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# The diminishing effects of winter heating on air quality in northern China

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**Abstract:** Cleaner winter heating has been promoted to abate the winter air pollution in northern China. Although improvements in air quality have been observed, the effectiveness and mechanism of cleaner heating measures on air quality have not been examined on the empirical ground. In this study, we estimate the annual effects of winter heating policy on air quality from 2014 to 2017 using a regression discontinuity design (RDD) and dynamic regression model. The results show that winter heating aggravates Air Quality Index (AQI). Specifically, the AQI raised by winter heating reduce from 85.3 in 2014 to 24.1 in 2017, indicating diminishing effects of winter heating with the implementation of clean heating measures. The heterogeneous characteristics of winter heating in terms of different pollutants and city scales are further quantified. The effects of clean heating are more evident for particulate pollutants (PM<sub>2.5</sub> and PM<sub>10</sub>) than for SO<sub>2</sub>, NO<sub>2</sub>, CO and O<sub>3</sub>. The promotion of clean heating is more effective in larger cities. These findings provided insights into the diminishing air pollution change with continuous advancement in clean heating policy and the heterogeneity among cities and pollutants should be taken into account when formulating future policies in response to energy transition and climate change.

**Keywords:** Air quality; Winter heating policy; Cleaner heating measures; Regression discontinuity design; Diminishing effects

## 1. Introduction

The rapid and intensive socio-economic development in China has led to severe air pollution issues that affect both human health and the economy (Ebenstein et al., 2015; He et al., 2016; Wang et al., 2019). In developing pollution control measures, winter becomes a crucial season when 42.3% of the hazy days due to particulate pollution occurs in China (Archer-Nicholls et al., 2016, China Meteorological Administration., 2013, Liu et al., 2016, Vu et al., 2019). Moreover, winter heating accounts for up to 45% of the total energy consumption of buildings in urban China largely relying on

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39 coal and causes severe human health risks in the densely populated northern region (Cai et al., 2009; Li  
40 et al., 2019; Zhang et al., 2019). As a result, clean heating measures, including mandatory replacement  
41 of coal with natural gas and electricity, coal rectification, and the closure of small coal-fired boilers,  
42 have become primary strategies for improving winter air quality (Cai and Jiang, 2008; Duan et al., 2014),  
43 and the national government has implemented a series of measures to facilitate such transition (Feng et  
44 al., 2019). While improvements in air quality have been observed, how these cleaner heating measures  
45 affect air pollution via the winter heating policy remains unclear. Considering that the winter air quality  
46 in northern China still to be improved against adverse health impacts, it is necessary to identify the  
47 effects of winter heating policy on air quality and explore the potential of clean heating control measures  
48 in the future.

49 Past studies have addressed the effects of winter heating on air quality by comparing the differences  
50 in air quality between heating and non-heating seasons. Xiao et al. (2015) found that the mean Aerosol  
51 Optical Depth (AOD) during the heating season was approximately five times higher than during the  
52 non-heating seasons, while Liang et al. (2015) found that winter heating increases the diurnal variation  
53 of sulfur dioxide concentrations. However, a simple comparison of the air pollution concentration  
54 between different periods may not be robust since meteorological conditions may easily mask the  
55 underlying emission changes.

56 Therefore statistical models are applied to investigate the effects of winter heating policy on air  
57 quality. Many previous studies quantify the impacts according to geographical boundary. Wang (2016)  
58 studied the effects of winter heating policy using difference-in-differences models. He found that central  
59 heating increases the Air Quality Index (AQI) by 53.1%. Almond et al. (2009) used the RDD model by  
60 exploiting variations in geographic distance from the Huai River and found that winter heating policy  
61 led to dramatically higher levels of total suspended particulates (TSPs) in northern cities, compared with  
62 the southern cities. Using the same method, Chen et al. (2013) and Ebenstein et al. (2017) found that  
63 ambient concentrations of TSPs were 55% higher in northern cities and a  $10 \mu\text{g}/\text{m}^3$  increase in  $\text{PM}_{10}$ .  
64 Moreover, the temporal variations at the start of the winter heating policy have been used to ascertain  
65 the short-term effects of air pollution. Li and Cao (2017) used the RDD model by setting the start date  
66 of the winter heating policy as a discontinuity and found that the winter heating policy led to great  
67 increases in the concentration of air pollutants. Wang et al. (2019) not only found that winter heating  
68 policy worsened the AQI in northern China but also reported the dynamic changes to demonstrate that  
69 the AQI has gradually improved due to a series of changes in heating policy. Fan et al. (2020) found that  
70 the start of winter heating system increased the weekly AQI by 36% and mortality rate by 14% with the  
71 RDD model. They also extend the air pollution effect studies to poor and rural areas where people are  
72 more vulnerable to the rapid deterioration in air quality. However, previous quantitative studies usually  
73 focus on a specific period and a single pollutant, neglecting the complicated effects of heating measures  
74 among different years and different pollutants. Besides, the RDD has only been exploited in identifying  
75 very short-term changes around the heating date.

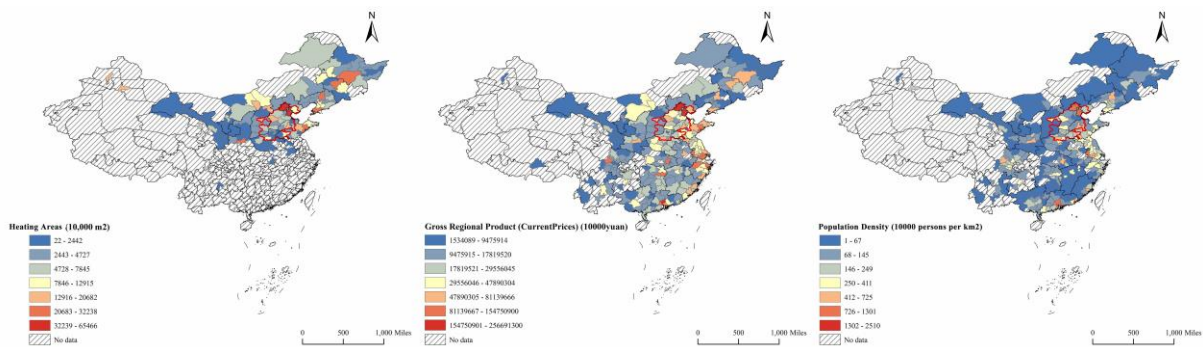
76 This study aims at evaluating the effect of cleaning heating measures in Beijing-Tianjin-Hebei  
77 region and its surrounding areas (“2+26” cities) via winter heating policy from 2014 to 2017. Compared  
78 with existing literature, our study focuses on the annual trend and heterogeneity of air pollutants over  
79 the process of clean heating promotion, contributing to mainly two aspects: firstly, significant effects of

80 winter heating on air pollutants are found using the RDD model. However, the effects diminished  
 81 dynamically each year. Secondly, more types of air pollutants, especially O<sub>3</sub>, and city scales are taken  
 82 into consideration to further explore the heterogeneity through the whole process of clean heating. These  
 83 fill the knowledge gaps in the previous literature and provide more thorough evidence of the cleaner  
 84 winter heating policy's contributions to air quality.

## 85 2. Methods and data

### 86 2.1 Study area

87 The “2+26” cities (including Beijing, Tianjin, and 26 other municipalities in the surrounding area)  
 88 (Fig. 1) were chosen as the critical targets for preventing and controlling air pollution by the Ministry  
 89 of Environmental Protection of China <sup>1</sup>. As the atmospheric transmission channels of air pollution in the  
 90 Beijing–Tianjin–Hebei (BTH) region (Xiao et al., 2020), these cities not only contribute more than a  
 91 quarter of China's gross domestic product (GDP) but also have high population densities. The total  
 92 amount of coal consumed in this region accounts for up to 34.36% of the national consumption, while  
 93 the spatial density of coal consumption is 30 times the global average (Wang et al., 2019). The heavy  
 94 use of coal not only leads to severe air pollution, but also poses higher health risks to the densely  
 95 populated region than other cities in China (Wang et al., 2019). Therefore, the central committees<sup>2</sup>  
 96 jointly released the ‘*Cleaner Winter Heating Plan for the Northern Region (2017–2021)*’ in December  
 97 of 2017, designating the “2+26” cities as a pilot area for the Clean Heating Action Plan (Meng et al.,  
 98 2019).



99  
 100 **Fig. 1.** The heating areas, the proportion of per capita GDP, and population density of the “2+26” cities<sup>3</sup>

### 101 2.2 Empirical model

102 Firstly, we employ regression discontinuity designs (RDD) model to estimate the short-term effects  
 103 of winter heating policy on air quality. RDD has been applied to test the nature of causal relationships  
 104 across a wide range of fields (Black, 1999; Chay et al., 2005; Feldman et al., 2016). In this study, the  
 105 winter heating policy is regarded as an external intervention to examine whether there were  
 106 discontinuous changes in air quality once the winter heating policy was started. The model is constructed

<sup>1</sup> The Ministry of Environmental Protection was renamed the Ministry of Ecology and Environment in 2018.

<sup>2</sup> The central committees include the National Development and Reform Commission, the National Energy Administration, the State Finance Bureau, and other 8 committees.

<sup>3</sup> The data of GDP, population density was collected from China Urban Statistical Yearbook 2017, and the population density is calculated by using Household Registered Population at Year-end / Total Land Area of Administrative region. The data of heating areas was collected from China Urban Construction Yearbook 2017.

107 as follows:

$$108 \quad P_{it} = \alpha + \beta heating_{it} + \gamma f[(t - c_i)] + \delta X_{it} + \varepsilon_{it}. \quad (1)$$

109 Where  $P_{it}$  is the concentration of the air pollutants in a city  $i$  at time  $t$ . We chose the  
110 comprehensive indicator of air quality, the daily mean AQI, and the daily mean concentrations of PM<sub>2.5</sub>,  
111 PM<sub>10</sub>, SO<sub>2</sub>, NO<sub>2</sub>, and CO as the dependent variables.  $heating_{it}$  is an indicator of regulatory status. If  
112 a city  $i$  is regulated at time  $t$ .  $heating_{it} = 1$ ; otherwise  $heating_{it} = 0$ . And the parameter of interest  $\beta$   
113 provided an estimate that whether there is an increase in air pollutants.  $c_i$  is the start time of winter  
114 heating policy in city  $i$ , and the actual heating time of each prefecture-level city was determined by  
115 sourcing the relevant information on heating from each city.  $(t - c_i)$  is the day from the start time,  
116  $f[(t - c_i)]$  is a polynomial function of time, here we select the first-order term, the second-order term  
117 and the third-order term respectively to prevent over-fitting of the results (Ye, 2017).  $X_{it}$  is a vector of  
118 control variables, including meteorological factors and dummy variables of weekendday-of-week. The  
119 daily mean temperature, daily mean relative humidity, daily mean wind speed, and daily precipitation  
120 (accumulated within 24 hours), and the quadratic term form of meteorological factors were selected as  
121 the meteorological factors.

122 Secondly, we establish a dynamic panel data model to measure the long-term correlation between  
123 winter heating activities and air quality according to the method of Zhang et al. (2020), and the model  
124 is set as follows:

$$125 \quad P_{it} = \sum_{s=1}^{\rho} \rho P_{i,t-s} + \alpha Heating_{it} + \beta Z_{it} + \lambda t + \mu_i + \pi_t + \varepsilon_{it}. \quad (2)$$

126 In equation (2),  $P_{i,t-s}$  is the lag term, and the lagging order is determined by a sequential t-rule  
127 which is used to determine whether the lag term of the highest order should be retained. The critical  
128 explanatory variable  $Heating_{it}$  is used as a dummy variable, which equals 1 when a city is in its  
129 heating period, and its coefficient  $\alpha$  is the main parameter of interest.  $Z_{it}$  is a vector of control  
130 variables, and we determine the weather conditions, weekend holidays (dummy variable) and the  
131 economic factor (pgdp, GDP per capita) as the control variables. Weather conditions include daily mean  
132 temperature, daily mean relative humidity, daily mean wind speed, and daily precipitation (accumulated  
133 within 24 hours). Holidays are set as dummy variables, which equal 1 if the t-date is in a holiday.  
134 Economic factor addresses the endogeneity from regional economic development level and regional air  
135 pollution. The data are collected from the local *City Yearbook 2014–2017*.  $\lambda t$  is the time trend term.  
136  $\mu_i$  is the fixed effects of a city;  $\pi_t$  is the fixed effects of time; and  $\varepsilon_{it}$  is the error term.

### 137 2.3 Data

138 The daily mean concentrations of air pollutants were collected from the National Urban Air Quality  
139 Real-time Release Platform. The daily mean AQI, PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO and O<sub>3</sub> in the study region  
140 from 2014.9.1–2017.12.31<sup>4</sup> are calculated based on 1-h mean data (Li et al., 2017).

141 The daily weather data were provided by the National Meteorological Information Center, which  
142 collects meteorological records from surface meteorological stations<sup>5</sup>. We use the daily mean

<sup>4</sup> As the study area was not set as an AQI testing site in 2013, the study period began in 2014. Data were calculated following the 'Technical Regulation for Ambient Air Quality Assessment and the Technical Regulation on Air Quality Index', which was established by the Ministry of Environmental Protection.

<sup>5</sup> The National Meteorological Information Center provided the daily data for the pressure, temperature, precipitation,

143 temperature, daily mean relative humidity, daily mean wind speed, and daily precipitation (accumulated  
144 over 24 hours) from 2014.9.1–2017.12.31.

145 The weather and air quality data are from different sets of stations. So we match the weather and  
146 air quality data based on the geographical coordinates of the stations and prefecture-level cities. The  
147 matching process follows the procedures employed in a previous study by Fan et al. (2018). For  
148 prefecture-level cities with urban monitoring stations, we use the averaged data from air quality  
149 monitoring stations located within each city. For cities without monitoring stations, we match the  
150 stations within a radius of 100 km to the geometric centre of each city and calculate their daily means.  
151 Table 1 reports the summary statistics of key variables in “2+26” cities.

152 **Table 1. Summary statistics of key variables.**

Variables	Description	Unit	Obs	Mean	Std.Dev.	Min	Max
AQI	Air Quality Index	N/A	33341	114.63	64.01	17.91	500.00
PM <sub>2.5</sub>	Particular matter less than 2.5 mm	μg/m <sup>3</sup>	33341	77.74	58.42	4.21	731.09
PM <sub>10</sub>	Particular matter less than 10 mm	μg/m <sup>3</sup>	33341	135.25	82.69	7.27	937.71
SO <sub>2</sub>	Sulfur dioxide	μg/m <sup>3</sup>	33341	39.40	34.57	1.42	428.75
NO <sub>2</sub>	Nitrogen dioxide	μg/m <sup>3</sup>	33341	46.72	21.27	4.64	201.27
CO	Carbon monoxide	mg/m <sup>3</sup>	33341	1.57	0.96	0.14	18.92
O <sub>3</sub>	Ozone	μg/m <sup>3</sup>	33341	57.94	36.20	1.21	242.42
Precipitation	Daily precipitation (accumulated over 24 hours)	mm	33341	13.84	10.31	-15.78	32.90
Temperature	Daily mean temperature	°C	33341	2.18	0.85	0.00	7.15
Wind speed	Daily mean wind speed	m/s	33341	60.98	18.27	12.67	100.00
Humidity	Daily mean relative humidity	1%	33341	1.60	6.90	0.00	247.65
pgdp	GDP (current year prices) per capita	10000 yuan per person	33341	0.08	0.27	0	1

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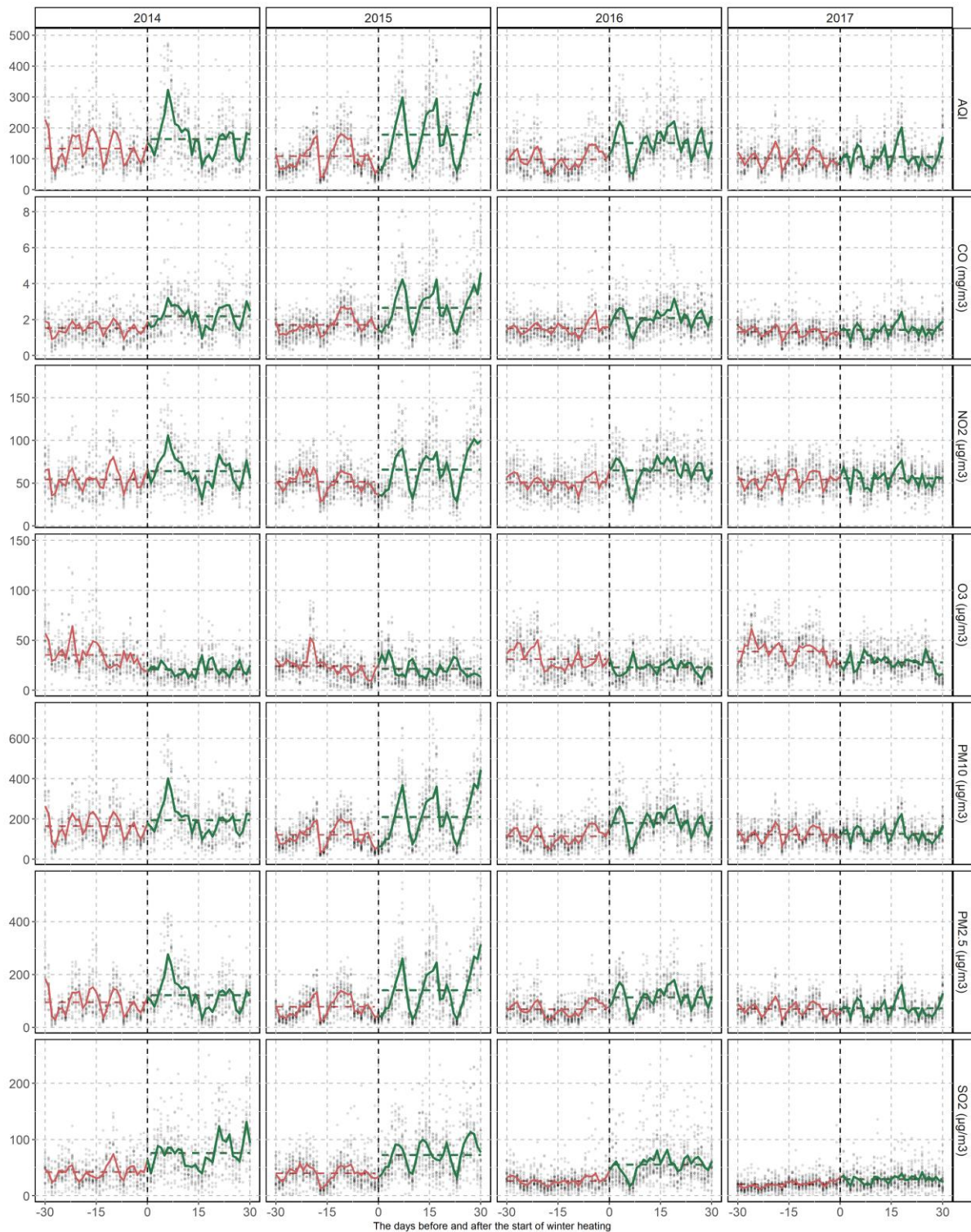
### 154 3. The annual variation effects of winter heating policy on air quality

#### 155 3.1 The trends of air pollutants before and after the winter heating

156 We first analyse the trends of air pollutants in the “2+26” cities before and after the winter heating  
157 season starts. Figure 2 shows the trends of different air pollutants in 30 days before and after the winter  
158 heating begins, including AQI, PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO and O<sub>3</sub>. The trends are similar for different  
159 air pollutants. The concentrations of air pollutants decreased by years except for O<sub>3</sub>, indicating that the  
160 air quality improved after the implementation of cleaner heating measures from 2014 to 2017. Moreover,  
161 the concentrations of AQI, PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub> and CO during the winter heating season are  
162 significantly higher than that before the season in 2014 and 2015, while there was no significant



163 difference in 2016 and 2017. As for O<sub>3</sub>, a secondary pollutant, the average concentrations drop in the  
164 heating seasons.



165

166

**Fig. 2.** The trends of air pollutants before and after the winter heating

167

Note: Daily mean concentrations of different air pollutants are shown. The black dash line

168

represents the start time of winter heating. The red line represents the change of the daily mean

169

air pollutants concentrations before the winter heating, while the green line represents the

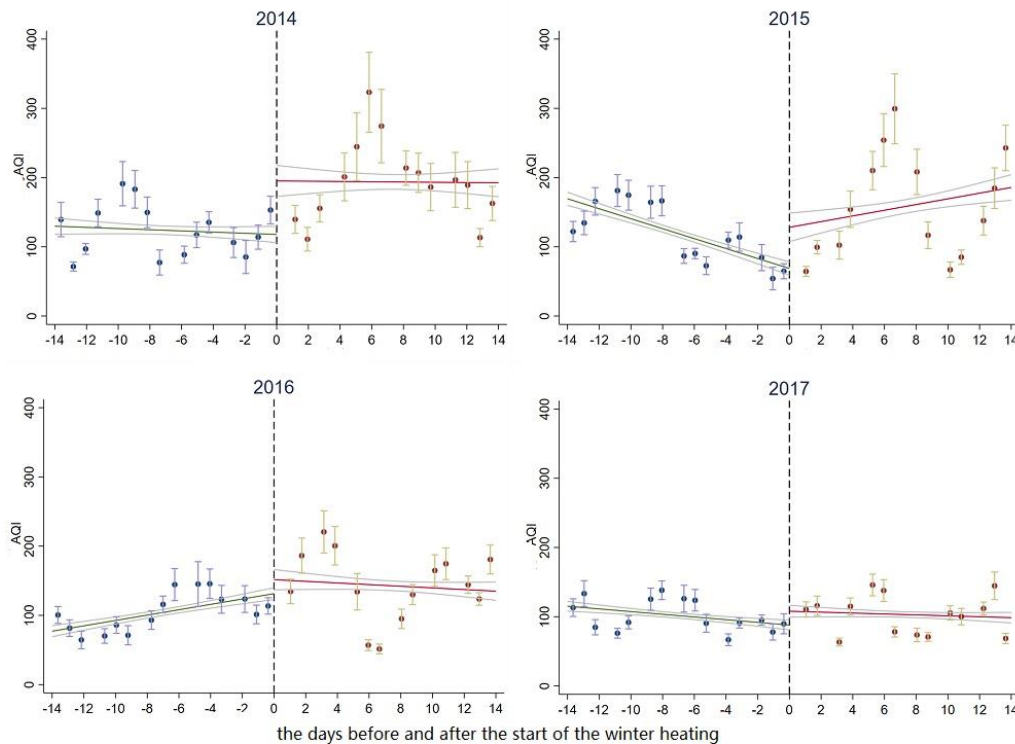
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change of the daily mean air pollutants concentrations after the winter heating.

## 171 3.2 Regression discontinuity results

### 172 3.2.1 The discontinuity of the AQI over the cut-off

173 First, it is necessary to prove whether there is a discontinuity over the cut-off (the start time of the  
174 winter heating policy). Figure 3 shows the discontinuity of the daily mean AQI over the cut-off from  
175 2014 to 2017. It can be seen that the daily mean AQI increases, which is significant in 2014 and 2015  
176 but not in 2016 and 2017, indicating that the winter heating increased daily mean AQI, but the effects  
177 decreased by years.



178

179 **Fig. 3.** The discontinuity of the AQI over the cut-off from 2014 to 2017

180 Note: The black dash line represents the start time of winter heating. The green line represents  
181 the local linear regression fit of AQI before the winter heating, while the red line represents the  
182 local linear regression fit of AQI after the winter heating. And the upper and lower lines show  
183 the 95% confidence interval.

### 184 3.2.2 The annual effects of winter heating policy on air quality

185 We estimate the annual effects of winter heating policy on daily mean AQI from 2014–2017 using  
186 the equation (1). Specifically, we divide the total sample into four sub-groups by year and the results of  
187 annual effects as shown in Table 2.

188 The winter heating policy increases AQI with different sets of control variables or time polynomials  
189 introduced, but the effects decreased by years from 2014 to 2017. The observation windows are 14 days  
190 before and after the heating begins. Therefore we regard the changes in air quality within the very short  
191 window are caused by cleaning heating measures alone rather than other air pollution control actions.  
192 The result is the most significant when the control variable is added and the time polynomial is set as  
193 the quadratic term. It can be seen that the effects of winter heating on air quality are diminishing by

194 years, which means the winter heating policy cleaned up with the implementation of clean heating  
 195 measures. The increases of AQI are relatively significant by 85.3 and 75.2 in 2014 and 2015, while the  
 196 increases are smaller by 32.3 and 24.1 in 2016 and 2017. It also provides empirical support for the  
 197 research of a cleaner winter heating policy.

198 **Table 2. The annual effects of winter heating on AQI.**

	(1) AQI	(2) AQI	(3) AQI	(4) AQI	(5) AQI	(6) AQI
year=2014	54.1*** (9.15)	71.1*** (9.92)	58.0** (11.9076)	67.4*** (6.97)	85.3*** (7.47)	56.5*** (8.95)
year=2015	34.9*** (7.44)	68.7*** (10.4)	10.8 (15.1732)	60.3*** (9.59)	75.2*** (10.8)	51.6** (15.0)
year=2016	28.0** (8.8903)	37.42** (8.68)	47.0*** (9.96)	12.8 (7.93)	32.3*** (8.27)	50.0*** (9.76)
year=2017	22.1*** (5.01)	32.5*** (5.07)	45.9*** (6.78)	20.9*** (3.85)	24.1*** (3.95)	24.6*** (5.11)
Weather controls	no	no	no	yes	yes	yes
Time polynomial	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>
Bandwidths	±14 day	±14 day	±14 day	±14 day	±14 day	±14 day

199 Note: The coefficient of AQI and their standard errors are shown by years. \*\*\*, \*\*, and \* indicate the 1%, 5%,  
 200 and 10% significance level.

201

### 202 3.2.3 Robustness

203 We analyse the robustness of the regression discontinuity results. The first necessary assumption  
 204 was that the weather covariates, including the daily mean temperature, daily mean relative humidity,  
 205 daily mean wind speed, and daily precipitation, changed smoothly over the cut-off (the start time of  
 206 winter heating) (Guo and Chen, 2019). Figure 4 ((a) - (d)) shows that there was no visually apparent  
 207 discontinuity over the cut-off within the 95% confidence interval, indicating the discontinuity of the air  
 208 pollutants over the cut-off was only caused by the implementation of winter heating policy.

209

210 **Fig. 4.** The changes of weather covariates over the cut-off from 2014 to 2017

211 Note: (a) Daily mean temperature; (b) Daily mean relative humidity; (c) Daily mean wind  
 212 speed; (d) Daily precipitation (24-hour accumulation). The black dash line represents the start  
 213 time of winter heating. The green line represents the local linear regression fit of AQI before the  
 214 winter heating, while the red line represents the local linear regression fit of AQI after the winter  
 215 heating. And the upper and lower lines show the 95% confidence interval.

216 The choice of bandwidth and the forms of weather controls are important factors affecting the  
 217 estimation results (Calonico, et al., 2020). We changed the bandwidth from 10 to 20 days and then the  
 218 orders of control variables to test the robustness of our results. The results are reported in Appendix  
 219 Table A1-2. The directions and significance levels of the estimated results are consistent with the main  
 220 results (Table 2), which proved the robustness of the regression discontinuity.

221 Finally, a placebo test is performed by changing the settings of the cut-off to ensure the accuracy  
 222 of the setting of the discontinuity. Table A3 respectively reports the results when the cut-off is two weeks  
 223 before the winter heating policy started (columns 1-3) and two weeks after the winter heating policy



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224 started (columns 4-6). There are no significantly robust results in most years except 2015, and negative  
225 effects are even observed in 2017 when two weeks before the winter heating policy started to set for the  
226 cut-off, which can further ensure the accuracy of the setting of the model.

### 227 **3.3 Dynamic panel regression results**

228 In order to observe the long-term effects of heating, a dynamic panel regression model (equation  
229 (2)) was designed. It can be seen as a comparison between the whole heating and the non-heating seasons.  
230 It is worth noting that the results can only represent the long-term correlation between heating activities  
231 and air quality because there is a more complicated mechanism affecting pollutant concentration over a  
232 more extended observation period. However, it serves as a good supplementary for the short-term effect  
233 of RDD model.

234 Table 3 shows the dynamic panel regression results of the long-term correlation between winter  
235 heating and air quality. The winter heating activity has significant positive effects on air pollutants,  
236 increasing AQI by 18.0. PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub> and CO increased by 22.1%, 15.4%, 25.1%, and 21.4%,  
237 respectively. The effects on NO<sub>2</sub> and O<sub>3</sub> are insignificant.

238 In terms of control variables, almost all meteorological factors have significant effects on air  
239 pollutants, but the magnitude is small. The effects of the holiday factor (dummy variable) on air  
240 pollutants are weak or insignificant, indicating little correlation with the air pollutants. And the economic  
241 indicator (pgdp) shows significant negative correlations with the air pollutants, but the effects are small.  
242 In addition, Year (dummy variable) and time trend items have significant negative correlations with  
243 pollutants, indicating that measures to control air pollution are improving air quality (Zhang et, al., 2020).

**Table 3. Results of dynamic panel regression.**

	AQI	lnPM <sub>2.5</sub>	lnPM <sub>10</sub>	lnSO <sub>2</sub>	lnNO <sub>2</sub>	lnCO	lnO <sub>3</sub>
heating	18.0*** (1.61)	0.221*** (0.0186)	0.154*** (0.0146)	0.251*** (0.0233)	0.00402 (0.0104)	0.214*** (0.0157)	0.00960 (0.0151)
temperature	0.0660 (0.0590)	0.000700 (0.000785)	0.00232*** (0.000614)	-0.0119*** (0.00103)	-0.00688*** (0.000532)	-0.00569*** (0.000628)	0.0274*** (0.00103)
windspeed	-2.36*** (0.502)	-0.0512*** (0.00625)	-0.0196** (0.00541)	-0.122*** (0.00766)	-0.0990*** (0.00390)	-0.0612*** (0.00441)	0.0528*** (0.00488)
humidity	0.469*** (0.0384)	0.00684*** (0.000412)	0.00243*** (0.000334)	-0.00598*** (0.000464)	-0.00144*** (0.000230)	0.00527*** (0.000299)	-0.00534*** (0.000347)
precipitation	-0.737*** (0.163)	-0.0102*** (0.00216)	-0.00929*** (0.00203)	-0.00867*** (0.00195)	-0.00359*** (0.000902)	-0.00493*** (0.00108)	0.000140 (0.000523)
holiday	2.37* (1.41)	0.0230 (0.0163)	0.0209* (0.0123)	0.0145 (0.0248)	-0.0240* (0.0130)	0.0138 (0.0154)	0.00409*** (0.01560)
pgdp	-0.306*** (0.0765)	-0.00308*** (0.000904)	-0.00342*** (0.000680)	-0.000739 (0.0602)	-0.00168*** (0.00123)	-0.00187** (0.000805)	0.00242*** (0.000809)
year	-1.81*** (0.417)	-0.0331*** (0.00491)	-0.0210*** (0.00375)	-0.156*** (0.00709)	0.00037 (0.00304)	-0.0367*** (0.00413)	0.0454*** (0.00421)
Time trend term	-0.0270*** (0.00440)	-0.000419*** (0.0000443)	-0.000237*** (0.0000339)	-0.000592*** (0.0000702)	0.000109*** (0.0000315)	-0.000288*** (0.0000450)	-0.000459*** (0.0000477)
Lagging order	2	2	2	2	2	2	2
Fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	366*** (840)	67.9*** (9.91)	43.7*** (7.58)	317*** (14.3)	1.20 (6.13)	74.2*** (8.32)	-89.7*** (8.48)
Observations	30169	lnPM <sub>2.5</sub>	lnPM <sub>10</sub>	lnSO <sub>2</sub>	lnNO <sub>2</sub>	lnCO	lnO <sub>3</sub>
R-squared	0.526	0.221***	0.154***	0.251***	0.00402	0.214***	0.00960

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245 Note: The coefficient of the logarithm of different air pollutant concentrations and their standard errors are shown respectively. \*\*\*, \*\*, and \* indicate the 1%, 5%, and 10%  
246 significance level. The results of PM2.5, PM10, SO2, NO2, CO, O3 are shown in natural logarithm to eliminate the differences in absolute value.

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## 247 4. Heterogeneous effects of winter heating policy on air quality

### 248 4.1 Heterogeneous effects of winter heating on different air pollutants

249 We estimated the heterogeneous effects of winter heating on different air pollutants (Table 4). It  
250 can be found that there were significant positive effects of the winter heating policy on different air  
251 pollutants except for O<sub>3</sub>, and the annual variations were consistent with the AQI from 2014-2017. The  
252 increases in air pollutants caused by the winter heating policy are significant in 2014 and 2015. PM<sub>2.5</sub>,  
253 PM<sub>10</sub> and SO<sub>2</sub> increase the most in the year of 2015. Specifically, the concentration of PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub>,  
254 NO<sub>2</sub> and CO increased by 73.0%, 61.9%, 53.2%, 34.6%, and 41.6% in 2014. The increased of PM<sub>2.5</sub>,  
255 PM<sub>10</sub>, SO<sub>2</sub>, NO<sub>2</sub> and CO are 83.2%, 70.3%, 56.6%, 22.0% and 35.0% in 2015. The effects were  
256 significantly smaller after 2015, where the increases of PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub> and NO<sub>2</sub> are 34.7%, 52.1%,  
257 20.8% and 14.2% in 2016. The increases of PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub> and CO are 37.8%, 19.6%, 9.0% and 20.9%  
258 in 2017. However, there is no stable pattern for O<sub>3</sub>.

259 By comparing the effects of winter heating on different air pollutants, PM<sub>2.5</sub> and PM<sub>10</sub> caused by  
260 winter heating are the most serious during the study period, which is consistent with the existing research  
261 (Guo et al., 2019). The winter heating activities in China are mainly based on coal burning, producing  
262 large amounts of smoke and sulfur compounds, which are the primary source of atmospheric particulate  
263 matter (PM<sub>2.5</sub> and PM<sub>10</sub>) (Zhao et al., 2019).

264 The effects of winter heating policy on SO<sub>2</sub> and NO<sub>2</sub> are positive in most years, but the effects are  
265 small or even insignificant in some years. Since the government replaced traditional coal-burning with  
266 desulfurized coal or natural gas, these measures had already significantly reduced the concentration of  
267 SO<sub>2</sub>. The SO<sub>2</sub> concentrations thirty days before heating are 42.2, 40.1, 26.5 and 20.5 µg/m<sup>3</sup> from 2014  
268 to 2017, experiencing a very sharp reduction. Moreover, the concentrations of SO<sub>2</sub> and NO<sub>2</sub> are not only  
269 affected by household heating but also other factors, such as industrial and vehicular emissions (Dong  
270 et al., 2020), which may lead to insignificant effects because of the greater effects of other emissions  
271 sources during the study period. In addition, there are positive effects of the winter heating policy on  
272 CO, which is caused by the incomplete combustion of fuels (such as coal or oil) in coal-fired boilers. As  
273 a secondary pollutant, the formation of ozone is influenced by precursor emissions, photochemical  
274 reaction, and meteorological conditions (Hao et al., 2021). The precursors (mainly NO<sub>x</sub> and VOCs)  
275 originate from more complicated sources than heating, such as traffic emissions, oil volatilization and  
276 even plant growth in nature (Min et al., 2021). And although there are more severe anthropogenic source  
277 emissions due to heating, solar radiation is weak and photochemical reaction is difficult to occur in  
278 winter. The precursor and the lack of radiation are the main reasons why ozone is not significantly  
279 disturbed by heating activities.

**Table 4. The heterogeneous effects of winter heating policy on air pollutants.**

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	AQI	lnPM <sub>2.5</sub>	lnPM <sub>10</sub>	lnSO <sub>2</sub>	lnNO <sub>2</sub>	lnCO	lnO <sub>3</sub>
year=2014	85.3*** (7.47)	0.730*** (0.0674)	0.619*** (0.0595)	0.532** (0.113)	0.346*** (0.0455)	0.416*** (0.0800)	-0.07301 (0.0785)
year=2015	75.2*** (10.8)	0.832*** (0.928)	0.703*** (0.0886)	0.566*** (0.101)	0.220*** (0.0517)	0.350*** (0.0651)	0.802*** (0.103)
year=2016	37.4** (8.68)	0.347*** (0.0986)	0.521*** (0.0896)	0.208* (0.111)	0.142** (0.0489)	0.0648 (0.0677)	-0.410*** (0.0951)
year=2017	24.1*** (3.95)	0.378*** (0.0634)	0.196*** (0.0525)	0.142 (0.0976)	0.090*** (0.0337)	0.209*** (0.0590)	0.753 (0.0677)
Weather controls	yes	yes	yes	yes	yes	yes	yes
Time polynomial	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>
Bandwidths	±14 day	±14 day	±14 day	±14 day	±14 day	±14 day	±14 day

281 Note: The coefficients of different air pollutants and their standard errors are shown by years. \*\*\*, \*\*, and \* indicate the 1%, 5%, and 10% significance level. The results of

282 PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub>, NO<sub>2</sub>, CO, O<sub>3</sub> are shown in natural logarithm to eliminate the differences in absolute value.

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## 283 4.2 Heterogeneous effects of winter heating on different city scales

284 Winter heating activities are related to the scales of the city. The measures and implementation  
285 intensity of the clean heating increase with the size of the city. To identify the heterogeneity effects of  
286 winter heating policy on the different city scales, we further divide the 28 cities into three categories  
287 (Megacity, Megalopolis and Large-sized city) according to urban resident population<sup>6</sup>. The detailed  
288 grouping information are shown in Appendix Table A4.

289 Table 5 reported the heterogeneous effects of winter heating policy on air pollutants in three city  
290 scales. It can be found that there are significant positive effects of winter heating policy on different  
291 pollutants in three city scales, and the coefficients decrease by years from 2014 to 2017, which is  
292 consistent with the full-sample results.

293 By comparing the heterogeneity effects in three city scales, it can be found that the effects of winter  
294 heating increased with the city scales. The differences were most significant in 2014 and 2015.  
295 Specifically, the daily mean AQI increased by 124 and 118 in megacities; the daily mean AQI increased  
296 by 81.3 and 62.1 in megalopolis; the daily mean AQI increased by 62.6 and 55.0 respectively in large-  
297 sized cities. It is because the larger the city, the more fuel-needing for winter heating.

298 By comparing the different effects from 2014-2017, the effects of clean winter heating increased  
299 with the city scales, which may be related to the stronger promotion intensity of clean winter heating in  
300 larger cities in China. As a result, the differences of the coefficients of winter heating policy on air  
301 pollutants increased with the city scales. Specifically, the daily mean AQI in megacities increased by  
302 35.2 in 2017, which decreased by 88.8 compared with 2014; the daily mean AQI in megalopolis  
303 increased by 21.5 in 2017, which decreased by 59.8 compared with 2014; In large cities, the daily mean  
304 AQI increased by 21.0 in 2017, which decreased by 41.6 compared with 2014. PM<sub>2.5</sub> and PM<sub>10</sub> follow  
305 the similar pattern as AQI, but SO<sub>2</sub>, NO<sub>2</sub> and CO in large-sized cities are less significant than in  
306 megacities.

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<sup>6</sup> The classification standards refer to *the Notice on Adjusting the City Size Division Standards* issued by the State Council of China. [http://www.gov.cn/zhengce/content/2014-11/20/content\\_9225.htm](http://www.gov.cn/zhengce/content/2014-11/20/content_9225.htm)



**Table 5. The heterogeneous effects of winter heating policy on air pollutants in the megacities, megalopolis and large-sized cities.**

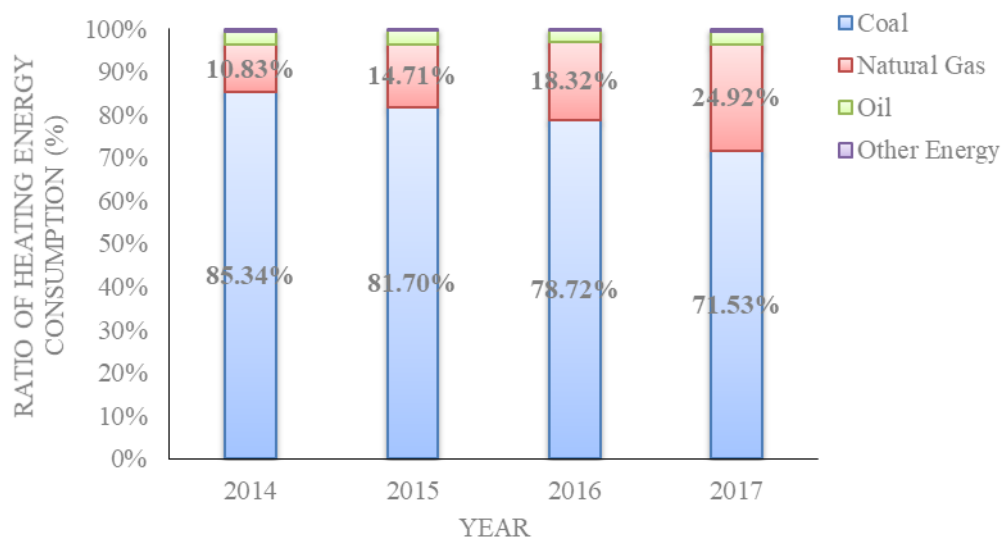
	megacities				megalopolis				large-sized cities			
Year	2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
AQI	124*** (21.9)	118*** (42.5)	71.8*** (16.2)	35.2*** (10.6)	81.3*** (9.06)	62.1*** (17.6)	39.7** (16.8)	21.5*** (5.55)	62.6*** (16.39)	55.0*** (14.2)	45.4*** (14.7)	21.0*** (6.52)
lnPM <sub>2.5</sub>	1.09*** (0.164)	1.35*** (0.291)	0.505*** (0.167)	0.513*** (0.196)	0.673*** (0.0779)	0.669** (0.144)	0.227 (0.168)	0.322*** (0.0927)	0.650*** (0.175)	0.454** (0.2001)	0.365** (0.152)	0.320*** (0.123)
lnPM <sub>10</sub>	0.968*** (0.155)	1.22*** (0.258)	0.693*** (0.164)	0.328* (0.172)	0.544*** (0.0735)	0.289 (0.209)	0.484*** (0.145)	0.162** (0.0667)	0.585*** (0.135)	0.380** (0.181)	0.472*** (0.136)	0.144* (0.0793)
lnSO <sub>2</sub>	1.22*** (0.267)	0.808*** (0.211)	0.862** (0.346)	0.249 (0.297)	0.307** (0.124)	0.439*** (0.160)	0.145 (0.109)	0.278*** (0.0952)	0.353 (0.231)	0.403** (0.159)	0.161 (0.213)	0.0436 (0.161)
lnNO <sub>2</sub>	0.694*** (0.0977)	0.632*** (0.110)	0.420*** (0.0864)	0.195** (0.0944)	0.273*** (0.0572)	-0.0762 (0.0903)	0.287*** (0.0772)	0.105** (0.0531)	0.285*** (0.0968)	0.178** (0.0735)	0.0635 (0.0672)	0.0672 (0.0549)
lnCO	0.975*** (0.158)	0.735*** (0.168)	0.156 (0.121)	0.360** (0.121)	0.343*** (0.0959)	-0.235** (0.113)	0.0474 (0.111)	0.169** (0.0815)	0.257 (0.170)	0.269*** (0.0968)	0.250** (0.125)	0.135 (0.129)
lnO <sub>3</sub>	-0.284 (0.173)	0.217 (0.321)	-0.613*** (0.172)	0.0829 (0.147)	0.0825 (0.101)	1.016*** (0.160)	-0.626*** (0.122)	0.0248 (0.105)	-0.328** (0.153)	0.654*** (0.171)	-0.128 (0.239)	0.152 (0.139)
Weather controls	yes											
Time polynomial	2 <sup>nd</sup>											
Bandwidths	±14 day											

308 Note: The coefficients of different air pollutants and their standard errors are shown by years. \*\*\*, \*\*, and \* indicate the 1%, 5%, and 10% significance level. The results of  
309 PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub>, NO<sub>2</sub>, CO, O<sub>3</sub> are shown in natural logarithm to eliminate the differences in absolute value.

## 5. Discussion on the reasons for cleaner winter heating policy

Our study found that the effects of the winter heating policy on air pollutants decreases by year from 2014-2017. In particular, the effects are relatively more significant in 2014 and 2015, but smaller in 2016 and 2017. This indicates that the winter heating was cleaner by years with the substitution of electricity or natural gas for traditional coal burning for winter heating.

There are several reasons for the cleaner winter heating policy. Firstly, the substitution of natural gas for traditional coal for winter heating may positively influence air quality. We collect the heating energy consumption in the BTH region from the *China Energy Statistical Yearbook 2014–2017*. The distribution of heating energy consumption includes coal, natural gas, oil, and other energy sources used for heating (Figure 5). We found that coal consumption for heating declined from 85% in 2014 to 71% in 2017, while natural gas consumption increased by from 11% in 2014 to 25% in 2017, indicating that promoting the substitution of natural gas for traditional coal has aided in improving winter air quality (Chengappa et al., 2007; Xue et al., 2016). However, the main energy consumption of winter heating is still dominated by coal, and there is still a large space for the replacement of clean energy.



**Fig. 5.** The heating energy consumption in the Beijing-Tianjin-Hebei region

Note: The percentage accumulation bar chart represents heating energy consumption include coal, natural gas, oil, and other energy used for heating.

Secondly, the substitution of other clean energy sources, such as electricity and other renewable energy (solar, geothermal, biomass, etc.), was of great attention in northern China. The number of households that completed the replacement transformation of clean energy for heating increased rapidly from 2014-2017 according to the government work report and the state of the ecological environment bulletin. Among them, 20,000 and 369,000 households in Beijing completed the replacement transformation of clean energy in 2014 and 2017, with the transformation scale expanded by about 20 times. In 2015, Tianjin completed the replacement of clean coal in the downtown area, and in 2016, it realized the full coverage of clean briquettes in rural areas. In 2017, a central heating system dominated by clean energy was gradually formed. Hebei Province and the whole region of Beijing, Tianjin, and Hebei also continue to clean the replacement of coal.

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338 Thirdly, other measures, such as eliminating coal-fired boilers and loose coal rectification were  
339 also of significant concern in northern China (Grammelis et al., 2016; Xu et al., 2021). The BTH region  
340 achieved the goal of eliminating small coal-fired boilers (i.e., those producing <10 tons of steam per  
341 hour) in built-up urban areas by the year 2015. Additionally, restrictions to the production, circulation,  
342 and use of bulk coal have been promoted in the BTH region since 2016, mainly focusing on the  
343 promotion of clean energy utilization in urban-rural fringe and rural areas. These efforts have proven to  
344 be effective for the continuous improvement of air quality. Beijing realized zero loose coal in the city's  
345 sixth district and the southern plain by 2017. 34,000 tons of steam have been renovated, and the  
346 transformation of coal-fired boilers in urban areas has been completed with remarkable results in  
347 reducing coal burning (BES, 2014-2017)<sup>7</sup>; Tianjin closed nearly 110,000 small coal-fired boilers from  
348 2014–2017, realizing zero loose coal in urban areas (TES, 2014-2017)<sup>8</sup>; Hebei has eliminated 80,000  
349 coal-fired boilers and more than 2.5 million households have been upgraded to replace coal with gas  
350 and electricity. Baoding, Langfang, and 18 other rural and urban areas in Hebei have also achieved zero  
351 coal emissions. (China Air 2018)<sup>9</sup>.

352 A series of clean heating measures implemented in China has achieved significant results, improved  
353 the heating mode and structure of winter heating, and effectively promoted the improvement of air  
354 quality in winter. All these actions above lead to a dramatic improvement in air quality in 2014 and 2015,  
355 making the room for improvement in 2016 and 2017 less obvious. This further provides compelling  
356 support for the research results of this paper; that is, with the promotion of clean heating measures, the  
357 winter heating in the study area is gradually clean during 2014-2017, which effectively reduces the  
358 impact on air quality.

## 359 **6. Conclusions and Policy implications**

360 This study establishes an RDD model to quantitatively estimate the annual variation effects of the  
361 winter heating policy on air quality from 2014 to 2017. We found that the effects of winter heating policy  
362 on air quality decreased by year with the promotion of cleaner heating measures. Moreover, a dynamic  
363 panel regression model is used to study the long-term correlations between winter heating activities and  
364 air quality. The results also show a significant positive effect.

365 We further study the heterogeneous effects of winter heating policy on different air pollutants and  
366 different city scales. We found the effects on PM<sub>2.5</sub> and PM<sub>10</sub> are more obvious than SO<sub>2</sub>, NO<sub>2</sub>, CO and  
367 O<sub>3</sub>. Through the promotion of clean heating, the disturbance of heating on PM<sub>10</sub>, SO<sub>2</sub> and NO<sub>2</sub> became  
368 rather small or even insignificant by the year of 2017, and PM<sub>2.5</sub> and CO still show more emission  
369 reduction room. The effects of different city sizes show that the larger the size of the city, the greater the  
370 impact of heating. There is also more effectiveness of the promotion of clean heating over the four years  
371 in larger cities. In addition, we sort out the implementation of cleaner heating measures in study areas  
372 from 2014 to 2017, which provides a supporting basis for the research results.

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<sup>7</sup> Beijing Environmental Statement (2014-2017)  
<http://sthjj.beijing.gov.cn/bjhrb/resource/cms/>

<sup>8</sup> Tianjin Environmental Statement (2014-2017)  
<http://sthj.tj.gov.cn/root16/mechanism/hjjcc/>

<sup>9</sup> 'China Air 2018: Air Pollution Prevention and Control Progress in Chinese Cities'  
(<http://allaboutair.cn/a/reports/2018/1227/526.html> )

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373 Based on our results, the winter heating policy has diminishing effects on air pollution in northern  
374 China, benefiting from the implementation of cleaner heating measures. The study puts forward the  
375 following policy suggestions: First of all, there is still a large space for development in the future. We  
376 should further increase the clean heating measures by actively promoting the substitution of clean energy  
377 and the improvement of technical support, to reduce the use of traditional coal as far as possible (Su et  
378 al., 2018; Zhao et al., 2019). Secondly, the government should promote clean heating measures such as  
379 formulation of more stringent standards in cities even in medium-size and small-size, and further  
380 complete the cleaner winter heating in northern China. Thirdly, we should monitor the atmospheric  
381 particulate pollutants, and take other auxiliary measures to strengthen the source prevention,  
382 atmospheric particulate pollutants control and terminal management during the heating period (Liu et  
383 al., 2019).

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539 **Appendix**

540 **Table A1. Robustness Test of different bandwidths**

	(1)	(2)	(3)	(4)	(5)	(6)
	AQI	AQI	AQI	AQI	AQI	AQI
year=2014	74.3*** (8.83)	80.3*** (7.92)	85.3*** (7.47)	90.8*** (7.28)	91.7*** (7.14)	92.1*** (7.23)
year=2015	60.8** (14.3)	70.7*** (11.9)	75.2*** (10.8)	75.20*** (9.31)	63.5*** (8.42)	64.3*** (8.09)
year=2016	30.7*** (9.32)	25.7*** (8.78)	32.3** (8.27)	29.39** (7.91)	32.3** (7.54)	36.4** (7.23)
year=2017	30.9*** (5.03)	26.6*** (4.28)	24.1*** (3.95)	24.4*** (3.77)	22.2*** (3.61)	19.2*** (3.55)
Weather controls	yes	yes	yes	yes	yes	yes
Time polynomial	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>
Bandwidths	±10 day	±12 day	±14 day	±16 day	±18 day	±20 day

541 Note: Columns 1-6 correspond to the results of 10 to 20 days before and after the winter heating respectively. \*\*\*,  
542 \*\*, and \* indicate the 1%, 5%, and 10% significance level.

543 **Table A2. Robustness Test of different forms of weather controls**

	(1)	(2)	(3)	(4)	(5)
	AQI	AQI	AQI	AQI	AQI
year=2014	71.1*** (9.92)	88.0*** (7.50)	85.3*** (7.47)	83.0*** (7.69)	81.1*** (7.94)
year=2015	78.7*** (10.4)	71.6*** (12.2)	75.2*** (10.8)	97.9*** (10.7)	98.6*** (11.8)
year=2016	37.4** (8.68)	36.9** (8.28)	32.3** (8.27)	34.9* (8.14)	36.5** (8.08)
year=2017	32.5*** (5.07)	27.1*** (3.96)	24.1*** (3.95)	22.5*** (4.08)	22.4*** (4.24)
Weather controls	No	linear	quadratic	cubic	quartic polynomial
Time polynomial	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>	2 <sup>nd</sup>
Bandwidths	±14 day	±14 day	±14 day	±14 day	±14 day

544 Note: Columns 1-5 correspond to the results of no weather control, linear, quadratic, cubic, and quartic polynomial  
545 of the weather controls respectively. \*\*\*, \*\*, and \* indicate the 1%, 5%, and 10% significance level.

546 **Table A3. Robustness Test of different cut-offs.**

	(1)	(2)	(3)	(4)	(5)	(6)
	Cut off (day=-14)			Cut off (day=14)		
year=2014	-14.9 (15.4)	-13.7 (16.2)	-31.1 (20.8)	-6.44 (11.7)	22.2** (10.7)	59.3*** (13.1)
year=2015	71.2*** (8.19)	78.5*** (7.95)	105*** (9.24)	47.8*** (16.8)	41.7** (17.2)	98.0*** (22.0)
year=2016	7.51 (4.64)	6.22 (4.71)	9.25 (6.48)	24.0*** (8.61)	23.0*** (8.36)	-1.61 (9.78)
year=2017	-23.9*** (6.02)	-21.2*** (5.82)	-21.7*** (7.34)	-1.70 (6.06)	1.01 (6.67)	-18.0** (8.21)
Weather controls	yes	yes	yes	yes	yes	yes
Time polynomial	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>
Bandwidths	±14 day	±14 day	±14 day	±14 day	±14 day	±14 day

547 Note: Columns 1-3 correspond to the results of 10 to 20 days before and after the winter heating respectively. \*\*\*,  
548 \*\*, and \* indicate the 1%, 5%, and 10% significance level.

**Table A4. Division of city scales.**

Urban hierarchy	Urban resident population	Cities included in the study area
Megacity	$\geq 10$ million	Beijing, Tianjin, Baoding, Handan, Shijiazhuang
Megalopolis	5 million - 10 million	Anyang, Cangzhou, Dezhou, Jinan, Jining, Kaifeng, Liaocheng, Heze, Tangshan, Xinxiang, Xingtai, Zhengzhou
Large-sized city	1 million - 5 million	Binzhou, Changzhi, Hebi, Hengshui, Jiaozuo, Jincheng, Langfang, Taiyuan, Yangquan, Zibo, Puyang
Medium-sized city	500 thousand - 1 million	None
Small-sized city	< 500 thousand	None