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## Research

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# **Does Quarantine of Wuhan Effectively Restrict Early Geographic Spread of Novel Coronavirus Epidemic During *Chunyun* in China? a Spatial Model Study**

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**Word count:** 2,359

## **Abstract**

Background: Prior to Wuhan quarantine in 2020, *chunyun*, the largest population mobility on this planet, had begun. We quantify impacts of Wuhan quarantine on COVID-19 spread during *chunyun* at a nationwide and a local level.

Methods: During the period of January 1 to February 9, 2020, a total of 40,278 confirmed COVID-19 cases from 319 municipalities in mainland China were modelled with the cross-coupled meta-population methods using between-city Baidu migration index. Four scenarios of geographic spread of COVID-19 included the presence of both *chunyun* and quarantine (baseline); quarantine without *chunyun* (scenario 1); *chunyun* without quarantine (scenario 2); and the absence of both *chunyun* and quarantine (scenario 3).

Results: Compared with the baseline, scenario 1 resulted in 3.84% less cases by February 9 while scenario 2 and 3 resulted in 20.22% and 32.46% more cases by February 9. Investigation of geographic distribution of cases revealed that *chunyun* facilitated the COVID-19 spread in most but not all cities, and effectiveness of city quarantine was offset by *chunyun*. Impacts of quarantine of Wuhan during *chunyun* on the COVID-19 spread demonstrate geographical heterogeneity.

Conclusion: Our result strongly supports the travel restriction as one of the effective emergency responses and highlight the importance of developing area-specific countermeasures.

## **Contributions to the literature**

- Chunyun, the largest population mobility on this planet, is a stimulus of the early geographic spread of COVID-19 in China.
- Domestic travel restriction serves as one of the effective emergency responses to the COVID-19 outbreak.
- Area-specific countermeasures would include continuing restriction on population mobility in particular relevance to many other countries around the world that face massive inter-city travel demands.

**Key words:** coronavirus; COVID-19; geographic spread; quarantine; *chunyun*; China

## Introduction

Since early December 2019, an increasing number of atypical pneumonia have been reported in Wuhan <sup>1</sup>, a city with a population of 11 million in the central part of China. In response to this outbreak, the Chinese Center for Disease Control and Prevention (China CDC) conducted an epidemiologic and etiologic investigation on December 31, 2019 <sup>2</sup>. It was found that human-to-human transmission occurred since the middle of December 2019 <sup>3</sup>, with a novel strain of coronavirus (COVID-19) isolated and confirmed on 7 January 2020 <sup>4</sup>. Along with the increasing number of COVID-19 cases in China, the geographic spread at a meta-population level (e.g. between cities in China, Asia-pacific regions, or northern hemisphere countries) has been reported <sup>5</sup>.

When it appears that human-to-human transmission poses a threat, use of restrictive measures such as isolation of cases and quarantine of contacts becomes apparent options for emergency response <sup>6</sup>. A typical challenge has emerged when *chunyun*, the largest human migration on the planet, began on Jan 10, 2020 with billions of trips made for family reunions to celebrate the Spring Festival during the national holidays from January 24 to 31 <sup>7</sup>. Geographic spread of COVID-19 would have potentially accelerated under this circumstance, and therefore prevention and control of the COVID-19 infiltration into local communities across the nation requires immediate actions to restrict human movements <sup>8</sup>. On January 23 and 24, 2020, the Chinese central government has implemented the metropolis-wide quarantine of Wuhan and several nearby cities <sup>3</sup>. In addition to the quarantine of Wuhan, the central government has announced the extended national holidays and set the back to work date as of February 10, 2020 (except Wuhan) <sup>9</sup>.

In the face of this unprecedented threat and incomplete knowledge of effective

countermeasures, it appears appropriate for the authorities to invoke the quarantine of Wuhan as a means to interrupt the geographic spread of COVID-19 and achieve the population health goals <sup>10</sup>. Despite a recent decreasing trend of daily number of confirmed cases <sup>11</sup>, population based evidence is inadequate regarding whether the implementation of quarantine is effective in the context of *chunyun*. This study aims to evaluate the effectiveness of quarantine for preventing the epidemic, and examine whether the effectiveness varies according to the presence or absence of *chunyun* and quarantine.

## Methods

### Data sources

Provincial Health Commissions in mainland of China have reported municipal-level incident numbers of COVID-19 suspected, confirmedly infected, recovered, and deceased individuals, respectively on a daily basis since January 2020 <sup>12</sup>. We include a total of 319 municipalities having at least one laboratory-confirmed case and ascertained their daily numbers of COVID-19 cases from January 1 to February 9, 2020. These data are publically available and therefore this study was exempted for ethics approval by institutional review boards with respect to data collection, analysis and reporting. The study outcome was the incident laboratory-confirmed COVID-19 pneumonia.

Baidu Migration Index is a free data analytic platform using Baidu web search and Baidu news to present massive behavior data among Baidu users, which has been frequently used to reflect population mobility in China <sup>13-15</sup>. We obtained Baidu Migration Index from January 1 to February 9, 2020 to quantify the daily traveler between pair-wise cities. The specific number of travelers from city  $i$  to  $j$  at day  $t$ ,  $X_{i,j,t}$ , is calculated as follows:

$$X_{i,j,t} = p_{i,j,t} * \frac{No\_wh}{p_{wh}} \quad (1)$$

where  $p_{i,j,t}$  is the migration index from city  $i$  to  $j$  at day  $t$ ,  $No\_wh$  is the number of travelers that left from Wuhan during January 10 to January 19, 2020 (prespecified as 4.10 million<sup>16</sup>), and  $p_{wh}$  is the sum of traveling index from Wuhan to all other cities at the same period.

### Statistical analysis

We used the following cross-coupled meta-population (epidemic) model to consider the geographic spread of COVID-19 between cities across the nation:

$$\frac{dS_i}{dt} = -\beta_t S_i \sum_{j=1}^n \frac{\varphi_{i,j,t} I_j}{N_i} \quad (2)$$

$$\frac{dE_i}{dt} = \beta_t S_i \sum_{j=1}^n \frac{\varphi_{i,j,t} I_j}{N_i} - \alpha E_i \quad (3)$$

$$\frac{dI_i}{dt} = \alpha E_i - \gamma I_i \quad (4)$$

$$\frac{dR_i}{dt} = \gamma I_i \quad (5)$$

where  $S_i$ ,  $E_i$ ,  $I_i$ , and  $R_i$  are the numbers of susceptible, exposed, infectious, and recovered individuals, respectively, and  $N_i$  is the total population size of city  $i$ ,  $\beta_t$  is the transmission parameter (we assume it is the same over all cities) at time  $t$ ,  $\varphi_{i,j,t}$  is the proportion of individuals moving to city  $i$  from city  $j$  at time  $t$ ,  $\alpha$  is the latent rate, and  $\gamma$  is the infectious rate. For model fitting convenience, we add another compartment ( $K$ ) to the above equations to keep track of cumulative incidence as follows:

$$\frac{dK_i}{dt} = \alpha E_i \quad (6)$$

Fitting was achieved by treating the differential equation (Eq 6) as representing the mean number of cumulative cases per day over China in our study period, and assuming that the observed number of cumulative cases over China were (approximately) Poisson distributed around this mean. Given the model and data, parameter inference was achieved by least

square (LS) estimation using L-BFGS-B optimization as implemented in the *optim()* function in the R statistical language (R Core Team 2020). Uncertainty in the parameter estimates was explored using parametric bootstrap as follows. 1000 simulations from the model (Eq 6 and Poisson noise) were firstly generated using the LS estimates of the parameters. Each simulated dataset was then re-fitted to the model to construct a joint sampling distribution of the parameters, and 95% confidence estimated as the lower 2.5% and upper 97.5% quantiles.

The instantaneous basic reproductive number ( $R0_t$ ) was calculated by  $\beta_t/\gamma$ . Based on these parameters, we then simulate the probable course of the disease transmission conditioned on the aforementioned three modelling scenarios.

## Results

During the period of January 1 to February 9, 2020, a total of 40,278 confirmed COVID-19 cases from 319 municipalities in mainland China were reported (Fig. 1). Fig. 2 shows the population inflow and outflow for Wuhan as well as China during the study period. On a national scale, the population mobility has been increasing since the start of *chunyun* and reached the greatest on January 21 and then decreased afterward. While the population inflow and outflow for China shows the similar pattern, these two trends for Wuhan present different patterns. The population outflow from Wuhan shows a generally increasing trend up to January 22 whereas the population inflow to Wuhan remains almost constant. It is noteworthy for Wuhan that the population outflow is always greater than the population inflow until January 26 (shortly after the announcement of quarantine). Change of population outflow from Wuhan is also noteworthy for the sharp increase after announcement of human-to-human transmission on January 20.

<Figures 1 and 2 about here>

Fig. 3a presents the result of model fitting and it demonstrates a reasonable fit. Fig. 3b illustrates the time-varying estimates of basic reproductive number ( $R0_t$ ) of COVID-19 during the study period. Although we assumed  $R0_t$  varies over time, it appears to have two stages, that is,  $R0_t$  levels off at 3.47 from January 1 to 25, 3.24 from January 26 to February 8. Note that it slightly increased to 3.27 on February 9. The modelled latent and infectious time of COVID-19 was 6.11 days (95% Credible Interval (CI) 3.13–10.63) and 3.26 days (95% CI 1.06–5.16), respectively.

<Figure 3 about here>

Under all the scenarios, we predicted the number of COVID-19 cases on February 9. Table 1 displays cumulative number of COVID-19 cases in China during the study period under different modelling scenarios. Under Scenario 1, the epidemic would have resulted in 3.84% less COVID-19 cases than the baseline by February 9, indicating that *chunyun* facilitated the disease spread. Compared with the baseline, scenario 2 would have produced 32.46% more COVID-19 cases, demonstrating the protective effectiveness of quarantine. Under Scenario 3, the epidemic would have resulted in 20.22% more COVID-19 cases than the baseline, which suggested a combined effect of *chunyun* and quarantine on the disease.

<Table 1 about here>

Fig.4 demonstrate geographical distribution of change of cumulative COVID-19 cases for modelling scenarios 1-3 in comparison with baseline scenario (the presence of both *chunyun* and quarantine) by February 9, 2020. Under scenario 1 (Fig. 4a), the majority of cities showed a relatively sharp change in case reduction despite the nuance expression in a few populous cities, indicating that *chunyun* is not a common stimulus for the COVID-19 spread across the nation. Under scenario 2 (Fig. 4b), all the cities would have had greater number of cases in the absence of quarantine, in particular, those in northeast, south and west China would have an increase over 100%, indicating the protective effects of quarantine of Wuhan

on additional spreading towards all the other cities in China. Under scenario 3 (Fig. 4c), the protective effect of quarantine was offset by *chunyun*, especially for those corridor cities near Wuhan, indicating mixed effects caused by the presence of both quarantine and *chunyun* vary in space. Note that areas with over 100% increase of cases (in dark red color) under this scenario were mainly located within the five city groups shown in Fig. 4d.

<Figure 4 about here>

## Discussion

In this retrospective analysis of 40,278 confirmed COVID-19 cases in China, we modelled 3 exposure scenarios using publically available data reported by local public health authorities on a daily basis. These scenarios differed in the exposure to *chunyun*, the largest population mobility on the earth, and quarantine of Wuhan, the unprecedented control of 11 million people movement in response to the rapid spread of COVID-19 from the epicenter. Of the simulations of three exposure scenarios, the quarantine of Wuhan demonstrated the most protective effects by preventing 32.46% COVID-19 cases by February 9, 2020, whereas *chunyun* contributed towards the observed geographic spread and would have produced 3.84% more cases by the same period. However, impacts of the presence of both *chunyun* and quarantine of Wuhan on the COVID-19 spread were heterogeneous in space, with the majority of cities well protected by the quarantine in spite of the *chunyun* offset. These findings complement the growing evidence of impact of population mobility on the geographic spread of COVID-19, justify the invocation of quarantine of Wuhan instead of simply claiming the precautionary principle, and provide additional vigilance against human movement at this critical point for next-stage informed decision making with respect to COVID-19 prevention and control in the communities.

In this study, we have also investigated the epidemiological characteristics of COVID-19. We

first estimated its instantaneous  $R0_t$ , and found a decrease from 3.47 to 3.24 on January 26, which is probably due to the observed decrease in population mobility (Fig. 2). In addition, our estimate of latent and infectious period is 6.11 and 3.26 days, respectively, with the former being comparable with existing clinical studies<sup>17, 18</sup> and the latter, which has been rarely reported so far. Compared with previously reported basic reproductive number ( $R0$ ) which were fixed and ranged from 2.24 to 3.80<sup>3, 18-20</sup>, our estimate is a time varying one and somewhat more reliable as we taken into account a larger sample size as well as population mobility between cities that would potentially affect contact rates between individuals and subsequently the calculation of COVID-19 spread. Notwithstanding the decrease of  $R0_t$ , there was an increasing trend on February 9 which corresponded to the time when migrants return to study or work. Considering the contribution of *chunyun* towards geographic spread of COVID-19, this rebound trend of  $R0_t$  suggest that the epidemic would spread more rapidly. Therefore, more rigorous prevention and control measures need to be strictly implemented in the communities including home quarantines and self-monitoring.

We estimated COVID-19 cases under three scenarios and their respective changes in relation to the baseline number for each city. We found that there was evidently spatial heterogeneity of effects of *chunyun* and/or quarantine of Wuhan. In principle, *chunyun* contributed towards the COVID-19 spread in China (Table 1) but not specifically for each locality (Fig. 4a), while quarantine of Wuhan restricted additional spread towards every city (Fig. 4b) across the nation (Table 1). In the absence of both *chunyun* and quarantine (Fig. 4c), more evident reduction in cases would have occurred to five major urban agglomerations. These urban agglomerations (Fig. 4d) consist of two kinds of city clusters, i.e., well-developed megacities and the other nested in the undeveloped regions of China. There is obvious speculation that these clusters would experience similar outgoing and ingoing travel demands all year round,

and therefore the effects of *chunyun* would be nuance. It is noteworthy that corridor cities near Wuhan (Fig. 4c) did not benefit much from the quarantine as its protective effects were offset by the effects of *chunyun*. These corridor cities would perhaps become a case reservoir prior to the quarantine of Wuhan. Therefore, these corridor cities should be given a priority for continuing effort in allocation of healthcare resources. Additional strategies should be developed based on area-level characteristics.

Evidence of comparative effectiveness of large-scale quarantine on 11-million populations is rare because the outbreak of contagious disease of this kind is highly unusual and so is to have reliable national data. Using a larger sample size than previous studies and clear evidence of exposure, our findings are somewhat robust. However, there are some limitations. First, our analysis did not consider the under-reporting of cases during the study period, which may result in underestimation bias of our results. Second, the mathematical model is a deterministic model which cannot capture stochastic effects during the spread of COVID-19 under influence of multiple socio-environmental factors. This may bias the number of incident cases of a modelled scenario. Third, the three simulated scenarios were based on different restrictive measures of population mobility, lacking control of other confounding factors, and therefore results should be interpreted with caution.

## **Conclusion**

Seventeen years after the Severe Acute Respiratory Syndrome (SARS) epidemic, the current COVID-19 outbreak serves as a reminder of how rapidly novel pathogens can appear and spread across the nation and in the world with devastating consequences. Our result strongly supports the travel restriction as one of the emergency responses to this global population health threat, provides evidence that *chunyun* is a stimulus of the geographic spread of

COVID-19 in China, and highlight the importance of developing area-specific countermeasures. The simulations suggest continuing restriction on population mobility help in prevention and control of the COVID-19 pandemic. This is in particular relevance to any receiving cities in China and many other countries around the world that face massive inter-city travel demands.

## **List of abbreviations**

CDC: Center for Disease Control and Prevention

COVID-19: COrona VIRus Disease 2019

SARS: Severe Acute Respiratory Syndrome

## **Declarations**

**Ethics approval and consent to participate:** Not required.

**Consent for publication:** Not applicable.

**Availability of data and materials:** Data are available from the authors upon reasonable request.

**Competing interests:** None declared.

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**Authors' contributions:** Analyzed the data: YH LCK. Wrote the first draft of the manuscript: YH WD. Contributed to the writing of the manuscript: YH LCK TY XDC WD. Agree with the manuscript's results and conclusions: YH LCK TY XDC WD. Conceived and designed

the analyses: YH. Contributed data: LCK TY XDC. All authors have read, and confirm that they meet, ICMJE criteria for authorship.

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## Tables

**Table 1 Total number (no.) of COVID-19 cases over China under different scenarios.**

Scenario	Description	No. of cases on Feb 9, 2020
Baseline	<i>Chunyun</i> (yes), Quarantine (yes)	48637
1	<i>Chunyun</i> (no), Quarantine (yes)	46769 ( <b>-3.84%</b> )
2	<i>Chunyun</i> (yes), Quarantine (no)	64424 ( <b>32.46%</b> )
3	<i>Chunyun</i> (no), Quarantine (no)	58473 ( <b>20.22%</b> )

Percentage change (%) was based on the baseline and highlighted in bold.

## Figure legends

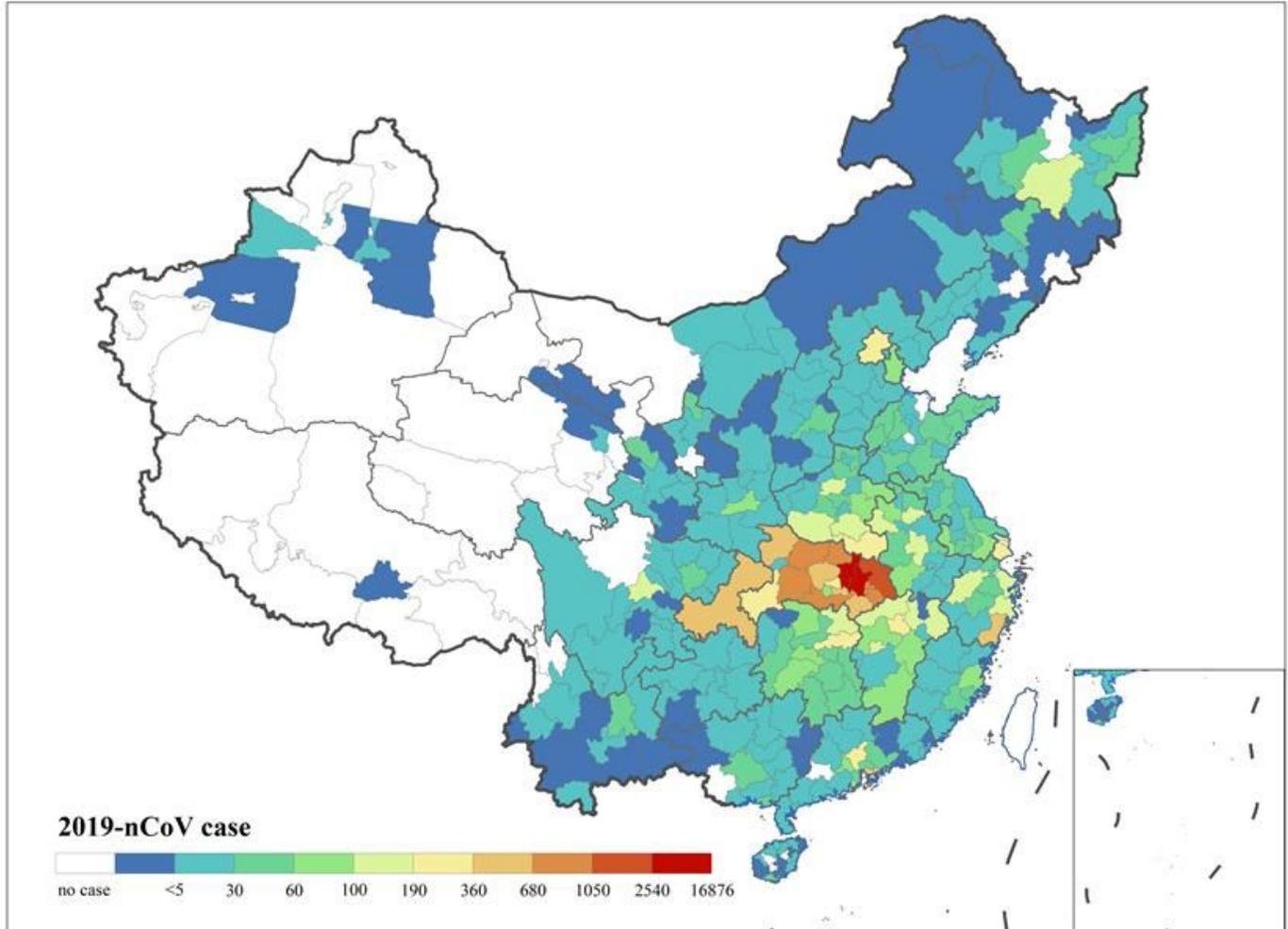
Fig. 1 Cumulative cases of COVID-19 over China on February 9, 2020

Fig. 2 Population mobility over Wuhan (a) and China (b and c)

Fig. 3 a, Model fitting to the cumulative cases of COVID-19 over China; b, instantaneous basic reproductive number ( $R_{0_t}$ ) of COVID-19 during Jan 1 to Feb 9, 2020

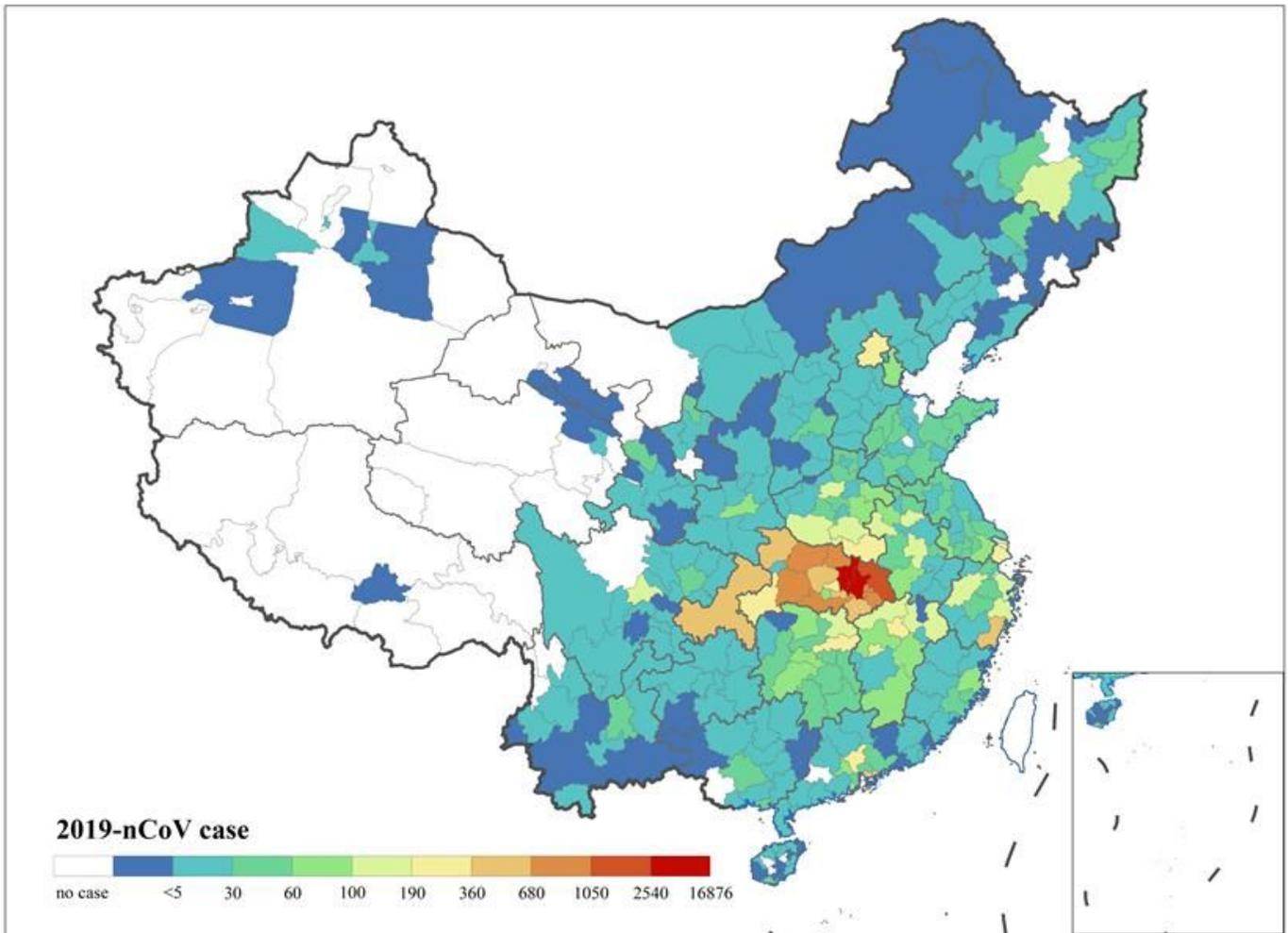
Fig. 4 Geographical distribution of change (quantified by percentage) of cumulative COVID-19 cases in comparison with baseline (the presence of both chunyun and quarantine) by February 9, 2020. a, scenario 1 (quarantine without chunyun); b, scenario 2 (chunyun without quarantine); c, scenario 3 (the absence of both chunyun and quarantine); d, location of urban agglomeration.

# Figures



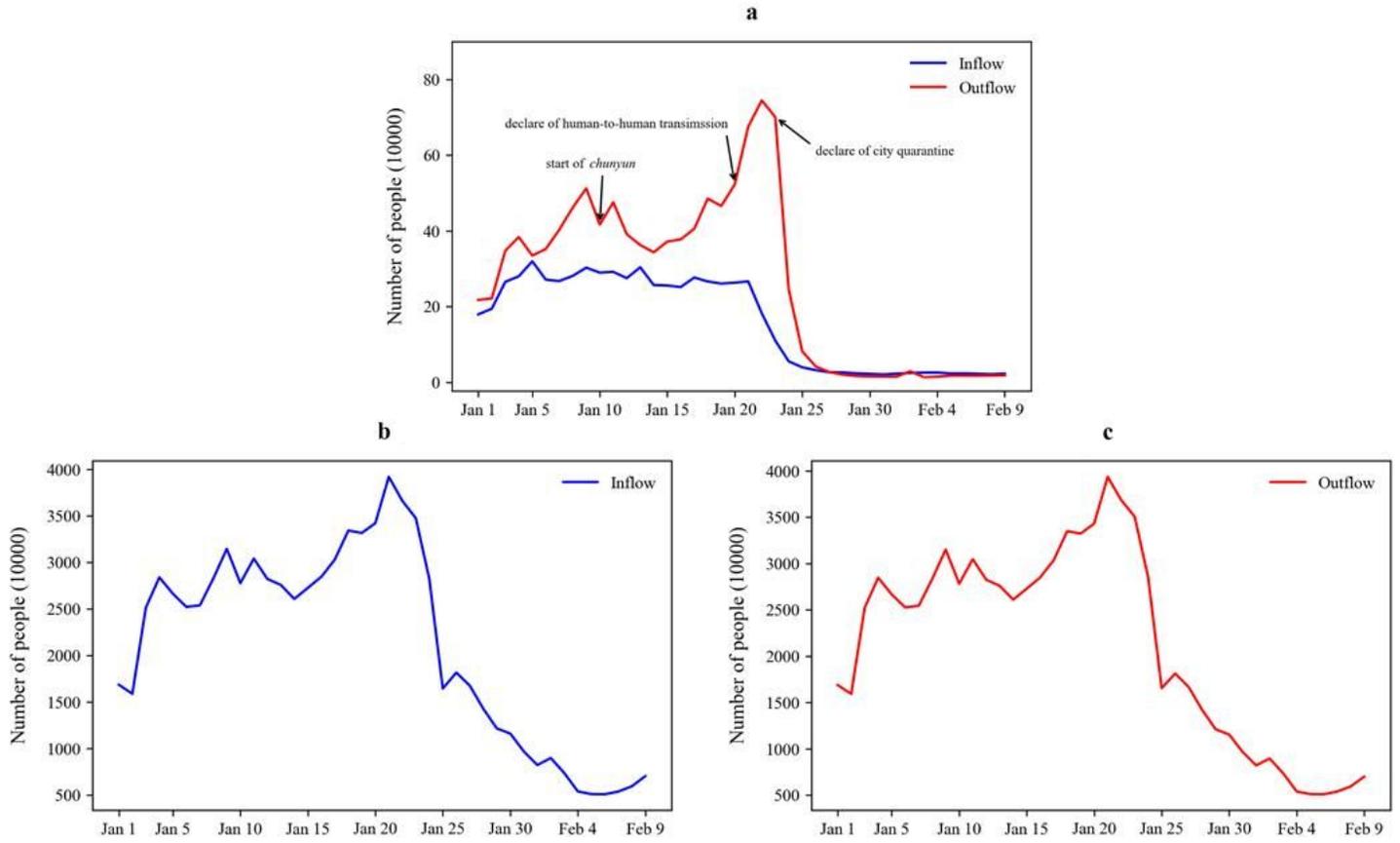
**Figure 1**

Cumulative cases of COVID-19 over China on February 9, 2020. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



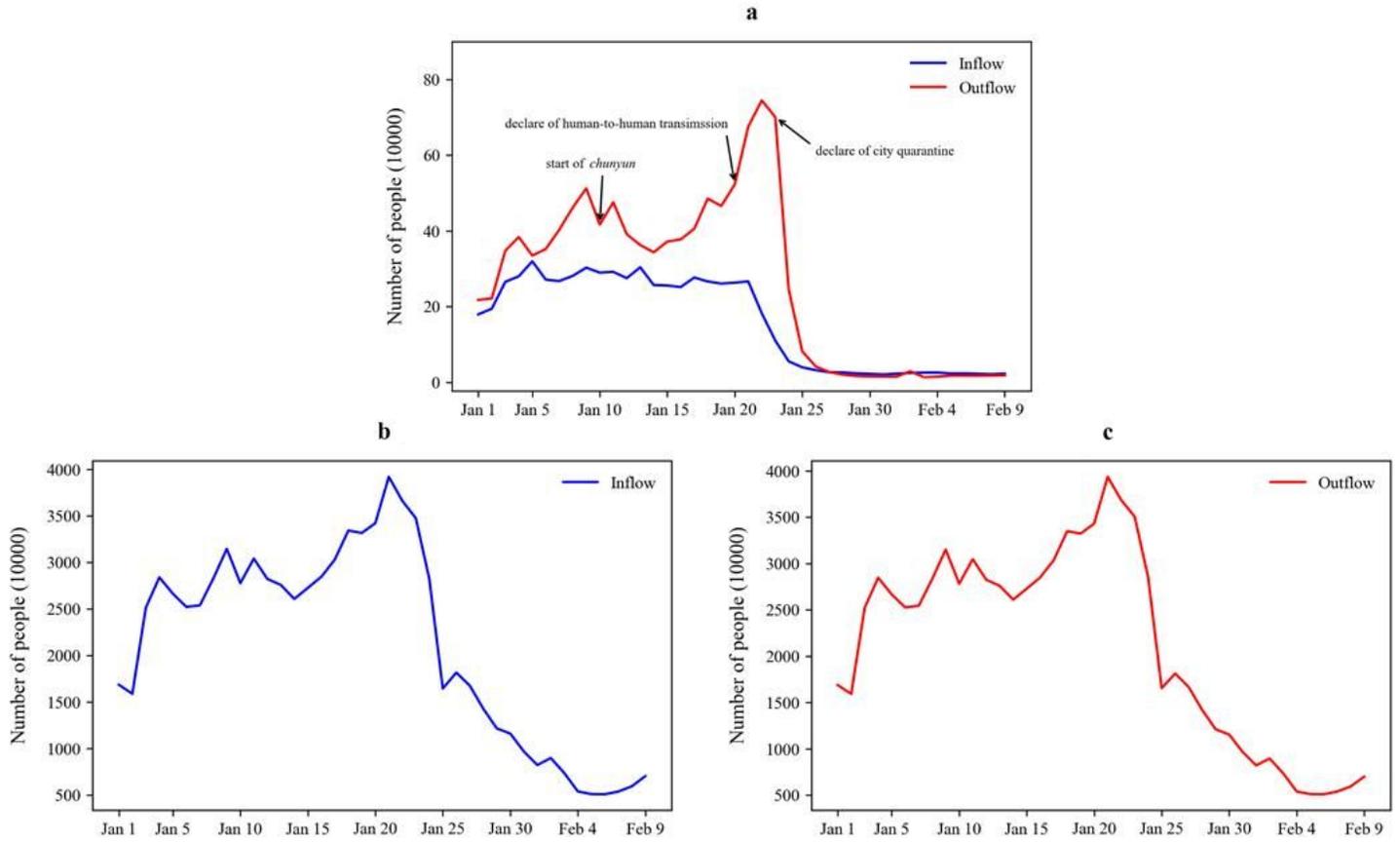
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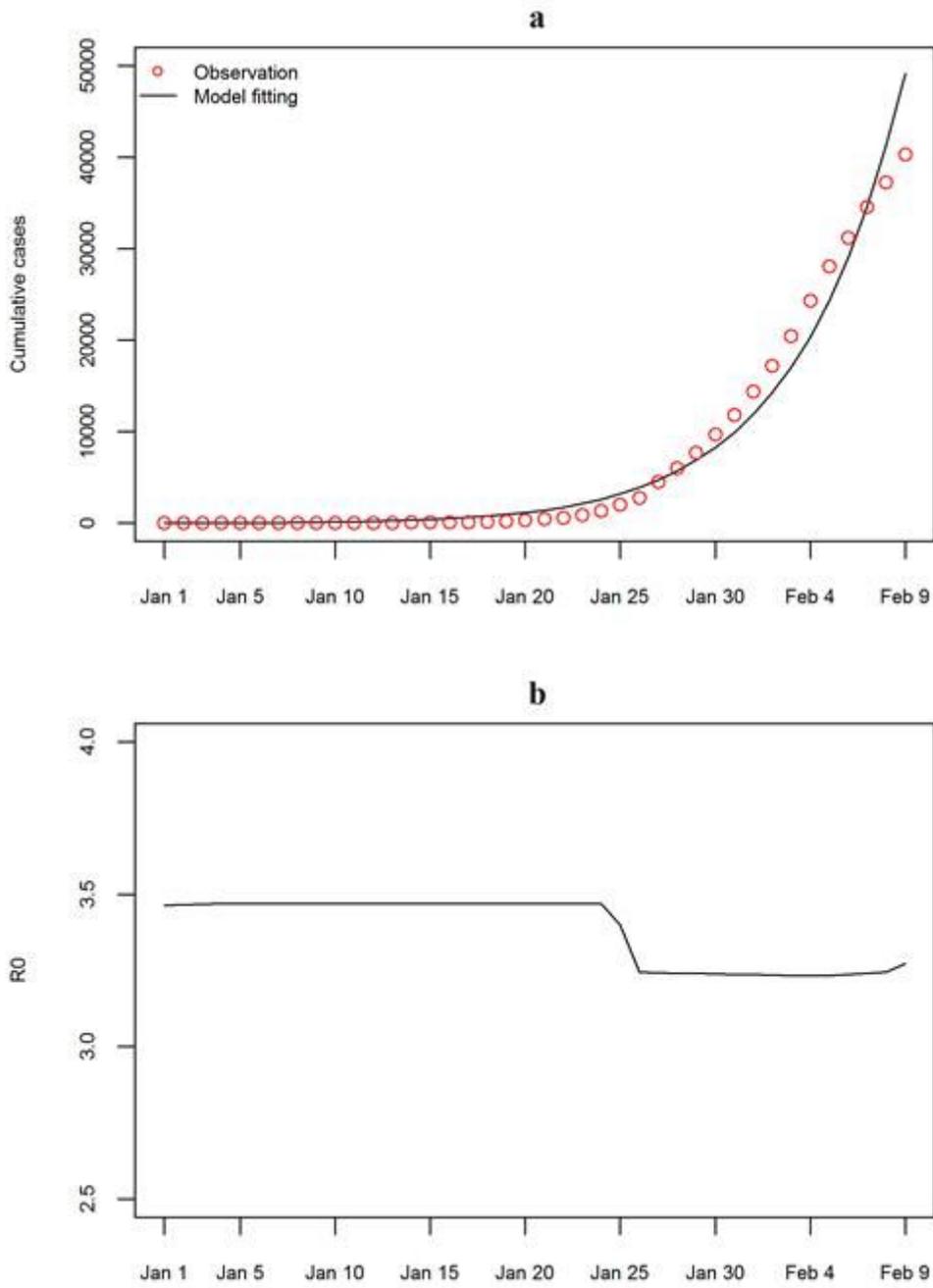
**Figure 2**

Population mobility over Wuhan (a) and China (b and c)



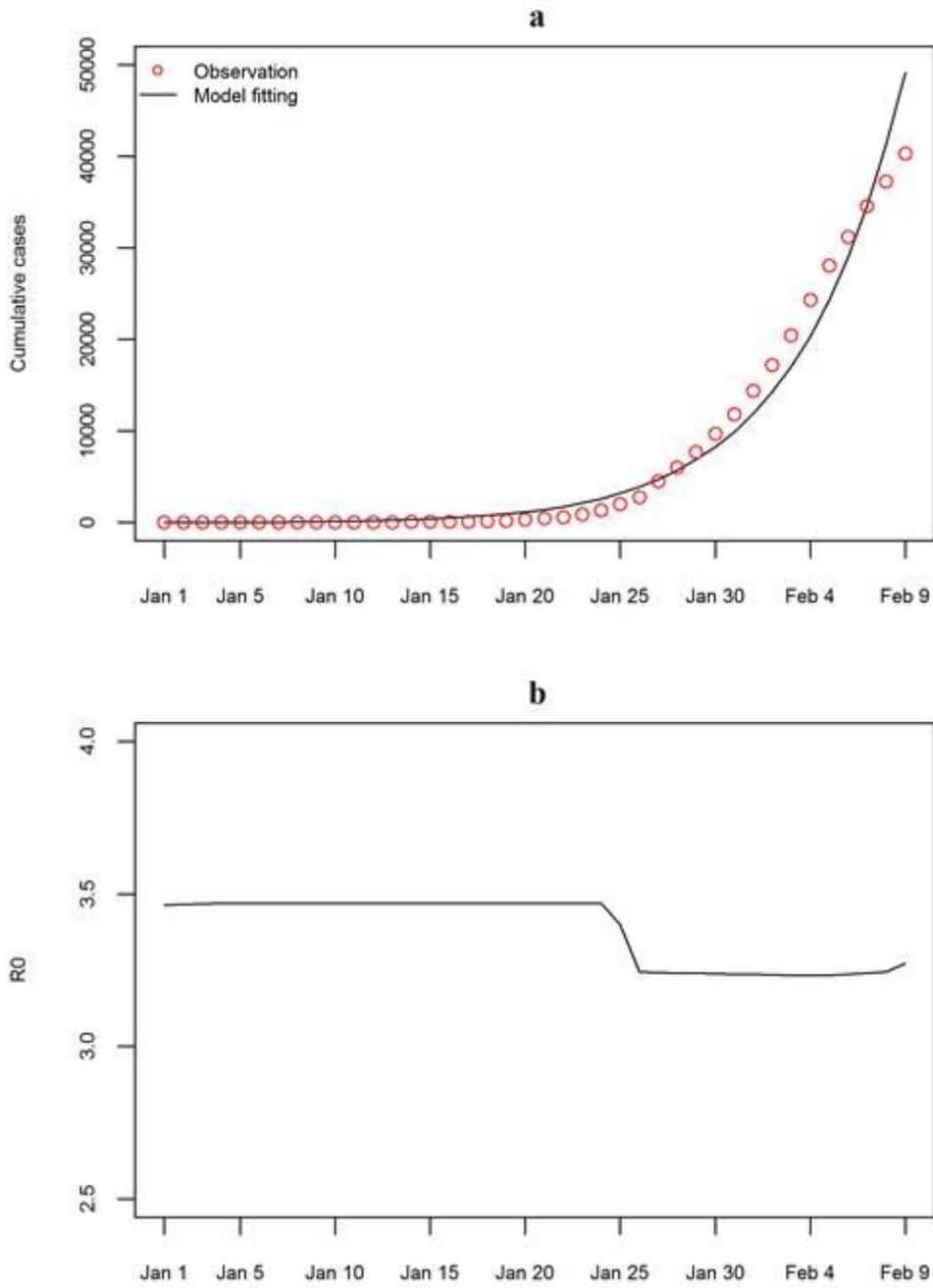
**Figure 2**

Population mobility over Wuhan (a) and China (b and c)



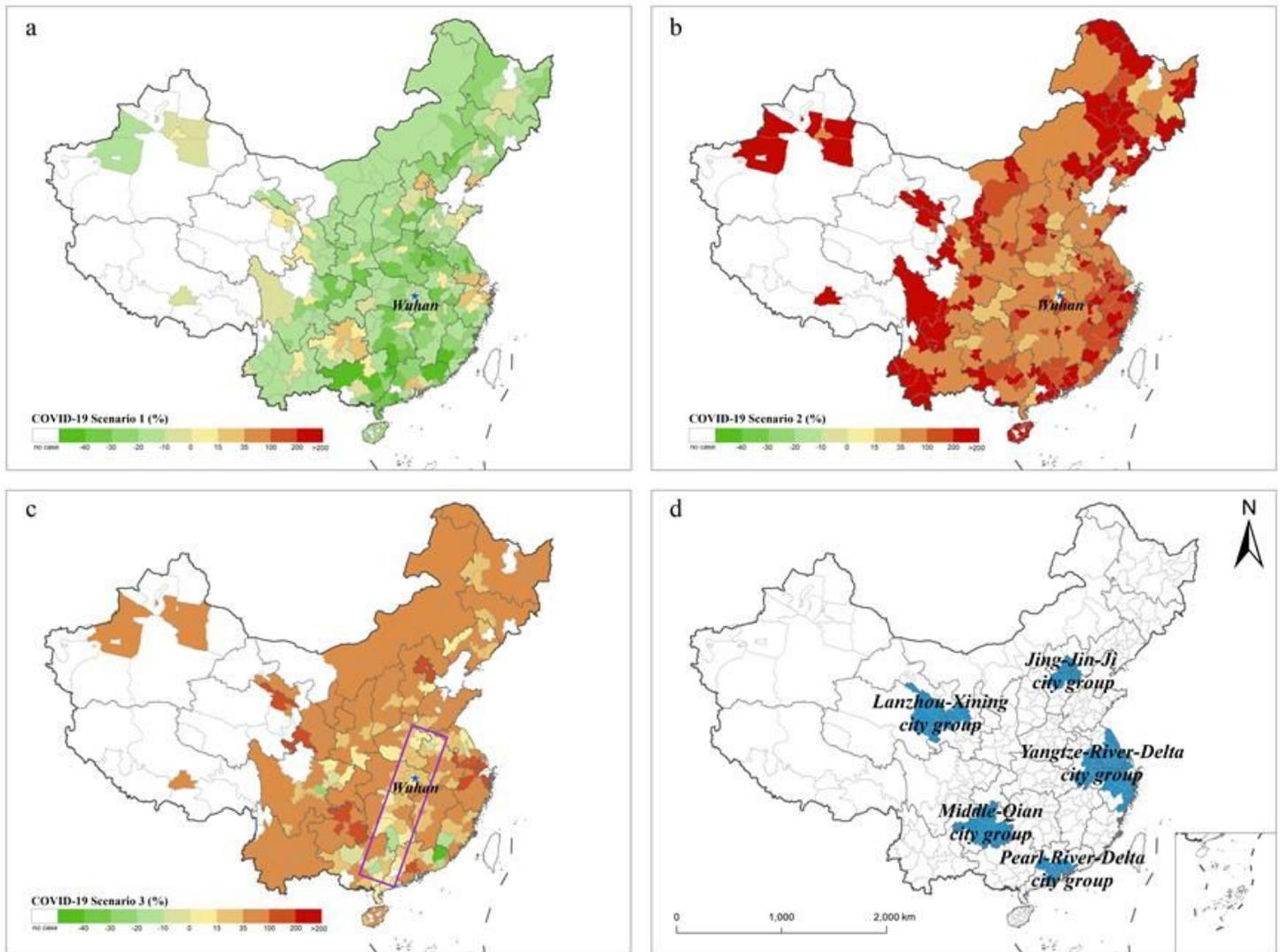
**Figure 3**

a, Model fitting to the cumulative cases of COVID-19 over China; b, instantaneous basic reproductive number ( $R_0$ ) of COVID-19 during Jan 1 to Feb 9, 2020



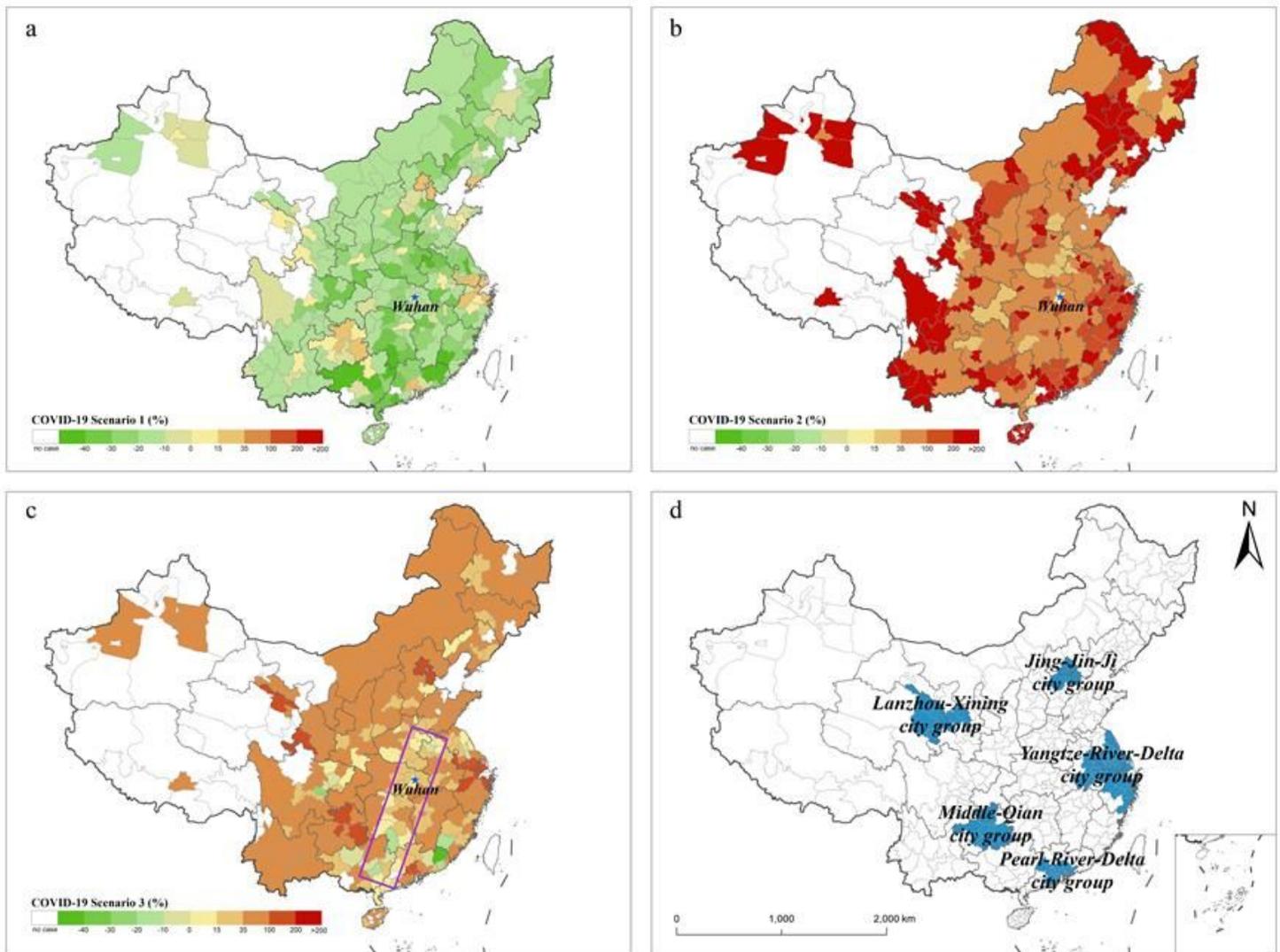
**Figure 3**

a, Model fitting to the cumulative cases of COVID-19 over China; b, instantaneous basic reproductive number ( $R_0$ ) of COVID-19 during Jan 1 to Feb 9, 2020



**Figure 4**

Geographical distribution of change (quantified by percentage) of cumulative COVID-19 cases in comparison with baseline (the presence of both chunyun and quarantine) by February 9, 2020. a, scenario 1 (quarantine without chunyun); b, scenario 2 (chunyun without quarantine); c, scenario 3 (the absence of both chunyun and quarantine); d, location of urban agglomeration. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



**Figure 4**

Geographical distribution of change (quantified by percentage) of cumulative COVID-19 cases in comparison with baseline (the presence of both chunyun and quarantine) by February 9, 2020. a, scenario 1 (quarantine without chunyun); b, scenario 2 (chunyun without quarantine); c, scenario 3 (the absence of both chunyun and quarantine); d, location of urban agglomeration. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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