Environmental Pollution 293 (2022) 118544

Contents lists available at ScienceDirect

Environmental Pollution

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

Differential health and economic impacts from the COVID-19 lockdown between the developed and developing countries: Perspective on air pollution☆

Yichen Wang[a,*,1], Rui Wu[b,1], Lang Liu[a], Yuan Yuan[a], ChenGuang Liu[a], Steven Sai Hang Ho[g], Honghao Ren[c,1], Qiyuan Wang[d], Yang Lv[f], Mengyuan Yan[d], Junji Cao[e]

[a] School of Public Policy and Administration, Northwestern Polytechnical University, Xi'an, 710129, China
[b] School of Business, Nanjing Normal University, Nanjing, 210023, China
[c] School of Management Science and Engineering, Shanxi University of Finance and Economics, Taiyuan, 030006, China
[d] Key Laboratory of Aerosol Chemistry and Physics, State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, 710061, China
[e] Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 100029, China
[f] School of Government Administration, Central University of Finance and Economics, Beijing, 100081, China
[g] Division of Atmosphere Sciences, Desert Research Institute, Reno, NV, 89512, United States

A R T I C L E I N F O

Keywords:
COVID-19 lockdown
Developed and developing countries
Air pollution
Health impacts
Economic impacts

A B S T R A C T

It is enlightening to determine the discrepancies and potential reasons for the degree of impact from the COVID-19 control measures on air quality as well as the associated health and economic impacts. Analysis of air quality, socio-economic factors, and meteorological data from 447 cities in 46 countries indicated that the COVID-19 control measures had significant impacts on the $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm) concentrations in 20 (reduced $PM_{2.5}$ concentrations of −7.4–29.1 μg m^{-3}) of the selected 46 countries. In these 20 countries, the robustly distinguished changes in the $PM_{2.5}$ concentrations caused by the control measures differed between the developed (95% confidence interval (CI): −2.7–5.5 μg m^{-3}) and developing countries (95% CI: 8.3–23.2 μg m^{-3}). As a result, the COVID-19 lockdown reduced death and hospital admissions change from the decreased $PM_{2.5}$ concentrations by 7909 and 82,025 cases in the 12 developing countries, and by 78 and 1214 cases in the eight developed countries. The COVID-19 lockdown reduced the economic cost from the $PM_{2.5}$ related health burden by 54.0 million dollars in the 12 developing countries and by 8.3 million dollars in the eight developed countries. The disparity was related to the different chemical compositions of $PM_{2.5}$. In particular, the concentrations of primary $PM_{2.5}$ (e.g., BC) in cities of developing countries were 3–45 times higher than those in developed countries, so the mass concentration of $PM_{2.5}$ was more sensitive to the reduced local emissions in developing countries during the COVID-19 control period. The mass fractions of secondary $PM_{2.5}$ in developed countries were generally higher than those in developing countries. As a result, these countries were more sensitive to the secondary atmospheric processing that may have been enhanced due to reduced local emissions.

1. Introduction

Ambient fine particulate matter (i.e., $PM_{2.5}$) is of great concern due to its effects on human health and global climate change (Forster et al., 2007; Lelieveld et al., 2015). The $PM_{2.5}$ pollution is closely related to human activities (Guan et al., 2014). With the outbreak of the novel coronavirus (COVID-19), each government has taken different measures to control the spreading of the virus within the country (Desvars et al., 2020). These policies include cancellation of mass gatherings, closures of educational institutions, shutdown of factories and public facilities,

☆ This paper has been recommended for acceptance by Da Chen.

* Corresponding author.
E-mail address: wangyichen@nwpu.edu.cn (Y. Wang).
[1] These authors contributed equally to the study.

https://doi.org/10.1016/j.envpol.2021.118544
Received 22 April 2021; Received in revised form 18 September 2021; Accepted 15 November 2021
Available online 18 November 2021

travel restrictions, and quarantine for immigrants (Desvars et al., 2020). The cessation of industrial production and limited travel have reduced the emissions of air pollutants (Wang et al., 2020) and thereby benefitted the air quality. The tragedy offers an opportunity to obtain fundamental answers concerning how air quality would be altered if human and economic activities were largely reduced. Such a question is definitely difficult to be resolved via calculations and simulation models.

Although there have been many studies on air quality during the COVID-19 control period (e.g., Chossiere et al., 2021; El-Sheekh et al., 2021; Kumari et al., 2020; Venter et al., 2020), only 13 studies have been focused on the global scale (Table S1), of which 2 studies have quantified the impact of the COVID-19 lockdown on changes in air quality and its consequent health and economic impacts during the COVID-19 control period (Chossiere et al., 2021; Venter et al., 2020). The results of these two studies suggested that the impacts of the lockdown policies could vary between countries or regions (Table S1). The basis of the problem is the discrepancies and potential reasons for the degree of impact on the air quality across the regions as well as the associated health and economic impacts.

$PM_{2.5}$ can pose adverse health effects and potentially lead to mortality or morbidity as a result of respiratory irritation, pulmonary dysfunction, and cardiovascular disease (WHO, 2016). $PM_{2.5}$ pollution can increase economic costs, e.g., the loss of labor productivity and the increase in health expenditures (Hunt et al., 2016). Most relevant studies that have focused on the health and economic impacts on air quality during COVID-19 lockdowns have been conducted in particular cities of China and the United States (e.g., Nie et al., 2020; Son et al., 2020). A more recent study compared the mortality burdens between European countries and China (Giani et al., 2020). To our knowledge, no systematic study has been conducted to compare both the health and economic effects due to the lockdown between the developed and developing countries at a global scale.

Global assessments could assist each government to establish particular pollution prevention measures suitable for local circumstances. The framework for such an endeavor could be divided into three sections: 1) estimating the effect of COVID-19 lockdown measures on the $PM_{2.5}$ concentrations using the fixed-effects model described in Liu et al. (2020); 2) elucidating the significance of the impact on the $PM_{2.5}$ concentration across the countries and examining the heterogeneity; and 3) comparing the health and economic impacts generated by the COVID-19 lockdown between developed and developing countries. The results are particularly important to establish unique and efficient air pollution control measures for those areas.

2. Literature review

The relevant studies could be divided into three categories: the changes in $PM_{2.5}$ concentrations, the changes in $PM_{2.5}$ concentrations caused by the control measures, and the relevant health and economic impacts. Most of the studies focused on the changes in $PM_{2.5}$ concentrations during the COVID-19 control period (e.g., Chen et al., 2020; El-Sheekh et al., 2021; Wang et al., 2020). The results showed that many countries experienced a large reduction of $PM_{2.5}$ concentration. For example, China experienced a reduction of 0.2–35.8 $\mu g\ m^{-3}$ in its major cities (Wang et al., 2020); the ambient $PM_{2.5}$ concentration in Alexandria, Egypt decreased by 29.3% (El-Sheekh et al., 2021). A 21–26% decline in average aerosol optical depth (AOD) was observed across Nigeria (Etchie et al., 2021). Some countries showed nonuniform changes in $PM_{2.5}$ concentration. For instance, the statistically significant reductions of $PM_{2.5}$ only occurred in the Northeast and California/Nevada metropolises of the United States (Chen et al., 2020).

Notably, the changes in $PM_{2.5}$ concentrations in the above studies were not necessarily due to the COVID-19 control measures. A few studies quantified the impact of the control measures on $PM_{2.5}$ concentration (e.g., Al-Abadleh et al., 2021; He et al., 2020; Sharma et al., 2020), and the results showed that the measures caused reductions of $PM_{2.5}$ concentrations by 19.8% in China (He et al., 2020) and by 43.0% in India (Sharma et al., 2020). However, statistical non-significance of the COVID-19 lockdown effect was found in most areas of Canada and in the Midwest of the United States (Al-Abadleh et al., 2021; Hammer et al., 2021). Thus, the impact of the control measures on $PM_{2.5}$ concentrations differed across countries. Not surprisingly, the health and economic impacts resulting from the changes in $PM_{2.5}$ concentration caused by the COVID-19 control measures also differed across countries (Venter et al., 2020). For example, the short-term averted premature deaths in China (24,200, 95% CI 22380–26010) were ~11 times higher than in Europe (2190, 1960–2420) (Giani et al., 2020).

Considering such difference across countries, the following questions need to be answered: 1) What are the features of such differences on a global scale? 2) How can we explain such features? The answers to these questions can help us understand the channels through which control measures affect global air quality.

3. Methods

3.1. Data sources

The data of $PM_{2.5}$ concentration in this study were obtained from the Air Quality Open Data Platform (https://aqicn.org/map/world/cn/). The $PM_{2.5}$ data in this study originated from the environmental protection administration, universities, research institutions and the U.S. embassies abroad (https://aqicn.org/sources/). The time series of $PM_{2.5}$ concentration for each country was inspected, and the outliers (i.e., defined as the absolute values of Z-scores > 3) were removed. The fixed-effects model requires a certain amount of data, i.e., each country or region should have $PM_{2.5}$ concentration data for more than five cities. These data cover the period before and after the COVID-19 control period in 2020 and the corresponding period from 2016 to 2019. Finally, the daily city-level data for the 447 cities of the 46 countries were considered in this work.

The daily weather parameters including temperature, relative humidity (RH), wind speed, and atmospheric pressure were collected from the National Oceanic and Atmospheric Administration (NOAA) (Alken et al., 2020). The same statistical method used for the $PM_{2.5}$ mass concentrations was applied to remove the outliers.

The socio-economic data, such as secondary industry share, tertiary industry share and population density, and the daily GDP data, were obtained from the official website of the World Bank (https://data.worldbank.org.cn/).

The lockdown information was collected in Desvars et al. (2020). The following measure(s) was/were implemented during the lockdown stage, and their strength of impact on the reduction of pollutant emissions was scored from 1 (minimum) to 4 (maximum) (Table S2): (i) non-essential movements forbidden for all cases (score = 4); (ii) factories closures (score = 3); (iii) non-essential movements forbidden for specific groups of people (score = 2); (iv) non-essential movements forbidden at specific periods of time (score = 2); and (v) schools or restaurant closures (score = 1).

The non-essential movements forbidden for all cases involved the shutdown of factories and caused large declines in the number of on-road vehicles, offering the strongest effect on the pollutant emissions. The gathering cancellation policy called for the closures of factories and thus suspended all industrial operations. In addition, the transportation sector could be diminished to a certain extent by those measures that limited the non-essential movements for specific periods or people. The closures of schools and restaurants not only limited the direct emissions from the activities taken places but also eased the demand for transportation. In comparison, this measure was expected to provide the least impact on the air quality.

Notably, the control measures implemented were city (region)-specific (Malpede and Percoco, 2021), i.e., different restrictions were implemented in specific cities or regions in each country. The score was thus assigned for each city according to the maximum strength of the aforementioned measures. For instance, the non-essential movements forbidden for all cases was implemented in Hubei province in China. Even though other measures (e.g., the factory closures) were also executed at the same time, the score of 4 was given to Hubei province. The average of the scores of all the cities in a country was defined as the score for that country. Based on this guideline, the final scores of each country are listed in Table S3 and Fig. S1.

3.2. Fixed-effects model

As the collected data were panel data, we followed Liu et al. (2020) and Ming et al. (2020) and applied a fixed-effects model to estimate the effect of lockdown policy. In the model, $PM_{2.5}$ concentration before the lockdown, climate factors and both city- and time-fixed effects were considered. The model was as follows:

$$Y_{i,t} = \alpha_1 Y_{i,prior\_t} + \alpha_2 COVID_t + \alpha_3 WIND_{i,t} + \alpha_4 PRES_{i,t} + \alpha_5 TEMP_{i,t} + \alpha_6 HEIG_{i,t} + \alpha_7 PREC_{i,t} + \gamma_i + \lambda_t + u_{i,t} \quad (1)$$

where $Y_{i,t}$ is the $PM_{2.5}$ concentration in city i in year t. $Y_{i,prior\_t}$ is the $PM_{2.5}$ concentration four weeks before the COIVD-19 lockdown in city i; $COVID_t$ is a dummy variable that equals 1 when t = 2020 and t = 0 otherwise; $WIND_{i,t}$, $PRES_{i,t}$, $TEMP_{i,t}$, $HEIG_{i,t}$, and $PREC$ are climate factors of wind speed, pressure, temperature, planetary boundary layer height, and precipitation rate in city i at year t, respectively; γ_i is the fixed-effects of city i; λ_t is the fixed-effects of time t; $u_{i,t}$ is an error term that is independently and identically distributed; *and* α_1–α_7 are the coefficients.

The application of the fixed-effects model enables us to accurately assess the impact of the lockdown policy, because city- and time-specific heterogeneity, variation of $PM_{2.5}$ concentration during prior years, and climate factors have been controlled. Moreover, we could apply modified Wald tests to analyze the heteroskedasticity (Baum, 2001) and estimate heteroskedasticity-robust results whenever necessary. The limitation of the fixed-effects model is that the spatial contagion of $PM_{2.5}$ concentrations is not considered in this model.

3.3. Integrated health and economic model

We evaluated the short-term health impacts on the exposures to ambient $PM_{2.5}$ concentration during the COVID-19 lockdown. The exposures to incremental $PM_{2.5}$ that could lead to health issues termed as health endpoints was categorized into incident cases, hospital admissions, and mortality. In addition, we calculated the health burdens for four main causes: lower respiratory infections, chronic obstructive pulmonary disease (COPD), ischaemic heart disease, and stroke. The total health endpoints $EP_{i,d}$ in each day were computed as follows:

$$EP_{i,d} = P_i \times B_{i,d} \times (1 - \exp(-\ln\beta_d \times \Delta C)) \quad (2)$$

where P_i is the population of country i; $B_{i,d}$ is the daily, disease-specific baseline risk rate for country i obtained from the Global Burden of Disease Study (2019) (GBD, 2019); β_d is the disease-specific relative risk of mortality obtained from a meta-analysis based on data of 652 cities in 24 regions or countries (Liu et al., 2019) and hospitalizations obtained from Li et al. (2016), Liu et al. (2018), Tian et al. (2019a), and Tian et al. (2019b) (Table S4); ΔC is the change in $PM_{2.5}$ concentration after the lockdown.

The economic impacts on the $PM_{2.5}$ pollution-related health endpoints comprise the health expenditure and costs of workday loss. The health expenditure was obtained by multiplying outpatient and hospital admission expenditure per case with total endpoints (Eq. (3)). The cost of workday loss was computed by multiplying outpatient visits and hospital admission days (Table S5) by the daily gross domestic product (GDP) per capita (Eq. (4)).

$$HE_{i,d} = EX_{i,d} \times EP_{i,d} \quad (3)$$

$$C_{i,d} = T_{i,d} \times G_i, \quad (4)$$

where $HE_{i,d}$ is the disease-specific health expenditure of country i; $EX_{i,d}$ is the disease-specific outpatient and hospital admission expenditure per case of country i; $C_{i,d}$ is the cost of work loss day; $T_{i,d}$ is the disease-specific outpatient visits and hospital admission days; and G_i is the daily GDP per capita of country i.

3.4. The structure of this study

The structure of this study is shown in Fig. 1. First, we screened the research object; The fixed-effects model requires a certain amount of data, i.e., each country or region should have $PM_{2.5}$ concentration data for more than five cities. These data covered the period before and after the COVID-19 control period in 2020 and the corresponding period from 2016 to 2019. Data from 46 countries were selected based on this requirement. Second, the fixed-effects model was used to quantify the impact of COVID-19 control measures on $PM_{2.5}$ concentration, and 20 countries with significant impact on $PM_{2.5}$ concentration were selected. Third, as for the 20 countries, the heterogeneity regarding the impact of COVID-19 control measures on $PM_{2.5}$ concentration was analyzed; an integrated health and economic model was used to calculate the health and economic impacts from the changes in $PM_{2.5}$ concentration caused by the control measures. Significant differences were found between developed and developing countries in the changes of $PM_{2.5}$ concentration caused by the control measures. Consequently, the health and economic benefits differed between developed and developing countries. Finally, we explain the difference between developed and developing countries and propose the corresponding policy inspiration.

4. Results

4.1. Changes of fine particulate matter ($PM_{2.5}$) concentrations between developed and developing countries

The COVID-19 prevention and control measures had significant impacts on the $PM_{2.5}$ concentrations in 20 of the selected 46 countries (Fig. 2). In terms of the changes in $PM_{2.5}$ concentrations caused by the control measures, reductions of 0.6–29.1 μg m^{-3} were found in 17

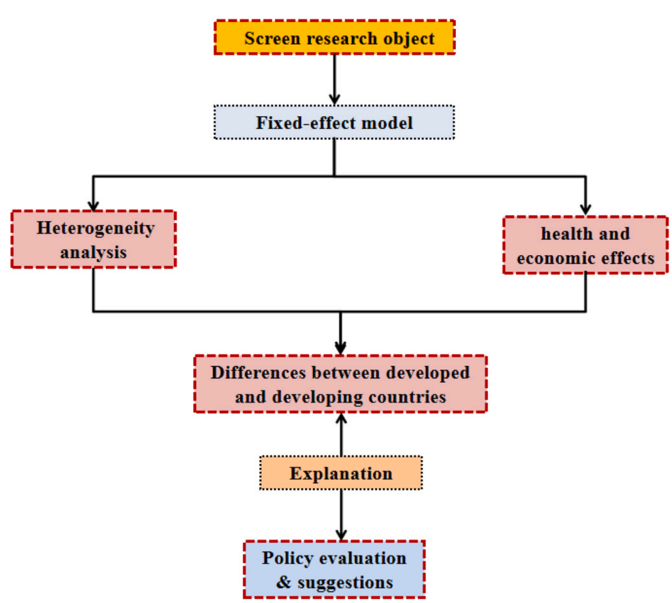

Fig. 1. The structure of this study.

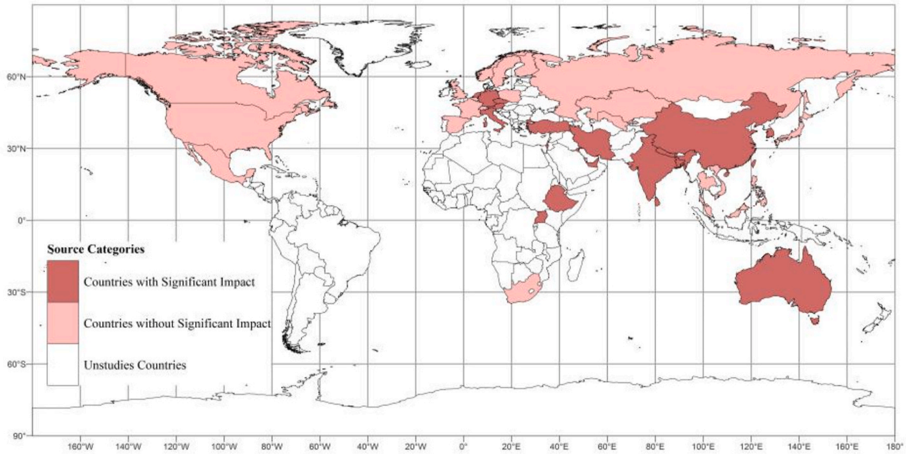

Fig. 2. The countries where the COVID-19 control measures had a significant impact on the $PM_{2.5}$ concentrations (Venter et al., 2020), and the distribution of $PM_{2.5}$ concentrations changes caused by the control measures.

countries, of which the largest declines were found in Bangladesh (29.1 μg m^{-3}) followed by India (25.3 μg m^{-3}) and Bahrain (13.2 μg m^{-3}), while minor decreases occurred in the Netherlands (0.6 μg m^{-3}), Australia (1.5 μg m^{-3}) and Israel (2.1 μg m^{-3}). However, unexpected increases of 7.4 μg m^{-3}, 2.7 μg m^{-3}, and 2.7 μg m^{-3} were found in the Czech Republic, Austria, and Germany, respectively.

Overall, the COVID-19 control measures caused a substantial reduction (5.6–29.1 μg m^{-3}) in $PM_{2.5}$ concentrations in all developing countries and a smaller reduction (4.6–11.3 μg m^{-3}) in $PM_{2.5}$ concentrations in five developed countries, and even increased $PM_{2.5}$ concentrations (1.8–7.4 μg m^{-3}) in three developed countries. Such differential effects between developed and developing countries were related to the difference in the chemical composition of $PM_{2.5}$ (details can be found in the Discussion section). The measure-induced changes in the $PM_{2.5}$ concentrations between developed and developing countries are illustrated in Fig. S2. Indeed, the measure-induced reductions of $PM_{2.5}$ concentrations were observed in all of the developing countries, in comparison to 37.5% of the developed countries, with several even showing increases of the measure-induced $PM_{2.5}$ concentrations (Fig. S2). In terms of the decline magnitude, the developing countries showed a range of 5.6–29.1 μg m^{-3} of $PM_{2.5}$ concentrations reductions caused by the control measures, greater than the 4.6–11.3 μg m^{-3} for the developed countries. The significant and robust changes in the $PM_{2.5}$ concentrations caused by the control measures are shown between the developed (95% confidence interval (CI): −2.7–5.5 μg m^{-3}) and developing countries (95% CI: 8.3–23.2 μg m^{-3}) (Fig. 3; Fig. S3-5). Such changes are robust when adjusted for the meteorological factors (Fig. S6).

In addition to developed and developing countries, we also examined whether the impacts of the control measures varied across other different categories of countries (He et al., 2020). The severity of the measures is a potential contributor; however, slight differences were found between the countries with either low or high severity (Fig. 3; Fig. S3–5). Interpreted via the socio-economic and meteorological factors, the differences were either insignificant (i.e., secondary industrial share and meteorological factors) (Fig. 3) or significant but not robust (i.e., tertiary industry share and population density) (Fig. S3–5).

.The differences between the high and low $PM_{2.5}$ concentration groups were significant and robust (Fig. 3; Fig. S3–5). The correlation analysis further supported the conclusion that the impacts of the control measures were greater in countries with higher $PM_{2.5}$ concentrations (R^2 = 0.40–0.55; Fig. 4; Fig. S7). Therefore, the control measures showed greater impact on the reductions of $PM_{2.5}$ concentrations in countries with higher $PM_{2.5}$ concentrations.

4.2. *Changes in health and economic factors associated with $PM_{2.5}$*

The one-month lockdown reduced the number of premature deaths and hospital admissions related to the $PM_{2.5}$ pollution by 7967 (95% CI: 6206–9821) cases and 83,050 (95% CI: 46,507–119,460) cases in the 20 countries. The circumvented deaths from lower respiratory infections, COPD, ischaemic heart disease, and stroke were estimated to be 882, 2,137, 2,843, and 2106 cases, respectively. COPD had the largest hospital admissions reduction (42,637 cases), followed by ischaemic heart disease (18,613 cases). The declines in the morbidity and mortality lessened the economic burdens on the residents. The circumvented health expenditure was approximately 50.7 million U.S. dollars (USD) (the same currency is used afterward). In addition, the circumvented cost of the workday loss was approximately 11.6 million dollars. The largest circumvented economic impacts from the changes on $PM_{2.5}$ concentration was seen in China (36.1 million dollars) followed by India (12.6 million dollars). The COVID-19 lockdown reduced the economic cost from the $PM_{2.5}$ related health burden by 54.0 million dollars in the 12 developing countries and by 8.3 million dollars in the eight developed countries.

Notably, there were differences in terms of health and economic impacts from the $PM_{2.5}$ concentration changes between the developed and developing countries. India and China were the two countries showing the most obvious reductions in overall deaths and hospital admissions, accounting for 87% and 86%, respectively, of the total cases. The eight developed countries only showed reductions of 1.0% and 1.5%, respectively, in the overall deaths and hospital admissions due to the trace decline in the $PM_{2.5}$ concentration levels (Table 1). The economic and health impacts were positive in all of the developing countries, while negative effects occurred in several developed countries such as Austria, the Czech Republic, and Germany (Table 1).

5. Discussion

Most of the latest research has focused the changes in $PM_{2.5}$ concentration in different countries during the COVID-19 control period (e.g., He et al., 2021; Kumari et al., 2020). A summary of these studies demonstrated that the $PM_{2.5}$ concentration decreased more in developing countries than in developed countries (e.g., He et al., 2021; Kumari et al., 2020). A few studies have quantified the impact of control measures on $PM_{2.5}$ concentration (e.g., Chossiere et al., 2021; Hammer et al., 2021). The results showed that the impacts on the reduction of $PM_{2.5}$ concentrations in China and India (two developing countries) were >10 times larger than in Europe and United States (developed countries) (e.g., Dang et al., 2020; Venter et al., 2020). However, there

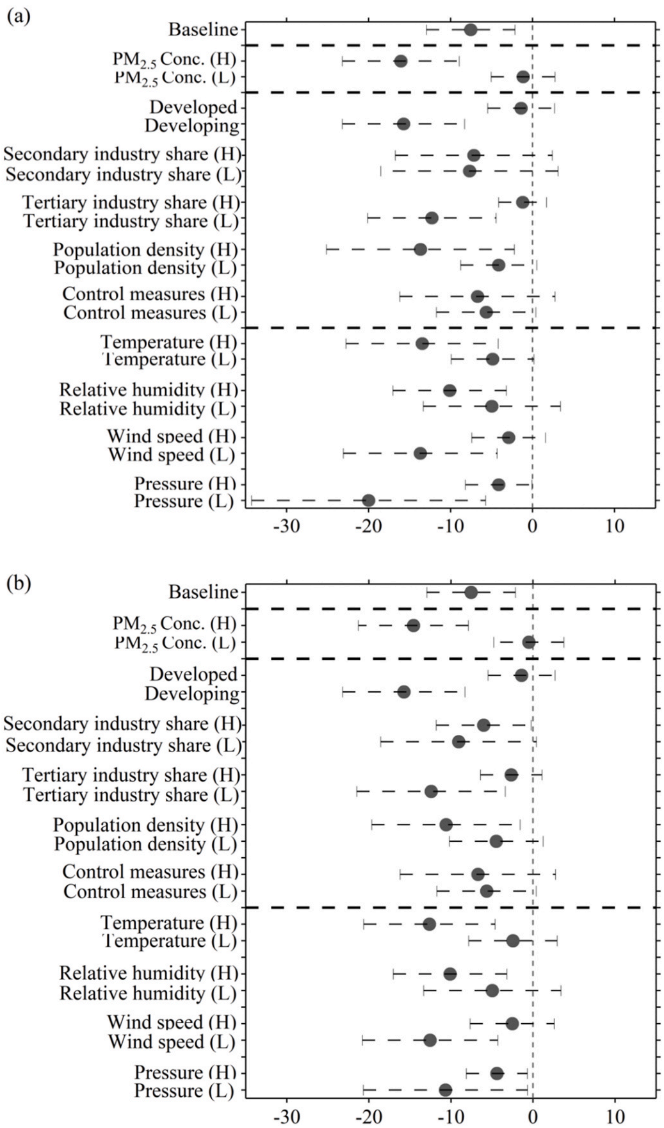

Fig. 3. The heterogeneous effects of COVID-19 lockdowns on the $PM_{2.5}$ concentrations one month before and during the COVID-19 lockdowns. Black solid circles represent the estimated coefficients and the dashed lines show 95% confidence intervals. The mean values (a) or median values (b) were used to separate the low group (L) from the high group (H).

are few studies on the impact of COVID-19 control measures on $PM_{2.5}$ concentration in developing countries, so we cannot confirm whether the impact was significantly different between developed and developing countries. In this study, we analyzed the data from 46 countries and found significant and robust changes in the $PM_{2.5}$ concentrations caused by the control measures between the developed and developing countries.

The emissions of primary components and secondary precursors in $PM_{2.5}$ decreased during the COVID-19 lockdown (Huang et al., 2020; Le et al., 2020), resulting in decreases of $PM_{2.5}$ concentrations. In contrast, the reduced emissions may have indirectly led to increases in the atmospheric oxidation capacity (Le et al., 2020), promoting the formation of secondary aerosols (Le et al., 2020). Our findings suggest that the reductions of emissions potentially outweighed the enhancement in the formation of secondary aerosols in the developing countries during the COVID-19 lockdown, while the enhancement was comparable to the reduction in those of the developed countries; The increase in $PM_{2.5}$ concentration in the Czech Republic, Austria, and Germany could be attributed to the enhanced secondary processing outweighing the

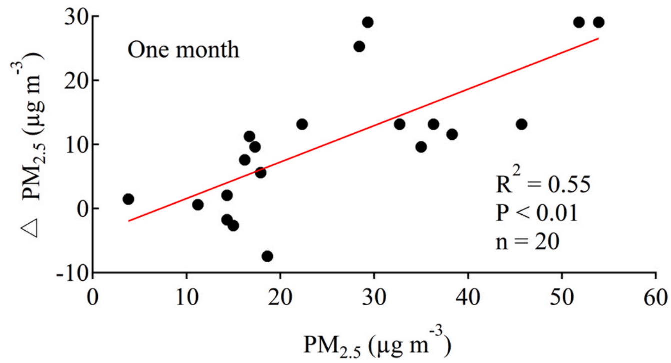

Fig. 4. The scatterplot and linear fit between the average $PM_{2.5}$ concentration in each country in one month before the COVID-19 lockdowns and the changes in the $PM_{2.5}$ concentrations ($\Delta PM_{2.5}$). $\Delta PM_{2.5}$ is defined as $\Delta PM_{2.5} = PM_{2.5\_before\ lockdowns} - PM_{2.5\_lockdowns}$, where $PM_{2.5\_before\ lockdowns}$ refers to the average $PM_{2.5}$ concentration in one month before the COVID-19 lockdowns, and $PM_{2.5\_lockdowns}$ refers to the average $PM_{2.5}$ concentration in one month during the lockdowns.

Table 1
The health and economic impacts from the $PM_{2.5}$ concentration changes.

Countries	Death (cases)	Hospital admissions change (cases)	Economic burden change (USD)
Australia	−4	−68	−1,046,277
Austria	3	42	633,224
Bahrain	−1	−20	−65,368
Bangladesh	−524	−5528	−905,726
China	−2740	−22,794	−36,068,508
Czech	17	144	745,486
Ethiopia	−57	−461	−44,289
Germany	25	315	4,815,609
India	−4222	−48,975	−12,572,127
Iran	−95	−1417	−1,979,499
Israel	−1	−17	−169,832
Italy	−71	−931	−7,984,318
Kuwait	−2	−40	−215,996
Nepal	−108	−1014	−187,455
Netherlands	−1	−23	−341,286
South Korea	−46	−676	−5,002,576
Sri Lanka	−63	−643	−338,304
Turkey	−50	−626	−796,372
United Arab Emirates	−5	−129	−758,442
Uganda	−21	−189	−27,550

decrease in primary emissions during the COVID-19 control period. In particular, the mass concentration of nitrogen oxides decreased during the COVID-19 control period in urban areas of these countries (Dang et al., 2021; Venter et al., 2020), such reductions may have led to increased ozone concentrations that further enhanced the atmospheric oxidizing capacity and facilitated the formation of secondary aerosols (Le et al., 2020).

The different responses to the emission reductions between the developed and developing countries were mainly associated with technological advances and the intensity of the government regulations. For the developing countries, the technology is less developed (Barbier et al., 2020), and the level of government supervision is inadequate (Barbier et al., 2019). These two factors could lead to increases of polluting enterprises and production of poor quality energy sources (e.g., vehicle fuels) (Jackson et al., 2019). Local pollutants emission was much higher in developing than in developed countries (Peters et al., 2020). Consequently, the concentrations of black carbon (BC, known as the most significant primary component in $PM_{2.5}$) were 3–45 times higher in the cities of the developing countries than in those of the developed countries (Fig. 5). As a result, the developing countries were more sensitive to the reductions of local emissions during the COVID-19

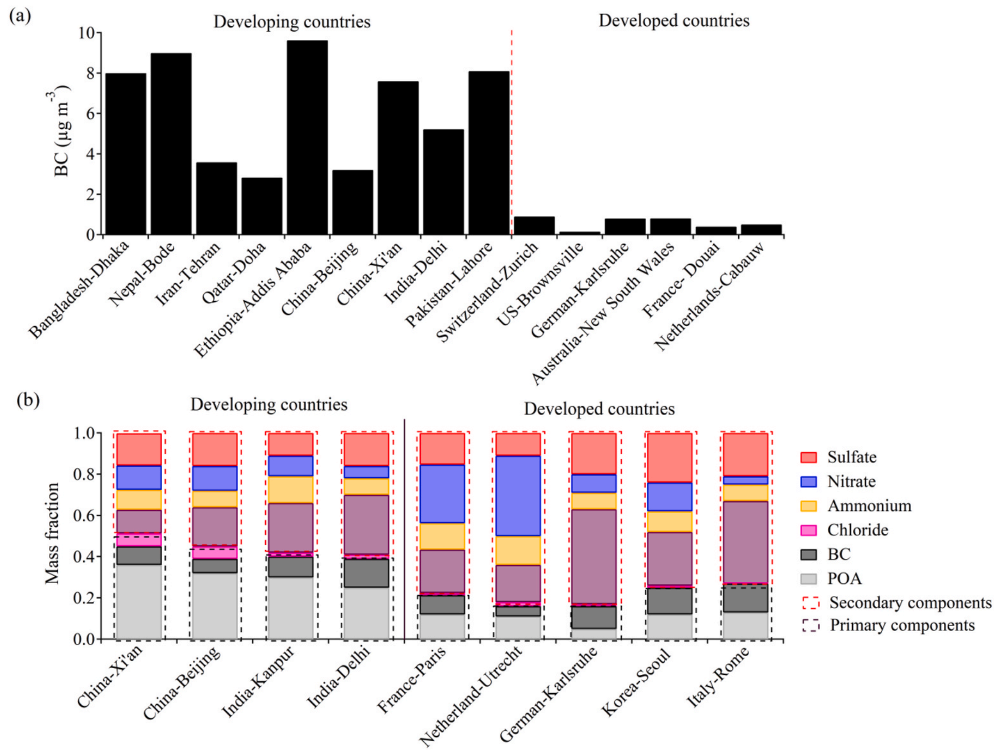

Fig. 5. (a) The average mass concentrations of BC and (b) the mass fractions of major components of submicron aerosols in major cities in developed and developing countries. The data sources were collected from the published studies which can be found in Table S5.

lockdown. In contrast, the $PM_{2.5}$ levels in the developed countries were dominated by secondary components, including sulfate, nitrate, ammonium, and secondary organic aerosols (Fig. 5). Therefore, these countries were more sensitive to secondary atmospheric processing than the developing countries.

The new findings of this study is the robustly distinguished changes in the $PM_{2.5}$ concentrations caused by the control measures between the developed and developing countries. As a result, the health and economic impacts were distinguished between the developed and developing countries. Such a disparity is related to the different chemical composition of $PM_{2.5}$. The present results could thus assist policymakers to establish particular pollution prevention measures that are suited to local circumstances.

The main limitations of this study was that it fails to cover all countries in terms of the impact of COVID-19 control measures on $PM_{2.5}$ concentration. For example, the countries located in South America were not included in this study, despite a sharp decrease in $PM_{2.5}$ concentrations being observed during the COVID-19 control period in this region (e.g., Nakada and Urban, 2020; Zambrano-Monserrate and Ruano, 2020), implying that the control measures possibly decreased the $PM_{2.5}$ concentrations. Such limitation could result in insufficient reflection of the disparities between the developed and developing countries worldwide. Furthermore, this study only quantifies the impact of changes in $PM_{2.5}$ concentration on health, while other air pollutants (e.g., SO_2, NO_x, O_3, or CO) also have an impact on health. Further research could consider the health effects caused by changes in the concentrations of other pollutants during the COVID-19 control period. Third, the impact of socio-economic factors (e.g., factory, vehicle) in addition to the COVID-19 control measures on $PM_{2.5}$ generation was not adjusted due to the lack of data. Therefore, the assumption is that in addition to COVID-19 control measures, the impact of other socio-economic factors on $PM_{2.5}$ generation would remain constant. Finally, we cannot distinguish between local and regional sources due to the lack of data concerning the emission inventory for each country. Despite these limitations, this study provide insights into the potential reasons for the different degrees of impacts on the air quality across regions as well as the associated health and economic impacts. Considering a large number of people infected with COVID-19, future epidemiological studies can investigate the health effect of the air pollution on people recovering from COVID-19.

6. Policy implications

The variation in the responses to the emission reductions suggests that unique air pollution control measures should be implemented in developed and developing countries. As expected, the top 10 most polluted cities in the world are in developing countries.(IQ Air, 2019; WHO et al., 2018). Severe air pollution can affect human health and thus indirectly obstruct economic development (Hunt et al., 2016; Wu et al., 2017). The changes in air quality during the COVID-19 lockdown indicated that mitigation measures could have an immediate effect on the air quality. Therefore, there is an urgent need to tackle air pollution in the developing countries. However, the developing countries are mostly in the stage of rapid economic growth (Reardon et al., 2003). To develop the domestic economy, environmental quality has been sacrificed in exchange for economic growth (Shah et al., 2016). It is worth noting that the quality of the environment and economic development should not be mutually exclusive. For instance, the government in China has made significant effort to control pollution, but this has been accompanied by rapid economic growth as indicated by the GDP (Wang et al., 2021). In fact, the economic benefits of air pollution control can outweigh the costs (Li et al., 2019). Therefore, developing countries should demonstrate that there is no conflict between economic growth and air pollution controls.

Different from the developing countries, the developed countries have more organized and detailed measures to tackle air pollution issues. However, most of the developed countries did not meet the health risk threshold standard of 10 μg m^{-3} for $PM_{2.5}$ set by the WHO (IQ Air et al., 2020). The secondary aerosols that dominated the $PM_{2.5}$ in the developed countries (Fig. 5) have been identified as more harmful to human health than the primary aerosols (Lippmann et al., 2013; Vedal et al., 2013). The control of the emissions of precursor species in the developed countries should thus become a consensus issue (Hallquist et al., 2009; Jimenez et al., 2009). Notably, the complicated atmospheric processes might make the control of precursors counterproductive. This reflects the importance of scientific treatment of the air pollution in the developed countries. For instance, a reliable chemical models should be applied to simulate the degree of air quality improvement under different scenarios involving reductions of precursor' emissions. The final goal is to determine the optimal emission reduction measures that could be practically implemented.

7. Conclusions

The COVID-19 prevention and control measures had impact on the $PM_{2.5}$ concentrations in 20 countries (reduced $PM_{2.5}$ concentrations of −7.4–29.1 μg m^{-3}) of the selected 46 countries. In particular, the COVID-19 control measures caused substantial reductions (5.6–29.1 μg m^{-3}) in $PM_{2.5}$ concentrations in all developing countries and smaller reductions (4.6–11.3 μg m^{-3}) in $PM_{2.5}$ concentrations in five developed countries, and even increased $PM_{2.5}$ concentrations (1.8–7.4 μg m^{-3}) in three developed countries. Robustly distinguished changes in the $PM_{2.5}$ concentrations caused by the control measures were demonstrated between the developed (95% confidence interval (CI): −2.7–5.5 μg m^{-3}) and developing countries (95% confidence interval (CI): 8.3–23.2 μg m^{-3}). As a result, the COVID-19 lockdown reduced death and hospital admissions change from the decreased $PM_{2.5}$ concentrations by 7909 and 82,025 cases in the 12 developing countries, and by 78 and 1214 cases in the eight developed countries. The COVID-19 lockdown reduced the economic cost from the $PM_{2.5}$ related health burden by 54.0 million dollars in the 12 developing countries and by 8.3 million dollars in the eight developed countries. The disparity was related to the different chemical compositions of $PM_{2.5}$. In particular, the concentrations of primary $PM_{2.5}$ (e.g., BC) in cities of developing countries were 3–45 times higher than those in developed countries, so the mass concentration of $PM_{2.5}$ was more sensitive to the reduced local emissions in developing countries during the COVID-19 control period. The mass fractions of secondary $PM_{2.5}$ in developed countries were generally higher than those in developing countries. As a result, these countries were more sensitive to the secondary atmospheric processing, which may have been enhanced due to reduced local emissions. The developing countries should demonstrate that there is no conflict between economic growth and air pollution control, while the developed countries should establish more science-based treatments in the control of air pollution.

Credit authorship statement

Yichen Wang: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Rui Wu**: Methodology, Writing – original draft. **Yuan Yuan**: Formal analysis. ChenGuang Liu: Conceptualization. **Steven Sai Hang Ho**: Writing – review & editing. **Honghao Ren**: Methodology, Writing – original draft. **Qiyuan Wang**: Formal analysis. Yang Lv: Formal analysis. **Mengyuan Yan**: Formal analysis. **Junji Cao**: Conceptualization, Writing – review & editing.

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.

Acknowledgement

This study was supported by the National Natural Science Foundation of China (71804115, 71804071) and the support from the Open Fund of the State Key Laboratory of Loess and Quaternary Geology (SKLLQG 1834).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2021.118544.

References

Alken, P., Chulliat, A., Nair, M., 2020. NOAA/NCEI and University of Colorado candidate models for IGRF-13. Earth Planets Space 73, 1. https://doi.org/10.1186/s40623-020-01313-z.
Al-Abadleh, H.A., Lysy, M., Neil, L., et al., 2021. Rigorous quantification of statistical significance of the COVID-19 lockdown effect on air quality: the case from ground-based measurements in Ontario, Canada. J. Hazard Mater. 413, 125445. https://doi.org/10.26434/chemrxiv.12887183.
Barbier, E.B., 2020. Is green rural transformation possible in developing countries? World Dev. 131, 104955. https://doi.org/10.1016/j.worlddev.2020.104955.
Barbier, E.B., Burgess, J.C., 2019. Sustainable development goal indicators: analyzing trade-offs and complementarities. World Dev. 122, 295–305. https://doi.org/10.1016/j.worlddev.2019.05.026.
Baum, C.F., 2001. Residual diagnostics for cross-section time series regression models. STATA J. 1 (1), 101–104. https://doi.org/10.1177/1536867x0100100108.
Chen, L.W.A., Chien, L.C., Li, Y., Lin, G., 2020. Nonuniform impacts of COVID-19 lockdown on air quality over the United States. Sci. Total Environ. 745, 141105. https://doi.org/10.1016/j.scitotenv.2020.141105.
Chossière, G.P., Xu, H., Dixit, Y., et al., 2021. Air pollution impacts of COVID-19–related containment measures. Sci. Adv. 7 (21), eabe1178. https://doi.org/10.1126/sciadv.abe1178.
Dang, H.A.H., Trinh, T.A., 2020. Does the COVID-19 lockdown improve global air quality? New cross-national evidence on its unintended consequences. J. Environ. Econ. Manag. 105, 102401. https://doi.org/10.1016/j.jeem.2020.102401.
Desvars-Larrive, A., et al., 2020. A Structured Open Dataset of Government Interventions in Response to COVID-19. Sci. Data. https://doi.org/10.1038/s41597-020-00609-9.
El-Sheekh, M.M., Hassan, I.A., et al., 2021. Lockdowns and reduction of economic activities during the COVID-19 pandemic improved air quality in Alexandria, Egypt. Environ. Monit. Assess. 193 (1), 11. https://doi.org/10.1007/s10661-020-08780-7.
Etchie, T.O., Etchie, A.T., Jauro, A., et al., 2021. Season, not lockdown, improved air quality during COVID-19 State of Emergency in Nigeria. Sci. Total Environ. 768, 145187. https://doi.org/10.1007/s10661-020-08780-7.
Forster, P., et al., 2007. Changes in atmospheric constituents and in radiative forcing. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.
GBD, 2019. Diseases and injuries collaborators. 2020. Global burden of 369 diseases and injuries, 1990–2019: a systematic analysis for the global burden of disease study 2019. Lancet. https://doi.org/10.1016/S0140-6736(20)30925-9.
Giani, P., Castruccio, S., Anav, A., et al., 2020. Short-term and long-term health impacts of air pollution reductions from COVID-19 lockdowns in China and Europe: a modelling study. Lancet Planet. Health 4 (10), e474–e482. https://doi.org/10.1016/s2542-5196(20)30224-2.
Guan, D.B., Su, X., Zhang, Q., Peters, G.P., Liu, Z., Lei, Y., He, K.B., 2014. The socioeconomic drivers of China's primary $PM_{2.5}$ emissions. Environ. Res. Lett. 9 (2), 024010 https://doi.org/10.1088/1748-9326/9/2/024010.
Hallquist, M., Wenger, J.C., Baltensperger, U., Rudich, Y., Simpson, D., Claeys, M., Dommen, J., Donahue, N.M., George, C., Goldstein, A.H., 2009. The formation, properties and impact of secondary organic aerosol: current and emerging issues. Atmos. Chem. Phys. 9, 5155e5236. https://doi.org/10.5194/acp-9-5155-2009.
Hammer, et al., 2021. Effects of COVID-19 lockdowns on fine particulate matter concentrations. Sci. Adv. 7 (26), eabg7670. https://doi.org/10.1126/sciadv.abg7670.
He, C., Hong, S., Zhang, L., et al., 2021. Global, continental, and national variation in $PM_{2.5}$, O_3, and NO_2 concentrations during the early 2020 COVID-19 lockdown. Atmos. Pollut. Res. 12 (3), 136–145. https://doi.org/10.1016/j.apr.2021.02.002.
He, G., Pan, Y., Tanaka, T., 2020. The short-term impacts of COVID-19 lockdown on urban air pollution in China. Nat. Sustain. 3 (12), 1005–1011. https://doi.org/10.1038/s41893-020-0581-y.
Huang, X., Ding, A., Gao, J., Zheng, B., Zhou, D., Qi, X., et al., 2020. Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China. NatI. Sci. Rev.
Hunt, A., Ferguson, J., Hurley, F., Searl, A., 2016. Social Costs of Morbidity Impacts of Air Pollution. OECD Environment Working Papers. https://doi.org/10.1787/5jm55j7cq0lv-en.
IQ Air, 2019. World air quality report. Region & city $PM_{2.5}$ ranking. IQ Air. Available from:https://www.airvisual.com/world-mostpolluted-cities/world-air-quality-report-2019-en.pdf.
Jackson, R.B., Le, C., Quéré, R.M. Andrew, Canadell, J.G., Korsbakken, J.I., Liu, Z., Peters, G.P., Zheng, B., Friedlingstein, P., 2019. Global Energy Growth Is Outpacing Decarbonization. A Special Report for the United Nations Climate Action Summit

September 2019. Global Carbon Project. International Project Office, Canberra Australia.

Jimenez, J.L., Canagaratna, M.R., Donahue, N.M., Prevot, A.S.H., Zhang, Q., Kroll, J.H., et al., 2009. Evolution of organic aerosols in the atmosphere. Science 326, 1525–1529. https://doi.org/10.1126/science.1180353.

Kumari, P., Toshniwal, D., 2020. Impact of lockdown on air quality over major cities across the globe during COVID-19 pandemic. Urban Clim. 34, 100719. https://doi.org/10.1016/j.uclim.2020.100719.

Le, T., Wang, Y., Liu, L., Yang, J., Yung, Y.L., Li, G., Seinfeld, J.H., 2020. Unexpected air pollution with marked emission reductions during the COVID-19 outbreak in China. Science 369, eabb7431. https://doi.org/10.1126/science.abb7431.

Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525, 361–371. https://doi.org/10.1038/nature15371.

Li, M.-H., Fan, L.-C., Mao, B., Yang, J.-W., Choi, A.M.K., Cao, W.-J., Xu, J.-F., 2016. Short-term exposure to ambient fine particulate matter increases hospitalizations and mortality in COPD: a systematic review and meta-analysis. Chest 149 (2), 447–458. https://doi.org/10.1378/chest.15-0513.

Li, N., Zhang, X., Shi, M., Hewings, G.J.D., 2019. Does China's air pollution abatement policy matter? An assessment of the Beijing-Tianjin-Hebei region based on a multi-regional CGE model. Energy Pol. 127, 213–227. https://doi.org/10.1016/j.enpol.2018.12.019.

Lippmann, M., Chen, L.-C., Gordon, T., Ito, K., Thurston, G.D., 2013. National Particle Component Toxicity (NPACT) Initiative: Integrated Epidemiologic and Toxicologic Studies of the Health Effects of Particulate Matter Components, vol. 177. Health Effects Institute, Boston. Research Report.

Liu, C., Chen, R., Sera, F., Vicedo-Cabrera, A.M., Guo, Y., Tong, S., Coelho, M.S.Z.S., Saldiva, P.H.N., Lavigne, E., Matus, P., Valdes Ortega, N., Osorio Garcia, S., Pascal, M., Stafoggia, M., Scortichini, M., Hashizume, M., Honda, Y., Hurtado-Díaz, M., Cruz, J., Nunes, B., Teixeira, J.P., Kim, H., Tobias, A., Íñiguez, C., Forsberg, B., Åström, C., Ragettli, M.S., Guo, Y.-L., Chen, B.-Y., Bell, M.L., Wright, C. Y., Scovronick, N., Garland, R.M., Milojevic, A., Kyselý, J., Urban, A., Orru, H., Indermitte, E., Jaakkola, J.J.K., Ryti, N.R.I., Katsouyanni, K., Analitis, A., Zanobetti, A., Schwartz, J., Chen, J., Wu, T., Cohen, A., Gasparrini, A., Kan, H., 2019. Ambient particulate air pollution and daily mortality in 652 cities. N. Engl. J. Med. 381 (8), 705–715. https://doi.org/10.1056/nejmc1913285.

Liu, F., Page, A., Strode, S.A., Yoshida, Y., Choi, S., Zheng, B., et al., 2020. Abrupt decline in tropospheric nitrogen dioxide over China after the outbreak of COVID-19. Sci. Adv. 6 (28), eabc2992 https://doi.org/10.1126/sciadv.abc2992.

Liu, H., Tian, Y., Xiang, X., Juan, J., Song, J., Cao, Y., Huang, C., Li, M., Hu, Y., 2018. Ambient particulate matter concentrations and hospital admissions in 26 of China's largest cities: a case-crossover study. Epidemiology 29 (5), 649–657. https://doi.org/10.1097/ede.0000000000000869.

Malpede, M., Percoco, M., 2021. Lockdown measures and air quality: evidence from Italian provinces. Lett. Sp. Resour. Sci. 1–10. https://doi.org/10.2139/ssrn.3714673.

Ming, W., Zhou, Z., Ai, H., Bi, H., Zhong, Y., 2020. COVID-19 and air quality: evidence from China. Emerg. Mark. Finance Trade 56 (10), 2422–2442. https://doi.org/10.1080/1540496x.2020.1790353.

Nakada, L.Y.K., Urban, R.C., 2020. COVID-19 pandemic: impacts on the air quality during the partial lockdown in São Paulo state. Brazil. Sci. Total Environ. 730, 139087 https://doi.org/10.1016/j.scitotenv.2020.139087.

Nie, D., Shen, F., Wang, J., et al., 2020. Changes of air quality and its associated health and economic burden in 31 provincial capital cities in China during COVID-19 pandemic. Atmos. Res. 249, 105328. https://doi.org/10.1016/j.atmosres.2020.105328.

Peters, G.P., Andrew, R.M., Canadell, J.G., Friedlingstein, P., Jackson, R.B., Korsbakken, J.I., et al., 2020. Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. Nat. Clim. Change 10, 2–10. https://doi.org/10.1038/s41558-019-0659-6.

Reardon, T., Timmer, C.P., Barrett, C.B., Berdegue, J., 2003. The rise of supermarkets in Africa, Asia, and Latin America. Am. J. Agric. Econ. 85 (5), 1140–1146. https://doi.org/10.1111/j.0092-5853.2003.00520.x.

Shah, K.U., Arjoon, S., Rambocas, M., 2016. Aligning corporate social responsibility with green economy development pathways in developing countries. Sustain. Dev. 24 (4), 237–253. https://doi.org/10.1002/sd.1625.

Sharma, S., Zhang, M., Gao, J., Zhang, H., Kota, S.H., et al., 2020. Effect of restricted emissions during covid-19 on air quality in India. Sci. Total Environ. 728, 138878. https://doi.org/10.1016/j.scitotenv.2020.138878.

Son, J., Fong, K., Heo, S., Kim, H., Lim, C., Bell, M., 2020. Reductions in mortality resulting from reduced air pollution levels due to COVID-19 mitigation measures. Sci. Total Environ. 744, 141012. https://doi.org/10.1016/j.scitotenv.2020.141012.

Tian, Y., Liu, H., Wu, Y., Si, Y., Li, M., Wu, Y., Wang, X., Wang, M., Chen, L., Wei, C., Wu, T., Gao, P., Hu, Y., 2019a. Ambient particulate matter pollution and adult hospital admissions for pneumonia in urban China: a national time series analysis for 2014 through 2017. PLoS Med. 16 (12), e1003010 https://doi.org/10.1371/journal.pmed.1003010.

Tian, Y., Liu, H., Wu, Y., Si, Y., Song, J., Cao, Y., Li, M., Wu, Y., Wang, X., Chen, L., Wei, C., Gao, P., Hu, Y., 2019b. Association between ambient fine particulate pollution and hospital admissions for cause specific cardiovascular disease: time series study in 184 major Chinese cities. BMJ 367, l6572. https://doi.org/10.1136/bmj.l6572.

Vedal, S., Kim, S.Y., Miller, K.A., Fox, J.R., Bergen, S., Gould, T., Kaufman, J.D., Larson, T.V., Sampson, P.D., Sheppard, L., Simpson, C.D., Szpiro, A.A., 2013. Section 1. NPACTepidemiologic study of components of fine particulate matter and cardiovascular disease in the MESA and WHI-OS cohorts. In: National Particle Component Toxicity (NPACT) Initiative Report on Cardiovascular Effects, Research Report 178. Health Effects Institute, Boston, MA, pp. 9–128.

Venter, Z.S., Aunan, K., Chowdhury, S., Lelieveld, J., 2020. COVID-19 lockdowns cause global air pollution declines. Proc. Natl. Acad. Sci. Unit. States Am. 117, 18984. https://doi.org/10.1101/2020.04.10.20060673. https://search.crossref.org/?q=COVID-19+lockdowns+cause+global+air+pollution+declines&from_ui=yes.

Wang, Y., Yuan, Y., Wang, Q., Liu, C., Zhi, Q., Cao, J., 2020. Changes in air quality related to the control of coronavirus in China: implications for traffic and industrial emissions. Sci. Total Environ. 731, 139133. https://doi.org/10.1016/j.scitotenv.2020.139133.

Wang, Y., Liu, C.G., Wang, Q., Qin, Q., Ren, H., Cao, J., 2021. Impacts of natural and socioeconomic factors on $PM_{2.5}$ from 2014 to 2017. J. Environ. Manag. 284, 112071. https://doi.org/10.1016/j.jenvman.2021.112071.

World Health Organization, 2016. Ambient air pollution: a global assessment of exposure and burden of disease. http://who.int/phe/publications/air-pollution-global-assessment/en/.

World Health Organization, 2018. AAP Air Quality Database available at: http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/. (Accessed 1 August 2019).

Wu, R., Dai, H., Geng, Y., et al., 2017. Economic impacts from $PM_{2.5}$ pollution-related health effects: a case study in Shanghai. Environ. Sci. Technol. 51 (9), 5035–5042. https://doi.org/10.1021/acs.est.7b00026.s001.

Zambrano-Monserrate, M.A., Ruano, M.A., 2020. Has air quality improved in Ecuador during the COVID-19 pandemic? A parametric analysis. Air Q. Atmos. Health 13, 929–938. https://doi.org/10.1007/s11869-020-00866-y.