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Mediation by human mobility of the association between temperature and COVID-19 transmission rate

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ABSTRACT

The coronavirus disease 2019 (COVID-19) pandemic is a major threat to global health. Relevant studies have shown that ambient temperature may influence the spread of novel coronavirus. However, the effect of ambient temperature on COVID-19 remains controversial. Human mobility is also closely related to the pandemic of COVID-19, which could be affected by temperature at the same time. The purpose of this study is to explore the underlying mechanism of the association of temperature with COVID-19 transmission rate by linking human mobility. The effective reproductive number, meteorological conditions and human mobility data in 47 countries are collected. Panel data models with fixed effects are used to analyze the association of ambient temperature with COVID-19 transmission rate, and the mediation by human mobility. Our results show that there is a negative relationship between temperature and COVID-19 transmission rate. We also observe that temperature is positively associated with human mobility and human mobility is positively related to COVID-19 transmission rate. Thus, the suppression effect (also known as the inconsistent mediation effect) of human mobility is confirmed, which remains robust when different lag structures are used. These findings provide evidence that temperature can influence the spread of COVID-19 by affecting human mobility. Therefore, although temperature is negatively related to COVID-19 transmission rate, governments and the public should pay more attention to control measures since people are more likely to go out when temperature rising. Our results could partially explain the reason why COVID-19 is not prevented by warm weather in some countries.

Author contribution

Wenjing Shao, Data curation, Writing- Original draft preparation, Visualization, Investigation. Jingui Xie, Conceptualization, Methodology, Supervision. Yongjian Zhu, Methodology, Validation, Writing-reviewing and editing.

1. Introduction

The COVID-19 outbreak was first detected in Wuhan, China. In recent weeks, the outbreak in China has been effectively contained, while novel coronavirus pneumonia has spread around the world. On January 13, 2020, novel coronavirus pneumonia was first diagnosed in a country (Thailand) other than China. According to the statistics of the World Health Organization, there have been more than 20 million confirmed cases of COVID-19 and more than 735,000 deaths worldwide as of August 5, 2020 (World Health Organization, 2020).

There are many factors that influence the spread of the COVID-19. In particular, temperature is an important factor. Both epidemiological and laboratory studies indicated that the effect of ambient temperature on the survival and transmission of coronavirus could not be ignored (Chan et al., 2011; Van Doremalen et al., 2013; Xie and Zhu, 2020). Thus, it is necessary to explore the effect of temperature on novel coronavirus transmission. Some studies have explored the connection between temperature and novel coronavirus. But the conclusion is controversial. On the one hand, temperature can influence the spread of COVID-19 (Tobias and Molina, 2020; Holtmanna et al., 2020; Wu et al., 2020). A study suggested that rising temperatures could reduce the number of COVID-19 cases (Mandal and Panwar, 2020). The results of Prata et al. (2020) also showed that there was a negative linear relationship between temperature and the number of confirmed cases for all 27 state capital cities in Brazil from February 27, 2020 to April 1, 2020, which was characterized by tropical temperature. On the other hand, some studies have reported the opposite finding that the transmission of novel

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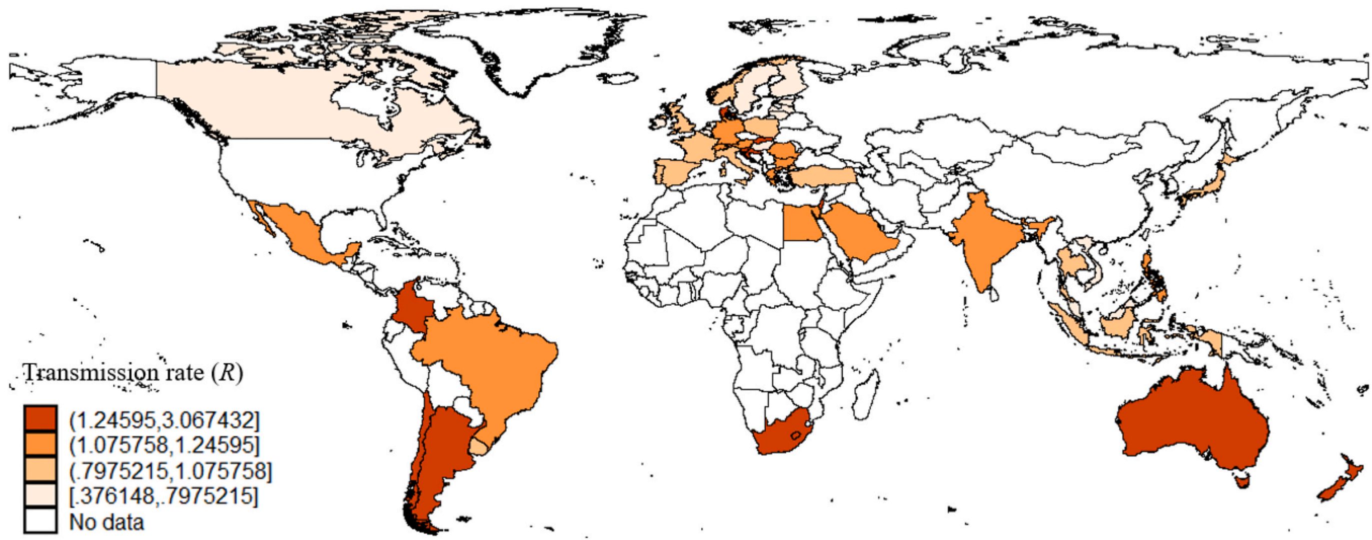

Fig. 1. Locations of 47 countries and transmission rate (*R*) in each country as of June 22, 2020.

coronavirus does not depend on temperature. Compared with temperature, a recent study showed that the rate of COVID-19 transmission was more susceptible to other factors, such as population density, population by age and number of travelers (Briz-Redón et al., 2020). Another study showed no association of COVID-19 transmission with temperature or UV radiation in 224 Chinese cities from early January to early March (Yao et al., 2020). Jahangiri et al. (2020) confirmed that novel coronavirus transmission rate had low sensitivity to temperature in different Iranian provinces from February 15, 2020 to March 22, 2020.

Moreover, previous studies have verified the relationships between weather conditions including temperature and outdoor activities or travel behaviors (Matthews et al., 2001; Bocker et al., 2016; Liu et al., 2014). It is commonly believed that people may prefer to participate in outdoor activities or travel in warm weather. For example, in the urban transport system, Arana et al. (2014) showed that warm weather was conducive to transit ridership and cold weather reduced ridership in Spain on all weekends (Saturdays and Sundays) journeys in 2010 and 2011. Good weather conditions could conduce individuals' travel to leisure destinations. Cools et al. (2010) suggested that warm, cold and snowy days significantly affected travel planning, and the choice of travel mode was mainly influenced by fog and storms based on a survey of 586 Flanders respondents. People tend to choose a closer destination for activities in severe weather conditions, especially in the case of heavy rain and extremely cold temperatures.

There are also some studies that have examined the impact of human mobility on the COVID-19 transmission. The analysis of Zhu et al. (2020a, 2020b) showed that there was a significant positive relationship between the human mobility and daily COVID-19 confirmed cases in 120 cities from China between January 23, 2020 and February 29, 2020. A study by Oztig and Askin (2020) observed a positive correlation between a country's air passenger volume and the number of COVID-19 patients in 144 countries. It was further found that countries with more airports had a higher number of COVID-19 cases. The results of Badr et al. (2020) showed that mobility patterns were closely related to the growth rate of COVID-19 cases in the worst-affected counties in the United States. A study by Cartenì et al. (2020) believed that mobility habit was one of the variables, along with the number of daily tests and environmental variables, that explained the number of COVID-19 infections. The details about the above studies are summarized in Table S1.

Therefore, human mobility is not only closely related to the pandemic of COVID-19, but also affected by temperature at the same time. Explore the underlying mechanism of the association of temperature with COVID-19 transmission by linking human mobility may be useful to explain the controversial conclusion in the literatures. In this study, we aimed to investigate the relationship between ambient temperature and COVID-19 transmission, and the mediation by human mobility in 47 countries.

2. Materials and methods

2.1. Data collection

The effective reproductive number (*R*) is often used as the primary indicator of COVID-19 transmission rates and plays an important role in epidemiology (Xiao et al., 2020). It measures the average number of people infected by a single infected person during the period of infection. We collected the data for the estimates of *R* from February 22, 2020 to June 22, 2020 (time span varies by country and the starting point is the date when the number of confirmed cases in a country reaches 100) from a previous work by Arroyo-Marioli et al. (2020). To construct this proxy, they used data on new cases, recoveries, and deaths and estimated the growth rate by Kalman-filtering techniques. Arroyo-Marioli et al. (2020) believed that "the method is robust in the sense that the estimates of *R* remain fairly accurate even when new cases are imperfectly measured, or the true dynamics of the disease do not follow the SIR model". Readers are referred to Arroyo-Marioli et al. (2020) for the details of estimating the reproductive number.

The meteorological data were obtained from the National Oceanic and Atmospheric Administration Center (https://www.ncdc.noaa.gov/isd). Based on previous studies on the effects of climate on influenza viruses and coronaviruses (Chan et al., 2011; Van Doremalen et al., 2013; Zhu et al., 2020a, 2020b), we selected three major meteorological factors, namely mean temperature, air pressure and wind speed. For each country, we averaged meteorological data at different meteorological stations to calculate the average daily data during the observation period. Table S2 reportes the number of meteorological stations in each country.

Human mobility data were collected from the Mobility Trends Reports provided by Apple, which reflects the relative volume of directional requests (the baseline is the volume on January 13, 2020) through the Apple Maps app. Apple's data include three kinds of mobility: driving, walking, and transit. These three types of mobility data are highly correlated with each other (Table 2). Therefore, we analyzed each mobility data separately to avoid the influence of collinearity. The final sample studied in our analysis includes 4056 observations from 47

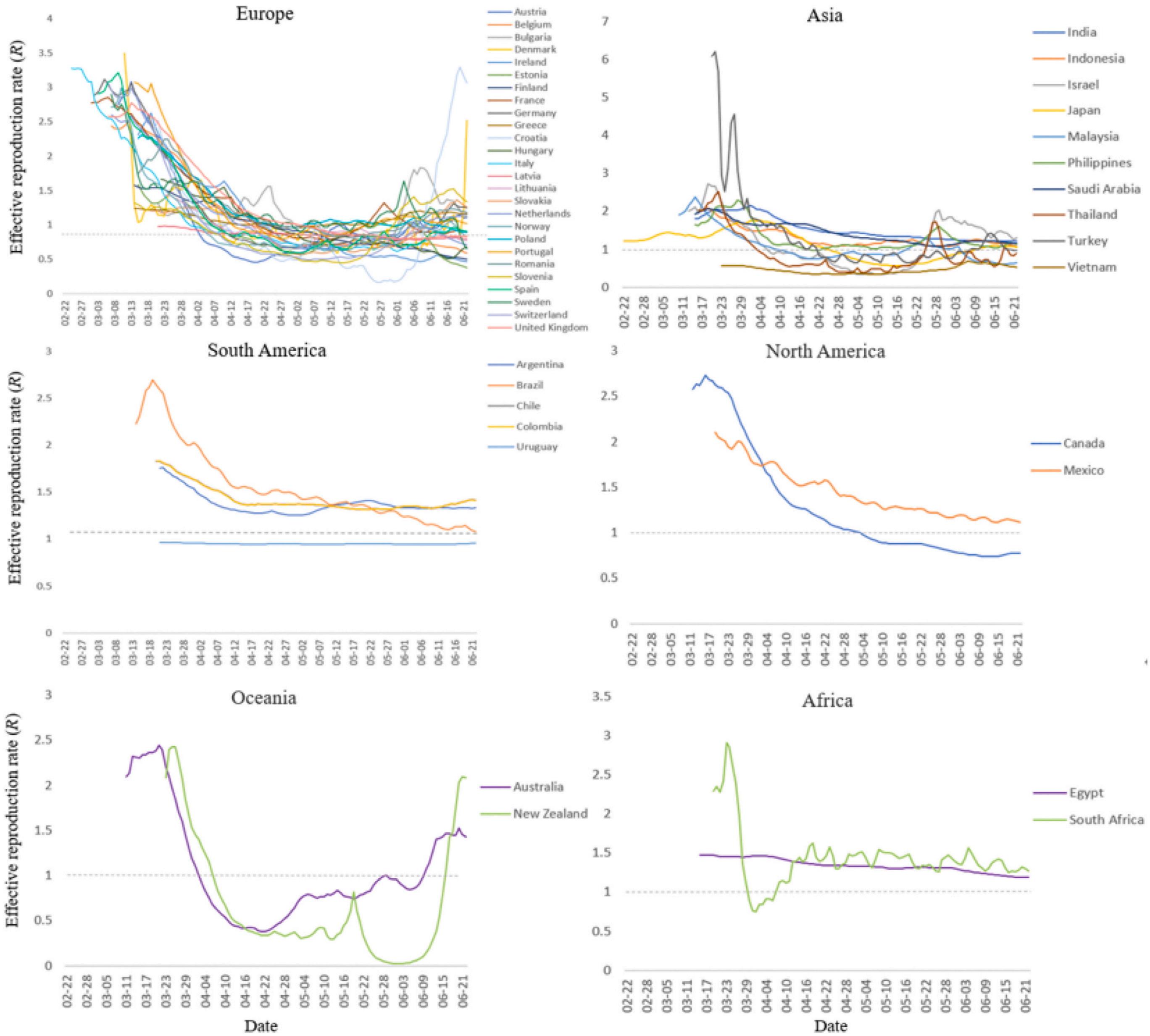

Fig. 2. The time trend of the effective reproduction rate (R) of COVID-19 for 47 countries on six continents.

countries during the 122-day observation period from February 22, 2020 to June 22, 2020 (Fig. 1). Fig. 2 plots the trend of R for 47 countries on six continents.

2.2. Statistical analysis

We used panel data models with fixed effects to study the association between daily mean temperature, human mobility and transmission rates. Considering the incubation period of COVID-19 (typically 2–14 days) (Lombardi et al., 2020), we applied the moving-average approach to investigate the moving average lag effect of mean temperature and human mobility on transmission rates, with a lag of 3 days, 7 days and 14 days, respectively. Our analyses include two parts. In the first part, we examined the relationship between temperature and transmission rates. The model is as follows:

$$R_{it} = \beta_0 + \beta_1 T_{il} + \beta_2 X_{il} + country_i + day_t + \varepsilon_{it} \quad (1)$$

where i and t represent the country and the date, respectively. R_{it} is the effective reproductive number (a proxy for COVID-19 transmission rates) in $country_i$ on day_t. T_{il} denotes the l day moving average term (lag1-l) of daily mean temperature in country i. X_{il} represents other meteorological variables as confounding factors including air pressure and wind speed for the same period. β_1 identifies the impact of temperature on transmission rates. We controlled time-invariant countries characteristics by including the country fixed effect $country_i$ day_t captures time fixed effect. ε_{it} is an error term.

In the second part, the mediation analysis is conducted to test the mediation by human mobility of the association between temperature and transmission rates. That is, temperature not only has a direct effect on transmission rates but may also affects transmission rates indirectly through human mobility. Specifically, the suppression effect occurs when direct and mediated effects of temperature have opposite signs, which is also called the inconsistent mediation effect (McFatter, 1979). According to the process of mediation analysis (Wen et al., 2014), two models are defined as follows:

$$M_{il} = \alpha_0 + \alpha_1 T_{il} + \alpha_2 X_{il} + country_i + day_t + u_{it} \quad (2)$$

Table 1
Descriptive statistics of transmission rate, meteorological variables and human mobility.

	Mean	SD	Min	Percentile			Max
				25th	50th	75th	
Effective reproductive number	1.212	0.571	0.025	0.830	1.104	1.439	6.202
Mean temperature (◦C)	15.352	8.330	−10.970	9.714	14.553	21.329	34.183
Air pressure (hPa)	1014.524	7.222	982.047	1009.990	1013.811	1018.869	1046.942
Wind speed (m/s)	9.629	4.091	2.665	6.356	8.953	11.142	24.682
Driving mobility	−33.614	36.061	−91.260	−60.890	−40.610	−10.260	130.560
Walking mobility	−42.898	31.570	−94.180	−67.220	−48.790	−25.810	120.670
Transit mobility	−55.825	28.316	−92.960	−77.735	−64.280	−40.480	60.560

Table 2
Spearman correlation coefficients between meteorological variables and human mobility.

	Mean temperature	Air pressure	Wind speed	Driving mobility	Walking Mobility	Transit Mobility
Mean temperature	1.000					
Air pressure	−0.180*	1.000				
Wind speed	−0.407*	0.096*	1.000			
Driving mobility	−0.064*	−0.059*	0.251*	1.000		
Walking mobility	−0.135*	−0.002	0.263*	0.940*	1.000	
Transit mobility	−0.054*	−0.089*	0.154*	0.915*	0.898*	1.000

*$p < 0.05$.

$$R_{il} = \gamma_0 + \gamma_1 T_{il} + \gamma_2 M_{il} + \gamma_3 X_{il} + country_i + day_t + e_{it} \quad (3)$$

where M_{il} denotes the l day moving average of Apple human mobility (driving, walking, or transit) in country i.

Equations (1)–(3) constitute a complete mediation analysis. The first step is to test whether the regression coefficient β_1 is statistically significant in Equation (1); the second step is to test whether the regression coefficient α_1 in Equation (2) is statistically significant; the third step is to test whether the regression coefficients γ_1, γ_2 in Equation (3) are statistically significant. If β_1, α_1, γ_1 and γ_2 are all significant, and the indirect effect ($\alpha_1 \times \gamma_2$) has the opposite sign of the direct effect (γ_1), the suppressing effect of human mobility is confirmed. Including a suppressor in Equation (3) could make the absolute value of the total effect of temperature on the transmission rate (β_1) less than the absolute value of the direct effect (γ_1) (Mackinnon et al., 2000).

In the sensitivity analysis, we further added country-specific linear time trend in our models, which could control the unobservable country-level factors that evolved over time (Liu and Bharadwaj., 2020). The details about the models and equations are reported in the online supplement.

3. Results

3.1. Descriptive analysis

Table 1 summarizes the descriptive statistics of meteorological variables, human mobility, and transmission rate in the study. During the observation period (February 22, 2020 to June 22, 2020), the average of transmission rate is 1.212. Average daily mean temperature, air pressure and wind speed are 15.352 °C, 1014.524 hPa and 9.629 m/s, respectively. The average of driving mobility, walking mobility and transit mobility are −33.614, −42.898 and −55.825, respectively.

Table 2 shows the spearman correlation coefficients between the meteorological variables and mobility data in Apple's reports. Mean temperature have significantly negative correlations with air pressure (r = −0.180, p < 0.05), wind speed (r = −0.407, p < 0.05), driving mobility (r = −0.064, p < 0.05), walking mobility (r = −0.135, p < 0.05) and transit mobility (r = −0.054, p < 0.05). Correlations between three types of mobility data are high.

3.2. Regression results

The columns (1), (4) and (7) in Table 3 show the moving average lag effects (lag1-3, lag1-7, lag1-14) of temperature on transmission rate of COVID-19 using Equation (1). We observed significant negative relationships between temperature and transmission rate of COVID-19 at all three lag levels. One degree increase in temperature is associated with a 0.012 (95% CI: −0.015 to −0.008) decrease in COVID-19 transmission rate at lag1-3, a 0.015 (95% CI: −0.019 to −0.011) decrease in transmission rate at lag1-7 and a 0.021 (95% CI: −0.025 to-0.017) decrease in transmission rate at lag1-14. These results indicated that the negative moving-average effect of temperature became stronger as the lag days accumulated, which is possibly caused by the incubation period of COVID-19.

The rest of the columns in Table 3 show the estimated results of our mediation analysis. The temperature is positively associated with walking mobility, and walking mobility is positively related to COVID-19 transmission rate. So, the indirect effect has the opposite sign of the direct effect. The regression results strongly support our hypothesis that walking mobility has a statistically significant suppression effect on the association between temperature and COVID-19 transmission rate.

The estimated results of the other two human mobility indicators (driving and transit) are shown in Tables S3–S4 separately, which are similar to the results of walking mobility. In the sensitivity analysis, the results are still robust (Tables S5–S7).

4. Discussion

The purpose of this paper is to explore the underlying mechanism of the association of temperature with COVID-19 transmission by assessing the suppression effect of human mobility. In this study, we observed that temperature was negatively associated with transmission rate. The mediation analysis showed that human mobility had a suppression effect on the relationship between temperature and COVID-19 transmission rate, providing evidence that temperature could influence the spread of COVID-19 by affecting human mobility.

Our results are consistent with previous studies. First, for the relationship between temperature and the transmission of COVID-19. A laboratory study found that SARS-CoV-2 was highly stable at 4 °C, but sensitive to heat. As temperature rose to 70 °C, the virus inactivation

Table 3
Suppressing effects of walking mobility on the association between mean temperature and COVID-19 transmission rate.

Variables	Lag1-3 Effective reproductive number (1)	Walking mobility (2)	Effective reproductive number (3)	Lag1-7 Effective reproductive number (4)	Walking mobility(5)	Effective reproductive number (6)	Lag1-14 Effective reproductive number (7)	Walking mobility (8)	Effective reproductive number (9)
Mean temperature	−0.012*** (-0.015,-0.008)	1.529*** (1.368,1.691)	−0.025*** (−0.029, −0.022)	−0.015*** (-0.019, −0.011)	1.531*** (1.362,1.701)	−0.031*** (-0.034,-0.027)	−0.021*** (-0.025,-0.017)	1.312*** (1.136,1.488)	−0.036*** (-0.040,-0.033)
Walking mobility			0.009*** (0.008,0.010)			0.010*** (0.010,0.011)			0.012*** (0.011, 0.013)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES	YES
Observations	4056	4056	4056	4056	4056	4056	4056	4056	4056

Note: This table reports Equations (1)–(3) estimated coefficients and 95% confidence intervals of interest variable and suppressor.
$^{***}p < 0.001$, $^{**}p < 0.01$.

time decreased to 5 min (Chin et al., 2020). Biryukov et al. (2020) observed that SARS-CoV-2 decayed more rapidly when temperature was increased. Li et al. (2020) believed that temperature was an important meteorological parameter that maintains a well negative correlation with COVID-19 incidence in Wuhan and Xiaogan. Most studies suggest that high temperatures are detrimental to the virus ability to survive.

Second, for the association of temperature with human mobility, previous studies have found a significant relationship between outdoor activities and temperature (Suminski et al., 2008; Xi et al., 2020). A study has shown that physical activity during adolescence is higher in the warmer months (Belanger et al., 2009), which is consistent with our finding. Temperature could be associated with behavioral patterns that increase human exposure to coronavirus, and accelerate the spread of COVID-19.

Third, for the relationship between human mobility and COVID-19 transmission rate. Since COVID-19 could be transmitted by aerosols and could travel a certain distance along air currents, leading to long-distance transmission of the disease (Wax and Christian, 2020; Van Doremalen et al., 2020), most people are susceptible to infection through respiratory droplets and direct contact (Shi et al., 2020). Zhou et al. (2020) revealed that mobility reduction had a significant impact on controlling the spread of COVID-19 across the ten regions of Shenzhen. Besides, a study suggested that asymptomatic carriers could also spread the virus (Gabutti et al., 2020). Thus, there is a positive relationship between population mobility and transmission rate. According to an article (Lai et al., 2020), timely and effective quarantine measures and travel restrictions in China are the key to controlling the epidemic. The number of cases would have increased 67 times without these measures. These features of novel coronavirus infection also highlight the need to strengthen physical isolation by increasing social distance to reduce the chance of transmission of novel coronavirus.

Our research has some implications. First, we found that temperature was negatively related to the transmission rate of COVID-19. However, governments should still take necessary human mobility restrictions during warm weather since people are more likely to go out when temperature rising. Besides, the suppression effect of human mobility could partially explain the current controversial conclusions in studies about the effect of temperature on COVID-19 transmission, which may also give us the reason why COVID-19 is not prevented by warm weather in some countries.

However, this paper also has some limitations. First, the average mean temperature in all available meteorological stations is used to represent the temperature of each country. So, exposure measurement error is inevitable in this study. Second, human mobility indicators from Apple are generated by the number of navigation requests made to Apple maps. On a country-level study, these variables could be largely biased. Third, although we added fixed effects in our models, a large number of confounders were still not controlled, which may affect the results.

5. Conclusion

This paper provides evidence that temperature can influence the spread of COVID-19 by affecting human mobility. Therefore, although temperature is negatively related to COVID-19 transmission rate, governments and the public should pay more attention to control measures since people are more likely to go out when temperature rising. Our results could partially explain the reason why COVID-19 is not prevented by warm weather in some countries.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.110608.

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