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EVALUATING THE IMPACT OF THE 2008 OLYMPIC GAMES ON AIR QUALITY

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ABSTRACT

To prepare for the 2008 Olympic Games, China adopted a number of radical measures to improve air quality. Using officially reported air pollution index (API) from 2000 to 2009, we show that these measures improved the API of Beijing during and after the Games, but 60% of the effect faded away by the end of October 2009. Since the credibility of API data has been questioned, an objective and indirect measure of air quality at a high spatial resolution – aerosol optimal depth (AOD), derived using the data from the NASA satellites – was analyzed and compared with the API trend. The analysis confirms that the improvement was real but temporary and most improvement was attributable to plant closure and traffic control. Our results suggest that it is possible to achieve real environmental improvement in an authoritarian regime but the magnitude of the effect and how long it lasts depend on the political motivation behind the policy interventions.

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1. Introduction

Air pollution is a great challenge for human health. What policy interventions are effective in improving air quality? How long will their effects last? The radical air-cleaning actions that China took before 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 risked China's stake to host the 2008 Beijing Olympic Games and put China's air pollution under the world's spotlight. Since the primary motive of hosting the Games was to establish a positive image of China, 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 standard, and stringent traffic control, cost over US$10 billion.[2] Plus 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.

Although poor air quality in Beijing drew public attention worldwide before and during the Olympics, China did not allow individual researchers to access *in situ* measurements of air pollution. Given the data constraints, we rely on the official daily air pollution index (API) published by the Ministry of Environmental Protection of China (MEP), as well as the aerosol optical depth (AOD) derived using the data from the Moderate Resolution Imaging Spectraradiomenter (MODIS) aboard NASA's Terra and Aqua satellites (which cross China daily at 10:30am and 1:30pm local time, respectively). API is a composite index of Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), and total suspended particles (TSP); and AOD represents the

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[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.

[2] Both UNEP (2009) and Zhang (2008) report that the planned environmental investment is $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 is $15.7 billion.

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

[4] An official audit from 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 spent by the local government in the name of the Olympic Games (http://www.runblogrun.com/2009/06/beijing_olympics_made_103_mill.html). 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/).

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 facing Chinese officials.

Our main methodology is comparing 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). Time-wise, we take the one and half years before the setup 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 seven-year preparation period (12/13/2001-8/7/2008), the one month during the Olympic and Paralympic Games (8/8/2008-9/17/2008), and 13 months after the Games (9/18/2008-10/31/2009).

After controlling for various factors, we find that the average API of Beijing dropped from 109.01 in 2000 and 2001 to 76.69 during the Games. Most of the improvement did not occur until the Games started. After the Games ended, we estimate that the API of Beijing reverts to 82.52 in one month and to 96.29 ten-to-thirteen months after the Games. In comparison, the AOD of Beijing (which shows a positive relationship with air pollution) started to decline before the Games, continued to decline during the Games, and reached the lowest level 2-6 months after the Games. In contrast to surface measures of API, aerosol can be circulated in the air for a longer life span, so the delay in AOD improvement is not surprising. Consistent with the API findings, the improvement in AOD started to revert since Spring 2009. This suggests that air quality improvement in Beijing was real but temporary. Further analysis of API and visibility (another official statistics related to air pollution but with less media attention) finds little evidence of gaming in API.

The unique setting of Beijing Olympics allows us to compare different air cleaning actions. Accounting for the different timing of actions, we find that the API improvement, especially the improvement in TSP, is most attributable to plant closure and traffic control. More importantly, the fine resolution of AOD enables us to link the center of each AOD observation to road density and plant closure within a five-kilometer radius. As expected, we find more AOD improvements in the areas with greater road density and more plant closures but all of the differential effects decline gradually over time. These findings are consistent with the fact that most plant closures and traffic controls were only 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, the related literature and the data respectively. Section 5 presents the main results on API and AOD. Section 6 addresses the concern of data gaming from Chinese officials. Section 7 examines the mechanisms that can potentially contribute to the air quality improvement of Beijing. Section 8 summarizes the main findings of this paper.

2. Background

China has been known for poor air quality. The 1996 national standard on Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), total suspended particles (TSP), and particulate matter with an aerodynamic diameter of 10 microns or smaller (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 twenty most polluted places in 2007.[5] Some athletes were so concerned about the air quality that they planned to either wear masks in competition or skip the Beijing Olympic Games (Los Angeles Times March 12, 2008; New York Times March 12, 2008).

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 BOCOG was preparing for the 2008 Games, this included infrastructure development, environment improvement, public relation, and logistics. The three main concepts promoted by 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

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[5] http://www.cbsnews.com/stories/2007/06/06/eveningnews/main2895653.shtml.

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 seven year window from the setup of 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 BOCOG (12/12/2001).

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

In 2003 and 2004, Beijing reduced the industrial use of coal by 10 million tons, desulfurated the air pollutants from the YanShan Petrochemical Company, shut down coal-fired generators in 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 in Beijing Thermal Power Plant and Power Plant of the 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 – for the Capital Steel Company – started from 2005 and the biggest action took place toward the end of 2007, the same time as the closure of the Second Beijing Chemical Plant and Beijing Eastern Petrochemical Co. Ltd. Based on these institutions, we define October 31, 2006 as the benchmark point for furnace renovation and December 31, 2007 as the benchmark for plant closure.

Beijing also attempted to control for vehicle emission by adopting new emission standards on March 1, 2008 (applicable to new vehicles only) and restricting 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 one weekday per week.

According to Streets (2007) neighboring provinces and municipalities such as Hebei, Shandong and Tianjin made a significant contribution to air pollution in Beijing. Therefore, co-host and neighbor cities adopted the 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. Given the limited access to time and location specific policies, we report the general API/AOD change for Beijing, co-host and neighbor cities, but restrict the detailed mechanism analysis to Beijing.

While the 2008 Olympic Games triggered many new efforts for cleaning air, some environmental protection policies existed even before 2000. For example, the central government started to build the green great wall in northern China since 1978. A nationwide policy was adopted in 1999 to encourage farmers to convert less productive farm into green land. These policies targeted desertification instead of air pollution, but the two are clearly linked. A more direct nationwide campaign for "blue sky" started in 1997. Defining "blue sky" if API below 100, the central government included the frequency of blue sky days as a performance measure reported by local officials. The 2002 amendment specified that a "model city" must have at least 80% of days with "blue sky" in a calendar year. This standard was raised to 85% in 2008.[6] To the extent that performance evaluation has a significant impact on local government policies, air quality improvements may have occurred nationwide long before the 2008 Games. In our analysis, we control for all the national air-cleaning policies by date fixed effects.

Some earlier air-cleaning efforts were Beijing specific. Before the setup of the BOCOG, the city government of Beijing 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.[7] 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 BOCOG, Beijing adopted many measures, including extended use of clean fuel, introducing desulfuration of equipment, covering

[6] 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).
[7] See Beijing municipal documents 1998 #24 (phase 1), 1999 #249 (phase 2), and 1999 #29 (phase 3) for more details.

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 trend.

3. 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 access to *in situ* measurements of 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 in 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 find that meteorological conditions such as wind, precipitation and humidity account for 40% of the total variation in PM_{10}. This finding motivates us to control for meteorological conditions that can greatly influence concentration and transportation of air pollutants (Kumar et al. 2011).

Wang et al. (2009b) compare 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 do not control for the nationwide trend of air quality between 2007 and 2008. The main finding of Wang et al. (2009b) is that the BC concentration was significantly better during the traffic controls than without the traffic controls. We could not find a precise definition of BC particles in Wang et al. (2009b), but we also suspect BC particles are much correlated to diesel exhaust (either from heavy duty vehicles or industries).

Unlike academic researchers, 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 couple of 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 in Figure 4, 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. Like this paper, UNEP (2009) has used several satellite images from NASA's Terra and Aqua satellites for August 2008, but our resolution of AOD (10 km x 10 km) is much smaller than theirs (100km x 100km) 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 attribute air quality improvement to specific policy interventions.

Andrews (2008) suspected that Beijing may have manipulated the official API data for several reasons: Beijing relocated monitoring stations over time; the 2000 MEP standard for air quality weakened the limits of Nitrogen Oxides and Ozone; the number of days with API between 96 and 100 was significantly higher than the number of days with API between 101 and 105. Guinot (2008) suggests that it is not uncommon to add monitoring stations with economic and urban development and the uncertainty in the API metrics may range from 15% to 25% due to measurement errors. In addition to using high resolution AOD data as an objective measure of air quality, another novel aspect of our research is to investigate the gaming of API using API and visibility, another official statistics related to air pollution but with less media attention.

A growing body of literature has attempted to evaluate the effect policy interventions on air quality in other developing countries. Davis (2008) examines the traffic restrictions in Mexico City (forcing vehicles off the road one 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 to 2001 had little impact on air quality improvement for two potential reasons. First, more vehicles were added on the road after policy went 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. (2009) examined air pollution distribution/redistribution in Delhi in response to a series of air quality regulations. Two alarming findings emerged from this study. First, the air quality of the City improved after the regulations, but the effects of the regulations faded away several years after the regulations. 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 and Kumar (2011) suggests that the improvement in air quality of the City improved respiratory health of Delhi residents and the deteriorated air quality in the neighboring areas is likely to have adverse health effects. Foster, Gutierrez and Kumar (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 less infant mortality due to respiratory causes.

Our research is also related to a broader literature on environmental policies. Several studies in the US have documented the health effects of air pollution (Chay and Greenstone 2002, 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 time 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 in the long run, they also help understand how much air quality improvement can be achieved if an authoritarian government is willing and able to implement intensive measures in a short time.

More specifically, this study is likely to augment our understanding of the political economy of environmental protection in a socialist country. 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 the 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 quicker and at a large scale. These politically motivated interventions set the stage for a social experiment to understand how policy interventions in an authoritarian regime can improve air quality and protect the environment in a relatively short time frame.

4. Data

The data for this research were acquired from several sources: the official API data published by the MEP, visibility and other meteorological data from the China Meteorological Administration (CMA) and the National Climatic Data Center (NCDC 2007), and 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 10km spatial resolution for every day within 100km 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 TSP into a daily air pollution index (API) ranging from 0 to 500.[8] Specifically, suppose a city has M stations and each station monitors NO_2, SO_2 and TSP for N times each day,[9] MEP first computes the daily average of all the MxN measures for each pollutant and then translate the daily mean intensity into pollutant-specific API according to linear spines with the cutoff points defined in Table 1.[10] 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 pollution." A crude categorization refers to a day with API at or below 100 as "blue sky."

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 TSP 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 TSP was upward bounded by the TSP level corresponding to the reported API. In comparison,

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

[9] 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.

[10] For example, if the daily mean of TSP is 370 $\mu g/m^3$, the corresponding API of TSP is (370-300)/(500-300)*(200-100)+100 = 135.

inference on NO_2 and SO_2 was 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. It allows us to control for local temperature, precipitation, barometric pressure, sunshine, humidity and wind. The data also include visibility, the greatest distance at which an observer with normal eyesight can discern a dark object from the horizontal sky. Researchers have shown that API and visibility are negatively correlated (Che et al. 2006, Fan and Li 2008) and visibility is considered to be an important predictor of fine particulates (Ozkaynak et al. 1985, Huang et al. 2009). [11] Like API, visibility is reported by Chinese officials but attracts less media attention than API. For this reason, Section 6 will use visibility to check the reliability and gaming of API. Should there be gaming of API , it should show greater improvement before, during and after the Games than the improvement in visibility.

Conditional on having non-break API and visibility data, our analysis consists of 37 cities.[12] 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.[13] BOCOG defined six cities close to Beijing as "Olympic Environment Protection Cities." Our sample included the three largest neighboring cities: Taiyuan, Shijiazhuang, Huhehaote.[14] The other 28 cities were grouped in the category of control cities. As shown in Figure 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 10km 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. The AOD extraction procedure is

[11] Fine particulates ($PM_{2.5}$), are defined as particulates with less than 2.5μm in aerodynamic diameter.
[12] Although the MEP reports API for 86 cities and the CMA visibility data cover 69 cities, only 42 cities has 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 on June 4, 2008 for all cities. So the "non-break" criterion ignores the missing data on June 4, 2008.
[13] 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.
[14] The other three "Olympic Environment Protection Cities" are Datong, Yangquan and Chifeng. None of them is provincial capital.

available elsewhere (Chu, Kaufman et al. 2003; Levy, Remer et al. 2007; Levy, Remer et al. 2007). In recent years, many researchers have shown that AOD, corrected for meteorological conditions, can predict air quality (Gupta, Christopher et al. 2006; Kumar, Chu et al. 2011). Focusing on Delhi and Kanpur in India and Cleveland in US, Kumar et al. (2009; 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. Since the *in situ* PM_{10} data were not available in China, this paper utilizes AOD corrected for meteorological conditions and spatiotemporal structure.

In addition to being immune to potential data manipulation from Chinese officials, AOD can be extracted at a high spatial resolution (~10km x 10km). 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, Gobron et al. 2002; Kaufman, Tanre et al. 2002). Since the sources of aerosol can be natural (such as dust storm, sea salt forest fire) and anthropogenic (combustion), air quality (PM_{10} concentration) predicted using AOD can vary regionally. We cannot extrapolate the PM_{10} predictive model of Delhi or Cleveland to China. Third, 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 AOD dataset (Kumar 2010).

In total, we retrieved 102,820 valid 10km AOD observations over Beijing from February 25, 2000 to December 31, 2009. Of all the 3,596 calendar days in the time span of this study, only 2,297 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 one hour time interval of AOD time on a given day. This means we assigned the same value of meteorological conditions (from the closest station) to all AOD values in a given city on a 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 in STATA (StataCorp 2010).

Information about location-specific actions was collected for Beijing only. We overlay a 2.5km x 2.5km grid over Beijing, and define 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 has 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 defined as from 7/20/2008 to 9/20/2008. The exact locations of permanently or temporarily closed plants are shown in Figure 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. Figure 3 shows the cell-by-cell distribution of major and secondary roads in Beijing.

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

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. These data were available up to 2008. In the main analysis, dummy variables were created to indicate missing socioeconomic variables in 2009.

To the extent that Beijing's unobservable economic growth may follow a different linear trend over time, it is controlled for in the city-specific trend. To further address the concern that Beijing may experience different economic growth in 2009, we use 2007 and 2008 economic development data to extrapolate the 2009 data for each city separately. In 2008, many economic activities of Beijing were Olympic specific, so this imputation tends to overestimate the 2009 economic growth in Beijing and therefore an analysis controlling for the imputed data should underestimate the fade-away effect in 2009. Our results are robust to the addition of the imputed data.

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 of 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.[15]

5. Main Results

5.1 Descriptive Analysis

Table 2 reports the average daily API by treatment periods and city groups. Before the establishment of 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 was before the setup of the BOCOG. Similar patterns appear in the absolute levels of TSP, which was inferred using

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

the reported API.[16].

Figure 4 shows the detailed API by date and city groups. To facilitate visual comparison, every data point plotted in Figure 4 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 value 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 the control and co-host cities.

Both Table 2 and Figure 4 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 on the causal impact of the Olympic Games.

Table 3 summarizes the average visibility by city groups and treatment periods. In the benchmark period, Beijing's visibility was slightly better than that of the co-host cities but worse than that of control and neighboring cities. After the setup of BOCOG, Beijing's visibility improved over time, while all other city groups reported the best visibility during the Games (Figure 5). Like API, visibility shows strong seasonal variation: low visibility in winter and high in summer.

Consistent with the literature, we find a significantly negative correlation between visibility and API (-0.276, p-value<0.01). Regressing visibility on API and all the other meteorological variables by city-day, resulted in an R-square of 0.404; the coefficient of API was -0.059 with t-statistics equal to -5.04. The strong correlation between visibility and API also indicates toward the fact that 80.12% of city-days in our sample reported TSP as the dominant pollutant.

Table 4 summarizes the average AOD by city groups and treatment periods. Since the small fraction of aerosols cycles and recycles longer (Textor, Schulz et al. 2006), policy interventions may have a lagged effect on AOD. Therefore, we decompose the post period

[16] Inference is available if the API is above 50 and the dominant pollutant is TSP.

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 of 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 Figure 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. Figure 6 shows strong seasonality as well as similarity across the four city groups for AOD. As we expect, AOD is positively correlated with API (correlation ~ 0.22) and negatively correlated with visibility (~ -0.47).

5.2 Regression Results of API

Defining the unit of observation as city (c) by date (d), we use the following specification to detect the effect of the Olympic Games on API:

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

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

We use several sets of control cities: all the other 36 cities as control; excluding the eight co-host and neighbor cities; all the 36 non-Beijing cities but with the co-host and neighbor cities. This amounts to:

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

In both specifications (1) and (2), W_{cd} denotes CMA reported weather conditions, including rainfall, temperature, barometric pressure, sunshine, humidity (if rainfall is zero), 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.[17] The error term, ε_{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 5 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. More specifically, Column 1 controls for daily weather city fixed effects and date fixed effects, Column 2 adds city-specific linear trends, Column 3 adds vehicle and energy controls which include the heating dummy and the interaction of t^2 with energy and vehicle numbers as of 1999. Column 4 adds socioeconomic factors. Column 5 uses the same specification as Column 4 but excludes the co-host and neighbor cities from the sample. Following specification (2), Column 6 keeps co-host and neighbor cities in the sample, but treats them as two separate groups with different coefficients in different periods.

One consistent finding is that most API improvement in Beijing was recorded during and immediately after the Games. Specifically, Column 1 shows that Beijing's API was slightly better (-0.334, statistically insignificant) in the preparation period than the API before the birth of 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 were

[17] The interactions of t*1999 energy use and t*1999 vehicle numbers are absorbed in city specific linear trends.

significant with 99% confidence. A similar pattern persisted when we added city-specific linear trend, energy and socioeconomic factors or used different sets of control cities. The only exception was that, with sufficient controls, the API improvement became statistically significant before the Games but its magnitude was still much smaller than during or after the Games.

Our main assumption is that Beijing was comparable with the control cities without the Game related interventions once controlled for the city-by-city differences using the city fixed effects, the nationwide fluctuation by date fixed effects, the city-specific linear trend, weather and other observable factors. To test this assumption, we perform a pre-treatment test using data before the setup of BOCOG. Specifically, we divided the pre-treatment period into two: 6/5/2000-12/31/2000 and 1/1/2001-12/12/2001. Using the first segment as benchmark, we regressed the pre-treatment API on the interaction of Beijing and the dummy of the second period, in addition to the same controls as in Columns 1-6. The F-statistics for this interaction coefficient, reported at the end of each column, is highly significant in Columns 1-3, but insignificant in Columns 4-6. This suggests that it is important to control for the city-specific trend, energy and socioeconomic factors before we interpret the estimated $\delta_{BJ,x}$ as a causal effect of the Olympic Games on Beijing.

In contrast, if we perform the same pretreatment test on co-host and neighbor cites, the F statistics are significant, suggesting that co-host and neighbor cities are not readily comparable to the 28 control cities and the coefficients reported in Column 6 ($\delta_{cohost,x}$ and $\delta_{neighbor,x}$) cannot be interpreted as the causal effect of the Olympic Games. For this reason, we believe Column 5, which excludes co-host and neighbor cities from the sample, yields the most robust results.[18]

To further examine how the effect of the Olympic Games has changed over time, we use the same specification as in Table 5 Columns 4-5 but decompose the preparation period into two sub-periods (prepare1 for 12/13/2001-12/31/2004, prepare2 for 1/1/2005--8/7/2008), and the post-Games into five sub-periods (1, 2-3, 4-6, 7-10 and 11-13 months after 9/18/2008).[19] Results reported in Table 6 suggest that the API of Beijing's API declined slightly in the two preparation

[18] In an unreported table, we replaced the dependent variable with ln (API) and found similar results in all five columns.

[19] 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 do not cause any significant API reduction in co-host cities.

periods (-5.076 and -2.154), but that improvement was much lower than the reduction of API during the Games (32.319). Interestingly, the API improvement declined to 26.494 one month immediately after the Games and 12.723 eleven to thirteen months after the Games. The F-tests conducted at the end of Table 6 suggest that most of the reversions are statistically significant. In short, the biggest effect of the Olympic Games on Beijing API took place during the Games and roughly 60% of the effect faded away one year after the Games.

5.3 Results on AOD

To address the concern that API may have been subject to manipulated (Andrew 2008), we resort to AOD as a more objective measure of air quality. Table 7 reports the regression results as we rerun specification (1) on AOD. Since the AOD locations are irregular (because of varying satellite path every day), we control for city fixed effects as well as dummies describing whether the distance from the center of AOD to the center of the city is less than 12.5km, between 12.5km and 25km, and greater than 25km. Since the point-time-specific weather conditions (dew point, temperature, wind speed, and relative humidity) were highly auto-correlated, factor analysis was employed to collapse these variables into three uncorrelated factors.

Table 7 focuses on the three crude time spans: before, during and after the Games. The improvement of AOD (meaning declines) was not statistically significant until after the Games. To better understand the timing of AOD improvements, Table 8 decomposed the preparation period into prepare1-2 and the post period into after1-5. Like before, we added controls progressively from Column 1 to Column 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. Table 8 only reports the coefficients of Beijing.

All six columns present a consistent finding: the improvement of AOD started before the Games, sped up during the Games, and reached the best level in 2-6 months after the Games. However, by spring 2009, the AOD improvement of Beijing reverted significantly as compared to the best level. These estimates are greater than that reported in Table 7 because the estimation is somewhat sensitive to how we decompose the preparation period. Different decompositions imply different identification on the coefficient of city-specific time trend. We tried a number of divisions on the preparation periods. While the point estimates vary, we always reach the same conclusion that AOD improvement was the best 2-6 months after the Games and gradually declined afterwards.

The sharper reversion of API after the Games suggest that the policy interventions adopted may have immediate effects on the surface measurement of air quality. However, the best improvement in AOD that represents the optical thickness in the atmosphere and influenced by meteorological conditions was achieved several weeks after the Games. This suggests that cycling and recycling of pollutants, especially fine mode aerosols in the atmosphere may take several weeks before the full effects of interventions are realized in the atmosphere and on the surface. In the exploratory analysis, we controlled for daily weather conditions up to 10 days before the study time. This is the best we can do given the potential colinearity between current and lagged weather. Like in Table 8, significant decline of AOD did not occur in Beijing except for 2-6 months after the Games.

An alternate explanation for the reversion of air quality improvement is economic development in 2009. Unfortunately, the National Bureau of Statistics of China has not published the city-specific report for 2009. Therefore we cannot control for it directly. In the exploratory analysis, we make a linear projection of 2009 socioeconomic factors based on city-specific data of 2007 and 2008. If anything, this tends to overestimate the economic development of Beijing in 2009 because a lot of development in 2008 was driven by one-time investment for the Olympic Games. With the imputed 2009 socioeconomic variable, we rerun Tables 5-10 and find that the results are very much similar to what is reported here. This robustness suggests that the reversion of air quality improvement in Beijing is unlikely driven by the unobserved economic development in 2009.[20]

6. Gaming of API

This section examines API more intensively and compares it with visibility, another official statistics reported by China but received with much less media attention. If the improvement in API was driven by gaming, visibility should not show much improvement.

Gaming of blue sky days: One reason that led Andrews (2008) to suspect the API data for Beijing was higher frequency in the range right below the cutoff for blue sky days (96-100) than in the range right above it (101-105). This pattern could be driven by gaming if Beijing

[20] Results are available upon request.

officials systematically underreported a slightly-above-100 API than slightly below the 100 mark. One may argue that such gaming is more likely than blatant cheating either because it is easier to manipulate air immediately surrounding the samplers, or because large scale underreporting is more likely to raise questions from the central government. However, gaming is not the only possibility. Besides measurement error, as argued in Guinot (2008), the density of the real API could have decreased between 96 and 105, even without gaming.

We plot the kernel density of API for each city group (Beijing, co-host, neighbor and control) in Figures 8(a) to 8(d). Each figure presents four densities, corresponding to before the setup of BOCOG, the preparation period, during the Games, and post the Games. If officials underreported API right above the 100 mark as compared to right below the 100 mark, the density curve should show a bump right below the 100 mark, and a dip right above the 100 mark. In contrast, if API was not subject to gaming, the density plot of API should be as smooth around 100 as in other neighborhoods.

An abnormal bump right below 100 does show up in some periods for the co-host, neighbor and control cities, but the pattern is less apparent in Beijing because most times the mode is close to 100 in Beijing. More importantly, when the mode of Beijing API shifts to the left during and after the Games, we do not observe any bump in the area right below the 100 mark. This is understandable because the goal of Beijing is not limited to the number of "blue sky days" and Beijing officials may be reluctant to game the system given the intensive media attention on Beijing preceding and succeeding the Games. In comparison, the bump right below 100 appears in the control cities, despite the lack of connection to the Games. This suggests that, if the above-mentioned gaming exists in control cities, they are more likely responsive to the nationwide performance evaluation of local officials, rather than to the Games per se. The below-100 bump for the co-host and neighbor cities could reflect response to both incentives.

Gaming in the second half of month: To facilitate performance evaluation, local governments are required to file monthly report on the number of blue sky days achieved in a calendar month. This could generate extra gaming toward the end of month. To evaluate this possibility, Figures 9(a) to 9(d) plot the kernel density of API for each city group, for the first- and second-half of the month separately. These densities exclude the days during the Olympic Games because Olympic-related cities should have incentive to maintain good API throughout the duration of the Games, not just in the days towards the end of the month.

In Beijing, the API density for the second-half of month does not have a more apparent bump right below 100 and the second half of month tends to have even higher API than the first half. Both patterns are inconsistent with the extra gaming incentives in the second half of month. However, it is more difficult to rule out extra gaming in the second half of month for the other three cities groups. The bump below 100 is similar in the first- and second-half of month for the control cities, and the bump seems more likely to stand out in the second-half of the month for the co-host and neighbor cities.

To detect whether the Olympic Games generate more gaming in the second half of a month than in the first half, we report two sets of results. The first set focuses on an indicator of whether the study date falls into the second half of a month. Since this indicator alone will be absorbed with date fixed effects, we interact it with the dummies for the three treatment city groups. As reported in Column 1 of Table 9, the coefficients of these interactions are all positive, which is against the gaming prediction. In Column 2 of Table 9, we add to Specification (2) a full set of interactions between the key variables $\{1_{BJ} \cdot period_x$, $1_{cohost} \cdot period_x$, and $1_{neighbor} \cdot period_x\}$ and an indicator of whether the study day falls into the second half of a month. The coefficients of these new variables capture the *additional* effect of the Games on the second-half of a month, relative to the first half. If Olympic Games introduced extra incentives to gaming around the threshold of 100 in the second half of a month, these new coefficients should be significantly negative. As shown in Table 9, one out of the nine coefficients is significantly positive, the rest are all indifferent from zero (by 95% confidence). We take this as evidence that the Olympic Games do not generate more gaming of the API data in the second half of the month than in the first half of month. That being said, it does not rule out the possibility that the same amount of gaming may exist in both halves of the month, and some gaming around the threshold of blue sky days may have existed nationwide independent of the Olympic Games.

Evidence from visibility: The CMA reported visibility data are not readily available to the public (we purchased them from CMA). Since visibility attracts little media attention, there should be little incentive to fabricate the visibility data. If the significant API improvement in Beijing was due to underreporting of air pollution during the Games (than before and after the Games) we should have observed a lower correlation between API and visibility during the Games. Throughout our sample, the correlation between API and visibility (by city-day) was

-0.2370 before the setup of the BOCOG, -0.2918 in the preparation period, -0.3903 during the Games, and -0.2737 after the Games. The higher correlation during the Games is at odds with the gaming prediction.

More importantly, we repeat specification (1) with visibility as the dependent variable. Since the co-host and neighboring cities have violated the pretreatment test, Table 10 only reports the regression results for Beijing, either pooling the co-host and neighboring cities with the control cities (Columns 1-4) or excluding co-host and neighboring cities from the sample (Columns 5).The key assumption here is that, before the treatment, the visibility of Beijing follows the same fluctuation pattern as that of the control cities, once we control for the daily weather, date fixed effects, city fixed effects, city-specific linear trend, energy, and socioeconomic factors. To test this assumption, we report the pretreatment test statistics at the end of each column. Like API, these statistics suggest that the comparability of Beijing, and other cities is not justified until we control for city-specific linear trend, energy, and socioeconomic factors. For this reason, we focus on Columns 4 and 5.

The regression results suggest that visibility made some improvement in the preparation period and such improvement was highest during the Games. It is tempting to interpret the insignificant coefficient of $\delta_{BJ,x}$ after the Games as an abatement of visibility improvement, but this is not conclusive given the large standard errors. These findings are inconsistent with the gaming explanation of API improvements.

One explanation for the less reversion of visibility is that gaseous pollutants captured in API (for example coarse particles) may not have a strong impact on visibility.[21] To examine this explanation, we regress API on visibility, take the residual as the non-visibility component of API, and use the residuals as the dependent variable for the same specification as Table 10 Column 6 (i.e. using the most extensive controls but excluding the co-host and neighbor cities from the sample). Results suggest that the late-occurring and short-lived effects of the Games on Beijing's API are likely driven by the non-visibility component of API.

Overall, all three datasets – API, visibility and AOD – suggest that Beijing witnessed real improvement in air quality due to the Olympic Games. However, both API and AOD data suggest that this improvement was short-lived and faded away significantly within one year of

[21] Huang et al. (2009) compare visibility with the in situ measure of each pollutant, conditional on data from Shanghai only. They show that visibility is more correlated with fine particles ($PM_{2.5}$) than with other pollutants.

the Games.

7. 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 in China and elsewhere, it is important to understand which actions were most effective in improving air quality in Beijing. The preparation period witnessed four types of actions: plant closure, furnace renovation, new automobile emission standard, and traffic control. It is difficult to distinguish these four actions because they overlap in time and their effects may be cumulative and gradual.

Given we have developed fine resolution data for Beijing, we present the results of two investigations for Beijing. First, we examine whether the API of Beijing changed significantly before and after the cutoff dates corresponding to each action, and assess whether we can attribute these changes to a particular action depending on how large the changes were, how immediate the effects of the action were, and to what extent the action overlapped with other actions. Second, we investigate location specific AOD with respect to location and time of interventions. We achieve this by linking the latitudes and longitudes of AOD data with the timing and location of plant closures and traffic control for major and secondary roads.[22] This approach was subject to the caveat that the effect of surface interventions on AOD may be delayed due to the prolonged life cycle of aerosols.

Evidence from API: Specification (3) mimics Specification (1) but replaces the interaction of Beijing and the treatment periods with a set of interactions between Beijing and a dummy of whether the study date *t* is after the above-mentioned cutoff date for action a. For example, the dummy of plant closure is defined as one if *t* is after December 31, 2007 and the dummy of traffic control is turned on if *t* falls into 8/17-8/20/2007 or 7/20/2008-9/20/2008.

(3) $$API_{cd}\ (or\ Visibility_{cd}) = \alpha_c + \beta_d + \gamma_c \cdot t$$
$$+\delta_{BJ,1} \cdot 1_{BJ} \cdot plantclosure_t + \delta_{BJ,2} \cdot 1_{BJ} \cdot furnacerenovate_t$$
$$+\delta_{BJ,3} \cdot 1_{BJ} \cdot newemission_t + \delta_{BJ,4} \cdot 1_{BJ} \cdot trafficcontrol_t$$
$$+\lambda \cdot W_{cd} + \eta \cdot X_{cy} + \phi \cdot E_{c,1999} \cdot t^2 + \varphi \cdot V_{c,1999} \cdot t^2 + \pi \cdot H_{cd} + \varepsilon_{cd}.$$

To better understand the overlap of the four actions, we first run Specification (3) with only one action included and then pool all four actions in the same regression. The results are

[22] We cannot find any geographic data on furnaces in Beijing.

reported in Table 11. When we look at each action separately, all actions were associated with a significant decline in API after the corresponding cutoff date than before the cutoff. However, with all four actions combined, only plant closure and traffic control showed significantly negative coefficients. The coefficient of furnace renovation was no longer significant, and the coefficient of new emission standard was even positive. The counter-intuitive sign for the new emission standard is probably because the new standard only applies to new vehicles, which could have a perverse effect of encouraging more use of old vehicles. Similarly, no-effect was shown in Delhi, India (Kathuria 2002).

Panels B and C examine how plant closure, traffic control, furnace renovation and new emission standard of Beijing correlate with the inferred TSP density and whether the reported dominant pollutant is SO_2. We dropped NO_2 because very few percent of days (0.35%) report NO_2 as the dominant pollutant. Like Panel A, we first focus on each single action and then pool the four actions in the same regression.

Panel B suggests that plant closure and traffic control accounted for the most reduction in the absolute density of TSP. Its similarity with the API results is not surprising because 72.9% of the total sample and 84.4% of the Beijing observations reported TSP as the dominant pollutant. Since we cannot infer the exact level of TSP when API is below 50 and API is more likely below 50 during and after the Games, we tend to underestimate the effects of Olympic-related actions on TSP. According to the last column of Panel C, only furnace renovation was associated with a lower likelihood of SO_2 being the dominant pollutant. In theory, plant closure should have had a similar effect on SO_2 but due to its strong effect on TSP it might have reduced the chance of SO_2 being the dominant pollutant. Like in Panel A, the introduction of new emission standard has a counter intuitive sign on TSP and SO_2.

Evidence from AOD and point-specific policies 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 2.5km cell, and aggregated them to match the spatial resolution of AOD (~ 10km x 10km). To capture the policy interventions due to the Games, 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 expected that the effects of the Games 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:

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

where α_G represent area fixed effects for each 10km x 10km square in Beijing.

Under this specification, Table 12 reports four sets of results with progressive control of date fixed effects, area fixed effects, and weather variables. Across all columns, it is clear that traffic control is more effective in improving AOD in the areas with more roads. While this improvement started to appear right after the Games, it was the greatest 2-3 months after the Games and then tampered off completely within 6 months after the Games. This suggests that the strictest traffic control (50% of vehicles off road) was very effective in reducing AOD temporarily but the weaker form of traffic control that continued after the Games (vehicles off road one of five weekdays) was ineffective. The latter is consistent with evidence shown in Mexico City (Davis 2008).

Similarly, temporary closure had the largest reduction effect on AOD one month after the closure and this effect declined afterwards. The effect of permanent closure was not significant until 4-6 months after the closure date and dropped quickly afterwards. 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 in ground emission, nearby aerosols may travel to mitigate the effects.

The estimates reported in Table 12 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 the best improve the AOD within 5km radius by 0.42 units. This is an enormous 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 needs to temporarily close 1.6 plants or restricting on-road vehicles to half in an AOD area that has a total length of 118.25km in major and secondary roads. Given the fact that the road length in a typical 5km radius surrounding a center point of AOD is no more than 12km, 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 wide the traffic control is applicable. How to compare the effectiveness of these measures in light of their economic and social cost is a potential topic for future research.

Overall, the detailed analysis of AOD within Beijing confirms the previous finding that traffic control and plant closure were most likely to be responsible for the air quality improvement in Beijing and their effects were temporary.

8. 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, especially plant closure and traffic control, effectively reduced the API (i.e. improvement in air quality) in Beijing by 29.65% during the Games as compared to one year before any Olympic-motivated action.[23] However, roughly 60% of this improvement in air quality dissipated one year after the Games.[24] The satellite based AOD data, acquired from NASA, confirms that air quality improvement in Beijing was real but temporary.

Our results imply that, in contrast to the common wisdom regarding the impact of political regime on environmental protection (Oates and Portney 2003), an authoritarian regime could use its administrative power to improve air (or environmental) quality but its effectiveness may largely depend on the underlying political motivation. Even if the regime has such motivation, it remains an open question as to whether the actions adopted by an authoritarian regime are in line with the public health and/or environmental interest in the long run. Is it possible that China has sacrificed other welfare-enhancing policies in order to boost its political image during the Games? Could it be more beneficial to the society if the same resources were distributed more evenly across geographic space and time? These questions, as well as the impact of the air quality improvement on human health and environment, call for future research.

[23] The estimated improvement is 32.23, which is a 29.65% reduction from the absolute level of API in Beijing before the setup of BOCOG (109.01).

[24] The estimated improvement of API in Beijing is 32.23 during the Games, 12.723 in 11-13 months after. (32.23-12.723)/32.23=60.5%.

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Figure 1: The map of the 37 study cities

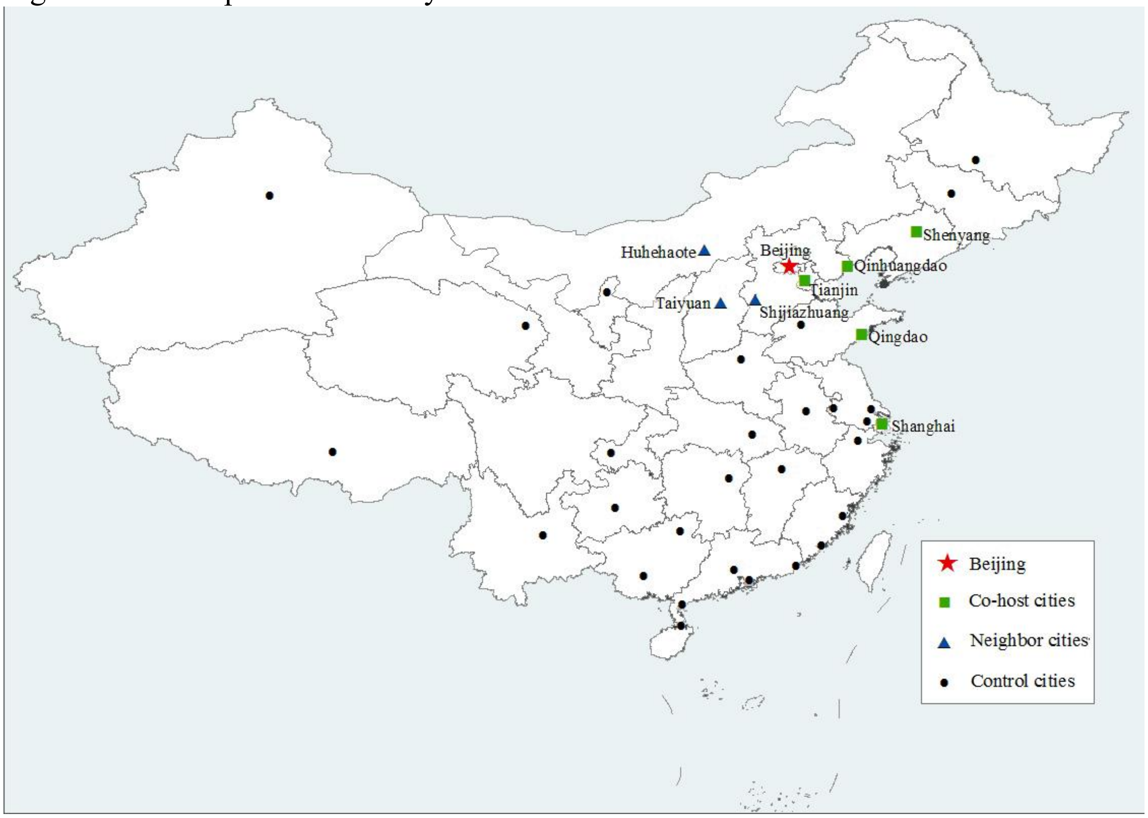
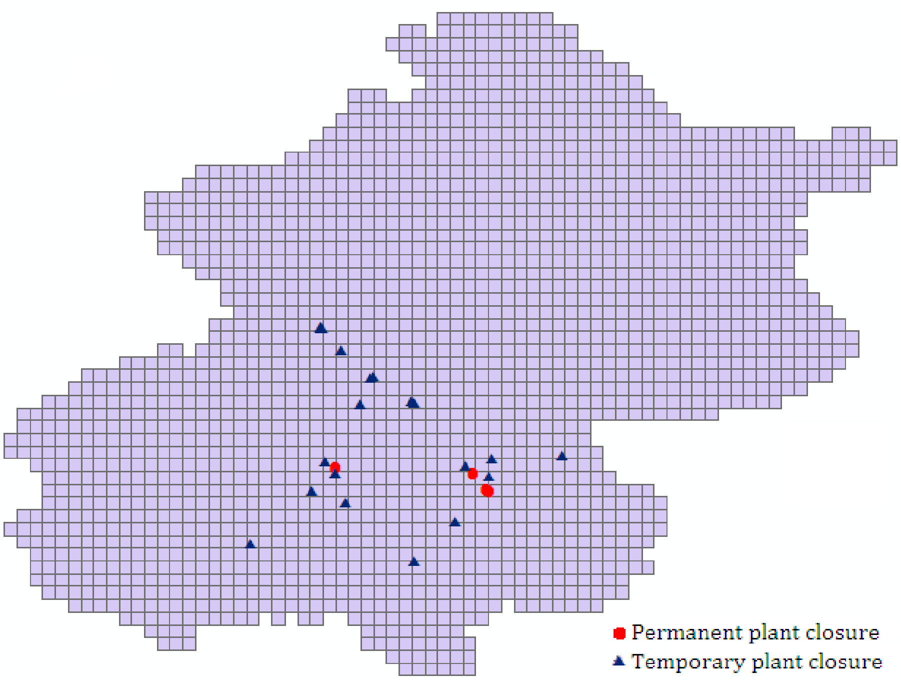
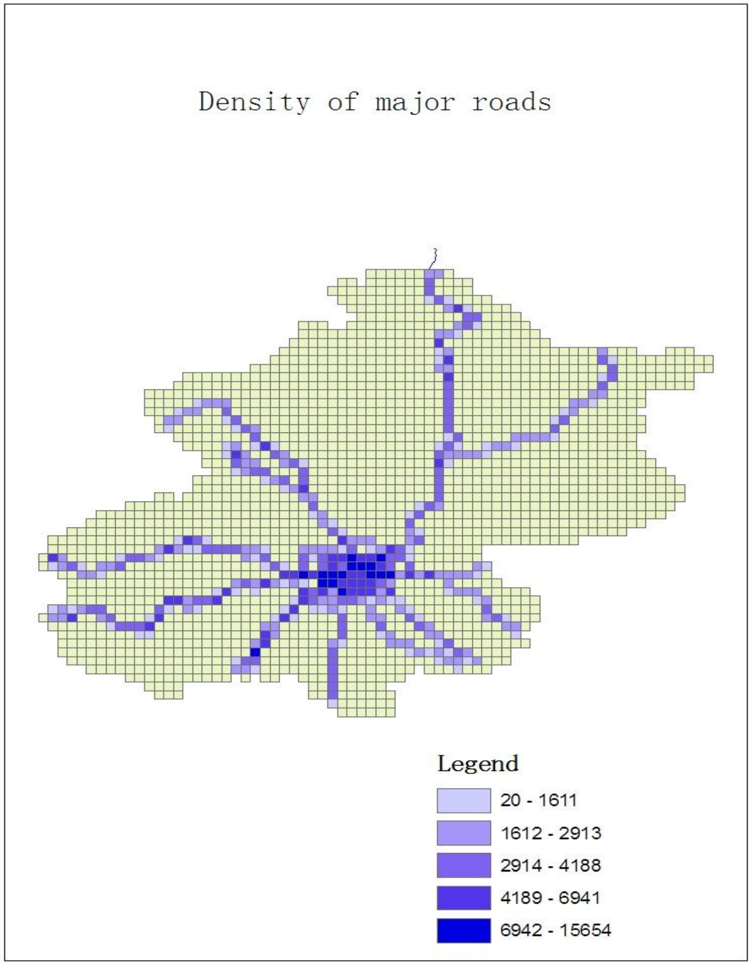


Figure 2: Distribution of Permanent and Temporary Plant Closures in Beijing



Data source: http://www.gov.cn/zwgk/2008-04/14/content_944313.htm

Figure 3: The distribution of major and secondary roads in Beijing, as of 2005



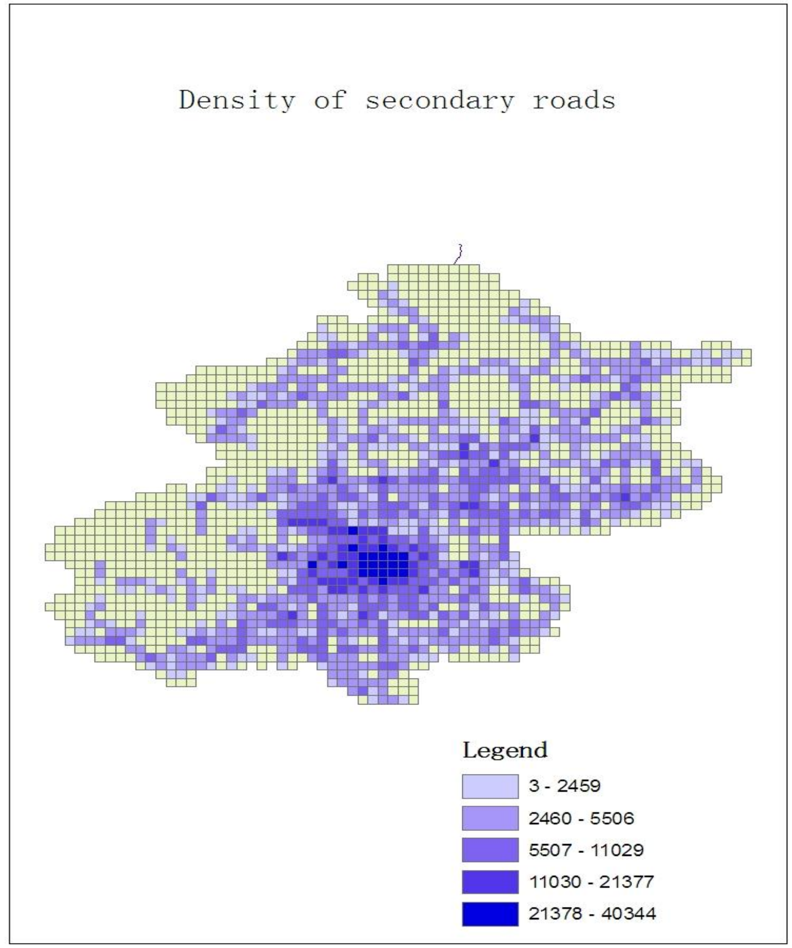


Figure 4: Time series of API by city group and treatment periods[25]

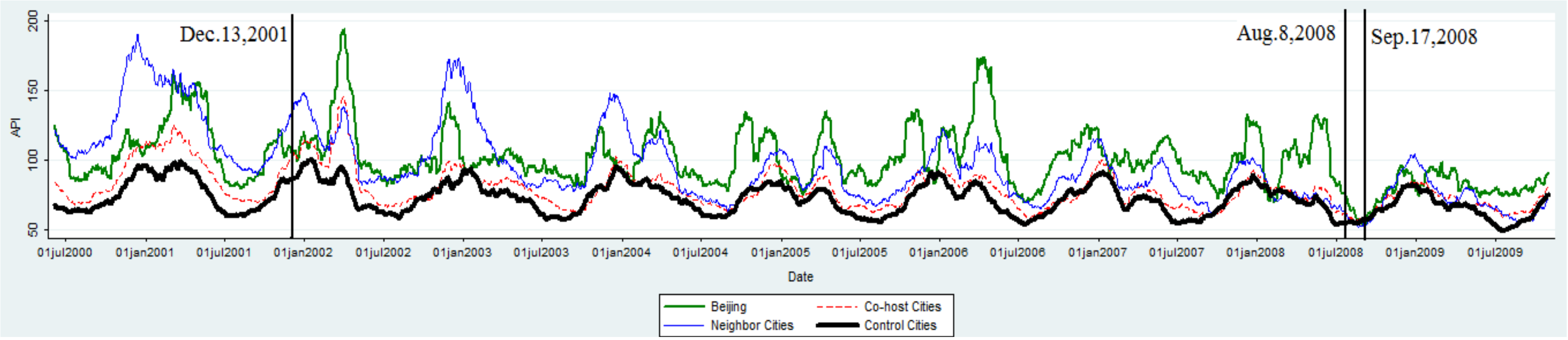
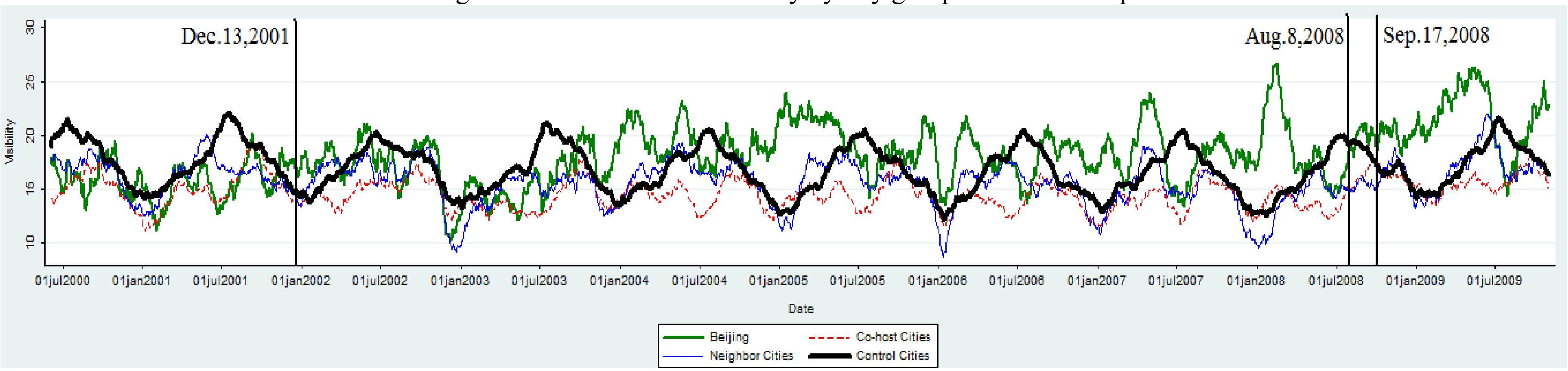


Figure 5: Time series of visibility by city group and treatment periods[26]



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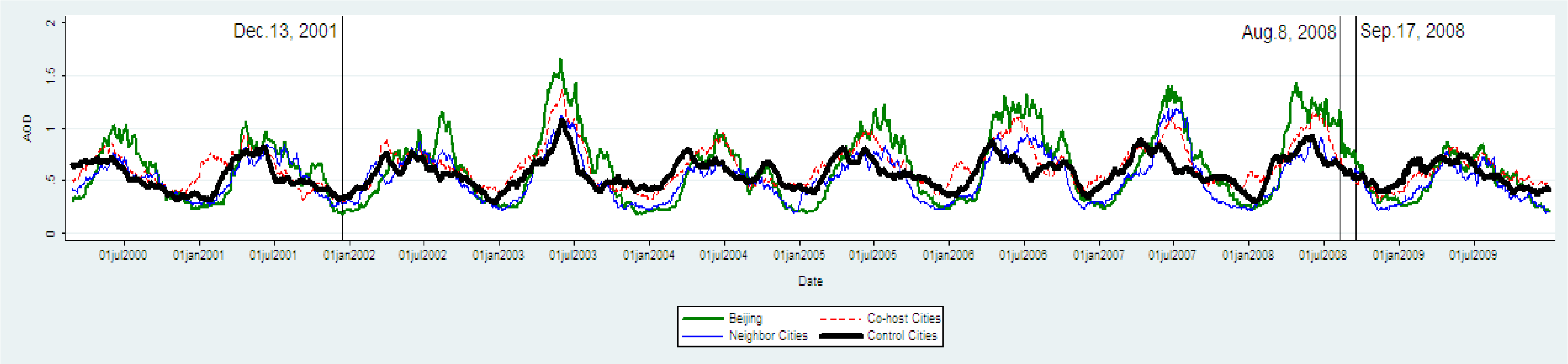
25 Moving average: The API at date t is $API(t) = \frac{1}{41}\sum_{i=-20}^{20} API(t+i)$.

26 Moving average: The visibility at date t is $visibility(t) = \frac{1}{41}\sum_{i=-20}^{20} visibility(t+i)$.

Figure 6: Time series of satellite-based AOD by city group and treatment periods[27]



[27] Moving average: The AOD at date t is $AOD(\mathrm{t}) = \frac{1}{41}\sum_{i=-20}^{20} AOD(t+i)$.

Figure 7: Satellite based AOD, corrected for meteorological conditions and spatiotemporal trends in and around Beijing.

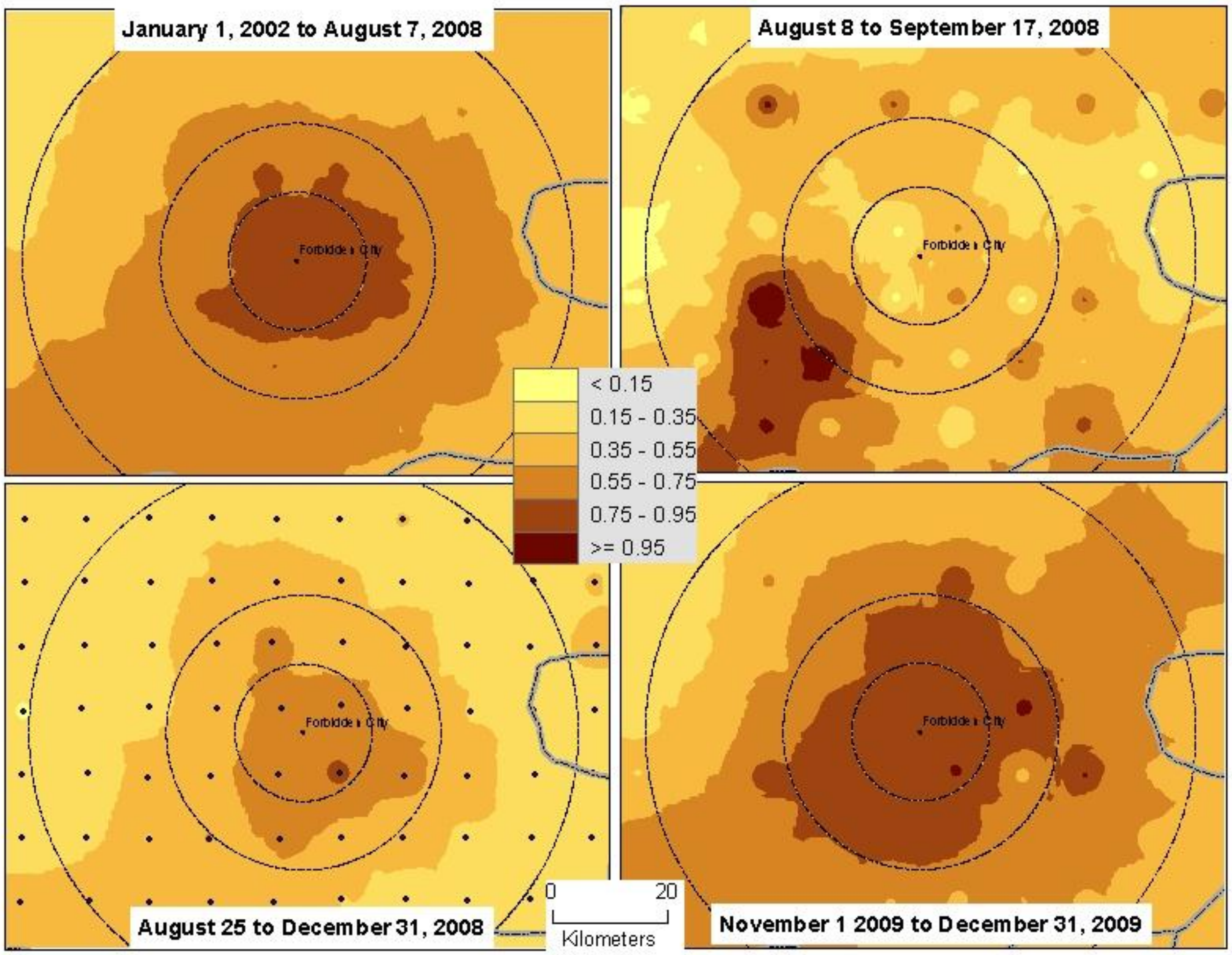


Figure 8: Kernel density of API by city group and period

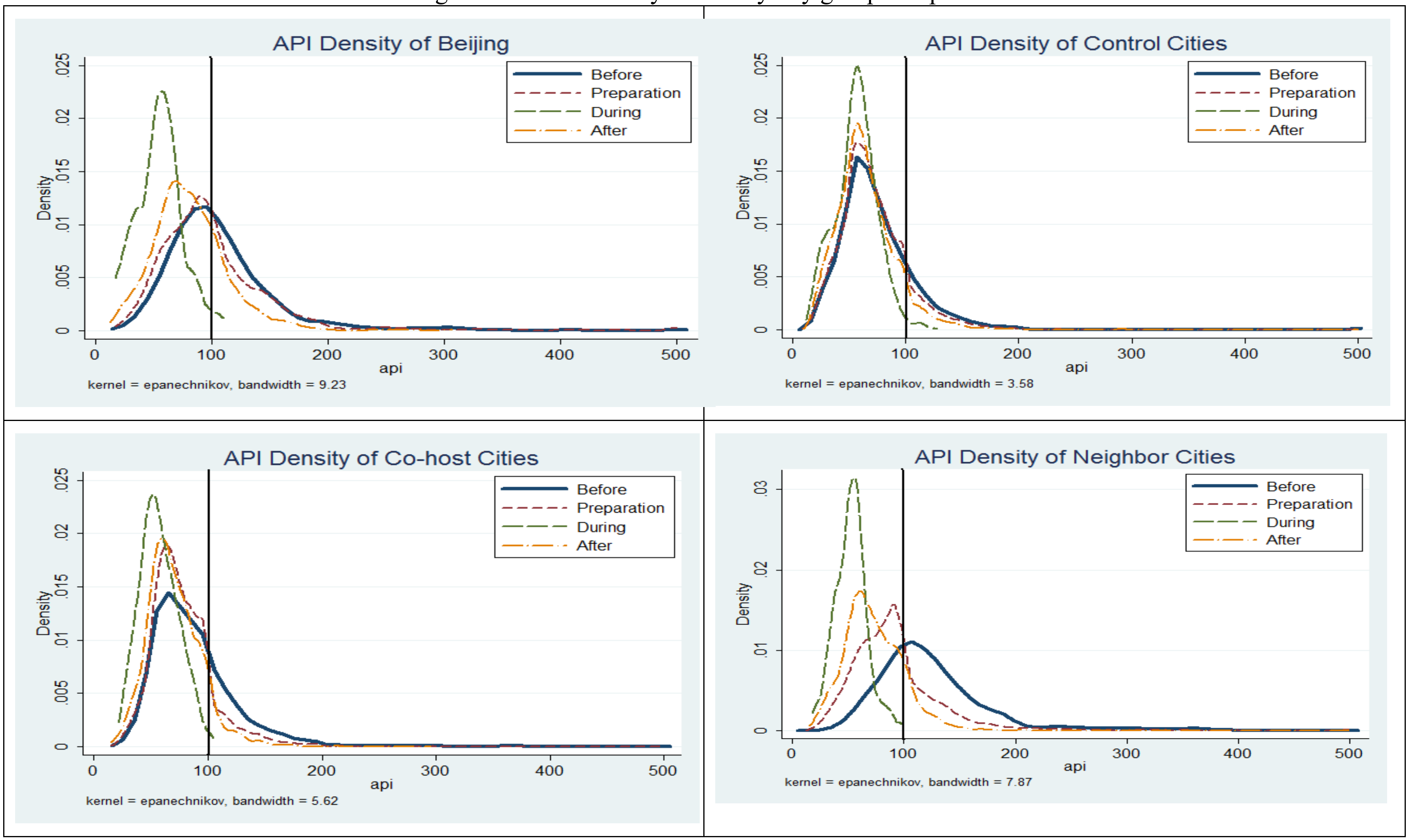


Figure 9: Kernel density of API by city group and half month

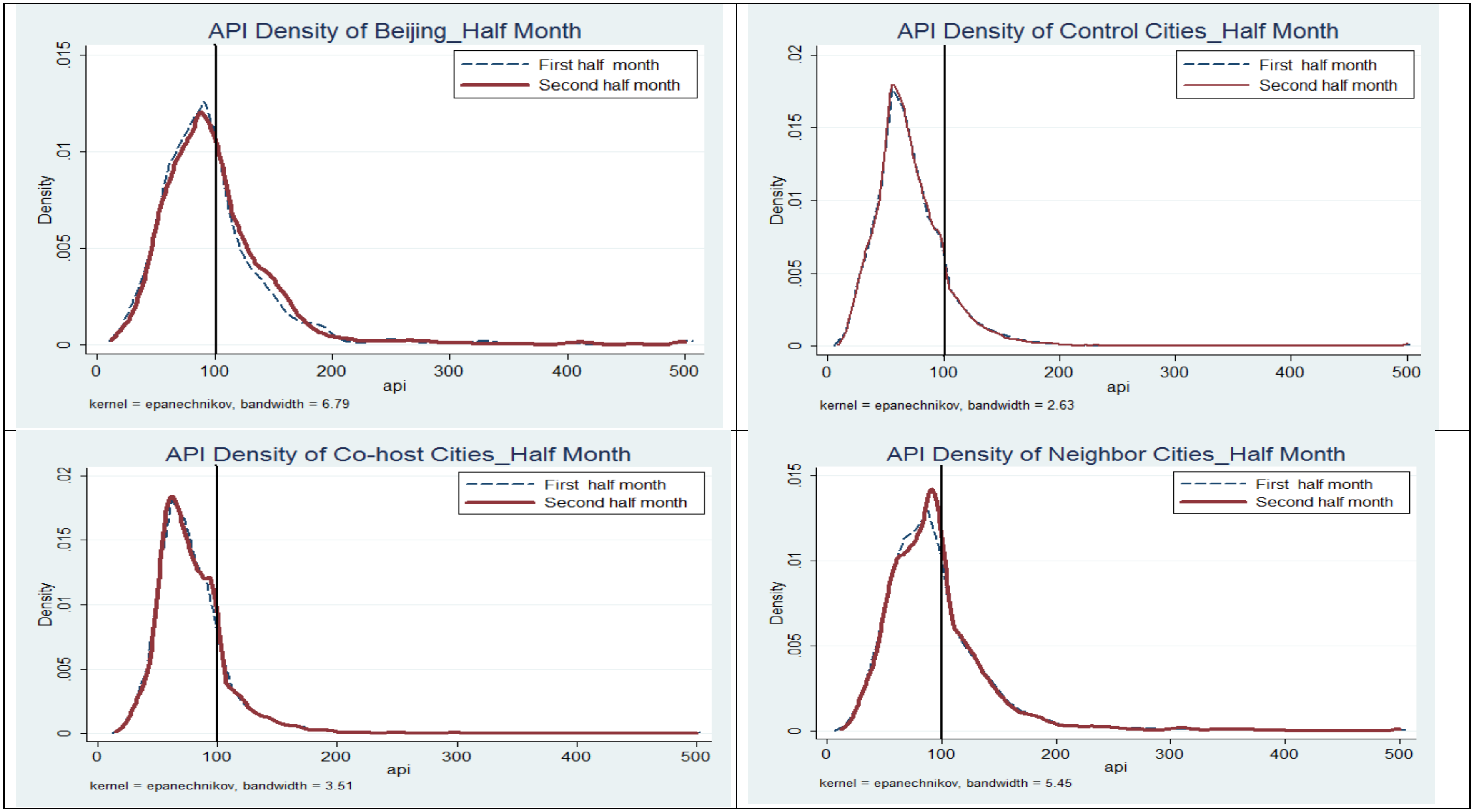


Table 1: MEP cutoff points for different levels of API

API	Pollutant intensity (μg/m^3)			Air quality level	Air Quality condition	Notes of health effects
	TSP	SO_2	NO_2			
500	1000	2620	940	V	Heavy pollution	Exercise endurance of the healthy people drops down, some will have strong symptoms. Some diseases will appear.
400	875	2100	750			
300	625	1600	565	IV	Moderate pollution	The 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	500	250	150	III	Slightly polluted	The symptom of the susceptible is slightly aggravated, while the healthy people will have stimulated symptoms.
100	300	150	100	II	Good	Daily activity will not be affected.
50	120	50	50	I	Excellent	Daily activity will not be affected.

Source: The first four columns are taken from the MEP website. The last three columns are copied from Table 2.2 of UNEP (2009).

Table 2: Summary of daily average API 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

TSP ($\mu g/m^3$) inferred from API (conditional on API>=50 & dominant pollutant=TSP)	Control cities	Beijing	Co-host cities	Neighbor cities
Benchmark period (06/05/00-12/12/01)	235.57	311.47	256.63	345.97
Preparation (12/13/01-08/07/08)	226.70	301.21	232.71	274.34
Preparation 1 (12/13/01-12/31/04)	234.70	305.09	243.98	294.28
Preparation 2 (01/01/05-08/07/08)	219.68	298.08	222.34	256.20
Olympic Games (08/08/08-09/17/08)	179.44	178.78	182.48	161.08
After Games (09/18/08-12/31/09)	211.04	249.81	211.99	217.60
After Games 1 (09/18/08-10/17/08)	201.99	226.84	202.36	209.93
After Games 2 (10/18/08-12/17/08)	227.41	269.48	230.84	253.31
After Games 3 (12/18/08-03/17/09)	234.69	266.64	238.87	244.62
After Games 4 (03/18/09-07/17/09)	202.04	240.30	200.11	215.95
After Games 5 (07/18/09-10/31/09)	192.61	243.11	202.45	187.71
Total	225.82	295.72	233.66	279.87

Table 3: Summary of visibility by treatment periods and city groups

Visibility (km)	Control cities	Beijing	Co-host cities	Neighbor cities
Benchmark period (06/05/00-12/12/01)	17.85	15.77	15.15	16.35
Preparation (12/13/01-08/07/08)	16.58	18.06	14.28	15.37
Preparation 1 (12/13/01-12/31/04)	16.83	17.44	14.42	15.74
Preparation 2 (01/01/05-08/07/08)	16.37	18.59	14.16	15.05
Olympic Games (08/08/08-9/17/08)	19.03	20.71	16.17	15.99
After Games (09/18/08-12/31/09)	17.33	21.24	15.78	16.78
After Games 1 (09/18/08-10/17/08)	17.24	19.80	17.43	14.47
After Games 2 (10/18/08-12/17/08)	16.69	19.33	16.07	17.48
After Games 3 (12/18/08-03/17/09)	14.74	21.38	14.58	14.37
After Games 4 (03/18/09-07/17/09)	18.50	23.70	15.41	18.91
After Games 5 (07/18/09-10/31/09)	18.55	19.77	16.57	16.62
Total	16.91	18.10	14.61	15.70

Table 4: 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

Table 5: Main results on API

	(1)	(2)	(5)	(6)	(7)	(8)
VARIABLES	API	API	API	API	API	API
BJ×Preparation	-0.334	-2.928	-4.922*	-5.085**	-6.353**	-5.455**
	(2.193)	(1.842)	(2.640)	(2.467)	(2.578)	(2.535)
BJ×During	-29.423***	-34.820***	-34.335***	-34.905***	-37.642***	-36.888***
	(3.611)	(2.346)	(2.260)	(2.428)	(2.813)	(2.397)
BJ×After	-13.208***	-19.173***	-19.643***	-22.035***	-23.580***	-22.593***
	(2.632)	(1.857)	(1.780)	(3.399)	(3.995)	(3.589)
Co-host× Preparation						-1.087 (1.514)
Co-host× During						-1.973 (2.054)
Co-host×After Games						3.842* (1.930)
Neighbor× Preparation						-15.701*** (2.340)
Neighbor× During						-20.677*** (2.904)
Neighbor× After Games						-7.838** (3.042)
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	126688	126688	126688	126688	99584	126688
R-squared	0.416	0.433	0.439	0.439	0.430	0.440
Pretreatment test for Beijing F-stat (p-value)	22.46 (0.0000)	35.13 (0.0000)	24.17 (0.0000)	0.37 (0.5484)	0.29 (0.5927)	0.73 (0.3988)
Pretreatment test for co-host and neighbor cities (p-value)						12.54 (0.0001)

Note: Clustered standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1. 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.

Table 6: 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.

	(1)	(2)	(3)	(4)
VARIABLES	API	API	API	API
BJ×Prepare	-5.085**		-6.353**	
	(2.467)		(2.578)	
BJ×Prepare1		-3.572		-5.076**
		(2.316)		(2.446)
BJ×Prepare2		0.073		-2.154
		(2.573)		(2.972)
BJ×During Games	-34.905***	-28.462***	-37.642***	-32.319***
	(2.428)	(2.872)	(2.813)	(2.720)
BJ×After	-22.035***		-23.580***	
	(3.399)		(3.995)	
BJ×After1		-22.965***		-26.494***
		(2.983)		(2.737)
BJ×After2		-15.382***		-18.497***
		(3.058)		(4.475)
BJ×After3		-22.997***		-26.444**
		(6.676)		(9.846)
BJ×After4		-10.423**		-12.329**
		(5.071)		(5.600)
BJ×After5		-10.252*		-12.723**
		(5.502)		(5.953)
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	126688	126688	99584	99584
R-squared	0.439	0.439	0.430	0.430

Note: Clustered standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1. 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.

Table 6-continued: F test for the decreasing effect

- Cells marked yellow imply that the effect in the latter period (column) is significantly smaller than the effect in the former (row) period.
- Cells marked green imply that the effect in the latter period (column) is significantly larger than the effect in the former (row) period.

F test for column 2 of table 6: test whether the effect is decreasing

F-stat (p-value)	BJ×After1	BJ×After2	BJ×After3	BJ×After4	BJ×After5
BJ×During	18.09*** (0.0002)	26.06*** (0.0000)	0.72 (0.4029)	15.85*** (0.0004)	13.17*** (0.0010)
BJ×After1		8.39*** (0.0070)	0.00 (0.9961)	7.37** (0.0109)	6.64** (0.0151)
BJ×After2			2.88 (0.1002)	2.04 (0.1640)	1.95 (0.1726)
BJ×After3				10.34*** (0.0031)	16.45*** (0.0003)
BJ×After4					0.01 (0.9214)

F test for column 4 of table 6: test whether the effect is decreasing

F-stat (p-value)	BJ×After1	BJ×After2	BJ×After3	BJ×After4	BJ×After5
BJ×During	13.62*** (0.0010)	10.59*** (0.0030)	0.34 (0.5641)	17.00*** (0.0003)	11.72*** (0.0019)
BJ×After1		3.81* (0.0609)	0.00 (0.9960)	8.38*** (0.0073)	6.09** (0.0199)
BJ×After2			1.55 (0.2231)	2.65 (0.1150)	2.62 (0.1168)
BJ×After3				4.08* (0.0530)	5.78** (0.0230)
BJ×After4					0.04 (0.8490)

Table 7: Main results on AOD

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	AOD*1000	AOD*1000	AOD*1000	AOD*1000	AOD*1000	AOD*1000
Beijing_prepare	15.309	-27.909**	-27.405	-35.567	-31.456	-44.025*
	(10.395)	(11.204)	(20.910)	(22.319)	(27.206)	(24.308)
Beijing_during	41.065**	-37.943	-39.418	-45.037	-38.270	-55.132
	(19.713)	(27.908)	(28.474)	(28.946)	(37.173)	(33.974)
Beijing_after	-22.236	-99.916***	-96.803***	-125.392***	-130.247***	-163.467***
	(16.763)	(30.641)	(30.420)	(31.304)	(37.851)	(35.335)
Co-host_prepare						-13.867
						(16.706)
Co-host_during						-49.676
						(47.491)
Co-host_after						-70.148
						(55.799)
Neighbor_prepare						-37.613**
						(17.045)
Neighbor_during						-11.749
						(27.824)
Neighbor_after						-82.243*
						(43.240)
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	2614734	2614734	2614734	2614734	1892832	2614734
R-squared	0.422	0.424	0.425	0.425	0.444	0.425
Pretreatment test for Beijing	3.00	3.95	4.17	1.79	2.72	2.33
F-stat (p-value)	(0.0916)	(0.0544)	(0.0485)	(0.1896)	(0.1100)	(0.1359)
Pretreatment test for Co-host and Neighbor cities F-stat (p-value)						8.23 (0.0011)

Note: Clustered standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1. Dummies for three distance categories are controlled for in all columns. Weather of point p in city c at date d and time t includes three factors: tr_fac1, tr_fac2 and tr_fac3. Energy includes 1999 energy*date quadratic, 1999 vehicle*date quadratic, heating*dummy of Nov 15-Mar 15. Socioeconomic factors include GDP growth rate, average GDP, industrial production and population density by city and year.

Table 8: Time-varying results on AOD

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	AOD*1000	AOD*1000	AOD*1000	AOD*1000	AOD*1000	AOD*1000
Beijing_prepare1	4.989	-38.608***	-40.850*	-51.349**	-53.292*	-60.503**
	(8.671)	(10.887)	(20.638)	(23.879)	(29.644)	(25.954)
Beijing_prepare2	22.776	-72.386***	-74.200**	-90.637***	-108.690**	-102.836***
	(13.711)	(17.069)	(27.482)	(32.890)	(40.704)	(36.593)
Beijing_during	41.173**	-89.594***	-92.019***	-109.326***	-128.030***	-124.411***
	(19.764)	(28.283)	(30.901)	(35.304)	(41.445)	(40.267)
Beijing_after1	-51.921**	-176.215***	-180.495***	-198.082***	-226.313***	-243.896***
	(23.875)	(36.645)	(38.431)	(42.056)	(55.393)	(46.113)
Beijing_after2	-57.941**	-186.188***	-178.617***	-196.663***	-255.381***	-241.003***
	(24.272)	(38.736)	(40.113)	(42.905)	(47.763)	(42.163)
Beijing_after3	-68.475***	-196.045***	-179.386***	-225.735***	-240.056***	-263.987***
	(21.986)	(32.596)	(34.771)	(45.843)	(57.076)	(50.921)
Beijing_after4	17.415	-119.584***	-121.364***	-181.546***	-183.402***	-238.637***
	(18.555)	(29.430)	(29.226)	(54.645)	(62.567)	(60.759)
Beijing_after5	28.634	-115.711***	-113.751***	-174.321***	-175.329***	-204.781***
	(17.871)	(32.906)	(32.904)	(50.565)	(61.413)	(57.103)
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			Y	Y	Y	Y
Socioeconomic factors				Y	Y	Y
Co-host and neighbor cities	included	included	included	included	excluded	included
Observations	2614734	2614734	2614734	2614734	1892832	2614734
R-squared	0.422	0.424	0.425	0.425	0.444	0.425

Note: Clustered standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1. Dummies for three distance categories are controlled for in all columns. Weather of point p in city c at date d and time t includes three factors: tr_fac1, tr_fac2 and tr_fac3. Energy includes 1999 energy*date quadratic, 1999 vehicle*date quadratic, heating*dummy of Nov 15-Mar 15. Socioeconomic factors include GDP growth rate, average GDP, industrial production and population density by city and year.

Table 8-continued: F test for after-Olympic periods

- Cells marked yellow imply that the effect in the latter (column) period is significantly smaller than the effect in the former (row) period.
- Cells marked green imply that the effect in the latter (column) period is significantly larger than the effect in the former (row) period.

F test for column 4 of table 10: test whether the effect is decreasing

F-stat (p-value)	BJ×After1	BJ×After2	BJ×After3	BJ×After4	BJ×After5
BJ×During	15.00*** (0.0004)	14.42*** (0.0005)	27.48*** (0.0000)	3.76* (0.0602)	5.27** (0.0276)
BJ×After1		0.00 (0.9569)	1.07 (0.3078)	0.16 (0.6930)	0.55 (0.4635)
BJ×After2			1.19 (0.2819)	0.11 (0.7477)	0.40 (0.5299)
BJ×After3				2.20 (0.1468)	9.62*** (0.0037)
BJ×After4					0.16 (0.6923)

F test for column 4 of table 6: test whether the effect is decreasing

F-stat (p-value)	BJ×After1	BJ×After2	BJ×After3	BJ×After4	BJ×After5
BJ×During	6.55*** (0.0162)	20.84*** (0.0001)	15.76*** (0.0005)	1.89 (0.1807)	1.63 (0.2128)
BJ×After1		0.57 (0.4569)	0.17 (0.6862)	1.03 (0.3178)	1.91 (0.1774)
BJ×After2			0.26 (0.6152)	4.75** (0.0380)	4.92** (0.0348)
BJ×After3				4.54** (0.0420)	8.33*** (0.0074)
BJ×After4					0.18 (0.6729)

Table 9: API results by first and second half of a month

Dependent variable = API, Observation = 126688

	(1)	*(2)*
BJ x second half month	1.767***	-0.859
	(0.233)	(1.091)
BJ×preparation		-7.237**
		(2.837)
BJ×preparation x second half month		3.751***
		(1.265)
BJ×during Games		-36.960***
		(2.442)
BJ×after Games		-22.281***
		(3.553)
BJ×after Games x second half month		-0.594
		(1.613)
Co-host x second half month	0.541**	1.698*
	(0.237)	(0.953)
Co-host×preparation		-0.520
		(1.832)
Co-host×preparation x second half month		-1.230
		(1.095)
Co-host×during Games		-1.844
		(2.093)
Co-host×after Games		4.974**
		(2.262)
Co-host×after Games x second half month		-2.397
		(1.477)
Neighbor x second half month	0.541**	-0.946
	(0.241)	(1.065)
Neighbor ×preparation		-16.595***
		(2.322)
Neighbor ×preparation x second half month		1.894
		(1.187)
Neighbor ×during Games		-20.749***
		(2.911)
Neighbor ×after Games		-8.293***
		(2.889)
Neighbor ×after Games x second half month		0.974
		(1.515)
Observations	126688	126688
R2	0.44	0.44

Note: Clustered standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1. All the coefficients are obtained in one regression with city fixed effects, day fixed effects, city-specific linear trend, energy, socioeconomic factors, and weather. Energy includes 1999 energy* date quadratic, 1999 vehicle*date quadratic, heating*dummy of Nov 15-Mar 15. 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, wind velocity, four dummies for wind direction (east, south, west and north) by city and date.

Table 10: Regression results on visibility

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Visibility	Visibility	Visibility	Visibility	Visibility	API residual
BJ×Preparation	3.195***	1.359***	0.867**	0.721	0.934*	-5.234**
	(0.217)	(0.207)	(0.406)	(0.431)	(0.495)	(2.544)
BJ×During	4.477***	1.120***	1.058***	0.933**	0.994**	-36.451***
	(0.429)	(0.337)	(0.367)	(0.374)	(0.466)	(2.857)
BJ×After	4.522***	0.869**	0.806**	0.721	0.933	-22.463***
	(0.390)	(0.348)	(0.344)	(0.656)	(0.773)	(3.795)
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	excluded
Observations	126688	126688	126688	126688	99584	99584
R-squared	0.569	0.573	0.574	0.575	0.587	0.418
Pretreatment test for Beijing F-stat (p-value)	9.46 (0.0044)	63.12 (0.0000)	45.06 (0.0000)	2.54 (0.1218)	2.56 (0.1206)	0.01 (0.9246)

Note: Clustered standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1. 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.

Table 11: Mechanism detection using API data

	(1)	(2)	(3)	(4)	(5)
Panel A: Dependent Variable = API					
BJ×Plant Closure	-13.886***				-32.940***
	(3.878)				(3.772)
BJ×Furnace Rennovation		-6.918**			-1.645
		(3.331)			(2.462)
BJ×New Emission			-7.521*		24.170***
			(3.782)		(3.910)
BJ×Traffic Control				-17.341***	-14.527***
				(3.196)	(3.885)
Observations	99584	99584	99584	99584	99584
R2	0.43	0.43	0.43	0.43	0.43
Panel B: Dependent Variable = Inferred TSP in μg/m^3 (conditional on API>=50 & dominant pollutant=TSP)					
BJ×Plant Closure	-27.740***				-77.646***
	(9.621)				(7.533)
BJ×Furnace Rennovation		-13.623			-4.381
		(8.562)			(6.757)
BJ×New Emission			-14.429		60.397***
			(9.711)		(9.338)
BJ×Traffic Control				-32.899***	-27.624***
				(7.721)	(8.739)
Observations	71173	71173	71173	71173	71173
R2	0.42	0.42	0.42	0.42	0.42
Panel C: Dependent Variable = Dummy of SO2 being the dominant pollutant					
BJ×Plant Closure	0.066**				-0.033
	(0.024)				(0.042)
BJ×Furnace Rennovation		-0.019			-0.044*
		(0.025)			(0.023)
BJ×New Emission			0.089***		0.129**
			(0.027)		(0.050)
BJ×Traffic Control				0.046**	0.007
				(0.020)	(0.019)
Observations	99584	99584	99584	99584	99584
R2	0.21	0.21	0.21	0.21	0.21
City FE	Y	Y	Y	Y	Y
Date FE	Y	Y	Y	Y	Y
City-specific linear trends	Y	Y	Y	Y	Y
Weather	Y	Y	Y	Y	Y
Energy & Vehicle*t^2	Y	Y	Y	Y	Y
Socioeconomic factors	Y	Y	Y	Y	Y
Co-host and neighbor cities	excluded	excluded	excluded	excluded	excluded

Note: Clustered standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1. Weather includes rainfall, temperature, barometric pressure, sunshine, humidity, wind velocity, four dummies for wind direction (east, south, west and north) by city and date.

Table 12: Mechanism detection using AOD data and location-specific policies

	(1)	(2)	(3)	(4)
VARIABLES	AOD*10^6	AOD*10^6	AOD*10^6	AOD*10^6
Road length*				
Preparation for Games	-0.123*	-0.097***	0.090***	0.085***
	(0.066)	(0.027)	(0.022)	(0.022)
During the Games	-0.484***	-0.340***	-0.020	-0.037
	(0.111)	(0.075)	(0.046)	(0.046)
1 month after Games	-0.835***	-0.589***	-0.248***	-0.265***
	(0.114)	(0.054)	(0.042)	(0.043)
2-3 months after Games	-0.967***	-0.834***	-0.347***	-0.354***
	(0.090)	(0.049)	(0.048)	(0.048)
4-6 months after Games	-1.179***	-1.109***	-0.335***	-0.299***
	(0.133)	(0.085)	(0.074)	(0.070)
7-10 months after Games	-0.302***	-0.076	0.085**	0.082**
	(0.105)	(0.048)	(0.041)	(0.041)
11-15 months after Games	-0.524***	-0.407***	-0.147***	-0.146***
	(0.125)	(0.051)	(0.043)	(0.043)
Permanent closure*				
1 month after closure	370832.547	298758.406**	138565.670	137525.013
	(318199.715)	(132060.006)	(125869.322)	(124835.985)
2-3 months after closure	78030.001	147721.110***	21077.080	19783.409
	(78360.028)	(44625.879)	(44526.709)	(44943.191)
4-6 months after closure	-183015.200***	-12341.830	-41435.026*	-41859.605**
	(51085.653)	(28451.278)	(21553.660)	(21242.877)
7+ months after closure	84565.870***	63411.523***	-18219.266*	-16803.589*
	(29437.937)	(14766.186)	(9746.093)	(9737.749)
Temporary closure *				
During closure	-81231.537**	9499.631	17981.410	18566.090
	(34284.373)	(16587.897)	(14662.832)	(14744.359)
1 month after closure	-75328.125**	-27882.007**	-25173.525**	-25978.657**
	(33585.856)	(13764.728)	(11877.424)	(12190.489)
2-3 months after closure	-77613.787***	-34092.672***	-13638.940*	-13266.406*
	(13316.433)	(7155.813)	(7825.291)	(7801.435)
4-6 months after closure	-64615.638***	-26413.263**	-21949.223**	-20069.643**
	(18004.374)	(10749.104)	(8570.402)	(8461.783)
Date FE		Y	Y	Y
10kmx10m area FE			Y	Y
Weather				Y
Observations	102820	102820	102820	102820
R-squared	0.100	0.839	0.885	0.886

Note: Clustered standard errors (by 10kmx10km area) in parentheses. ***p<0.01, **p<0.05, *p<0.1. 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.