上海市现代应用数学重点实验室研究报告

Research Report Series of SKLCAM

(2020 年第七期)

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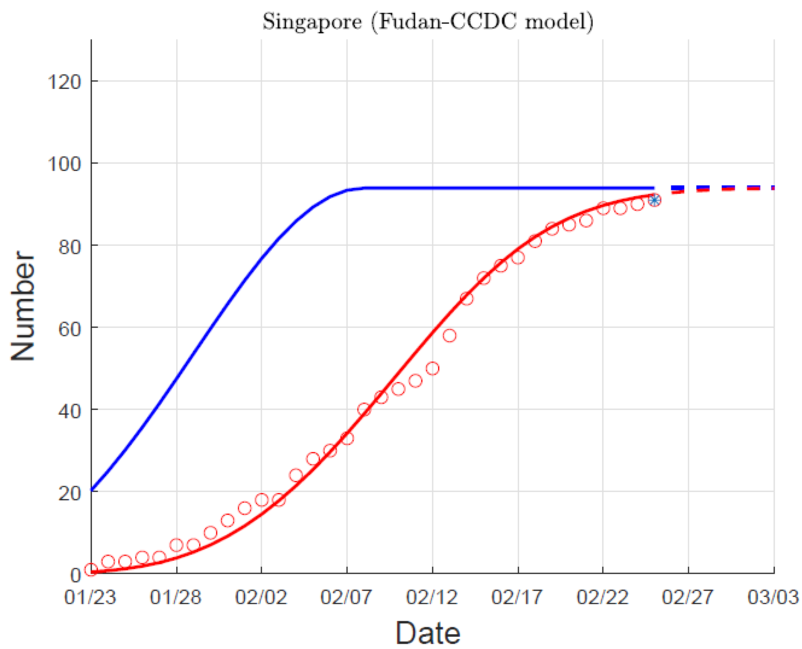

上海市现代应用数学重点实验室
Shanghai Key Laboratory of Contemporary Applied Mathematics

COVID-19 in Singapore: another story of success

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In this paper, we develop the Fudan-CCDC model by adding a source term to describe the imported infectors. The model is applied to analyze the situation of COVID-19 in East Asia, and then in Singapore. By data fitting, our model reveals that Singapore has a much higher isolation rate and earlier quarantine measures compared to other countries. We conclude that Singapore has been doing extraordinarily well on epidemic prevention and control. Finally we discuss the specific measures in Singapore's success, and suggest other countries to learn from the Singapore model, so as to be well-prepared in the future.

Introduction

In late December 2019, COVID-19 broke out in Wuhan, Hubei Province, China, and quickly spread all over China. The outbreak has raised global attention. As of Feb 25, 2020, there have been more than 77,000 confirmed cases in mainland China and more than 2000 outside of China. Thirty-three countries have reported imported cases [26].

COVID-19 has also attracted considerable attention in academia. New models and analysis on the spread of the epidemic have been studied. Jin's group proposed a novel TDD-NCP model to simulate the evolution of the epidemic in selected areas in mainland China and successfully predicted the trend of the outbreak and analyze the impact of immigrant infectors [14, 13, 29, 17]. Chen's group developed a novel statistical time delay dynamic system [22, 21] (Fudan-CCDC model) to estimate the basic reproductive number R_0 of COVID-19 based on Wallinga and Lipsitch's framework [25] with the distribution of the generation interval of the infection obtained from [16]. In addition, Fudan-CCDC model revealed the importance of early and effective quarantine measures. The authors later applied the model to analyze the epidemic in Japan and drew conclusions that a possible rapid outbreak might happen in Japan if no effective quarantine measures were carried out immediately. Other models could be found in [20, 18, 27, 30, 15, 28, 19].

In the rest of this paper, we start with explaining our model. Then, we apply the model to briefly analyze the current situation of COVID-19 in East Asia. After that, the epidemic in Singapore is studied and the reason of its success is discussed. Finally, we suggest other countries learn from Singapore's success and be well-prepared when the next battle comes.

Model

We introduce our model by adding a source term on the discrete version of the FUDAN-CCDC model that we proposed recently in [22]: for $t > t_0$,

$$
\begin{aligned}
I(t+1) &= I(t) + rI_0(t) + I_{\mathrm{s}}(t), \\
J(t+1) &= J(t) + r\sum_{s\le t} f_4(t-s)I_0(s), \\
G(t+1) &= G(t) + \ell(t)\sum_{s\le t} f_2(t-s)I_0(s) - \ell(t)\sum_{s\le t} f_4(t-s)I_0(s).
\end{aligned}
$$

A sketch map of the model is displayed in Figure 1. At day t, groups $I(t)$, $J(t)$ and $G(t)$ represent the cumulative infected people and the cumulative confirmed cases, respectively. $G(t)$ is the instant (not cumulative) number of isolated infected not yet confirmed by the hospital. The infected ones are put into isolation (with isolation rate ℓ) once they show illness symptoms, and the newly confirmed should be removed from the isolated group. $I_0(t) := I(t) - J(t) - G(t)$ is the number of people who are potentially infectious to healthy ones–they are infected actually but not in quarantine or hospitalization. $I_{\mathrm{s}}(t)$ is the the number of imported infectors from outer source. $f_2(t)$ and $f_4(t)$ are the transition probabilities from infection to illness onset, and from infection to hospitalization, respectively, which are reconstructed from one important paper [16] by China Center for Disease Control and Prevention (CCDC), see Fig 2 therein. The parameters in the model are described as follows. All of them are identified by fitting real data.

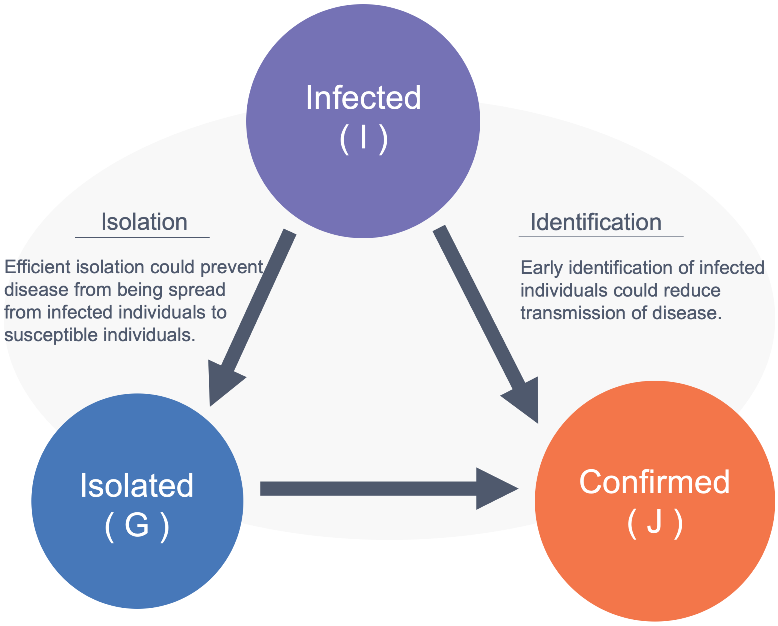


Figure 1: Sketch map of the model.

First infection date t_0. Given the initial number of the infected $I(t_0)$, our model is able to find the first infection date t_0 of the epidemic statistically correct. Tracking this initial date of the epidemic is really important and meaningful for analyzing the evolution of the epidemic.

Isolation rate ℓ. We assume that the quarantine strategy is changed at the day t_ℓ, in order to speed down the spread of the epidemic. It is modeled by a piecewise constant isolation rate ℓ:

$$\ell = \begin{cases} \ell_1, & \text{if } t_0 < t < t_\ell, \\ \ell_2, & \text{if } t \geq t_\ell. \end{cases} \tag{1}$$

We should mention here that ℓ actually impacts significantly on the final containment of the epidemic.

Growth rate r. The growth rate describes how fast the epidemic could spread. Once the growth rate r is identified, the reproductive number R_0 of COVID-19 could be determined [22].

Data source

The data employed in this paper are the cumulative confirmed cases acquired from the Coronavirus disease (COVID-19) situation reports published online by World Health Organization at [26]. All the data can be accessed publicly. No other data are used in this paper.

A brief cast on COVID-19 in East Asia

In a previous work [23], we have analyzed the current situation of the epidemic in mainland China. Our model has been performing well predicting the trend of COVID-19. We have observed that the number of infected cases grew exponentially in the early stage of the epidemic, later on restrained gradually, and finally stepped into a stable stage these days. Moreover, we have deeply studied the isolation rate ℓ and the change day t_l of quarantine strategy, and found that all the selected areas had strengthened their quarantine strategy in mid January, which could be seen from a level-up of ℓ_2 (compared to ℓ_1) in Table 1 in [23]. Therefore, we should conclude that China has indeed made great great efforts to control the epidemic. Thanks to China for saving so many lives.

Meanwhile, we are also very concerned about our close neighbours in East Asia. In [23], we have studied the epidemic in Japan and found a threshold 0.4 for Japan's isolation rate. In details, when the quarantine strategy is strict enough that the corresponding isolation rate is above the threshold 0.4, the spread of the epidemic will gradually slow down, otherwise the outbreak would be totally out of control.

The growth rate r and the isolation rate ℓ_1 for Japan and South Korea are listed in Table 1.

	r	ℓ_1
Japan	0.31867	0.31728
South Korea	0.8023	cannot be determined

Table 1: Parameters for Japan and South Korea.

The evolution of COVID-19 in Japan is demonstrated in Figure 2. Data are displayed in red scattered circles. By fitting data through the model, we show in the blue and red lines respectively the cumulative number of the infected and the confirmed. Predictions are displayed in dotted lines.

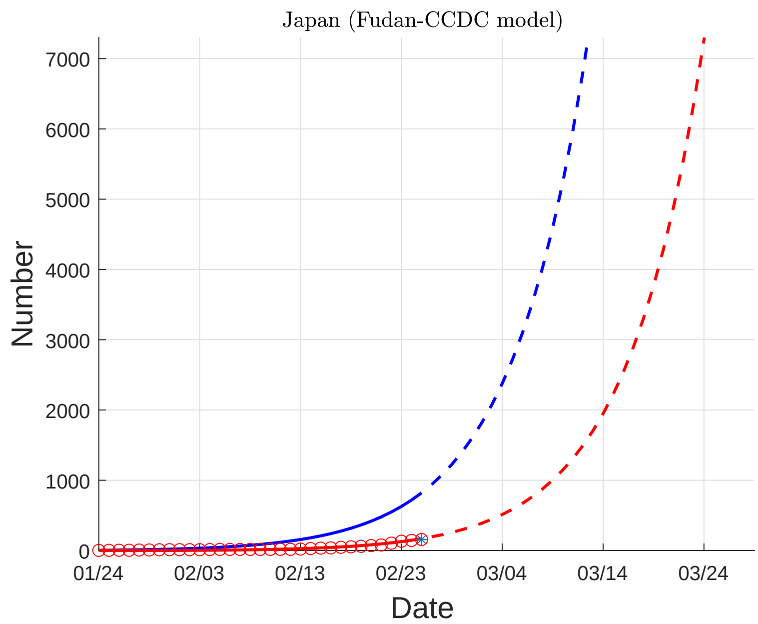


Figure 2: Epidemic evolution in Japan. Scattered: data; Blue: cumulative infected; Red: cumulative confirmed; Dotted: predictions.

We can clearly see from Figure 2 that Japan is going through an exponential growth of the epidemic under the current r and ℓ_1. The epidemic in Japan right now is very much similar to that in Wuhan in its early stage. Moreover, the current isolation rate is 0.31876, lower than the threshold 0.4, which means that the epidemic in Japan could be out of control unless more strict quarantine measures are carried out.

In Figure 3, evolutions of $\frac{1}{t}\ln\left(\frac{J(t)}{J(t_0)}\right)$ and $\frac{1}{t}\ln\left(\frac{I(t)}{I(t_0)}\right)$ are shown. We see that the curves will tend to the value of around 0.15, which means that the number of both the infected and the confirmed will continue to grow at a rate of around 0.15, if Japan maintain the current quarantine measures. The predicted numbers of the confirmed people are listed in Table 2.

Date	Mar 3	Mar 10	Mar 17	Mar 24
Predicted number	447	1145	2894	7263

Table 2: Predicted number of confirmed people in the next 28 days, under the current isolation rate.

To this end, we think it better for Japan to raise its level of quarantine measures, e.g., to isolate the confirmed people with mild symptom in hospital instead of letting them go home. We suggest Japan ask for assistance from the Chinese government.

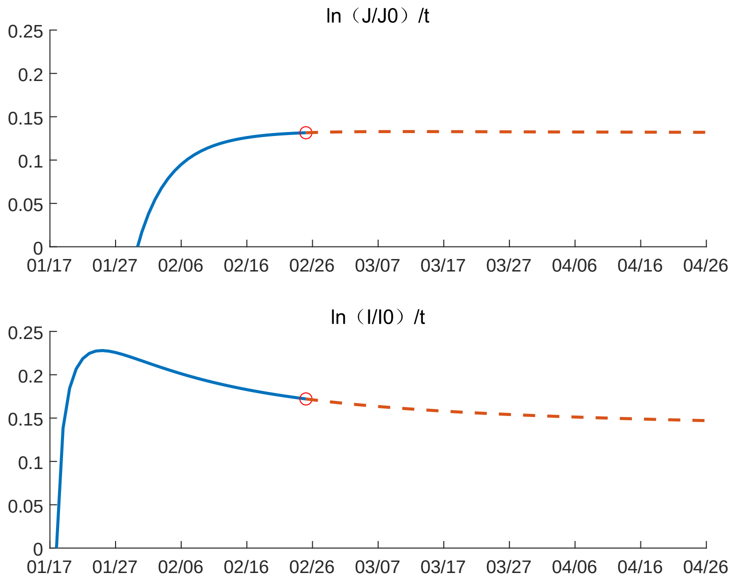


Figure 3: Evolution of $\frac{1}{t}\ln\left(\frac{J(t)}{J(t_0)}\right)$ and $\frac{1}{t}\ln\left(\frac{I(t)}{I(t_0)}\right)$.

The evolution of COVID-19 in South Korea is demonstrated in Figure 4, which shows a strong evidence of exponential growth. We may also find in Table 1 that the growth rate of the epidemic in South Korea is 0.8023, far greater than the growth rate in other countries. We are so worried that we strongly suggest South Korea attach importance to this issue. In addition, we hope more mathematicians in Japan and South Korea to notice our model and results. Discussions and verifications are always welcomed.

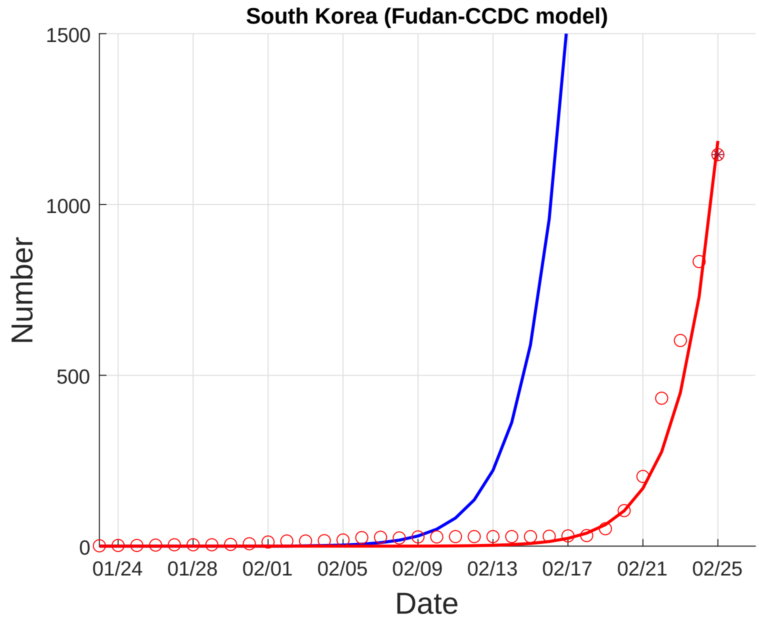
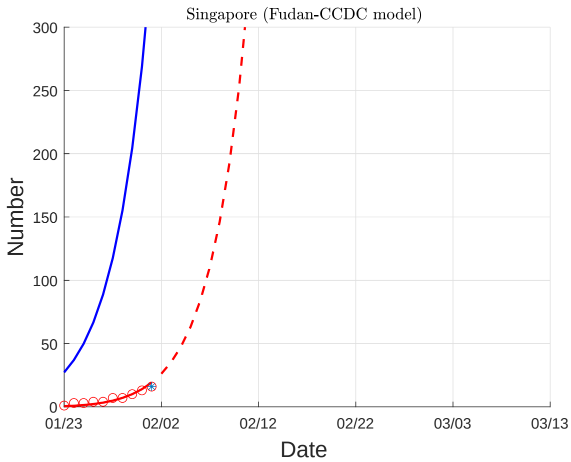


Figure 4: Epidemic evolution in South Korea. Legends are the same as that in Figure 2.

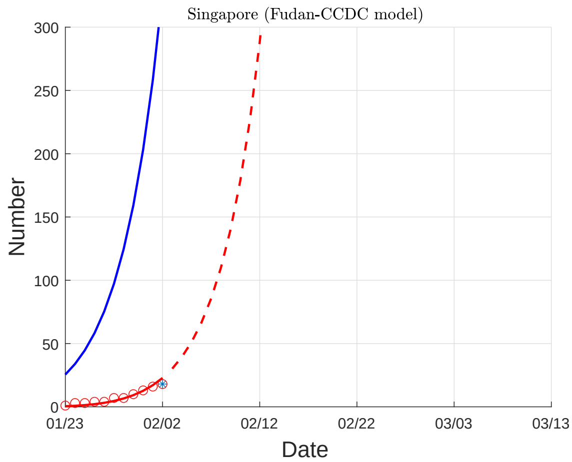
COVID-19 in Singapore

We have to admit that, we were a little worried when we heard of the speech made by the Singapore's Prime Minister Lee Hsien Loong on Feb 8, in which he did not encourage his citizens to wear face masks. We wondered whether Singapore had taken enough awareness and precautions, so we started studying the epidemic in Singapore.

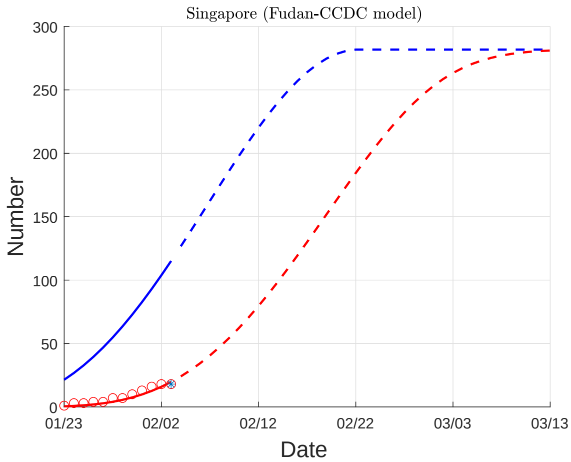
We use data from different time periods to fit in our model. Figure 5 shows the evolution of COVID-19 in Singapore between Jan 23-Feb 4. As before, red scattered circles are the data; the blue line and the red line are the number of infected people and the number of confirmed people; dotted lines are our predictions. The parameters identified by model, as well as the evolution trend are compared, as we continue to add one datum day by day in this period. We need to mention here that the growth rates r in almost all the selected periods are identified between the interval [0.33, 0.34], which is consistent with the isolation rate in China discussed in [23], so we just spare the space to study the isolation rate. From the figure we can observe that the isolation rate ℓ_1 levels up from 0.049556 on Feb 1 to 0.46146 on Feb 3, possibly indicating that Singapore might have begun its quarantine measures in a very early stage of its epidemic. Moreover, we also find in this figure that the epidemic will continue experiencing an exponential growth if the isolation rate is below the threshold 0.4 obtained in [23].



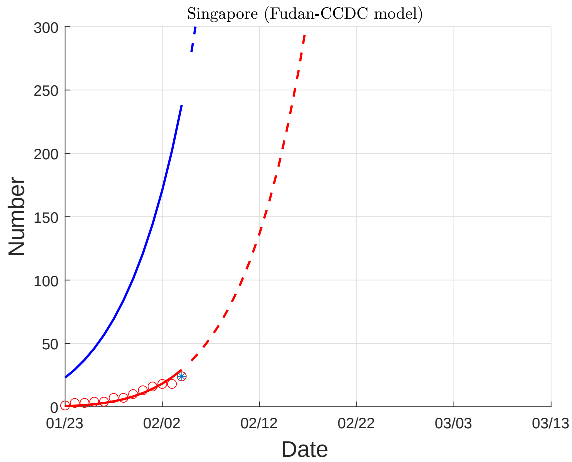
(a) $\ell_1 = 0.049556$, Jan 23-Feb 1.



(b) $\ell_1 = 0.17105$, Jan 23-Feb 2.



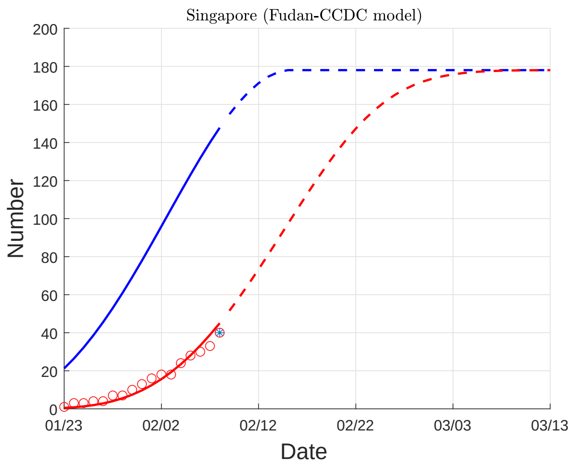
(c) $\ell_1 = 0.46146$, Jan 23-Feb 3.



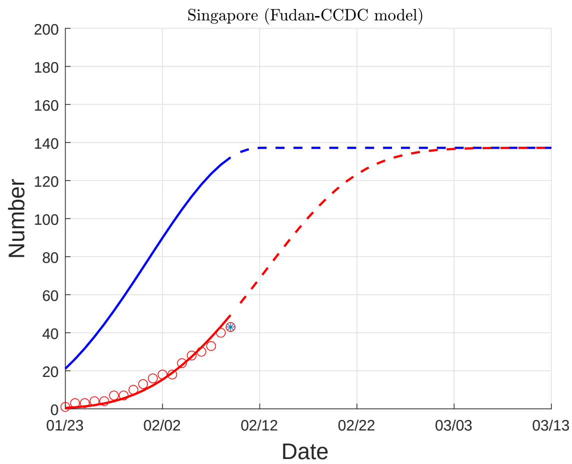
(d) $\ell_1 = 0.35539$, Jan 23-Feb 4.

Figure 5: Epidemic evolution in Singapore with data fitting period Jan 23-Feb 4.

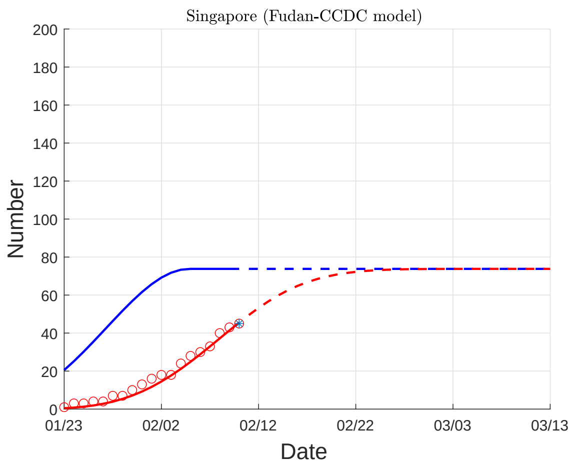
Figure 6 shows the evolution of COVID-19 in Singapore between Jan 23-Feb 11. The isolation rate ℓ_1 keeps rising from Feb 8 to Feb 11, while the predicted final total number of the infected is decreasing. It might be related to the enhancement of the quarantine strategy around this period, say, leveling up the DORSCON state to Orange on Feb 7.



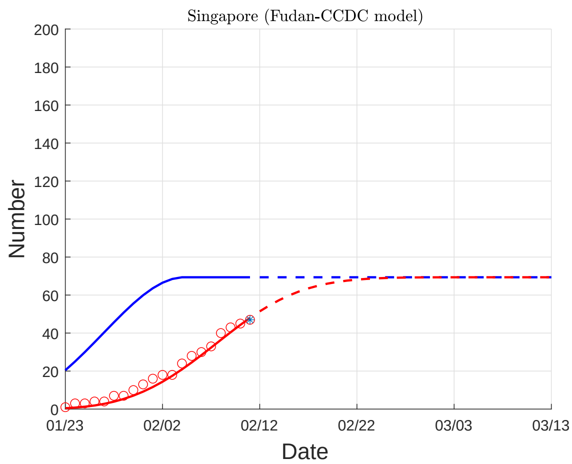
(a) $\ell_1 = 0.47585$, Jan 23-Feb 8.



(b) $\ell_1 = 0.4871$, Jan 23-Feb 9.



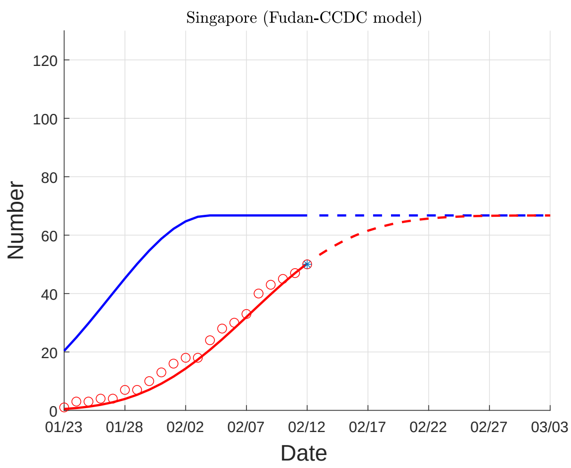
(c) $\ell_1 = 0.52846$, Jan 23-Feb 10.



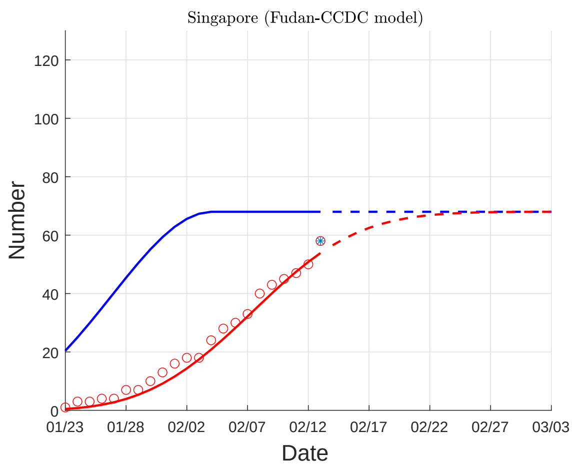
(d) $\ell_1 = 0.53415$, Jan 23-Feb 11.

Figure 6: Epidemic evolution in Singapore with data fitting period Jan 23-Feb 11.

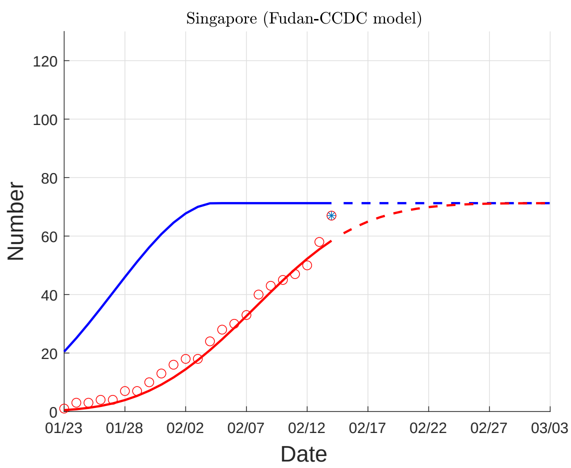
Figure 7 shows the evolution of COVID-19 in Singapore between Jan 23-Feb 15. Note that the final total number of the infected has gone up again, changing from sixties to eighties. We suspect that there might be imported infectors during this period, making contributions to the total number.



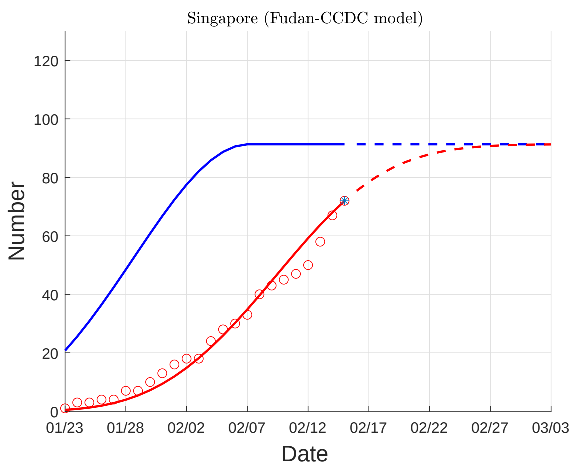
(a) $\ell_1 = 0.53791$, Jan 23-Feb 12.



(b) $\ell_1 = 0.53616$, Jan 23-Feb 13.



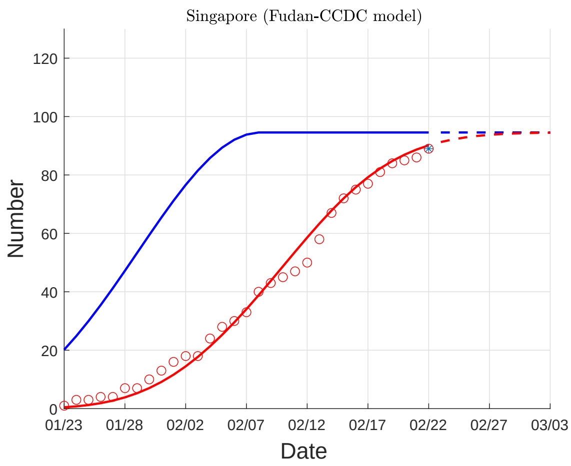
(c) $\ell_1 = 0.53148$, Jan 23-Feb 14.



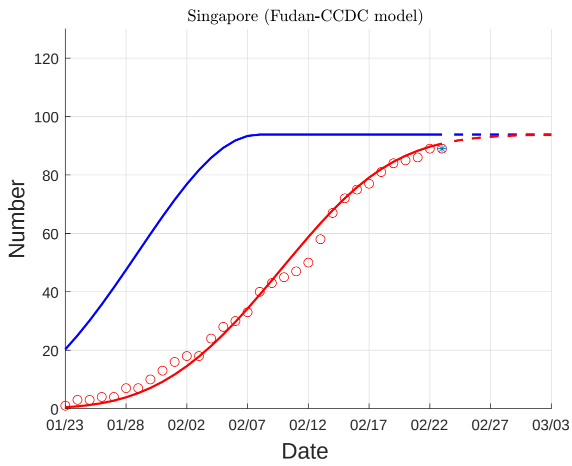
(d) $\ell_1 = 0.51126$, Jan 23-Feb 15.

Figure 7: Epidemic evolution in Singapore with data fitting period Jan 23-Feb 15.

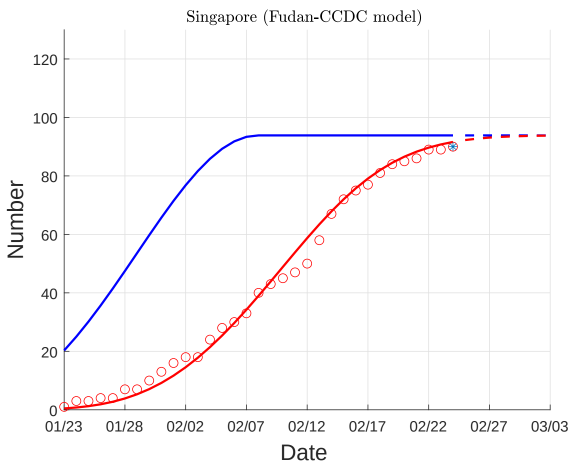
Figure 8 shows the evolution of COVID-19 in Singapore between Jan 23-Feb 25. We see that both the isolation rate ℓ_2 and the final infected number become stable, at a value of around 0.499 and 94 people, respectively.



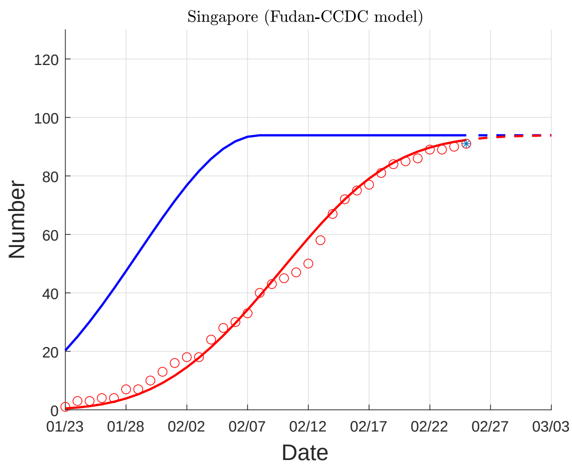
(a) $\ell_1 = 0.49596$, Jan 23-Feb 22.



(b) $\ell_1 = 0.49949$, Jan 23-Feb 23.



(c) $\ell_1 = 0.49917$, Jan 23-Feb 24.



(d) $\ell_1 = 0.49899$, Jan 23-Feb 25.

Figure 8: Epidemic evolution in Singapore with data fitting period Jan 23-Feb 25.

To conclude from the above four figures, Singapore has a relatively high isolation rate defending COVID-19. Thanks to their prompt and effective quarantine measures, the predicted final total number has decreased from above 300 to less than 100. We are surprised but also relieved to see these results. Singapore is in a much better condition than we had thought. We don't think a severe outbreak would happen in Singapore anymore as long as the current quarantine measures are maintained. Our only concern comes from those imported infectors, since Singapore is a global transportation hub. We suggest Singapore keep alert on the travellers from other countries, so as to block the external sources of transmission as much as possible.

Discussion

We had once worried whether Singapore would become the next country stricken by COVID-19. However, the truth is beyond our expectation. Our model reveals that actually Singapore has a very high isolation rate at the early stage of the epidemic there. Singapore is fighting the epidemic in a most effective and efficient way. In what follows we discuss some of their measures, all of which have been contributing in the high isolation rate in Singapore. We hope that these measures could provide reference for other countries, so that when the next battle comes, all of us would be ready.

Prompt response and advanced preparation

Respond early. Singapore has the fastest response to COVID-19 among the whole world. According to the Ministry of Health of Singapore, the Singapore government began a temperature scan of Wuhan passengers entering Singapore airport on Jan 3, 2020 [7], long before the first confirmed case in Singapore was reported. The Ministry of Health of Singapore frequently sent out information and reminders about ”new coronavirus”, as well as requirements and suggestions for epidemic preparedness in schools, kindergartens, hospitals, nursing homes and other places, while other countries did not take enough action at the very early stage which now seems to be the most important stage of epidemic control.

Prepare medical resources. As early as in January, Singapore’s medical system has already been in full action, including preparing negative pressure isolation wards and special ambulances for the epidemic, designating university dormitories as temporary isolation centers [12], etc. In addition, after experiencing SARS in 2003 with up to 238 infected, the Singapore government has set up more than 800 Public Health Preparedness Clinics (PH-

PC) to respond to public health emergencies [10]. All of these ahead-of-time preparations have saved Singapore from a potential outbreak.

Effective quarantine policies

Isolate relevant personnel. On Feb 1, all foreign tourists who had travel history to mainland China within 14 days were prohibited from entering Singapore [3]. The DORSCON (Disease Outbreak Response System Condition) level, created after the SARS outbreak in 2003, was stepped up to Orange on Feb 7, to alert the public of a possible outbreak [8]. All workers returning from China were placed under a 14-day mandatory leave of absence from work [5], and violators can be sentenced to six months' imprisonment or a fine of 10000 Singapore dollar or both [11].

Postpone gatherings. Large gatherings and meetings have been postponed or cancelled to avoid mass spread of the disease [1]. The National University of Singapore (NUS) has shifted the courses that contain more than 50 students to E-learning [2].

Provide subsidised treatment. Figure 9 shows a clinical guide provided by the Singapore Government, indicating where to go if its citizens have flu symptoms. The guide suggests a patient with mild flu symptoms going to a PHPC to receive subsidised treatment to assess whether this patient should be sent to hospital. If not necessary, the patient will receive a five-day home-treatment. Generally, an ordinary flu should be cured within five days, otherwise it may be the new coronavirus, and in this case the patient should go to the same PHPC for further diagnose. Setting up PHPCs not only helps prevent cross-infections to some extent, but also leaves the limited medical resources to those in greatest need.

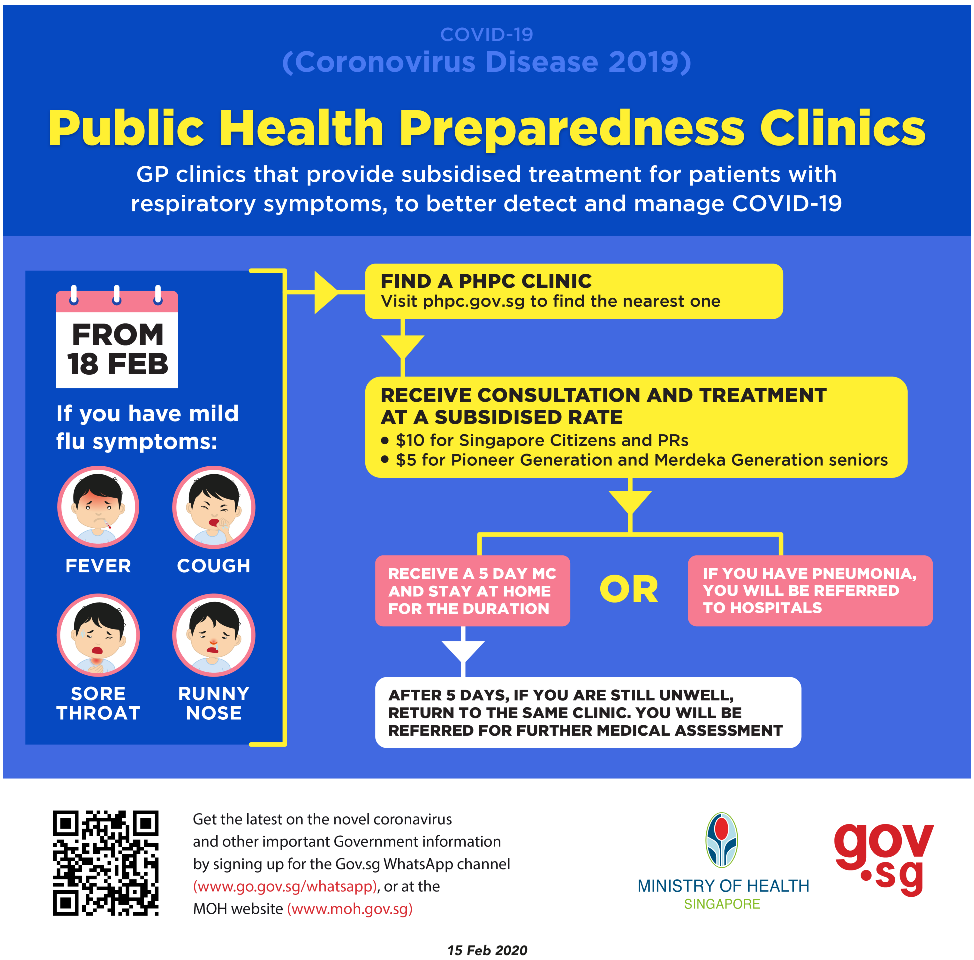


Figure 9: A clinical guide provided by the Singapore government. Source: see [4].

Trace contacts. The Singapore government publishes online the detailed activity history of each patient [9]. Cluster infections are also reported [6]. Open and transparent information by government makes contact track more efficient. In the meantime, it also helps reducing public panic.

Singapore's success in fighting COVID-19 says a great deal about how a country with virtually no natural resources can defense so strongly upon a global pandemic. The government of Singapore has expressed a strong sense of responsibility, as well as a great respect for scientists. As Sir Kenneth Stowe, former Permanent Secretary of the UK's Department of Health and

Social Security, once described an effective public bureaucracy as 'a good piano' in his paper [24] on governance, the model of Singapore is now playing a wonderful piece of music for the whole world to listen.

Acknowledgments

We thank Xudong Chen at Department of Electrical and Computer Engineering, National University of Singapore, Lady Yanmin Yang at Agency Magic, our graduated student Yuesong Nan (who now is a PhD student at Department of Mathematics, National University of Singapore), and our old friends Zhaojun Bai at UC Davis and Xiaoming Wang at South University of Science and Technology of China. Wenbin Chen also thanks Wei Ge, Rongmin Li and Bo Wu at Fudan University, Zhihua Shen at Fusion Fin Trade (fusionfintrade.com), Ling Ye at China CDC in Daishan, Zhejiang, Allen at Wind, Long Chen at University of California, Irvine, Ning Liu at Winning Health Technology Group Company (winning.com.cn), Xinkang Cao and Jinwu Zhuo at Mathworks, and Wenbin's graduated master student Weili Zhang. All of us thank our families' supports.

Funding

Wenbin Chen was supported by the National Science Foundation of China (11671098, 91630309) and supported in part by Guangdong Provincial Key Laboratory for Computational Science and Material Design 2019B030301001. Jin Cheng was supported in part by the National Science Foundation of China (11971121).

Authors contributions

The simulations are main implemented by Shao Nian and designed by Wenbin Chen. All authors conceived the study, carried out the analysis, discussed the results, drafted the first manuscript, critically read and revised the manuscript, and gave final approval for publication.

Conflict of interests

The authors declare no competing interests.

Data and materials availability The data employed in this paper are acquired from the situation reports of the World Health Organization (url: `https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports`). All the data can be accessed publicly. No other data are used in this paper.

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