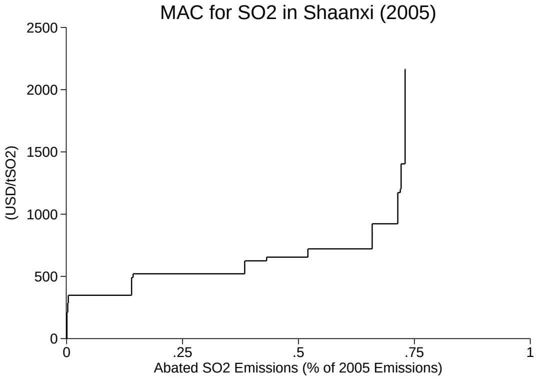
MAC for SO2 in Neimongol (2005)



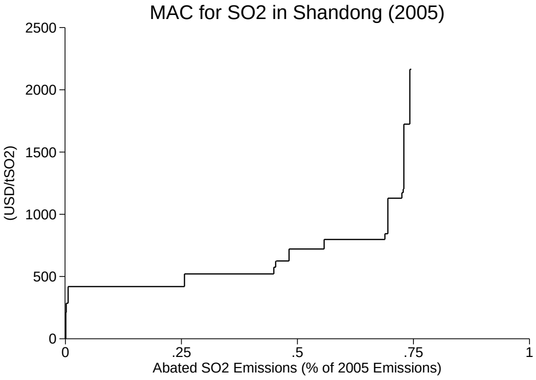
MAC for SO2 in Ningxia (2005)



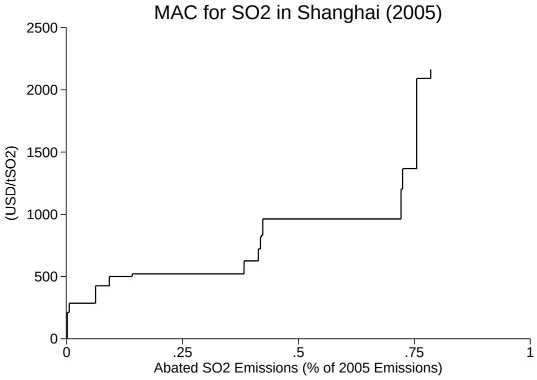
MAC for SO2 in Qinghai (2005)



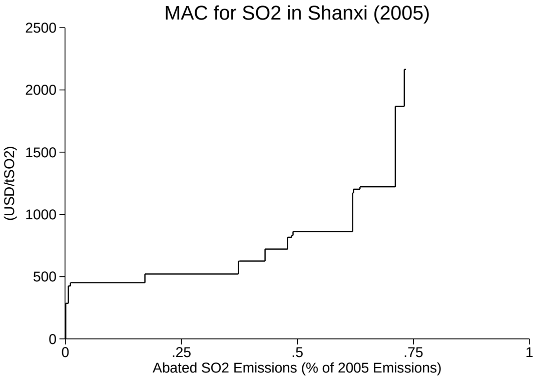
MAC for SO2 in Shaanxi (2005)

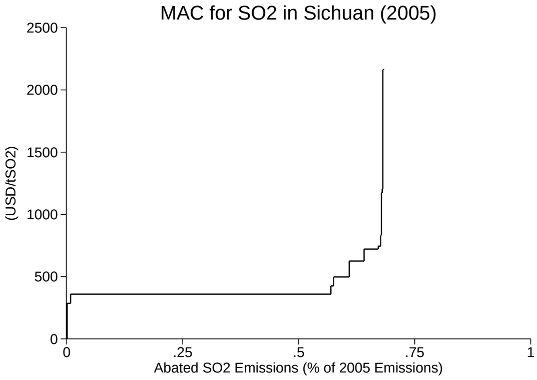


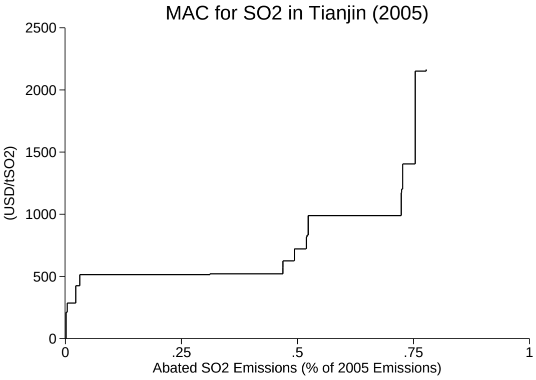
MAC for SO2 in Shandong (2005)

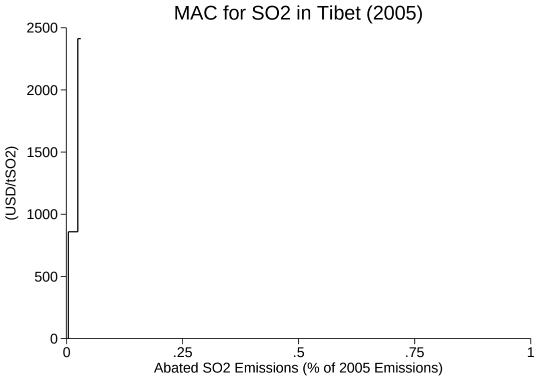


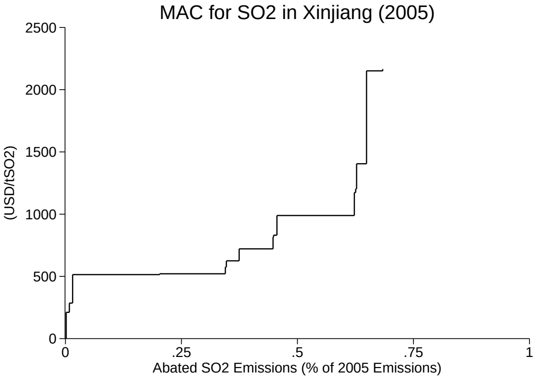
MAC for SO2 in Shanghai (2005)

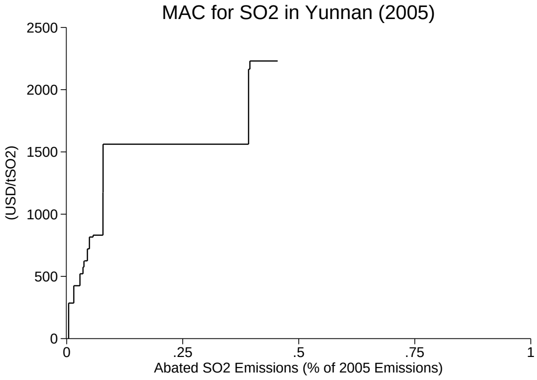

MAC for SO2 in Shanxi (2005)

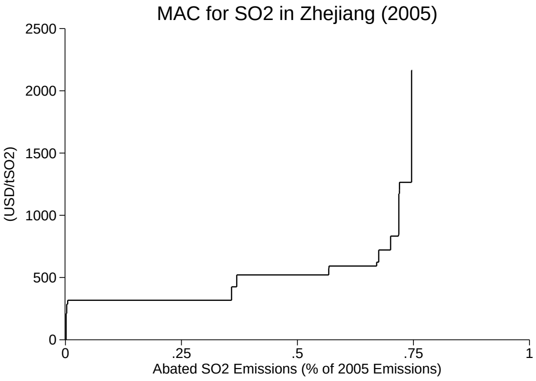

MAC for SO2 in Sichuan (2005)


MAC for SO2 in Tianjin (2005)


MAC for SO2 in Tibet (2005)


MAC for SO2 in Xinjiang (2005)


MAC for SO2 in Yunnan (2005)


MAC for SO2 in Zhejiang (2005)