

Modeling the Control of COVID-19: Impact of Policy Interventions and Meteorological Factors

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Abstract

In this paper, we propose a dynamical model to describe the transmission of COVID-19, which is spreading in China and many other countries. To avoid a larger outbreak in the worldwide, Chinese government carried out a series of strong strategies to prevent the situation from deteriorating. Home quarantine is the most important one to prevent the spread of COVID-19. In order to estimate the effect of population quarantine, we divide the population into seven categories for simulation. Based on a Least-Squares procedure and officially published data, the estimation of parameters for the proposed model is given. Numerical simulations show that the proposed model can describe the transmission of COVID-19 accurately, the corresponding prediction of the trend of the disease is given. The home quarantine strategy plays an important role in controlling the disease spread and speeding up the decline of COVID-19. The control reproduction number of most provinces in China are analyzed and discussed adequately. We should pay attention to that, though the epidemic is in decline in China, the disease still has high risk of human-to-human transmission continuously. Once the control strategy is removed, COVID-19 may become a normal epidemic disease just like flu. Further control for the disease is still necessary, we focus on the relationship between the spread rate of the virus and the meteorological conditions. A comprehensive meteorological index is introduced to represent the impact of meteorological factors on both high and low migration groups. As the progress on the new vaccine, we design detail vaccination strategies for COVID-19 in different control phases and show the effectiveness of efficient vaccination. Once the vaccine comes into use, the numerical simulation provide a promptly prospective research.

Keywords COVID-19, dynamical model, isolation strategy, meteorological index, vaccination strategy.

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1 Introduction

Coronavirus is a kind of virus that causes infectious diseases in mammals and birds. Usually, the viruses cause respiratory infections among people and the first identification is in the 1960s [1]. The main transmission of coronavirus is like other viruses: through sneezing, coughing, coming into contact with the infected people, or touching daily-used items [2]. On December 26, 2019, the first detected novel coronary pneumonia case in China was reported as an unknown etiology pneumonia in Wuhan. Evidences pointing

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to the human-to-human transmission in hospitals and families are found in retrospective studies [3–6]. It takes a few days to arouse people’s attention and Chinese Center for Disease Control and Prevention (China CDC) isolated the first strain of the causative virus (2019-nCoV) successfully on January 7, 2020. With Chinese New Year migration, the large epidemics occur in China and spread to many countries rapidly. The World Health Organization (WHO) declares that the pneumonia outbreak caused by 2019-nCoV as a public health emergency of international concern on January 31, 2020 [7]. WHO has announced the official name of the disease caused by a novel coronavirus as COVID-19 [7] on February 11, 2020, it is the seventh member of the family of coronaviruses that infect humans [8]. As of February 19, 2020, there have been 74576 confirmed COVID-19 cases, including 2118 deaths in China, there are about 30 countries around the world reported over 1000 diagnosed cases.

Among the seven known human coronavirus, four of them are common pathogens of human influenza. SARS-CoV, MERS-CoV and 2019-nCoV will cause fatal respiratory diseases [1]. Although people have identified and analyzed the coronavirus for a long time, knowledge of the coronavirus is quite limited and there are no vaccines or antiviral drugs to prevent or treat human coronavirus infections. Last major outbreak in China was SARS which is an acute respiratory infectious disease with high fatality rate caused by SARS-CoV in 2003. Chinese people managed the outbreak of SARS through multiple control and prevention measures effectively. Compared with SARS, the incubation period of COVID-19 is significant and rather long. Different mean incubation period of COVID-19 is reported, 5.2 days [9] in the early stage, 3.0 days [10] and 4.75 days [11] in recent research. The patient with up to 24 days of incubation period is reported in [10], even 38 days is also reported in Enshi Tujia and Miao Autonomous Prefecture in Hubei Province. Notice that there is quite a lot of people infected with asymptomatic [6] and the fatality is much lower than SARS-CoV and MERS-CoV [10]. Genetic studies of viruses show that the homology of SARS-CoV and 2019-nCoV is 85% [12]. But 2019-nCoV binds ACE2 with higher affinity than SARS-CoV S [13]. By the end of January 29, 2020, the confirmed cases caused by COVID-19 are surpassed SARS. The uncertain of incubation period, asymptomatic cases and super transmissibility of the virus bring great difficulties in epidemic control.

Extensive research for COVID-19 with multiple perspectives are reported. Corresponding diagnostic criteria and medication guide are designed and updated timely. Rapid detection reagent, anti-splash device for respirator and other special apparatus come into service quickly. Chinese government started first-level response of emergency health and safety, the mechanism for joint prevention and control is established in a short time. As the disease evolves, it is not only a medical problem, COVID-19 becomes a problem concern with many society questions. Collect the massive data related to COVID-19 and analyze the inherent linkage are quite important for the next step control strategy. Epidemic dynamics and population ecology are the key methods to study infectious diseases, theoretically.

Dynamical modeling of COVID-19 transmission are performed by many scholars. A modified SEIR model with eight components is proposed by Tang *et al.* [14], the control reproduction number under their estimation is 6.47. The travel related risks of disease spreading is evaluated in [15], which indicates the potential of domestic and global outbreak [3]. The travel restriction effect are also discussed by means of the simulation result for Beijing, it shows that with travel restriction (no imported exposed individuals to Beijing), the number of infected individuals in seven days will decrease by 91.14%, compared with the scenario of no travel restriction. A Bats-Hosts-Reservoir-People network is developed in [16] for simulating the potential transmission from the infection source (probable be bats) to the human infection and the analytic form of basic reproduction number for a simplified Reservoir-People network is calculated. Ming *et al.* [17] apply a modified SIR model to project the actual number of infected cases and the specific burdens on isolation wards and intensive care units (ICU). The estimation suggests that assuming 50% diagnosis rate if no public health interventions are implemented, the actual number of infected cases could be much higher than the reported. Chen *et al.* [18] propose a novel dynamical system with time delay to present the incubation period behavior of COVID-19, the estimated parameters show that the prediction is highly dependent on the population size and public policy carrying on by the local governments.

In this paper, we propose an extended SEIR model to describe the transmission of COVID-19 in China. In order to avoid the situation worsening, Chinese government has pursued the most strictest

isolation strategy for all people throughout the country to restrict the population mobility. Traffic control, limitation of travel, extension of the Chinese New Year vacations, delay to return to work, rigorous management of communities and even the wartime management ensure the susceptible population stay at home. At this stage, the main aim of the disease control is called 'the prevention of disease spreading inside'. The proposed model mainly focuses on the home quarantine strategy. It requires people to stay at home for at least 14 days, which is aiming at reduce the chance of contact with the infected people as much as possible. The asymptomatic transmission and isolation treatment policy are also taking into account in this paper. We use the official data published by China CDC and employ a Least-Squares procedure to estimate the parameters. We simulate the cases of most provinces in China, calculate the control reproduction number (\mathcal{R}_c^0) for each selected provinces. To capture the variation of effective control reproduction number ($\mathcal{R}_c(t)$), we divide the control process into three periods, calculate the average of $\mathcal{R}_c(t)$ for each stage and compare the results inside and outside Hubei province. The numerical results show that the intervention and support strategy carried out by the government decreases $\mathcal{R}_c(t)$ quickly. Chinese government provide free medical care for the diagnostic COVID-19 patient. Furthermore, as of 24:00 on February 14, 217 medical teams (military medical teams are not included) including 25633 team members have arrived Hubei from all over China. It relieved the medical pressures of Hubei Province greatly. We estimate the disease burden by means of accumulated medical resource needed in 90 days, the peak value and peak time of the diagnostic population are also given in the numerical simulation part.

Study shows that SARS-CoV and 2019-nCoV share high homology with genes, there should be similarity between them. Back to 2003, there is no vaccine or specific medicine for SARS, however, it seems disappear overnight. Weather factor is considered as an important reason for the vanishing of SARS [19, 20]. It has pointed out that high temperature will weaken the activity of SARS-CoV [21]. Spring is coming in China, the meteorological factors, such as temperature and humidity, is changing. To clarify the relationship between the meteorological condition and the transmission of COVID-19, we obtain the weather data from China Meteorological Data Service Center (CMDSC) and define a comprehensive meteorological index MeI . The outbreak of COVID-19 coincides with Chinese New Year Migration, based on the migration level, we separate all the selected provinces into two groups. The correlation analysis shows that for the spread rate are significantly associated with MeI in each group. The air index plays an important but interesting role, it is a positive factor in the low-migration group, but negative in the high-migration group. The high relative humidity helps to control the spread of COVID-19 for both groups.

Some progress on the vaccines for COVID-19 are reported, we change the quarantined compartment into the vaccinated in the proposed model to describe the effect of vaccination. We simulate three scenarios to represent the vaccination starting from the three control phases, say, the first 7 days (prophase), the second 7 days (metaphase) and the following 14 days (anaphase). The results show that the efficient vaccination accelerates the diagnostic population to the peak and contributes to reduce $\mathcal{R}_c(t)$ effectively.

The remaining parts of the paper are organized as follows. Based on the proposed dynamical model, we analyze the current control strategy in Section 2. We discuss the impact of meteorological factors and vaccines in Section 3. Finally, we present some concluding remarks in Section 4.

2 Analysis for current control strategy

2.1 Model formulation

Based on the epidemiological feature of COVID-19 and the isolation strategy carrying out by the government, we extend the classical SEIR model to describe the transmission of COVID-19 in China. We use a short-term model to describe the strictest isolation strategy, the population is assumed relatively fixed. Consideration must be given to both the actual situations and theoretical analysis, some simplifications are necessary. This model satisfies the following assumptions,

- (1) All coefficients involved in the model are positive constants.
- (2) It is a short-term model, so the natural birth and death rate are not considered.
- (3) If one has been cured well, the immune efficacy will maintain for some time, i.e. second infection is not considered in the model.

Based on the above assumptions and actual isolation strategy, the spread of COVID-19 in the populations is shown in Figure 1.

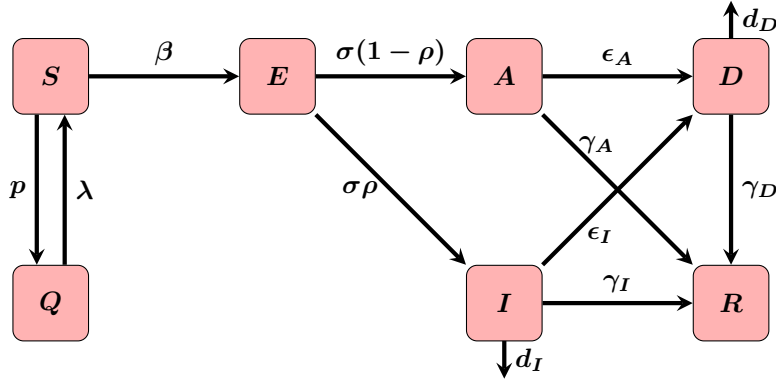


Figure 1 Flow diagram of the compartmental model of COVID-19 in China

And the corresponding dynamical model is formulated as follows,

$$\begin{aligned}
 \frac{dS}{dt} &= -\beta S(I + \theta A) - pS + \lambda Q \\
 \frac{dQ}{dt} &= pS - \lambda Q \\
 \frac{dE}{dt} &= \beta S(I + \theta A) - \sigma E \\
 \frac{dA}{dt} &= \sigma(1 - \rho)E - \epsilon_A A - \gamma_A A \\
 \frac{dI}{dt} &= \sigma\rho E - \gamma_I I - d_I I - \epsilon_I I \\
 \frac{dD}{dt} &= \epsilon_A A + \epsilon_I I - d_D D - \gamma_D D \\
 \frac{dR}{dt} &= \gamma_A A + \gamma_I I + \gamma_D D
 \end{aligned} \tag{2.1}$$

The population is divided into seven compartments, where $S(t)$, $E(t)$, $I(t)$, $R(t)$, $Q(t)$, $A(t)$ and $D(t)$ denote the susceptible, exposed, infectious with symptoms, recovered, home quarantined, asymptomatic infected and diagnosed individuals at time t , respectively. The exposed class means low-level virus carriers, which are considered to be no infectiousness. The class $Q(t)$ denotes the class in which the individual who is in the process of home quarantine, according to their travel limitation and the rigorous management of communities, we suppose that they won't contact with the infected population. Specially, in order to match the reported data better, the class $D(t)$ represents the number of medical confirmed cases which are in isolation treatment at time t .

In system (2.1), we adopt bilinear incidence rates to describe the infection of disease and parameter β denotes the contact rate. The spread ability between infectious individuals with symptoms and asymptomatic infectious class is different, parameter $\theta \in (0, 1)$ is used to describe the difference. We use parameter p and λ to present the quarantined rate and release rate of quarantined compartment Q ,

respectively. Transition rate of exposed to infected class is denoted as σ . Once infected, the proportion of becoming symptomatic is ρ and asymptomatic is $1 - \rho$. Diagnostic rate of asymptomatic and symptomatic infectious are ϵ_A and ϵ_I . And the mean recovery period of class A, I, D are $1/\gamma_A, 1/\gamma_I$ and $1/\gamma_D$, respectively. The parameters d_I and d_D represent the disease-induced death rate.

Under the isolation control strategy, we employ the next generation matrix approach [22] to calculate the control reproduction number,

$$\begin{aligned}\mathcal{R}_c^0 &= r(\mathcal{F} \cdot \mathcal{V}^{-1}) \\ &= \left(\frac{\beta\theta(1-\rho)}{\epsilon_A + \gamma_A} + \frac{\beta\rho}{\gamma_I + d_I + \epsilon_I} \right) S_0.\end{aligned}\quad (2.2)$$

where r denotes the spectral radius and the matrices \mathcal{F} and \mathcal{V} are given by

$$\mathcal{F} = \begin{pmatrix} 0 & \beta S\theta & \beta S \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \mathcal{V} = \begin{pmatrix} \sigma & 0 & 0 \\ -\sigma(1-\rho) & \epsilon_A + \gamma_A & 0 \\ -\sigma\rho & 0 & \gamma_I + d_I + \epsilon_I \end{pmatrix},$$

And the corresponding effective control reproduction number is defined as

$$\mathcal{R}_c(t) = \left(\frac{\beta\theta(1-\rho)}{\epsilon_A + \gamma_A} + \frac{\beta\rho}{\gamma_I + d_I + \epsilon_I} \right) S(t).\quad (2.3)$$

It provides us a clear index to evaluate the control strategy for any time t .

2.2 Data-Based Parameter Estimation

Data preparation

On January 23, 2020, China CDC and each provincial CDC started to publish the epidemic data in their official websites, we collect these data up to February 19 for parameter estimation. The period we select is 28 days, it is just twice of the least home quarantine period. According to the average incubation period, we divide the total control period into three phases: prophase (1-7 days), metaphase (8-14 days) and anaphase (15-28 days). $D(t)$ is an important variable in model (2.1), it can be calculated by the published data, say, $D(t)$ is equal to the accumulated diagnostic cases subtract the recovered and death cases. The counting rule of $D(t)$ is subtraction, it can avoid the loss of data immensely. We take $D(t)$ as the benchmark for fitting problem. Qinghai and Tibet have only few of diagnostic cases and the epidemic is already under control by the government, so these two provinces are excluded in our research, Hong Kong, Macao and Taiwan are also not included because of their different diagnostic criteria and control strategy.

Parameter Estimation and Prediction Procedure

In order to estimate the value of \mathcal{R}_c^0 and $\mathcal{R}_c(t)$, we use the daily published data to perform fitting. The data pre-processing is as above mentioned, the basic time scale is day. Some parameters are assumed as follows. According to the response of each province, $1/p$ is estimated as 3 to 5 days, $1/\lambda$ is taken as 60 days for most provinces. The mean incubation period ($1/\sigma$) is about 7 days [14, 23]. Based on the percentage of symptomatic infected patients reported in [23], we estimate the proportion of symptomatic in the infected class in [0.7, 0.99]. Although the testing kits are developed and come into service quickly, the shortage of capacity delays the diagnosis. Refer to the detail of confirmed cases, the average time of diagnosis ($1/\epsilon_I$) for infectious with symptoms is taken in [3, 9]. The diagnosis of asymptomatic infected is much harder, we estimate the period ($1/\epsilon_A$) as 3 to 15 days. Luckily, the spread ability of asymptomatic infected is limited, we set parameter $\theta \in [0.005, 0.2]$. Back to model (2.1), the mortality rate (mr) of disease can be written as

$$mr = \frac{d_D}{d_D + \gamma_D}.$$

By calculation, we set mr as 2.1% for most provinces. The death rate of patient without effective medicine care will be higher, we describe it as $d_I = c_I \cdot d_D$, where $c_I \in [1.1, 1.6]$. The relationship in average recover

period is assumed as $\gamma_A = c_A \cdot \gamma_I$ and $\gamma_D = c_D \cdot \gamma_I$, where $c_A, c_D \in [1.1, 1.5]$. The reason is that the speed of recovery in asymptomatic infected and patients with medicine care is quicker than those infected without treatment.

We employ a Least-Squares procedure to estimate parameter β and γ_I . Suppose we have a proper estimation for other parameters in (2.1), we need to solve the following optimization problem.

$$\min_{\beta, \gamma_I} \|D(t; \beta, \gamma_I) - D_{pub}\|_2, \quad (2.4)$$

where D_{pub} is the data published by CDC. Then the estimation and prediction procedure follows,

- (1) Set the initial condition for $\{S(t_0), Q(t_0), E(t_0), A(t_0), I(t_0), R(t_0)\}$ and the proper guess for the parameters in (2.1), except for β and γ_I .
- (2) Based on the official published data D_{pub} , solve the optimization problem (2.4) to obtain the estimated β^* and γ_I^* .
- (3) Based on β^* and γ_I^* , the initial condition and parameters set in Step (1), solve the dynamical system (2.1) to obtain $\{S(t), Q(t), E(t), A(t), I(t), R(t), D(t)\}$.

Remark 2.1. For initial values, the total population data is based on the report published by the National Bureau of Statistics [24]. Due to the Chinese New Year, many people are in vacation and they stay at home originally. We estimate the fraction of original home quarantine as about 30%.

Remark 2.2. Due to the change of diagnostic criteria from nucleic acid detection to clinical diagnosis, there is a jump for D_{pub} of Hubei Province on February 12, 2020 (see Figure 2(b)).

Accumulated Medical Resource Estimation

In order to avoid the delay of medical treatment caused by personal economic ability, Chinese government started to carry out free medical care strategy timely. National finance support the treatment for COVID-19 patients strongly. We introduce an index to evaluate the finance support for the disease treatment. The diagnostic compartment $D(t)$ represents the population of confirmed infected patients being treated in hospital at time t , we define the accumulated medical resource (*AMR*) needed until t_f as the integration of $D(t)$,

$$AMR = k \int_0^{t_f} D(t) dt, \quad (2.5)$$

where the parameter k represents the average index of medical resource a patient needs daily.

2.3 Numerical simulation

Prediction and Estimation

The first confirmed COVID-19 patient of China is in Wuhan, because of the limited knowledge of the disease, the control measure in Wuhan is insufficient at the beginning. It results in the outbreak of COVID-19 in Hubei Province. Due to the different circumstance inside and outside Hubei Province, the estimation and prediction are investigated for the two cases. Notice that, the spread of COVID-19 is very strong, it may cause twice outbreak without effective control. Zhong declares that, the disease may be controlled well by the end of April [25] under our powerful control strategy, we take parameter $1/\lambda$ as 90 days. Based on the procedure in Section 2.2, the corresponding parameter β and γ_I are given. The results of inside and outside Hubei province are presented in Figure 2, the blue solid line shows the fit based on current circumstances and the trends until the end of April are shown. Asterisks represent the D_{pub} . All the other parameters, initial values and the corresponding \mathcal{R}_c^0 for inside and outside of Hubei Province can be seen in Tabel 1. We find that the \mathcal{R}_c^0 outside Hubei is much higher than it in inside Hubei. This is mainly caused by the huge total size of Chinese population, it represent the initial situation in a way. To evaluate the strictest isolation strategy, we calculate the average $\mathcal{R}_c(t)$ for three stages and show them in Table 2. We can clearly see that the values of the average $\mathcal{R}_c(t)$ decrease quickly under current control strategy. It almost down to 1 in metaphase outside Hubei Province and below 1

now. The situation in Hubei Province is more complex, though the average $\mathcal{R}_c(t)$ decreases sharply, it is still greater than 1 in anaphase. The disease isn't under control completely, it still has a high risk of sustainable spread. Specific medicine and effective vaccine are absent till now, the strictest isolation strategy makes great contribution to the prevention of the disease spread, it needs to persist in.

Table 1 Parameter estimation and initial value

Parameter	Outside Hubei	Inside Hubei	Parameter	Outside Hubei	Inside Hubei
β	5.5010×10^{-9}	1.0014×10^{-7}	ϵ_I	1/4	1/3
θ	0.1000	0.1600	γ_A	0.1496	0.1500
p	1/3	1/6.2	γ_I	0.0998	0.1000
λ	1/90	1/90	γ_D	0.1496	0.1400
σ	1/7	1/7	d_I	0.0046	0.0105
ρ	0.8800	0.8800	d_D	0.0031	0.0030
ϵ_A	1/5	1/10			
\mathcal{R}_c^0	12.7700	8.5423			
$S(0)$	921984900	41419000	$I(0)$	563	1206
$Q(0)$	414225100	17751000	$D(0)$	227	494
$E(0)$	3207	2280	$R(0)$	3	31
$A(0)$	595	1450			

Table 2 Average $\mathcal{R}_c(t)$

	Prophase	Metaphase	Anaphase
Outside Hubei	6.0295	1.0843	0.6208
Inside Hubei	5.6870	2.2426	1.0560

To make a better illustration of quarantine strategy, we test different home quarantine period ($1/\lambda$) in Figure 2. The corresponding peak value, peak time of $D(t)$ and the accumulated medical resource needed in 90 days by AMR which defined in (2.5) are listed in Table 3. In Figure 2, the colorful dashed lines show that if the quarantine period isn't long enough, the isolation strategy can not work well. There needs a longer quarantine period in Hubei Province than outside. The longer quarantine period, the earlier peak time of $D(t)$ comes. Unlike normal infectious disease, the ward for COVID-19 is particular. To avoid nosocomial infection, it requires maximal barrier precautions in the hospital and there are quite a few critically ill patient in ICU. Our medical system is facing the huge challenges caused by patients shoot up rapidly, especially the peak value of $D(t)$. The study of the maximum capacity to deal with the emergency is necessary for disease control. In the simulation, the peak time of $D(t)$ in outside Hubei is on February 12, 2020 and inside Hubei is February 24, 2020, which is in line with the actual data (the last line in Table 3). By adjust the parameter λ , we find that, if we fix the quarantine period as 30 days, both the peak value and AMR are more than triple as now inside Hubei. Particularly, the peak time won't reach in three months in Hubei. The situation outside Hubei is not much better than that in Hubei. The peak time delays a week, though the peak value isn't increase much, the AMR almost doubled. More details of shorter quarantine period can be seen in Table 3. Notice that, in shorter quarantine period (5, 10 and 20 days), T_{peak} seems proportional to $1/\lambda$. It is mainly caused by a large amount of infected people, that is, the disease almost infected every susceptible person. The medical burden in shorter quarantine period situation is horrible.

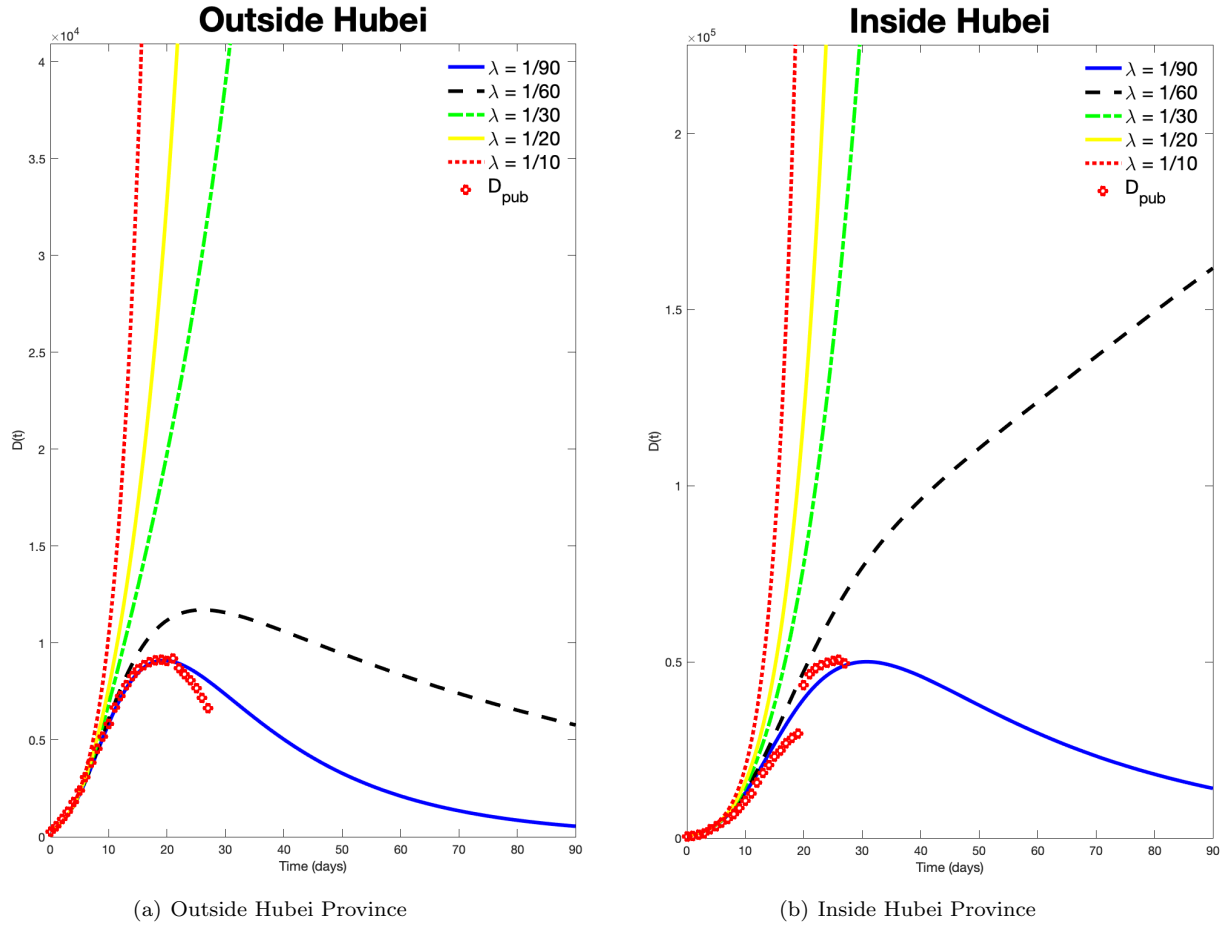


Figure 2 Optimal simulation and prediction of the transmission trend

Above study gives an intuitionistic understanding of COVID-19 in China. According to the different characters in each province, we study the transmission and control strategy of COVID-19 more intensively. The simulation for other provinces are shown in Figure 3 with blue solid lines. Colorful dashed lines represent the trends of $D(t)$ under different quarantine period. All the parameters are shown in Appendix Table 8 and Table 9. The peak value, peak time of $D(t)$ for each province under different λ can be found in Appendix Table 7. Our model fit the published data accurately for most of the provinces. We estimate the \mathcal{R}_c^0 for each province and plot the distribution heat map in Figure 4, the initial situation for each province is serious. If the control strategy is insufficient, the disease will out of control in each province. Back to the strictest isolation strategy, up to February 19, 2020, the disease is in the decline phase for most provinces, it is effective for controlling the transmission of COVID-19. Inner Mongolia, Xinjiang and Heilongjiang should pay more attention, they are in the key period of the disease control. The home quarantine period in most province can be much shorter than Hubei and the disease can also be controlled well. From Figure 3, we find that, the trends of $D(t)$ between 30 days and 60 days quarantine period are roughly the same, such as GanSu, Yunnan, Tianjin and so on. Considering the need of daily production, the workers of these provinces can return to work actively and orderly.

Table 3 Peak value, peak time of $D(t)$ and AMR during 90 days.

	Outside Hubei			Inside Hubei		
$1/\lambda$	$Peak$	T_{peak}	AMR	$Peak$	T_{peak}	AMR
90	9094	20	354017k	50041	32	2649863k
30	11706	27	743494k	161780	*	8342449k
20	1540394	*	25210395k	2503084	78	100643586k
10	47382685	*	618221390k	4372193	60	185123007k
5	142619535	67	4664793399k	7810630	45	264760516k
Data	9211	22	-	50633	27	-

¹ * do not reach peak in 90 days.

² - not applicable.

Table 4 Accumulated medical resource, 3A and designated hospital comparison

Province	Anhui	Beijing	Chongqing	Fujian	Gansu	Guangdong	Guangxi	Guizhou
AMR	28759	10216	12705	8866	1639	32278	8093	4203
N_3	20	30	11	24	12	66	25	23
N_d	271	90	104	765	99	886	48	1143
MB_3	1438	341	1155	369	137	489	324	183
MB_W	92	68	101	11	13	32	83	4
Province	Hainan	Hebei	Heilongjiang	Henan	Hubei	Hunan	Inner Mongolia	Jiangsu
AMR	4078	7495	16502	30486	2649863	21867	3167	20035
N_3	5	32	31	24	36	20	13	38
N_d	317	394	493	508	678	325	213	769
MB_3	816	234	532	1270	73607	1093	244	527
MB_W	12	16	30	55	3533	60	13	24
Province	Jiangxi	Jilin	Liaoning	Ningxia	Shaanxi	Shandong	Shanghai	Shanxi
AMR	24493	2086	3336	1384	6093	16992	7036	3371
N_3	33	20	36	3	25	21	24	32
N_d	307	133	228	73	354	541	29	205
MB_3	742	104	93	461	244	809	293	105
MB_W	66	12	11	18	15	29	91	13
Province	Sichuan	Tianjin	Xinjiang	Yunnan	Zhejiang			
AMR	16921	3660	2868	5330	28601			
N_3	36	17	9	5	26			
N_d	1910	27	176	350	323			
MB_3	470	215	319	1066	1100			
MB_W	9	60	15	15	76			

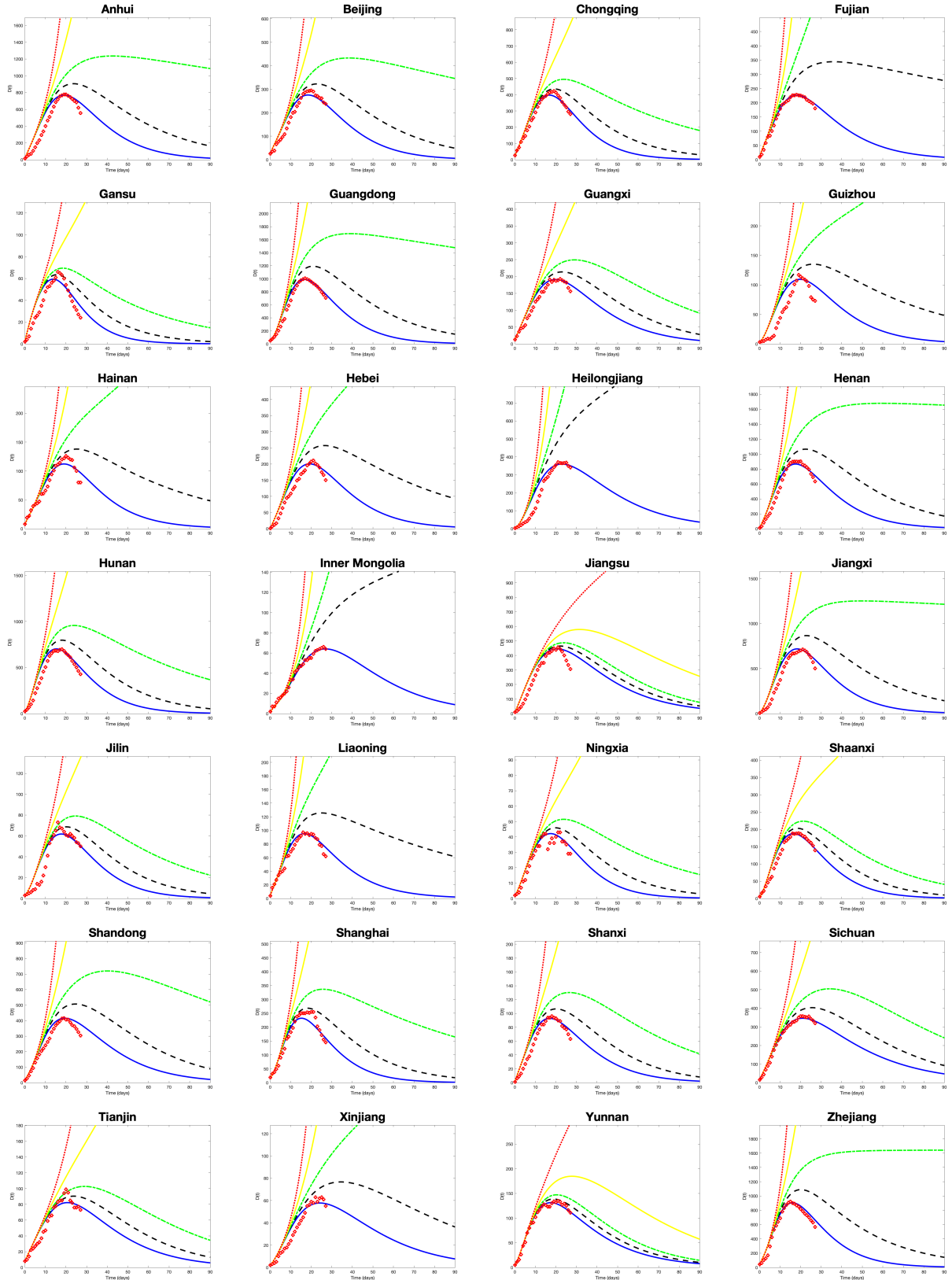


Figure 3. Simulation results of $D(t)$ (Solid blue line: $\lambda = 1/60$, dashed dark line: $\lambda = 1/30$, dash-dot green line: $\lambda = 1/20$, solid yellow line: $\lambda = 1/10$, dotted red line: $\lambda = 1/5$) and published data D_{pub} (Red asterisk).

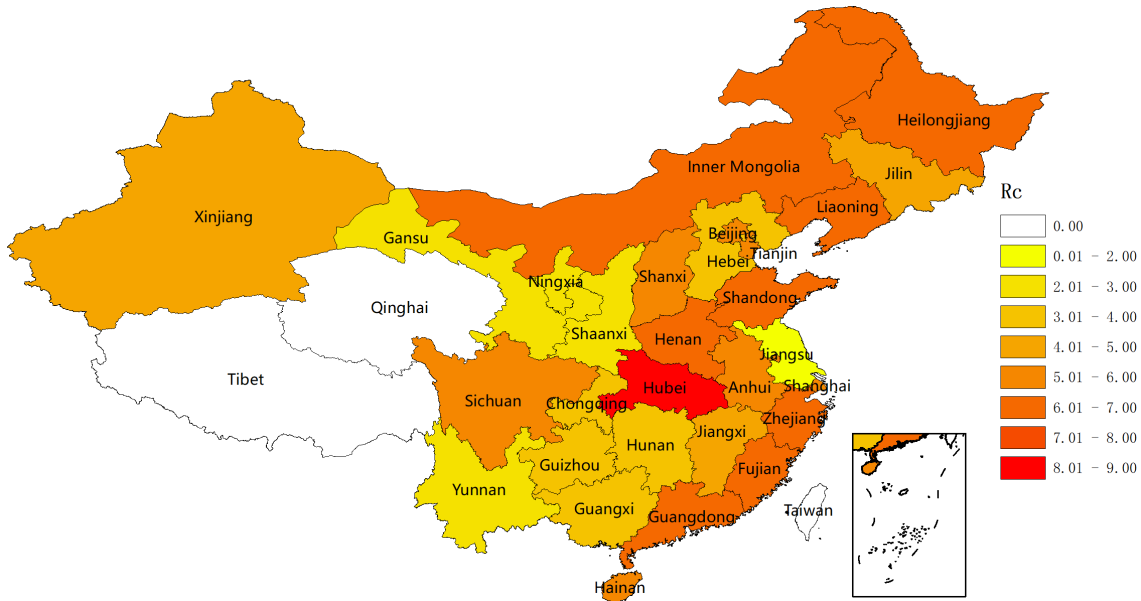


Figure 4 \mathcal{R}_c^0 distribution heat map

The medical resources in each province are distributed unevenly. After the disease outbreak, the government deployed medical resources to rescue Hubei Province. We estimate the AMR needed for each provinces by integrating $D(t)$ from 0 (Jan 23) to 90 (Apr 22) days under different quarantine period (5 – 60 days). The detail parameter values and corresponding AMR in 90 days are shown in Table 7. We collect the number of 3A hospital in each province, which can reflect the level of medical resources. In Table 4, we show the 3A hospital (N_3) number in each province, the medical burden (MB) is measured by

$$MB_3 = \frac{AMR}{N_3}.$$

The value of AMR is taken as the optimal simulation results, i.e., $\lambda = 1/60$. The median of MB_3 among 29 provinces is 461, then for which province the MB_3 Index is more than 461, it should be paid more attention. However, after the disease outbreak, The government established many designated hospitals and fever clinics to relieve the stress of medical resources. Denote N_d as the number of designated hospital, we set a weight between the 3A hospital and designated hospital. The weighted medical burden is described as

$$MB_W = \frac{AMR}{3 * N_3 + (N_d - N_3)}.$$

Comparing the value of MB_3 with MB_W in each province, we can clearly see that, thanks to the adjoint of designated hospital, it has decreased the medical burden sharply. It is benefit for early diagnosis, early isolation and better treatment. But the disease burden in Hubei is still huge, it is almost 60 times greater than other province. On one hand, we have taken full advantage of current medical resources; on the other hand, the additional medical workers and materials from other province are supported to Hubei Province spare no effort. Sufficient and effective medical support is the basic foundation to control COVID-19.

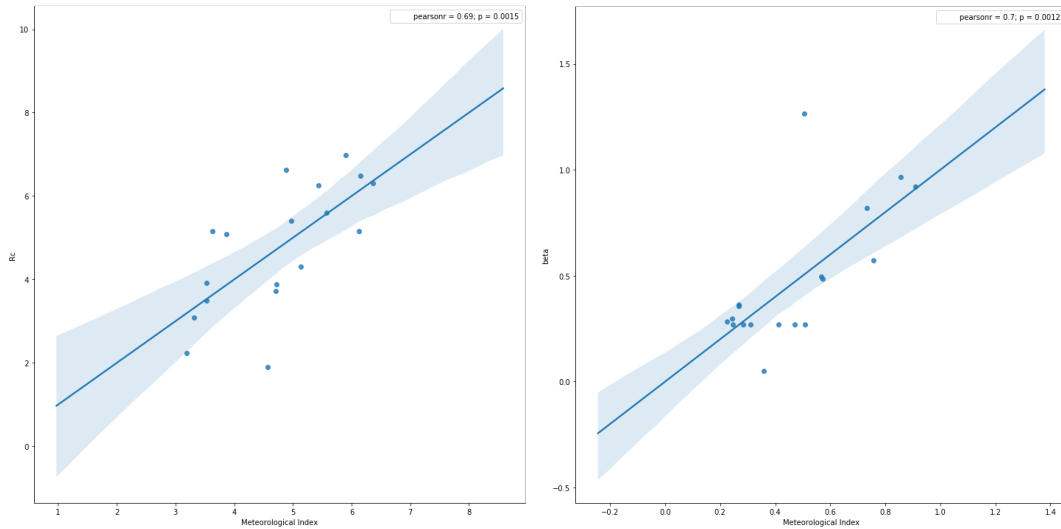
3 Further trends for the control of COVID-19

In previous section, the transmission of COVID-19 inside and outside Hubei is discussed. Simulations for most provinces can conduce to understand the effect of control strategy in China. And the corresponding analysis for medical resources are given. Isolation strategy plays an important role in the prevention of disease spreading. But the strictest isolation strategy brings great inconvenient to people's daily life.

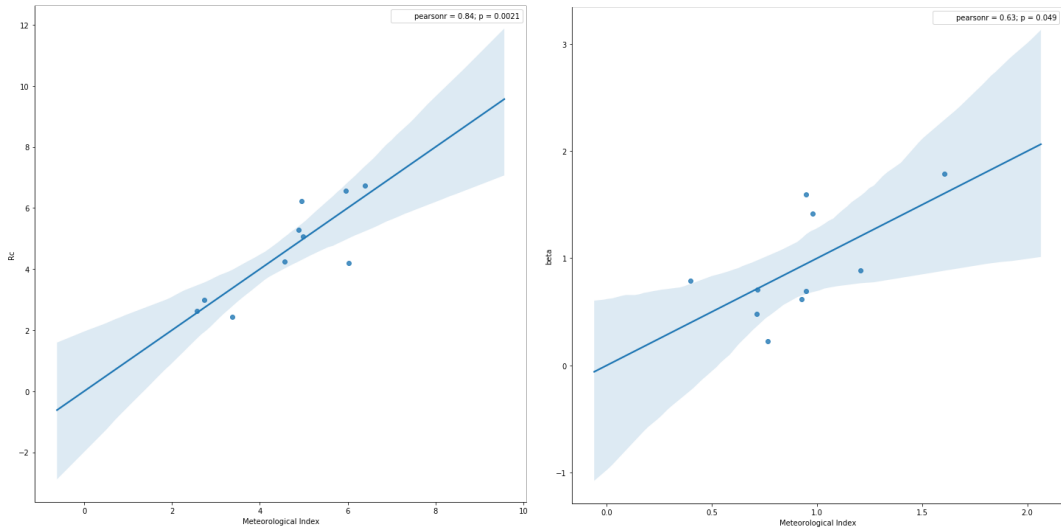
Now the disease spread is in decline, more and more people will return to their normal life paths. In this section, we will explore further control strategy from different perspectives for the following control phase.

3.1 The impact of Meteorological Index (MeI)

Seventeen years ago, SARS outbreaked in China, it spread quickly and disappeared suddenly. There is no specific medicine and vaccine, the medical level and control strategy are not as complete as today. Meteorological factor is regarded as a critical role for the vanishing of SARS [19, 20]. Due to the high genetic homology of SARS-CoV and 2019-nCoV, we want to clarify the meteorological influence in the spreading of COVID-19. We collect the official published the average meteorological data during the simulation period, including air index (AI), temperature (TE), precipitation (PR), relative humidity (RH) and wind power (WP) from China Meteorological Data Service Center (CMDC) website [26] for correlation analysis.



(a) Group I. (Left, \mathcal{R}_c^0 , $r = 0.69$, $p = 0.0015$; Right, β , $r = 0.70$, $p = 0.0012$.)



(b) Group II. (Left, \mathcal{R}_c^0 , $r = 0.84$, $p = 0.0021$; Right, β , $r = 0.63$, $p = 0.049$.)

Figure 5 Correlation analysis of \mathcal{R}_c^0 , β and MeI .

The outbreak of COVID-19 coincided with Chinese New Year, the population migration is busy at that time. Wuhan is the towngate of nine provinces, a large number of people moved out or passed by Wuhan. Population migration is a key factor in the spread process and this factor cannot be ignored in the analysis. We define an index MiI for each provinces to reflect the population migrate from Hubei Province, the geographical distance from Wuhan is also considered.

$$MiI = C \frac{PE}{DIS^2},$$

where PE is the percentage of population moving in from Hubei, DIS is the distance between the capital of destination province and Wuhan, $C = 10^{10}$ is an adjustment constant. The parameter PE and DIS are from Baidu Migration [27] and Baidu Map [28].

Based on the descending order of MiI for provinces outside Hubei (see Table 5 for details), we separate them into two groups to represent different migration levels. We set critical value as $MiI_y = 100$. If the value of MiI is greater than MiI_y , it is in the high level group called Group I, others provinces are in low level group called Group II. From Table 5, the high MiI areas are almost the province surround Hubei Province.

Table 5 Migration Index Computation

Province	Hunan	Jiangxi	Henan	Anhui	Jiangsu	Chongqing	Guangdong
PE	15.65%	7.75%	18.66%	6.58%	3.86%	8.23%	7.27%
DIS	284.4	254.5	468.2	304.3	452.3	759.1	835.9
MiI	19349	11965	8512	7106	1887	1428	1041
Province	Zhejiang	Shaanxi	Shandong	Fujian	Sichuan	Hebei	Shanghai
PE	3.1%	3.59%	2.74%	2.47%	4.49%	1.84%	1.13%
DIS	558.3	662.5	726.1	690.3	985.4	836.6	684.7
MiI	995	818	520	518	462	320	241
Province	Guizhou	Shanxi	Guangxi	Beijing	Yunnan	Gansu	Hainan
PE	1.68%	1.25%	1.98%	1.44%	1.24%	0.84%	0.86%
DIS	869.5	825.8	1048.1	1054.7	1295.3	1155	1242.1
MiI	222	183	180	130	74	63	56
Province	Liaoning	Tianjin	InnerMongolia	Heilongjiang	Jilin	Ningxia	Xinjiang
PE	0.67%	0.28%	0.32%	0.52%	0.36%	0.11%	0.26%
DIS	1480.4	976.6	1161.4	2000.2	1760.4	1145.6	2770.4
MiI	31	29	24	13	12	8	3

Based on above grouping criteria, we use the following formula and linear regression procedure to calculate a comprehensive meteorological index MeI and apply the correlation analysis to \mathcal{R}_c^0, β and MeI for each group.

$$MeI = c_1 \ln(AI) + c_2 TE + c_3 PR^2 + c_4 RH + c_5 WP + c_6. \quad (3.1)$$

The coefficients and intercepts are listed in Table 6. For each group, we calculate $MeI_{\mathcal{R}_c^0}$ and MeI_{β} and perform the correlation analysis with \mathcal{R}_c^0 and β , respectively. The results are presented in Figure 5, it shows that \mathcal{R}_c^0 and β are significantly associated with MeI .

The coefficients in Table 6 remind us that the effort of meteorology factors on the disease spread is quite different between the two groups. For example, air index is the most important meteorology factor

Table 6 Linear regression coefficients and intercept for \mathcal{R}_c^0, β and MeI .

	c_1	c_2	c_3	c_4	c_5	c_6
Group I						
$MeI_{\mathcal{R}_c^0}$	-2.0598	0.1193	1.6884×10^{-4}	-0.1439	0.1843	21.5757
$MeI_{\beta}(\times 10^{-8})$	-6.6671	-0.2991	3.9571×10^{-4}	-0.1833	-2.1504	50.3030
Group II						
$MeI_{\mathcal{R}_c^0}$	1.8802	-0.1799	0.0132	-0.1390	1.1656	-0.3215
$MeI_{\beta}(\times 10^{-8})$	2.5854	0.0188	0.0269	-0.1984	-2.1882	9.7468

in our study, in high MiI group, $\ln(AI)$ is inversely proportional to $MeI_{\mathcal{R}_c^0}$, however, in low MiI group, the result is inverse. The reason is that, the fraction of imported cases is high in high MiI group, if the value of AI is small, it represents good air condition, the social activities will increase. In this case, the probability of contact with infected people is increased. In low MiI group, the bad air condition will aggravate the spread. The impact of wind power in both group has similar pattern. Bad air condition and strong wind suggests that, people should pay more attention to the personal protection. In high MiI group, higher temperature will cause undesirable impact on the control of disease. However, in low MiI group, the result shows that higher temperature will reduce the spread. Precipitation shows low influence on COVID-19 spread. Notice that, the results in both groups show that higher relative humidity is the protection factor for the disease control.

3.2 Further control with new vaccine

On February 22, 2020, Zhejiang Government reported some progress on the vaccine of 2019-nCoV. It is said that the first vaccine has produced antibodies and the process is in the animal experiment [29]. The director-general of WHO said that there are more than 20 COVID-19 vaccines candidates are currently in development phase and some new treatment are in clinical trials, the results will be expected within a few weeks [30]. The progress of the development of vaccines is much quicker than expected. If the new vaccine of COVID-19 comes into service, it will be great benefit for the disease control. Considering the strictest isolation strategy, from the mathematical point of view, the process of the strategy is just like a short-time vaccine for susceptible population. The effect of stay away from the source of infection is equal to contact with infected people but doesn't get infected. After a little modification on model (2.1), it can describe the impact of the vaccine, by changing the quarantine compartment Q into the vaccine compartment V and setting parameter p as the vaccination rate, $1/\lambda$ as the mean protection period of the new vaccine.

Though the vaccine hasn't come into service, the theoretical analysis is necessary to make better control. In this section, we show the effect of different starting time we begin to use vaccine inside and outside Hubei Province. Considering the three control phases we defined, we take the starting day on January 28 (prophase), February 2 (metaphase) and February 12 (anaphase). We assume the average vaccination period is five year, it means $\lambda = 1/1825$. We test different parameter p to present the impact of vaccination efficiency, the corresponding numerical results are shown in Figure 6 and Figure 7. In the area of outside Hubei Province, we take the parameter p as $1/3$ and $1/7$ to compare with current control strategy ($p = 1/3$). We find that the application of vaccine accelerates the epidemic process, bring the peak forward and reduce total amount of diagnostic population. The trends of $\mathcal{R}_c(t)$ with vaccine are much lower than that in current strategy. In the simulation inside Hubei, we take p as $1/7$ and $1/14$, which is smaller than optimal simulation ($p = 1/6.2$). Totally speaking, the effect will be better as the parameter p increases. The vaccination strategy does an excellent job of reducing $\mathcal{R}_c(t)$ and effective action of taking the vaccine immunity is very important to prevent the growth of diagnostic population.

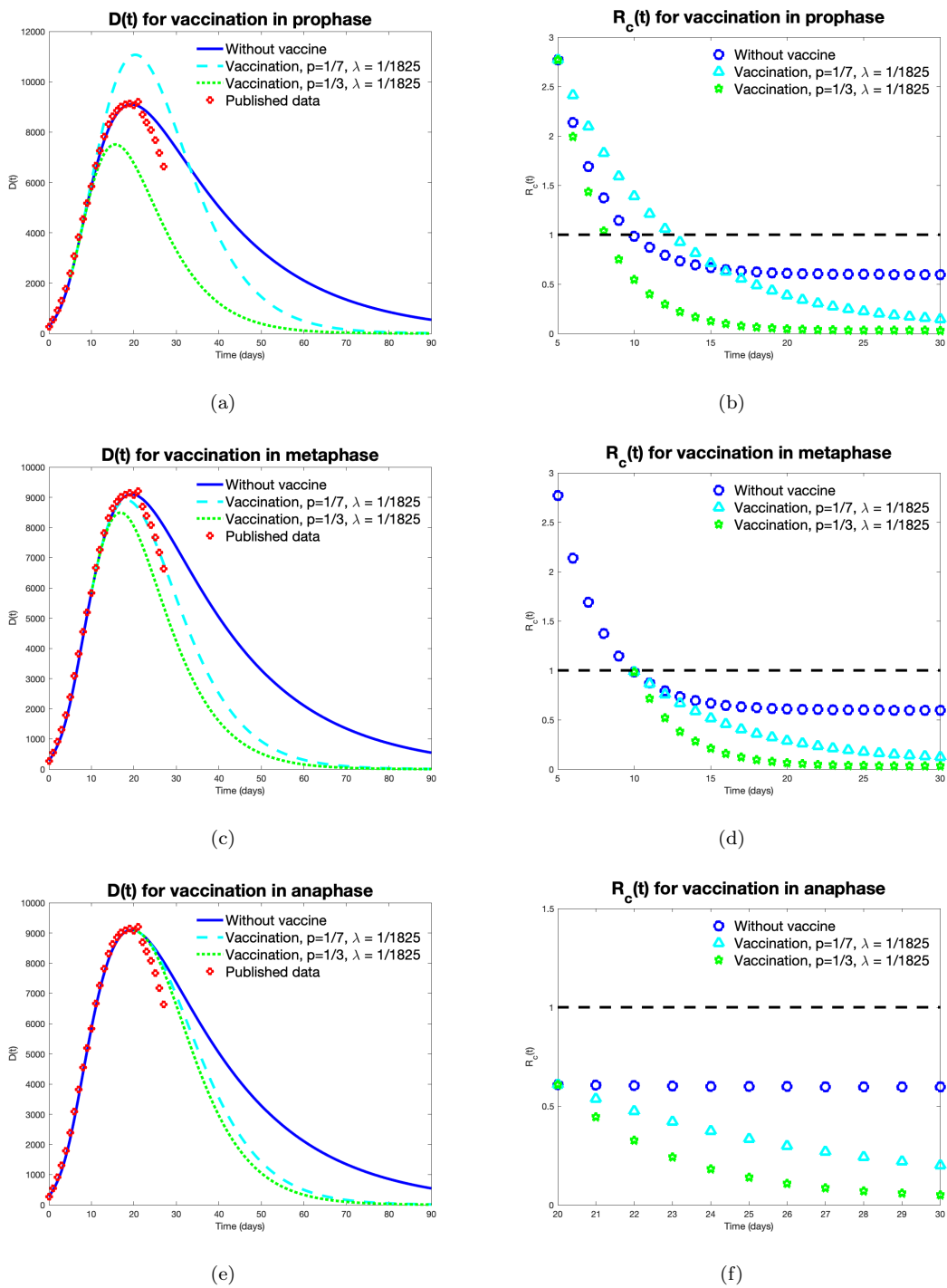


Figure 6 Impact of vaccination strategy outside Hubei Province

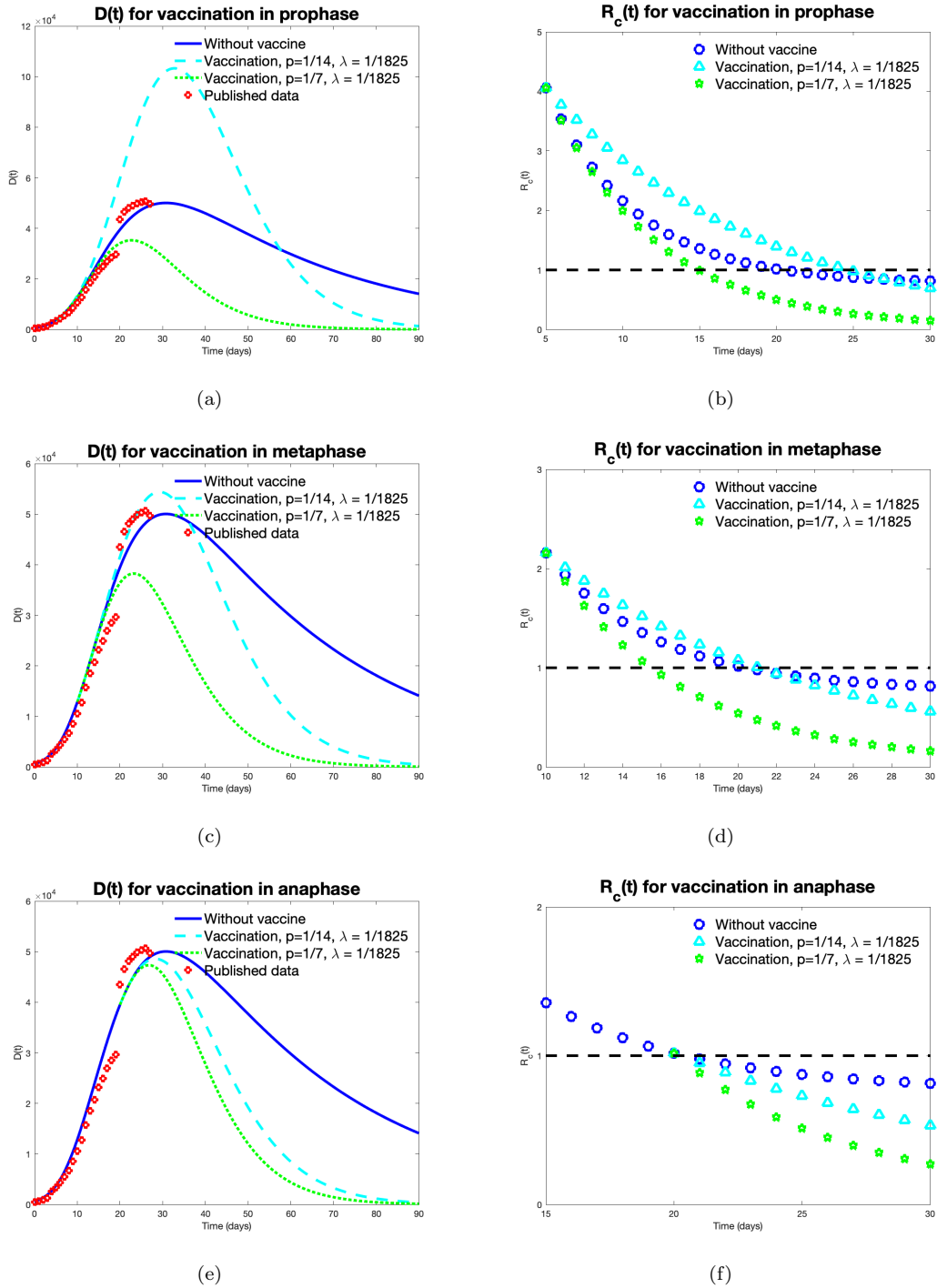


Figure 7 Impact of vaccination strategy inside Hubei Province

Both inside and outside Hubei, the control of disease in prophase should be paid more attention. If the parameter p is smaller than that in isolation strategy, the peak value of $D(t)$ will be greater than current situation. It means that, in the prophase of control, it is suitable for taking both vaccination and isolation strategy into account. Compared with isolation strategy, vaccination strategy is more convenient for our daily life and the effect persists long.

4 Conclusion

The strictest isolation strategy in China has achieved great success in current control stage. Although the control reproduction number \mathcal{R}_c^0 is high, the effective control reproduction number $\mathcal{R}_c(t)$ decreases sharply under intervention. $\mathcal{R}_c(t)$ of outside Hubei drops to the critical value on February 2, 2020, and in our simulation the value will maintain about 0.6 (see Figure 6b). In Hubei Province, $\mathcal{R}_c(t)$ reaches 1 on February 13, 2020, we can see that it is a continued momentum of decline (see Figure 7b). To have a better understanding of the isolation strategy, we simulate for each selected province, the goodness of fit shows that the proposed model is suitable to describe the situation of control in China. We find that if the isolation period isn't long enough, the strategy won't work. In Hubei Province, the quarantine period is simulated as 90 days, our result coincides with Zhong's study [25]. That is, the control period we suggest in Hubei is from January to the end of April. In the area outside Hubei, the trends of COVID-19 in most provinces between 30 days and 60 days isolation period are similar. Under careful personal protection, the people can return to their work actively and orderly in these provinces.

After the outbreak of COVID-19, China government pushed a series of policies to ensure the medical care for patients, such as early diagnosis, early isolation, free treatment and etc. We discuss the peak value and peak time of $D(t)$ in many cases. An index called AMR is well defined to measure the needs of medical resources. Sufficient medical resources is the basic of the disease control. So it is necessary to assign medical resources to deal with the shocks caused by booming demand of patients. To study the detail situation of each province, AMR and original medical power are both considered. We find that, the set up of designated hospital decreases the medical burden sharply. It has released the pressure of diagnosis and isolation in each province. But the situation of Hubei is crisis, the disease burden is still huge. Medical workers and materials are transferred to Hubei from other provinces to ensure the control of COVID-19.

There are many similarities between SARS and COVID-19, following this characteristic, we explore the relationship between the spread of COVID-19 and meteorological factors, which is considered as a key factor for the disappearance of SARS. The impact of meteorological factors is different in high and low migration groups (see Table 6). Results show that, air index is the most important meteorology factor. It strongly suggests that for low MiI group, if the air condition is bad with strong wind, please pay more attention to the personal protection. High relative humidity is a positive factor for the COVID-19 control.

In the last part, we do some preparatory work for the coming new vaccine. The situations after the vaccine comes into use are shown. We tested the different starting time in each control phase inside and outside Hubei. Vaccination strategy is more convenient for daily control. But the development cycle of new vaccine is relatively long, the isolation strategy is still necessary in early control. The analysis helps to design the final vaccination strategy once the new vaccine comes out. All of our study matches the actual control strategy in China and the results are discussed adequately. It could be a guideline for the control of COVID-19 in other countries.

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References

- 1 Wikipedia Website. <https://en.wikipedia.org/wiki/Coronavirus/>
- 2 Coronavirus: Common Symptoms, Preventive Measures, & How to Diagnose It. <https://www.caringlyyours.com/coronavirus/>. Caringly Yours. 28 January 2020. Retrieved 28 January 2020.
- 3 Joseph T Wu, Kathy Leung, Gabriel M Leung. Nowcasting and forecasting the potential domestic and international spread of the 2019-nCoV outbreak originating in Wuhan, China: A modeling study. *The Lancet*, 2020;395: 689-697.
- 4 Phan Lan T, Nguyen Thuong V, Luong Quang C, *et al.* Importation and Human-to-Human Transmission of a Novel Coronavirus in Vietnam. *New England Journal of Medicine*, 2020; 382:872-874.
- 5 Jasper Fuk-Woo Chan, Shuofeng Yuan, Kin-Hang Kok, *et al.* A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission: a study of a family cluster. *The Lancet*, 2020;395: 514-523.
- 6 Rothe C, Schunk M, Sothmann P, *et al.* Transmission of 2019-nCoV infection from an asymptomatic contact in Germany. *New England Journal of Medicine*, 2020.doi: 10.1056/NEJMc2001468.
- 7 World Health Organization Website. <https://www.who.int/>
- 8 Na Zhu, Dingyu Zhang, Wenling Wang, *et al.* A Novel Coronavirus from Patients with Pneumonia in China, 2019. *New England Journal of Medicine*, 2020; 382:727-733.
- 9 Qun Li, Xuhua Guan, Peng Wu, *et al.* Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus-Infected Pneumonia. *New England Journal of Medicine*, 2020.doi: 10.1056/NEJMoa2001316.
- 10 Weijie Guan, Zhengyi Ni, Yu Hu, *et al.* Clinical characteristics of 2019 novel coronavirus infection in China. medRxiv, 2020.doi: 10.1056/NEJMoa2002032.
- 11 Yang Yang, Qingbin Lu, Mingjin Liu, *et al.* Epidemiological and clinical features of the 2019 novel coronavirus outbreak in China. medRxiv, 2020.doi: <https://doi.org/10.1101/2020.02.10.20021675>.
- 12 Diagnosis and treatment of novel coronavirus pneumonia. (trial version Sixth, in Chinese.)
- 13 Wrapp D, Wang N, Corbett K, *et al.* Cryo-EM structure of the 2019-nCoV spike in the prefusion conformation. *Science*, 2020.doi: 10.1126/science.abb2507.
- 14 Biao Tang, Xia Wang, Qian Li, *et al.* Estimation of the Transmission Risk of the 2019-nCoV and Its Implication for Public Health Interventions. *Journal of Clinical Medicine*, 2020;9(2): 462.
- 15 Bogoch II, Watts A, Thomas-Bachli A, *et al.* Pneumonia of unknown etiology in Wuhan, China: potential for international spread via commercial air travel. *Journal of Travel Medicine*, 2020.doi:10.1093/jtm/taaa008.
- 16 Tianmu Chen, Jia Rui, Qiupeng Wang, *et al.* A mathematical model for simulating the transmission of Wuhan novel Coronavirus. bioRxiv, 2020.doi: <https://doi.org/10.1101/2020.01.19.911669>.
- 17 Wai-Kit Ming, Jian Huang, Casper J.P. Zhang. Breaking down of the healthcare system: Mathematical modelling for controlling the novel coronavirus (2019-nCoV) outbreak in Wuhan, China. bioRxiv, 2020.doi: <https://doi.org/10.1101/2020.01.27.922443>.
- 18 Yu Chen, Jin Cheng, Yu Jiang, *et al.* A Time Delay Dynamical Model for Outbreak of 2019-nCoV and the Parameter Identification. arXiv, 2020.arXiv:2002.00418.
- 19 Zhenghong Chen. A comparative study on the relationship between the epidemic of atypical pneumonia, meteorology and climate in various parts of China (in Chinese). Hubei Province Science and Technology Association. 2004: 23-28.
- 20 Zhenghong Chen, Dianxiu Ye, Hongqing Yang, *et al.* Relationship between SARS and meteorological factors in various parts of China (in Chinese). *Meteorology*, 2004 (02): 42-45.
- 21 Miriam E.R. Darnell, Kanta Subbarao, Stephen M. Feinstone, *et al.* Inactivation of the coronavirus that induces severe acute respiratory syndrome, SARS-CoV. *Journal of Virological Methods*, 2004;121(1): 85-91.
- 22 Driessche P, Watmough J. Reproduction numbers and sub-threshold endemic equilibria for compartmental models of disease transmission. *Mathematical Biosciences*. 2002;180: 29-48.
- 23 Report of the WHO-China joint mission on Coronavirus disease 2019 (COVID-19).
- 24 National Bureau of Statistics Website. <http://www.stats.gov.cn/>
- 25 Zifeng Yang, Zhiqi Zeng, Ke Wang, *et al.* Modified SEIR and AI prediction of the epidemics trend of COVID-19 in China under public health interventions. *Journal of Thoracic Disease*, 2020. doi: 10.21037/jtd.2020.02.64.
- 26 China Meteorological Data Service Center Website. <http://data.cma.cn/>
- 27 Baidu Migration Website. <http://qianxi.baidu.com/>
- 28 Baidu Map Website. <http://map.baidu.com/>
- 29 COVID-19 Information Release Platform of Zhejiang Province. <http://www.blueskyinfo.com.cn/wjwApp/webinfo/infoList.do>. Retrieved February 24, 2020.
- 30 WHO Director-General's opening remarks at the media briefing on COVID-19. <https://www.who.int/en/dg/speeches/>. Retrieved February 28, 2020.

Appendix

Table 7 Estimation of peak value, peak time of $D(t)$ and medical resource needed in 90 days.

$1/\lambda$	<i>Peak</i>	T_{peak}	<i>AMR</i>	<i>Peak</i>	T_{peak}	<i>AMR</i>	<i>Peak</i>	T_{peak}	<i>AMR</i>	<i>Peak</i>	T_{peak}	<i>AMR</i>
	Anhui			Beijing			Chongqing			Fujian		
data	777	20	–	295	21	–	423	20	–	228	19	–
60	770	20	28759k	275	19	10216k	398	18	12705k	227	19	8866k
30	905	25	46939k	322	24	16313k	436	20	18344k	344	37	25911k
20	1235	44	93412k	433	39	32269k	495	25	29820k	4989	*	135973k
10	66800	*	1231648k	27116	*	489384k	6186	*	181709k	1736757	*	18675280k
5	4348428	*	48700375k	2067882	*	24241821k	215309	*	2846363k	7237440	74	212118841k
	Gansu			Guangdong			Guangxi			Guizhou		
data	66	17	–	1007	18	–	193	23	–	117	20	–
60	59	15	1639k	988	18	32278k	191	21	8093k	109	21	4203k
30	63	16	2289k	1192	22	55932k	214	24	10768k	135	27	8058k
20	69	19	3609k	1692	40	128580k	249	30	15598k	343	*	19080k
10	718	*	23135k	257422	*	3953350k	2062	*	70888k	18929	*	299589k
5	37961	*	487756k	16571603	*	285227509k	97897	*	1273544k	1058173	*	10532875k
	Hainan			Hebei			Heilongjiang			Henan		
data	126	21	–	211	22	–	370	22	–	901	21	–
60	112	20	4078k	200	20	7495k	362	24	16787k	865	18	30486k
30	138	26	8172k	257	28	15477k	1120	*	62745k	1064	23	53455k
20	427	*	21573k	917	*	43993k	18180	*	382084k	1678	60	127687k
10	32644	*	471386k	102473	*	1343808k	3041233	*	35868972k	334575	*	4768513k
5	771931	*	11927662k	7477953	*	77594648k	7732929k	74	232380351k	17625745	*	334589749k
	Hunan			Inner Mongolia			Jiangsu			Jiangxi		
data	698	19	–	66	27	–	456	22	–	712	22	–
60	702	16	21867k	64	28	3167k	445	22	20035k	718	19	24493k
30	797	19	33027k	160	*	9703k	465	23	22492k	866	24	42908k
20	957	25	58685k	1882	*	43991k	487	25	25453k	1251	51	95956k
10	28641	*	670425k	300866	*	2807802k	579	32	37983k	112385	*	1870821k
5	3334809	*	39348405k	6566392	*	98519328k	1479	*	82541k	4696779	*	69937216k
	Jilin			Liaoning			Ningxia			Shaanxi		
data	73	17	–	97	17	–	43	22	–	189	20	–
60	62	19	2086k	95	18	3336k	42	18	1384k	187	18	6093k
30	69	21	2909k	126	26	8210k	46	21	1934k	203	19	8089k
20	79	26	4488k	892	*	32358k	51	25	2960k	223	22	11401k
10	780	*	25419k	255742	*	2739032k	385	*	13577k	816	*	40286k
5	46330	*	575506k	5402772	84	119906271k	8998	*	136715k	22248	*	391375k
	Shandong			Shanghai			Shanxi			Sichuan		
data	416	20	–	255	21	–	189	20	–	357	21	–
60	415	20	16992k	232	16	7036k	187	18	6093k	346	22	16921k
30	507	26	26645k	268	19	11108k	203	19	8089k	403	26	22616k
20	720	41	51630k	337	27	22023k	223	22	11401k	504	35	33486k
10	54739	*	955181k	25816	*	473809k	816	*	40286k	7264	*	207899k
5	11784044	*	116251444k	2900252	*	42717157k	22248	*	391375k	1016284	*	10516655k
	Tianjin			Xinjiang			Yunnan			Zhejiang		
data	99	21	–	63	23	–	135	22	–	921	16	–
60	82	22	3660k	58	25	2868k	131	18	5330k	905	17	28601k
30	90	25	4662k	77	35	5010k	139	20	6007k	1089	21	51192k
20	103	30	6341k	196	*	10834k	147	21	6861k	1642	*	127746k
10	526	*	21782k	10969	*	168818k	185	29	11161k	374851	*	5368778k
5	15458	*	236496k	1041128	*	8958716k	862	*	39412k	8395172	83	210982965k

¹ * do not reach peak in 90 days.² - not applicable.

Table 8 Simulation parameter Part I

Parameter	Anhui	Beijing	Chongqing	Fujian	Gansu	Guangdong	Guangxi
β	2.7096E-08	9.1997E-08	3.6320E-08	9.6503E-08	6.2034E-08	2.7096E-08	2.7083E-08
θ	0.1100	0.0110	0.0800	0.0900	0.0100	0.0050	0.0050
p	1/4.1	1/4	1/6.4	1/3	1/6.5	1/3	1/4
λ	1/60	1/60	1/60	1/60	1/60	1/60	1/60
σ	1/7	1/7	1/7	1/7	1/7	1/7	1/7
ρ	0.9000	0.9400	0.9900	0.9300	0.9000	0.9100	0.8800
ϵ_A	1/7	1/8	1/9	1/5	1/7	1/10	1/10
ϵ_I	1/5	1/4	1/4.5	1/4	1/4	1/3.3	1/4.5
γ_A	0.0993	0.0996	0.1190	0.0988	0.2597	0.1075	0.0579
γ_I	0.0736	0.0766	0.0992	0.0882	0.1998	0.0716	0.0386
γ_D	0.0883	0.0843	0.1487	0.0970	0.2398	0.1039	0.0560
d_I	0.0027	0.0026	0.0040	0.0022	0.0073	0.0024	0.0013
d_D	0.0018	0.0017	0.0033	0.0015	0.0049	0.0016	0.0009
R_c	5.0939	5.1544	3.0885	6.4914	2.9989	6.3126	3.7215
S(0)	56912400	19601400	27918000	24434200	24524100	96441000	40885800
Q(0)	6323600	1938600	3102000	14975800	1845900	17019000	8374200
E(0)	591	123	580	80	175	886	95
A(0)	288	81	90	65	50	37	52
I(0)	101	58	88	50	5	93	49
D(0)	15	26	27	10	2	51	13
R(0)	6	0	0	0	0	2	0
	Guizhou	Hainan	Hebei	Heilongjiang	Henan	Hunan	Inner Mongolia
β	4.9543E-08	1.8064E-07	2.7096E-08	7.9315E-08	3.5675E-08	2.9823E-08	8.8785E-08
θ	0.0500	0.1000	0.0300	0.2000	0.2000	0.1000	0.0130
p	1/4.5	1/5	1/5	1/3.5	1/3	1/3	1/5
λ	1/60	1/60	1/60	1/60	1/60	1/60	1/60
σ	1/7	1/7	1/7	1/7	1/7	1/7	1/7
ρ	0.7000	0.9000	0.9000	0.9500	0.8900	0.9100	0.9700
ϵ_A	1/15	1/10	1/7	1/7	1/4	1/10	1/5
ϵ_I	1/9	1/6	1/4	1/5	1/3	1/5.1	1/4
γ_A	0.1298	0.1495	0.1085	0.0967	0.0993	0.1085	0.0709
γ_I	0.0998	0.0997	0.0724	0.0744	0.0764	0.0986	0.0473
γ_D	0.1098	0.1396	0.1049	0.0818	0.0840	0.1085	0.0662
d_I	0.0008	0.0045	0.0024	0.0026	0.0026	0.0035	0.0020
d_D	0.0006	0.0030	0.0021	0.0018	0.0017	0.0023	0.0014
R_c	3.9208	5.1065	3.8753	6.2331	6.6235	3.5025	6.5656
S(0)	23400000	8406000	51380800	22638000	83563500	37944500	22806000
Q(0)	12600000	934000	24179200	15092000	12486500	31045500	2534000
E(0)	280	110	168	308	556	1500	16
A(0)	28	45	40	25	211	145	9
I(0)	8	25	33	15	22	65	4
D(0)	3	8	1	3	9	24	2
R(0)	0	0	0	0	0	0	0

Table 9 Simulation parameter Part II

Parameter	Jiangsu	Jiangxi	Jilin	Liaoning	Ningxia	Shaanxi	Shandong
β	5.0000E-09	4.8409E-08	4.7838E-08	6.9683E-08	1.5932E-07	2.8218E-08	2.7094E-08
θ	0.2000	0.2000	0.0050	0.0100	0.1000	0.0900	0.2000
p	1/5	1/4.5	1/4	1/3	1/7.9	1/4.5	1/3
λ	1/60	1/60	1/60	1/60	1/60	1/60	1/60
σ	1/7	1/7	1/7	1/7	1/7	1/7	1/7
ρ	0.9800	0.8000	0.9600	0.9500	0.9000	0.7000	0.9800
ϵ_A	1/10	1/10	1/6	1/10	1/5	1/10	1/5
ϵ_I	1/7	1/3.9	1/5	1/5	1/4	1/9	1/3
γ_A	0.0474	0.1296	0.1029	0.1196	0.1462	0.1298	0.0618
γ_I	0.0379	0.0997	0.0686	0.0997	0.0975	0.0999	0.0515
γ_D	0.0455	0.1087	0.0960	0.1296	0.1365	0.1098	0.0567
d_I	0.0010	0.0037	0.0029	0.0007	0.0042	0.0009	0.0017
d_D	0.0007	0.0023	0.0020	0.0007	0.0028	0.0006	0.0012
R_c	1.8970	4.3156	4.2087	6.7287	2.4398	2.2381	6.2478
S(0)	70041090	37184000	24877352	30513000	5916800	23184000	90423000
Q(0)	10465910	9296000	2163248	13077000	963200	15456000	10047000
E(0)	452	840	87	44	70	640	165
A(0)	145	50	6	25	5	36	60
I(0)	125	67	5	38	4	20	36
D(0)	9	7	3	4	3	5	15
R(0)	0	0	0	0	0	0	0
	Shanghai	Shanxi	Sichuan	Tianjin	Xinjiang	Yunnan	Zhejiang
β	1.2638E-07	8.1979E-08	2.7018E-08	1.4151E-07	7.0499E-08	2.2519E-08	5.7383E-08
θ	0.0100	0.1000	0.1100	0.0050	0.0100	0.0900	0.1000
p	1/3	1/3	1/3	1/5	1/4	1/3.2	1/3
λ	1/60	1/60	1/60	1/60	1/60	1/60	1/60
σ	1/7	1/7	1/7	1/7	1/7	1/7	1/7
ρ	0.9200	0.9000	0.9200	0.9000	0.8900	0.9800	0.9600
ϵ_A	1/4	1/3	1/4	1/10	1/9	1/4	1/6
ϵ_I	1/3	1/2.5	1/3	1/4	1/5	1/3	1/3
γ_A	0.1213	0.0809	0.0387	0.1254	0.0540	0.0491	0.1190
γ_I	0.0808	0.0622	0.0322	0.0836	0.0415	0.0327	0.0793
γ_D	0.1132	0.0685	0.0355	0.1170	0.0457	0.0458	0.1150
d_I	0.0035	0.0001	0.0011	0.0036	0.0014	0.0014	0.0017
d_D	0.0023	0.0001	0.0007	0.0024	0.0009	0.0009	0.0012
R_c	5.6066	5.4060	5.1509	5.2949	4.2468	2.6164	6.9822
S(0)	20119200	33462000	75069000	14036400	16412616	43465500	52206700
Q(0)	4120800	3718000	8341000	1559600	8454984	4829500	5163300
E(0)	266	48	140	40	40	134	456
A(0)	22	21	64	26	11	12	145
I(0)	11	8	28	15	5	10	133
D(0)	19	1	15	8	2	5	42
R(0)	3	0	0	0	0	0	1