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 ($PM_{2.5}$ and PM_{10}) than for SO_2, NO_2, CO and O_3. 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 coal and causes severe human health risks in the densely populated northern region (Cai et al., 2009; Li et al., 2019; Zhang et al., 2019). As a result, clean heating measures, including mandatory replacement of coal with natural gas and electricity, coal rectification, and the closure of small coal-fired boilers, have become primary strategies for improving winter air quality (Cai and Jiang, 2008; Duan et al., 2014), and the national government has implemented a series of measures to facilitate such transition (Feng et al., 2019). While improvements in air quality have been observed, how these cleaner heating measures affect air pollution via the winter heating policy remains unclear. Considering that the winter air quality in northern China still to be improved against adverse health impacts, it is necessary to identify the effects of winter heating policy on air quality and explore the potential of clean heating control measures in the future.

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

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

This study aims at evaluating the effect of cleaning heating measures in Beijing-Tianjin-Hebei region and its surrounding areas ("2+26" cities) via winter heating policy from 2014 to 2017. Compared with existing literature, our study focuses on the annual trend and heterogeneity of air pollutants over the process of clean heating promotion, contributing to mainly two aspects: firstly, significant effects of winter heating on air pollutants are found using the RDD model. However, the effects diminished dynamically each year. Secondly, more types of air pollutants, especially O_3, and city scales are taken into consideration to further explore the heterogeneity through the whole process of clean heating. These fill the knowledge gaps in the previous literature and provide more thorough evidence of the cleaner winter heating policy's contributions to air quality.

2. Methods and data

2.1 Study area

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

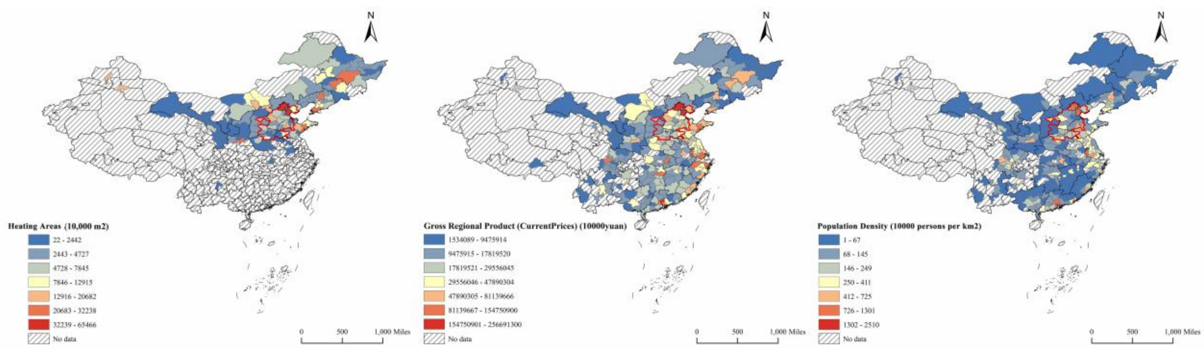

Fig. 1. The heating areas, the proportion of per capita GDP, and population density of the "2+26" cities[3]

2.2 Empirical model

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

[1] The Ministry of Environmental Protection was renamed the Ministry of Ecology and Environment in 2018.

[2] The central committees include the National Development and Reform Commission, the National Energy Administration, the State Finance Bureau, and other 8 committees.

[3] 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.

as follows:

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

Where P_{it} is the concentration of the air pollutants in a city i at time *t*. We chose the comprehensive indicator of air quality, the daily mean AQI, and the daily mean concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO as the dependent variables. $heating_{it}$ is an indicator of regulatory status. If a city *i* is regulated at time *t*. $heating_{it}$ = 1; otherwise $heating_{it}$= 0. And the parameter of interest β provided an estimate that whether there is an increase in air pollutants. c_i is the start time of winter heating policy in city i, and the actual heating time of each prefecture-level city was determined by sourcing the relevant information on heating from each city. $(t - c_i)$ is the day from the start time, $f[(t - c_i)]$ is a polynomial function of time, here we select the first-order term, the second-order term and the third-order term respectively to prevent over-fitting of the results (Ye, 2017). $\mathrm{X_{it}}$ is a vector of control variables, including meteorological factors and dummy variables of weekendday-of-week. The daily mean temperature, daily mean relative humidity, daily mean wind speed, and daily precipitation (accumulated within 24 hours), and the quadratic term form of meteorological factors were selected as the meteorological factors.

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

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

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

2.3 Data

The daily mean concentrations of air pollutants were collected from the National Urban Air Quality Real-time Release Platform. The daily mean AQI, $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO and O_3 in the study region from 2014.9.1–2017.12.31[4] are calculated based on 1-h mean data (Li et al., 2017).

The daily weather data were provided by the National Meteorological Information Center, which collects meteorological records from surface meteorological stations[5]. We use the daily mean

[4] 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.

[5] The National Meteorological Information Center provided the daily data for the pressure, temperature, precipitation,

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

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

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
$PM_{2.5}$	Particular matter less than 2.5 mm	μg/m^3	33341	77.74	58.42	4.21	731.09
PM_{10}	Particular matter less than 10 mm	μg/m^3	33341	135.25	82.69	7.27	937.71
SO_2	Sulfur dioxide	μg/m^3	33341	39.40	34.57	1.42	428.75
NO_2	Nitrogen dioxide	μg/m^3	33341	46.72	21.27	4.64	201.27
CO	Carbon monoxide	mg/m^3	33341	1.57	0.96	0.14	18.92
O_3	Ozone	μg/m^3	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	℃	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	%	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

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

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

We first analyse the trends of air pollutants in the “2+26” cities before and after the winter heating season starts. Figure 2 shows the trends of different air pollutants in 30 days before and after the winter heating begins, including AQI, $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO and O_3. The trends are similar for different air pollutants. The concentrations of air pollutants decreased by years except for O_3, indicating that the air quality improved after the implementation of cleaner heating measures from 2014 to 2017. Moreover, the concentrations of AQI, $PM_{2.5}$, PM_{10}, NO_2, SO_2 and CO during the winter heating season are significantly higher than that before the season in 2014 and 2015, while there was no significant

evaporation, relative humidity, wind direction and speed, sunshine duration, and ground temperature at 699 surface meteorological stations across China since January 1951.

difference in 2016 and 2017. As for O3, a secondary pollutant, the average concentrations drop in the heating seasons.

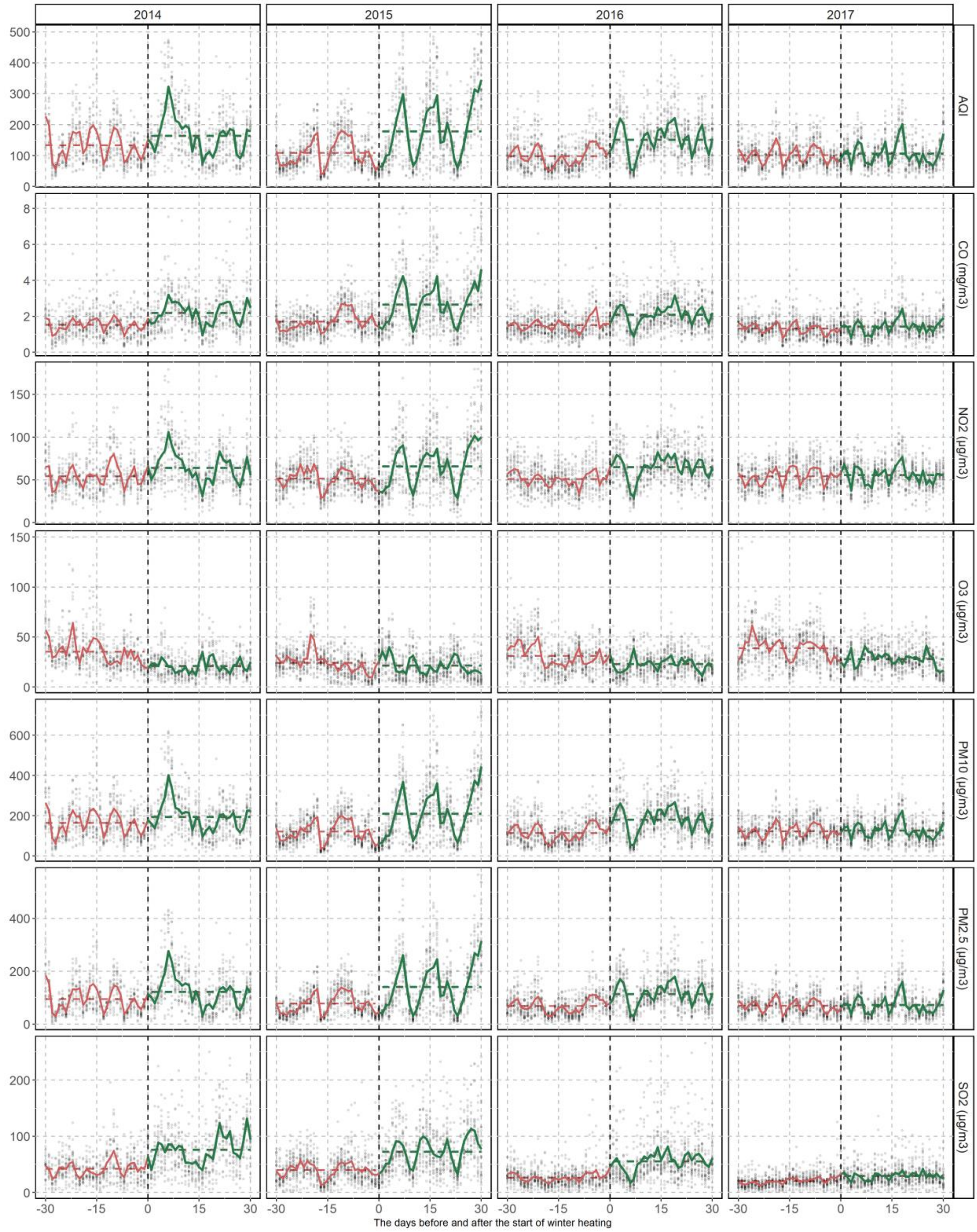

Fig. 2. The trends of air pollutants before and after the winter heating

Note: Daily mean concentrations of different air pollutants are shown. The black dash line represents the start time of winter heating. The red line represents the change of the daily mean air pollutants concentrations before the winter heating, while the green line represents the change of the daily mean air pollutants concentrations after the winter heating.

3.2 Regression discontinuity results

3.2.1 The discontinuity of the AQI over the cut-off

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

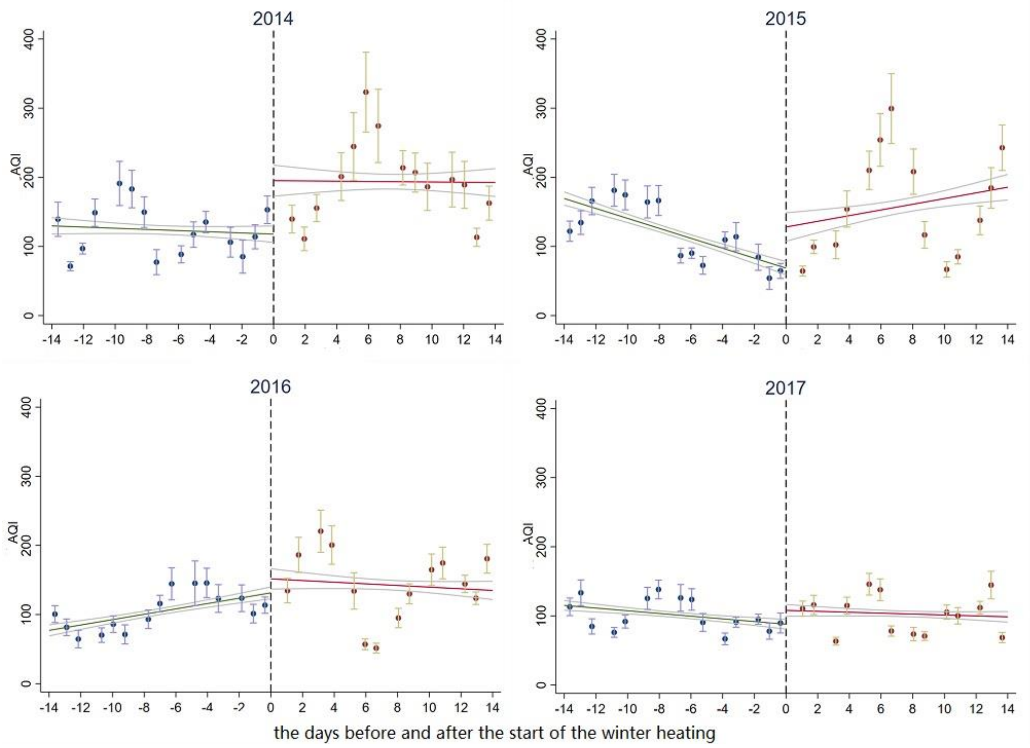

Fig. 3. The discontinuity of the AQI over the cut-off from 2014 to 2017

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

3.2.2 The annual effects of winter heating policy on air quality

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

The winter heating policy increases AQI with different sets of control variables or time polynomials introduced, but the effects decreased by years from 2014 to 2017. The observation windows are 14 days before and after the heating begins. Therefore we regard the changes in air quality within the very short window are caused by cleaning heating measures alone rather than other air pollution control actions. The result is the most significant when the control variable is added and the time polynomial is set as the quadratic term. It can be seen that the effects of winter heating on air quality are diminishing by years, which means the winter heating policy cleaned up with the implementation of clean heating measures. The increases of AQI are relatively significant by 85.3 and 75.2 in 2014 and 2015, while the increases are smaller by 32.3 and 24.1 in 2016 and 2017. It also provides empirical support for the research of a cleaner winter heating policy.

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

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

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

3.2.3 Robustness

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

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

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

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

Finally, a placebo test is performed by changing the settings of the cut-off to ensure the accuracy of the setting of the discontinuity. Table A3 respectively reports the results when the cut-off is two weeks before the winter heating policy started (columns 1-3) and two weeks after the winter heating policy started (columns 4-6). There are no significantly robust results in most years except 2015, and negative effects are even observed in 2017 when two weeks before the winter heating policy started to set for the cut-off, which can further ensure the accuracy of the setting of the model.

3.3 Dynamic panel regression results

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

Table 3 shows the dynamic panel regression results of the long-term correlation between winter heating and air quality. The winter heating activity has significant positive effects on air pollutants, increasing AQI by 18.0. $PM_{2.5}$, PM_{10}, SO_2 and CO increased by 22.1%, 15.4%, 25.1%, and 21.4%, respectively. The effects on NO2 and O3 are insignificant.

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

Table 3. Results of dynamic panel regression.

	AQI	$lnPM_{2.5}$	$lnPM_{10}$	$lnSO_2$	$lnNO_2$	lnCO	lnO_3
heating	18.0***	0.221***	0.154***	0.251***	0.00402	0.214***	0.00960
	(1.61)	(0.0186)	(0.0146)	(0.0233)	(0.0104)	(0.0157)	(0.0151)
temperature	0.0660	0.000700	0.00232***	-0.0119***	-0.00688***	-0.00569***	0.0274***
	(0.0590)	(0.000785)	(0.000614)	(0.00103)	(0.000532)	(0.000628)	(0.00103)
windspeed	-2.36***	-0.0512***	-0.0196**	-0.122***	-0.0990***	-0.0612***	0.0528***
	(0.502)	(0.00625)	(0.00541)	(0.00766)	(0.00390)	(0.00441)	(0.00488)
humidity	0.469***	0.00684***	0.00243***	-0.00598***	-0.00144***	0.00527***	-0.00534***
	(0.0384)	(0.000412)	(0.000334)	(0.000464)	(0.000230)	(0.000299)	(0.000347)
precipitation	-0.737***	-0.0102***	-0.00929***	-0.00867***	-0.00359***	-0.00493***	0.000140
	(0.163)	(0.00216)	(0.00203)	(0.00195)	(0.000902)	(0.00108)	(0.000523)
holiday	2.37*	0.0230	0.0209*	0.0145	-0.0240*	0.0138	0.00409***
	(1.41)	(0.0163)	(0.0123)	(0.0248)	(0.0130)	(0.0154)	(0.01560)
pgdp	-0.306***	-0.00308***	-0.00342***	-0.000739	-0.00168***	-0.00187**	0.00242***
	(0.0765)	(0.000904)	(0.000680)	(0.0602)	(0.00123)	(0.000805)	(0.000809)
year	-1.81***	-0.0331***	-0.0210***	-0.156***	0.00037	-0.0367***	0.0454***
	(0.417)	(0.00491)	(0.00375)	(0.00709)	(0.00304)	(0.00413)	(0.00421)
Time trend term	-0.0270***	-0.000419***	-0.000237***	-0.000592***	0.000109***	-0.000288***	-0.000459***
	(0.00440)	(0.0000443)	(0.0000339)	(0.0000702)	(0.0000315)	(0.0000450)	(0.0000477)
Lagging order	2	2	2	2	2	2	2
Fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	366***	67.9***	43.7***	317***	1.20	74.2***	-89.7***
	(840)	(9.91)	(7.58)	(14.3)	(6.13)	(8.32)	(8.48)
Observations	30169	$lnPM_{2.5}$	$lnPM_{10}$	$lnSO_2$	$lnNO_2$	lnCO	lnO_3
R-squared	0.526	0.221***	0.154***	0.251***	0.00402	0.214***	0.00960

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% significance level. The results of PM2.5, PM10, SO2, NO2, CO, O3 are shown in natural logarithm to eliminate the differences in absolute value.

4. Heterogeneous effects of winter heating policy on air quality

4.1 Heterogeneous effects of winter heating on different air pollutants

We estimated the heterogeneous effects of winter heating on different air pollutants (Table 4). It can be found that there were significant positive effects of the winter heating policy on different air pollutants except for O_3, and the annual variations were consistent with the AQI from 2014-2017. The increases in air pollutants caused by the winter heating policy are significant in 2014 and 2015. $PM_{2.5}$, PM_{10} and SO_2 increase the most in the year of 2015. Specifically, the concentration of $PM_{2.5}$, PM_{10}, SO_2, NO_2 and CO increased by 73.0%, 61.9%, 53.2%, 34.6%, and 41.6% in 2014. The increased of $PM_{2.5}$, PM_{10}, SO_2, NO_2 and CO are 83.2%, 70.3%, 56.6%, 22.0% and 35.0% in 2015. The effects were significantly smaller after 2015, where the increases of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 are 34.7%, 52.1%, 20.8% and 14.2% in 2016. The increases of $PM_{2.5}$, PM_{10}, NO_2 and CO are 37.8%, 19.6%, 9.0% and 20.9% in 2017. However, there is no stable pattern for O_3.

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

The effects of winter heating policy on SO_2 and NO_2 are positive in most years, but the effects are small or even insignificant in some years. Since the government replaced traditional coal-burning with desulfurized coal or natural gas, these measures had already significantly reduced the concentration of SO_2. The SO_2 concentrations thirty days before heating are 42.2, 40.1, 26.5 and 20.5 $\mu g/m^3$ from 2014 to 2017, experiencing a very sharp reduction. Moreover, the concentrations of SO_2 and NO_2 are not only affected by household heating but also other factors, such as industrial and vehicular emissions (Dong et al., 2020), which may lead to insignificant effects because of the greater effects of other emissions sources during the study period. In addition, there are positive effects of the winter heating policy on CO, which is caused by the incomplete combustion of fuels (such as coal or oil) in coal-fired boilers. As a secondary pollutant, the formation of ozone is influenced by precursor emissions, photochemical reaction, and meteorological conditions (Hao el al., 2021). The precursors (mainly NO_x and VOCs) originate from more complicated sources than heating, such as traffic emissions, oil volatilization and even plant growth in nature (Min et al., 2021). And although there are more severe anthropogenic source emissions due to heating, solar radiation is weak and photochemical reaction is difficult to occur in winter. The precursor and the lack of radiation are the main reasons why ozone is not significantly disturbed by heating activities.

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

	(1) AQI	(2) $lnPM_{2.5}$	(3) $lnPM_{10}$	(4) $lnSO_2$	(5) $lnNO_2$	(6) lnCO	(7) lnO_3
year=2014	85.3***	0.730***	0.619***	0.532**	0.346***	0.416***	-0.07301
	(7.47)	(0.0674)	(0.0595)	(0.113)	(0.0455)	(0.0800)	(0.0785)
year=2015	75.2***	0.832***	0.703***	0.566***	0.220***	0.350***	0.802***
	(10.8)	(0.928)	(0.0886)	(0.101)	(0.0517)	(0.0651)	(0.103)
year=2016	37.4**	0.347***	0.521***	0.208*	0.142**	0.0648	-0.410***
	(8.68)	(0.0986)	(0.0896)	(0.111)	(0.0489)	(0.0677)	(0.0951)
year=2017	24.1***	0.378***	0.196***	0.142	0.090***	0.209***	0.753
	(3.95)	(0.0634)	(0.0525)	(0.0976)	(0.0337)	(0.0590)	(0.0677)
Weather controls	yes	yes	yes	yes	yes	yes	yes
Time polynomial	2^{nd}	2^{nd}	2^{nd}	2^{nd}	2^{nd}	2^{nd}	2^{nd}
Bandwidths	±14 day	±14 day	±14 day	±14 day	±14 day	±14 day	±14 day

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 $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, O_3 are shown in natural logarithm to eliminate the differences in absolute value.

4.2 Heterogeneous effects of winter heating on different city scales

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

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

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

By comparing the different effects from 2014-2017, the effects of clean winter heating increased with the city scales, which may be related to the stronger promotion intensity of clean winter heating in larger cities in China. As a result, the differences of the coefficients of winter heating policy on air pollutants increased with the city scales. Specifically, the daily mean AQI in megacities increased by 35.2 in 2017, which decreased by 88.8 compared with 2014; the daily mean AQI in megalopolis increased by 21.5 in 2017, which decreased by 59.8 compared with 2014; In large cities, the daily mean AQI increased by 21.0 in 2017, which decreased by 41.6 compared with 2014. $PM_{2.5}$ and PM_{10} follow the similar pattern as AQI, but SO_2, NO_2 and CO in large-sized cities are less significant than in megacities.

[6] 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

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***	118***	71.8***	35.2***	81.3***	62.1***	39.7**	21.5***	62.6***	55.0***	45.4***	21.0***
	(21.9)	(42.5)	(16.2)	(10.6)	(9.06)	(17.6)	(16.8)	(5.55)	(16.39)	(14.2)	(14.7)	(6.52)
$\ln PM_{2.5}$	1.09***	1.35***	0.505***	0.513***	0.673***	0.669**	0.227	0.322***	0.650***	0.454**	0.365**	0.320***
	(0.164)	(0.291)	(0.167)	(0.196)	(0.0779)	(0.144)	(0.168)	(0.0927)	(0.175)	(0.2001)	(0.152)	(0.123)
$\ln PM_{10}$	0.968***	1.22***	0.693***	0.328*	0.544***	0.289	0.484***	0.162**	0.585***	0.380**	0.472***	0.144*
	(0.155)	(0.258)	(0.164)	(0.172)	(0.0735)	(0.209)	(0.145)	(0.0667)	(0.135)	(0.181)	(0.136)	(0.0793)
$\ln SO_2$	1.22***	0.808***	0.862**	0.249	0.307**	0.439***	0.145	0.278***	0.353	0.403**	0.161	0.0436
	(0.267)	(0.211)	(0.346)	(0.297)	(0.124)	(0.160)	(0.109)	(0.0952)	(0.231)	(0.159)	(0.213)	(0.161)
$\ln NO_2$	0.694***	0.632***	0.420***	0.195**	0.273***	-0.0762	0.287***	0.105**	0.285***	0.178**	0.0635	0.0672
	(0.0977)	(0.110)	(0.0864)	(0.0944)	(0.0572)	(0.0903)	(0.0772)	(0.0531)	(0.0968)	(0.0735)	(0.0672)	(0.0549)
$\ln CO$	0.975***	0.735***	0.156	0.360**	0.343***	-0.235**	0.0474	0.169**	0.257	0.269***	0.250**	0.135
	(0.158)	(0.168)	(0.121)	(0.121)	(0.0959)	(0.113)	(0.111)	(0.0815)	(0.170)	(0.0968)	(0.125)	(0.129)
$\ln O_3$	-0.284	0.217	-0.613***	0.0829	0.0825	1.016***	-0.626***	0.0248	-0.328**	0.654***	-0.128	0.152
	(0.173)	(0.321)	(0.172)	(0.147)	(0.101)	(0.160)	(0.122)	(0.105)	(0.153)	(0.171)	(0.239)	(0.139)
Weather controls	yes											
Time polynomial	2^{nd}											
Bandwidths	±14 day											

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 PM2.5, PM10, SO2, NO2, CO, O3 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.

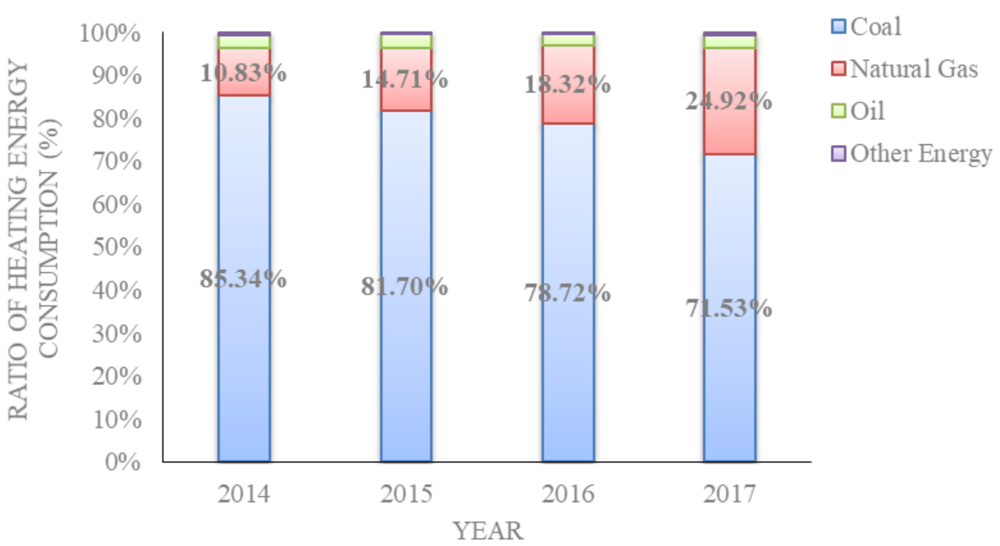

Fig. 5. The heating energy consumption in the Beijing-Tianjin-Hebei region

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.

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

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

6. Conclusions and Policy implications

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

We further study the heterogeneous effects of winter heating policy on different air pollutants and different city scales. We found the effects on $PM_{2.5}$ and PM_{10} are more obvious than SO_2, NO_2, CO and O_3. Through the promotion of clean heating, the disturbance of heating on PM_{10}, SO_2 and NO_2 became rather small or even insignificant by the year of 2017, and $PM_{2.5}$ and CO still show more emission reduction room. The effects of different city sizes show that the larger the size of the city, the greater the impact of heating. There is also more effectiveness of the promotion of clean heating over the four years in larger cities. In addition, we sort out the implementation of cleaner heating measures in study areas from 2014 to 2017, which provides a supporting basis for the research results.

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

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

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

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

Acknowledgments

This work was supported by the National Natural Science Foundation of China [grant number 72174097] and the Fundamental Research Funds for the Central Universities.

Declaration of interest: no competing interest.

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Appendix

Table A1. Robustness Test of different bandwidths

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

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

Table A2. Robustness Test of different forms of weather controls

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

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

Table A3. Robustness Test of different cuf-offs.

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

Note: Columns 1-3 correspond to the results of 10 to 20 days before and after the winter heating respectively. ***, **, 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	⩾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