Early evaluation of the Wuhan City travel restrictions in response to the 2019 novel coronavirus outbreak

Huaiyu Tian[1]*†, Yidan Li[1]*, Yonghong Liu[1]*, Moritz Kraemer[2,3,4]*, Bin Chen[5]*, Jun Cai[6]*, Bingying Li[1], Bo Xu[6], Qiqi Yang[1], Peng Yang[7], Yujun Cui[8], Yimeng Song[9], Pai Zheng[10], Quanyi Wang[7], Ottar Bjornstad[11,12], Ruifu Yang[8]†, Oliver G. Pybus[2]†, Bryan Grenfell[13,14]†, Christopher Dye[2]†

[1] State Key Laboratory of Remote Sensing Science, College of Global Change and Earth System Science, Beijing Normal University, Beijing, China
[2] Department of Zoology, University of Oxford, Oxford, UK
[3] Harvard Medical School, Harvard University, Boston, MA, USA
[4] Boston Children's Hospital, Boston, MA, USA
[5] Department of Land, Air and Water Resources, University of California Davis, CA, USA
[6] Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing, China
[7] Beijing Center for Disease Prevention and Control, Beijing, China
[8] State Key Laboratory of Pathogen and Biosecurity, Beijing Institute of Microbiology and Epidemiology, Beijing, China
[9] Department of Urban Planning and Design, The University of Hong Kong, Hong Kong
[10] Department of Occupational and Environmental Health Sciences, School of Public Health, Peking University, China
[11] Center for Infectious Disease Dynamics, Department of Biology, Pennsylvania State University, University Park, Pennsylvania, USA
[12] Department of Entomology, College of Agricultural Sciences, Pennsylvania State University, University Park, Pennsylvania, USA
[13] Division of International Epidemiology and Population Studies, Fogarty International Center, National Institutes of Health, Bethesda, MD, USA
[14] Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ, USA.

*These authors contributed equally to this work.
†Corresponding author. Email: tianhuaiyu@gmail.com (H.Y.T.); christopher.dye@zoo.ac.uk (C.D.); grenfell@princeton.edu (B.G.); oliver.pybus@zoo.ox.ac.uk (O.G.P.); ruifuyang@gmail.com (R.F.Y.);

Author contributions: H.T., P.Z., R.F.Y., O.G.P., B.G., C.D. designed the study. B.C. and Y.M.S. collected and processed the Tencent's LBS data. Y.H.L., B.Y.L., B.X., Q.Q.Y., P.Y., Y.J.C., Q.Y.W. collected the statistical data. H.Y.T. and J.C. conducted the analyses. M.K., O.B., R.F.Y., O.G.P., B.G., and C.D. edited the manuscript. H.T. and Y.D.L. wrote the manuscript. All authors read and approved the manuscript.

One Sentence Summary-40 characters

The travel shutdown delayed the dispersal of 2019-nCoV infection from Wuhan to other cities in China

Abstract

An ongoing outbreak of a novel coronavirus (2019-nCoV) was first reported in China and has spread worldwide. On January 23rd 2020 China shut down transit in and out of Wuhan, a major transport hub and conurbation of 11 million inhabitants, to contain the outbreak. By combining epidemiological and human mobility data we find that the travel ban slowed the dispersal of nCoV from Wuhan to other cities in China by 2.91 days (95% CI: 2.54-3.29). This delay provided time to establish and reinforce other control measures that are essential to halt the epidemic. The ongoing dissemination of 2019-nCoV provides an opportunity to examine how travel restrictions impede the spatial dispersal of an emerging infectious disease.

Key words: 2019 novel coronavirus; Wuhan; spatiotemporal transmission; China;

At end of December 2019, less than a month before Chinese New Year (Spring Festival), a cluster of pneumonia cases caused by an unknown pathogen were reported in Wuhan City, the largest transport hub in Central China. A novel coronavirus provisionally named 2019-nCoV [1] has since been identified as the etiological agent. Human-to-human transmission of 2019-nCoV has been confirmed [2,3] and by 28th January 2020 all provinces in China except Tibet had reported 2019-nCoV infections, and the population at risk of infection sin the country stands at >1.2 billion people. The increasing movement of people for Chinese New Year is expected to spread the virus further throughout cities in China and elsewhere. To prevent further dissemination of nCoV from its source, Wuhan prohibited all transport in and out of the city as of 10:00 on 23rd January 2020. To our knowledge, this is the largest quarantine/movement restriction in human history to prevent infectious disease spread. By 25th January, 30 provinces in China had raised their public health response level to the highest state of emergency (level-1). Here we present an analysis and quantification of the consequences and importance of the Wuhan travel prohibition on the ongoing spread of nCoV-2019 across China.

Assessment and measurement of the effects of large-scale interventions are crucial for the design of efficient responses against this and future epidemics. To this end, we collected all city-level case reports across China and noted the onset time of the first case of nCoV (arrival time) and the timing of the local response. We analyse these dates together with high-resolution data on human movement among cities in China, obtained from a large dataset of geolocated mobile phone records, spanning 2018, from the Tencent network. This dataset describes patterns of human mobility across China *before* nCoV was discovered.

In order to quantify the effect of the Wuhan travel shutdown on nCoV epidemic spread we analyzed the arrival time of nCoV from Wuhan to each city as a function of geographic distance (between city centers) and of human movement by air, train, and road (as recorded by Tencent's location-based services database). Spatial spread of 2019-nCoV (Fig. 1A) was rapid, with 262 cities reporting cases within only 28 days (for comparison, the 2009-H1N1pdm took 132 days to reach the current extent of nCoV-2019 in China). Most cities with early arrival dates were in southeast China and tend to exhibit greater mobility and higher population density. The rate at which cities first reported nCoV peaked on 23 January (the day of the Wuhan travel ban), with 60 reports, after which the spatial dissemination of nCoV slowed.

Table 1 shows that the Wuhan travel intervention significantly slowed disease spread. As expected, the time it took nCoV to arrive in each city increased with distance from Wuhan City, and decreased with passenger flow from Wuhan. Thus the epidemic arrived sooner in those cities that had larger population and had more travelers from Wuhan. On average, the Wuhan shutdown delayed the arrival time of nCoV in other cities by 2.91 days (95%CI: 2.54-3.29 days) (Fig. 1B). Our results show that >130 cities, covering more than half geographic area and population of China, benefited from this intervention (Fig. 1C).

Our analysis evaluates a unique intervention against an emerging infectious disease – the cessation of travel from a large, well-connected city in an industrialized country (Fig. 1D). We find that this intervention was effective in slowing nCoV invasion of new locations. However, other measures need to be reinforced to halt the ongoing epidemic. The Wuhan travel ban provided extra time to make progress on these responses. In addition to governmental responses, public awareness is critical for controlling the spread of this novel coronavirus. Early detection of nCoV cases in new locations in China is needed in the coming weeks and months to prevent other cities becoming major exporters of nCoV. China is better equipped than in the past to meet this challenge and a direct reporting system for notifiable epidemic diseases was established in the country after the 2003 SARS outbreak. However, the experience of nCoV in China suggests that urbanization and the development of modern transport systems increase the urgency of control measures against emerging infectious diseases, as demonstrated by the faster spatial spread of nCoV than H1N1pdm in China.

While emerging data from mainland China on nCoV epidemiology and virus genomics have generated important insights into the origin, transmissibility, and severity of this unfolding epidemic [1,4], many uncertainties remain [5] and important questions remain unanswered. For example the role of mobility network structure on disease diffusion is unknown, and the degree to which the delay in spatial spread (due to the Wuhan travel ban) will impact on the final size of the epidemic is unclear. Our analysis is only a preliminary step and further analyses and models are urgently required to evaluate the impact of quarantine and other intervention.

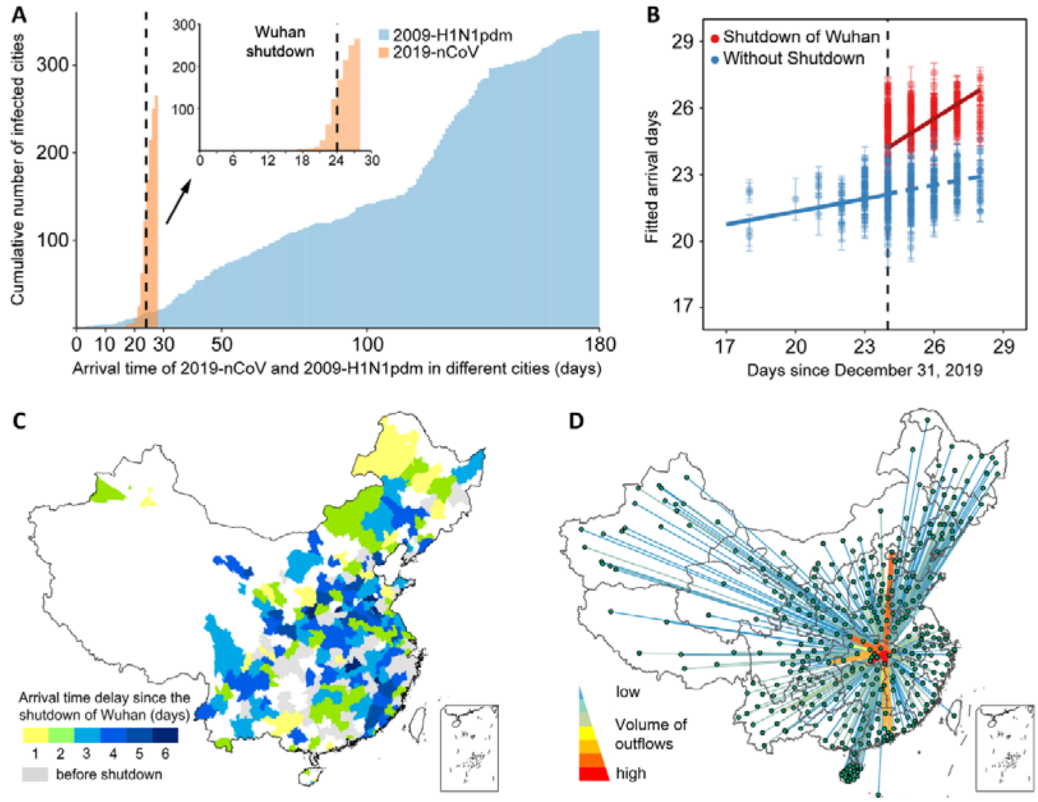

Fig.1 Spatial diffusion of 2019-nCoV in China. (A) Cumulative number of cities reporting disease. Arrival days, defined as the time interval (days) from the date of the first case in the first infected city to the date of the first case in each newly infected city, to characterize the inter-city transmission rate of 2019-nCoV and 2009-H1N1pdm, respectively. Dashed line shows the date of Wuhan shutdown. (B) Before (blue) and after (red) the intervention. The plotted line reports the fitted values from a regression of predicted arrival time (solid line, with shutdown of Wuhan in red and without in blue). Each observation (point) represents one city. Error bars give ±2 standard deviations. Dashed line shows the date of Wuhan shutdown. (C) Map of arrival time delayed by the shutdown of Wuhan. Colors represent the change in arrival time (days) after 23 January, 2020. The arrival time is estimated using the data before the shutdown of Wuhan. (D) Human movement outflows from Wuhan city to other cities in 2018. The warmer and thick lines denote higher volume of outflows (high-connectivity) while the cool and thin lines denote a lower volume of outflows (low-connectivity).

Table 1. Estimating the impact of the Wuhan travel ban on 2019-nCoV dissemination

Covariates	Coefficient	95% CI	P
(Intercept)	25.95	(23.43, 28.48)	<0.001
Longitude	-0.03	(-0.05, -0.01)	0.003
Latitude	0.03	(0.01, 0.06)	0.014
log10.Population	-0.70	(-1.12, -0.28)	0.001
log10.Total flow	-0.12	(-0.22, -0.02)	0.024
Shutdown intervention (days)	2.91	(2.54, 3.29)	<0.001

R^2/R^2 adjusted, 0.59 /0.58

Materials and Methods

Epidemiological and demographic data

We collected raw data from the daily official reports of the health commission of 34 provincial-level administrative units and 341 city-level units. Only laboratory-confirmed cases were used. We constructed a real-time database recording the date of the first reported case in all newly-infected cities with daily updates from 31 December 2019 to 28 January 2020. Population sizes for each city were collected from the China City Statistical Yearbook (http://olap.epsnet.com.cn/). The population sizes recorded for 2018 were used. We calculated the distance between Wuhan and each city reporting 2019-nCoV cases. The location of each city is geocoded by the latitude and longitude coordinates of the city center and the Euclidean distance between the two cities we calculated.

Human mobility data

Human movement can be observed directly from mobile phone data, through the location-based services (LBS) employed by popular Tencent applications, such as WeChat and QQ. Average movement outflows from Wuhan City to other cities, by air, train, and road, were calculated from the migration flows database (https://heat.qq.com/) over the entire 2018.

Statistical model

The association between distance, human movement, interventions and epidemic timing of 2019-nCoV was assessed with a regression analysis using a General Linear Model framework (GLM) with Gaussian family. The best model that emerged from this analysis:

$$Y_j = \alpha + \beta_1 \log 10\left(TotalFlow_j\right) + \beta_2 \log 10\left(Pop_j\right) + \beta_3 Lon_j + \beta_4 Lat_j + \beta_5 Shutdown_j \qquad [1]$$

where $TotalFlow_j$ represents the average passenger volume from Wuhan City to city j by airplane, train, and road. Pop_j is the population in city j. Lat_j and Lon_j represent *latitude* and *longitude* of city j. The dumb variable $shutdown_j$ is used to identify whether the arrival time of the newly infected city j is influenced by the shutdown of Wuhan, where 0 represents no-intervention and 1 represents intervention. The dependent variable Y_j is the arrival time of epidemic in city j, which measures the spatial spread of 2019-nCoV. β_i denote the regression coefficients.

Acknowledgements

We thank the many thousands of CDC staff and local health workers in China who collected data and continue to strive to contain 2019-nCoV in China and elsewhere. Funding for this study was provided by the Beijing Natural Science Foundation (JQ18025); Beijing Advanced Innovation Program for Land Surface Science; National Natural Science Foundation of China (81673234); Young Elite Scientist Sponsorship Program by CAST (YESS)(2018QNRC001); HT and OGP acknowledge support from the Oxford Martin School. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

References

1. Zhu N, Zhang D, Wang W, et al. A Novel Coronavirus from Patients with Pneumonia in China, 2019. New Eng J Med 2020:DOI: 10.1056/NEJMoa2001017.

2. Cai J, Xu B, Chan KKY, et al. Roles of Different Transport Modes in the Spatial Spread of the 2009 Influenza A (H1N1) Pandemic in Mainland China. Int J Environ Res Public Health 2019;16:222.

3. Wang C, Horby PW, Hayden FG, Gao GF. A novel coronavirus outbreak of global health concern. Lancet 2020:DOI:https://doi.org/10.1016/S0140-6736(20)30185-9.

4. Chan JFW, Yuan S, Kok KH, et al. A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission: a study of a family cluster. Lancet 2020:DOI:https://doi.org/10.1016/S0140-6736(20)30154-9.

5. Heymann DL. Data sharing and outbreaks: best practice exemplified. Lancet 2020:DOI:https://doi.org/10.1016/S0140-6736(20)30184-7.