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RESEARCH ARTICLE

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Strong policies control the spread of COVID-19 in China

Bao-Zhu Li[1,2] | Nv-Wei Cao[1,2] | Hao-Yue Zhou[1,2] | Xiu-Jie Chu[1,2] | Dong-Qing Ye[1,2]

[1]Department of Epidemiology and Biostatistics, School of Public Health, Anhui Medical University, Hefei, Anhui, China

[2]Inflammation and Immune Mediated Diseases Laboratory of Anhui Province, Anhui Medical University, Hefei, Anhui, China

Correspondence
Dong-Qing Ye, Department of Epidemiology and Biostatistics, School of Public Health, Anhui Medical University, 230032 Hefei, Anhui, China.
Email: ydqahmu@126.com

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Abstract

The coronavirus disease 2019 (COVID-19) outbroke in Wuhan, Hubei Province, China, affecting more than 200 countries and regions. This study aimed to predict the development of the epidemic with specific interventional policies applied in China and evaluate their effectiveness. COVID-19 data of Hubei Province and the next five most affected provinces were collected from daily case reports of COVID-19 on the Health Committee official website of these provinces. The number of current cases, defined as the number of confirmed cases minus the number of cured cases and those who have died, were examined in this study. A modified susceptible-exposed-infectious-removed (SEIR) model was used to assess the effects of interventional policies on the epidemic. In this study, 28 January was day 0 of the model. The results of the modified SEIR model showed that the number of current cases in Hubei and Zhejiang provinces tended to be stabilized after 70 days and after 60 days in the four other provinces. The predicted number of current cases without policy intervention was shown to far exceed that with policy intervention. The estimated number of COVID-19 cases in Hubei Province with policy intervention was predicted to peak at 51 222, whereas that without policy intervention was predicted to reach 157 721. Based on the results of the model, strong interventional policies were found to be vital components of epidemic control. Applying such policies is likely to shorten the duration of the epidemic and reduce the number of new cases.

KEYWORDS
coronavirus disease 2019, epidemic, policy, susceptible-exposed-infectious-removed

1 | INTRODUCTION

The coronavirus disease 2019 (COVID-19) has emerged to become extremely serious and is affecting more than 200 countries and regions. On 11 March, the World Health Organization (WHO) assessed COVID-19 as a pandemic.[1] The WHO has also determined that the global COVID-19 communication risk and impact risk level were very high.[2]

In December 2019, patients with pneumonia of unknown origin were reported in Wuhan, Hubei Province, China. By the end of January 2020, the epidemic had spread across the country. On 29 January, confirmed cases have appeared in all provinces of Chinese mainland. On 11 February, the International Committee on Taxonomy of Viruses officially named the new coronavirus as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). It has been proven that SARS-CoV-2 is transmitted from person to person through respiratory droplets and close contact.[3] Therefore, the occurrence of familial pneumonia is readily facilitated.[4] A range of timely and effective policies were implemented to control the spread of SARS-CoV-2. And the epidemic in China has now eased significantly. At the end of 17 April (in Beijing), 82 719 cases of COVID-19 had been confirmed in the

Bao-Zhu Li and Nv-Wei Cao are co-first authors of this paper.

mainland of China, with a total of 81 661 cases having been discharged and dead, and with 1058 current cases.

In controlling the epidemic, it is critical to address the immediate problem, and to prevent a reoccurrence in the long term, which are both equally important.[5] The task now is not only to save lives, but also to improve the overall response to the epidemic.[5] After the spread of COVID-19, policy was proposed to control the spread of the SARS-CoV-2, which mean quarantine infected individuals to block transmission routes. Furthermore, strong policies include closing cities, extending holidays, restricting population mobility, banning crowd gathering and taking temperatures,[6] which is to duly and effectively separate the infected from the susceptible. At present, researchers have focused on the clinical symptoms[7,8] and treatment options[9,10] in relation to COVID-19. Few studies have concentrated on long-term prevention and control. However, improved understanding of the possible long-term development of the epidemic is likely to help with prevention and control. To understand the development of COVID-19, a modified susceptible-exposed-infectious-removed (SEIR) model—a modified Policy-SEIR model—with control measures, was used to explore the effects of policies on the development process of COVID-19. The results of this Policy-SEIR model are intended to supply relevant data to help ensure that COVID-19 is contained and evaluate the effectiveness of interventions used in controlling the epidemic.

2 | METHODS

2.1 | Data sources

We selected Hubei Province and the next five provinces with the largest numbers of confirmed cases—Guangdong, Henan, Zhejiang, Hunan, and Anhui provinces—for investigation. The number of current COVID-19 cases was collected from daily case reports of COVID-19 on the official website of the Health Committee of these provinces. The number of current cases, defined as the number of confirmed cases minus the number of cured cases and those who have died, was examined in this study. In this study, 28 January was the start time of the model, as day 0.

2.2 | The establishment of Policy-SEIR model

Python 3.7 was used in this study to establish the Policy-SEIR model. Jupyter Notebook was applied to implement the integrated development environment. Using the traditional SEIR model, the population is divided into four categories: S represents the susceptible population; E indicates individuals in the incubation period after being infected; I indicates individuals who could infect susceptible individuals after the incubation period; and R represents individuals who have not affected the dynamics of epidemic transmission because of their immunity, effective isolation, and death. In the initial stage of an epidemic, susceptible individuals comprise almost the entire population, with only a few exposed and infected individuals.

To express the model more clearly, we adopted further specifications to represent the number of people in each category: *S*(*t*) represents the total number of susceptible individuals at time t; *E*(*t*) is the total number of individuals exposed at time t; *I*(*t*) is the cumulative number of infectious individuals after the incubation period at time *t*; and *R*(*t*) is the cumulative number of individuals who were removed from the epidemic process at time *t*. *N* represents the total number of people, giving the formula $N = S\ (t) + E\ (t) + I\ (t) + R\ (t)$. When $t = 0$, *N* approaches *S*.

After the outbreak, the government introduced strict control measures, but the traditional SEIR model did not take these into account. The results of the traditional SEIR model were defective, and the predicted results differed significantly from the actual situation. It was necessary to adjust the SEIR model.

According to the known route of transmission, isolation measures are carried out to separate infected individuals into isolated and non-isolated categories. An isolated person is an individual who has been isolated and treated after being infected with SARS-CoV-2. A non-isolated person was an individual who had been infected with SARS-CoV-2, but who has not been isolated because no symptoms of infection are present and who has not been treated. To better reflect and predict the epidemic situation in the six provinces, we proposed the Policy-SEIR model based on the SEIR model, which considered whether the infected individuals were isolated or not. Iu and Is were added to the traditional model, which represent the infected but not isolated individuals and infected and isolated individuals, respectively. In addition, we considered current policies as strong policies, and evaluated the impact of different policy intensities on the results by changing the proportions of Iu and Is. The changed probabilities in the SEIR process are shown in Table 1. The Policy-SEIR model process is shown in Figure 1. The model consisted of the following equations:

$$\frac{dS(t)}{dt} = -\frac{\beta_1 S(t) I_u(t) + \beta_2 S(t) I_s(t)}{N}.$$

$$\frac{dE(t)}{t} = \frac{\beta_1 S(t) I_u(t) + \beta_2 S(t) I_s(t)}{N} - \gamma_1 E(t) - \gamma_2 E(t).$$

$$\frac{dI_u(t)}{t} = \gamma_1 E(t) - \gamma_3 I_u(t).$$

$$\frac{dI_s(t)}{t} = \gamma_2 E(t) - \gamma_4 I_s(t).$$

$$\frac{dR(t)}{t} = \gamma_3 I_u(t) + \gamma_4 I_s(t).$$

2.3 | Estimation of model parameters

The unknown parameters in the model were obtained through fitting the published data. A specific method was used to minimize the subsequent loss of mean square deviation in the search interval in the following equation:

$$\text{argmin}\Sigma_{t=1}^{N}\sqrt{\frac{\left(y_t - \hat{y}_t\right)^2}{N}}$$

TABLE 1 Parameter estimates for modified susceptible-exposed-infectious-removed model

Parameter	Definitions	Starting value	Search scope
β1	Probability of entering incubation period in Iu individuals	0.6	0-1
β2	Probability of entering incubation period in Is individuals	0.1	0-1
γ^1	Transition rate of exposed individuals to infected individuals but not isolated	0.1	0-1
γ_2	Transition rate of exposed individuals to isolated infected individuals	0.1	0-1
γ_3	Probability of Iu individuals being removed	0.05	0-1
γ_4	Probability of Is individuals being removed	0.05	0-1
S(0)	Susceptible population at t = 0	3000[a]	Non
E(0)	Exposed population at t = 0	200	Non
Iu(0)	Population infected but not isolated at t = 0	200	Non
Is(0)	Infected and isolated population at t = 0	Number of announces	Non
R(0)	Population removed at t = 0	Number of announces	Non

[a]S(0) = 60 000 as starting value in Hubei Province.

Among the equation, y_t is the real data and $\hat{y}_t$ is the data obtained through the fitting model. When the error between the model prediction and the real data was the smallest within the N-day observation range, relevant estimated parameters could be obtained.

3 | RESULTS

3.1 | Model-based estimates in Hubei Province

Based on the cumulative number of confirmed COVID-19 cases and the number of discharged patients and those who have died in Hubei Province, the results of the Policy-SEIR model are shown in Figure 2. It was clear that the numbers of predicted and actual current cases were extremely close, indicating that the predicted results were in line with the actual situation. On day 15, there was a rapid increase in the actual number of COVID-19 cases involving individuals with clinical manifestations of COVID-19 who were identified as clinically diagnosed cases and included in the confirmed cases. The cumulative number of current cases continued to increase in the first 20 days, reaching a peak of 50 255 cases on day 21, and then declining. In the predicted results, the peak comprised 51 222 cases, reached on day 19. Furthermore, according to the predicted results, the current cumulative confirmed cases tend to be stable after day 70 (Figure 2A). Considering policy as a factor in the model, there was a wide gap in the number of cases in terms of the intervention policies applied. After the implementation of strong interventional policies, the current number of COVID-19 cases was and smaller than that without policies. Without the application of such policies, the number of current cases was found to reach at 157 721. Under the current strong interventional policies, the predicted peak number of current cases was smaller than under alternative scenarios in Figure 2B. Table 2 shows the forecast results and the actual results.

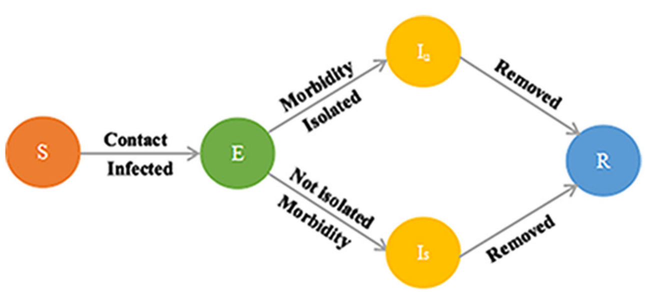


FIGURE 1 The process of modified susceptible-exposed-infectious-removed model

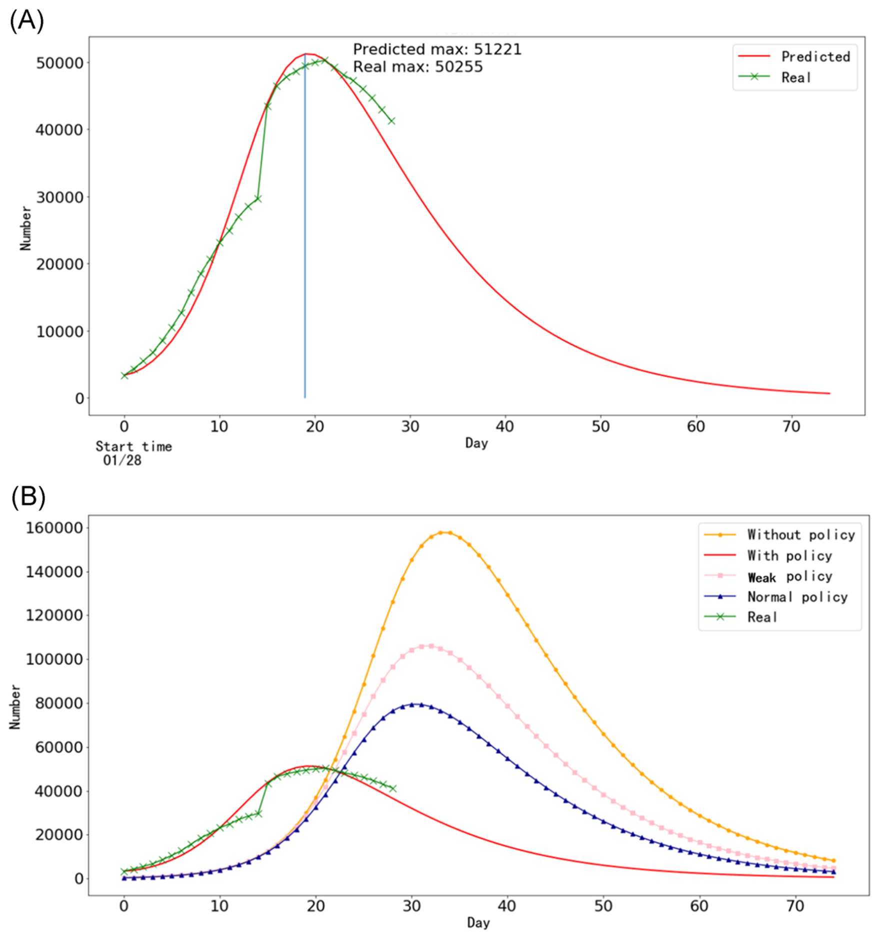
3.2 | Model-based estimates in Guangdong Province

The Policy-SEIR model results of Guangdong Province are shown in Figure 3. The numbers of predicted and actual current cases were close, indicating that the predicted results were in line with the actual situation. The cumulative number of current confirmed cases continued to increase in the first 11 days, peaking on day 12 at 1010 and then declining, according to predicted results. In the actual situation, the peak reached 1007 on day 12. The model results suggested that the number of COVID-19 cases tended to flatten from day 60 (Figure 3A). Interventional policies had a significant effect on the predicted results of the model. The number of cases would have been 1542 on day 20 without using interventional policies, which was far more than that would have occurred using current policies. (Figure 3B)

3.3 | Model-based estimates in Henan Province

The Policy-SEIR model results of Henan Province are shown in Figures 4 and 5. The numbers of predicted and actual current cases

FIGURE 2 Modified susceptible-exposed-infectious-removed model results of Hubei Province



were close, revealing that the predicted results were similar to the actual situation. The cumulative number of current cases continued to increase in the first 14 days, peaking at 901 on day 15, and then declining, whereas the predicted number peaked at day 11. The model results suggested that the number of COVID-19 cases would be stable after day 60 (Figure 4A). The effect of interventional policies was significant, with the number of patients shown to reach 2068 on day 21 without interventional policies, which was considerably more than the figure with policies (Figure 5A).

3.4 | Model-based estimates in Zhejiang Province

The Policy-SEIR model results of Zhejiang Province are shown in Figures 4 and 5. The numbers of predicted and actual current cases were close, revealing that the predicted results were similar to the actual situation. The cumulative number of current cases continued to increase in the first 9 days, peaking at 921 on day 10, and then declining, whereas the predicted number peaking at 895. The model results suggested that the number of COVID-19 cases tended to flatten from day 70 (Figure 4B). The predicted number of patients

TABLE 2 Summary of predicted and real values of six provinces

Provinces	R_m	R_t	P_m	P_t	W_m	W_t	$\bar{x} \pm s$
Hubei	50 255	21	51 222	19	157 721	33	9.88 ± 8.86
Guangdong	1007	12	1010	12	1542	20	10.61 ± 14.88
Henan	901	15	941	11	2068	21	11.45 ± 6.56
Zhejiang	921	10	895	10	1047	19	7.28 ± 13.72
Hunan	698	13	702	10	968	23	15.51 ± 8.38
Anhui	777	14/15	775	14	6189	35	4.74 ± 5.51

Note: R_m, Maximum real number; R_t, Peak time of real number; P_m, Maximum predictive number with intervention; P_t, Peak time of predictive number with intervention; W_m, Maximum predictive number without intervention; W_t, Peak time of predictive number without intervention; $\bar{x} \pm s$, The error between predicted number and real number with intervention.

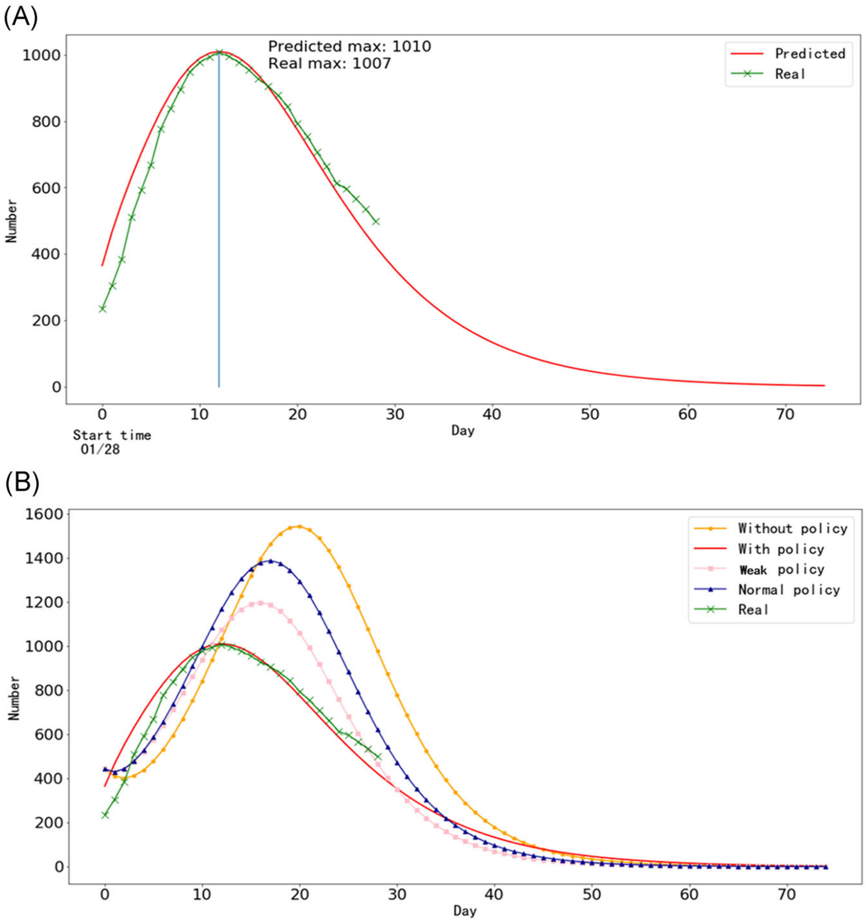


FIGURE 3 Modified susceptible-exposed-infectious-removed model results of Guangdong Province

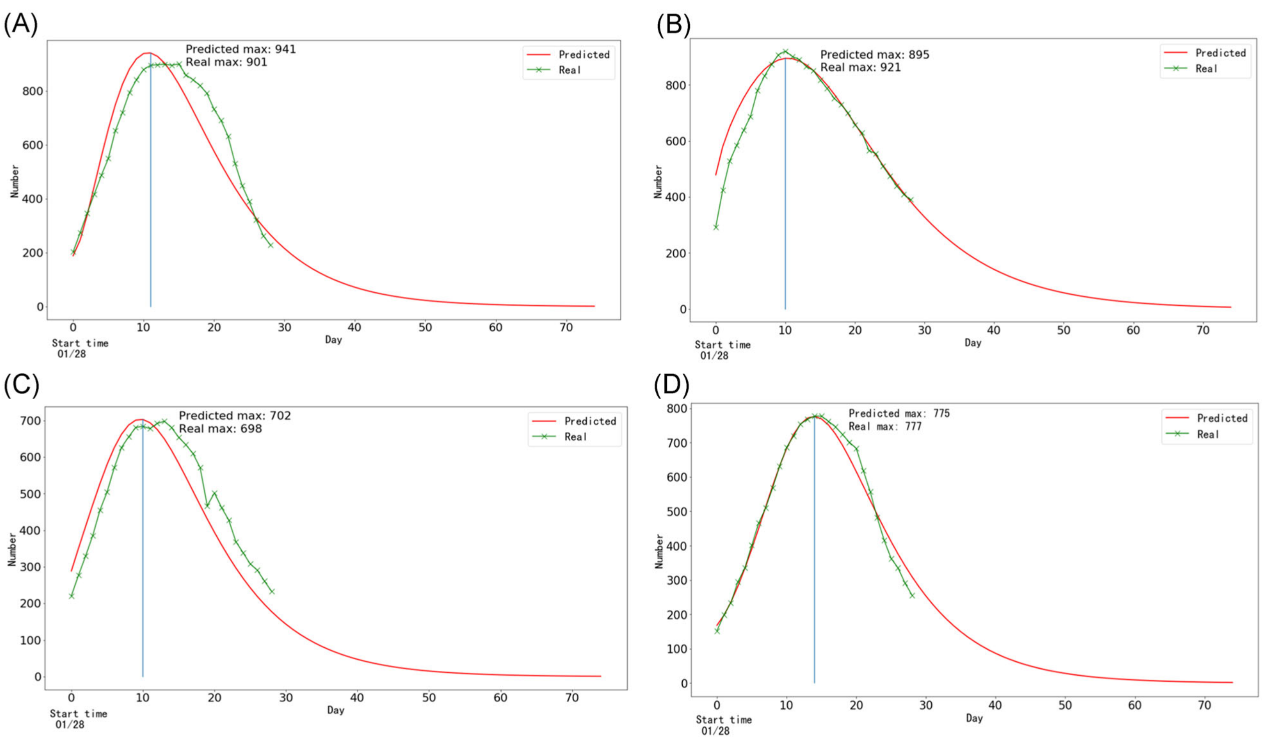


FIGURE 4 Predicted results of other four provinces (A) Henan Province; (B) Zhejiang Province; (C) Hunan Province; (D) Anhui Province

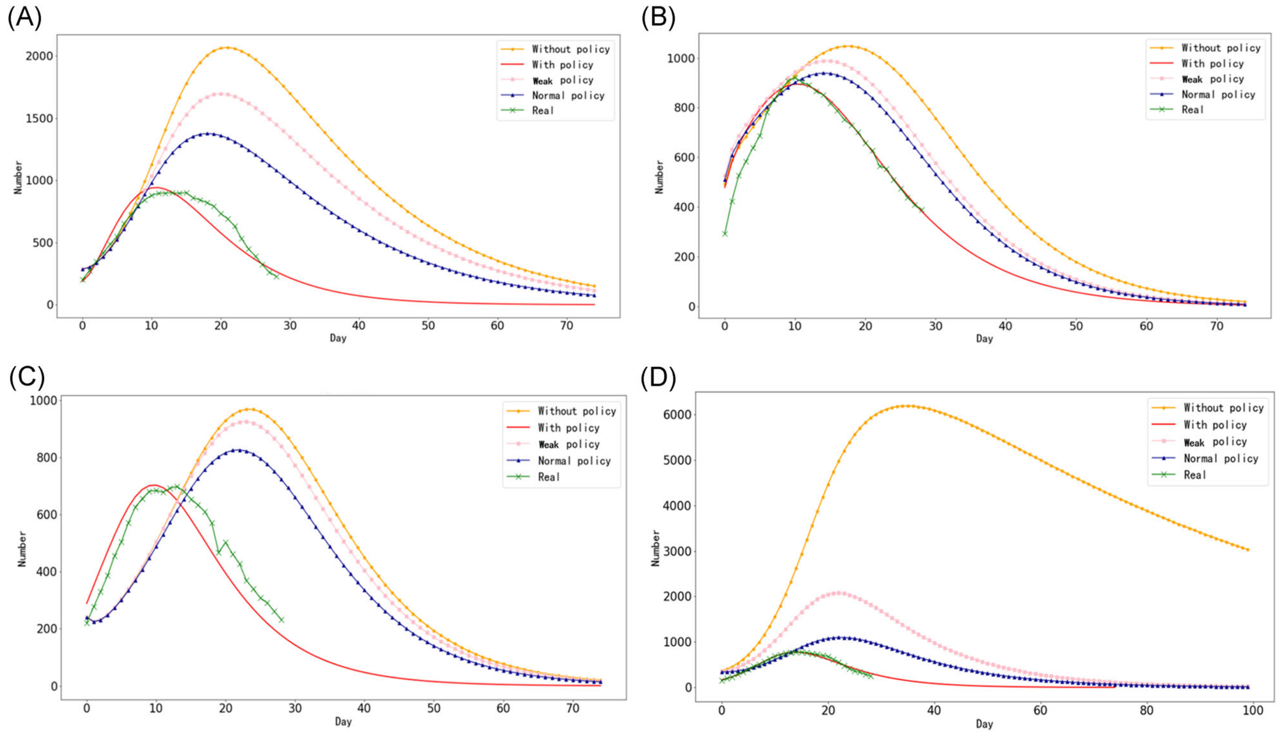


FIGURE 5 Predicted results under different policy intensities of other four provinces (A) Henan Province; (B) Zhejiang Province; (C) Hunan Province; (D)Anhui Province

would exceed 1000 on day 19 without less interventional policies (Figure 5B).

3.5 | Model-based estimates in Hunan Province

The Policy-SEIR model results of Hunan Province are shown in Figures 4 and 5. There was a difference between the predicted results and the actual results. The cumulative number of current cases peaked on day 13 at 698, and then declined, whereas, in the predicted results, the peak was 702 on day 10. The model results suggested that the curve of current COVID-19 cases in Hunan Province tended to be flatten from day 60 (Figure 4C). Policy intervention had a significant effect on the prediction results of the model, as the number of cases was shown as 968 on day 23 without interventional policies, which was far more than the figure with such policies (Figure 5C).

3.6 | Model-based estimates in Anhui Province

The Policy-SEIR model results of Anhui Province are shown in Figures 4 and 5. The numbers of predicted and actual current cases were similar, indicating that the predicted results were consistent with the actual situation. The cumulative number of current cases continued to increase in the first 13 days, peaking at 777 on days 14 and 15, and then declining. The number of COVID-19 cases was stable after day 60 (Figure 4D). Policy intervention had a particularly significant effect on the increase in current cases according to the predicted results of the model. The peak number of cases would have been close to 6189 on day 35 without interventional policies, which far exceeded the number of cases occurring when applying policies and the situation would also have not become stable until after 140 days (Figure 5D).

4 | DISCUSSION

According to the results of the Policy-SEIR model, policy played an important role in controlling the spread of the COVID-19 pandemic. From 23 January, each province started to launch a first-level response to this major public health emergency in succession. At the same time, specific interventional policies were initiated, including isolating confirmed cases and those who had been in close contact with such cases, delaying or canceling public activities, taking temperatures in public place, such as railway stations and airports. Public transportation and roads were shut down in several cities in Hubei. At that time, as the epicenter of the epidemic, Wuhan closed public transportation roads out of city to prevent outflows on 23 January[11] and suspended public transportation,[12] such as buses and trains. Spring Festival holiday was extended nationwide for 3 days since 31 January. On 27 January, the Ministry of Education announced that the school start date would be postponed. The purpose of these policies was to reduce crowd gathering, cut off transmission routes, and control the spread of SARS-CoV-2. Besides, early detection of suspected cases and comprehensive nucleic acid testing are important.

When it became clear that COVID-19 cases involved symptoms such as fever, fever clinics in hospitals play an important role to check suspected cases. In addition, the government and experts called on people to stay at home as much as possible to reduce social contact, and to wear protective masks when they needed to go out. And people actively did a good job in self-protection. With the joint efforts of the government and the people, the number of confirmed and current cases has decreased significantly. On 18 March, there were no new domestic confirmed cases reported in China for the first time since the initial outbreak,[13] with only imported cases reported, which can be considered an exceptional achievement.

The segregation policy for confirmed cases adopted in China was extremely strict. In Wuhan, according to the severity of the disease, people diagnosed with COVID-19 were quarantined in different places. Severely affected patients were isolated in special hospitals such as Huoshenshan and Leishenshan Hospital.[14] People with mild infections were isolated in specific locations, known as "Fangcang" hospitals, which comprised former public buildings such as gymnasiums and conference centers that have been converted for medical purposes.[15] Unaffected individuals were isolated at home and reduced the number to go out home. Each local community had to ensure that temperature tests were undertaken for people entering or leaving the community. A study showed that transmission of COVID-19 can be effectively controlled through efficient contact tracking and case isolation.[16] If individuals who affected with COVID-19 were not separated from those unaffected, it may cause more susceptible individuals to become infected. Firm and strictly applied interventional policies were found to be more effective in quickly bringing the COVID-19 epidemic under control as the results of model, specifically involving case isolation to protect susceptible people from infection.

Some studies have indicated the importance of appropriately applied interventional policies. Yang et al[5] predicted that with control measures, the number of confirmed COVID-19 patients would have reached a first peak of 51 581 and a second peak of 47 144 in Hubei province. Read et al[17] predicted that the number would have reached a peak of 185 412 without control measures in Wuhan on 29 January. In this study, the predicted number of confirmed cases was shown to be alarmingly high without the application of firm control measures in Hubei Province. The actual number of COVID-19 cases following the application of appropriate interventional policies was much smaller than the number without the application of such policies, demonstrating the effectiveness of strong and strictly applied interventional policies in controlling the number of COVID-19 cases. Globally confirmed cases of COVID-19 continue to grow rapidly, and the full manifestation and severity of the disease required thorough investigation.[18] As of April 17, COVID-19 has severely affected many countries, especially the United States with 632 781 confirmed cases. In addition, there are 182 816 confirmed cases in Spain and 168 941 in Italy, with 133 830 confirmed cases in Germany, 107 778 in France and 103 097 in the United Kingdom.[19] On April 17, the WHO reported that 207 4529 cases of COVID-19 had been confirmed and that 139 378 deaths had occurred globally.[19] No matter from the actual or the model results, policies in China are effective in controlling the epidemic. It suggests a good choice for other countries to implement strong policies in accordance with their national conditions. Studies have shown that a range of measures, including community screening, contact tracking, and isolation, may be effective in reducing the spread of influenza and the negative effects of an influenza pandemic.[20] In terms of COVID-19, the strict policies were implemented to block the route of transmission and protect the susceptible population. These policies have proven to be effective in controlling the domestic epidemic and are in line with relevant WHO recommendations.[21] There are some limitations in this study. First, the model is driven by actual data,[22] of which results are affected by actual data. The fitting degree of the actual data to the model is different, leading to the difference between the results of prediction and actual. To estimate the parameters in this model such as probability of entering incubation period and transition rate, we fitted the actual data with the model output. But a group of parameters is not unique. Different groups of parameters will lead to very different prediction results of the pandemic, which produce the uncertainties of model results. Besides, the differences of policy implementation among regions will also affect the model prediction and cause uncertainties. Local population density, geographical area, topography, and other factors affect policies with various effects in control of epidemic. Infection rate and isolation rate are different in various regions, with uncertainties in model prediction. Furthermore, in reality, the policies are changing in different stages of epidemic. But this model cannot reflect the process of policy change. These uncertainties will affect the deviation of the prediction results. More comprehensive investigations should be subjected to predict the development of COVID-19 and help to control the pandemic.

5 | CONCLUSION

A modified SEIR model—the Policy-SEIR model—was applied in this study to predict the development of COVID-19 cases in selected provinces of Chinese mainland and to evaluate the role of interventional policies in epidemic control. Based on the results, strong interventional policies were shown to vital components of epidemic control. Through implementing such policies, the duration of the epidemic was shown to have been shortened and the number of currently infected individuals to have been reduced in comparison to what otherwise would have been the case without those policies.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

AUTHOR CONTRIBUTIONS

Contributors BZL and DQY conceived and designed the study. NWC, HYZ, and XJC collected and assembled of data. BZL and NWC analyzed and interpreted the data. NWC wrote the manuscript. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

ORCID

Bao-Zhu Li http://orcid.org/0000-0001-8081-9857
Nv-Wei Cao http://orcid.org/0000-0003-2931-8939
Hao-Yue Zhou http://orcid.org/0000-0003-4179-0363
Xiu-Jie Chu http://orcid.org/0000-0002-9693-7273
Dong-Qing Ye http://orcid.org/0000-0002-4708-3451

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