Journal of Environmental Economics and Management 66 (2013) 424–443

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

# The promise of Beijing: Evaluating the impact of the 2008 Olympic Games on air quality ☆

Yuyu Chen [a], Ginger Zhe Jin [b,*], Naresh Kumar [c], Guang Shi [d]

[a] Peking University, People's Republic of China
[b] University of Maryland & NBER, United States
[c] University of Miami, United States
[d] Development Research Center of the State Council of China, People's Republic of China

ARTICLE INFO

*Article history:*
Received 22 March 2011
Available online 12 October 2013

*Keywords:*
Air pollution
Air quality
AOD
China
Olympic Games

ABSTRACT

To prepare for the 2008 Olympic Games, China adopted a number of radical measures to improve air quality. Using the officially reported air pollution index (API) from 2000 to 2009, we show that these measures improved the API of Beijing during and a little after the Games, but a significant proportion of the effect faded away by October 2009. For comparison, we also analyze an objective and indirect measure of air quality at a high spatial resolution – aerosol optimal depth (AOD), derived using the data from NASA satellites. The AOD analysis confirms the real but temporary improvement in air quality, it also shows a significant correlation between air quality improvement and the timing and location of plant closure and traffic control. These results suggest that it is possible to achieve real environmental improvement via stringent policy interventions, but for how long the effects of these interventions will last will largely depend on the continuation of the interventions.



## Introduction

Air pollution in developing countries including China poses major challenges to human health. Thus, it is important to raise questions about what policy interventions are effective to improve air quality, and for how long does the effects of these interventions last? The radical air-cleaning actions that China took in order to host the 2008 Olympic Games provide a unique opportunity to answer these questions.

Before the Games, China was often cited for elevated air pollution levels. This threatened China's chances of hosting the 2008 Beijing Olympic Games and put China's air pollution in the world's spotlight. The primary motive of hosting the Games was to establish a positive image of China. Thus, improving air quality became one of the most visible tasks for the Chinese Government. Under an authoritarian regime,[1] China was able to take a series of radical actions quickly at a large scale. These actions, including plant closure/relocation, furnace replacement, introduction of new emission standards, and stringent

☆ We thank Douglas Almond, Hanming Fang, Erica Li, Shinsuke Tanaka, Kenneth Rahn and participants at the 2011 NBER China Group meeting, the 2012 International Industrial Organization Conference, and the 2012 NBER conference on public finance issues in China for constructive comments. Financial support from Peking University is gratefully acknowledged. All errors are ours.

* Corresponding author. Fax: +1 301 405 3542.
*E-mail addresses:* chenyuyu@pku.edu.cn (Y. Chen), jin@econ.umd.edu (G.Z. Jin), nkumar@med.miami.edu (N. Kumar), shiguang@drc.gov.cn (G. Shi).

[1] China is classified as an authoritarian regime according to the Economist Intelligence Unit's Democracy Index (2008), accessed at www.economist.com/node/12499352?story_id=o12499352.

0095-0696/$ - see front matter 
http://dx.doi.org/10.1016/j.jeem.2013.06.005

traffic control, cost over US\$10 billion.[2] In addition, given the \$42.9 billion[3] spent on city infrastructure and Olympic stadiums,[4] Beijing Olympics were arguably the largest natural experiment in air cleaning and the most expensive Games in the Olympic history. Because most adopted measures were temporary, lessons learned from this special event will help us understand the effectiveness of intensive but temporary policies in the fight against air pollution.

One major difficulty in this policy evaluation exercise is lack of *in situ* measurements of air pollution. The Chinese government collects such data on a regular basis but did not allow researchers and public to access to these data until recently.[5] As a result, we rely on the official daily air pollution index (API) published by the China's Ministry of Environmental Protection (MEP), as well as the aerosol optical depth (AOD) derived using the data from the MODerate resolution Imaging Spectraradiometer (MODIS) aboard NASA's Terra and Aqua satellites. The data from these two satellites have daily global coverage and the local crossing time globally (including China) of Terra and Aqua are ~10:30am and ~1:30pm local time, respectively. API is a composite index of sulfur dioxide ($SO_2$), nitrogen dioxide ($NO_2$), and particulate matter with an aerodynamic diameter of 10 μm or smaller ($PM_{10}$); AOD represents the concentration of airborne solid and liquid particulates that can absorb, reflect, and scatter the electromagnetic radiation. The credibility of API has been questioned (Andrews, 2008), but AOD is an objective measure retrieved from satellite data and immune from any gaming incentives on the part of Chinese officials. In a companion paper (Chen et al., forthcoming), we show a stable correlation between API, AOD, and visibility, despite some discontinuity of API around the cutoff of “Blue Sky” days (API = 100). In this paper, we treat both API and AOD as imperfect measures of air quality and analyze them independently.

Our main methodology is to compare Beijing with 28 non-Olympic cities before, during, and after the Games while controlling for a long list of differential factors. We also separately control for five cities that co-hosted the Games in other parts of China (referred to as co-host cities) and three cities surrounding Beijing that adopted measures to improve air quality in and around Beijing (referred to as neighbor cities). In terms of time, we take the one and half years before the establishment of the Beijing Organizing Committee for the Games of the XXIX Olympiad (BOCOG) as the benchmark period (6/5/2000–12/12/2001) and detect treatment effects in three windows: the 7-year preparation period (12/13/2001–8/7/2008), the 1 month of the Olympic and Paralympic Games (8/8/2008–9/17/2008), and 13 months after the Games (9/18/2008–10/31/2009).

The raw data show that the average API of Beijing dropped from 109.01 before the setup of the BOCOG to 54.88 during the Games and then climbed back to 81.83 after the Games. A similar pattern of temporal improvement persists after we control for various factors (including city-specific trends) and break the after-Games period into five segments. In comparison, the AOD of Beijing (which shows a positive relationship with air pollution) started to decline from the preparation period to during the Games, reached the lowest level 2–6 months after the Games, and then increased afterwards. Unlike API's focus on surface measures, aerosol can circulate in the air for a longer time, so the delay in AOD improvement is not surprising. Both API and AOD data suggest that air quality improvement in Beijing was real but temporary.

The unique setting of Beijing Olympics allows us to exploit location- and time-specific policies. After linking the center of each AOD observation to road density and plant closure within a five-kilometer radius, we find more AOD improvements in the areas with greater road density and more plant closures, but these differential effects decline gradually over time. These findings are consistent with the fact that most plant closures and traffic controls were more effective in the periods immediately before or during the Games.

The rest of the paper is organized as follows. Sections 2–4 summarize the background, related literature, and data respectively. Section 5 presents main results on API and AOD. Section 6 examines the mechanisms that can potentially contribute to the air quality improvement of Beijing. Section 7 concludes.

## Background

China has been known for its poor air quality. The 1996 national standards on $SO_2$, $NO_2$, total suspended particles (TSP), and $PM_{10}$ were 2–7 times higher than the standards established by the World Health Organization (UNEP, 2009). An amendment in 2000 further weakened the Chinese standard for $NO_2$ and ozone. Even so, the relatively generous standard is hard to enforce in China. Sixteen Chinese cities appeared on the list of the world's top 20 most polluted places in 2007.[6] Some athletes were so concerned about the air quality that they planned either to wear masks in competition or skip the Beijing Olympic Games (*Los Angeles Times* March 12, 2008; *New York Times* March 12, 2008).

[2] Both UNEP (2009) and Zhang (2008) report that the planned environmental investment was \$5.6 billion between 1998 and 2002, and \$6.6 billion between 2003 and 2007. According to Zhang (2008), the actual environmental investment made between 1998 and 2007 was \$15.7 billion.

[3] According to the city government of Beijing, the total city infrastructure investment made between 2001 and 2008 was roughly 280 billion RMB (or US\$41 billion) and the total investment in Olympic stadiums was 13 billion RMB (or US\$1.9 billion). See more details at http://finance.people.com.cn/GB/7609928.html.

[4] An official audit by the State Council of China concludes that the Olympics made a modest profit of US\$145 million with total expenditure of US \$2.8093 billion and total income of \$2.975 billion. However, this report does not include many expenditures made by the local government in the name of the Olympic Games (http://www.runblogrun.com/2009/06/beijing_olympics_made_103_mill.html). The media has estimated the total expenditure to be \$43 billion (http://www.sourcejuice.com/1183548/2009/06/19/China-announced-results-audit-confirmed-clean-Olympics/).

[5] Beijing started to post $PM_{10}$ measures by hour and monitoring location in January 2012, a few large cities have followed suit. But there are no complete historical *in situ* data to compare Beijing with other cities.

China adopted a number of air cleaning policies for the Olympic Games. After the International Olympic Committee awarded Beijing the 2008 Games on July 13, 2001, China established the Beijing Organizing Committee for the Games of the XXIX Olympiad (BOCOG) on December 13, 2001. The main responsibility of the BOCOG was preparing for the 2008 Games; this included infrastructure development, environment improvement, public relations, and logistics. The three main concepts promoted by the BOCOG were "Green Olympics, High-tech Olympics and People's Olympics," highlighting the importance of environmental protection and public interests.

We assume that December 13, 2001 was the earliest date when the Chinese government started to implement air quality improvement policies for the Olympic Games. To the extent that the Olympic-related air cleaning efforts started before the setup of the BOCOG, our results represent a conservative estimate of the overall effect. The main treatment period ranged from the start of the 2008 Olympic Games (8/8/2008) to the end of the Paralympic Games (9/17/2008). The 7-year window from the setup of the BOCOG to the start of the Games is referred to as "Games Preparation" and the 13 months after the Games (9/18/2008 to 10/31/2009) is referred to "Post Games." All these are compared to the "benchmark" period from the start of our data (6/5/2000 for API and 2/26/2000 for AOD) to the setup of the BOCOG (12/12/2001).

To prepare for the Games, China took most air cleaning actions in Beijing. December 31, 2002 marked the end of Beijing's Phase 8 environmental cleaning efforts (phase 1 started in 1998), which included conversion of 1500 coal furnaces into clean fuels, retirement of 23,000 old automobiles, reduction in emissions from major industrial plants by 30 thousand tons, and an increase of 100 $km^2$ area under green coverage.

In 2003 and 2004, Beijing reduced its industrial use of coal by 10 million tons, desulfurated air pollutants from the YanShan Petrochemical Company, shut down coal-fired generators at the Capital Steel Company and Beijing Coking Plant, and closed Beijing Dyeing Plant. Between 2005 and 2006, China constructed desulfuration, dust removal, and denitrification facilities at the Beijing Thermal Power Plant and the power plant of Capital Steel. By the end of October 2006, Beijing renovated 100% of the furnaces for clean fuel in five districts, and 50% in the three other districts.

The largest plant relocation – of the Capital Steel Company – started in 2005 and its largest production unit was permanently closed at the end of 2007. However, Capital Steel did not completely stop all production until the end of 2010, 27% of its production capacity was in operation even during the Olympic Games.[7] Since we do not know the full details of the closure process, we use 12/31/2007 as the benchmark closure date for Capital Steel. In addition, the Second Beijing Chemical Plant completed its production closure by the end of 2007, Beijing Coking Plant was closed on 07/23/2006, and Beijing Dyeing Plant was closed on 6/30/2003.[8] During the Games, many large plants stopped production temporarily (7/20/2008–9/20/2008). We are able to find confirmative closure news reports for 20 of them and therefore code their latitudes and longitudes according to the reported addresses. In total, our analysis includes 4 permanent closures and 20 temporary closures, effective at various times.

Beijing also attempted to control for vehicle emission by adopting new emission standards on March 1, 2008 (applicable to new vehicles only) and restricting the number of on-road vehicles to half, based on even or odd vehicle registration number during 8/17/2007–8/20/2007 and 7/20/2008–9/20/2008. A weaker form of traffic control continued after the Games as each registered vehicle was required to be off the road 1 weekday per week.

According to Streets et al. (2007) neighboring provinces and municipalities such as Hebei, Shandong, and Tianjin significantly contributed to air pollution in Beijing. Therefore, co-host and neighbor cities adopted similar measures to improve air quality, but the magnitudes were smaller than those for Beijing. For example, Tianjin implemented the same odd-even traffic control but only during the Olympic Games, Shandong requested closure of 132 heavy polluting plants during the Games, Shenyang invested 163 million RMB to replace old buses, and Shanghai installed desulfuration facilities for large electricity generating plants. Due to limited access to time- and location-specific policies, we report general API/AOD changes for Beijing, co-host and neighbor cities, but confine our detailed mechanism analysis to Beijing. In Beijing, because the new emission standard is applicable only to new vehicles and because we do not have data for the exact time and location of furnace renovation, our mechanism analysis focuses on plant closure and traffic restriction.

While the 2008 Olympic Games triggered many new efforts toward cleaning the air, some environmental protection policies existed before 2000. For example, the central government started to build the Green Great Wall in northern China in 1978. A nationwide policy was adopted in 1999 to encourage farmers to convert less productive farm land into green land. These policies targeted desertification instead of air pollution, but the two are clearly linked.

A more direct nationwide "blue sky" campaign started in 1997. Defining "blue sky" as an API below 100, the central government included the frequency of blue sky days as a performance measure reported by local officials.[9] To the extent that performance evaluation has an impact on local governments, air quality improvements may have occurred nationwide long before the 2008 Games. In this paper, we control for all the national air-cleaning policies by date fixed effects. A more detailed analysis of the "blue sky" policy is available in Chen et al. (forthcoming).

[6] http://www.cbsnews.com/stories/2007/06/06/eveningnews/main2895653.shtml citing the World Bank's "The Little Green Data Book" (May 2007, ISBN 0-8213-6967-9).

[7] http://cn.reuters.com/article/cnInvNews/idCNChina-1721320080717, and http://jingji.cntv.cn/20110113/111677.shtml, accessed on October 28, 2012.

[8] http://sports.gansudaily.com.cn/system/2007/7/28/010272920.shtml, http://www.bjepb.gov.cn/bjhb/tabid/68/InfoID/7967/frtid/283/Default.aspx, http://finance1.jrj.com.cn/news/2007-11-27/000002980016.html, accessed in February 2010.

[9] For more details, see MEP documents #1997-349 (stipulated in May 1997), #2002-132 (stipulated on November 19, 2002) and #2008-71 (stipulated on September 21, 2008, effective January 1, 2010).

Some earlier air-cleaning efforts were Beijing-specific. Before the setup of the BOCOG, the city government of Beijing had already carried out seven phases of air cleaning. Probably due to the increasing occurrence of sand storms, Beijing realized that its early efforts were fruitless and it was necessary to adopt more stringent measures to improve air quality. This led to the start of phase 1 cleaning on December 16, 1998.[10] As time went by, the 50th National Day (10/1/1999) helped to further justify air cleaning, but the efforts of Beijing continued after the celebration. During the seven phases of air cleaning before the setup of the BOCOG, Beijing adopted many measures, including extended use of clean fuel, introducing desulfuration of equipment, covering bare land with grass and trees, enforcing the retirement of heavy-duty vehicles, dust control on construction sites, and a ban on outdoor barbeques. To the extent that Beijing had specific reasons to adopt these policies, it was important to control for the city fixed effects and city-specific trends.

## Literature review

Although researchers have attempted to investigate air quality change in response to the Olympic-related interventions (Wang et al., 2009a; Tang et al., 2009; Yao et al., 2009; Simorich, 2009), the lack of *in situ* air pollution data has constrained researchers' ability to fully evaluate the effects of these interventions.

Two studies have used their own measurements of air quality instead of the published API. Wang et al. (2009a) collected $PM_{10}$ and $PM_{2.5}$ data at Peking University between July 28 and October 7, 2008. They found a significant correlation between the self-measured and published $PM_{10}$, but the absolute level of their self-measure is 30% higher. This finding triggered some concerns that the official API must have been subject to manipulation, but this discrepancy can be attributed to sampling (through systematic bias in the locations of samplers and types of samplers used) and methodological differences (Tang et al., 2009; Yao et al., 2009; Simorich, 2009). Wang et al. (2009a) also found that meteorological conditions such as wind, precipitation and humidity account for 40% of the total variation in $PM_{10}$. This finding emphasizes the importance of controlling for meteorological conditions.

Wang et al. (2009b) compared the self-measured ambient concentrations of Black Carbon (BC) in Beijing in the summers of 2007 and 2008. Although their data covered a longer time span than that of Wang et al. (2009a), they did not control for the nationwide trend in air quality between 2007 and 2008. The main finding of Wang et al. (2009b) is that the BC concentration was significantly better during the periods of traffic control than without the traffic control.

Unlike academic researchers, the United Nations published a summary report (UNEP, 2009) based on *in situ* measures of CO, $PM_{10}$, $SO_2$ and $NO_2$ from the Beijing Environmental Protection Bureau (EPB). Their data ranged from 2000 to 2008 including a few months immediately after the Olympic Games. The report examines Beijing's *in situ* measurements before, during, and immediately after the Games while controlling for meteorological factors. As shown later, the officially reported API data shows a nationwide trend toward better air. This implies that a simple before–after comparison within Beijing is likely to confound the nationwide trend with the actual air quality improvement due to the policy interventions adopted for the Games. We overcome this shortcoming by comparing Beijing with other big Chinese cities in the same time horizon. We also employ API data until 13 months after the Games so as to better evaluate the fade-away effect after the Games. As we do, UNEP (2009) used several satellite images from NASA's Terra and Aqua satellites for August 2008, but our resolution of AOD (10 km $\times$ 10 km) is much smaller than theirs (100 km $\times$ 100 km) and our frequency is daily instead of monthly. These rich details allow us to link AOD to the exact date and geographic location of plant closure and traffic control, a process essential to attempting to attribute air quality improvement to specific policy interventions.

Using API and detailed station-level $PM_{10}$ data for Beijing only, Andrews (2008) expressed concern that Beijing may have manipulated the official API report because (1) Beijing had relocated monitoring stations over time; (2) the 2000 MEP regulation switched one component of API from TSP to $PM_{10}$, and weakened the limits of nitrogen oxides and ozone; and (3) the number of days with an API between 96 and 100 is significantly higher than the number of days with an API between 101 and 105. Guinot (2008) argued that it is not uncommon to add monitoring stations as part of economic and urban development and that the uncertainty in the API metrics may range from 15% to 25% due to measurement errors. In a separate paper (Chen et al., 2012), we confirm API discontinuity around 100 but show a stable correlation between API, visibility, and AOD. This finding suggests that API contains useful information about air pollution despite its likely underreporting around 100.

Focusing on Beijing only, Viard and Fu (2011) used both API and station-level $PM_{10}$ data to investigate the impact of traffic restriction on air quality. They found that traffic restriction led to a 19% decline of API during every-other-day restriction and a 7% decline during 1-day-per-week restriction. As shown below, this finding is consistent with our findings. By comparing Beijing with other big cities, we are able to control for the national trend in air-quality improvement. By using both API and AOD data, we also examine the impact of plant closure and compare it with that of traffic restriction.

A growing body of literature has evaluated air pollution policies in other developing countries. Davis (2008) examined the traffic restrictions in Mexico City (forcing vehicles off the road 1 day per week) and finds no effect on air quality. He attributes the finding to more vehicles in circulation and a composition change toward high-emission vehicles. In a similar study, Kathuria (2002) finds that the emission controls that Delhi adopted in 1999–2001 had little impact on air quality improvement for two potential reasons. First, more vehicles were added to the traffic volume after the policy went

[10] See Beijing municipal documents 1998 #24 (phase 1), 1999 #249 (phase 2), and 1999 #29 (phase 3) for more details.

into effect. Second, no supplemental policies were in place to check the traffic volume despite the fact that new vehicles had better emission standards. Kumar et al. (in preparation) examined air pollution distribution/redistribution in Delhi in response to a series of air quality regulations. Two alarming findings emerged from that study. First, the air quality of the city improved after the regulations, but the effects of the regulations faded away after several years. Second, while the regulations improved air quality in the city, the air quality of neighboring areas, without the regulations in place, deteriorated. Another study by Foster et al. (2009) suggests that the improvement in air quality of the city improved the respiratory health of Delhi residents and the deteriorated air quality in the neighboring areas is likely to have adverse health effects. Foster et al. (2009) examine Mexican plants' voluntary participation in a major pollution reduction program. They find evidence that measures of voluntary participation are related to lower AOD and lower infant mortality due to respiratory causes.

Our research is also related to a broader literature on environmental policies. Several studies in the USA have documented the health effects of air pollution (Chay and Greenstone, 2003; Almond et al., 2009; Currie and Neidell, 2005), the effect of environmental policies on polluting industries (Henderson, 1996; Becker and Henderson, 2000; List et al., 2003), and the social costs of environmental policies (Hazilla and Kopp, 1990). Most of these studies suggest that air quality improvement is a long term process and largely depends on the dynamic interplay of government policies and private compliance. In contrast, the actions that China undertook for the Beijing Olympics were largely government-driven, much more intensive, and implemented in a relatively short period. Not only do these features help separate the effects of the Chinese efforts from other confounding factors; they also help us understand how much air quality improvement can be achieved if a government is willing and able to implement intensive measures in a short time.

In this sense, our study is related to the political economy of environmental protection. It has been argued that authoritarian regimes are more reluctant to protect the environment as they enjoy a greater-than-median income share and have a shorter-than-average time horizon than a democratic regime. Congleton (1992) and Murdoch and Sandler (1997) show that democratic countries are more likely to support and enforce chlorofluorocarbon emissions control under the Montreal Protocol. However, one factor less noticed in the literature is the greater administrative power of authoritarians. If political opportunities motivate authoritarians to protect the environment, an authoritarian regime like China may overcome industrial resistance and implement environmental protection policies more quickly and on a larger scale.

## Data

We acquired data from several sources: (1) the official API data published by the MEP, (2) meteorological data from the China Meteorological Administration (CMA) and the National Climatic Data Center (NCDC, 2007), and (3) the AOD data from NASA. Data from China, reported by city and day, were available from June 5, 2000 to October 31, 2009; AOD was extracted at 10 km spatial resolution for every day within 100 km distance to the city center for each city from February 26, 2000 to December 31, 2009.

### *API data*

For each focal city, the MEP aggregates the measured intensities of $NO_2$, $SO_2$ and $PM_{10}$ into a daily air pollution index (API) ranging from 0 to 500.[11] Specifically, suppose a city has $M$ stations and each station monitors $NO_2$, $SO_2$ and $PM_{10}$ for $N$ times each day.[12] MEP first computes the daily average of all the $M \times N$ measures for each pollutant and then translates the daily mean intensity into pollutant-specific API according to linear spines with the cutoff points defined in Table 1.[13] The overall API is the maximum of all the pollutant-specific APIs. If that maximum is above 500, the overall API is capped at 500. An API below 50 is defined as “excellent” air quality, 50–100 as “good,” 100–200 as “slightly polluted,” 200–300 as “moderately polluted,” and above 300 as “heavily polluted.” A crude categorization refers to a day with API at or below 100 as a “blue sky” day.

MEP reports API data by city and day, and the category of the dominant pollutant(s) if API is above 50. By this definition, we can infer the absolute level of $PM_{10}$ for 72.9% of data points across all cities. For the other 19.9% of the data where API was less than 50, we knew $PM_{10}$ was upward bounded by the $PM_{10}$ level corresponding to the reported API. In comparison, inferences about $NO_2$ and $SO_2$ were much more difficult because only 0.35% of city-days reported $NO_2$ and 6.85% reported $SO_2$ as the dominant pollutant.

**Meteorological data** from CMA are reported at 2pm each day at a fixed point in each city. This allows us to control for local temperature, precipitation, barometric pressure, sunshine, humidity, and wind.[14]

---

[11] MEP monitors the intensity of CO, but does not include it in the current API calculation because the calculation formula was set 10 years ago and at that time the vehicle volume in China was very low. MEP is considering adding CO and other pollutants for the future API. *Source*: http://news.163.com/09/0312/11/5470SBA9000120GU.html.

[12] The MEP stipulates the number of monitoring stations according to city population and the size of the established area. For a large city like Beijing, one monitoring station is required for every 25–30 $km^2$ and the total number of stations must be at least 8.

[13] For example, if the daily mean of $PM_{10}$ is 220 $\mu g/m^3$, the corresponding API of $PM_{10}$ is $(220-150)/(350-150)\times(200-100)+100=135$.

[14] Our CMA data also include visibility, another arguably more objective measure of particulate matter. In Chen et al. (forthcoming), we use API, visibility, and AOD data to investigate potential gaming of API.

**Table 1**
MEP cutoff points for different levels of API.

| API | Pollutant intensity (μg/m$^3$) | | | Air quality level | Air quality condition | Notes of health effects |
|---|---|---|---|---|---|---|
| | PM10 | $SO_2$ | $NO_2$ | | | |
| 500 | 600 | 2620 | 940 | V | Heavy pollution | Exercise endurance of healthy people decreases. |
| 400 | 500 | 2100 | 750 | | | Some will have strong symptoms. Some diseases will appear. |
| 300 | 420 | 1600 | 565 | IV | Moderate pollution | Symptoms of the patients with cardiac and lung diseases will be aggravated remarkably. Healthy people will experience a drop in endurance and increased symptoms. |
| 200 | 350 | 250 | 150 | III | Slightly polluted | The symptoms of the susceptible are slightly aggravated, while healthy people will have stimulated symptoms. |
| 100 | 150 | 150 | 100 | II | Good | Daily activity will not be affected. |
| 50 | 50 | 50 | 50 | I | Excellent | Daily activity will not be affected. |

Conditional on having non-break API and meteorological data, our analysis consists of 37 cities.[15] We grouped these cities into four categories: Beijing was a category by itself because most of the Games were held in Beijing; Qingdao, Shenyang, Tianjin, Shanghai, and Qinghuangdao were categorized as the “co-host” cities because they hosted some of the Games in the treatment period.[16] The BOCOG defined six cities close to Beijing as “Olympic Environment Protection Cities.” Our sample included the three largest neighboring cities: Taiyuan, Shijiazhuang, Huhehaote.[17] The other 28 cities were grouped in the category of control cities. As shown in Fig. 1, the sample covered almost every provincial capital in China and most treatment cities (Beijing, co-host and neighboring cities) are located in the developed parts of east China.

*AOD data*

The daily 10 km AOD data (Level 2, collection 5.0) were acquired from NASA (NASA, 2010). AOD is retrieved using the data from Moderate Resolution Imaging Spectroradiometer (MODIS) aboard Terra and Aqua satellites. Information about the AOD extraction procedure is available elsewhere (Chu et al., 2003; Levy et al., 2007a, 2007b). Imagine that radiation travels from a satellite to the earth's surface. By definition, AOD captures the amount of radiation absorbed, reflected, and scattered due to the presence of solid and liquid particulates suspended in the atmospheric column (Kaufman et al., 2002a, 2002b). While the AOD is potentially available everywhere at the local satellite crossing time (~10:30am and ~1:30pm of Beijing time), it is sensitive to the point- and time-specific weather and available only for days with less than 10% cloud cover. Despite this fact, researchers have shown that the AOD, corrected for meteorological conditions, can predict air quality (Gupta et al., 2006; Kumar, 2010; Kumar et al., 2011). Focusing on Delhi and Kanpur in India and Cleveland in the USA, Kumar et al. (in preparation, 2011) demonstrate how AOD can be converted to $PM_{10}$ estimates. They develop an empirical relationship between *in situ* measurements of $PM_{10}$ and AOD. They conclude that the AOD captured 70% of the variations in the $PM_{10}$ (monitored on the surface) after controlling for meteorological conditions and seasonality. Because the *in situ* $PM_{10}$ data were not available in China, this paper utilizes AOD corrected for meteorological conditions.

AOD is related to both human activities and natural sources, and variations in sources of aerosols and meteorological conditions play important roles in AOD retrieval (Kumar et al., 2011). Li et al. (2003) validated the usage of AOD data in China and found that all areas with relatively high values of AOD are in the regions of dense population and fast economic development. They also found that AOD values are related to weather conditions (especially strong sandstorm episodes) and the contribution to AOD from local floating dust and soot attributed to human activities are more significant in China than in developed countries.

In addition to being immune to potential data manipulation by Chinese officials, AOD can be extracted at a high spatial resolution (~10 km × 10 km). This enabled us to evaluate change in AOD with respect to the location-specific interventions of plant closure and traffic control. Despite these advantages, there are several concerns about the AOD data.

First, without the *in situ* measurements of air pollution, it is difficult to develop and validate robust air quality estimates. This implies that the air quality improvement detected from AOD is relative instead of absolute. Second, by definition, AOD captures the amount of radiation absorbed, reflected, and scattered due to the presence of solid and liquid particulates suspended in the atmosphere (Kaufman et al., 2002a, 2002b). Since the sources of aerosol can be natural (such as dust storms, sea salt, or forest fires) and anthropogenic (combustion), air quality ($PM_{10}$ concentration) predicted using AOD may vary regionally. Thus, we cannot extrapolate the $PM_{10}$ predictive model of Delhi or Cleveland to China. Third, for the same reasons, AOD is more correlated with particulate matter (especially fine particulates) than with $SO_2$, $NO_2$ or other chemicals

[15] Although the MEP reports API for 86 cities and the CMA visibility data cover 69 cities, only 42 cities had API data in 2000 and the visibility data are incomplete for some cities between 1993 and 2009. For an unknown reason, the API data are missing for June 4, 2008 for all cities. So the “non-break” criterion ignores the missing data for June 4, 2008.

[16] Qinhuangdao is the only city that violates our sampling rule because its API data is not available until 2001. We include it in the sample in order to cover all co-host cities. Results are robust if we exclude Qinhuangdao from the sample.

[17] The other three “Olympic Environment Protection Cities” are Datong, Yangquan and Chifeng. None of them is a provincial capital.

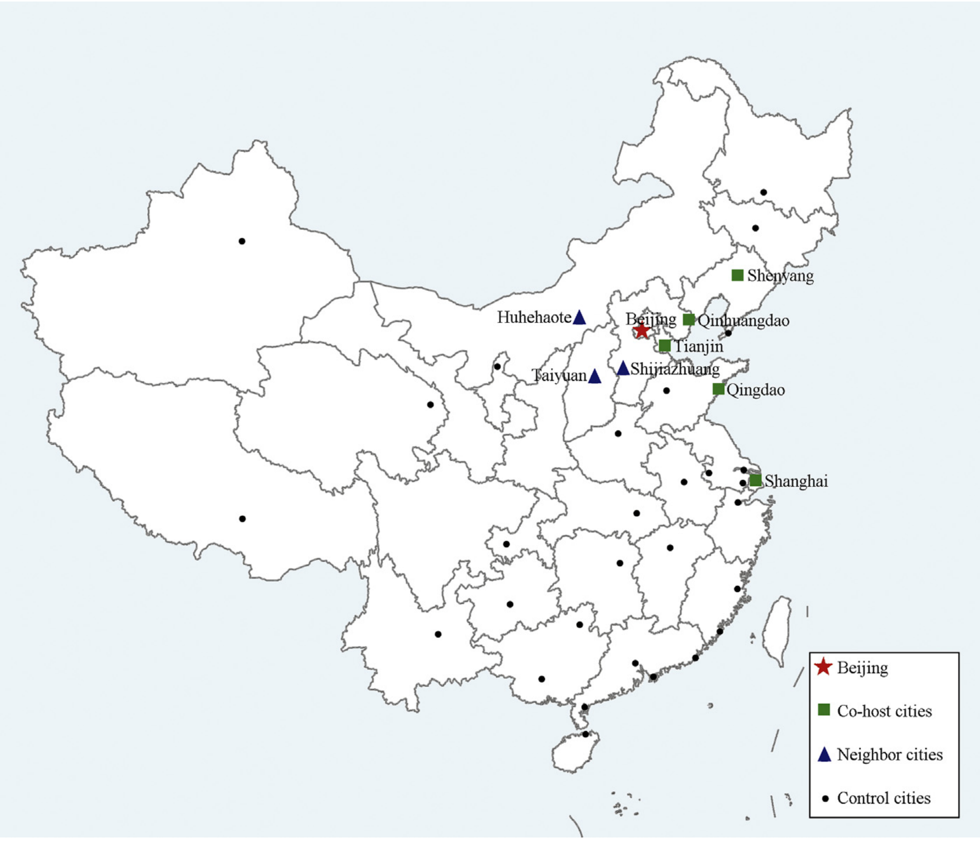


**Fig. 1.** Map of the 37 study cities.

in the air. This implies that the comparison of AOD and API is imperfect, even if the API is reported based on $PM_{10}$ as the main pollutant. Fourth, AOD is sensitive to the point- and time-specific weather conditions, and it is not possible to retrieve AOD under cloudy conditions; therefore, there are systematic gaps (across time and geographic space) in the AOD dataset (Kumar, 2010).

Finally, the suspended particulates that AOD does capture can exist in any part of the atmosphere but API is based on air pollutant measures on the surface of the earth. Depending on the speed and direction at which pollutants travel in the atmosphere, AOD measured at nearby locations or nearby times are likely correlated, and empirical analysis needs to account for the spatial-temporal structure of AOD. Moreover, the atmospheric lifetime of pollutants vary. Via simulations, Textor et al. (2006) showed that the average residence time is half a day for sea salt, 4 days for sulfate and dust, and 6-to-7 days for particulate organic matter and black carbon. We also consulted Professor Kenneth Rahn in the University of Rhode Island,[18] who stated that atmospheric lifetime is typically a few days for aerosol, a day or two for $SO_2$, and around a decade for $CO_2$. Moreover, the short lifetime of aerosol can increase with altitude, to a month or so in upper troposphere and years in the stratosphere. Because we cannot decompose AOD into aerosol contributions from different altitudes, we expect a noisy and probably delayed correlation between AOD and air cleaning actions on the surface.

With these caveats in mind, we retrieved 102,820 valid 10 km AOD observations over Beijing from February 25, 2000 to December 31, 2009. Of all the 3596 calendar days in the time span of this study, only 2297 days (64%) had valid AOD observations due to gaps in the data. On average, we had 45 data points of AOD per day over Beijing. Similarly, the AOD data were retrieved for the other 36 cities, which brought the total sample of AOD to 2,614,734 data points.

To control for time-specific meteorological conditions at the observation time of AOD, we acquired hourly global surface meteorological data from the monitoring stations in and around the selected cities. The details on these data are available elsewhere (NCDC, 2007). These data were collocated with the AOD data within a 1-h time interval of the AOD time on a given day. This means that we assigned the same value of meteorological conditions (from the closest station) to all AOD values in a given city on the same day. Since there were subtle gaps in the meteorological and AOD data, it resulted in missing values in 6% of the sample. Therefore, meteorological conditions were imputed for missing days when AOD was available. The procedure impute was employed to estimate missing values with the aid of continuous time and other city-specific meteorological conditions.[19]

[18] We owe special thanks to Shinsuke Tanaka for consulting Professor Rahn for us in October 2010.

[19] When meteorological variables are missing, we usually miss some but not all of them. Suppose we only miss the meteorological variable $K$ for date $t$ in city c. Conditional on the days when $K$ is available, we regress $K$ on the other meteorological variables and continuous time (days since 2000). We then impute $K$ on date $t$, using these regression coefficients and other meteorological variables that are available on date $t$.

**Information about location-specific actions** was collected for Beijing only. We overlaid a 2.5 km × 2.5 km grid over Beijing, and defined three variables for each cell of the grid. The first is a dummy variable that indicates whether the cell has any permanent plant closure at present or before the study date *d* ($close\_per_{gd}$). This was defined using the exact addresses and closure dates of four large plants. The second variable is also a dummy variable and includes information on whether the cell had any temporary plant closure during the study date ($close\_tem_{gd}$). This included 20 temporary closures reported in the local newspapers; the plant closure dates were 7/20/2008–9/20/2008. The exact locations of permanently or temporarily closed plants are shown in Fig. 2. The third variable is the length of major and secondary roads in cell *g* during 2005 ($road\_den_g$). This variable is time-invariant and will be interacted with the period dummies to capture policy interventions due to the Games. Fig. 3 shows the cell-by-cell distribution of major and secondary roads in Beijing.

To merge these location-specific interventions with AOD, we took the center of each AOD observation (by latitude and longitude) and drew a 5 km radius around it. We then summed and averaged the values of all three variables ($close\_per_{gd}$, $close\_tem_{gd}$ and $road\_den_g$) in all 2.5 km cells that overlap with the search radius.

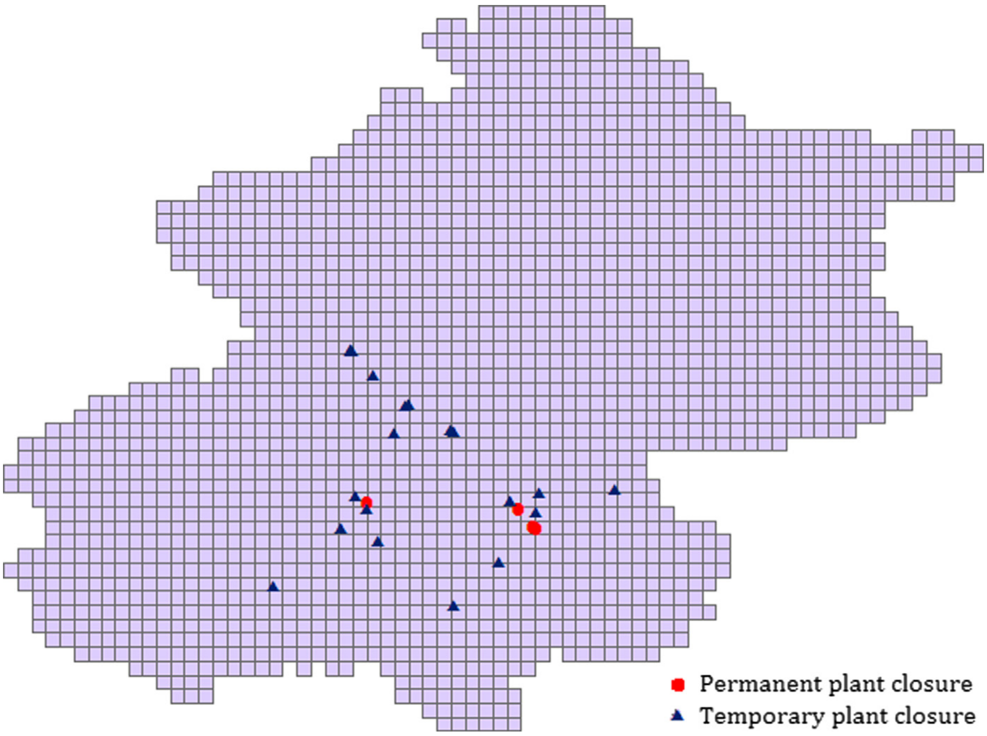


**Fig. 2.** Distribution of permanent and temporary plant closures in Beijing. .
*Data source*: http://www.gov.cn/zwgk/2008-04/14/content_944313.htm.

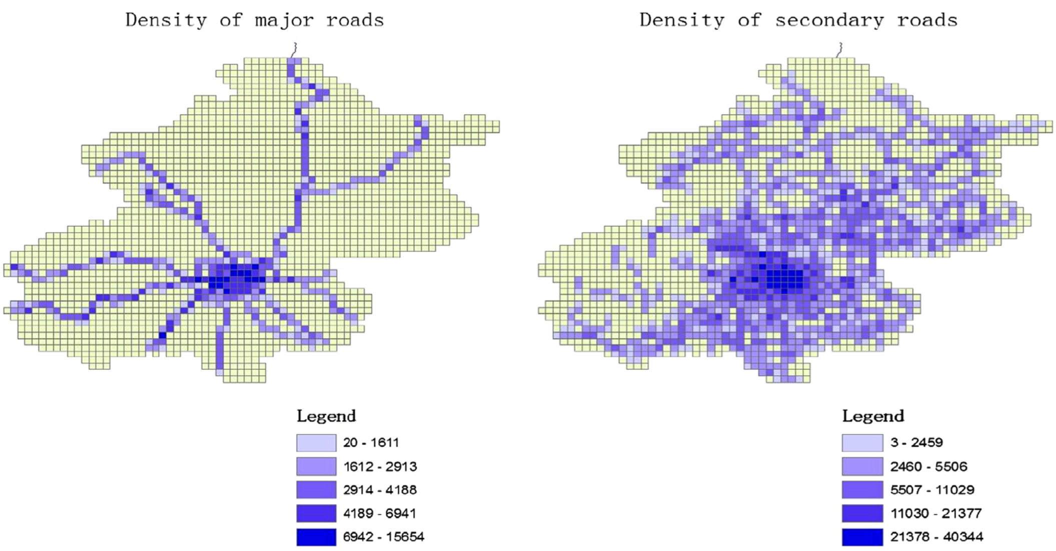


**Fig. 3.** Distribution of major and secondary roads in Beijing, as of 2005.

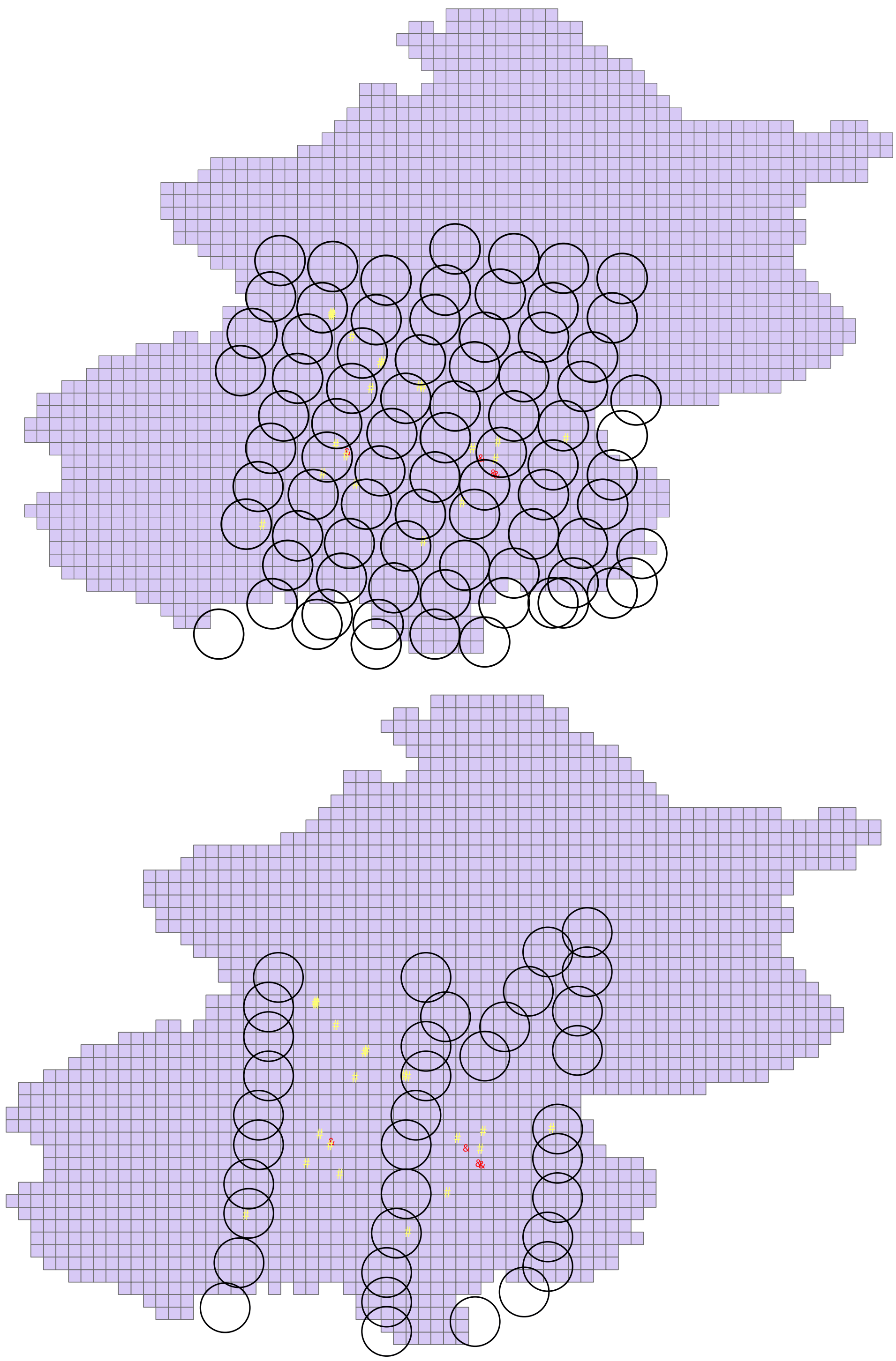

**Fig. 4.** Map of Beijing with AOD circles. *Note*: Every 5 km-radius circle is drawn around the central point of an AOD observation. Yellow # mark temporary closure locations, red & mark permanent closure locations. The background grid is 2.5 km × 2.5 km. (For interpretation of references to color in this figure legend, the reader is referred to the web version of this article.)

In Fig. 4, we show the 5 km-radius circles around all AOD points observed on July 1, 2000 and July 2, 2000 respectively. The 10 km resolution of AOD data implies that nearby AOD points should be roughly 10 km apart if they are from the same satellite. However, we have two satellites per day, the two satellites follow different paths, and the path of each satellite varies in a 16-day cycle. This explains why some of the AOD circles overlap in a day and the exact locations of AOD circles move from one day to another. In principle, combining data from the two satellites gives us a daily spatial resolution of AOD finer than 10 km. To better display our data variations, we overlay the AOD circles on a map of Beijing, together with the 2.5 km × 2.5 km grid and locations of plant closure. As shown in Fig. 4, 12 AOD circles cover a closure location on July 1, 2000 and this number is 4 in the next day. Throughout our AOD sample (2297 days, Beijing only), there are on average 48 AOD points per day, 11% of which cover at least one closure location.

*Supplemental data*

In addition to the API, meteorological, and satellite data, we acquired data on economic development indicators, including GDP growth rate, GDP per capita, total industrial production, and population density by city and year from the statistical yearly book published by the National Statistical Bureau.

Other data include the 1999 total energy consumption at the provincial level from the China Energy Data Book, and the 1999 total number of motor vehicles by city from the China Transportation Yearbook of 2000. Our analysis allows these two variables to affect a quadratic time trend of air pollution. We do not use the after-2000 data on energy consumption and motor vehicles because a couple of Olympic-motivated policies target them directly. A dummy for heating season is defined as one if a city has a regular heating supply during the winter and if the date under study is between November 15 and March 15.[20]

## Main results

*Descriptive analysis*

Table 2 reports the average daily API by treatment periods and city groups. Before the establishment of the BOCOG, the average APIs of Beijing and its neighboring cities were 20–50 points higher than that of control and co-host cities. While the API of every city group improved before the end of the Games, neighboring cities did not show improvement in the preparation period. In comparison, the improvement in Beijing was not obvious until the start of the Games. During the Games, the API of Beijing and its neighbor cities was better than the rest of the sample. After the Games, every city group reverted, but not fully to where it had been before the setup of the BOCOG. Similar patterns appear in the absolute levels of TSP, which were inferred using the reported API.[21]

Fig. 5 shows the detailed API by date and city groups. To facilitate visual comparison, every data point plotted in Fig. 5 represents a 40-day moving average of API surrounding a specific date. Over time, API is trended down for every group. There are strong seasonal variations: high values in winter and low in summer. This suggests that the better API during the summer Games (as shown in Table 2) could be driven by season instead of real improvement and a simple before-after comparison of Beijing (as in UNCP 2009) tends to overestimate the air quality improvement due to the Olympic Games. Across groups, control and co-host cities show similar fluctuations in API. In comparison, Beijing and neighboring cities are more similar to each other in terms of variation in API than to the control and co-host cities.

Both Table 2 and Fig. 5 indicate significant variations across time, cities, and seasons. A pretreatment trend test, after controlling for city fixed effects and day fixed effects, still shows significantly different trends across the four city groups, suggesting that more specific controls such as city-specific trends might be needed to derive any meaningful inferences about the causal impact of the Olympic Games.[22]

Table 3 summarizes the average AOD by city groups and treatment periods. Fig. 6 shows strong seasonality as well as similarity across the four city groups for AOD. As we expected, AOD is positively correlated with API (correlation $\sim$0.22). As stated above, the suspended particulates that AOD captures can exist in any part of the atmosphere, and atmospheric lifetime depends on pollutants and altitudes. In light of this, we decompose the Post-Games period into 5 spans, namely 1 month, 2–3 months, 4–6 months, 7–10 months, and 11–16 months after the Games. As shown in Table 4, the AOD of Beijing increased during the Games and the most significant drop in AOD appeared in 2–5 months after the Games. By spring 2009, the AOD of Beijing bounced back to that of the benchmark period but improved somewhat in the rest of 2009. Similar improvement and reversion patterns appear in Fig. 7 when we plot the satellite-based AOD over Beijing for the periods before, during, immediately after, and one year after the Games. The plotted AOD were corrected for meteorological conditions and spatiotemporal trends in and around Beijing.

*Regression results of API*

Defining the unit of observation as city ($c$) by date ($d$), we use the following two specifications to detect the effect of the Olympic Games on API.[23] The first specification compares Beijing to other cities as a whole, the second specification allows

[20] Roughly speaking, cities to the north of the Huai River have a regular heating supply. More detailed city-by-city variation is borrowed from Almond et al. (2009). November 15 to March 15 are the heating supply dates for Beijing. We do not know the exact heating supply dates for other cities with regular heating supply.

[21] Inference is available if the API is above 50 and the dominant pollutant is $PM_{10}$.

[22] One possible explanation for differential trends is that some co-host and neighbor cities tend to have idiosyncratic features that do not exist for Beijing and control cities. For example, two neighbor cities (Taiyuan and Huhehaote) and one co-host city (Shenyang) have many heavy industries such as iron and steel. Mega cities around Beijing, including Tiayuan and Huhehaote, are particularly rich in coal mines, which cause significant pollution. Such problem does not exist in control and other treatment cities in our sample. Another two co-host cites – Qingdao and Qinhuangdao – are tourism driven and in general have much better air pollution.

[23] Using API instead of ln(API) as the dependent variable yields similar results. We choose to report API for an easier comparison of regression coefficient and the raw data summary.

**Table 2**
Summary of daily average API and inferred $PM_{10}$ by treatment periods and city groups.

| API | Control cities | Beijing | Co-host cities | Neighbor cities |
|---|---|---|---|---|
| Benchmark period (06/05/00–12/12/01) | 76.08 | 109.01 | 88.16 | 126.79 |
| Preparation (12/13/01–08/07/08) | 72.36 | 102.93 | 78.79 | 93.11 |
| Preparation 1 (12/13/01–12/31/04) | 74.91 | 104.02 | 82.82 | 102.90 |
| Preparation 2 (01/01/05–08/07/08) | 70.18 | 102.01 | 75.36 | 84.81 |
| Olympic Games (08/08/08–09/17/08) | 56.16 | 54.88 | 57.34 | 52.47 |
| After Games (09/18/08–12/31/09) | 65.55 | 81.83 | 70.78 | 73.11 |
| After Games 1 (09/18/08–10/17/08) | 63.58 | 66.63 | 65.93 | 62.16 |
| After Games 2 (10/18/08–12/17/08) | 73.12 | 89.36 | 76.08 | 86.09 |
| After Games 3 (12/18/08–03/17/09) | 74.13 | 85.07 | 79.60 | 86.99 |
| After Games 4 (03/18/09–07/17/09) | 61.82 | 81.35 | 67.18 | 70.26 |
| After Games 5 (07/18/09–10/31/09) | 58.82 | 79.62 | 65.84 | 60.35 |
| Total | 71.96 | 100.84 | 78.9 | 95.7 |

| $PM_{10}$ ($\mu g/m^3$) inferred from API (conditional on API $>=50$ and dominant pollutant $=PM_{10}$) | Control cities | Beijing | Co-host cities | Neighbor cities |
|---|---|---|---|---|
| Benchmark period (06/05/00–12/12/01) | 120.22 | 173.51 | 134.6 | 200.15 |
| Preparation (12/13/01–08/07/08) | 113.63 | 165.46 | 117.15 | 145.96 |
| Preparation 1 (12/13/01–12/31/04) | 119.21 | 168.29 | 124.97 | 160.82 |
| Preparation 2 (01/01/05–08/07/08) | 108.73 | 163.18 | 109.95 | 132.43 |
| Olympic Games (08/08/08–09/17/08) | 83.21 | 83.00 | 84.75 | 72.82 |
| After Games (09/18/08–12/31/09) | 103.33 | 128.35 | 103.2 | 106.7 |
| After Games 1 (09/18/08–10/17/08) | 97.13 | 111.81 | 97.93 | 100.72 |
| After Games 2 (10/18/08–12/17/08) | 113.82 | 146.62 | 114.96 | 130.85 |
| After Games 3 (12/18/08–03/17/09) | 119.17 | 139.31 | 120.75 | 123.74 |
| After Games 4 (03/18/09–07/17/09) | 97.33 | 121.76 | 95.49 | 104.87 |
| After Games 5 (07/18/09–10/31/09) | 91.31 | 121.78 | 96.91 | 88.44 |
| Total | 113.17 | 161.66 | 118.01 | 150.63 |

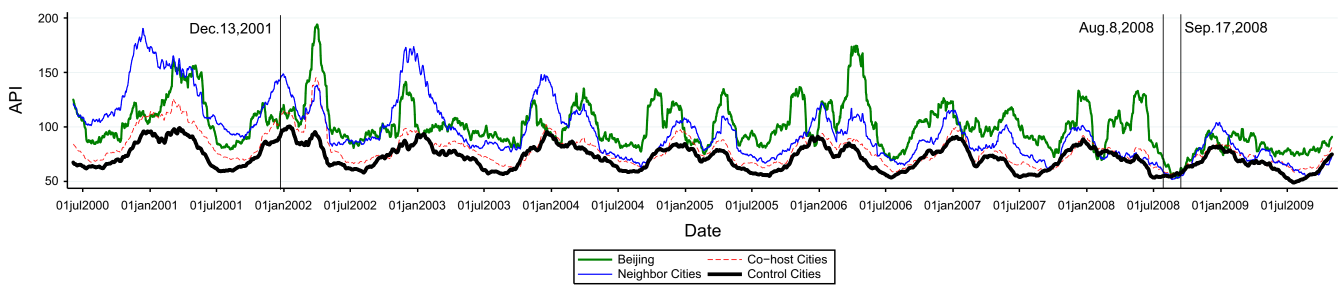


**Fig. 5.** Time series of API by city group and treatment periods. (Forty-day moving average: the API at date $t$ is $API(t)=1/41\sum_{i=-120}^{20}API(t+i)$.)

**Table 3**
Summary of AOD by treatment periods and city groups.

| AOD | Control cities | Beijing | Co-host cities | Neighbor cities |
|---|---|---|---|---|
| Benchmark period (02/25/00–12/12/01) | 0.55 | 0.53 | 0.52 | 0.48 |
| Preparation (12/13/01–08/07/08) | 0.62 | 0.61 | 0.62 | 0.53 |
| Preparation 1 (12/13/01–12/31/04) | 0.59 | 0.59 | 0.57 | 0.50 |
| Preparation 2 (01/01/05–08/07/08) | 0.64 | 0.63 | 0.65 | 0.55 |
| Olympic Games (08/08/08–9/17/08) | 0.57 | 0.56 | 0.55 | 0.45 |
| After Games (09/18/08–12/31/09) | 0.53 | 0.44 | 0.46 | 0.35 |
| After Games 1 (09/18/08–10/17/08) | 0.59 | 0.54 | 0.50 | 0.42 |
| After Games 2 (10/18/08–12/17/08) | 0.42 | 0.26 | 0.31 | 0.21 |
| After Games 3 (12/18/08–03/17/09) | 0.50 | 0.27 | 0.39 | 0.30 |
| After Games 4 (03/18/09–07/17/09) | 0.72 | 0.63 | 0.65 | 0.51 |
| After Games 5 (07/18/09–12/31/09) | 0.49 | 0.45 | 0.47 | 0.33 |
| Total | 0.60 | 0.58 | 0.59 | 0.50 |

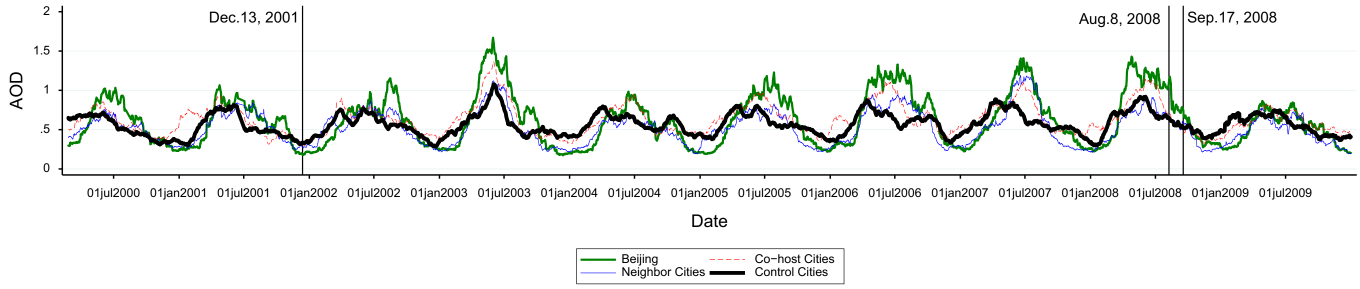


**Fig. 6.** Time series of satellite-based AOD by city group and treatment periods. (Forty-day moving average: the AOD at date $t$ is $AOD(t) = 1/41\sum_{i=\,120}^{20} AOD(t+i)$.)

**Table 4**
Main results on API (unit of observation: city–day).

| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | API | API | API | API | API | API |
| BJ × Preparation | −0.334 (2.193) | −2.928 (1.842) | −4.922* (2.640) | −3.974 (2.692) | −4.030 (2.998) | −4.093 (2.790) |
| BJ × During | −29.423*** (3.611) | −34.820*** (2.346) | −34.335*** (2.260) | −33.971*** (2.260) | −35.234*** (2.547) | −35.579*** (2.350) |
| BJ × After | −13.208*** (2.632) | −19.173*** (1.857) | −19.643*** (1.780) | −19.090*** (2.001) | −19.605*** (2.312) | −19.750*** (2.140) |
| Co-host × Preparation | | | | | | −1.081 (1.587) |
| Co-host × During | | | | | | −1.806 (2.110) |
| Co-host × After Games | | | | | | 4.709** (2.233) |
| Neighbor × Preparation | | | | | | −13.225*** (1.733) |
| Neighbor × During | | | | | | −18.875*** (2.339) |
| Neighbor × After Games | | | | | | −6.742** (2.644) |
| Weather | Y | Y | Y | Y | Y | Y |
| City FE | Y | Y | Y | Y | Y | Y |
| Date FE | Y | Y | Y | Y | Y | Y |
| City-specific linear trends | | Y | Y | Y | Y | Y |
| Energy&Vehicle*date ^ 2 | | | Y | Y | Y | Y |
| Heating | | | Y | Y | Y | Y |
| Socioeconomic factors | | | | Y | Y | Y |
| Co-host and neighbor cities | Included | Included | Included | Included | Excluded | Included |
| Observations | 126,688 | 126,688 | 126,688 | 126,688 | 99,584 | 126,688 |
| *R*-squared | 0.416 | 0.433 | 0.439 | 0.439 | 0.429 | 0.440 |

*Note*: Clustered standard errors in parentheses. Socioeconomic factors include GDP growth rate, average GDP, industrial production, and population density by city and year. Weather includes rainfall, temperature, barometric pressure, sunshine, humidity if rainfall is zero, wind velocity, four dummies for wind direction (east, south, west and north) by city and date.

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

separate treatment effects on co-host and neighbor cities.

$$\text{API}_{cd} = \alpha_c + \beta_d + \gamma_c t + \sum_x \delta_{BJ,x} 1_{BJ}\text{period}_x + \lambda W_{cd} + \eta X_{cy} + \phi E_{c,1999} t^2 + \varphi V_{c,1999} t^2 + \pi H_{cd} + \varepsilon_{cd} \quad (1)$$

$$\text{API}_{cd} = \alpha_c + \beta_d + \gamma_c t + \sum_x \delta_{BJ,x} 1_{BJ}\text{period}_x + \sum_x \delta_{cohost,x} 1_{cohost}\text{period}_x + \sum_x \delta_{neighbor,x} 1_{neighbor}\text{period}_x + \lambda W_{cd} + \eta X_{cy} + \phi E_{c,1999} t^2 + \varphi V_{c,1999} t^2 + \pi H_{cd} + \varepsilon_{cd}. \quad (2)$$

In both specifications, $\alpha_c$ denotes city fixed effects, $\beta_d$ denotes date fixed effects, $t$ denotes the day count between 6/5/2000 and $d$ so that $\gamma_c t$ captures city-specific time trend. The key variables are the interaction of the Beijing dummy and each treatment period. In the most basic form, $\{period_x\}$ distinguishes preparation from during and after the Games. A more detailed version decomposes preparation into 2001–2004 and 2005–2008, and the Post-Games period into 1, 2–3, 4–6, 7–10, and 11–13 months post the Games.

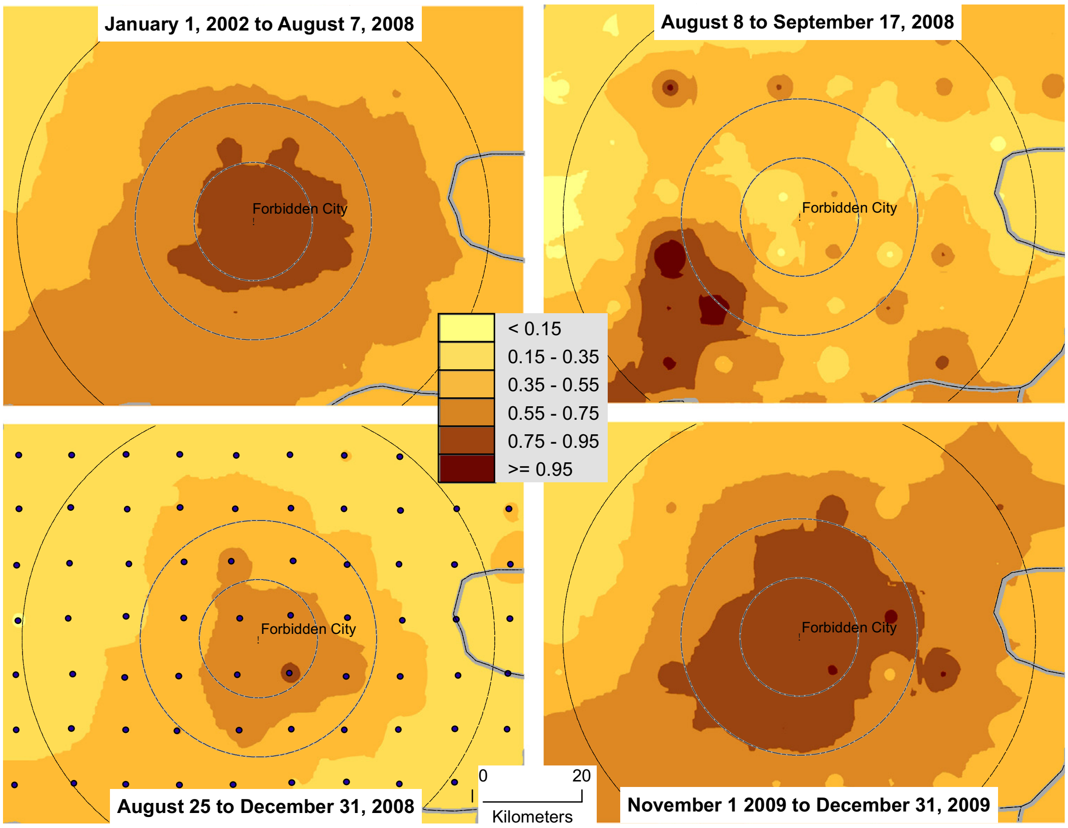


**Fig. 7.** Satellite-based AOD, corrected for meteorological conditions and spatiotemporal trends in and around Beijing.

$W_{cd}$ denotes CMA reported weather conditions, including rainfall, temperature, atmospheric pressure, visibility, relative humidity, wind velocity, and four dummies for wind direction (east, south, west and north) by city and date, $X_{cy}$ denotes socioeconomic factors including GDP growth rate, GDP per capita, industrial production, and population density by city and year, $E_{c,1999}$ denotes energy use of city c in year 1999, $V_{c,1999}$ denotes the number of registered motor vehicles of city c in year 1999, and $H_{cd}$ is the dummy of heating season. We use 1999 instead of yearly data on energy use and vehicle stock because many Olympic preparation efforts might have a direct impact on them. To account for their potential growth independent of the Olympic Games, we include the interactions of $t^2$ with the 1999 energy use and the 1999 vehicle numbers.[24] The error term, $\varepsilon_{cd}$, is clustered by each individual city, except that all the co-host cities are pooled as one cluster and all neighbor cities are pooled as another cluster.

Table 4 presents the estimates of $\delta_{BJ,x}$, $\delta_{cohost,x}$ and $\delta_{neighbor,x}$ in six columns. Columns 1–4 contrast Beijing with all the other 36 cities. Controlling for daily weather, city fixed effects, and date fixed effects, Column 1 shows that Beijing's API was slightly better (−0.334, statistically insignificant) in the preparation period than the API before the creation of the BOCOG (109.31). The effect, measured by decline in API, was the highest during the Games (a decline of 29.42 in API) but significantly smaller (13.21) after the Games. Both numbers are significant with 99% confidence. To test the comparability of Beijing and other cities, we perform a pre-treatment test using data before the setup of the BOCOG. Specifically, we divided the pre-treatment period into two sub-periods: 6/5/2000–12/31/2000 and 1/1/2001–12/12/2001. Using the first segment as a benchmark, we regressed the pre-treatment API on the interaction of Beijing and the dummy of the second period, after controlling for weather, city fixed effects and date fixed effects. The *F*-statistics for this interaction coefficient are positive and significant (22.46).

This finding motivates us to progressively add the city-specific trend in Column 2, vehicle, energy and heating controls in Column 3, and city–year socioeconomic factors in Column 4. Column 5 uses the same specification as Column 4 but excludes co-host and neighbor cities from the sample. Column 6 keeps co-host and neighbor cities in the sample, but treats them as two separate groups with different coefficients in different periods.[25]

The estimates of $\delta_{BJ,x}$ are robust across columns, all showing the greatest improvement during the Games and less improvement after the Games. According to Column (5), Beijing improved the API by 35.234 during the Games (relative to an average of 109.01 before the establishment of the BOCOG) and this improvement dropped to 19.09 in the 13 months after

[24] The interactions of $t\times$ 1999 energy use and $t\times$ 1999 vehicle numbers are absorbed in city-specific linear trends.

[25] Since we only have 1.5 years before the creation of the BOCOG, it is difficult to conduct pretreatment tests after incorporating city-specific linear trends. City-specific variations before the BOCOG could be driven by city-specific seasonality as well. As a robustness check, we have rerun Tables 4 and 5 with city–month fixed effects instead of date fixed effects, and the results are similar.

the Games. In comparison, co-host cities do not demonstrate API improvement during or after the Games, whereas neighbor cities show effects similar to those of Beijing but of smaller magnitudes.

To further examine how the effect of the Olympic Games on Beijing has changed over time, we use the same specification as in Table 4 Columns 4–5 but decompose the preparation period into two sub-periods (prepare1 for 12/13/2001–12/31/2004, prepare 2 for 1/1/2005–8/7/2008), and the Post-Games period into five sub-periods (1, 2–3, 4–6, 7–10 and 11–13 months after 9/18/2008).[26] The results reported in Table 5 suggest that Beijing's API did not change significantly in the two preparation periods and that the most significant improvement of API are observed in the 1 month during the Games (27.122, Column 4). In 1 year, the API improvement dropped to 5.555, though still marginally significant. The *F*-tests conducted at the end of Table 5 suggest that most post-Games reversions of the API improvement are statistically significant.

*Results on AOD*

To address the concern that API may have been subject to manipulation (Andrews, 2008; Chen et al., 2012), we turn to AOD as a more objective measure of air quality. Table 6 reports the regression results as we rerun specification (1) on AOD.[27] We use the city–day average of AOD instead of the original point-specific AOD, partly because the location of each original AOD point is irregular due to varying satellite paths every day, and partly because the point-specific AODs are spatially correlated but we do not have satellite data outside of the 37 cities. Using city–day average of AOD also makes our AOD regression results more comparable to those of API. In the next section, we will account for the spatial structure of point-specific AODs when we examine the mechanisms of air quality improvement within Beijing.

Table 6 focuses on the three crude time spans: before, during, and after the Games. As before, we added controls progressively from Columns 1 to 4, excluded co-host and neighboring cities in Column 5, and estimated the treatment effects for co-host and neighboring cities separately in Column 6. The improvement in AOD (meaning declines) was not statistically significant until after the Games.

To better understand the timing of AOD improvements, Table 7 decomposed the preparation period into prepare1–2 and the post-period into after1–5. For comparison, we reproduce Columns (4) and (5) of Table 6 in Table 7, and contrast them with corresponding results under specification (2). The specification (2) results suggest that AOD improvement reached its peak in 1 and 4–6 months after the Games ($-263.998$ and $-279.421$ for AOD $\times 10^6$). However, after Spring 2009, the AOD improvement of Beijing reverted to $-167.412$ and $-197.149$ (AOD $\times 10^6$). As shown in the *F*-test following Table 7, the reversion is statistically significant.

The reversion of API after the Games suggests that policy interventions may have immediate effects on the surface measurement of air quality. However, the best AOD improvement was achieved several weeks after the Games. The most likely explanation is that cycling and recycling of pollutants, especially fine mode aerosols in the atmosphere, may take time before the full effects of interventions are realized in the atmosphere. While the atmospheric lifetime of aerosol can range from a few days to 1 or more months depending on altitude, our AOD data do not allow us to decompose aerosols by altitude.

One consistent pattern in the API and AOD results is that the air quality improvement does not dissipate monotonically over time. In particular, the treatment effect was reduced from 1 month after the Games (After1) to 2–3 months after the Games (After2), but went back to a level similar to that of After1 in 4–6 months after the Games (After3) before eventually dropping off. We speculate the big dip of treatment effect in After2 is because many economic units reduced their regular economic activities during the Games and had to catch up before the end of 2008.

One may argue that the overall reversion of air quality improvement is due to economic development in 2009. As shown above, the key coefficients are similar with and without controls on GDP growth rate, GDP per capita, industrial production, and population density by city–year (including 2009). This suggests that economic development in 2009 is unlikely to explain the reversion of API and AOD after the Olympic Games, unless the 2009 development is more concentrated on pollution-intensive activities.

## Mechanisms of air quality improvement in Beijing

The above analysis suggests real air quality improvement in Beijing during and after the Games. Before policy makers use this finding to guide future policy interventions, it is important to understand which actions were most effective in improving Beijing's air quality. Four major actions were taken during the preparation period: plant closure, furnace renovation, new automobile emission standards, and traffic control. It is difficult to distinguish these four actions because (1) they overlap in time, (2) some measures such as permanent plant closure and furnace renovation are adopted gradually, and (3) effects from each measure may take time to realize and dissipate over time.

---

[26] As a robustness check, we have examined the time-varying effects differently by singling out 2007, 2006, 2005, 2004, and 2003 from the rest of the preparation period progressively. The API results on Beijing and neighbor cities are similar to what is reported in the draft. The API results on co-host cities are less stable (some coefficients become positive and significant), but they lead to the same conclusion that the Olympic Games did not cause any significant API reduction in co-host cities.

[27] In an unreported table, we have used ln (AOD) as the dependent variable and obtained similar results.

**Table 5.**
Time varying effects of the Olympic Games on API.

- After1 is the first month after Olympics.
- After2 is 2–3 months after the Olympics.
- After3 is 4–6 months after the Olympics.
- After4 is 7–10 months after the Olympics.
- After5 is the rest.

| Variables | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | API | API | API | API |
| BJ × Prepare | −3.974 (2.692) | | −4.030 (2.998) | |
| BJ × Prepare1 | | −2.249 (2.599) | | −2.158 (2.950) |
| BJ × Prepare2 | | 1.944 (2.868) | | 2.433 (3.559) |
| BJ × During Games | −33.971*** (2.260) | −26.558*** (2.386) | −35.234*** (2.547) | −27.122*** (2.352) |
| BJ × After | −19.090*** (2.001) | | −19.605*** (2.312) | |
| BJ × After1 | | −21.082*** (2.701) | | −21.300*** (2.698) |
| BJ × After2 | | −13.518*** (2.921) | | −13.309*** (4.774) |
| BJ × After3 | | −18.922*** (4.237) | | −19.526** (7.504) |
| BJ × After4 | | −5.990* (3.053) | | −5.123 (3.186) |
| BJ × After5 | | −5.889* (3.278) | | −5.555* (3.181) |
| Weather | Y | Y | Y | Y |
| City FE | Y | Y | Y | Y |
| Date FE | Y | Y | Y | Y |
| City-specific linear trends | Y | Y | Y | Y |
| Energy&Vehicle*date ^ 2 | Y | Y | Y | Y |
| Heating | Y | Y | Y | Y |
| Socioeconomic factors | Y | Y | Y | Y |
| Co-host and neighbor cities | Included | Included | Excluded | Excluded |
| Observations | 126,688 | 126,688 | 99,584 | 99,584 |
| *R*-squared | 0.439 | 0.439 | 0.429 | 0.429 |

***F* test for the decreasing effect**

Each *F*-test presented below tests whether, in the same regression, the coefficient corresponding to the row period represents the same treatment effect as the coefficient corresponding to the column period. A cell is marked yellow if the effect in the column (latter) period is significantly smaller than the effect in the row (former) period.
A cell is marked green if the effect in the column (latter) period is significantly larger than the effect in the row (former) period.

*F* test for column 2 of Table 5: test whether the effect is decreasing

| *F*-stat (*p*-value) | BJ × After1 | BJ × After2 | BJ × After3 | BJ × After4 | BJ × After5 |
|---|---|---|---|---|---|
| BJ × During | 18.02*** (0.0002) | 25.67*** (0.0000) | 4.15* (0.0505) | 102.51*** (0.0000) | 79.13*** (0.0000) |
| BJ × After1 | | 8.30*** (0.0073) | 0.32 (0.5732) | 50.28*** (0.0000) | 55.52*** (0.0000) |
| BJ × After2 | | | 6.81** (0.0140) | 6.03** (0.0201) | 7.98*** (0.0083) |
| BJ × After3 | | | | 9.46*** (0.0045) | 14.58** (0.0006) |
| BJ × After4 | | | | | 0.00 (0.9535) |

*F* test for column 4 of Table 5: test whether the effect is decreasing

| *F*-stat (*p*-value) | BJ × After1 | BJ × After2 | BJ × After3 | BJ × After4 | BJ × After5 |
|---|---|---|---|---|---|
| BJ × During | 13.58*** (0.0010) | 10.41*** (0.0032) | 1.14 (0.2938) | 123.34*** (0.0000) | 79.73*** (0.0000) |
| BJ × After1 | | 3.77* (0.0623) | 0.06 (0.8015) | 45.22*** (0.0000) | 44.45** (0.0000) |
| BJ × After2 | | | 3.20* (0.0845) | 3.11* (0.0885) | 4.99** (0.0337) |
| BJ × After3 | | | | 3.79* (0.0616) | 5.29** (0.0291) |
| BJ × After4 | | | | | 0.04 (0.8370) |

*Note*: Clustered standard errors in parentheses. Socioeconomic factors include GDP growth rate, average GDP, industrial production and population density by city and year. Weather includes rainfall, temperature, barometric pressure, sunshine, humidity if rainfall is zero, wind velocity, four dummies for wind direction (east, south, west and north) by city and date.
*$p < 0.1$.
**$p < 0.05$.
***$p < 0.01$.

To address these difficulties, we link the latitudes and longitudes of point-specific AOD data with local policy interventions in Beijing. Since we could not find any location-specific data for furnace renovation and new automobile emission standards, this section focuses on the timing and location of plant closures and traffic control for major and secondary roads in Beijing.

One complication of using point-specific AOD data is that we have to account for the autocorrelation between nearby AOD points. In fact, such autocorrelation can take place along both temporal and spatial dimensions: over time, fresh pollutants from the surface may stay in the atmosphere for an extended period, generating a positive correlation between today's AOD and the AOD of previous days at the same location; across space, aerosol movement may generate a correlation between AOD at point *p* and AOD at nearby points.

**Table 6**
Main results on city-day average of AOD.

| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | AOD × $10^3$ | AOD × $10^3$ | AOD × $10^3$ | AOD × $10^3$ | AOD × $10^3$ | AOD × $10^3$ |
| BJ × Prepare | 9.052 (9.771) | −63.546*** (9.455) | −65.751*** (17.438) | −72.872*** (18.030) | −63.301** (23.597) | −74.719*** (19.037) |
| BJ × During | 123.862*** (32.698) | −3.649 (30.034) | −10.666 (30.492) | −16.517 (31.255) | 9.394 (35.492) | −17.109 (37.885) |
| BJ × After | −57.830*** (15.898) | −191.272*** (24.753) | −178.174*** (27.152) | −196.655*** (26.934) | −207.364*** (26.153) | −214.750*** (27.413) |
| Co-host × Prepare | | | | | | 10.209 (25.531) |
| Co-host × During | | | | | | −40.503 (67.725) |
| Co-host × After | | | | | | −29.529 (59.797) |
| Neighbor × Prepare | | | | | | −48.071** (23.388) |
| Neighbor × During | | | | | | 38.074 (56.278) |
| Neighbor × After | | | | | | −74.934 (64.710) |
| Weather | Y | Y | Y | Y | Y | Y |
| City FE | Y | Y | Y | Y | Y | Y |
| Date FE | Y | Y | Y | Y | Y | Y |
| City_specific linear trend | | Y | Y | Y | Y | Y |
| Energy&Vehicle*date ^ 2 | | | Y | Y | Y | Y |
| Heating | | | Y | Y | Y | Y |
| Socioeconomic factors | | | | Y | Y | Y |
| Co-host and neighbor cities | included | included | included | included | excluded | included |
| Observations | 66,427 | 66,427 | 66,427 | 66,427 | 48,558 | 66,427 |
| *R*-squared | 0.399 | 0.401 | 0.404 | 0.405 | 0.426 | 0.405 |

*Note*: Clustered standard errors in parentheses. Socioeconomic factors include GDP growth rate, average GDP, industrial production and population density by city and year. Weather includes rainfall, temperature, barometric pressure, sunshine, humidity if rainfall is zero, wind velocity, four dummies for wind direction (east, south, west and north) by city and date.

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Let $AOD_{it}$ denote AOD observed over $D \times \{1, 2, \dots, T\}$ where $D \subset R^2$ denotes the spatial domain and $t$ indexes discrete time stamps (days). If distance is partitioned into $S$ intervals for $s = \{1, 2, \dots S\}$ and time lag is partitioned into $L$ intervals for $l = \{1, 2, \dots L\}$, the spatiotemporal autocorrelation coefficient $\rho_{sl}$ between $AOD_{it}$ and $AOD_{i-s,t-l}$ can be computed as

$$\rho_{sl} = \frac{1}{\sigma^2_{AOD}} \frac{\sum_{i \in D, t \in T} \sum_{-i \in D, -t \in T} \forall_{(i,-i)(t,-t)} (AOD_{i,t} - \overline{AOD})(AOD_{-i,-t} - \overline{AOD})}{\sum_{i \in D, t \in T} \sum_{-i \in D, -t \in T} \forall_{(i,-i)(t,-t)}}$$

where $\forall_{(i,-i)(t,-t)} = 1$ if the geographic distance and time intervals between $i$th and $-i$th locations are no more than $s$ and $l$ respectively. $\overline{AOD}$ and $\sigma^2_{AOD}$ are mean and variance of AODs used in the calculation of $\rho_{sl}$.

Using all the AOD data of Beijing (2000–2009), Table 8 presents $\{\rho_{sl}\}$ for time intervals of every 3 days up to 30 days lag and for distance of every twentieth degree up to 0.25° (1° is roughly 111.2 km). As we expected, $\rho_{sl}$ is the highest (0.6944) for 0–3 days lag and 0–0.05° away. Within 0–3 days lag, $\rho_{sl}$ drops gradually across distances. Within the same distance, $\rho_{sl}$ drops sharply from 0–3 days lag to 3–6 days lag, and then stabilizes around 0.16–0.25. One explanation is that both natural sources and human-made air pollution contribute to AOD. As shown in Kumar et al. (2011), air pollution is more local across space and time, so its representation changes abruptly by distance and time. In comparison, natural sources of aerosol are likely to have less heterogeneity, for example, relative humidity (that indirectly represents water vapors) is likely to be same within hundreds of miles and within several days.

We use Table 8 to construct a spatial matrix that indicates AOD autocorrelation across time and distance for every AOD point in our sample for Beijing only. Note that this matrix, denoted as $M_{n \times n}$, is asymmetric, as AOD of day t is set to influence only the AOD of later days, not the AOD of previous days. Since we do not have AOD data immediately outside Beijing, AOD points on the border of Beijing are set to be correlated only with nearby AOD points in Beijing. For ease of computation, we treat autocorrelation beyond 30 days lag and 0.25° away as zero.[28] Autocorrelation persistent throughout the sample should be captured by the constant term and area fixed effects in regression. Because our spatial matrix already accounts for correlations up to 30 days, Table 8 uses year-month fixed effects instead of date fixed effects.

[28] There is a tradeoff between the size of spatial matrix and data limit. The bigger the spatial matrix is (in terms of covered days and distance), the more data points do not have a full set of nearby observations corresponding to the spatial matrix. We have redone the analysis with a spatial matrix that lasts 60 days instead of 30 days, results are similar.

**Table 7.**
Time varying effects of the Olympic Games on city-day average AOD.

- After1 is the first month after Olympics.
- After2 is 2–3 months after the Olympics.
- After3 is 4–6 months after the Olympics.
- After4 is 7–10 months after the Olympics.
- After5 is the rest.

| Variables | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | AOD × $10^3$ | AOD × $10^3$ | AOD × $10^3$ | AOD × $10^3$ |
| BJ × Prepare | −72.872*** (18.030) | | −63.301** (23.597) | |
| BJ × Prepare1 | | −63.802*** (19.668) | | −61.743** (26.709) |
| BJ × Prepare2 | | −41.858 (27.885) | | −58.473 (37.790) |
| BJ × During | −16.517 (31.255) | 21.862 (36.768) | 9.394 (35.492) | 16.133 (43.797) |
| BJ × After | −196.655*** (26.934) | | −207.364*** (26.153) | |
| BJ × After1 | | −219.711*** (33.688) | | −263.998*** (36.531) |
| BJ × After2 | | −127.692*** (42.186) | | −164.958*** (47.657) |
| BJ × After3 | | −232.143*** (43.421) | | −279.421*** (46.483) |
| BJ × After4 | | −119.656*** (30.855) | | −167.412*** (29.029) |
| BJ × After5 | | −148.945*** (40.247) | | −197.149*** (41.403) |
| Weather | Y | Y | | Y |
| City FE | Y | Y | | Y |
| Date FE | Y | Y | | Y |
| City_specific linear trend | Y | Y | | Y |
| Energy&Vehicle*date ^ 2 | Y | Y | | Y |
| Heating | Y | Y | | Y |
| Socioeconomic factors | Y | Y | | Y |
| Co-host and neighbor cities | Included | Included | Excluded | Excluded |
| Observations | 66,427 | 66,427 | 48,558 | 48,558 |
| *R*-squared | 0.405 | 0.405 | 0.426 | 0.426 |

***F* test for after-Olympic periods**

Each *F*-test presented below tests whether, in the same regression, the coefficient corresponding to the row period represents the same treatment effect as the coefficient corresponding to the column period. A cell is marked yellow if the effect in the column (latter) period is significantly smaller than the effect in the row (former) period. A cell is marked green if the effect in the column (latter) period is significantly larger than the effect in the row (former) period.

*F* test for column 2 of Table 7: test whether the effect is decreasing

| *F*-stat (*p*-value) | BJ × After1 | BJ × After2 | BJ × After3 | BJ × After4 | BJ × After5 |
|---|---|---|---|---|---|
| BJ × During | 43.90*** (0.0000) | 10.40*** (0.0027) | 28.34*** (0.0000) | 18.09*** (0.0001) | 17.53*** (0.0002) |
| BJ × After1 | | 9.99*** (0.0032) | 0.14 (0.7115) | 22.46* (0.0000) | 9.14** (0.0046) |
| BJ × After2 | | | 24.40*** (0.0000) | 0.07 (0.7889) | 1.01 (0.3210) |
| BJ × After3 | | | | 18.06*** (0.0001) | 12.08*** (0.0013) |
| BJ × After4 | | | | | 1.45 (0.2365) |

*F* test for column 4 of Table 7: test whether the effect is decreasing

| *F*-stat (*p*-value) | BJ × After1 | BJ × After2 | BJ × After3 | BJ × After4 | BJ × After5 |
|---|---|---|---|---|---|
| BJ × During | 63.65** (0.0000) | 21.18*** (0.0001) | 58.31*** (0.0000) | 31.11** (0.0000) | 59.23** (0.0000) |
| BJ × After1 | | 7.56** (0.0104) | 0.16 (0.6884) | 13.14*** (0.0011) | 6.50** (0.0166) |
| BJ × After2 | | | 31.57*** (0.0000) | 0.00 (0.9453) | 0.83 (0.3689) |
| BJ × After3 | | | | 14.09*** (0.0008) | 4.75** (0.0379) |
| BJ × After4 | | | | | 0.90 (0.3513) |

As described in Section 4, we construct variables for permanent plant closure ($close\_per_{gd}$), temporary plant closure ($close\_tem_{gd}$) and road density ($road\_den_g$) for each 2.5 km cell, and aggregate them to match the spatial resolution of AOD (~10 km × 10 km). To capture Olympic-motivated policy interventions, we interact the time-invariant $road\_den_g$ with seven period dummies of preparation for the Games, during the Games, and 1, 2–3, 4–6, 7–10 and 11–15 months after the Games. We expect the effects of the Games to be greater in an area with more major and secondary roads. To capture the potentially time-varying effect of $close\_per_{gd}$ and $close\_tem_{gd}$, we interact $close\_per_{gd}$ with 1, 2–3, 4–6, and 7+ months after the closure date and $close\_tem_{gd}$ with during, 1 month after, 2–3 months after, and 4–6 months after the temporary closure.

We apply the AOD data of Beijing (at center point $p$ date $d$) to the following specification:

$$AOD_{pd} = \alpha_G + \beta_d + M \cdot \overrightarrow{AOD} + \sum_{k=1}^{7} \theta_k \cdot road\_den_p \cdot period_d^k + \sum_{m=1}^{4} \mu_m \cdot close\_per_{pd} \cdot period_d^m + \sum_{n=1}^{4} \delta_n \cdot close\_tem_{pd} \cdot period_d^n + \lambda W_{pd} + \varepsilon_{pd} \quad (3)$$

where $\alpha_G$ represent area fixed effects for each 10 km × 10 km square in Beijing and $\overrightarrow{AOD}$ denotes the whole vector of AOD data in our Beijing sample.

**Table 8**
Time-space lagged autocorrelation of point-specific AOD.

| Time lag (days) | Distance lag (deg) 1°~111.2 km | | | | |
|---|---|---|---|---|---|
| | 0–0.05 | 0.5–0.1 | 0.1–0.15 | 0.15–0.2 | 0.2–0.25 |
| 0–3 | 0.69442 | 0.53919 | 0.540604 | 0.540204 | 0.523047 |
| 3–6 | 0.20762 | 0.209963 | 0.211243 | 0.208595 | 0.207493 |
| 6–9 | 0.173835 | 0.177126 | 0.174498 | 0.172113 | 0.16961 |
| 9–12 | 0.192621 | 0.188814 | 0.189442 | 0.185158 | 0.181928 |
| 12–15 | 0.214691 | 0.215945 | 0.211458 | 0.206985 | 0.205432 |
| 15–18 | 0.254826 | 0.252079 | 0.24252 | 0.245517 | 0.242826 |
| 18–21 | 0.212634 | 0.212047 | 0.21218 | 0.211591 | 0.209375 |
| 21–24 | 0.169435 | 0.165713 | 0.168869 | 0.165481 | 0.164262 |
| 24–27 | 0.166789 | 0.16738 | 0.164855 | 0.164314 | 0.163078 |
| 27–30 | 0.176688 | 0.181337 | 0.182621 | 0.180129 | 0.178192 |

**Table 9**
Mechanism detection using point-specific AOD and location-specific policies in Beijing.

| Variables | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | AOD × $10^6$ | AOD × $10^6$ | AOD × $10^6$ | AOD × $10^6$ |
| M × AOD × $10^6$ | 0.012*** (0.000) | 0.012*** (0.000) | 0.012*** (0.000) | 0.009*** (0.000) |
| roadlen_prepare | −0.363*** (0.060) | −0.282*** (0.062) | −0.274*** (0.061) | −0.296*** (0.066) |
| roadlen_during | −0.246** (0.096) | −0.159* (0.094) | −0.163* (0.094) | −0.356*** (0.079) |
| roadlen_after1 | −0.673*** (0.081) | −0.527*** (0.078) | −0.530*** (0.078) | −0.590*** (0.088) |
| roadlen_after2 | −0.960*** (0.090) | −0.667*** (0.090) | −0.652*** (0.086) | −0.799*** (0.075) |
| roadlen_after3 | −0.725*** (0.154) | −0.495*** (0.143) | −0.457*** (0.140) | −0.744*** (0.154) |
| roadlen_after4 | −0.144 (0.101) | −0.007 (0.098) | 0.007 (0.096) | −0.050 (0.094) |
| roadlen_after5 | −0.260** (0.100) | −0.331*** (0.111) | −0.307** (0.114) | −0.327*** (0.110) |
| close_per1 | 445,525.725* (256,636.738) | 659,358.984** (266,452.755) | 655,929.676** (262,980.583) | 544,865.483** (266,562.235) |
| close_per2 | −15,195.653 (69,649.222) | 23,448.655 (65,706.364) | 16,674.837 (62,490.297) | 50,054.209 (45,399.643) |
| close_per3 | −121,136.575** (58,745.127) | −83,118.285* (42,318.534) | −86,676.662** (42,697.589) | −90,844.879*** (32,961.998) |
| close_per4 | 42,502.676** (19,653.300) | 51,466.056** (19,753.803) | 46,521.674** (19,436.654) | 50,342.507*** (17,811.943) |
| close_tem0 | −42,025.005 (39,510.433) | −20,206.625 (37,156.966) | −19,740.399 (37,012.460) | −23,531.310 (31,071.707) |
| close_tem1 | −47,131.959* (25,725.985) | −42,592.546 (25,299.158) | −40,530.280 (25,189.519) | −40,040.400* (20,657.620) |
| close_tem2 | −53,514.269*** (17,103.852) | −25,380.400 (15,931.675) | −20,193.290 (16,099.744) | −25,715.695 (16,748.430) |
| close_tem3 | −16,327.612 (18,736.924) | −20,254.426 (17,502.749) | −17,842.166 (16,925.686) | 7840.524 (16,452.493) |
| Year*month FE | | Y | Y | Y |
| Grid FE | | | Y | Y |
| Weather | | | | Y |
| Observations | 102,369 | 102,178 | 102,178 | 102,178 |
| *R*-squared | 0.216 | 0.310 | 0.313 | 0.474 |

*Note*: Clustered standard errors (by 10 km × 10 km area) in parentheses. Linear date count is controlled for in the first column. Weather of point $p$ at date $d$ includes three independent factors derived from the raw data on temperature, humidity, *etc.* M refers to the spatial matrix. Roadlen_after1–5 refers to the interactions of road length and the dummies of 1, 2–3, 4–6, 7–10 and 11–15 months after the Games. Close_per1–4 refers to the interactions of permanent plant closure to the dummies of 1, 2–3, 4–6, and 7+ months after the permanent closure date. Close_tem0–4 refers to the interactions of temporary plant closure to the dummy of during temporary closure or the dummies of 1, 2–3, and 4–6 months after temporary closure.

* $p < 0.1$.

** $p < 0.05$.

*** $p < 0.01$.

Obviously, $\overrightarrow{AOD}$ is endogenous on the right hand side. Given the spatial structure $M$ (as calculated from autocorrelations in Table 8), spatial econometrians have several ways to address the endogeneity problem (Anselin, 2010; Kelejian and Prucha, 1998; Drukker et al., 2013). One is to move $M \cdot \overrightarrow{AOD}$ to the left hand side and estimate parameters by maximum likelihood. Another is to apply the spatial structure $M$ to exogenous variables $(road\_den_p, close\_per_{pd}, close\_tem_{pd}, W_{pd})$ on the right hand side, use $M \cdot \overrightarrow{close\_per}$, $M \cdot \overrightarrow{close\_tem}$, $M \cdot \overrightarrow{road\_len}$ and $M \cdot \overrightarrow{W}$ as instruments for $M \cdot \overrightarrow{AOD}$ and estimate parameters using two-stage least square. We adopt the second approach because $M$ is too high-dimensional for maximum likelihood estimation.

Table 9 reports four sets of results with progressive control of year-month fixed effects,[29] area fixed effects, and weather variables. As we expect, the temporal–spatial structure of AOD plays a significant role across all columns. In addition, it is clear that traffic control was effective in improving AOD in the areas with more roads. While this improvement was

[29] Controlling for date fixed effects creates a collinearity problem with the spatial structure.

significant during the Games, it was the greatest 2–3 months after the Games and then tapered off 6 months after the Games. This finding suggests that the effect of traffic control on AOD is still delayed, even after we control for the temporal and spatial autocorrelation of AOD. It also suggests that the strictest traffic control (50% of vehicles off road) was effective in reducing AOD temporarily, but the weaker form of traffic control that continued after the Games (vehicles off road one of 5 weekdays) was less effective. The latter is consistent with evidence from Mexico City (Davis, 2008).

Similarly, temporary closure had the largest reduction effect on AOD 1 month after the closure and this effect declined afterwards. In comparison, the effect of permanent closure was not significant until 4–6 months after the closure date and dropped quickly afterwards. This is probably because some permanent closures were gradual: for example, the largest production unit of Capital Steel was closed in December 2007 (and therefore we use 12/31/2007 as the closure date for Capital Steel) but Capital Steel kept some minor production even during the Games.

The lack of permanent effects was not surprising, as temporary closure was only effective immediately before and during the Games, and even if permanent closure had a permanent effect on ground emission, nearby aerosols may travel to mitigate the effects.

The estimates reported in Table 9 allow us to compare the effectiveness of permanent plant closure, temporary plant closure, and traffic control. The largest coefficient of permanent plant closure on AOD improvement suggests that closing one plant permanently will at best improve the AOD within a 5 km radius by 0.091 units. This is a non-trivial effect, considering the fact that the average AOD of Beijing was 0.53 before the setup of the BOCOG. In comparison, to achieve the same effect by other measures, one would need to temporarily close 2.27 plants or restrict on-road vehicles to half in an AOD area that had a total length of 113.7 km in major and secondary roads. Given the fact that the road length in a typical 5 km radius surrounding a center point of AOD is no more than 12 km, plant closure is much more effective than traffic control for a specific AOD area. However, traffic control can be applied to many AOD areas at the same time, but plant closure is tied to a specific address. In this sense, the total effect of traffic control can be comparable or even greater than closing a single plant, depending on how widely the traffic control is applicable. How to compare the effectiveness of these measures in light of their economic and social costs is a potential topic for future research.

Overall, the detailed analysis of AOD within Beijing shows that both traffic control and plant closure were largely responsible for the air quality improvement in Beijing. But this improvement temporary and short lived after the Games.

## Conclusion

Viewing the 2008 Olympic Games as a political opportunity, China adopted a series of radical measures to improve air quality in Beijing. Based on the publicly reported air pollution index (API), we find that these actions effectively reduced API (*i.e.* improvement in air quality) in Beijing by 24.9% during the Games as compared to one year before any Olympic-motivated action.[30] However, most of this improvement in air quality dissipated 1 year after the Games.[31] The satellite-based AOD data, acquired from NASA, confirms that air quality improvement in Beijing was real but temporary. The AOD analysis also shows a significant correlation between air quality improvement and the timing and location of plant closure and traffic control.

Our results imply that, it is possible to improve air quality through intensive cleaning actions in a fairly short period, but its effectiveness may decline when the motivation for cleaning wanes. It remains an open question as to whether it is more beneficial to society if the same resources were distributed more evenly across geographic space and time. This question, as well as the impact of the air quality improvement on human health and environment, calls for future research.

## References


Almond, D., Chen, Yuyu, Greenstone, Michael, Li, Hongbin, 2009. Winter heating or clean air? Unintended impacts of China's Huai river policy. Am. Econ. Rev. Pap. Proc. 99 (2), 184–190.

Andrews, Steven, 2008. Inconsistencies in air quality metrics: 'Blue Sky' days and PM10 concentrations in Beijing. Environ. Res. Lett. 2008 (3), 034009.

Anselin, Luc, 2010. Thirty years of spatial econometrics. Pap. Reg. Sci. 89 (1).

Becker, Randy, Henderson, Vernon, 2000. Effects of air quality regulations on polluting industries. J. Political Econ. 108 (2), 379–421.

Chay, Kenneth, Greenstone, Michael, 2003. The impact of air pollution on infant mortality: evidence from geographic variation in pollution shocks induced by a recession. Q. J. Econ. 118, 3.

Chen, Yuyu, Jin, Ginger Z., Kumar, Naresh, Shi, Guang, 2012. Gaming in air pollution data? Evidence from China. B.E. J. Econ. Anal. Policy. (advanced tier) 12 (3), ISSN (Online) 1935-1682, http://dx.doi.org/10.1514/1935-1682.3227.

Congleton, R., 1992. Political institutions and pollution control. Rev. Econ. Stat. 74, 412–421.

Chu, D.A., Kaufman, Y.J., Zibordi, G., Chern, J.D., Mao, J., Li, C., Holben, B.N., 2003. Global monitoring of air pollution over land from EOS-Terra MODIS. J. Geophys. Res. 108 (D21), 4661.

Currie, Janet, Neidell, Matthew, 2005. Air pollution and infant health: what can we learn from California's recent experience? Q. J. Econ. 120 (3), 1003–1030.

Davis, Lucas W., 2008. The effect of driving restrictions on air quality in Mexico city. J. Political Econ. 116 (1), 37–80.

Drukker, D.M., Egger, P., Prucha, Ingmar, 2013. On two-step estimation of spatial autoregressive models with autoregressive disturbances and endogenous regressors. Econometric Rev 32 (5–6), 686–733.

Foster, A., Gutierrez, E., Kumar, N., 2009. Voluntary compliance, pollution levels, and infant mortality in Mexico. Am. Econ. Rev. Pap. Proc. 99 (2), 1–11.


[30] The estimated improvement is 27.122 (Column 4 Table 4), which is a 24.9% reduction from the absolute level of API in Beijing before the setup of the BOCOG (109.01).

[31] The estimated improvement of API in Beijing was 27.122 during the Games, and 5.555 11–13 months after. (27.122 − 5.555)/27.122 = 79.52%.

Guinot, Benjamin, 2008. Olympic Games: Beijing Air Quality accessed at ⟨http://www.ambafrance-cn.org⟩ /奥林匹克运动会：北京大气质量, 4570. html on January 10, 2010.
Gupta, Pawan, Christopher, Sundar A., Wang, Jun, Gehrig, Robert, Lee, Yc, Kumar, Naresh, 2006. Satellite remote sensing of particulate matter and air quality assessment over global cities. Atmos. Environ. 40 (30), 5880–5892.
Hazilla, Michael, Kopp, Raymond J., 1990. Social cost of environmental quality regulations: a general equilibrium. J. Political Econ. 98 (4), 853–873.
Henderson, J.Vernon, 1996. Effects of air quality regulation. Am. Econ. Rev. 86 (4), 789–813.
Kathuria, Vinish, 2002. Vehicular pollution control in Delhi: need for integrated approach. Econ. Political Wkly. 37 (12), 1147–1155.
Kaufman, Yoram J., Gobron, Nadine, Pinty, Bernard, Widlowski, Jean-Luc, Verstraete, Michel M., 2002a. Relationship between surface reflectance in the visible and mid-IR used in MODIS aerosol algorithm – theory. Geophys. Res. Lett. 29 (23), 31–34. (0094-8276).
Kaufman, Yoram J., Tanre, D., Halben, B.N., Mattoo, S., Remer, L.A., Eck, T.F., Vaughan, J., Chatenet, B., 2002b. Aerosol radiative impact on spectral solar flux at the surface, derived from principal-plane sky measurements. J. Atmos. Sci. 59 (3), 635–646.
Kelejian, Harry H., Prucha, Ingmar, 1998. A generalized spatial two stage least squares procedure for estimating a spatial autoregressive model with autoregressive disturbances. J. Real Estate Finance Econ. 17 (1998), 99–121.
Kumar, N., 2010. A hybrid approach for predicting PM2.5 exposure. Environ. Health Perspect. 118, 10.
Kumar, N., Foster, A., Tripathi, S.N., Dasguptai, A., Chu, A.D., 2009. Predicting air quality using MODIS data, (in preparation).
Kumar, N., Chu, A.D., Foster, A.D., Peters, T., Willis, R., 2011. Satellite remote sensing for developing time and space resolved estimates of ambient particulate in Cleveland, OH. Aerosol Sci. Technol. 45, 1090–1108.
Levy, R.C., Remer, L.A., et al., 2007a. Global aerosol optical properties and application to Moderate Resolution Imaging Spectroradiometer aerosol retrieval over land. J. Geophys. Res. Atmos. 112, D13.
Levy, R.C., Remer, L.A., et al., 2007b. Second-generation operational algorithm: retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance. J. Geophys. Res. Atmos. 112 (D13).
Li, Chengcai, Mao, Jietai, Lau, Kai-Hon Alexis, Chen, Jay-Chung, Yuan, Zibing, Liu, Xiaoyang, Zhu, Aihua, Liu, Guiqing, 2003. Characteristics of distribution and seasonal variation of aerosol optical depth in eastern China with MODIS products. Chin. Sci. Bull. 48 (22), 2488–2495.
List, John A., Millimet, Daniel L., Fredriksson, Per G., McHone, W.Warren, 2003. Effects of environmental regulations on manufacturing plant births: evidence from a propensity score matching estimator. Rev. Econ. Stat. 85 (4), 944–952.
Murdoch, J., Sandler, T., 1997. The voluntary provision of a pure public good: the case of reduced CFC Emissions and the Montreal Protocol. J. Public Econ. 63, 331–350.
NASA, 2010. The Level 1 and Atmosphere Archive and Distribution System. Retrieved July 3, 2010, from ⟨http://ladsweb.nascom.nasa.gov⟩.
NCDC, 2007. National Climatic Data Center from ⟨http://www.ncdc.noaa.gov/oa/ncdc.html⟩.
Simonich, Stacil L.Massey, 2009. Response to comments on 'Atmospheric Particulate Matter Pollution during the 2008 Beijing Olympics'. Environ. Sci. Technol. (43), 7590–7591.
Streets, David G., Fu, Joshua S., Jang, Carey J., Hao, Jiming, He, Kebin, Tang, Xiaoyan, Zhang, Yuanhang, Wang, Zifa, Li, Zuopan, Zhang, Qiang, Wang, Litao, Wang, Binyu, Yu, Carolyne, 2007. Air quality during the 2008 Beijing Olympic Games. Atmos. Environ. 41, 480–492.
Tang, Xiaoyan, Shao, Min, Hu, Min, Wang, Zifa, Zhang, Junfeng (Jim), 2009. Comment on 'Atmospheric Particulate Matter Pollution during the 2008 Beijing Olympics'. Environ. Sci. Technol. 43, 7588.
Textor, C., Schulz, M., et al., 2006. Analysis and quantification of the diversities of aerosol life cycles within AeroCom. Atmos. Chem. Phys. 6, 1777–1813.
United Nations Environment Programme, 2009. Independent Environmental Assessment Beijing 2008 Olympic Games. Accessed at ⟨http://www.unep.org/publications/UNEP-eBooks/BeijingReport_ebook.pdf⟩.
Viard, V. Brian, Fu, Shihe, 2011. The effect of Beijing's driving restrictions on pollution and economic activity. Working Paper. Accessed at ⟨http://www.ckgsb.edu.cn/personalsites/brianviard/papers.htm⟩.
Wang, Wentao, Primbs, Toby, Tao, Shu, Simonich, Stacil L.Massey, 2009a. Atmospheric particulate matter pollution during the 2008 Beijing Olympics. Environ. Sci. Technol. 43, 5314–5320.
Wang, Xing, Westerdahl, Dane, Chen, Lung Chi, Wu, Ye, Hao, Jiming, Pan, Xiaochuan, Guo, Xinbiao, Zhang, K.Max, 2009b. Evaluating the air quality impacts of the 2008 Beijing Olympic Games: on-road emission factors and black carbon profiles. Atmos. Environ. 43, 4535–4544.
Yao, Xiaohong, Xu, Xiaohong, Sabaliauskas, Kelly, Fang, Ming, 2009. Comment on 'Atmospheric Particulate Matter Pollution during the 2008 Beijing Olympics'. Environ. Sci. Technol. 43, 7589.
Zhang, Qiupei, 2008. Beijing Olympics Environmental Evaluation Report" published by Greenpeace.org at ⟨http://www.greenpeace.org/raw/content/china/zh/press/reports/2008.pdf⟩.