Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Mediation by human mobility of the association between temperature and COVID-19 transmission rate

Wenjing Shao\textsuperscript{a}, Jingui Xie\textsuperscript{b}, Yongjian Zhu\textsuperscript{a,*}

\textsuperscript{a} School of Management, University of Science and Technology of China, Hefei, China
\textsuperscript{b} School of Management, Technical University of Munich, Heilbronn, Germany

**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.

**ARTICLE INFO**

Keywords: COVID-19, Temperature, Human mobility, Suppression effect, Mediation analysis

**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; Holtmann et al., 2020; Wu et al., 2020). A study suggested that rising temperatures could reduce the number of confirmed 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
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 produce 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 Carotenì 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 reports 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
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:

\[ R_{it} = \beta_0 + \beta_1 T_{il} + \beta_2 X_{il} + \text{country}_i + \text{day}_t + \epsilon_{it} \]  

(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. \( \beta_1 \) identifies the impact of temperature on transmission rates. We controlled time-invariant countries characteristics by including the country fixed effect \( \text{country}_i \) and day fixed effect \( \text{day}_t \). \( \epsilon_{it} \) 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:

\[ M_{ij} = a_0 + a_1 T_{ix} + a_2 X_{ix} + \text{country}_i + \text{day}_j + u_{ij} \]  

(2)

Fig. 2. The time trend of the effective reproduction rate (\( R \)) of COVID-19 for 47 countries on six continents.
Table 1
Descriptive statistics of transmission rate, meteorological variables and human mobility.

| Variable                        | Mean  | SD    | Min   | 25th  | 50th  | 75th  | Max   |
|---------------------------------|-------|-------|-------|-------|-------|-------|-------|
| 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                | −42.896| 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| 60.500|
| Temperature                     | 33.614| 36.061| 91.260 | 40.480 | 60.500 |

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

| Variable                        | Mean   | SD    | Min   | 25th  | 50th  | 75th  | Max   |
|---------------------------------|--------|-------|-------|-------|-------|-------|-------|
| Mean temperature (°C)           | 1.000  |       |       |       |       |       |       |
| Air pressure (hPa)              | −0.180*| 1.000 |       |       |       |       |       |
| Wind speed (m/s)                | −0.403*| 0.096*| 1.000 |       |       |       |       |
| Driving mobility                | −0.064*| −0.095*| 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 |       |

Note: *p < 0.05.

Equations (1)–(3) constitute a complete mediation analysis. The first step is to test whether the regression coefficient \( \beta_1 \) is statistically significant in Equation (1); the second step is to test whether the regression coefficient \( \alpha_1 \) in Equation (2) is statistically significant; the third step is to test whether the regression coefficients \( \gamma_1, \gamma_2 \) in Equation (3) are statistically significant. If \( \beta_1, \alpha_1, \gamma_1 \) and \( \gamma_2 \) are all significant, and the indirect effect \( (\alpha_1 \times \gamma_2) \) has the opposite sign of the direct effect \( (\beta_1) \), 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 \( (\beta_1) \) less than the absolute value of the direct effect \( (\alpha_1) \) (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, −42.896 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 | Effective reproductive number (1) | Effective reproductive number (2) | Effective reproductive number (3) | Effective reproductive number (4) | Effective reproductive number (5) | Effective reproductive number (6) | Effective reproductive number (7) | Effective reproductive number (8) |
|-----------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Lag1-3    | Mean temperature                  | Walking mobility                  | Control                           | Observations                      |
|           | -0.012***                         | 1.329***                         | -0.015***                         | 0.069***                          |
|           | (-0.015, -0.009)                  | (1.361, 1.691)                   | (-0.029, -0.022)                  | (0.048, 0.091)                    |
| Lag1-7    | Mean temperature                  | Walking mobility                  | Control                           | Observations                      |
|           | 0.025***                          | 1.531***                         | -0.034***                         | 0.010***                          |
|           | (0.022, 0.027)                    | (1.362, 1.701)                   | (-0.034, -0.027)                  | (0.000, 0.011)                    |
| Lag1-14   | Mean temperature                  | Walking mobility                  | Control                           | Observations                      |
|           | 0.031***                          | 1.312***                         | -0.035***                         | 0.010***                          |
|           | (0.025, 0.037)                    | (1.361, 1.481)                   | (-0.035, -0.027)                  | (0.000, 0.011)                    |

Note: This table reports Equations (1)–(3) estimated coefficients and 95% confidence intervals of interest variable and suppressor.

**W. Shao et al.**

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.

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.
Acknowledgements

This research was supported by the National Natural Science Foundation of China (NSFC) with grant Nos: 71921001 and 71571176.

Appendix A. Supplementary data

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

References

Arroyo-Mariel, F., Bullano, F., Kucinskas, S., Rondón-Moreno, C., 2020. Tracking R of COVID-19: a new real-time estimation using the kalman filter. https://doi.org/10.2139/sers.3581633.

Arana, P., Cabezudo, S., Péñalba, M., 2014. Influence of weather conditions on transit ridership: a statistical study using data from Smartcards. Transport. Res. Pol. Pract. 59, 1–12. https://doi.org/10.1016/j.trr.2013.10.019.

Bocker, L., Dijst, M., Faber, J., 2016. Weather, transport mode choices and emotional travel experiences. Transport. Res. Pol. Pract. 360–373. https://doi.org/10.1016/j.trr.2016.09.021.

Badr, H.S., Du, H., Marshall, M., Dong, E., Squire, M.M., Gardner, L.M., 2020. Association between mobility patterns and COVID-19 transmission in the USA: a mathematical modelling study. The Lancet Infectious Diseases. https://doi.org/10.1016/S1473-3099(20)30253-2.

Belanger, M., Graydonald, K., Oloughlin, J., Paradis, G., Hanley, J.A., 2009. Influence of weather on health outcomes: evidence from hospital records in a northern province of Canada. Can. J. Public Health. 99, 102–105. https://doi.org/10.1007/s12630-010-01591-x.

Wax, R.S., Christian, M.D., 2020. Practical recommendations for critical care and anesthesiology teams caring for novel coronavirus (2019-nCoV) patients. Campaign Journal of Anaesthesia-Journal Canadien D Anesthésie 1–9. https://doi.org/10.1007/s12630-020-01591-x.

World Health Organization. 2020. https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200805-covid-19-sitrep-198.pdf?sfvrsn=fc9d1754_2.

Xie, J., Zhu, Y., 2020a. Meta-regression analysis for exploring the effect of temperature on COVID-19 early evolution in Spain. Environ. Res. 186, 109553. https://doi.org/10.1016/j.envres.2020.109553.

Wu, Y., Ying, C., Wu, L., Xie, D., Wang, L., Li, X., 2020. No association of temperature and humidity on the daily new cases and new deaths of COVID-19 in 166 countries. Sci. Total Environ. 729 https://doi.org/10.1016/j.scitotenv.2020.139051.

Yao, Y., Pan, J., Liu, Z., Meng, X., Wang, W., Kan, H., Wang, W., 2020. No association of COVID-19 transmission with temperature or UV radiation in Chinese cities. Eur. J. Public Health 1–2. https://doi.org/10.1016/j.puhe.2020.05.065.

Yang, Y., Zhao, J., Peng, J., Li, J., Lu, J., Guo, X., 2020. Association between human mobility and COVID-19 transmission in (sub)tropical cities of Brazil. Sci. Total Environ. 729 https://doi.org/10.1016/j.scitotenv.2020.138862.

Zhu, Y., 2020b. Meteorological impact on the COVID-19 pandemic: a study across 189 countries. Sci. Total Environ. 745. https://doi.org/10.1016/j.scitotenv.2020.138201.

Zhu, Y., 2020a. Temperature significantly changes COVID-19 transmission in (sub)tropical regions of Brazil. Sci. Total Environ. 729 https://doi.org/10.1016/j.scitotenv.2020.109625.

Zhu, Y., 2020c. The effect of temperature on COVID-19 early evolution in Spain. Sci. Total Environ. 741, 140489. https://doi.org/10.1016/j.scitotenv.2020.140489.

Zhu, Y., 2020d. The effect of temperature on COVID-19 early evolution in Spain. Sci. Total Environ. 741, 140489. https://doi.org/10.1016/j.scitotenv.2020.140489.

Zhu, Y., 2020e. Temperature significantly changes COVID-19 transmission in (sub)tropical regions of Brazil. Sci. Total Environ. 729 https://doi.org/10.1016/j.scitotenv.2020.109625.