Title: Risk of 2019 novel coronavirus importations throughout China prior to the Wuhan quarantine

Authors: Zhanwei Du[1,+], Lin Wang[2,+], Simon Cauchemez[2], Xiaoke Xu[3], Xianwen Wang[4], Benjamin J. Cowling[5], and Lauren Ancel Meyers[1,6*]

Affiliations:

1. The University of Texas at Austin, Austin, Texas 78712, The United States of America
2. Institut Pasteur, 28 rue du Dr Roux, Paris 75015, France
3. Dalian Minzu University, Dalian 116600, China.
4. Dalian University of Technology, Dalian 116024, China
5. The University of Hong Kong, Sassoon Rd 7, Hong Kong SAR, China
6. Santa Fe Institute, Santa Fe, New Mexico, The United States of America

Corresponding author: Lauren Ancel Meyers

Corresponding author email: laurenmeyers@austin.utexas.edu

[+] These first authors contributed equally to this article

Abstract

On January 23, 2020, China quarantined Wuhan to contain an emerging coronavirus (2019-nCoV). Here, we estimate the probability of 2019-nCoV importations from Wuhan to 369 cities throughout China before the quarantine. The expected risk exceeds 50% in 128 [95% CI 75 186] cities, including five large cities with no reported cases by January 26th.

Keywords: Wuhan, coronavirus, epidemiology, importation

A novel coronavirus (2019-nCoV) has emerged in Wuhan, China (1). On January 30, 2020, the World Health Organization declared it a public health emergency of international concern. As of January 31, 2020, there were 192 reported fatalities and 3215 laboratory-confirmed cases in Wuhan, 8576 additional cases spread across over 300 cities in mainland China, and 127 exported cases in 23 countries spanning Asia, Europe, North America, and Oceania. The rapid global expansion, rising fatalities, unknown animal reservoir, and evidence of person-to-person transmission potential (2) resemble the 2003 SARS epidemic and raise concerns about global spread.

On January 22nd, China announced a travel quarantine of Wuhan and, by January 30th, enlarged the radius to include 16 cities totalling 45 million people. At the time of the quarantine, China was already two weeks into the forty-day Spring Festival period, during which hundreds of millions of people travel to celebrate the Lunar New Year (3). Based on the timing of exported cases reported outside of China, we estimate that among cases that were infected by January 12th, only 9.82% (95% CrI: 2.58% - 59.44%) may have been confirmed in Wuhan by January 22nd. By limiting our estimate to infections occurring at least ten days before the quarantine, we are accounting for a 5-6 day incubation period followed by 4-5 days between symptom onset and case detection (2,4,5) (see Appendix for details). This lag between infection and detection (5) coupled with an overall low detection rate also suggests that newly infected cases that traveled out of Wuhan just prior to the quarantine may have remained infectious and undetected in dozens of Chinese cities for days to weeks. Moreover, these silent importations may have seeded sustained outbreaks that have not yet become apparent.

We estimated the probability of 2019-nCoV importations from Wuhan to cities throughout China before January 23rd using a simple model of exponential growth coupled with a stochastic model of human mobility among 370 Chinese cities (see Appendix). Given that 98% of all trips during this period are taken by train or car, our analysis of air, rail and road travel data yields more granular risk estimates than possible with air passenger data alone (6).

By fitting our epidemiological model to data on the first 19 cases reported outside of China, we estimate an epidemic doubling time of 7.38 (95% CrI: 5.58 - 8.92) days and a total cumulative infections in Wuhan by January 22nd of 11,213 (95% CrI: 1,590 - 57,387) (see Appendix for details), which are consistent with a recent epidemiological analysis of the first 425 patients confirmed in Wuhan (7). Based on these estimates of early epidemic growth, 128 Chinese cities have at least a 50% chance of having had 2019-nCoV case importations from Wuhan in the three weeks preceding the Wuhan quarantine (Figure 1). By January 26th, 107 of these high risk cities had reported cases and 21 had not, including five cities with importation probabilities exceeding 99% and populations over two million people: Bazhong, Fushun, Laibin, Ziyang, and Chuxiong. Under our lower bound estimate for the doubling time (5.58 days), 186 of the 369 cities lie above the 50% importation risk threshold.

This risk assessment identified several cities throughout China that were likely to have undetected cases of 2019-nCoV in the week following the quarantine, and suggests that early 2020 ground and rail travel seeded cases far beyond the Wuhan region quarantine. We note that these conclusions are based on several key assumptions. Our mobility model may be demographically biased by the user base of Tencent, a major social media company that hosts apps including WeChat (~1.13 billion active users in 2019) and QQ (~808 million active users in 2019) (8). Further, there is considerable uncertainty regarding the lag between infection and case detection. Our assumption of a 10-day lag is based on early estimates for the incubation period of 2019-nCoV (7) and prior estimates of the lag between symptom onset and detection for SARS (9). We expect that estimates for the doubling time and incidence of 2019-nCoV will improve as reconstructed linelists (6) and more granular epidemiological data become available (see Appendix Table S2 for sensitivity analysis). However, our key qualitative insights are likely robust to these uncertainties, including extensive pre-quarantine 2019-nCoV exportations throughout China and far greater case counts in Wuhan than reported prior to the quarantine.

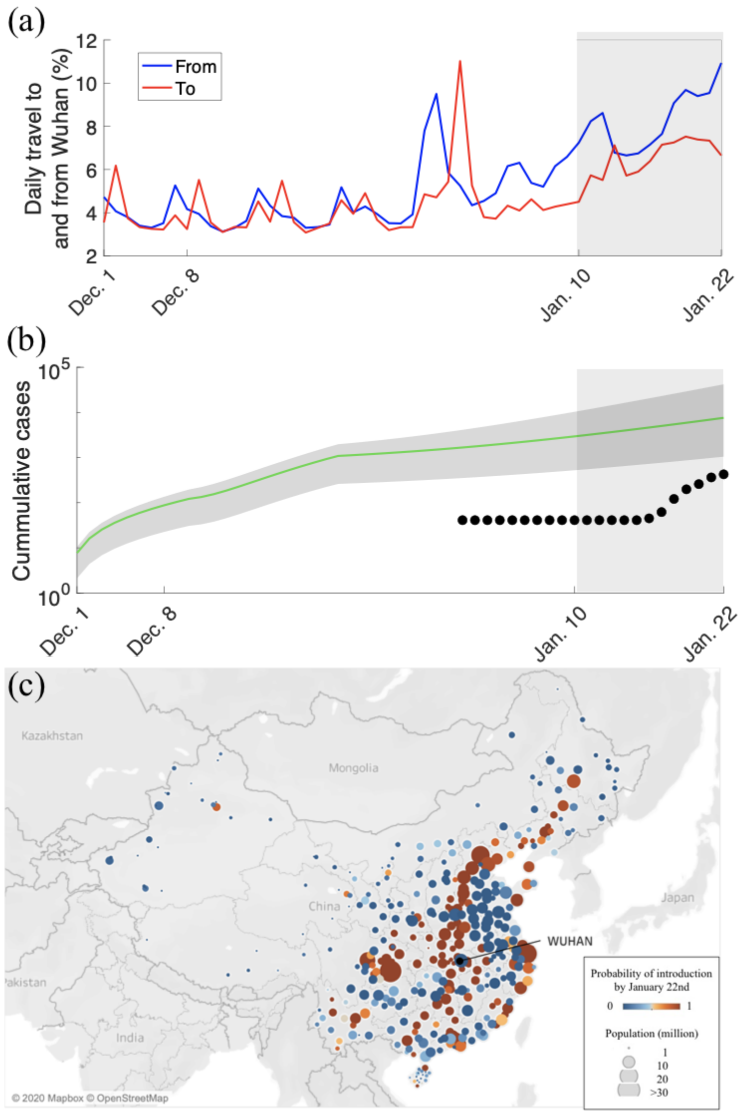

Figure 1. Risks of 2019-nCoV importation from Wuhan, China, prior to the Wuhan quarantine. (a) Daily travel volume to and from Wuhan, given as a proportion of the Wuhan population. (b) Estimated and reported daily prevalence in Wuhan. The green line and shading indicate model estimates of *cumulative* cases since December 1, 2019 with 95% credibility bounds, respectively, assuming an epidemic doubling time of 7.38 (95% CrI: 5.58 - 8.92). Black points are cumulative confirmed case counts from January 1, 2020, through January 22, 2020 (10). The shading on the right side of the top two panels indicates the start of Spring Festival season (January 10, 2020), a peak travel period throughout China. (c) The probability that at least one case infected in Wuhan traveled to cities throughout China by January 22nd, 2020. The 128 cities above and 241 cities below a risk threshold of 50% are indicated in orange and blue, respectively.

Supplementary Appendix

Data

We analyze the daily number of passengers traveling between Wuhan and 369 other cities in mainland China. We obtained mobility data from the location-based services (LBS) of Tencent (https://heat.qq.com/). Users permit Tencent to collect their real-time location information when they install apps (e.g., WeChat, QQ, and Tencent Map). From the geolocation of their users over time, Tencent reconstructed anonymized origin-destination mobility matrices by mode of transportation (air, road and train) between 370 cities in China (368 cities in mainland China and the Special Administrative Regions of Hong Kong and Macau). The data are anonymized and include 28 and 32 million trips to and from Wuhan, respectively, between December 3, 2016 to January 24, 2017. We estimate daily travel volume throughout the seven weeks preceding the Wuhan quarantine (December 1, 2019 - January 22, 2020) by aligning the dates of the Lunar New Year, resulting in a three day shift. To infer the number of new infections in Wuhan per day between December 1, 2019 and January 22, 2020, we use the mean daily number of passengers travelling to the top 27 foreign destinations from Wuhan in 2019 or 2018, which are provided by recent studies (11–13).

Model

We consider a simple hierarchical model to describe the dynamics of 2019-nCoV infections, detections and spread.

(1) Epidemiological model

Based on the epidemiological evidence of the first 425 patients of 2019-nCoV that were confirmed in Wuhan by January 22, 2020 (7), we make the following assumptions regarding the number of new cases $dI_w(t)$ infected in Wuhan per day *t*:

- The 2019-nCoV epidemic was growing exponentially between December 1, 2019 and January 22, 2020:

$$dI_w(t) = i_0 \cdot \exp(\lambda \cdot t),$$

  where i_0 denotes the number of initial cases on December 1, 2019 (14), and λ denotes the epidemic growth rate in Wuhan between December 1, 2019, and January 22, 2020.

- After infection, new cases were detected with an average delay of D = 10 days (15), which comprises an incubation period of 5-6 days (7,16–20) and a delay from symptom onset to detection of 4-5 days (4,21). During this 10-day interval, cases are labeled *infected*. Given the uncertainty in these estimates, we also performed the estimates by assuming either a shorter delay (D = 6 days) or a longer delay (D = 14 days) between infection and case detection (Table S2).

Our model can be improved by incorporating the probability distribution for the delay between infection and detection, as reconstructed linelists (22–25) and more granular epidemiological data is becoming available.

Under these assumptions, the number of infected cases at time t is given by

$$I_w(t) = \int_{u=t-D}^{t} dI_w(u)du,$$

and the prevalence of infected cases is given by

$$\xi(t) = \frac{I_w(t)}{N_w},$$

where N_w=11.08 million is the population size of Wuhan .

(2) Mobility model based on the Poisson process

We assume that visitors to Wuhan have the same daily risk of infection as residents of Wuhan.

Risk of exportation from infected residents: Under this assumption, the rate at which infected residents of Wuhan travel to city j on day t is $\gamma_{j,t} = \xi(t) \cdot W_{j,t}$, where $W_{j,t}$ is the number of Wuhan's local residents that travel to city j on day t.

Risk of exportation from infected travelers: Similarly, the rate at which travelers from city j get infected and return to their home city while still infected is $\psi_{j,t} = \xi(t) \cdot M_{j,t}$, where $M_{j,t}$ is the number of travelers from city j to Wuhan on day t. We make the simplifying assumption that newly infected visitors to Wuhan will return to their home city while still infectious.

Assuming that the introduction of cases from the epidemic origin, Wuhan, to each city j is essentially a non-homogeneous Poisson process (26–28), we calculate the probability of introducing at least one case from Wuhan to city j by day t using

$$1 - \exp\left[-\int_{u=t_0}^{t} (\gamma_{j,u} + \psi_{j,u})du\right],$$

where t_0 denotes the start time of the studied period (i.e., December 01, 2019).

Inference of epidemic parameters

We applied a likelihood-based method to estimate model parameters (i.e. the number of initial cases i_0 and epidemic growth rate λ) from the arrival times of the first 19 reported cases that travelled from Wuhan to 11 different cities outside of China, as of January 22, 2020 (Table S1).

All 19 cases were Wuhan residents. We aggregated all other cities without cases reported by January 22, 2020 into a single location (*j* = 0).

Let N_j denote the number of Wuhan resident cases detected in location *j* outside of China, and $x^-_{j,i}$ and $x^+_{j,i}$ denote the start and end time of the day in which the *i*-th resident case was detected in location *j*. Let $x_{j,0}$ denote the start of international surveillance for travelers from Wuhan (i.e. January 01, 2020 (21)) and *E* denote the end of the study period (i.e., January 22, 2020). As indicated above, the daily rate of infected residents of Wuhan arriving in location *j* at time *t* is $\gamma_{j,t}$. The log-likelihood for all the 19 cases reported outside of China by January 22, 2020, is given by:

$$\sum_{j=1}^{11}\sum_{i=1}^{N_j}\log\left(\int_{x^-_{j,i}}^{x^+_{j,i}}\gamma_{j,t}dt\right)-\frac{\sum_{j=0}^{11}W_{j,t}}{N_w}\cdot\frac{i_0}{\lambda^2}\cdot[\exp(\lambda\cdot E)-\exp(\lambda\cdot x_{j,0})$$
$$+\exp(\lambda\cdot(x_{j,0}-D))-\exp(\lambda\cdot(E-D))]$$

Parameter estimation

We directly estimate the number of initial cases i_0 on December 01, 2019, and the epidemic growth rate λ during the period between December 01, 2019 and January 22, 2020.
We infer these parameters in a Bayesian framework via Markov Chain Monte Carlo (MCMC) method with Hamiltonian Monte Carlo sampling. We use non-informative flat prior with $i_0 \in [0.1, 10]$ and $\lambda \in [0.01, 0.5]$. From these, we derive the doubling time of incident cases as $d_T = \log(2)/\lambda$ and the cumulative number of cases and of reported cases by January 22, 2020. We also derive the basic reproduction number, assuming a susceptible-exposed-infectious-recovery (SEIR) model for 2019-nCoV in which the incubation period is exponentially distributed with mean $L \in [3, 6]$ and the infectious period is also exponentially distributed with mean $Z \in [2, 7]$. The reproduction number is then given by $R_0 = (1+\lambda\cdot L)\cdot(1+\lambda\cdot Z)$.

We estimate the *case detection rate in Wuhan* by taking the ratio between the number of reported cases in Wuhan by January 22, 2020 and our estimates for the number of infections occurring at least 10 days prior (i.e., by January 12, 2020). We truncate our estimate 10 days before the quarantine to account for the estimated time elapsed between infection and case detection, assuming a 5-6 day incubation period (7,16–19,30) followed by 4-5 days between symptom onset and case detection (4,21). Given the uncertainty in these estimates, we also provide estimates assuming shorter and longer delays in the lag between infection and case reporting (Table S3).

We ran 10 chains in parallel. Our trace plot and diagnosis confirmed the convergence of MCMC chains with posterior median and 95% credible intervals (CrI) estimates as follows:

- Epidemic growth rate λ: 0.09394 (95% CrI: 0.0777 - 0.124), corresponding to an epidemic doubling time (of incident cases) of 7.38 (95% CrI: 5.58 - 8.92) days;
- Number of initial cases in Wuhan on December 1, 2019: 7.28 (95% CrI: 2.04 - 9.87);
- Basic reproduction number R_0: 1.96 (95% CrI: 1.52 - 2.83);
- Cumulative number of infections in Wuhan by January 22, 2020: 11,213 (95% CrI: 1,590 - 57,387);
- Case detection rate by January 22, 2020: 9.82% (95% CrI: 2.58% - 59.44%). This is the ratio between the 425 cases confirmed in Wuhan during this period (31) and our estimate that 4,326 (95% CrI: 715 - 16,479) cumulative infections occurred by January 12, 2020 (i.e., at least ten days prior to the quarantine to account for the typical lag between infection and case detection).

Supplementary Figures and Tables

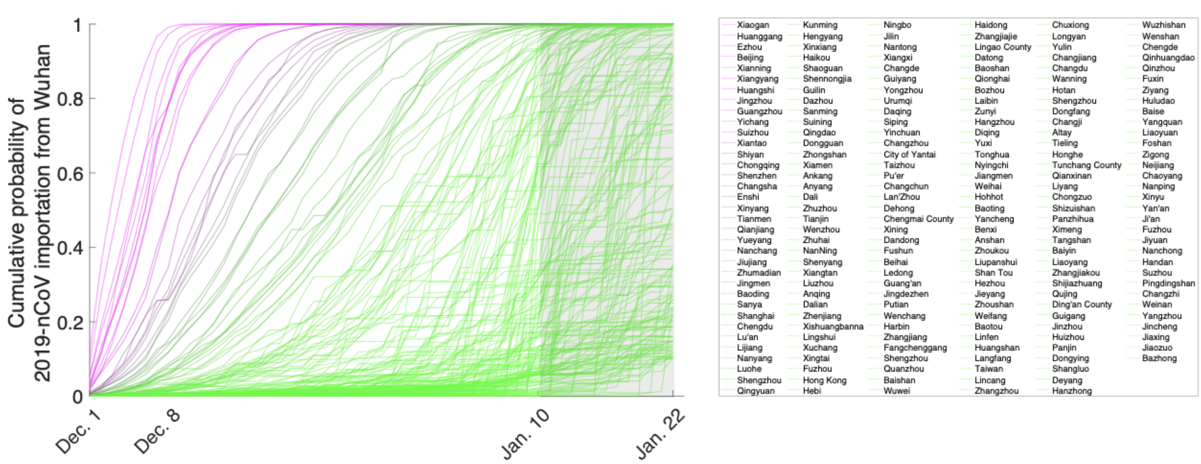

Figure S1. The risks of 2019-nCoV introductions from Wuhan to other cities in China prior to the January 23, 2020 quarantine of Wuhan. Lines indicate the probability that at least one individual infected in Wuhan has arrived in each city by the date indicated on the x-axis. The estimates are based on mobility data from December 3, 2016 to January 24, 2017 (corresponding to the Spring Festival period of December 1, 2019 to January 22, 2020). All 207 cities with an expected importation probability exceeding 10% by January 22 are shown.

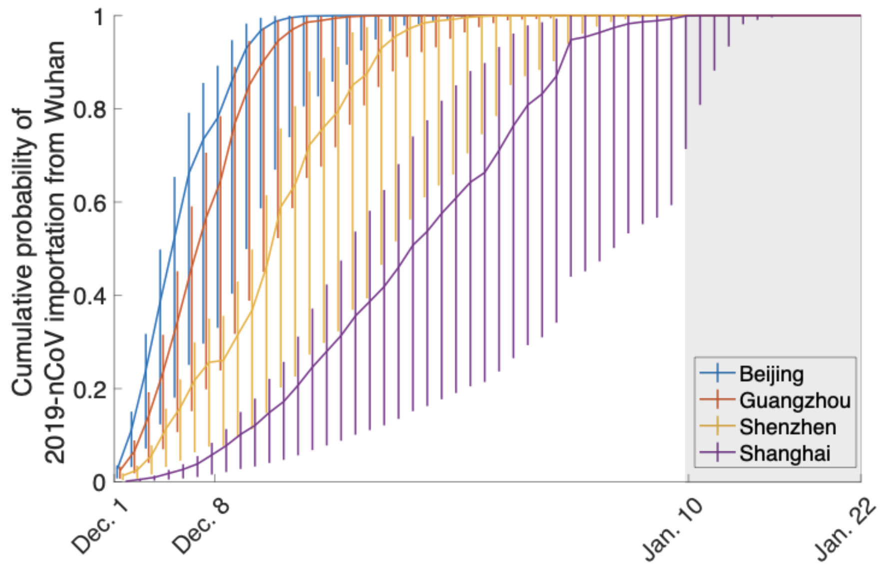

Figure S2. Uncertainty analysis with respect to the number of 2019-nCoV exposed infections (I_w) in Wuhan per day. Lines show the probabilities of at least one importation occurring from Wuhan into the four major metropolitan areas of Beijing, Guangzhou, Shenzhen and Shanghai between December 1, 2020 and January 22, 2020. Error bars indicate 95% credible intervals.

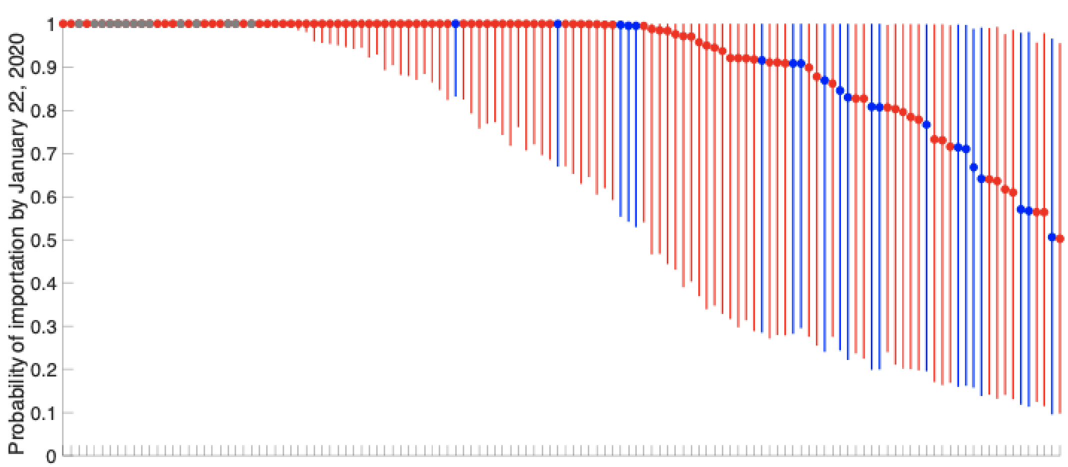

Figure S3. Risk of 2019-nCoV importations from Wuhan, China by January 23, 2020. All 128 cities in this graph have mean importation probabilities exceeding 50%. As of January 26th, 107 of these 128 have reported cases. Grey circles denote cities that have been included in the quarantine as of January 24th. Red and blue circles denote cities outside the quarantine with and without confirmed cases as of January 26th, respectively.

Table S1. Wuhan resident cases detected outside of China

Country	**City**	**Arrival time**
Thailand	Bangkok	2020/01/08
Thailand	Bangkok	2020/01/17
Thailand	Bangkok	2020/01/19
Thailand	Bangkok	2020/01/21
Thailand	Chiang Mai	2020/01/21
Nepal	Kathmandu	2020/01/09
Vietnam	Haoni	2020/01/13
USA	Chicago	2020/01/13
USA	Seattle	2020/01/15
Singapore		2020/01/21
Korea	Seoul	2020/01/19
Korea	Seoul	2020/01/22
Japan	Tokyo	2020/01/18
Japan	Tokyo	2020/01/19
Taiwan, China	Taipei	2020/01/20
Taiwan, China	Taipei	2020/01/21
Taiwan, China	Taipei	2020/01/21
Australia	Sydney	2020/01/18

Australia	Sydney	2020/01/20

Table S2. Sensitivity analysis for the delay between infection and case confirmation, assuming that cases were confirmed either 6 days, 10 days (baseline) or 14 days after infection.

Delay from infection to case reporting		Posterior median	95% CrI
D = 6 days	Epidemic doubling time (days)	6.80	5.28 - 8.02
	Initial number of cases on December 1, 2019 (i_0)	7.30	2.02 - 9.89
	Basic reproduction number R_0	2.07	1.58 - 2.96
	Cumulative cases by January 22, 2020	15,841	2,254 - 79,074
	Cumulative cases by January 16, 2020 (D = 6 days prior to January 22, 2020)	8,543	1,331 - 35,844
	Reporting rate through January 22, 2020	4.97%	1.19% - 31.93%
D = 10 days	Epidemic doubling time (days)	7.38	5.58 - 8.92
	Initial number of cases on December 1, 2019 (i_0)	7.28	2.04 - 9.87
	Basic reproduction number R_0	1.96	1.52 - 2.83
	Cumulative cases by January 22, 2020	11,213	1,590 - 57,387
	Cumulative cases by January 12, 2020 (D = 10 days prior to January 22, 2020)	4,326	715 - 16,479
	Reporting rate through January 22, 2020	9.82%	2.58% - 59.44%
D = 14 days	Epidemic doubling time (days)	7.77	5.72 - 9.58
	Initial number of cases on December 1, 2019 (i_0)	7.33	2.02 - 9.89
	Basic reproduction number R_0	1.90	1.48 - 2.76
	Cumulative cases by January 22, 2020	9,224	1,266 - 50,326
	Cumulative cases by January 8, 2020 (D = 14 days prior to January 22, 2020)	2,582	441 - 9,130
	Reporting rate through January 22, 2020	16.46%	4.65% - 96.37%

Table S3. Mobility between Wuhan and 369 Chinese cities from December 3, 2016 to January 24, 2017, derived from Tencent user geolocation data. Cities are sorted according to the overall travel volume to and from Wuhan. These data are also available at https://github.com/ZhanweiDU/2019nCov.git.

ID	City	Total trips	From Wuhan	To Wuhan	Population (millions in 2016)
1	Xiaogan	9646286	5333682	4312604	4.9
2	Huanggang	7786732	4436928	3349804	6.32
3	Xianning	3987334	2149524	1837810	2.53
4	Beijing	3921153	1956195	1964958	1.07
5	Ezhou	3858883	1508938	2349945	21.73
6	Jingzhou	3439123	2216479	1222644	5.7
7	Xiangyang	3160473	1959413	1201060	5.64
8	Huangshi	2787922	1521685	1266237	2.47
9	Guangzhou	2555286	705205	1850081	14.04
10	Yichang	2266974	1420349	846625	4.13
11	Shenzhen	1675478	188316	1487162	11.91
12	Suizhou	1536742	934564	602178	2.2
13	Xiantao	1492596	856578	636018	1.15
14	Shiyan	1252190	897666	354524	3.41
15	Chongqing	1177096	720442	456654	30.48
16	Enshi	869910	610937	258973	4.56
17	Tianmen	716794	447408	269386	1.29
18	Changsha	644273	318784	325489	7.65

19	Shanghai	571458	72150	499308	24.2
20	Xinyang	564841	338180	226661	6.44
21	Qianjiang	489747	288200	201547	0.96
22	Jingmen	408465	269703	138762	2.9
23	Yueyang	352512	185672	166840	5.68
24	Zhumadian	316181	214425	101756	6.99
25	Nanchang	301903	123239	178664	5.37
26	Jiujiang	229539	106873	122666	4.85
27	Baoding	205124	126334	78790	11.63
28	Nanyang	173653	127666	45987	10.07
29	Luohe	155591	32443	123148	7.29
30	Hengyang	153337	103153	50184	2.64
31	Sanya	151726	29147	122579	0.75
32	Dazhou	121669	33825	87844	1.29
33	Lijiang	120983	120983	0	5.6
34	Qingyuan	117242	53698	63544	4.77
35	Luan	116218	35704	80514	3.85
36	Chengdu	113938	50532	63406	15.92
37	Kunming	108452	46613	61839	6.73
38	Guilin	102565	18274	84291	4.71
39	Shijiazhuang	100723	92078	8645	5.01
40	Shengzhou	94847	11483	83364	2.96
41	Shaoguan	93102	70128	22974	10.78

42	Ankang	81065	81065	0	2.66
43	Xinxiang	73246	54707	18539	5.74
44	Shennongjia	66818	37240	29578	0.08
45	Suining	64847	43223	21624	3.3
46	Shenyang	64774	30848	33926	2.24
47	Haikou	64258	33663	30595	8.29
48	Hanzhong	58082	58074	8	3.45
49	Anyang	57825	38146	19679	5.13
50	Liuzhou	57672	44125	13547	8.26
51	Handan	56640	43180	13460	3.96
52	Dongguan	53890	27321	26569	4.02
53	Fuzhou	52175	42872	9303	9.49
54	Zhuzhou	50264	11069	39195	7.57
55	NanNing	48697	36007	12690	2.55
56	Xuchang	47505	33242	14263	7.06
57	Sanming	44627	33727	10900	7.32
58	Xingtai	44397	41839	2558	4.38
59	Anqing	41590	17398	24192	4.61
60	Yongzhou	40710	17524	23186	3.56
61	Xiamen	40530	40530	0	5.47
62	Dali	40039	14993	25046	3.92
63	Nanchong	36803	21919	14884	9.2
64	Qingdao	33778	33764	14	6.4

65	Pingdingshan	30833	25945	4888	4.98
66	Tieling	30807	13535	17272	2.65
67	Putian	30488	21972	8516	2.89
68	Zhuhai	30263	20698	9565	1.68
69	Jiaozuo	29609	15634	13975	9.18
70	Wenzhou	26455	26445	10	3.55
71	Guangan	25597	24288	1309	3.26
72	Nantong	22577	7753	14824	7.3
73	Langfang	22283	7879	14404	2.84
74	Suzhou	21900	7301	14599	4.62
75	Huludao	21343	12018	9325	15.62
76	Zhenjiang	21092	17499	3593	3.18
77	Jincheng	20366	0	20366	10.65
78	Tianjin	19114	18044	1070	2.55
79	Xiangtan	18326	18318	8	2.32
80	Shangluo	17782	3610	14172	3.2
81	Siping	17190	6147	11043	6.99
82	Zhongshan	17181	14989	2192	3.23
83	Dalian	17033	16740	293	2.37
84	Beihai	16142	6120	10022	1.64
85	Changzhi	14729	14729	0	3.44
86	Bazhong	14705	14705	0	3.31
87	Hebi	14173	9224	4949	1.61

88	Urumqi	11767	6146	5621	1.17
89	Hong Kong	11453	5823	5630	7.45
90	Zhoukou	11066	11066	0	8.82
91	Xishuangbanna	10893	10058	835	3.52
92	Weinan	10110	5991	4119	10.98
93	Harbin	9964	5272	4692	7.88
94	Panjin	9743	9743	0	5.37
95	Changchun	9379	6040	3339	7.51
96	Ningbo	9200	8652	548	2.2
97	Laibin	9130	8398	732	1.44
98	Yuxi	8616	2506	6110	2.64
99	City of Yantai	8223	4390	3833	7.06
100	Xiangxi	7895	5513	2382	2.38
101	Tangshan	7604	7152	452	7.84
102	Hangzhou	7477	1792	5685	0.36
103	Nanping	7414	5460	1954	2.33
104	Liyang	7291	7291	0	3.63
105	Xining	7274	7274	0	2.04
106	Zigong	7112	797	6315	9.19
107	Hezhou	7053	3854	3199	2.66
108	Lingshui	6789	3364	3425	2.08
109	Fushun	6761	6761	0	4.71
110	Yinchuan	6705	6681	24	2.78

111	Jinzhou	6576	5816	760	2.07
112	Chengde	6335	3781	2554	2.62
113	Yangzhou	6269	2362	3907	6.08
114	Taizhou	6131	4946	1185	5.84
115	Puer	6034	5919	115	3.06
116	Changzhou	5937	5786	151	3.53
117	Yangquan	5840	5840	0	4.49
118	Qujing	5396	5041	355	6.08
119	Anshan	5313	5269	44	1.4
120	Changde	5308	4044	1264	3.61
121	Jian	5183	3207	1976	4.7
122	Zhangjiajie	5157	4112	1045	1.53
123	Quanzhou	5127	1705	3422	8.58
124	Wuwei	5126	0	5126	4.92
125	Liaoyang	4965	4679	286	1.82
126	Ledong	4807	3014	1793	0.53
127	Guiyang	4554	4255	299	1.84
128	Qinhuangdao	4550	4439	111	4.54
129	Jiangmen	4154	2226	1928	3.71
130	Ziyang	4147	3883	264	3.09
131	Diqing	3971	3933	38	2.54
132	Neijiang	3971	1916	2055	1.65
133	Panzhihua	3933	1123	2810	0.41

134	Shengzhou	3871	1134	2737	0.96
135	LanZhou	3645	1735	1910	1.29
136	Foshan	3536	2197	1339	1.24
137	Zhangjiang	3526	3493	33	3.75
138	Baoshan	3422	3157	265	7.46
139	Dandong	3377	1426	1951	7.27
140	Deyang	3287	1321	1966	0.51
141	Shengzhou	3278	2905	373	3.09
142	Qionghai	3155	2974	181	4.31
143	Jingdezhen	3136	2165	971	2.41
144	Chuxiong	3135	2962	173	3.52
145	Dehong	3114	1767	1347	2.61
146	Hohhot	2967	1486	1481	0.93
147	Zunyi	2966	2419	547	2.74
148	Datong	2881	1914	967	3.42
149	Fangchenggang	2775	1544	1231	6.23
150	Baotou	2464	1031	1433	4.24
151	Chengmai County	2421	1062	1359	1.45
152	Benxi	2378	1947	431	2.86
153	Liupanshui	2301	905	1396	0.59
154	Daqing	2226	959	1267	1.38
155	Haidong	2166	1886	280	1.71

156	Jilin	2087	1124	963	0.56
157	Huangshan	2086	589	1497	2.91
158	Wenchang	2085	1349	736	0.52
159	Honghe	2062	715	1347	2.76
160	Fuzhou	2031	1014	1017	0.48
161	Zhangjiakou	1960	1262	698	4.68
162	Yiyang	1901	927	974	2.52
163	Bozhou	1855	790	1065	7.24
164	Lingao County	1847	786	1061	5.58
165	Dongying	1846	0	1846	4
166	Dongfang	1845	1743	102	4.43
167	Yancheng	1820	1365	455	4.43
168	Huizhou	1794	1624	170	2.13
169	Shan Tou	1792	749	1043	2.17
170	Weihai	1765	940	825	6.09
171	Jieyang	1759	894	865	0.44
172	Wanning	1745	1694	51	4.78
173	Jiyuan	1744	677	1067	2.82
174	Lincang	1741	792	949	0.57
175	Tonghua	1555	1461	94	0.73
176	Xinyu	1535	508	1027	2.63
177	Longyan	1535	953	582	0.23
178	Changjiang	1474	796	678	1.16

179	Baishan	1471	0	1471	1.17
180	Qianxinan	1448	260	1188	0.2
181	Zhoushan	1372	930	442	9.36
182	Changji	1371	514	857	2.84
183	Nyingchi	1347	674	673	1.2
184	Chongzuo	1326	744	582	1.6
185	Weifang	1203	777	426	2.07
186	Hotan	1181	369	812	0.68
187	Linfen	1168	460	708	0.17
188	Qitaihe	1146	671	475	2.14
189	Baoting	1118	793	325	4.46
190	Fuxin	1090	489	601	0.27
191	Changdu	1087	569	518	0.87
192	Tunchang County	1065	823	242	1.78
193	Tongren	980	335	645	5.05
194	Matsubara	967	461	506	5.76
195	Dingan County	945	802	143	0.6
196	Zhangzhou	930	330	600	2.78
197	Yulin	923	553	370	1.84
198	Qinzhou	902	491	411	3.24
199	Haibei	900	577	323	0.28
200	Shihezi	893	893	0	3.14

201	Karamay	882	494	388	0.29
202	Wuzhishan	824	446	378	0.62
203	Chaoyang	806	429	377	0.11
204	Altay	779	192	587	1.18
205	Baise	760	392	368	0.42
206	Aral	750	704	46	2.95
207	Ganzi	722	402	320	3.62
208	Wuzhong	720	377	343	0.54
209	Jixi	711	365	346	0.33
210	Shizuishan	705	481	224	1.35
211	Nujiang	705	429	276	1.39
212	Yingkou	704	348	356	2.44
213	Shuangyashan	690	446	244	2.89
214	Ordos	672	481	191	0.8
215	Ningde	630	458	172	2.06
216	Haixi	629	458	171	1
217	Chifeng	609	185	424	1.46
218	Tower	585	313	272	3.27
219	Chaozhou	585	253	332	0.48
220	Yanan	583	262	321	1.72
221	Baiyin	570	230	340	2.65
222	Hainan	566	458	108	0.52
223	Liaoyuan	552	487	65	4.31

224	Leshan	522	379	143	2.1
225	Ximeng	520	492	28	2.25
226	Yanbian	512	352	160	1.18
227	Wenshan	500	282	218	3.62
228	Yili	496	419	77	4.62
229	Xian	494	212	282	0.34
230	Rizhao	485	326	159	2.9
231	Guigang	480	172	308	6.12
232	Xingan League	479	287	192	0.23
233	Maoming	475	261	214	4.33
234	Baisha	455	249	206	1.77
235	Meishan	451	262	189	0.12
236	Shuozhou	450	450	0	8.83
237	Shannan	446	219	227	3
238	Qiongzhong	439	91	348	1.6
239	Mianyang	434	332	102	2.11
240	Wulanchabu	423	275	148	1.68
241	Alxa League	398	288	110	4.81
242	Bayannaoer	397	288	109	0.72
243	Bazhou	389	286	103	0.25
244	Wuhai	373	202	171	2.46
245	Qiannan	369	230	139	0.56
246	Wujiaqu	367	201	166	3.12

247	Shigatse	357	103	254	0.09
248	Yichun	357	216	141	1.28
249	Jiaxing	348	299	49	3.26
250	Zhengzhou	332	29	303	1.1
251	Aksu	326	178	148	0.1
252	Tongliao	324	217	107	1.15
253	Kashgar	321	45	276	4.61
254	Qingyang	319	83	236	9.72
255	Zhongwei	318	142	176	0.27
256	Bijie	309	177	132	4.21
257	Cangzhou	306	253	53	1.91
258	Zibo	303	187	116	7.51
259	Nagqu	294	256	38	2.24
260	Huangnan	265	227	38	6.64
261	Chizhou	261	206	55	2.33
262	Tumshuk	241	134	107	4.69
263	Anshun	235	144	91	1.12
264	Jiuquan	233	231	2	0.48
265	Ali	227	128	99	2.79
266	Jinchang	220	107	113	3.5
267	Turpan	214	191	23	1.44
268	Dingxi	210	32	178	0.17
269	Hechi	204	96	108	2.53

270	Yangjiang	203	147	56	0.47
271	Hulunbeir	199	84	115	4.82
272	Yaan	197	157	40	0.63
273	Pingliang	196	151	45	2.53
274	Jinzhong	187	18	169	3.35
275	Yulin	184	130	54	1.54
276	Qiqihar	175	129	46	2.1
277	Linxia	175	167	8	0.2
278	Binzhou	158	45	113	0.44
279	Golow	155	72	83	3.38
280	Zhaoqing	146	69	77	3.89
281	Liangshan	143	112	31	4.08
282	Lishui	143	52	91	1.22
283	Daxinganling	143	85	58	5.05
284	Jiayuguan	142	58	84	2.03
285	Zhangye	130	55	75	0.25
286	Suihua	127	41	86	2.17
287	Taiyuan	121	81	40	5.21
288	Guyuan	119	99	20	1.22
289	Heyuan	110	37	73	3.08
290	Luliang	110	59	51	2.63
291	Wuzhou	108	61	47	3.02
292	White	107	11	96	0.62

293	Yingtan	107	11	96	3.85
294	Tianshui	103	0	103	4.34
295	Yunfu	101	82	19	3.32
296	Heihe	99	38	61	1.64
297	Laiwu	94	87	7	0.41
298	Pingxiang	94	94	0	3.78
299	Jiamusi	94	65	29	1.38
300	Shaoxing	93	44	49	2.48
301	Tongchuan	88	9	79	1.16
302	Kezhou	81	60	21	0.85
303	Xinzhou	76	0	76	1.91
304	Dezhou	76	38	38	2.36
305	Shanwei	76	44	32	4.99
306	Jinhua	72	19	53	3.16
307	Yushu	70	43	27	3.04
308	Baoji	68	24	44	5.79
309	Lhasa	63	0	63	5.52
310	Yuncheng	61	41	20	4.36
311	Mudanjiang	61	31	30	0.61
312	Meizhou	60	60	0	0.6
313	Hami	59	42	17	5.31
314	Gannan	51	26	25	0.71
315	Liaocheng	36	0	36	6.04

316	Zhaotong	35	35	0	5.48
317	Jinan	30	30	0	7.23
318	Hegang	28	19	9	2.64
319	Guangyuan	26	19	7	1.04
320	Luoyang	21	0	21	6.8
321	Tongling	18	0	18	1.6
322	Shengzhou	17	0	17	4.04
323	Huzhou	16	0	16	2.98
324	Shengzhou	13	7	6	5.1
325	Taian	11	0	11	5.64
326	Shengzhou	10	0	10	2.16
327	Huaibei	10	0	10	2.21
328	Zaozhuang	9	0	9	3.92
329	Huainan	8	0	8	4.92
330	Xuancheng	7	0	7	3.33
331	Hengshui	7	0	7	3.46
332	Longnan	6	0	6	2.6
333	Hefei	6	0	6	4.45
334	Huaihua	6	0	6	2.6
335	Ganzhou	0	0	0	7.87
336	Shuanghe	0	0	0	8.59
337	Maanshan	0	0	0	0.05
338	Bengbu	0	0	0	2.78

339	Bazhou	0	0	0	0.94
340	Linyi	0	0	0	10.44
341	Beitun	0	0	0	0.08
342	Yibin	0	0	0	4.51
343	Shangqiu	0	0	0	7.28
344	Taizhou	0	0	0	4.65
345	Shaoyang	0	0	0	7.32
346	Heze	0	0	0	8.62
347	Yichun	0	0	0	5.53
348	Wuxi	0	0	0	6.53
349	Fuyang	0	0	0	7.99
350	Yutian County, Xinjiang	0	0	0	0.22
351	Xuzhou	0	0	0	8.71
352	Suqian	0	0	0	4.88
353	Hetian County, Xinjiang	0	0	0	0.28
354	Huaian	0	0	0	4.89
355	Kaifeng	0	0	0	4.55
356	Nanjing	0	0	0	8.27
357	Loudi	0	0	0	3.89
358	Suzhou	0	0	0	5.6
359	Macau	0	0	0	0.63
360	Jining	0	0	0	8.35

361	Qiandongnan	0	0	0	3.51
362	Kokodala	0	0	0	0.08
363	Xianyang	0	0	0	4.99
364	Lianyungang	0	0	0	4.5
365	Gejiu, Yunnan	0	0	0	0.47
366	Shangrao	0	0	0	6.75
367	Moyu County, Xinjiang	0	0	0	0.53
368	Wuhu	0	0	0	3.67
369	Sanmenxia	0	0	0	2.26

Acknowledgements

We thank Henrik Salje, Dongsheng Luo, Bo Xu, Cécile Tran Kiem, Dong Xun, and Lanfang Hu for helpful discussions. We acknowledge the financial support from NIH (U01 GM087719), the Investissement d'Avenir program, the Laboratoire d'Excellence Integrative Biology of Emerging Infectious Diseases program (Grant ANR-10-LABX-62-IBEID), European Union V.E.O project, the Open Fund of Key Laboratory of Urban Land Resources Monitoring and Simulation, Ministry of Land and Resources (KF-2019-04-034), and the National Natural Science Foundation of China (61773091).

Code for estimating epidemiological parameters and probabilities of case introductions, as well as aggregate mobility data are available at: https://github.com/linwangidd/2019nCoV_EID.

Aggregate data are also available in Appendix Table S3. Additional code and data requests should be addressed to Lauren Ancel Meyers (laurenmeyers@austin.utexas.edu, 512-471-4950).

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