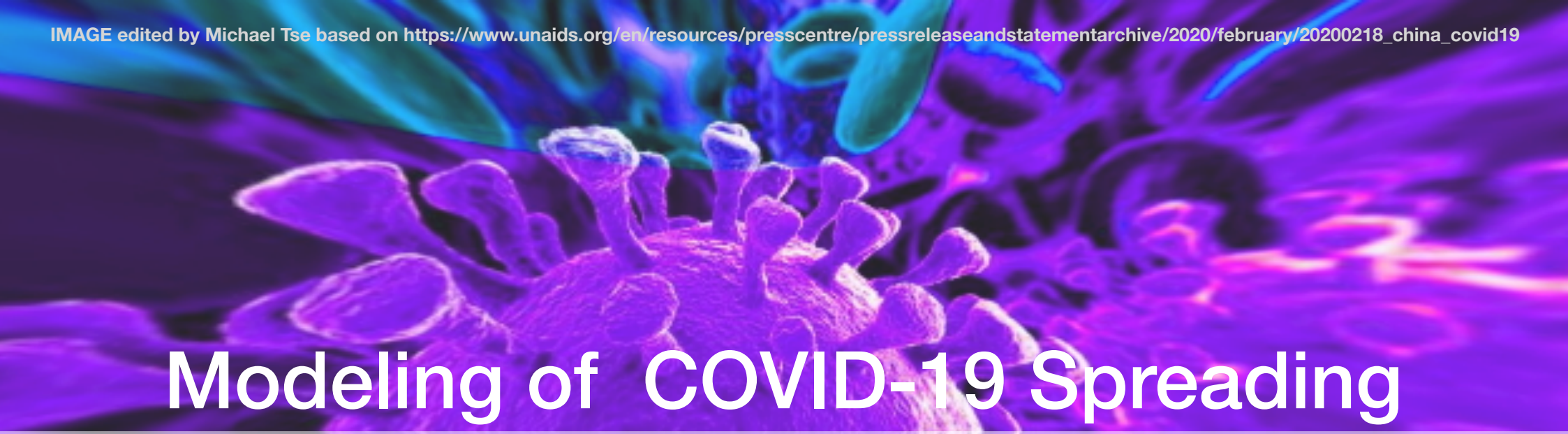

Modeling of COVID-19 Spreading with Human Migration Data

Choujun Zhan[1] and Michael Tse[2]
[1]South China Normal University
[2]City University of Hong Kong

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City University of Hong Kong
Prof. C. K. Michael Tse

华南师范大学
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Dr Choujun Zhan

COVID-19 Facts

8 DEC 2019

JAN 2020

Lunar New Year

- **2019 New Coronavirus Disease (COVID-19)** began to spread from early December 2019 in **Wuhan**
- First confirmed case: December 8, 2019
- Human-to-human transmission found to occur in mid December 2019
- Virtually no control until late January 2020, though official instruction from central was sent down on January 7, 2020.*

  *State media Qiu Shi Magazine reported President Xi's speech at the Standing Committee of the Central Political Bureau of CCP on Feb 3, 2020, sending instruction down on Jan 7, 2020 regarding control of the new coronavirus outbreak in Wuhan.
- Wuhan was locked down on January 24, 2020. Other cities began to impose stringent travel control.

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As of February 28, 2020

COVID-19 Cases

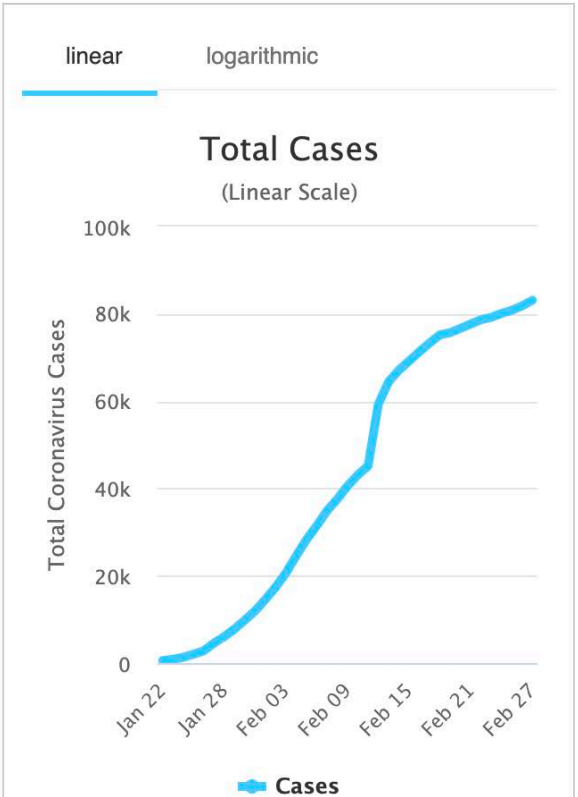
83,725

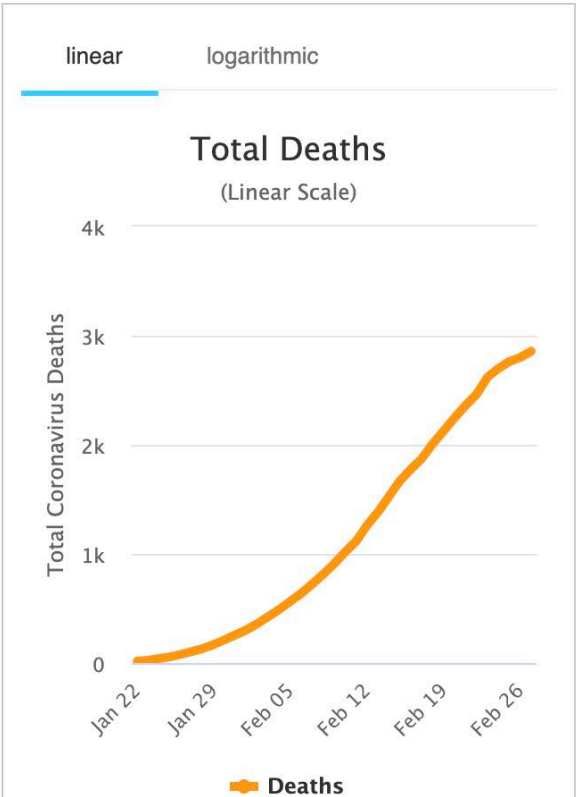
Deaths

2,859

Recovered

36,669





https://www.worldometers.info/coronavirus

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Country, Other	Total Cases	New Cases	Total Deaths	New Deaths	Total Recovered	Serious, Critical
China	78,832	+335	2,788	+44	36,272	7,952
S. Korea	2,337	+571	13		24	10
Diamond Princess	705		4		10	36
Italy	655		17		45	56
Iran	245		26		54	
Japan	226	+12	5	+1	32	13
Singapore	96				66	8
Hong Kong	93	+1	2		18	6
USA	60				6	
Germany	49				16	2
Kuwait	45	+2				
France	41	+3	2		11	1
Thailand	41	+1			22	2

Country, Other	Total Cases	New Cases	Total Deaths	New Deaths	Total Recovered	Serious, Critical
Taiwan	34	+2	1		5	1
Bahrain	33					
Malaysia	25	+3			20	
Spain	25				2	2
Australia	24	+1			15	
U.A.E.	19				5	2
U.K.	16				8	
Vietnam	16				16	
Canada	14				3	
Macao	10				6	
Switzerland	8					
Iraq	7					
Sweden	7					
Oman	6					
Austria	5					

As of February 28, 2020

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The epicenter

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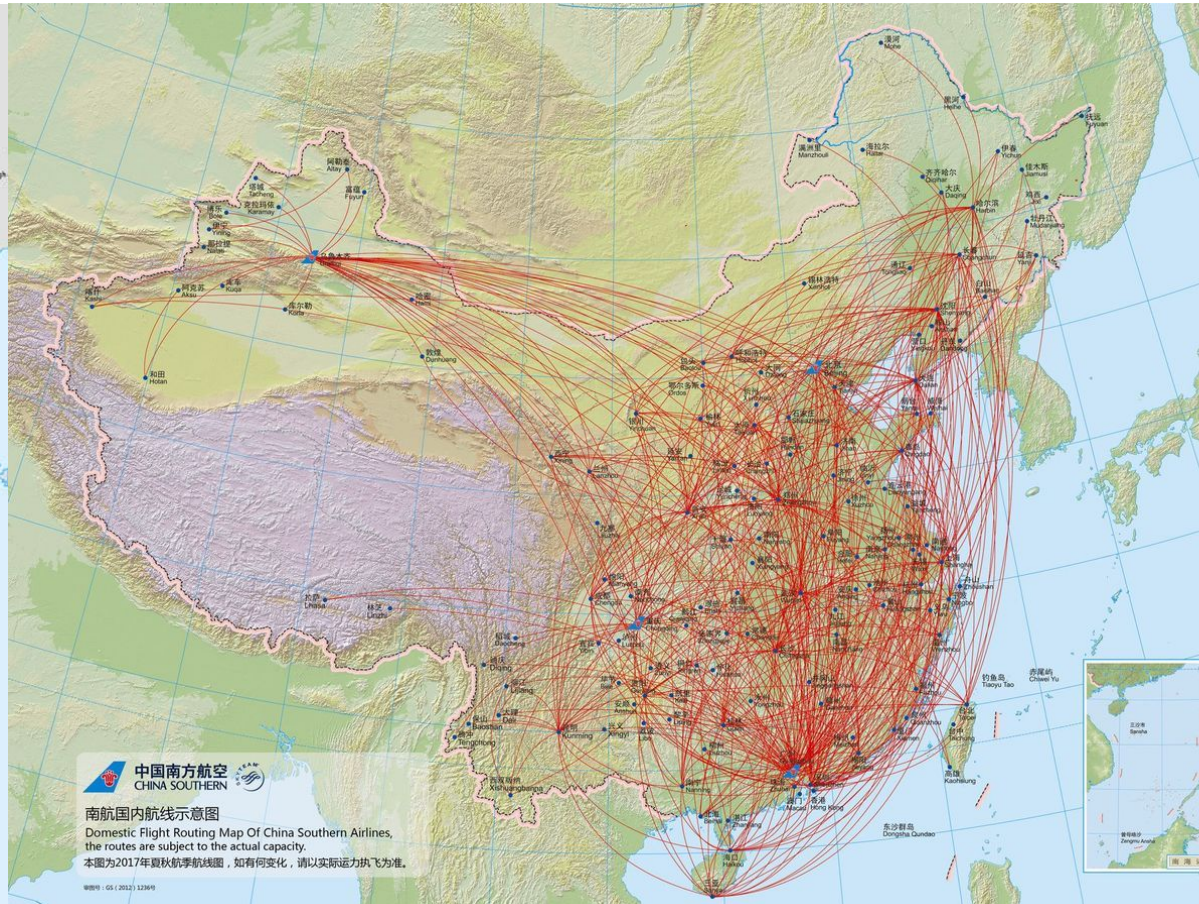
WUHAN

A very important city in China

- 11 million people
- ***major traffic hub***
- center of higher education, manufacturing plants, industry and business

Gathering of people and **intercity travel** of infected and exposed individuals within China have been the main drives that escalated the spreading of the virus. *How to get indicative travel volume data?*



Spreading escalated by the *spring travel rush*

- 30 days surrounding the Lunar New Year
- Migrant workers and students travel from major cities to country towns for family reunions, and return to the cities at the end of the holiday period. Holiday goers also travel to and from tourist cities.
- Ministry of Transport estimates ~3 billion trips taken during the spring travel rush.
- Wuhan, being a major transport hub and having a large number of higher education institutions as well asmanufacturing plants, is among the cities with the largest outflow and inflow traffic during the spring travel rush.

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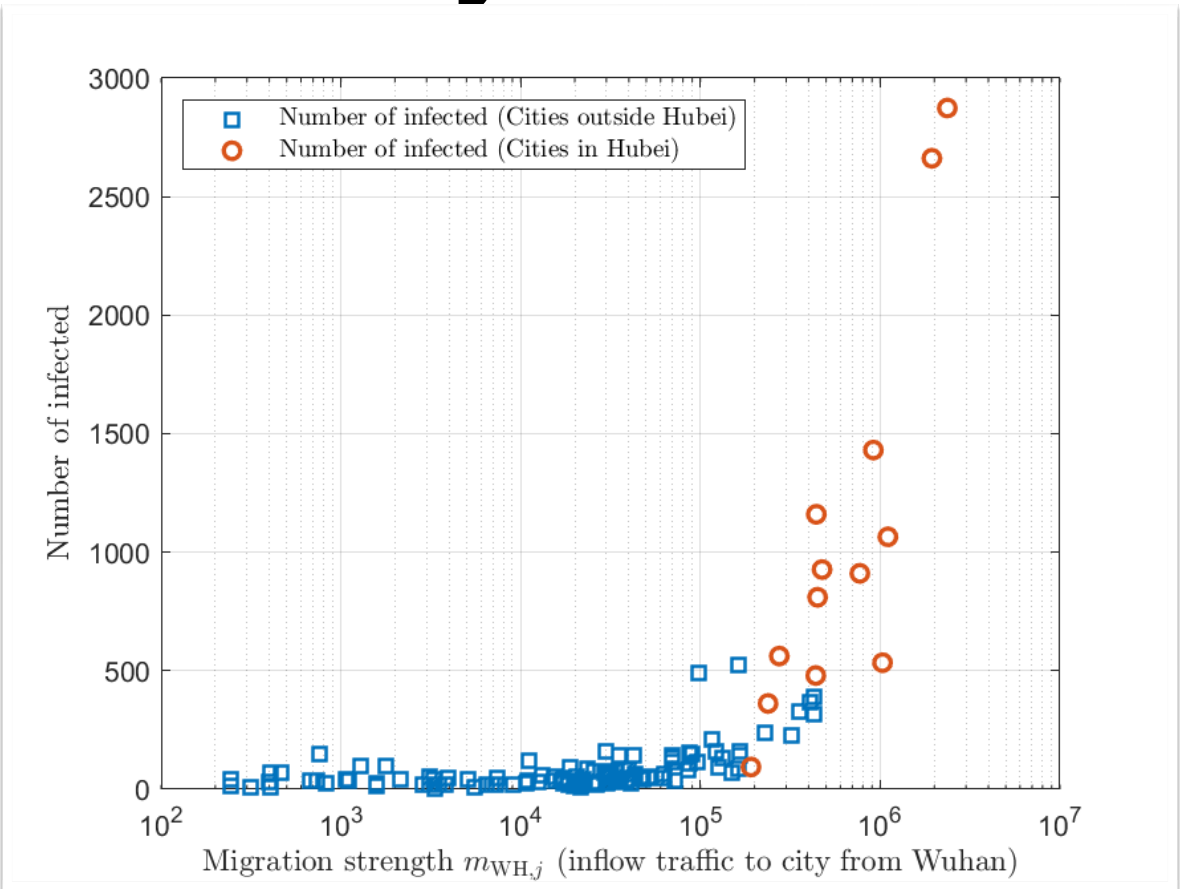
Impact of Intercity Travel

- Number of infections in a city farther from Wuhan increases almost ***linearly*** with the *Baidu Migration Strength* (inflow strength) of the city from Wuhan



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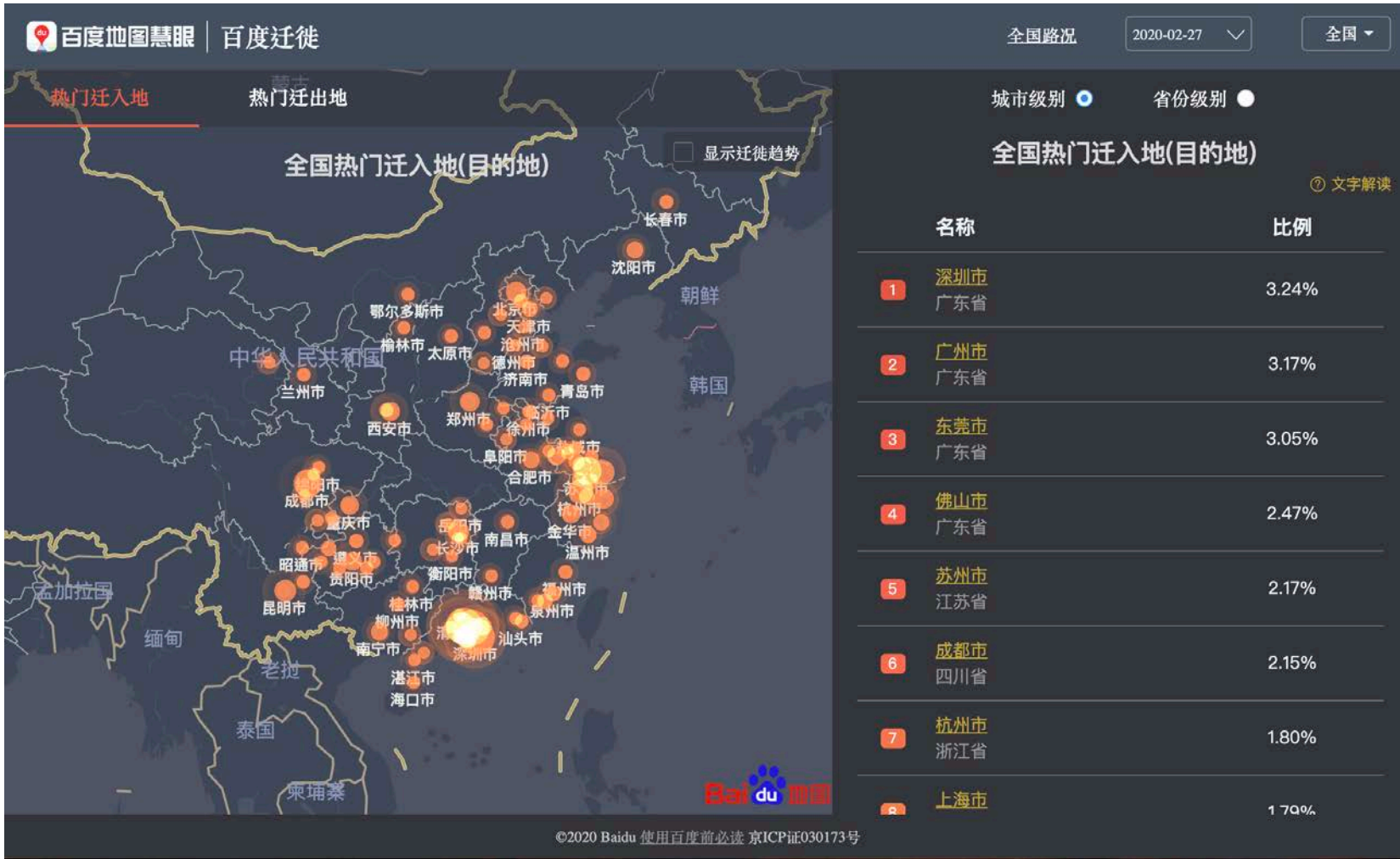
Data

Baidu Migration Data

Mobile-app based human migration tracking data system provides indicative inflow and outflow volume of travellers between cities



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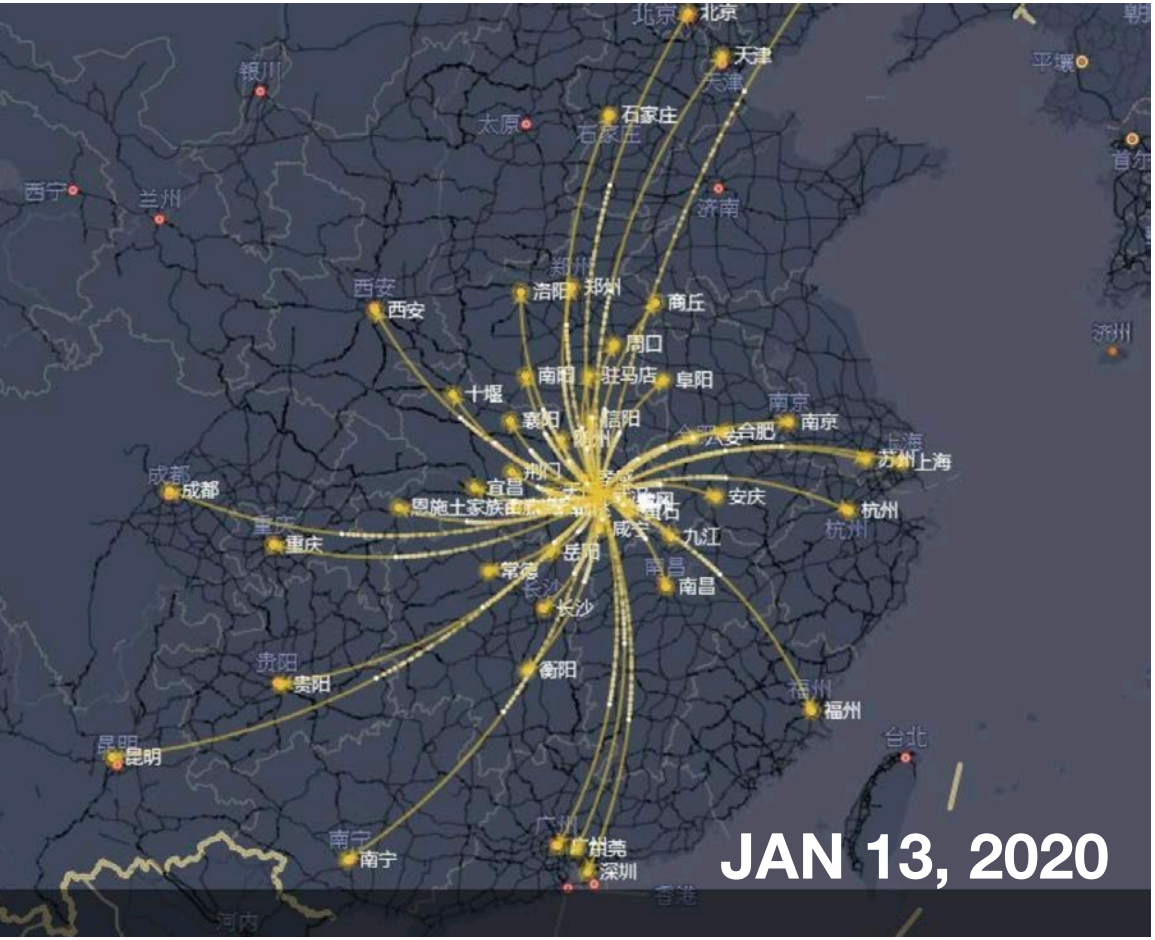

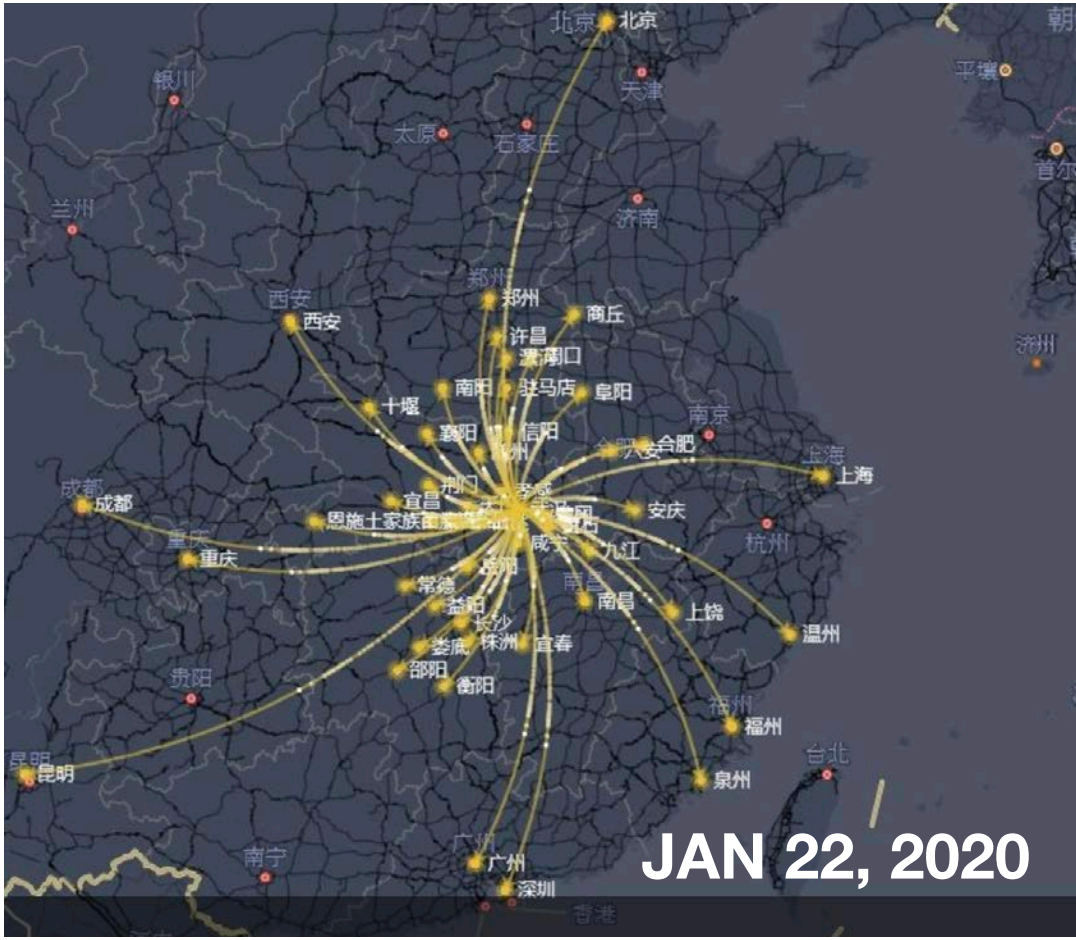

Baidu Migration Wuhan Outflow Strength

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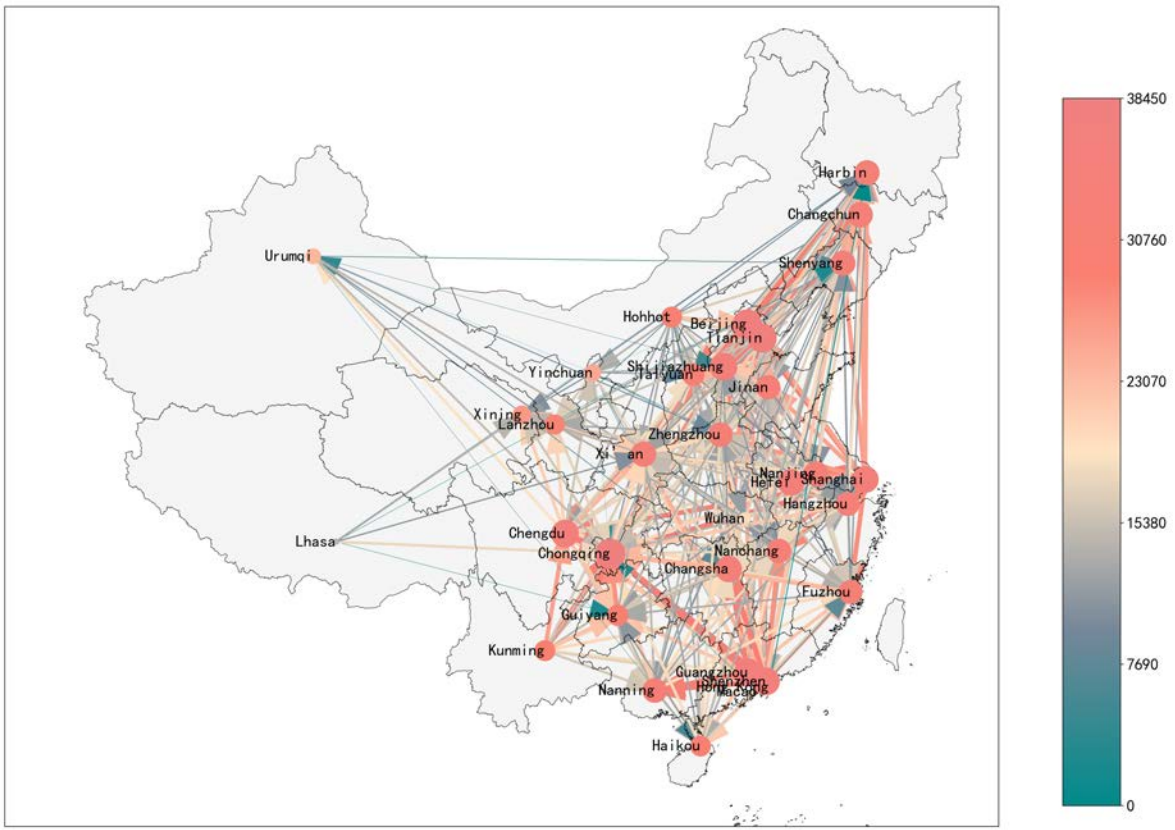
Data collection

- Baidu Migration data for 367 cities (or administrative regions) in China over the period of January 1, 2020, to February 13, 2020.

- The data provide the migration strengths of cities which are indicative measures of the human traffic volume moving in and out of 367 cities and administrative regions.



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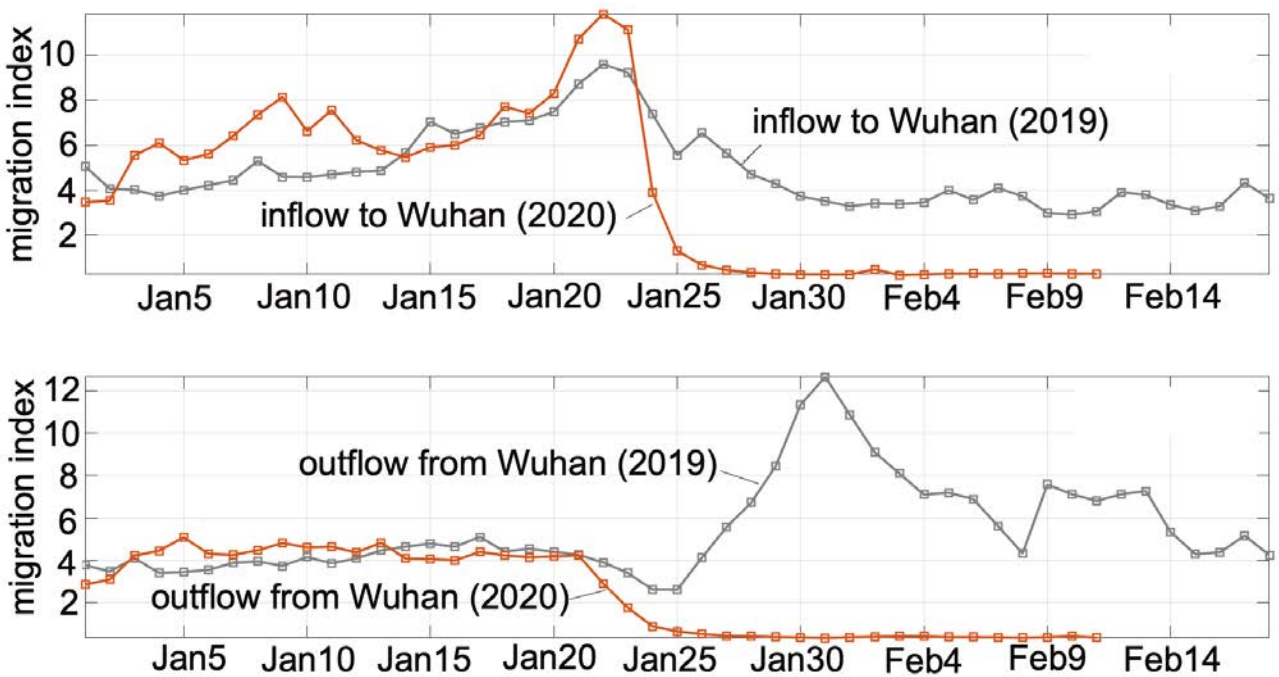
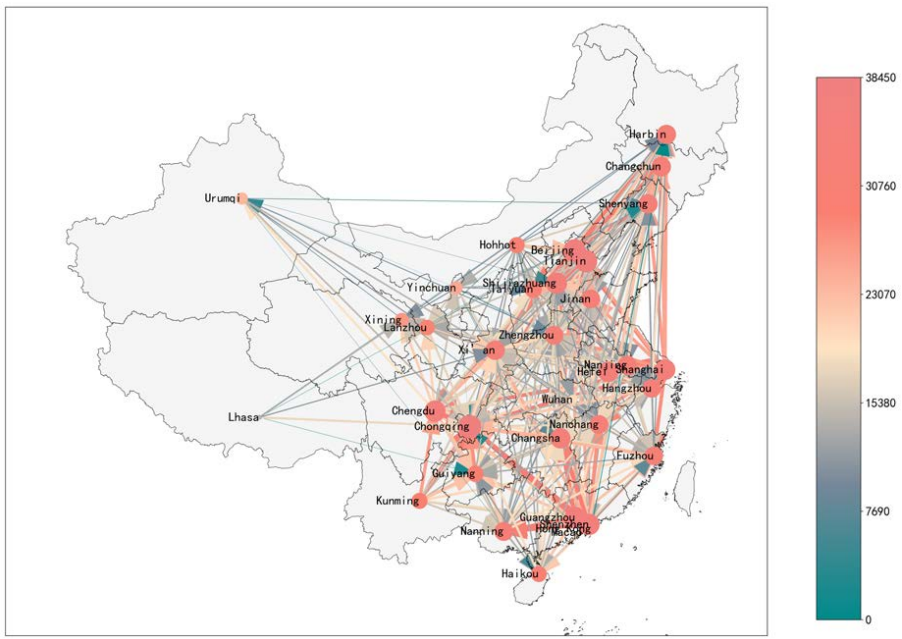
Wuhan inbound and outbound traffic





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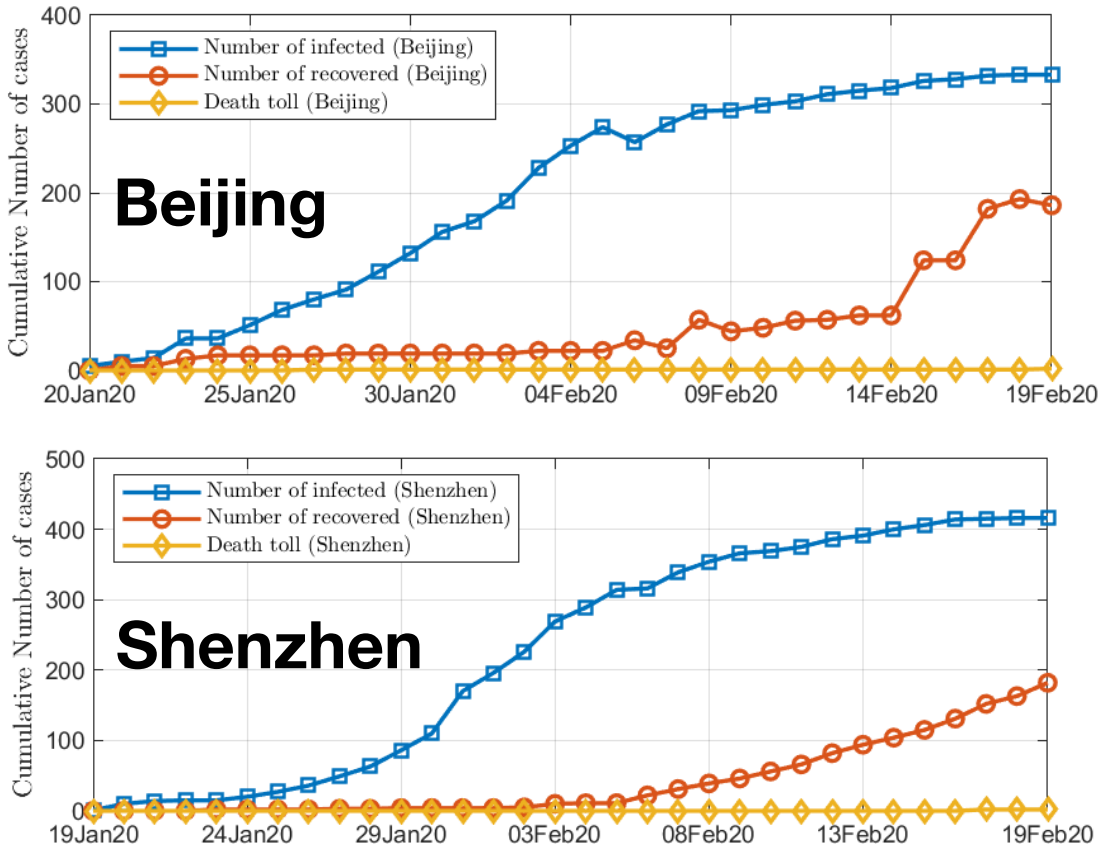
Data of Infection Cases

- **National Health Commission of China**
- Daily data from January 24, 2020, to February 16, 2020, including the daily total number of confirmed cases in each city, daily total cumulative number of confirmed cases in each city, daily cumulative number of recovered cases in each city, and daily cumulative death toll in each city.
- Data collected for **367** cities



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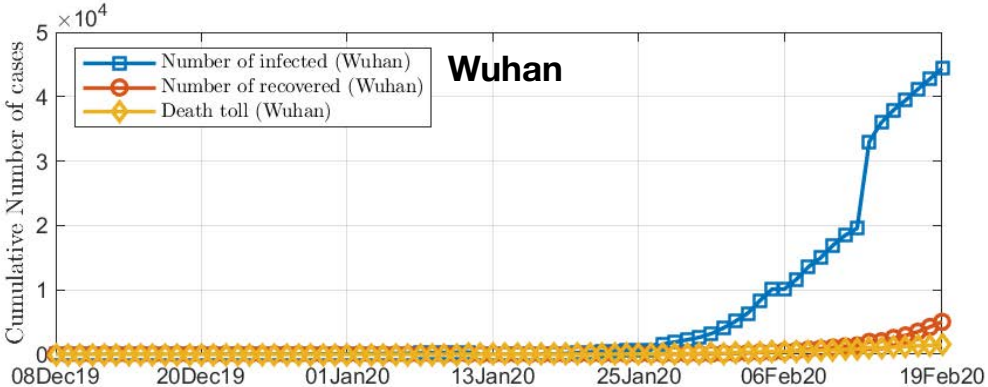
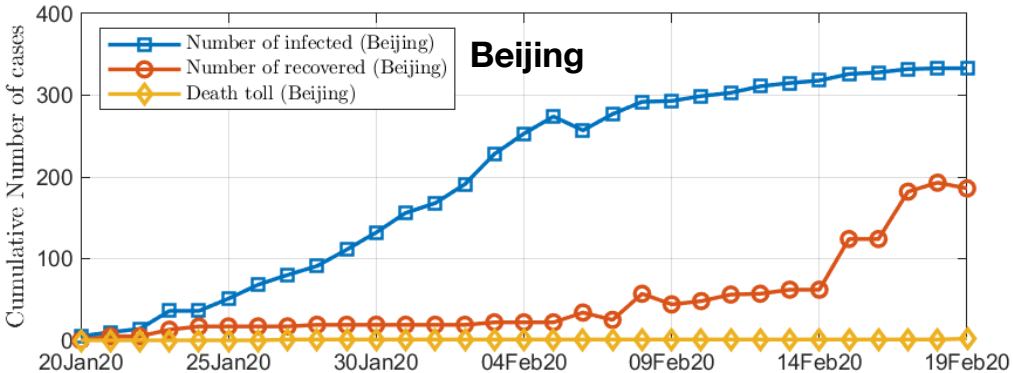
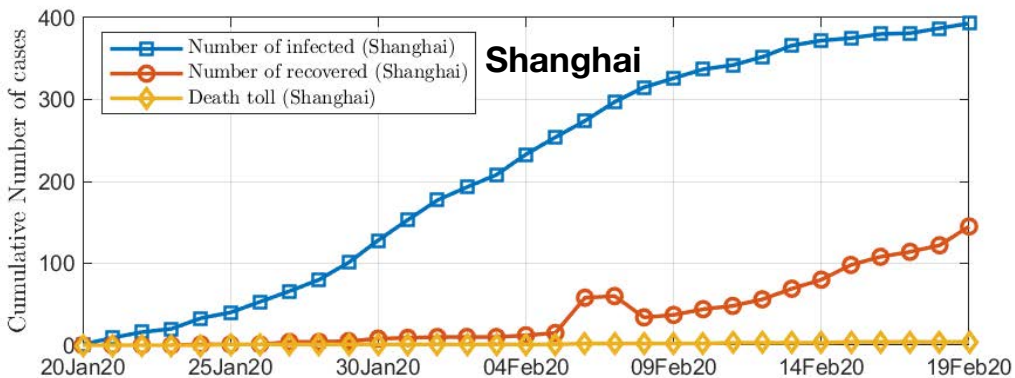
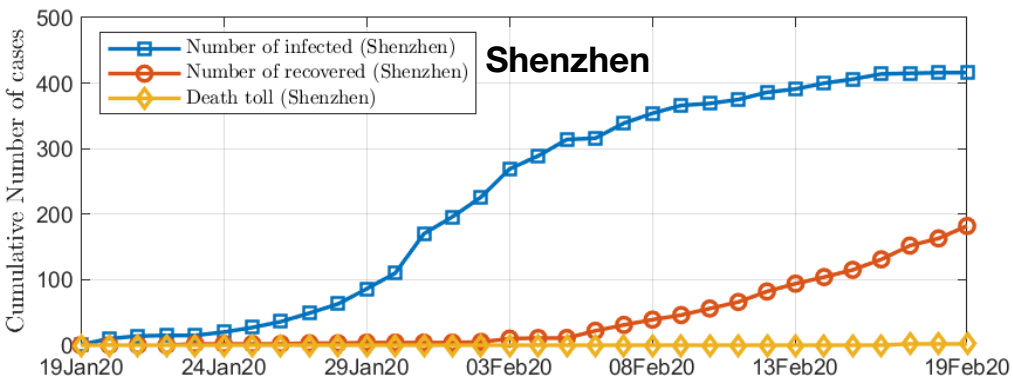
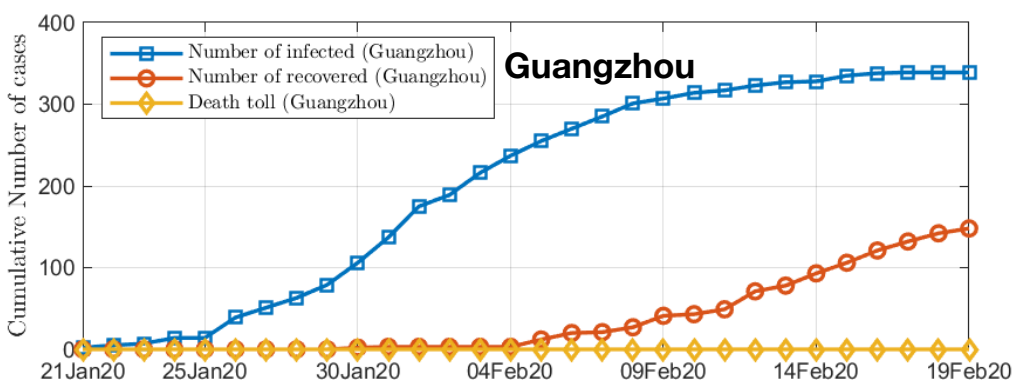
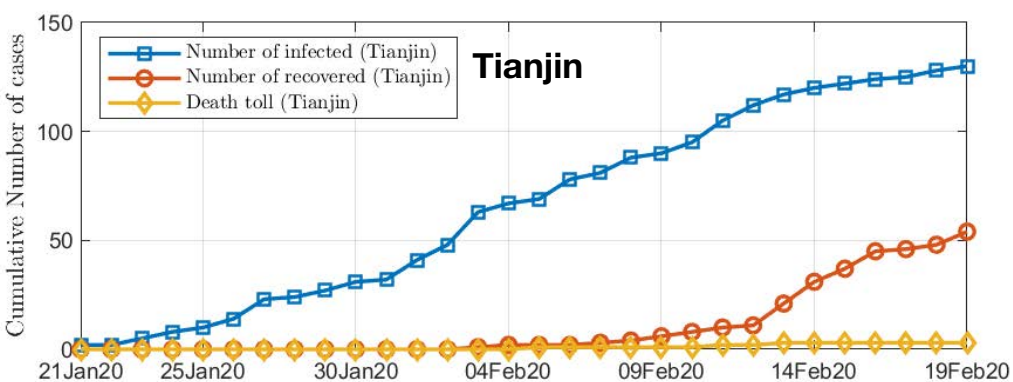

Wuhan
Number of infected (Wuhan)
Number of recovered (Wuhan)
Death toll (Wuhan)
Cumulative Number of cases
×10^4
08Dec19
20Dec19
01Jan20
13Jan20
25Jan20
06Feb20
19Feb20


Beijing
Number of infected (Beijing)
Number of recovered (Beijing)
Death toll (Beijing)
Cumulative Number of cases
20Jan20
25Jan20
30Jan20
04Feb20
09Feb20
14Feb20
19Feb20


Shanghai
Number of infected (Shanghai)
Number of recovered (Shanghai)
Death toll (Shanghai)
Cumulative Number of cases
20Jan20
25Jan20
30Jan20
04Feb20
09Feb20
14Feb20
19Feb20


Shenzhen
Number of infected (Shenzhen)
Number of recovered (Shenzhen)
Death toll (Shenzhen)
Cumulative Number of cases
19Jan20
24Jan20
29Jan20
03Feb20
08Feb20
13Feb20
19Feb20


Guangzhou
Number of infected (Guangzhou)
Number of recovered (Guangzhou)
Death toll (Guangzhou)
Cumulative Number of cases
21Jan20
25Jan20
30Jan20
04Feb20
09Feb20
14Feb20
19Feb20


Tianjin
Number of infected (Tianjin)
Number of recovered (Tianjin)
Death toll (Tianjin)
Cumulative Number of cases
21Jan20
25Jan20
30Jan20
04Feb20
09Feb20
14Feb20
19Feb20

Model

SEIR Model

On day *t*, there are

- **S**usceptible $S_i(t)$
- **E**xposed $E_i(t)$
- **I**nfected $I_i(t)$
- **R**ecovered/ removed $R_i(t)$

City *i* with population = P_i

Eventual percentage of infection = δ_i

Total susceptible population $N_i^s = \delta_i P_i$

$$N_i^s(t) = S_i(t) + E_i(t) + I_i(t) + R_i(t)$$

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IMAGE: https://zabulionis.files.wordpress.com/2014/06/people-network.jpg

Basic SEIR Dynamics

For a single population (network), we can write the state equations as

$$\begin{aligned}
\dot{S}(t) &= -\beta S(t) I(t) \\
\dot{E}(t) &= \beta S(t) I(t) - k E(t) \\
\dot{I}(t) &= \kappa E(t) - \gamma I(t) \\
\dot{R}(t) &= \gamma I(t)
\end{aligned}$$

$$\Rightarrow \begin{cases}
\Delta S(t) &= -\beta S(t-1) I(t-1) \\
\Delta E(t) &= \beta S(t-1) I(t-1) - \kappa E(t-1) \\
\Delta I(t) &= \kappa E(t-1) - \gamma I(t-1) \\
\Delta R(t) &= \gamma I(t-1)
\end{cases}$$

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Parameters

- Infection rates: $S \rightarrow E$ and $E \rightarrow I$, i.e., β_i and κ_i for each city
- Recovery rate: $I \rightarrow R$, i.e., γ_i for each city
- Eventual infection percentage: δ_i for each city

Data

- Population: P_i for each city
- Infected: I_i , R_i for each city

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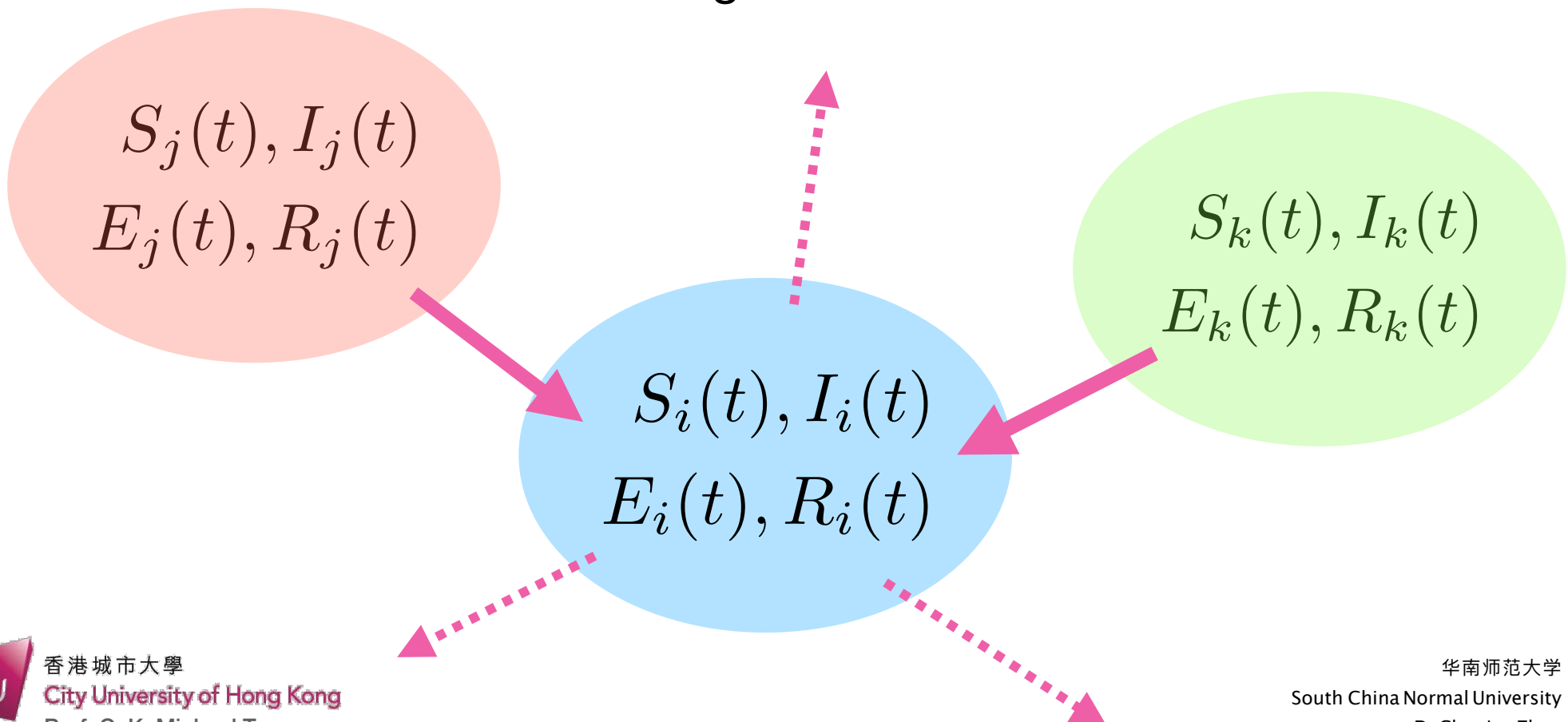
With intercity travel

367 cities are interacting via inflow and outflow traffic



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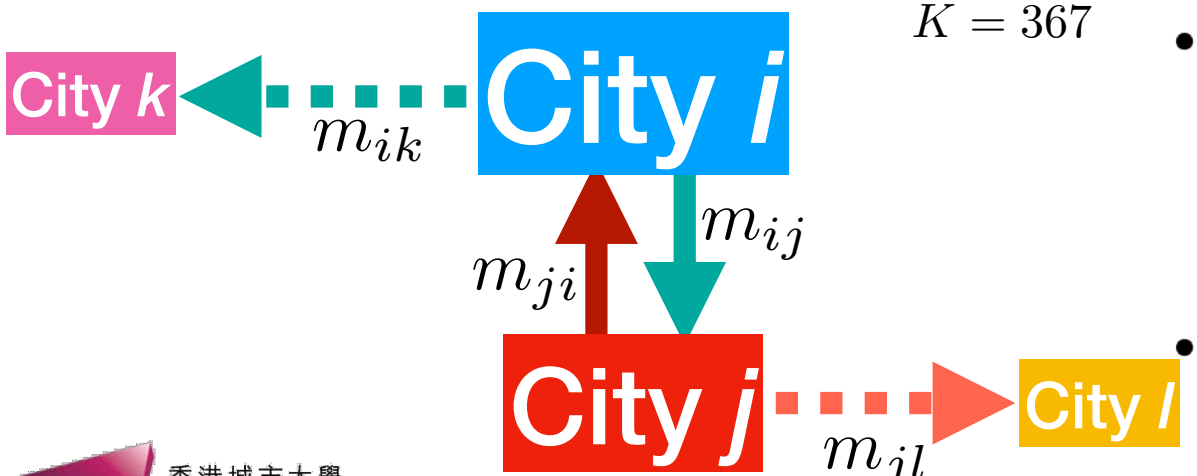
Intercity migration matrix

$$M(t) = \begin{bmatrix} m_{11}(t) & m_{12}(t) & \cdots & m_{1K}(t) \\ m_{21}(t) & m_{22}(t) & \cdots & m_{2K}(t) \\ \vdots & \vdots & \ddots & \vdots \\ m_{N1}(t) & m_{N2}(t) & \cdots & m_{KK}(t) \end{bmatrix}$$

$K = 367$



- M records migration from one city to another. Movement within a city is not counted, i.e., $m_{ii}(t) = 0$ for all i.
- M is non-symmetric as traffic from one city to another is not necessarily reciprocal at any given time, i.e., $m_{ij}(t) \neq m_{ji}(t)$.
- Number of outflow migrants of city i at time t is

$$m_i^{(\text{out})}(t) = \sum_{i=j}^{K} m_{ij}(t).$$

- Number of inflow migrants of city i at time t is

$$m_i^{(\text{in})}(t) = \sum_{j=1}^{K} m_{ji}(t).$$

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From city *i* to city *j*

$$\Delta I_{ij}^{\text{in}}(t) = \frac{I_i(t) m_{ij}(t)}{P_i}$$

Leaving city *j*

$$\Delta I_{j}^{\text{out}}(t) = \frac{I_j(t) \sum_{i=1}^{N} m_{ji}(t)}{P_j}$$

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Assumptions

- Susceptible and Exposed individuals can move from one city to another.
- Infected individuals, once confirmed, do NOT move to another city.
- Recovered individuals also do NOT move to another city.
- All parameters are theoretically different in different cities.
    - For computational convenience, we only assume recovery rates and infection percentages to be different in different cities.

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Modified SEIR Model

Modified populations

$$\Delta P_j(t) = \sum_{i=1}^{N} m_{ij}(t) - \sum_{i=1}^{N} m_{ji}(t),$$

$$\Delta N_j^s(t) = k_I \left(\sum_{i=1}^{N} \left(\frac{I_i(t) m_{ij}(t)}{P_i(t)} \right) - \frac{I_j(t) * \sum_{i=1}^{N} m_{ji}(t)}{P_j(t)} \right) + \sum_{i=1}^{N} \left(\frac{E_i(t) m_{ij}(t)}{P_i(t)} \right) - \frac{E_j(t) * \sum_{i=1}^{N} m_{ji}(t)}{P_j(t)} + \sum_{i=1}^{N} \left(\frac{S_i(t) m_{ij}(t)}{P_i(t)} \right) - \frac{S_j(t) \sum_{i=1}^{N} m_{ji}(t)}{P_j(t)}$$

$$\Delta I_j(t) = \kappa_j(t) E_i(t) - \gamma_j(t) I_j(t) + k_I \left(\sum_{i=1}^{N} \left(\frac{I_i(t) m_{ij}(t)}{P_i(t)} \right) - \frac{I_j(t) * \sum_{i=1}^{N} m_{ji}(t)}{P_j(t)} \right),$$

$$\Delta E_j(t) = \frac{\beta_j(t)}{N_j^s(t)} I_j(t) S_j(t) + \frac{\alpha_j(t)}{N_j^s(t)} E_j(t) S_j(t) - \kappa_j(t) E_i(t) + \sum_{i=1}^{N} \left(\frac{E_i(t) m_{ij}(t)}{P_i(t)} \right) - \frac{E_j(t) * \sum_{i=1}^{N} m_{ji}(t)}{P_j(t)},$$

$$\Delta S_j(t) = -\frac{\beta_j(t)}{N_j^s(t)} I_j(t) S_j(t) - \frac{\alpha_j(t)}{N_j^s(t)} E_j(t) S_j(t) + \sum_{i=1}^{N} \left(\frac{S_i(t) m_{ij}(t)}{P_i(t)} \right) - \frac{S_j(t) \sum_{i=1}^{N} m_{ji}(t)}{P_j(t)},$$

$$\Delta R_j(t) = \gamma_j(t) I_j(t),$$

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Parameter Extraction

- Set of parameters: $\theta_j = \{\alpha_j, \beta_j, \gamma_j, \kappa_j, \delta_j, I_{j,0}\}$ for city j
- Initial infected and exposed numbers: $\lambda_I I_j(t_0)$ and $\lambda_E I_j(t_0)$

Modeling to be completed by finding all parameters that match the historical data.

The number of exposed individuals, $E_j(t)$, is also unknown.

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Method

- Constrained nonlinear optimisation problem

$$\mathrm{P}_0: \min_{\Theta} \sum_{j=0}^{N} \left\| w_j(I(t_j) - \hat{I}(t_j)) \right\|_l$$

$$s.t. \begin{cases} (i) & \hat{x}(t+1) = \hat{x}(t) + F(\hat{x}(t)), \\ (ii) & \Theta_U \geq \Theta \geq \Theta_L, \end{cases}$$

where $\hat{x}$ is the set of estimated parameters, and $F(\,.\,)$ is the model.

- $\hat{x}(t) = [\hat{I}(t), \hat{R}(t), E(t), S(t), P(t), N^s(t)]$

Optimization Problem

- To find the parameters from best fitting of the model
- In other words, the model generates the solution that is ***as close to the data as possible***.
- Minimize the Root Mean Square Percentage Error:

$$\text{RMSPE} = \sqrt{\frac{1}{K}\sum_{i=1}\sum_{j=1}\left(\frac{\hat{I}_i(t_j) - I_i(t_j)}{I_i(t_j)}\right)^2}$$ where K is the number of cities.

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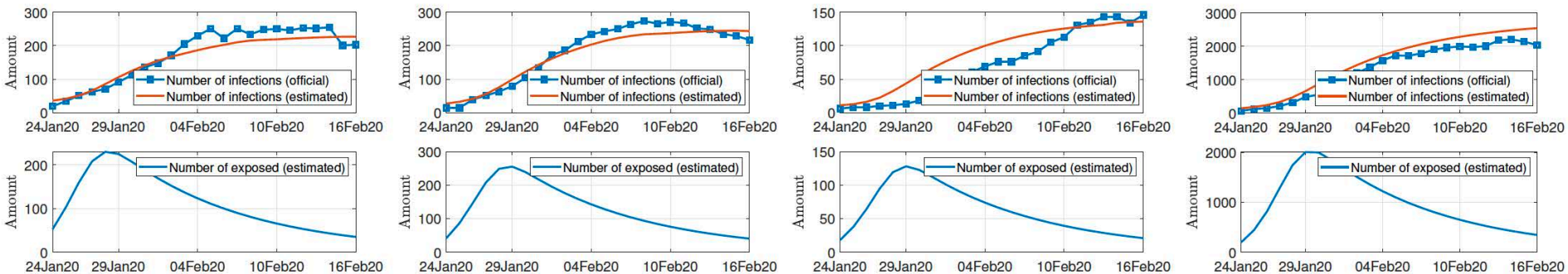
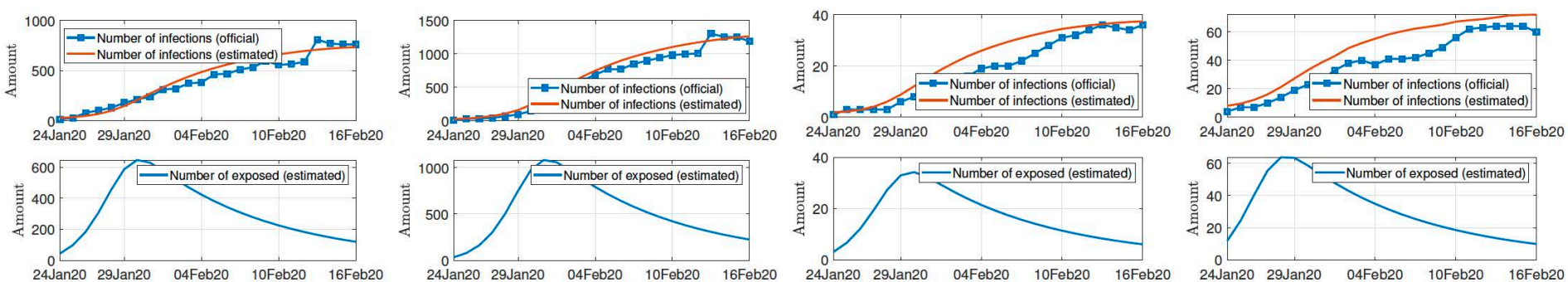
Fitting Results

No of infected cases
‖
Not the total cumulated
(i.e., less the recovered)



(a) Beijing (b) Guangzhou (c) Haerbin (d) Huanggang



(e) Jingmen (f) Jingzhou (g) Lianyungang (h) Nanjing

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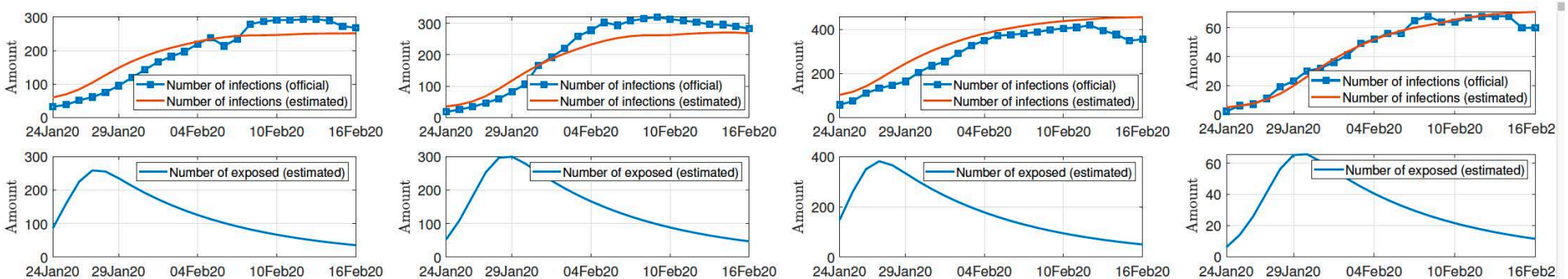
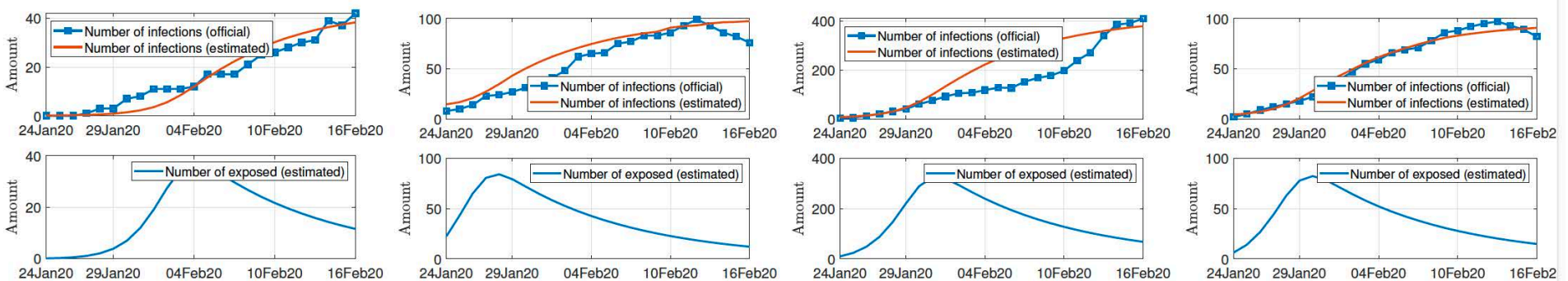
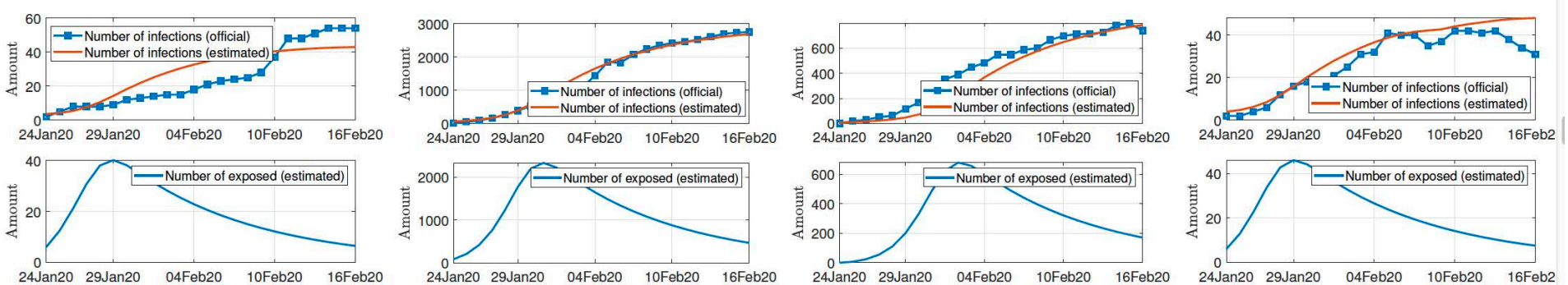


(i) Shanghai (j) Shenzhen (k) Chongqing (l) Suzhou



(m) Tangshan (n) Tianjin (o) Tianmen (p) Xian

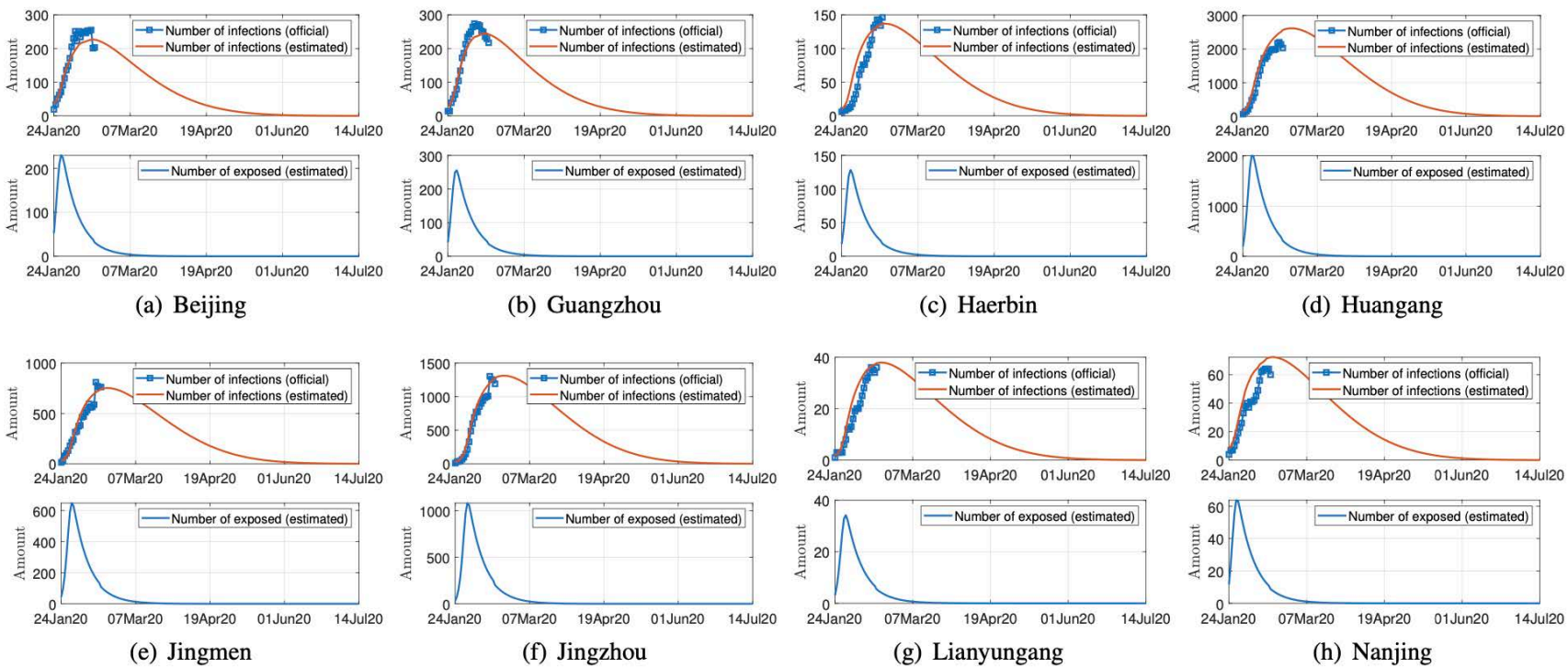


(q) Hong Kong (r) Xiaogan (s) Yichang (t) Zhongshan

Predictions

- Once we have the parameters, the model can be used for prediction assuming the validity of the same set of parameters.

No of infected cases
‖
Not the total cumulated (i.e., less the recovered)



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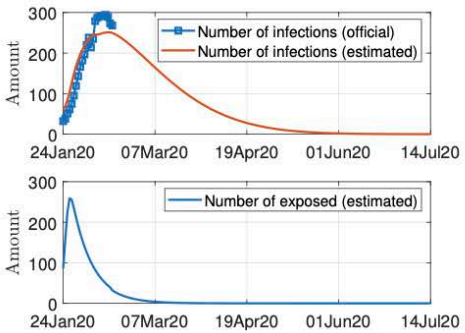
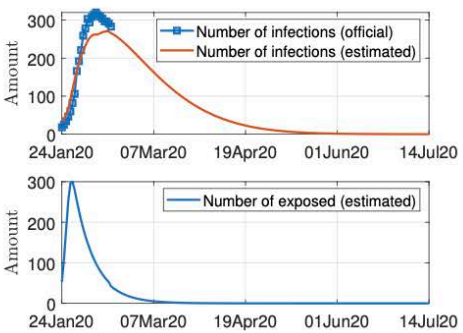
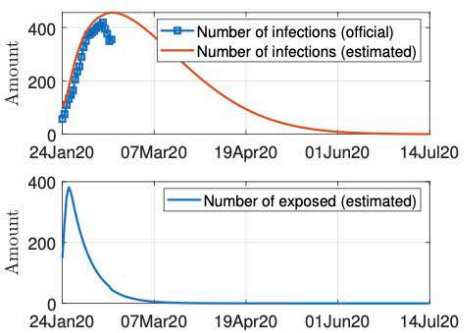


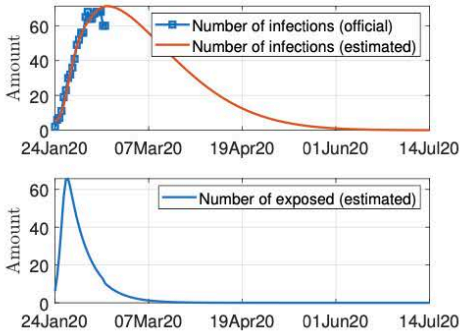
(i) Shanghai



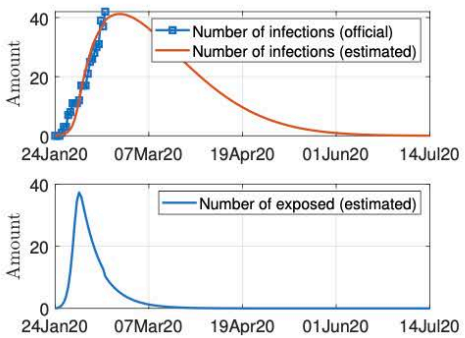
(j) Shenzhen



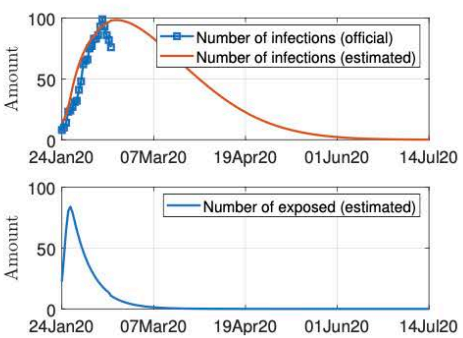
(k) Chongqing



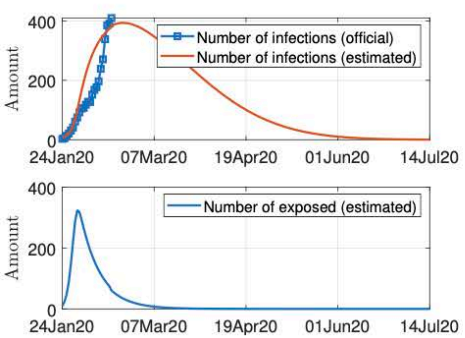
(l) Suzhou



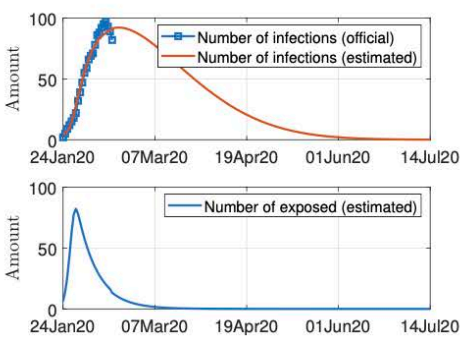
(m) Tangshan



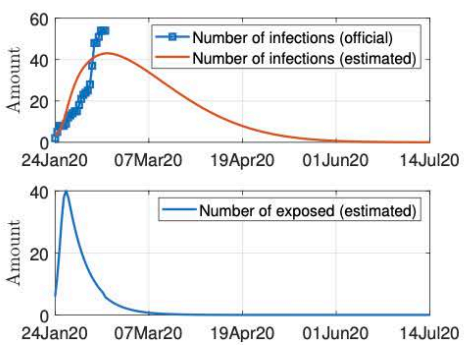
(n) Tianjin



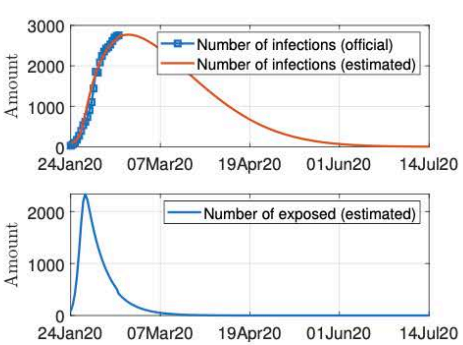
(o) Tianmen



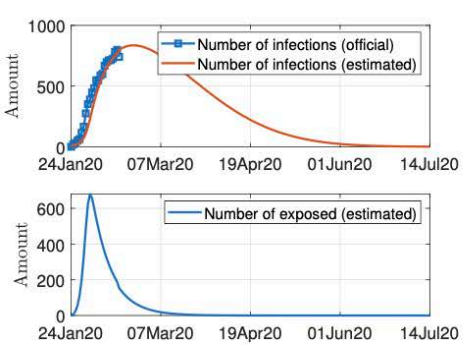
(p) Xian



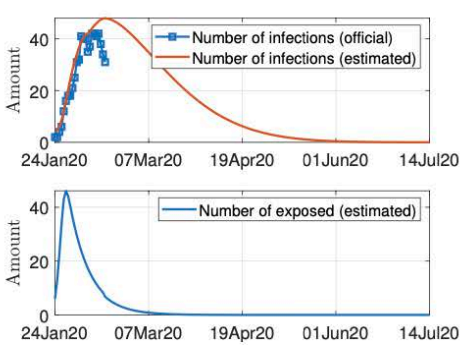
(q) Hong Kong



(r) Xiaogan

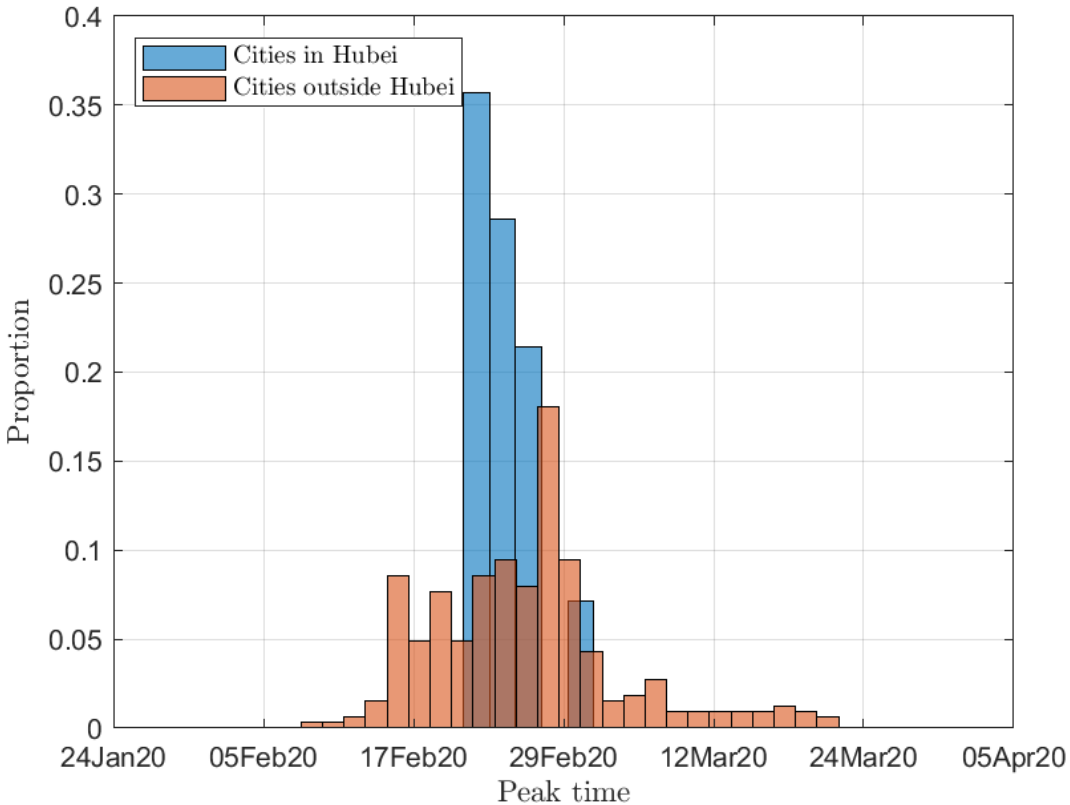


(s) Yichang



(t) Zhongshan

Findings



PEAK TIME

For most cities, the infection numbers would peak between mid February to early March 2020

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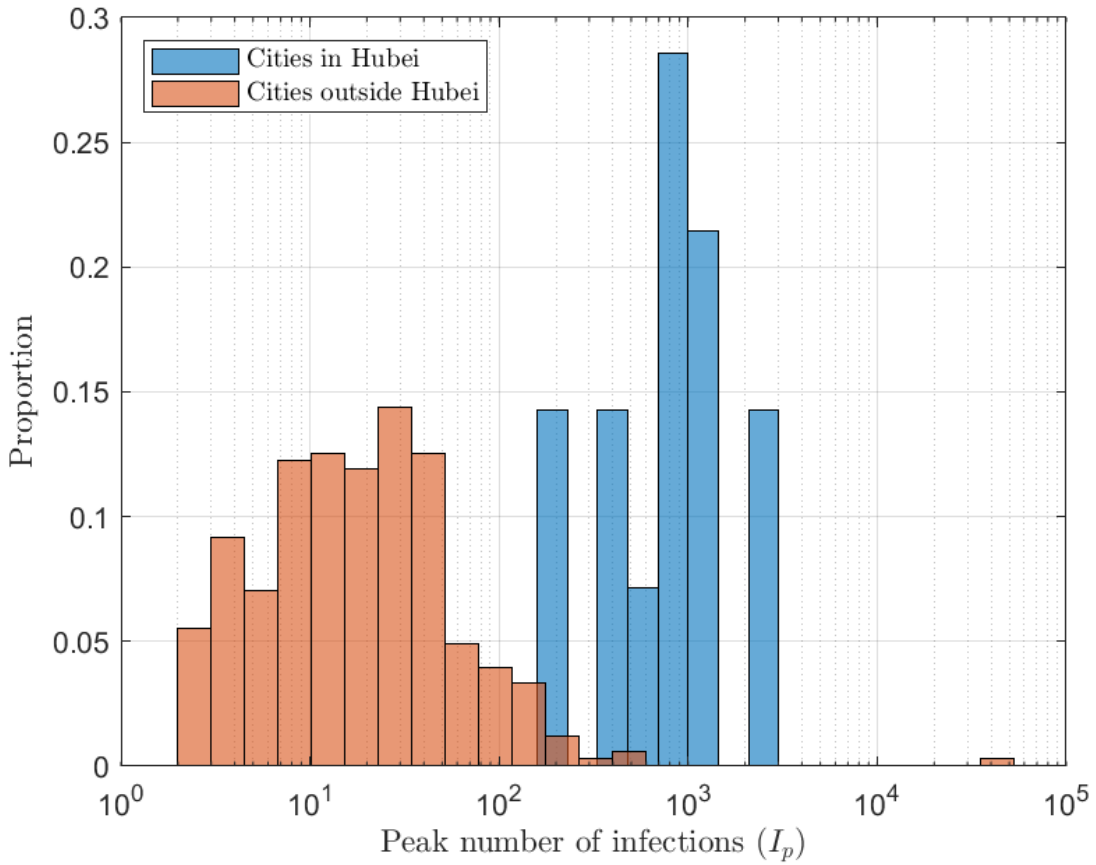
PEAK NO. OF INFECTIONS

The peak number of infected individuals will be between 1,000 to 5,000 for cities in Hubei, and that outside Hubei will be below 500.



January 24, 2020, to February 16, 2020

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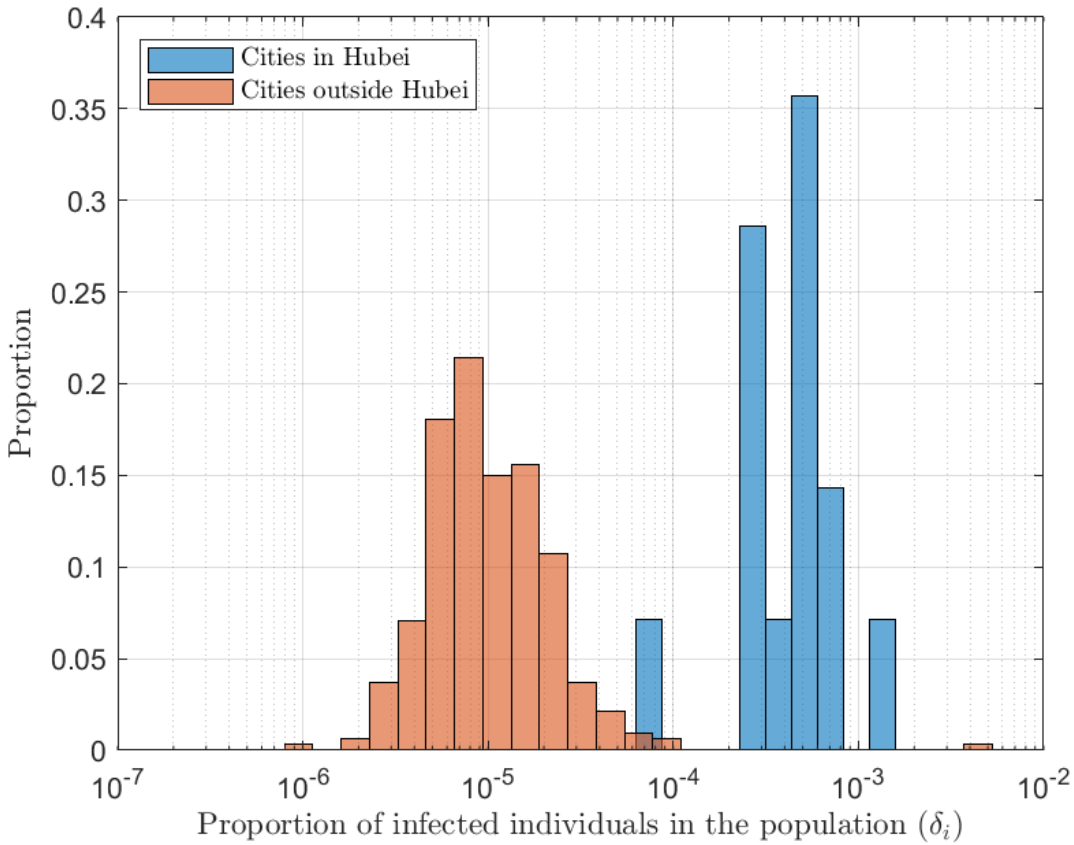

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PROPORTION OF INFECTED IN EACH CITY δ_i

At the end, about 0.8%, less than 0.1% and less than 0.01% of the population would get infected in Wuhan, Hubei Province and the rest of China, respectively.

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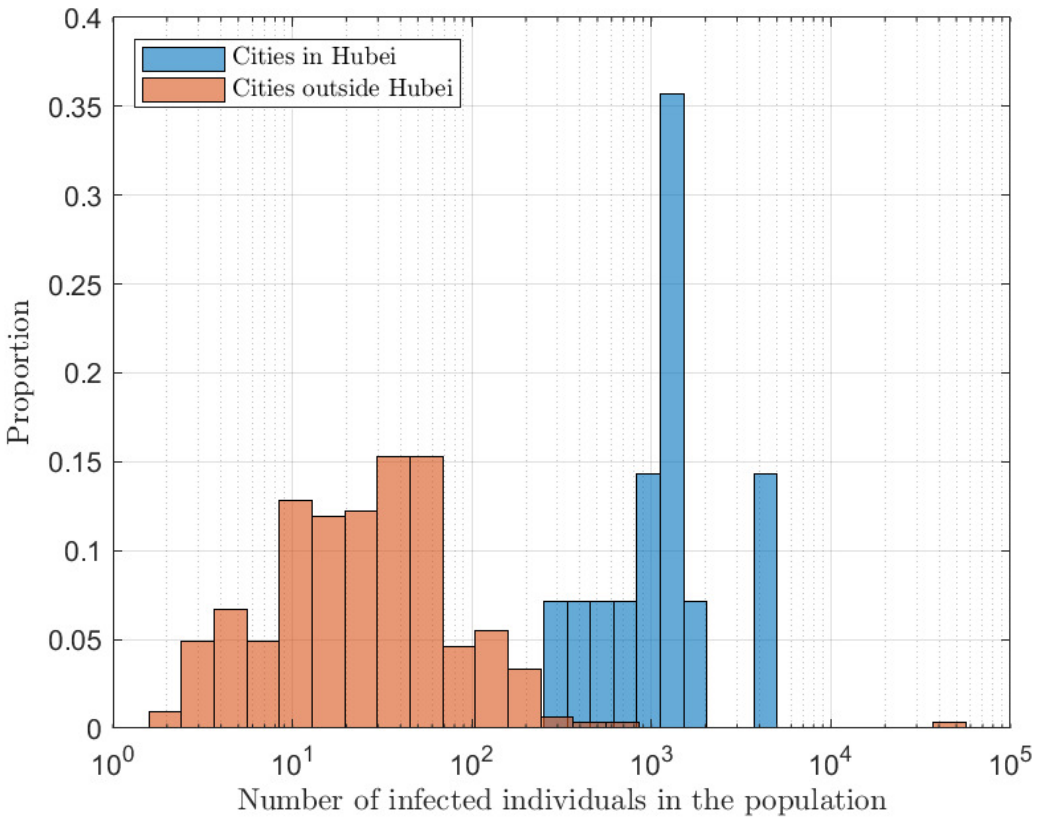
NUMBER OF INFECTED IN EACH CITY

Translating to actual figures, for most cities outside and within Hubei Province (excet Wuhan), the total number of infected individuals was expected to be fewer than 300 and 4000, respectively



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Discussions

- Our results were expected to be optimistic, under normal circumstances, in the sense that the projected severity and duration of the epidemic were valid ***provided stringent measures continue to be in place*** to curb the spreading of the virus, especially before mid March

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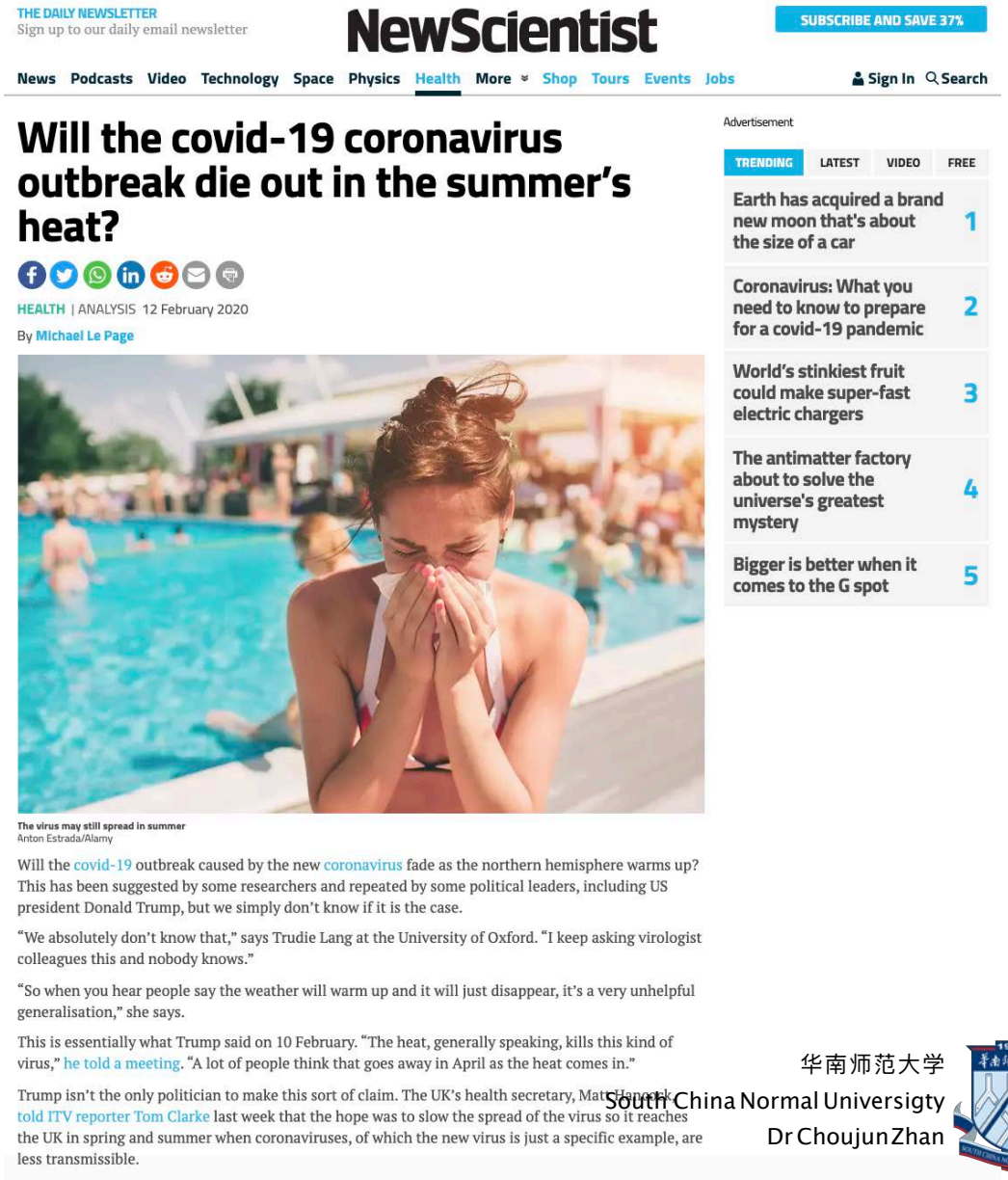
Discussions

As temperature generally rises from February to May in much of China, the infection peaks would unlikely occur later than the predicted times as the new coronavirus epidemic is generally known to subside in warm weather, provided parameters do not change significantly.



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Will the covid-19 coronavirus outbreak die out in the summer's heat?

HEALTH | ANALYSIS 12 February 2020

By Michael Le Page

The virus may still spread in summer
Anton Estrada/Alamy

Will the covid-19 outbreak caused by the new coronavirus fade as the northern hemisphere warms up? This has been suggested by some researchers and repeated by some political leaders, including US president Donald Trump, but we simply don't know if it is the case.

"We absolutely don't know that," says Trudie Lang at the University of Oxford. "I keep asking virologist colleagues this and nobody knows."

"So when you hear people say the weather will warm up and it will just disappear, it's a very unhelpful generalisation," she says.

This is essentially what Trump said on 10 February. "The heat, generally speaking, kills this kind of virus," he told a meeting. "A lot of people think that goes away in April as the heat comes in."

Trump isn't the only politician to make this sort of claim. The UK's health secretary, Matt Hancock, told ITV reporter Tom Clarke last week that the hope was to slow the spread of the virus so it reaches the UK in spring and summer when coronaviruses, of which the new virus is just a specific example, are less transmissible.

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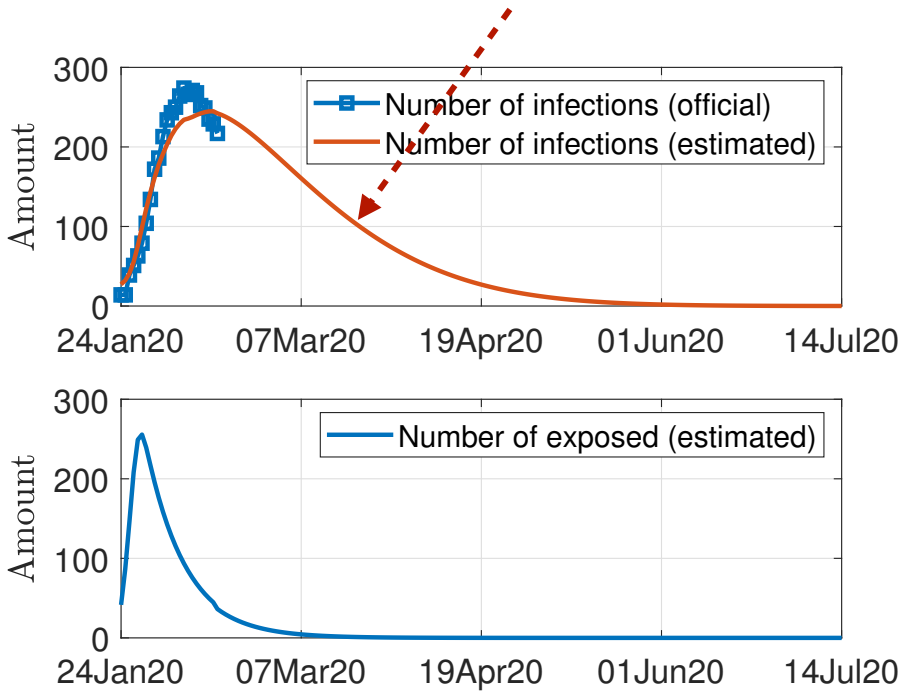
The End

How fast it can come down?



The **effectiveness of medical treatment** is expected to improve and the recovery rate will increase in the coming months. As our simulation is based on current data, the recovery rate could be under-estimated.

Should the recovery rate increase by 0.0005 each day, namely, the number of daily recovered individuals increases by 1\% of the total number of infected individuals every 20 days, most cities in China will have zero infection case by June 2020.

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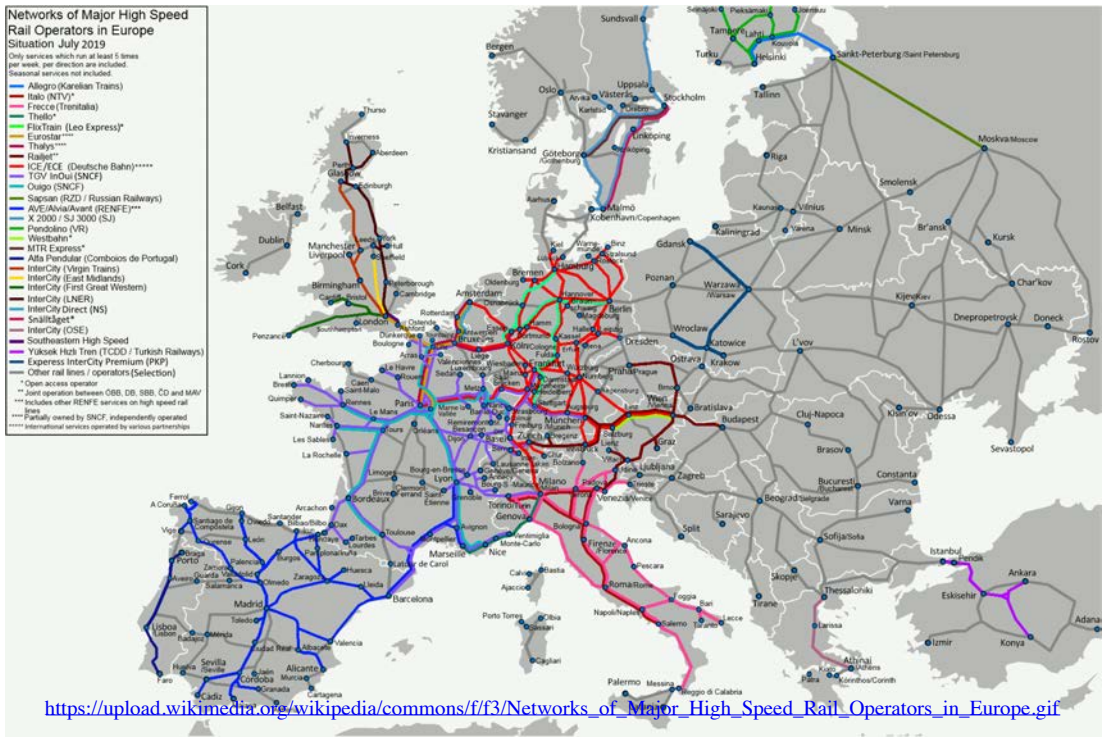
Conclusions

- Prediction of the severity and duration of the epidemic provides essential information for illuminating social and non-pharmaceutical preventive interventions.

- Gathering of people (single population) and **intercity travel** (multiple populations) are key factors!



https://upload.wikimedia.org/wikipedia/commons/f/f3/Networks_of_Major_High_Speed_Rail_Operators_in_Europe.gif

Can we predict? We need rapid model building, data collection, and parameter extractions. Infection numbers began to soar in Italy and South Korea from Feb 25, 2020.

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Acknowledgement

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