PREDICTION OF CUMULATIVE RATE OF COVID-19 DEATHS IN BRAZIL: A MODELING STUDY

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Artigo especial

PREDICTION OF CUMULATIVE RATE OF COVID-19 DEATHS IN BRAZIL: A MODELING STUDY

PROJEÇÃO DA TAXA CUMULATIVA DE ÓBITOS POR COVID-19 NO BRASIL: UM ESTUDO DE MODELAGEM

Prediction of cumulative rate of COVID-19 deaths in Brazil

Projeção da taxa cumulativa de óbitos por COVID-19 no Brasil

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RESUMO

Objetivo: estimar o número potencial de mortes por COVID-19 no Brasil nos próximos meses. **Métodos**: O estudo incluiu todos os casos confirmados de óbitos do COVID-19, desde o primeiro óbito confirmado em 17 de março até 15 de maio de 2020. Esses dados foram coletados no site oficial do Ministério da Saúde. A função Boltzmann foi aplicada a uma simulação de dados para cada conjunto de dados referente a todos os estados do país. **Resultados**: Os dados do modelo foram bem ajustados, com valores de R^2 próximos a 0,999. Até 15 de maio, 14.817 mortes de COVID-19 foram confirmadas no país. O Amazonas possui a maior taxa de casos acumulados por 1.000.000 habitantes

(321,14), seguido por Ceará (161,63). Estimou-se que o Rio de Janeiro, Roraima, Amazonas, Pará e Pernambuco sofrerão um aumento substancial na taxa de casos acumulados até 15 de julho. Mato Grosso do Sul, Paraná, Minas Gerais, Rio Grande do Sul e Santa Catarina apresentarão taxas potenciais mais baixas por 1.000.000 habitantes. **Conclusão**: Foi estimado um aumento substancial na taxa de casos cumulativos no Brasil nos próximos meses. A função Boltzmann provou ser uma ferramenta simples para previsão epidemiológica que pode auxiliar no planejamento de medidas para conter o COVID-19.

Descritores: COVID-19, Epidemiologia, Modelagem matemática, Pandemia, Brasil.

ABSTRACT

Purpose: We estimated the potential number of COVID-19 deaths for Brazil for the next months. **Methods**: The study included all confirmed cases of COVID-19 deaths, from the first confirmed death on March 17 until May 15, 2020. These data were collected from an official Brazilian website of the Ministry of Health. The Boltzmann function was applied to a data simulation for each set of data regarding to all states of the country. **Results**: The model data were well-fitted, with R^2 values close to 0.999. Up to May 15, 14,817 COVID-19 deaths were confirmed in the country. Amazonas has the highest rate of accumulated cases per 1,000,000 inhabitants (321.14), followed by Ceará (161.63). We estimated that Rio de Janeiro, Roraima, Amazonas, Pará, and Pernambuco will experience a substantial increase in the rate of cumulative cases until July 15. Mato Grosso do Sul, Paraná, Minas Gerais, Rio Grande do Sul, and Santa Catarina will show lower rates per 1,000,000 inhabitants. **Conclusion**: We estimate a substantial increase in the rate of cumulative cases in Brazil over the next months. The Boltzmann function

proved to be a simple tool for epidemiological forecasting that can assist in the planning of measures to contain COVID-19.

Keywords: COVID-19, Epidemiology, Mathematical modeling, Pandemic, Brazil.

1. INTRODUCTION

The world is facing a serious and acute public health emergency due to the spread of the disease caused by the coronavirus SARS-CoV-2, known as COVID-19. The World Health Organization (WHO) declared on January 30, 2020, that the outbreak of the disease was characterized as a Public Health Emergency of International Importance, the highest alert level of the Organization, as provided for in the International Health Regulations, beginning to be considered, on March 11, 2020, as a pandemic.[1]

Despite the restrictive social isolation measures imposed by health authorities around the world in an attempt to slow the spread of the virus and, consequently, reduce the number of patients who may need hospitalization and avoid overloading the health system and its collapse, the number of infected people continues to grow, as well as the number of deaths caused by the disease.

According to the COVID-19 world map, presented in real time by the Johns Hopkins Coronavirus Resource Center by the end of the evening of May 31, 2020, 6,194,508 cases of the disease and 372,501 deaths were confirmed worldwide. At that date, the three countries with the highest number of confirmed cases were the United States (1,790,191), Brazil (514,849), and Russia (414,878). Those who lead the number of deaths were the United States (104,383), the United Kingdom (38,571), and Italy (33,415), with Brazil in the fourth position (29,314) until that time.[2]

A study published by a group of researchers from the United Kingdom already predicted different scenarios of the pandemic in 202 countries, until the epidemiological week ending on April 26, 2020, when it proposed three possible models regarding mitigation strategies: (1) without any interventions' mitigation, that is, without non-pharmacological intervention, without social distance and others; (2) with social distance from the entire population; and (3) with improved social distance for the elderly. According to the adopted mitigation strategy, estimates for the total number of infected people in Brazil would be 187,799,806, 122,025,818, and 120,836,850 cases, respectively. As for the number of deaths from COVID-19, the respectively forecast was 1,152,283 for the first condition, 627,047 for the second, and 529,779 for the third condition. The mentioned report concluded that measures such as social isolation, school closures and services considered non-essential, among others, can save million lives.[3]

In support of the Ministry of Health of Brazil, the Pan American Health Organization (PAHO) has developed a series of tools to assist governments in decision-making regarding the tightening or loosening of measures, such as the technical guide "Considerations on adjustments to social distance measures and travel-related measures in the context of the response to the COVID-19 pandemic". Another important tool is the "Epidemic Calculator", which produces scenarios (and not predictions about the future) from values, data, and parameters (number of available beds, transmission speed, and social contact). The effectiveness of the model is directly related to the quality of the information used in the calculation.[4]

Despite the availability of these tools, the low testing of suspected cases of COVID-19, combined with an upward curve of new deaths, generates an enormous underreporting of cases and, to a lesser extent, of deaths from the disease. Other factors, such as a still very high rate of contagion and the low adherence of the population to social isolation measures, have projected an extremely critical scenario for Brazil until the end of May. Three months after the first case confirmed by the Ministry of Health, and two months after the first announced death, Brazil surpassed the mark of more than one thousand daily deaths due to the coronavirus.[5] The current lethality rate of the disease is 6.3%, being among the 10 highest in the world, and the mortality rate is currently 10.5 deaths per 100,000 inhabitants.[6]

When the growth of an event is exponential, the uncertainties also grow exponentially, as is the case with the COVID-19 pandemic. Several mathematical models built from the knowledge and data available can simulate different scenarios and identify trends. Even considering the possibility of a certain level of uncertainty, like any scientific result, the discoveries made from mathematical models are considered of paramount importance for the planning of public policies.[7] A simpler model in terms of understanding and application, which has already been used in studies carried out in China, is Boltzmann's model.[8-10] Thus, the objective of this study was to estimate the total potential number of deaths by COVID-19 for Brazil in the next two months, using Boltzmann's function - based on regression analysis.

2. METHODS

Design and study area

This was an epidemiological study that used mathematical modeling and geoprocessing techniques. The spatial units of analysis were all twenty-seven states of Brazil, a country with continental dimensions and a territorial extension of 8,514,876

km^2. Its area corresponds to about 1.6% of the entire surface of the planet and occupies 20.8% and 48% of the area of all of America and South America, respectively.[11]

Data sources and measures

The study included all confirmed cases of COVID-19 deaths, from the first confirmed death until May 15, 2020. COVID-19 was defined as a case with a positive result for viral nucleic acid testing in respiratory specimens or with a positive serological test. This data was collected from the official website[6] that reports on the situation regarding COVID-19 in Brazil. The data for model development were updated on May 16, 2020. The rates of cumulative cases of disease per 1,000,000 inhabitants were calculated considering the number of COVID-19 deaths in each state divided by the population at risk based on the estimates for the states, according to the Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística-IBGE).*[11]

Data analysis

Data were organized in Microsoft Excel (Windows version 2016, Microsoft Corporation; Redmond, WA, USA) and incorporated into Microcal Origin software version 6.0. The Boltzmann function[8-10,12] was applied to the data simulation for each set of data regarding different geographical regions in the northeast of Brazil. We obtained the parameters of each function, with the potential total number of confirmed cases being directly given by the parameter A_2. The Boltzmann function for future simulation is expressed as follows:

$$C(x) = A_2 + \frac{A_1 - A_2}{1 + e^{(x - x_0)/dx}} \quad (1),$$

where C(x) is the cumulative number of confirmed cases after the first day x; A_1, A_2, x0, and dx are constants. X0 corresponds to the inflection point and indicates the date on which the daily cases will reach their maximum. After that date, there will be a downward trend in total daily cases; dx is the adjustment coefficient, indicating the degree of increase in y (number of COVID-19 deaths) as a function of the increase in x (days after the first case); A_2 represents the estimated potential total number of deaths.[16] Data from parameter A_2 was used to calculate the rate of cumulative COVID-19 deaths per 1,000,000 inhabitants.

Density maps with inverse distance weighting (IDW) interpolation type were setup with the spread of the cumulative COVID-19 deaths per 1,000,000 habitants, using actual and modelled Boltzmann data. For this, we used the cartographic base of Brazil available in the IBGE electronic database and reported data on COVID-19.[11] Terra Datum model SIRGAS 2000 and the cartographic projection corresponding to the Mercator Transversal Universal system were used. The georeferenced data were incorporated into Quantum GIS (Open Source Geospatial Foundation, OSGeo, CHI, USA, Version 3.10.5).

3. RESULTS

The first case of COVID-19 death in Brazil was documented in the state of São Paulo on March 17, 2020. From that date until May 15, 2020, 14,817 COVID-19 deaths were confirmed across the country. São Paulo is one of the states with the highest number of confirmed deaths due to COVID-19 (4,501 deaths) and is the seventh among the states with the highest death rates (98.02) per 1,000,000 inhabitants (Figure 1). It is considered the epicenter of the disease in Brazil, followed by Rio de Janeiro, Ceará, Pernambuco, and Amazonas, which total almost 11,000 deaths.

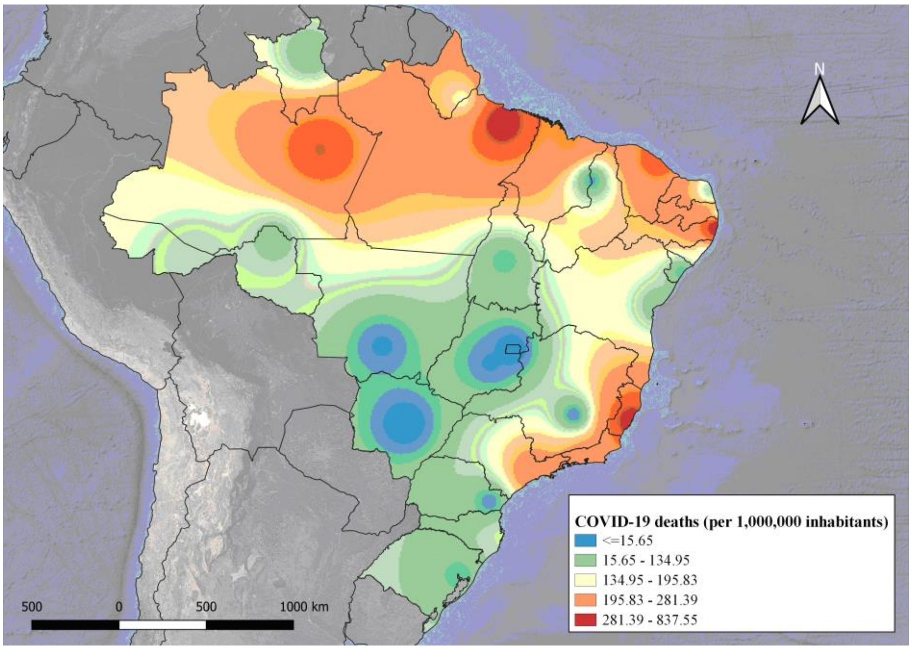

Figure 1. Cumulative rates of COVID-19 deaths in states of Brazil (per 1,000,000 inhabitants) since the first case described in March 17, 2020 until May 15, 2020.

The state of Amazonas had the highest cumulative rate of COVID-19 deaths per 1,000,000 inhabitants (321.14) during this period, followed by the states of Ceará (161.63), Pernambuco (144.50), Rio de Janeiro (141.21) and Pará (133.10). The lowest rates of cumulative COVID-19 deaths per 1,000,000 inhabitants were reported by the states of Mato Grosso do Sul (5.04), Minas Gerais (6.90), Mato Grosso (7.46) and Goiás (9.55).

For Boltzmann data analysis, each region was well-fitted and all R^2 values were close to 0.999 (from March 17 to May 15, 2020) (Table 1). The potential total numbers of COVID-19 deaths in Brazil for the next 60 days after May 15 were estimated and the results and are shown in Table 1. The potential number of cumulative COVID-19 deaths per 1,000,000 inhabitants until June 15, 2020 will be higher for Roraima (881.98), Rio de Janeiro (761.45), Amazonas (665.56) Pará (559.62) and Pernambuco (316.87), and lower for Mato Grosso do Sul (6.32), Minas Gerais (12.07), Paraná (12.18), Rio Grande do Sul (18.24) and Santa Catarina (19.86).

Table 1. Fitting the cumulative rate of COVID-19 deaths to Boltzmann function in the states of Brazil until July 15, 2020.

	A1	**A2**	**x0**	**dx**	**R^2**
North region					
Acre	-0.15±0.63	102.42±10.68	36.77±1.69	8.60±0.59	0.99
Amazonas	-19.60±7.32	2899.68±318.44	53.55±1.92	9.88±0.46	0.99
Amapá	-0.61±0.94	144.82±16.41	36.69±1.78	8.30±0.62	0.99
Para	-6.56±5.67	5052.10±1791.59	52.86±3.79	7.36±0.43	0.99
Rondônia	0.78±0.32	75.26±3.51	38.90±0.61	5.81±0.29	0.99
Roraima	1.72±0.29	640.67±1744.86	61.57±22.40	7.10±0.72	0.99
Tocantins	0.85±0.51	145.10±294.22	40.68±16.37	5.91±1.40	0.97
Northeast region					
Alagoas	-1.88±0.74	467.66±48.70	49.27±1.51	8.52±0.31	0.99
Bahia	-10.22±2.78	969.17±243.97	59.69±5.14	13.07±0.86	0.99
Ceará	-11.12±5.97	2846.21±179.96	49.90±1.08	9.21±0.31	0.99
Maranhão	-6.81±2.26	730.79±29.39	41.16±0.66	8.21±0.27	0.99
Paraíba	-10.15±4.48	1187.45±1322.99	70.25±22.64	14.83±2.24	0.99
Pernambuco	-65.44±10.80	3415.53±448.49	56.67±2.81	12.67±0.66	0.99
Piaui	0.37±1.32	1112.84±4492.33	90.56±68.28	14.51±2.43	0.99
Rio Grande do Norte	-14.21±5.37	1395.25±3277.18	95.18±61.79	20.70±4.31	0.99
Sergipe	2.87±0.36	108.82±21.26	45.63±2.56	7.24±0.57	0.99
Central-West region					
Distrito Federal	-55.68±227.69	436.12±6139.00	138.05±1368.82	68.34±332.04	0.97

Goiás	-8.66±7.22	793.31±4445.00	104.96±164.92	23.23±11.38	0.97
Mato Grosso do Sul	-3.76±2.88	18.78±4.18	27.20±3.36	17.36±6.12	0.98
Mato Grosso	-2.96±3.75	284.61±1993.07	92.68±192.11	21.46±13.96	0.97
Southeast region					
Espírito Santo	-2.48±2.01	528.80±59.48	44.32±1.89	9.30±0.52	0.99
Minas Gerais	-24.12±6.61	301.60±59.23	46.09±5.63	17.72±2.46	0.99
Rio de Janeiro	-79.06±18.19	32522.73±39799.7	94.57±21.42	14.58±0.96	0.99
São Paulo	-104.17±28.23	7007.81±380.92	53.39±1.24	11.75±0.4893	0.99
South region					
Parana	-15.92±2.59	141.05±3.66	28.34±0.43	11.85±0.62	0.99
Rio Grande do Sul	0.28±1.29	215.56±23.13	48.55±2.17	10.58±0.75	0.99
Santa Catarina	114.70±267.86	731.99±5884.61	146.05±868.40	77.11±230.81	0.99

For July 15, the total number of deaths predicted in the country will be 56,955. However, the total number of deaths according to model A_2 may be of 64.262. This value can be higher or lower according to the standard deviation presented for each state (table 1). The potential number of cumulative cases per 1,000,000 inhabitants will be higher for Rio de Janeiro, Roraima, Amazonas, Pará, and Pernambuco, with 1586.02, 1054.57, 697.91, 586.77 and 353.16, respectively. For the state of São Paulo, a rate of 152.12 COVID-19 deaths per 1,000,000 inhabitants is estimated. Mato Grosso do Sul, Paraná, Minas Gerais, Rio Grande do Sul, and Santa Catarina will show lower death rates per 1,000,000 inhabitants (6.68, 12.32, 13.79, 18.90 and 30.24 respectively). The mapping of the country shows the all states with the potential of rates of cumulative

COVID-19 deaths along June 15 (Figure 2), and July 15 (Figure 3), according the smoothing or intensification of colors.

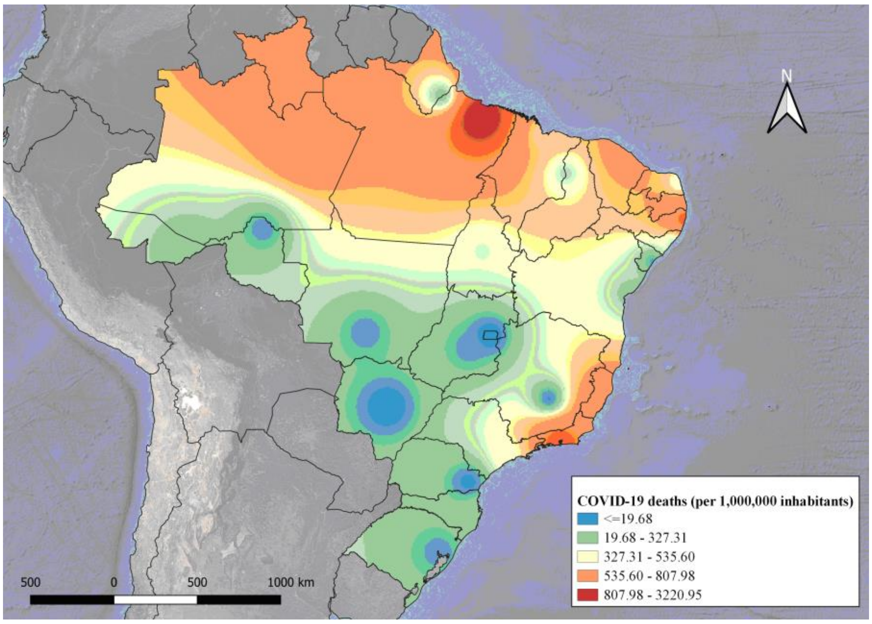

Figure 2. Mapping of cumulative rates of COVID-19 deaths in states of Brazil (per 1,000,000 inhabitants) according to Boltzmann's function forecast to June 15, 2020.

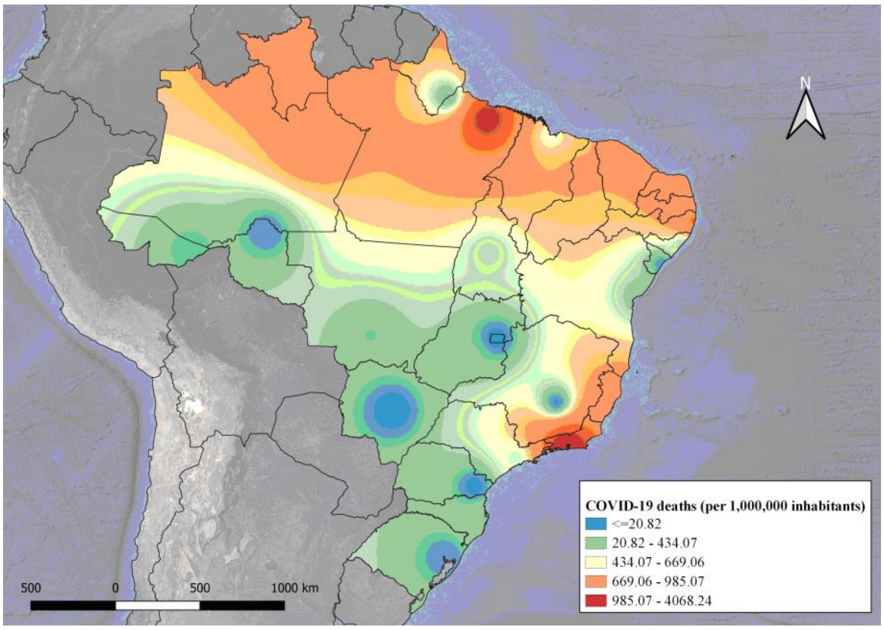

Figure 3. Mapping of cumulative rates of COVID-19 deaths in states of Brazil (per 1,000,000 inhabitants) according to Boltzmann's function forecast to July 15, 2020.

4. DISCUSSION

In this study, we provide an estimation of the rate of cumulative of COVID-19 deaths per 1,000,000 inhabitants in Brazil for the next two months, specifically for June 15 and July 15, 2020, using the existing available data from March 17, 2020 to May 15, 2020 and a mathematical model.

We estimated that states located in the southeast and north regions will see a substantial increase in the rate of cumulative COVID-19 deaths up to 5.39, 13.36, and 4.20 times in a month and 11.23, 15.97 and 4.41-fold increases until July 15, for Rio de Janeiro, Roraima and Pará, respectively. We also observed that the states of Amazonas (north region) and Pernambuco (northeast region) are in the potential period of stabilization of death cases with a slight increase in the mortality rate (2.17 and 2.44, respectively), although it is predicted that these states will still be among the states with the highest death rate at the end of the period. States located in the midwest and south regions will show a more discreet increase in the modeling with the lowest potential cumulative case rates until the end of the estimated period.

Death data caused by COVID-19 in territorial spaces is of paramount importance not only to assess the severity of SARS-CoV-2 infection but also to indirectly determine the number of accumulated cases and, consequently, to assess the quality of the assistance provided, since prevention until the diagnosis and treatment of patients. These data also can contribute to the planning of strategic measures to contain the pathogen transmission cycle.

Brazil has been presenting a series of failures that may be related to the high record of deaths by COVID-19 in its territory. The severity of the coranavirus pandemic in a nation depends to a great extent the promptness of government authorities to provide adequate support to diagnose the infection and treat the patients. The current situation shows that Brazil is among the countries carrying out the lower number tests for the diagnosis of coronavirus per million inhabitants, different from what is observed in other countries that have a mass testing strategy.[13-15]

In addition, the results of tests performed with the real-time molecular test of the reverse polymerase chain reaction (RT-PCR) still take more than 15 days to be released in many places of the country. This factor leads to underreporting of cases, excludes the diagnosis of asymptomatic people or those with mild symptoms who do not seek health care or who cannot access health institutions, and delays the early diagnosis of cases with a higher risk of developing the severe form of COVID-19.[13,16]

Social isolation measures and the use of masks adopted in several countries and recommended by local governments in Brazil were constantly contradicted by the central government, which speeches and attitudes minimize their importance as prevention measures.[17,19] In the state with the highest death rate due to COVID-19 (Amazonas), no city reached the minimum ideal adherence rate (70%) to social isolation.[20] As many Brazilian cities have experienced low rates of social isolation in the world, the rate of transmission of the coronavirus SARS-CoV-2 in Brazil is one of the highest.[21]

In addition to the scope of prevention and diagnosis, it is worth mentioning that the prediction of deaths by COVID-19 is also useful in the hospital organization for the provision of care to individuals who evolve to the severe form of infection. A study carried out in Brazil showed that health regions with the highest averages in mortality from hypertension, neoplasms, diabetes, heart, and respiratory diseases are located in regions with scarcity of beds in intensive care units and mechanical ventilators.[22] This leads to the understanding that an efficient planning on the distribution of assistance resources is necessary for an equitable confrontation of the epidemic by COVID-19 in Brazil. Otherwise, a breakdown in the health system can further aggravate the number of deaths in the country.

Finally, our results suggest that the model used is adequate to analyze and predict cumulative cases of deaths caused by COVID-19, since all data sets were well adjusted to the Boltzmann function. Factors related to the host and its behavior, the pathogen's ability to survive, and environmental influences can also alter the analyzed estimate because the estimate of the model is based on the assumption that the general conditions are maintained. In addition, predicted deaths may be even greater when considering the possibility of underreporting. Despite this, the main advantage of the model used is that it only needs the cumulative number of confirmed cases or deaths, and this represents a quick method that can assist in the decision of measures to contain the pandemic by COVID-19.

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