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Effects of meteorological conditions and air pollution on COVID-19 transmission: Evidence from 219 Chinese cities

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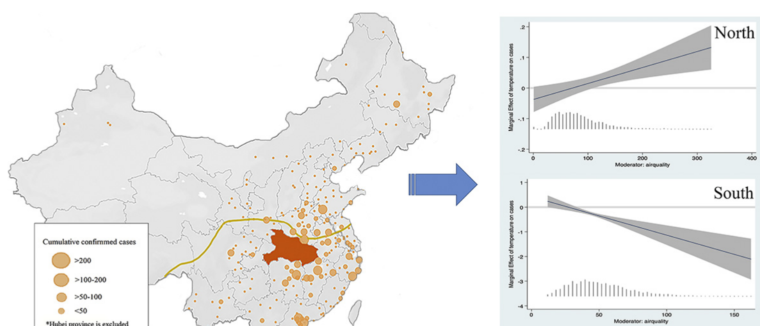
HIGHLIGHTS

- There exists a nonlinear dose-response relationship between temperature and COVID-19 transmission
- Air pollution has exerted a positive impact on the transmission of and infection by COVID-19.
- In northern China the negative effects of rising temperature on COVID-19 were counteracted by aggravated air pollution.
- In southern cities, the rising temperature restrained the facilitating effects of air pollution on COVID-19.

GRAPHICAL ABSTRACT



Temperature with moderate affect of air quality

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ABSTRACT

The spatial distribution of the COVID-19 infection in China cannot be explained solely by geographical distance and regulatory stringency. In this research we investigate how meteorological conditions and air pollution, as concurring factors, impact COVID-19 transmission, using data on new confirmed cases from 219 prefecture cities from January 24 to February 29, 2020. Results revealed a kind of nonlinear dose-response relationship between temperature and coronavirus transmission. We also found that air pollution indicators are positively correlated with new confirmed cases, and the coronavirus further spreads by 5–7% as the AQI increases by 10 units. Further analysis based on regional divisions revealed that in northern China the negative effects of rising temperature on COVID-19 is counteracted by aggravated air pollution. In the southern cities, the ambient temperature and air pollution have a negative interactive effect on COVID-19 transmission, implying that rising temperature restrains the facilitating effects of air pollution and that they jointly lead to a decrease in new confirmed cases. These results provide implications for the control and prevention of this disease and for the anticipation of another possible pandemic.

1. Introduction

The novel coronavirus disease 2019 (COVID-19), acknowledged as a global pandemic by the World Health Organization (WHO) on March 11, 2020, has posed a severe threat to human health and caused widespread panic all around the world. Following the first confirmed case reported in Wuhan in late December 2019, COVID-19 spread to other provinces and eventually covered almost all the regions in China, despite a mandatory lockdown policy initially launched in Wuhan on January 23 and followed shortly afterwards by another 95 cities (He et al., 2020; Kang et al., 2020; Liu, 2020).

Fig. 1 shows the cumulative confirmed cases in 219 prefecture-level cities in China (excluding cities in Hubei province) as of February 29,

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Fig. 1. The cumulative confirmed cases in 219 cities in China as of February 29, 2020.

2020. It is noticeable that even though local governments had taken timely and consistent restriction measures, the coronavirus spread widely across the country, aggregating in certain regions. This spatial distribution of coronavirus infection cannot be explained through the epidemic model, geographical distance, or population distribution and age composition (Becchetti et al., 2020; Setti et al., 2020; Travaglio et al., 2020; Wu et al., 2020).

In addition to the unique transmission model of coronavirus and the restriction policies utilized by the government to limit the COVID-19 epidemic, atmospheric conditions are considered as the other crucial concurring factor that could affect the transmission of and infection by the disease (Bashir et al., 2020a; Becchetti et al., 2020; Fattorini and Regoli, 2020; Qi et al., 2020; Xie and Zhu, 2020; Wang et al., 2020b). As the novel coronavirus spreads via respiratory droplets and close contact (Wang et al., 2020c) and even airborne transmission via aerosols (Paules et al., 2020; van Doremalen et al., 2020), it is imperative to investigate whether and how atmospheric conditions affect the survival and spread of coronaviruses and thereby the transmission of COVID-19.

Meteorological conditions including temperature, humidity, and wind are considered as crucial atmospheric factors in predicting COVID-19 transmission (Auler et al., 2020; Bashir et al., 2020a; Iqbal et al., 2020; Qi et al., 2020; Xie and Zhu, 2020; Wu et al., 2020). Among others, Bi et al. (2007), Casanova et al. (2010), and Chan et al. (2011) have revealed the impact of the ambient temperature on survival and transmission of coronaviruses (such as SARS-CoV and MERS-CoV). Recent literature has reiterated the suppressing impact of temperature on COVID-19 transmission based on samples from Brazil, China, and other countries (Prata et al., 2020; Qi et al., 2020; Wang et al., 2020b; Wu et al., 2020); however, other researchers have found contradicting results (Auler et al., 2020; Jahangiri et al., 2020; Xie and Zhu, 2020; Iqbal et al., 2020). Humidity is another crucial contributor to the transmission of coronavirus disease (Ali and Alharbi, 2020; Auler et al., 2020; Bashir et al., 2020a) despite the argument that the COVID-19 pandemic may be partially suppressed when humidity increases (Ahmadi et al., 2020; Wu et al., 2020). Wind can act as a vital factor in the spread of respiratory infectious diseases, as it may modulate the dynamics of various vectors and pathogens (Ellwanger and Chies, 2018) and indirectly impact coronavirus infection by affecting air quality (Frontera et al., 2020; Wang et al., 2020d; Zhu et al., 2020). However, the impact of wind on COVID-19 transmission is quite controversial in the empirical literature, ranging from positive (Şahin, 2020), to negative (Ahmadi et al., 2020), to insignificant (Bashir et al., 2020a).

Air quality is a comprehensive indicator reflecting the emissions of particulate matters (including $PM_{2.5}$ and PM_{10}), Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), and other pollutants (Bashir et al., 2020b; Collivignarelli et al., 2020; Riccò et al., 2020; Travaglio et al., 2020; Zambrano-Monserrate et al., 2020). Air pollution can be a crucial contributor to the transmission of and infection by coronavirus in two ways. Firstly, the spread of some airborne viruses (such as measles and influenza) have appeared to increase through ambient fine particles that remain airborne longer, travel longer distances, cover larger areas, and penetrate the lungs much more deeply (Andrée, 2020). This is actually the case as COVID-19 is a respiratory disease and the novel coronavirus can linger in viable aerosols for hours (van Doremalen et al., 2020; Zhu et al., 2020). Secondly, it is well acknowledged that severe air pollution produces abnormalities in lung surfactant composition and damages the lungs' "working efficiency" (Pastva et al., 2007), making humans more vulnerable to disease and more likely to suffer from respiratory infections, asthma, and chronic obstructive pulmonary disease (Fattorini and Regoli, 2020; Kim et al., 2018; Korber, 2020). Since the lungs are the main target of this virus, and the virus spikes (binding domains) attach to the lungs' cell receptors (Ali and Alharbi, 2020), the chances of inflection could rise if a person is exposed to severe air pollution.

In this paper, we analyze the effects of atmospheric conditions on daily new confirmed cases of COVID-19 at a city level, using data on new confirmed cases from 219 Chinese prefecture cities from January 24 to February 29, 2020. The Kendall and Spearman rank correlation tests and multivariate estimation models with city cluster-robust standard error adjustment were performed, respectively. The results revealed a kind of nonlinear dose-response relationship between temperature and coronavirus transmission, and we found that air pollution indicators were positively correlated with the new confirmed cases. Further analysis based on regional division revealed that in northern China the negative effects of rising temperature on COVID-19 were counteracted by aggravated air pollution, while in southern cities, rising temperatures restrained the facilitating effects of air pollution and they jointly led to a decrease in coronavirus spread.

This research contributes to the existing literature in the following ways. Firstly, we provide a comprehensive framework for identifying and explaining whether and how meteorological conditions (e.g., the ambient temperature, relative humidity, and wind speed) and air pollution affect coronavirus transmission in China. This differs from previous COVID-19 research that in general has only partially focused on the exclusive effects of atmospheric conditions and lacked explanations for its controversial findings. Secondly, compared with province-based analysis, city-level analysis should be more precise and factual in identifying the effects of weather factors, considering the vast size of Chinese provinces and their apparent climate disparity. Thirdly, to the best of our knowledge, this is the first research to conduct an interactive analysis regarding the impact of temperature and air pollution on COVID-19 transmission. Fourthly, we compare the difference in the effects of atmospheric conditions on coronavirus between the north and south regions in China, which has not previously been researched.

2. Material and methods

Our study includes 219 prefecture-level cities in mainland China between January 24 and February 29, 2020. At least 10 confirmed cases were reported for each of the sample cities. Cities in Hubei province (including Wuhan) were excluded to eliminate the effects of extreme values and endogenous influence.

The dependent variable of this research is the daily new confirmed cases at city level, *CityNew*, spanning the period from January 24 to February 29, 2020. As shown in Fig. 2, the COVID-19 epidemic in China spread mainly during this period, and cases confirmed before January 24 were excluded to eliminate the potential inclusion of imported cases from Wuhan, which was locked down on January 23 (Xie and Zhu, 2020; Zhu et al., 2020).

Among the meteorological variables in our research, ambient temperature is regarded as crucial factors influencing the survival and spread of coronaviruses by Bi et al. (2007), Casanova et al. (2010), Chan et al. (2011), and many others. Ambient temperature is measured by maximum temperature (*TempMax*), minimum temperature (*TempMin*), and average temperature (*TempAvg*) in this research. It is essential to examine the impact of temperature on COVID-19 transmission systematically and thoroughly, given the contradicting conclusions in recent empirical literature (Iqbal et al., 2020; Qi et al., 2020; Wang et al., 2020b; Wu et al., 2020; Xie and Zhu, 2020). The quadratic term of daily average temperature for each city, $TempAvg^2$, is introduced to capture the non-linear impact of temperature on COVID-19 transmission, as explained by Wang et al. (2020b), and Xie and Zhu (2020). Relative humidity (*Humidity*) is another important weather factor affecting the transmission of coronavirus, although there are as yet no conclusive arguments and explanations about the impacts of humidity on COVID-19 (Ali and Alharbi, 2020; Wu et al., 2020). Wind (*Wind*) may directly modulate the dynamics of various vectors and pathogens (Ellwanger and Chies, 2018), and indirectly impact coronavirus infection by affecting air quality (Frontera et al., 2020; Wang et al., 2020d; Zhu et al., 2020).

Air pollution, measured by the air quality index (AQI), may exert a significant impact on the transmission of and infection by COVID-19. This is partly because COVID-19 is a respiratory disease, and a denser concentration of ambient fine particulate matter could carry the coronavirus in the air for longer, and across larger distances (Andrée, 2020; Zhu et al., 2020).It is also because heavy air pollution could damage lung function and render people more vulnerable to coronavirus disease (Kim et al., 2018; Korber, 2020). Many researchers (e.g., Becchetti et al., 2020; Coccia, 2020; Fattorini and Regoli, 2020; Setti et al., 2020; van Doremalen et al., 2020; Zhu et al., 2020) have demonstrated that the risk of coronavirus infection can increase if a person is exposed to air pollution, whether long- or short-term. Previous studies on disease outbreak have demonstrated that the risk of virus infection apparently increases after one to three days of exposure to heavy air pollution (Chen et al., 2017; Peng et al., 2020). In this research we have introduced the daily city-level AQI of the last day (*AQI-1*), the average AQI of the last 3 days (*AQI-3*), and the average AQI of the last 5 days (*AQI-5*), to capture the impact of short-term exposure to air pollution on COVID-19 transmission. Furthermore, as other researchers have pointed out that ambient air quality and temperature could synergistically weaken lung function (Wu et al., 2014; Zhang et al., 2015), we have introduced the interaction items of temperature and AQI to identify the combined effects of meteorological conditions and air pollution.

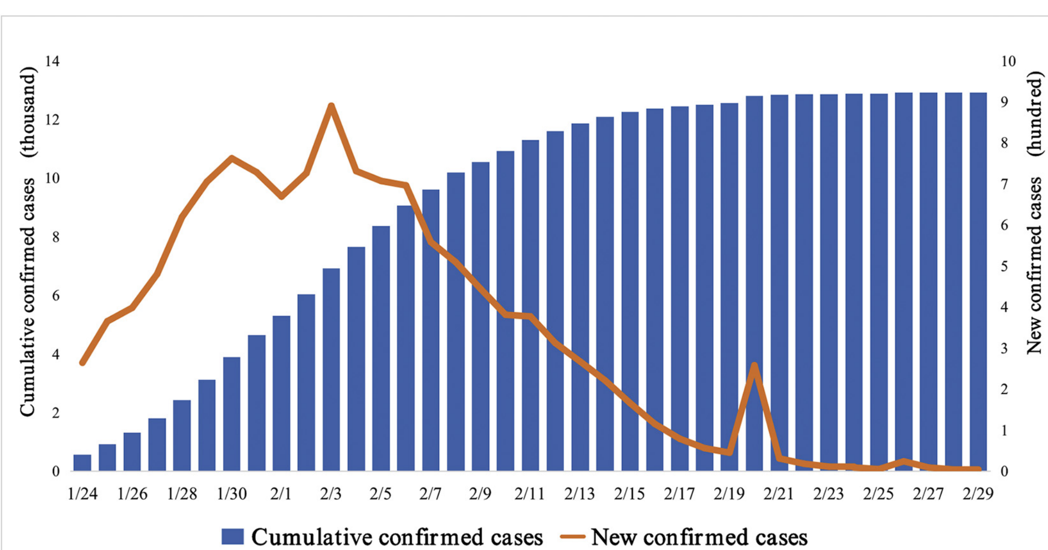

Fig. 2. Daily changes in cumulative confirmed cases and new confirmed cases of COVID-19 in China.

Table 1
Results of Kendall and Spearman rank correlation tests.

Variables	COVID-19: city-level new confirmed cases (219 cities)	
	Kendall correlation coefficient	Spearman correlation coefficient
TempMax	−0.036***	−0.062***
TempMin	−0.011*	−0.021*
TempAvg	−0.024***	−0.043***
Humidity	0.035***	0.063***
Wind	0.001	0.001
AQI-1	0.021**	0.361**
AQI-3	0.030***	0.052***
AQI-5	0.043***	0.074***

*** Stands for 1% level of significance.
** Stands for 5% level of significance.
* Stands for 10% level of significance.

The country-level daily new confirmed cases (100 people), *CountryNew*, is introduced into our analysis in order to control the effects of overall trends of the COVID-19 epidemic situation in China. It is also an imperfect but acceptable method to control for the effects of the national intervention policy on the coronavirus disease. The indicator variable, *Province*, is also included in the regression model to control the effects of provincial characteristics. Since the residuals of a given city may be corrected across days, we performed multivariate estimation models with city cluster-robust standard error adjustment in our research.

Data on meteorological conditions (i.e., temperature, humidity, and wind) and air pollution (i.e., AQI) were retrieved from the National Meteorological Information Center (http://data. cma.cn) and the Online Air Quality Monitoring and Analysis Platform (https://www.aqistudy.cn/), respectively. Data on COVID-19, including country-level and city-level new confirmed cases, were gathered from daily reports published by the China National Health Commission (http://www.nhc.gov.cn/).

3. Results and discussion

3.1. Kendall and Spearman rank correlation tests

As the variables are not normally distributed, the Kendall and Spearman rank correlation tests were performed to examine the correlation between city-level new confirmed cases and the variables indicated for meteorological conditions and air pollution. As shown in Table 1, in both the Kendall and Spearman correlation tests, the daily maximum temperature, minimum temperature, and average temperature are negatively significantly correlated to the new cases, indicating valid depression effects of ambient temperature on COVID-19 transmission. Relative humidity presents a positive correlation to new confirmed cases. Air pollution indicators are all positively correlated to the new confirmed cases at a 5% significance level or higher, consistently valid across the three pollution indicators.

3.2. Estimation results of multivariate regression

In Table 2 we report the effects of meteorological conditions on the city-level daily new confirmed cases of COVID-19. The first two columns present how temperature affects coronavirus transmission. Columns 3 and 4 show the estimation results for humidity and wind, respectively.

As shown in column 1, both the maximum temperature and minimum temperature have a significant and negative impact on new confirmed cases ($p < .01$). The second column shows a positive and negative relationship between city-level new confirmed cases and average temperature ($p < .01$), and its quadratic term ($p < .01$). The results demonstrate a kind of nonlinear dose-response relationship between temperature and coronavirus transmission, supporting the conclusion proposed by Wang et al. (2020b) and Xie and Zhu (2020), that there may be an optimal temperature for COVID-19 transmission. Wind speed is reported to be negatively correlated with coronavirus infection at a 1% significance level, consistent with the findings of Ahmadi et al. (2020) and Coccia (2020). The result supports the arguments that higher wind speed may modulate the dynamics of various vectors and pathogens, clear the fine particles in the air, and decrease the risk of coronavirus infection (Ellwanger and Chies, 2018; Frontera et al., 2020; Wang et al., 2020d; Zhu et al., 2020). Relative humidity is found to be negatively but insignificantly related to new cases, providing slight support for the findings of Ali and Alharbi (2020), Auler et al. (2020), Bashir et al. (2020a), among others.

In Table 3 we present the effects of air pollution on city-level daily new confirmed COVID-19 cases. According to Wu et al. (2014) and Zhang et al. (2015), ambient air quality and temperature could synergistically weaken lung function and increase the risk of virus infection; hence the interaction items (normalized) of average temperature and air pollution are introduced in columns 2, 4, and 6 in the table.

As shown in Table 3, ambient temperature has a robust and negative effect on COVID-19 transmission, consistently across all the estimation models ($p < .01$). Air pollution indicators, including the AQI of the last day (*AQI-1*), average AQI of the last 3 days (*AQI-3*), and average AQI of the last 5 days (*AQI-5*), are all reported to be positively correlated with the new confirmed cases at 1% significance levels. The coronavirus further spreads by 5–7% as the AQI increases by 10 units. Results are consistent with previous literature stating that short-term exposure to air pollution could increase the spread of and infection by coronavirus (Ali and Alharbi, 2020; Andrée, 2020; Korber, 2020; Travaglio et al.,

Table 2
Effects of meteorological conditions on city-level daily new confirmed cases.

Variables	(1)	(2)	(3)	(4)	(5)
TempMax	−0.040***(0.012)				
TempMin	−0.034***(0.012)				
TempAvg		−0.046***(0.012)			−0.049***(0.011)
TempAvg^2		−0.003***(0.001)			−0.003***(0.001)
Humidity			−0.036(0.049)		−0.019(0.050)
Wind				−0.149***(0.045)	−0.229***(0.048)
Province	0.036***(0.015)	0.029**(0.015)	−0.002(0.012)	−0.006(0.012)	0.025(0.016)
CountryNew	0.-12***(0.002)	0.013***(0.002)	0.013***(0.002)	0.013***(0.002)	0.013***(0.002)
Constant	1.005***(0.242)	1.241***(0.262)	1.172***(0.231)	1.468***(0.252)	1.836***(0.328)
Wald χ^2	82.72***	88.40***	83.498***	79.77***	114.34***
R^2	0.026	0.030	0.010	0.011	0.033*
Obs.	7396	7396	7396	7396	7396

Standard errors adjusted for 219 clusters in cities (clustered standard errors in parentheses).
*** Stands for 1% level of significance.
** Stands for 5% level of significance.
* Stands for 10% level of significance.

Table 3
Effects of air pollution on city-level COVID-19 daily new confirm cases.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
TempAvg	−0.075***(0.009)	−0.101***(0.013)	−0.073***(0.009)	−0.104***(0.016)	−0.069***(0.009)	−0.111***(0.018)
AQI-1	0.005***(0.001)	0.005***(0.001)				
AQI-3			0.006***(0.002)	0.005***(0.002)		
AQI-5					0.007***(0.002)	0.006***(0.002)
TempAvg ∗ *AQI-1*		0.228***(0.070)				
TempAvg ∗ *AQI-3*				0.267***(0.097)		
TempAvg ∗ *AQI-5*						0.369***(0.125)
Province	0.040**(0.016)	0.042***(0.016)	0.039**(0.016)	0.042***(0.016)	0.038**(0.016)	0.041***(0.016)
CountryNew	0.012***(0.002)	0.012***(0.002)	0.012***(0.001)	0.012***(0.002)	0.012***(0.001)	0.012***(0.001)
Constant	0.579**(0.275)	0.724***(0.280)	0.522*(0.309)	0.694**(0.304)	0.469(0.336)	0.695**(0.328)
Wald χ^2	83.070***	84.73***	79.55***	81.24***	79.80***	82.58**
R^2	0.031	0.033	0.031	0.033	0.030	0.034
Obs.	7396	7396	7396	7396	7396	7396

Standard errors adjusted for 219 clusters in cities (clustered standard errors in parentheses). Interaction items are normalized.
*** Stands for 1% level of significance.
** Stands for 5% level of significance.
* Stands for 10% level of significance.

2020; van Doremalen et al., 2020; Zhu et al., 2020). Further analyses were performed to investigate the interactive impact of temperature and AQI. We can see that the interaction items are all significantly and positively correlated with the city-level new confirmed cases ($p < .01$), indicating that ambient temperature and air pollution exert a combined impact on the transmission of, and infection by COVID-19, supporting the findings of Wu et al. (2014) and Zhang et al. (2015). Specifically, the influence of air pollution on COVID-19 transmission increases with ambient temperature rise; that is, the negative effects of rising temperature on coronavirus are counteracted by worsening air pollution. Besides, according to the coefficients of interaction items, the depression effects increase from 22.8% to 36.9% as a person is exposed to air pollution from one to five days.

Table 4 shows the estimation results of the difference in the effects of atmospheric conditions between the northern cities (Panel A) and southern cities (Panel B) in China. As shown in Panel A, in north China the impact of ambient temperature, wind speed, and air pollution on COVID-19 transmission are consistent with our findings listed in Tables 2 and 3. However, the nonlinear dose-response relationship between temperature and new cases no longer exists, becoming insignificant and U-shaped instead. This may be because in north China, where there is much heavier air pollution than in southern regions, the depression impact of rising temperature may be counteracted by the facilitating effects of worsening air pollution (see Fig. 3). On the other hand, Panel B presents a significant nonlinear dose-response relationship between ambient temperature and new cases in south China ($p < .05$), and the interaction item of temperature and AQI is reported to be negatively correlated with new confirmed cases ($p < .05$). The results demonstrate that rising temperature restrains the facilitating effects of air

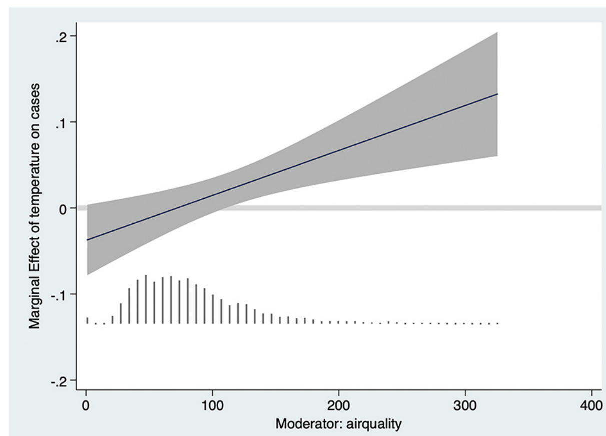

Fig. 3. Marginal effects of temperature with moderate effect of air quality in northern China.

Table 4
Further estimation based on regional divisions.

Variables	Panel A: Northern China			Panel B: Southern China		
	(1)	(2)	(3)	(4)	(5)	(6)
TempAvg	−0.010(0.015)	−0.021(0.015)	−0.065**(0.030)	−0.030(0.069)	−0.180***(0.023)	−0.087**(0.043)
TempAvg^2	0.001(0.002)			−0.006**(0.003)		
Humidity	0.031(0.097)			−0.065(0.052)		
Wind	−0.132**(0.058)			−0.289***(0.074)		
AQI-3		0.007***(0.002)	0.008***(0.002)		0.020***(0.005)	0.036***(0.010)
TempAvg ∗ *AQI-3*			0.327**(0.157)			−1.009**(0.405)
Province	0.018(0.011)	0.017(0.012)	0.020*(0.011)	−0.080**(0.074)	−0.072**(0.036)	−0.069*(0.036)
CountryNew	0.009***(0.002)	0.008***(0.002)	0.008***(0.002)	0.015***(0.002)	0.016***(0.002)	0.016***(0.002)
Constant	0.770***(0.168)	−0.017(0.243)	0.049(0.223)	4.635***(1.026)	3.470***(0.890)	1.996*(1.204)
Wald χ^2	41.48***	24.13***	26.55***	71.04***	68.42***	71.43***
R^2	0.008	0.012	0.013	0.066	0.071	0.073
Obs.	3297	3297	3297	4099	4099	4099

Standard errors adjusted for 219 clusters in cities (clustered standard errors in parentheses). Interaction items are normalized.
*** Stands for 1% level of significance.
** Stands for 5% level of significance.
* Stands for 10% level of significance.

pollution on COVID-19 transmission and jointly leads to a decrease of new confirmed cases (see Fig. 4).

Certain factors may contribute to the difference between the north and south of China. Firstly, air pollution in north China is much heavier than in the southern regions; in fact the Chinese Ministry of Ecology and Environment stated that in February 2020 the top 10 cities with the worst air quality were all in the north. Secondly, coal-based house heating and thermal power generation became major sources of air pollution in China as local governments locked their cities down, suspended transport, and closed factories (He et al., 2020; Wang et al., 2020d). In southern China, which is far warmer and has fewer thermal power plants, the reduction in air pollution may be more obvious than in the north as the temperature rose during the lockdown period. Thirdly, as well as the pollutant emissions from coal consumption, the northern regions have suffered increasingly from extraneous and local dust, and experienced more hazy weather than the south from January to March, which could counteract the suppression impacts of rising temperature on COVID-19 transmission.

4. Conclusions and policy implications

In addition to the well-acknowledged epidemic model and policy restraints, atmospheric conditions are presumed to be crucial factors affecting the survival and spread of COVID-19. In this research we investigated how meteorological conditions and air pollution impact COVID-19 transmission in China, using data on new confirmed cases from 219 prefecture cities from January 24 to February 29, 2020. Multivariate estimation models with city cluster-robust standard error adjustment were performed to examine the specific effects of weather indicators, air quality index, and their interaction items on COVID-19 transmission. This research has investigated the difference in atmospheric effects between the northern and southern regions of China, which has not been done before.

Results demonstrate that: (1) there exists a kind of nonlinear dose-response relationship between temperature and coronavirus transmission, and wind speed is negatively correlated with coronavirus infection; (2) air pollution indicators are positively correlated with new confirmed cases, and every 10 units increase in the AQI leads to an increase in the daily confirmed cases by 5% to 7%; (3) in northern China, the interaction effects of temperature and AQI are positive and the influence of air pollution on COVID-19 transmission increases as the ambient temperature rises, indicating that the negative effects of rising temperature on coronavirus are counteracted by worsening air pollution; (4) however, in the south, COVID-19 transmission presents a nonlinear dose-response relationship with the ambient temperature, and the

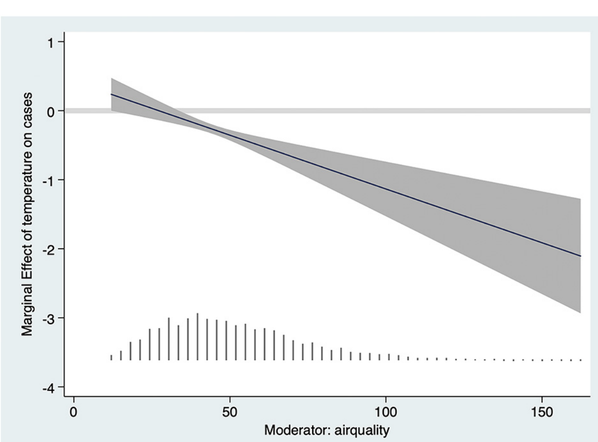

Fig. 4. Marginal effects of temperature with moderate effect of air quality in southern China.

interaction effects of temperature and AQI are negative, implying that rising temperature restrains the facilitating effects of air pollution and jointly leads to a decrease in new confirmed cases. The findings of our research have some practical implications. Firstly, weather indicators are significant and integral in predicting and preventing COVID-19 transmission. Colder regions in the world should take far more restrictive measures to prevent coronavirus from becoming widespread. It is also the case that all countries should draw up anti-epidemic polices if the novel coronavirus coexists with humans for a long time (Xie and Zhu, 2020; Wang et al., 2020b). Secondly, the significant and valid impact of air pollution on COVID-19 transmission has strong implications for mitigation strategies required to prevent spreading and to anticipate other novel pandemics (Andrée, 2020). Urgent action must be taken globally to reverse the deteriorating environment, alteration of ecosystems, and fragmenting international cooperation in sustainable development and its supervision. Thirdly, China should increase its effort to convert its energy structure from coal to clean energies, especially in power generation and house heating, which are the major sources of air pollution (especially in northern China) besides industrial production and traffic.

Our findings have several limitations, highlighting provision for further studies on this subject. Firstly, the low values of the predicted R-square in estimation models indicate that the findings of our research are not statistically sufficient. Further analysis should introduce more explanatory variables and capture other crucial concurring factors, such as regulatory stringency and population mobility within and between cities. Furthermore, the sample of this analysis may not actually reflect the effects of atmospheric conditions, because the official data regarding imported cases (from abroad and from other cities) is not available. Secondly, our findings on the effects of meteorological factors on coronavirus are derived from statistical results and causal inference. Further research should provide more experimental and observational evidence on this infectious epidemic. Thirdly, long-term studies covering wider regions, especially with similar socio-economic development but significantly different environmental status, could provide more robust results and anticipate other possible pandemics (Ahmadi et al., 2020; Frontera et al., 2020; Riccò et al., 2020).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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