

1 **Population movement, city closure and spatial transmission of the 2019-nCoV**

2 **infection in China**

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16 Abstract

17 The outbreak of pneumonia caused by a novel coronavirus (2019-nCoV) in Wuhan
 18 City of China obtained global concern, the population outflow from Wuhan has
 19 contributed to spatial expansion in other parts of China. We examined the effects of
 20 population outflow from Wuhan on the 2019-nCoV transmission in other provinces
 21 and cities of China, as well as the impacts of the city closure in Wuhan. We observed
 22 a significantly positive association between population movement and the number of
 23 cases. Further analysis revealed that if the city closure policy was implemented two
 24 days earlier, 1420 (95% CI: 1059, 1833) cases could be prevented, and if two days
 25 later, 1462 (95% CI: 1090, 1886) more cases would be possible. Our findings suggest
 26 that population movement might be one important trigger of the 2019-nCoV infection
 27 transmission in China, and the policy of city closure is effective to prevent the
 28 epidemic.

29 **Keywords:** 2019-nCoV infection; Wuhan; Population movement; Infection
 30 transmission

32 Introduction

33 In December 2019, a series of pneumonia cases caused by a novel coronavirus,
 34 namely 2019-nCoV, emerged in Wuhan, the capital city of Hubei Province in China
 35 (1), Similar with severe acute respiratory syndrome (SARS), the Wuhan pneumonia
 36 outbreak was highly suspected to be linked to the wild animals in the seafood market,
 37 although the definitive source of this virus was not clear yet (2).

38 As of Jan 31, 2020, the infection has been transmitted to all the provinces in China
39 and a few other countries. Epidemiology evidence shown that most of the cases had a
40 history of living or travelling to Wuhan, the household cluster cases and cases of
41 health-care workers indicated the human-to-human transmission route (3), which
42 might be the reason for a rapid increasing rate of infection across the country and
43 globally (4).

44 Considering the person-to-person transmission and the large travel volume during
45 the traditional Chinese New Year (the largest annual population movement in the
46 world), it is expected that the population movement would lead to further expansion
47 of the infection, so the government imposed a lockdown on Wuhan City at 10:00 am
48 on January 23, as well as some other cities later on. However, an estimated 5 million
49 individuals had already left Wuhan for the holiday or travelling, some of which rushed
50 out after the lockdown announcement (5). In addition, the novel coronavirus is
51 infectious during the incubation period and when the symptoms are not obvious,
52 which is likely to make the huge floating population potential sources of infection (6).
53 Therefore, it is reasonable to hypothesize that the population transported from Wuhan
54 may have a significant impact on the potential outbreaks in other parts of China.

55 Recent studies on the novel coronavirus pneumonia focused more on its etiology (7,
56 8), transmission route (9, 10), and epidemiological characteristics (11, 12), there is
57 still a lack of investigating the relationship between the migrating population and the
58 outbreak, which is of great importance for making intervention policies. Thus, we
59 conducted this study with the following objectives: 1) to depict the impacts of the

60 population movement on the spatial transmission of the 2019-nCoV cases at the
61 provincial and city levels in China; 2) to estimate the potential outbreak risk at areas
62 with the population outflowed from Wuhan; 3) to evaluate the effectiveness of the city
63 closure measures on the epidemic control.

64

65 **Methods**

66 **Data collection**

67 The data on the daily number of cases were derived from the real-time update of the
68 China Health Commission (<http://www.nhc.gov.cn/>), 2019-nCoV epidemic report on
69 Phoenix and Dingxiangyuan website. The case definition has been introduced
70 previously (13, 14). In brief, a confirmed case was defined as a pneumonia that was
71 laboratory confirmed 2019-nCoV infection with related respiratory symptoms and a
72 travel history to Wuhan or direct contact with patients from Wuhan. We collected each
73 reported 2019-nCoV case in mainland China till 12:00 pm January 31, 2020.

74

75 **The floating population**

76 As the city closure took place at 10:00 AM Jan 23rd, 2020, and the incubation period
77 of the infection was estimated to be about 3-7 days (15), we obtained the daily index
78 of population outflow from Wuhan and the proportion of the daily index from Wuhan
79 to other provinces and top 50 cities, from January 1 to 31 in 2020, the information
80 was retrieved through the Spring Festival travel information of China released by
81 Baidu Qianxi. The data is consisted of Baidu Location Based Services (LBS) and

82 Baidu Tianyan, using the positioning system and transportation information system,
83 which be display dynamic visual regional population outflow in real-time. Data of
84 Baidu Qianxi was freely available to the public (<http://qianxi.baidu.com>).

85

86 **Statistical analysis**

87 **Number of 2019-nCoV cases per unit outflow population**

88 The daily index of population outflow from Wuhan to other provinces and top 50
89 cities was obtained by multiplying the daily index of population outflow within
90 Wuhan by the corresponding proportion for each province. To evaluate the effect of
91 prevention and control measures of the local government, we calculated the number
92 of 2019-nCoV cases per unit outflow population, the formula can be specified as:

93 The total index of outflow population from Wuhan from Jan 1 to 31:

$$94 \quad A = \{a_i\} (i = 1, 2, \dots, 31)$$

95 The daily proportion of the daily index from Wuhan to other provinces from Jan 1 to
96 31:

$$97 \quad B = \{b_{ij}\} (i = 1, 2, \dots, 31; j = 1, 2, \dots, 31)$$

98 The cumulative 2019-nCoV cases in each province from Jan 1 to 31:

$$99 \quad C = \{c_j\} (j = 1, 2, \dots, 31)$$

100 The total index of population inflow from Wuhan to other provinces:

$$101 \quad D = \{d_j\} (j = 1, 2, \dots, 31)$$

102 Number of cases per unit outflow population for each province:

$$103 \quad \sum_{j=1}^{31} c_j / \sum_{j=1}^{31} d_j$$

104 **Evaluation of the effects of earlier city closure dates**

105 After the city closure was taken in force, some population still outflowed from Wuhan.

106 We subtracted the outflow index on Jan 23 from the average outflow index from Jan

107 24 to 31, to obtain the index of outflow population within Wuhan reduced by the

108 advance city closure on Jan 23 and 22 (the advance outflow index). And then we

109 calculated the average proportion of the outflow index from Jan 24 to 31 for each

110 province (the average proportion). The number of cases reduced by the advance city

111 closure in each province was estimated by multiplied the advance outflow index by

112 the average proportion and one corresponding unit. The formula can be specified as:

113 The reduced index of outflow population:

$$114 \sum_{i=1}^p a_{n+1-i}$$

115 Here, n was the date that government announced city closure; p was the advance days

116 of city closure.

117 The increased index of outflow population:

$$118 \frac{\sum_{i=n+1}^m a_i}{m-n}, \quad n=23, m=31$$

119 The net loss of index of outflow population:

$$120 \sum_{i=1}^p a_{n+1-i} - p \frac{\sum_{i=n+1}^m a_i}{m-n}, \quad n=23, m=31$$

121 The average proportion of the outflow index from Wuhan into each province during

122 the city closure:

$$123 \quad \frac{\sum_{i=n+1}^m b_{ij}}{m-n}, \quad n=23, m=31$$

124 The net loss index of outflow population caused by advance Wuhan city closure for
125 each province:

$$126 \quad \left(\sum_{i=1}^p a_{n+1-i} - p \frac{\sum_{i=n+1}^m a_i}{m-n} \right) \frac{\sum_{i=n+1}^m b_{ij}}{m-n}, \quad n=23, m=31$$

127 The total reduced number of 2019-nCoV cases:

$$128 \quad \sum_{j=1}^{31} \left\{ \left(\sum_{i=1}^p a_{n+1-i} - p \frac{\sum_{i=n+1}^m a_i}{m-n} \right) \frac{\sum_{i=n+1}^m b_{ij}}{m-n} \cdot \frac{\sum_{j=1}^{31} c_j}{\sum_{j=1}^{31} d_j} \right\}, \quad n=23, m=31$$

129 Similarly, we evaluated the impacts of one-day and two-day delayed city closure. We
130 took the average index of the population outflow between Jan 21 and 23 as the daily
131 index of population outflow before the city closure, and used the same calculation
132 method to estimate the index of population outflow within Wuhan increased by the
133 delayed city closure on Jan 24 and Jan 25 (the delayed outflow index). We multiplied
134 the delayed outflow index by the average proportion and one corresponding unit to
135 estimate the increased number of cases caused by one-day and two-day delayed city
136 closure in each province.

137

138 Results

139 As of January 31, 2020, a total of 11791 confirmed cases and 259 deaths due to the
140 2019-nCoV infection were reported in China, which were widely dispersed in all of
141 31 provincial administrative areas. The overall trend of 2019-nCoV cases is upward.

142 During the period of January 11, 2020 through January 31, the cumulative number of
143 cities infected with 2019-nCoV cases increased rapidly (appendix). A total of 313
144 cities in mainland China reported the occurrence of 2019-nCoV infection, of which
145 the number of reported cases from January 20 to 29 increased rapidly from 7 to 313,
146 an increase of nearly 44 times. Among the cities, 97 of them belong to the regions
147 with high population exodus out of Wuhan, and 7138 cases have been reported,
148 accounting for 83.23% of the total reported cases outside Wuhan (appendix).

149 Population outflow of Wuhan could be divided into four periods based on the
150 migration data of Baidu (figure 1 and 2). In the first stage from Jan 1 to Jan10,
151 migrant population flowed out of Wuhan normally and returned to hometown without
152 the influence of the epidemic situation. At this point, the mean daily index of
153 population outflow was 58039.71 (95% CI: 48883.38-66454.00), and 2019-nCoV
154 cases were mainly distributed in Wuhan. From beginning of Spring Festival travel
155 rush on Jan 10 and announcement of 2019-nCoV infection, the mean index of
156 population outflow rose to 66777.98 (95% CI: 61125.90-72962.78), which increased
157 by 15.1% compared with the previous period. Meanwhile, 2019-nCoV cases
158 gradually appeared in Wuhan and several nearby cities. The third period was from
159 January 20 to 23 when Academician Nanshan Zhong disclosed the human-to-human
160 transmission and a large number of Wuhan residents fled from Wuhan with increasing
161 panic. The corresponding mean index of population outflow of this period surged to
162 112385.88 (95% CI: 107367.44-118403.21), which increased by 93.6% comparing to
163 the earlier period. Thereafter, a strict city closure policy was implemented to prohibit

164 the population relocation from Wuhan. In the wake of sharp decline of outflow
165 population from Wuhan, the index reduced to 9180·29 (95% CI: 3055·35-19101·40),
166 falling by 91·8% comparing with the third period and the effective controlling of the
167 outflow population prevented suspected cases from spreading to the whole country,
168 however, 2019-nCoV cases has been widely dispersed in all of 31 provinces.

169 We applied scatter diagram to demonstrate the association between the number
170 of 2019-nCoV cases and index of outflow population at the scales of province and city.
171 In general, at the scale of province (figure 3), outflow population from Wuhan was
172 mainly distributed in Henan, Hunan, Guangdong, Anhui, Zhejiang, etc. And the top
173 four provinces with the most serious epidemic were Zhejiang, Guangdong, Henan,
174 and Hunan provinces. Therefore, we could observe that there were more 2019-nCoV
175 cases in the provinces with higher index of outflow population. Nevertheless, the two
176 provinces of Zhejiang and Guangdong with relatively lower index of outflow
177 population had more 2019-nCoV cases compared with Henan and Hunan provinces.
178 In Henan, the index of outflow population was about 50000, while there were fewer
179 than 450 cases, which might be lower than expected. In contrast, about 600 confirmed
180 cases were observed in Zhejiang, which had only one fifth of outflow population of
181 Henan. Similar results were obtained using the number cases per unit outflow
182 population (appendix). The mean value of the number of 2019-nCoV cases per unit
183 outflow population across the whole country was 129·72, however, the value in
184 Zhejiang province was more than 450 and the corresponding result in Henan was
185 lower than average.

186 At the city-level analysis (figure 4), we observed that there was a large number
187 of cases in the cities of Hubei province such as Huanggang, Xiaogan, Xiangyang,
188 Jingzhou, etc. Overall, the association between the number of 2019-nCoV cases and
189 index of outflow population at the city-level was in line with that at the provincial
190 level, which both showed that the cities with more index of outflow population would
191 trigger more cases. Similarly, we observed some cities deviated from the general trend
192 including Wenzhou, Taizhou, Xuchang, Luoyang, and Guiyang. For instance, the
193 index of outflow population of Wenzhou and Luoyang was close to identical level,
194 whereas there was tremendous difference in the number of 2019-nCoV cases in the
195 two cities. From the city of Taizhou and Xuchang, we could obtain the analogous
196 results.

197 To evaluate the effect of the city closure on the infection transmission one and
198 two days in advance, we used the index of population outflow of January 21-23, 2020
199 when the Wuhan was still open and index of population outflow of January 24-31,
200 2020 when the city closure policy had been implemented, and the calculations gave
201 the reduced index of population outflow: 102206.69 for city closure one day in
202 advance and 211429.60 for city closure two days in advance. In addition, we obtained
203 the reduced index of population outflow of each other province and correspondingly
204 reduced 2019-nCoV cases. Finally, about 687 and 1420 2019-nCoV cases would be
205 avoided with implementing city closure policy one and two days in advance (table 1).
206 Consistently, if city closure policy of Wuhan was delayed by one or two days, there
207 would be 722 or 1462 extra 2019-nCoV cases respectively.

208

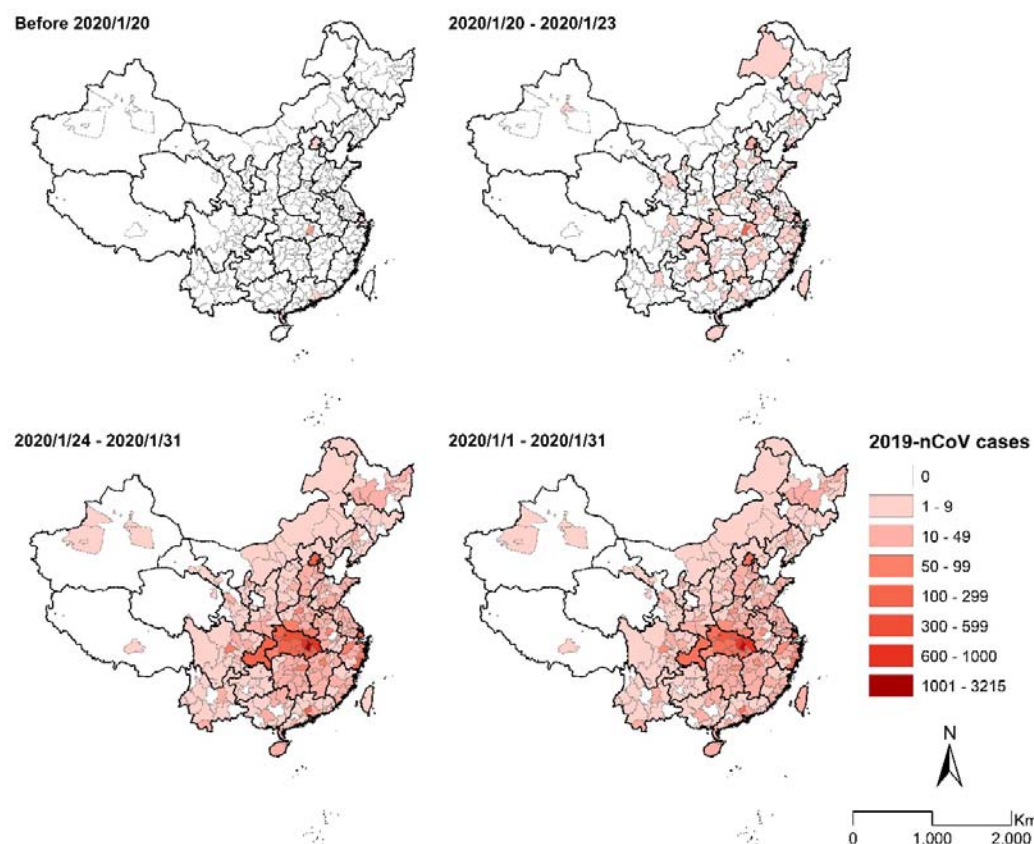
209 **Table 1. The impact of different city closure dates on the number of 2019-nCoV**

210 **infections in China**

Alternative implementing dates	Reduced or increased 2019-nCoV cases*	95% CI*
Two days earlier: 2020-01-21	-1420	-1833, -1059
One day earlier: 2020-01-22	-687	-886, -512
One day later: 2020-01-24	722	539, 932
Two days later: 2020-01-25	1462	1090, 1886

211 *Table footnotes: 2019-nCoV=2019 novel coronavirus. CI=confidence interval.

212



213

214 **Figure 1. The spatial distribution of 2019-nCoV cases in China during period of**

215 **January 1-31, 2020.**

216

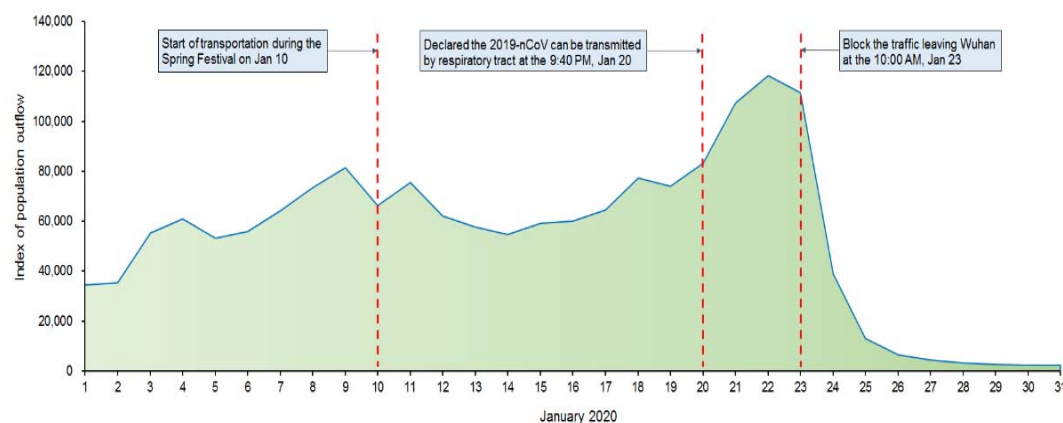


Figure 2. Index of population outflow of Wuhan City during period of January

1-31, 2020.

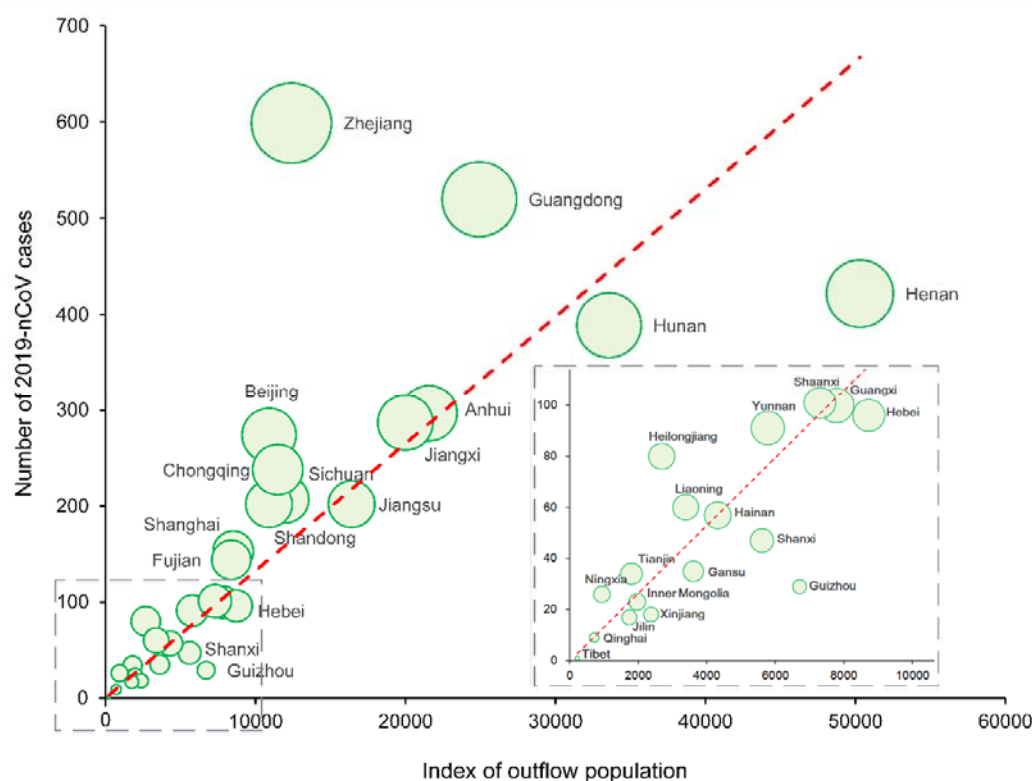


Figure 3. The association between the number of 2019-nCoV cases and the total index of population outflow at the provincial scale.

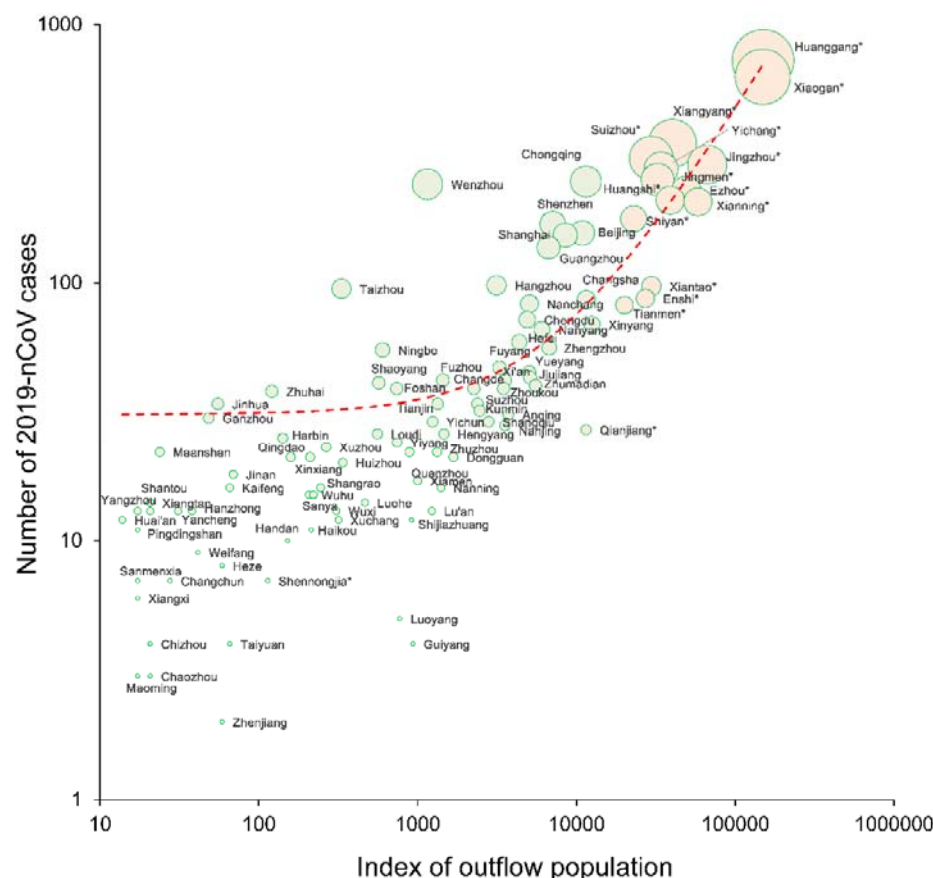


Figure 4. The association between the number of cases and the total index of population outflow at the city scale.

Discussion

Understanding the driving factors of the infectious disease is of particular importance for the timely formulation of effective controlling measures. Our results revealed a close relationship between the population outflow from Wuhan and the 2019-nCoV infection in other areas of China. We assessed the contributions of the lockdown and explored the potential effects of the measure with different implementation dates.

The fluctuation of outflowing population of Wuhan indicated that the lockdown in Wuhan reduced the outward movement of the population effectively. However, the

237 migration data also suggested that a large number of populations of Wuhan had
238 flowed out before 10:00 am Jan 23, 2020. and 2019-nCoV cases has been widely
239 dispersed nationwide.

240 Distribution of population outflows and cases varied across provinces. Our
241 finding on the effects of population movement on the disease transmission was
242 consistent with other coronaviruses (16-18). Since the infection is transmitted through
243 the respiratory tract and close contact, it is greatly affected by population movements.
244 Firstly, a great number of people flowing out of Wuhan may transmit the virus to the
245 whole country and even worldwide during the Chinese Spring Festival. Secondly, the
246 absence of detectable symptoms during the long incubation period made it difficult to
247 identify the cases in the early stage (13, 19). Thirdly, population movements increase
248 the difficulty of case management and health education. All these factors promoted
249 the transmission of 2019-nCoV. Specially, different from the H1N1 outbreak in 2009
250 (20), the railways might play an important role in the disease transmission. Since
251 railways were widely used before and during the Spring Festival, the area closely
252 connected to Wuhan by railway should be the priority of infection control.

253 Our study provided timely evidence for the formulation of efficient strategies to
254 prevent diseases from spreading out. On the one hand, the result could help assess
255 effectiveness of the prevention and control efforts. For example, the cases in Zhejiang
256 and Guangdong are apparently more than estimated, which indicated a better health
257 emergency response system (i.e. higher detection efficiency) or inadequate isolation.
258 Whereas the cases reported in Henan were much lower than expected. Two possible

259 explanations were considered: (1) Strong prevention and control measures were
 260 adopted in Henan; (2) The epidemic in Henan has been underestimated and enhanced
 261 screening efforts should be enforced. On the other hand, exploring the association was
 262 expected to help identify high-risk areas and guide health strategy formulation (21,
 263 22). Take Henan for example, great difference between estimated and reported data
 264 may imply a great increase of cases in the future, which required enhancement of the
 265 surveillance system and rational allocation of resources (18). The medicine supply,
 266 personal protective equipment, hospital supplies, and the human resources necessary
 267 to respond to an outbreak should be always ensured (23). In addition, this study could
 268 be used to guide the assessment of the risk of disease transmission and help raise
 269 public awareness. As a large number of infected people had transported to all of 31
 270 provinces, epidemics across the country may be inevitable. To halt the spread of the
 271 epidemic, harsh measures including quarantine and isolation of exposed persons,
 272 cancellation of mass gatherings, school closures, and travel restriction were needed to
 273 reduce transmission in affected areas. Furthermore, screening of people who have
 274 been to Wuhan recently was of crucial importance, especially cities with close ties to
 275 Wuhan.

276 Considering the impact of population movements on the outbreak, the Wuhan
 277 government announced the suspension of public transportation on Jan 23, 2020, with
 278 a closure of airports, railway stations, and highways, to prevent further disease
 279 transmission (24). Despite inconsistent reports on the role of the lockdown in halting
 280 the disease transmission across China (22, 23, 25), the unprecedented measure might

281 play an important role in slowing the epidemic spread, especially when an effective
 282 vaccine was developed (26, 27). In addition, to explore the impact of date selection,
 283 we estimated the changes of cases when the measure was implemented on different
 284 date. The results varied significantly, 1420 cases could be prevented with the measure
 285 implemented two days earlier, and the number of cases will increase by 1462 with the
 286 lockdown implemented two days later, suggesting that the effect of the lockdown
 287 depending on the choice of date greatly, which could provide a reference for the
 288 future outbreaks. Since the political and economic effects were not considered, further
 289 studies on secondary impacts of the measure, like socioeconomic impacts, were also
 290 warranted. Though we estimated that some cases would possibly be prevented if the
 291 policy was implemented earlier, it was actually hard to make such a huge decision
 292 given the whole picture of the infection was not clear at that stage. The authors
 293 believe that the current policy was appropriate at this complex situation.

294 There were a few limitations of our study. Firstly, for practical reasons, we used
 295 an indicator to reflect the real-time magnitude of population movements, which was
 296 acceptable considering our research purpose. Secondly, the influence of some
 297 important factors, such as socioeconomic and demographic characteristics, were not
 298 considered. Thirdly, it is assumed that the infected travelers in the population are
 299 randomly distributed (28), and that there was no significant difference in surveillance
 300 capability between cities (18), which might not be the case in reality. In addition,
 301 daily data used in this study was reported infection data, rather than the actual number
 302 of incident cases. More detailed and further in-depth studies are warranted in the

303 future.

304 In conclusion, our study indicates that the population outflow from Wuhan might
305 be one important trigger of the 2019-nCoV infection transmission in China, and the
306 policy of city closure is effective to prevent the epidemic and earlier implementation
307 would be more effective. The magnitude of epidemic might be under-estimated and
308 should be paid more attention, such as Henan and Hunan provinces.

309

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315 submit for publication.

316

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