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

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Abstract

On January 23, 2020, China enacted a travel quarantine of Wuhan and nearby cities to curb the geographic expansion of a novel coronavirus (2019-nCoV). Here, we use ground, rail and air travel data to estimate the probability that 2019-nCoV cases were imported from Wuhan to 370 cities throughout China in the three weeks prior to the quarantine. Based on an estimated R_0 of 2.56 [95% CI: 2.09, 2.78], we find that the probability of a pre-quarantine introduction exceeds 50% in 131 [95% CI 72, 232] cities, including six cities with populations over two million people with no reported cases as of January 27th.

Keywords: Wuhan, coronavirus, epidemiology, importation

A novel coronavirus (2019-nCoV) has emerged in Wuhan, China (1). As of January 26, 2020 there were 56 reported fatalities and 618 laboratory-confirmed cases in Wuhan, 1463 additional cases spread across 217 cities in Mainland China, and 56 exported cases in 14 countries spanning Asia, Europe and North America. The rapid global expansion, rising fatalities, unknown animal reservoir, and evidence of person-to-person transmission potential (2,3) resemble the 2003 SARS epidemic and raise concerns about global spread.

On January 22nd, China announced a travel quarantine of Wuhan and, by January 26th, enlarged the radius to include 14 cities totalling 41 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 (4). Based on the timing of exported cases reported outside of China, we estimate that only 2.4% of 2019-nCoV cases may have been detected in Wuhan by January 22, 2020 (see Appendix for details). The low detection rate coupled with an average lag of 10 days between infection and detection (5,6) suggests that newly infected cases that traveled out of Wuhan just prior to the quarantine may still be infectious and undetected in dozens of Chinese cities. Moreover, these silent importations may have already seeded sustained outbreaks that are not yet 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 (7).

By fitting our epidemiological model to data on the first 19 cases reported outside of China, we estimate an R_0 of 2.56 (95% CI: 2.09, 2.78) and 15,364 (95% CI: 1,447, 196,313) cumulative infections in Wuhan up to January 22nd (see Appendix for details). Based on these rates of early epidemic growth, 131 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, 109 of these high risk cities had reported cases and 22 had not, including five cities with importation probabilities exceeding 99% and populations over two million people: Bazhong, Fushun, Laibin, Ziyang, and Chuxiong. Under our upper bound estimate for epidemic growth (R_0 =2.78), 232 of the 370 cities lie above the 50% importation risk threshold.

This risk assessment identified several cities throughout China likely to be harboring yet undetected cases of 2019-nCoV and suggests that early 2020 ground and rail travel seeded cases far beyond the Wuhan region quarantine.

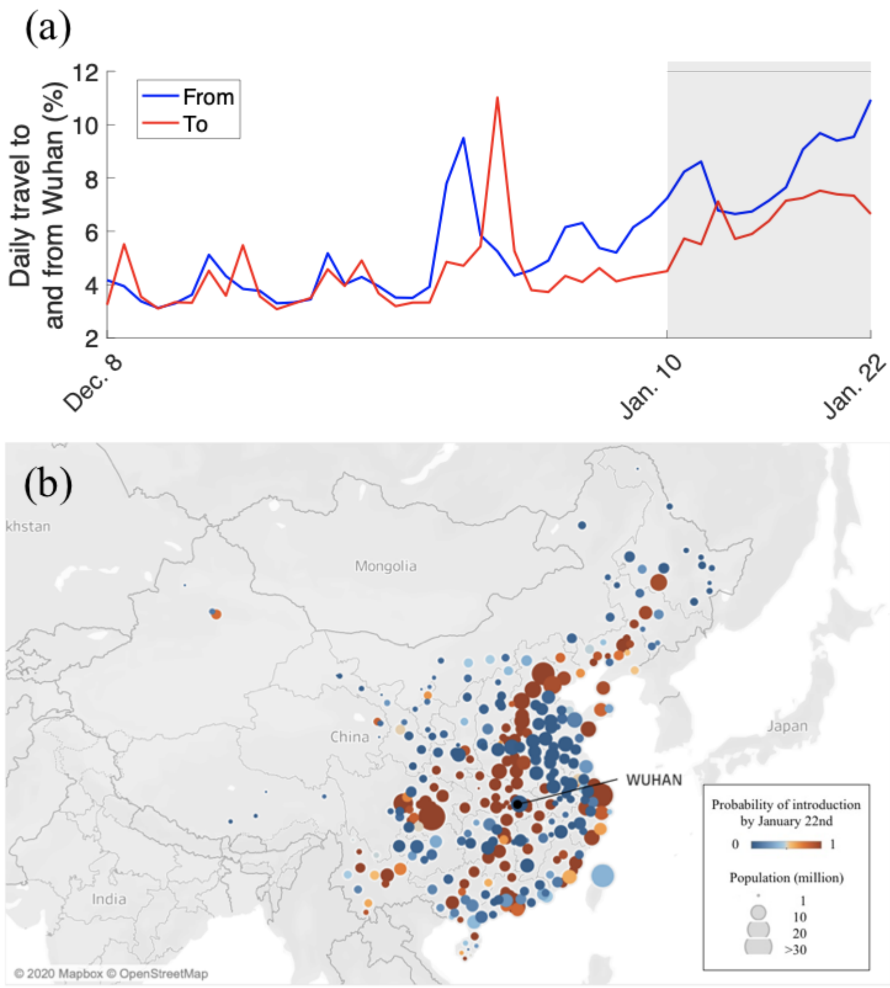

Figure 1. Risks of 2019-nCoV importation from Wuhan, China prior to the Wuhan quarantine. (a) Daily travel volume to and from Wuhan, given as a proportion of the Wuhan population. Shading indicates the start of Spring Festival season (January 10, 2020), a peak travel period throughout China. (b) The probability that at least one case infected in Wuhan traveled to cities throughout China by January 22nd, 2020. The 131 cities above and 239 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 370 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. The data are anonymized and include 25 and 29 million trips to and from Wuhan, respectively, between December 10, 2017 to January 24, 2018. We estimate daily travel volume throughout the three weeks preceding the Wuhan quarantine (December 8, 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 8, 2019, and January 22, 2020, we use the mean daily number of passengers travelling to the top 20 foreign destination from Wuhan between January 1 and March 31, 2018, which are provided in a recent study (8).

Model

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

(1) Epidemiological model

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 08, 2019 and January 22, 2020:
$$dI_w(t) = i_{w,0} \cdot \exp(\gamma_w \cdot t),$$
where $i_{w,0}$ denotes the number of initial cases on December 08, 2019, and γ_w denotes the epidemic growth rate between December 08, 2019, and January 22, 2020.

- After infection, new cases were detected with a delay of $D = 10$ days (9), which comprises an incubation period of 5-6 days (10,11) and a delay from symptom onset to detection of 4-5 days (12,13). During this 10-day interval, cases are labeled *infectious*.

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

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

and the prevalence of infectious 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 $\gamma_{t,j} = \xi(t) \cdot W_{t,j}$, where $W_{t,j}$ 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 $\lambda_{t,j} = \xi(t) \cdot M_{t,j}$, where $M_{t,j}$ 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 (14–16), we can calculate the probability of introducing at least one case from Wuhan to city *j* by day *t* using $1 - \exp(\gamma_{t,j} + \lambda_{t,j})$.

Inference of epidemic parameters

We applied a likelihood-based method to estimate our model parameters, including the number of initial cases $i_{w,0}$ and the epidemic growth rate γ_w, from the arrival times of the 19 reported case importation from Wuhan to cities outside of China, as of January 22, 2020. All 19 cases were Wuhan residents (See Table S1). 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 $x_{j,i}$ denote the arrival time of the *i*-th resident case detected in location *j*. Let $x_{j,0}$ and *E* denote the start and end of the study period, respectively. As indicated above, the daily rate of infected residents of Wuhan arriving in location *j* at time *t* is $\gamma_{t,j}$. The likelihood of the process describing these arrivals is given by

$$L_R = \prod_{j=0}^{11} \exp(-\int_{x_{j,N_j}}^{E} \gamma_{t,j} dt) \prod_{i=1}^{N_j} \gamma_{x_{j,i},j} \exp(-\int_{x_{j,i-1}}^{x_{j,i}} \gamma_{t,j} dt)$$

Log-Likelihood

The log-likelihood for all the 19 cases detected outside of China is given by:

$$\sum_{j=1}^{11}\sum_{i=1}^{N_j}\log(\gamma_{x_{j,i},j})-\frac{\sum_{j=0}^{11}W_j}{N_w}\cdot\frac{i_0}{r_w^2}[\exp(r_w\cdot E)-D\cdot r_w-\exp(r_w\cdot(E-D))]$$

Parameter estimation

We estimate the epidemic parameters in a Bayesian framework via Markov Chain Monte Carlo (MCMC) method with Hamiltonian Monte Carlo sampling and non-informative flat prior. We ran 10 chains in parallel. Trace plot and diagnosis confirmed the convergence of MCMC chains with posterior median and 95% CrI estimates as follows:

- Basic reproductive number R_0: 2.56 [2.09, 2.78]
- Number of cases in Wuhan on December 8, 2019: 1.86 [1.03, 9.77]
- Epidemic growth rate γ_w: 0.156 [0.11, 0.178]
- Cumulative number of infections in Wuhan by January 22, 2020: 15,364 [1,447, 196,313]
- Cumulative number of detected cases by January 22, 2020: 3,225 [476, 33,004]. Note that China reported only 363 cases during this period (17), suggesting a case detection rate of 2.4%.

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

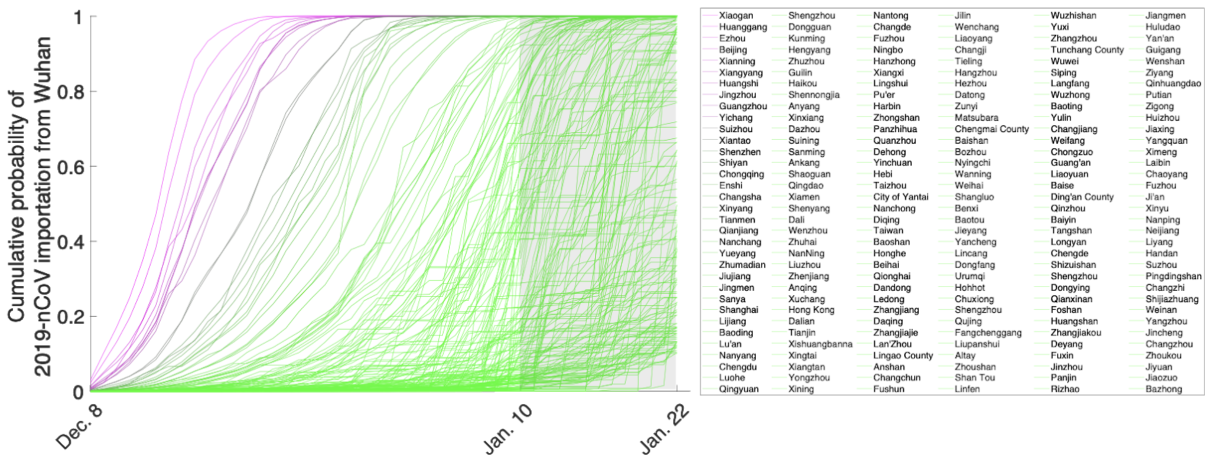

Figure S1. The risk of 2019-nCoV introductions from Wuhan to other cities in China prior to the January 23, 2020 quarantine of Wuhan. Lines indicate probabilities that at least one individual infected in Wuhan has arrived in the given city by the date indicated on the x-axis. The estimates are based on mobility data from December 10, 2017 to January 24, 2018 (corresponding to the Spring Festival period of December 8, 2019 to January 22, 2020). All 204 cities with an expected importation probability exceeding 10% by January 22 are shown.

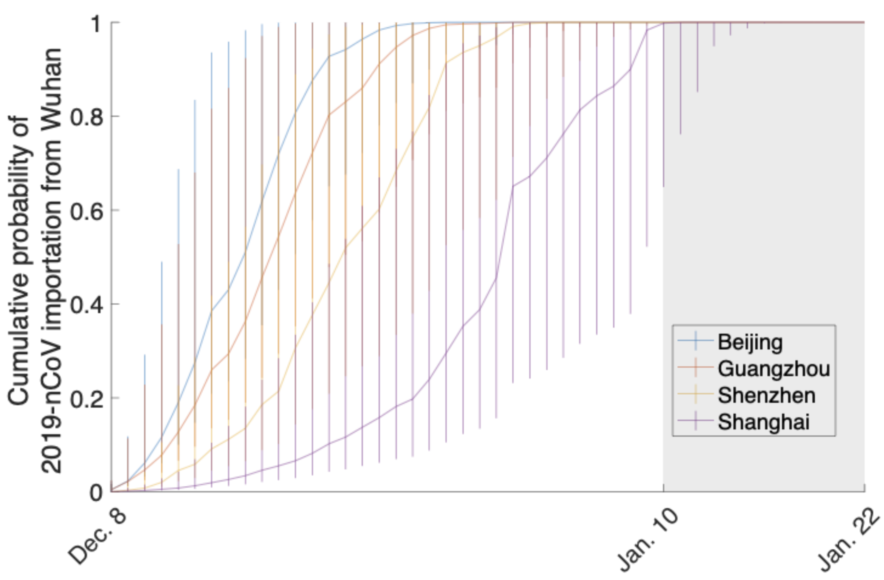

Figure S2. Uncertainty analysis with respect to the number of 2019-nCoV exposed infections (I_w) in Wuhan per day. Lines show the probability of at least one importation occurring from Wuhan into Beijing, Guangzhou, Shenzhen and Shanghai between December 8, 2020 and January 22, 2020. Error bars indicate 95% credible intervals.

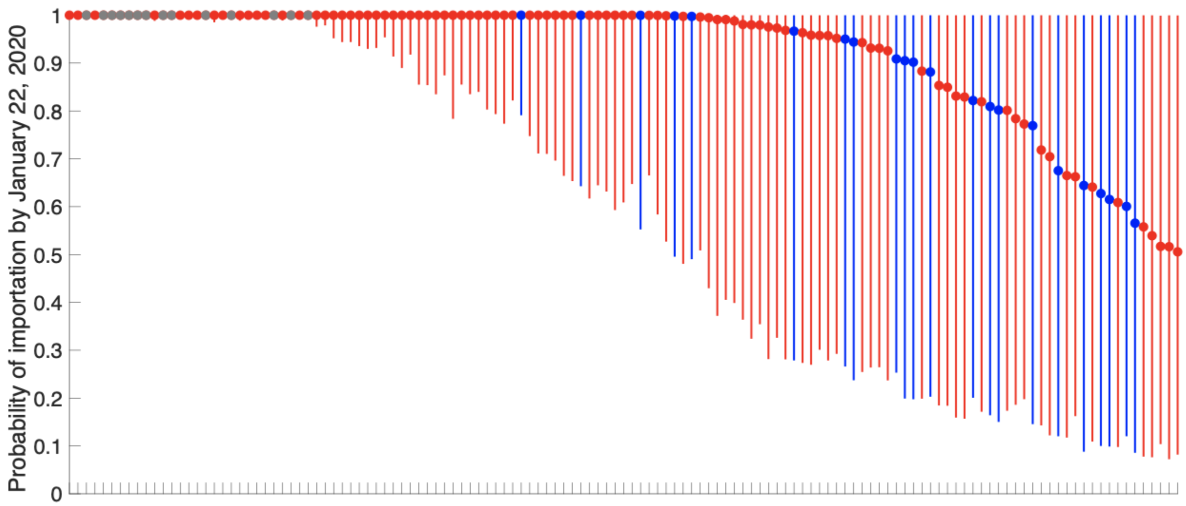

Figure S3. Risk of 2019-nCoV importations from Wuhan, China by January 23, 2020. All 131 cities in this graph have mean importation probabilities exceeding 50%. As of January 26th, 109 of these 131 have reported cases. Grey circles denote cities that were included in the quarantine as of January 24th. Red and blue circles denote cities outside the quarantine with and without confirmed cases as of January 26th, respectively.

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