SARS-Cov-2 trajectory predictions and scenario simulations from a global perspective: a modelling study

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The coronavirus SARS-CoV-2 emerging from Wuhan, China has developed into a global epidemic. Here, we combine both human mobility and non-pharmaceutical interventions (social-distancing and suspected-cases isolation) into SEIR transmission model to understand how coronavirus transmits in a global environment. Dynamic trends of region-specific time-variant reproduction number, social-distancing rate, work-resumption rate, and suspected-cases isolation rate have been estimated and plotted for each region by fitting random walk transmission processes to the real total confirmed cases of each region. We find after shutdown in Wuhan, the reproduction number in Wuhan greatly declined from 6.982 (95% CI, 2.558-14.668) on January 23, 2020 to 1.130 (95% CI, 0.289-3.279) on February 7, 2020, and there was a higher intervention level in terms of social distancing and suspected-case isolation in Wuhan than the Chinese average and Western average, for the period from the shutdown in Wuhan to mid-March. Future epidemic trajectories of Western countries up to October 10, 2020, have been predicted with 95% confidence intervals. Through the scenario simulation, we discover the benefits of earlier international travel ban and rigorous intervention strategies, and the significance of non-pharmaceutical interventions. From a global perspective, it is vital for each country to control the risks of imported cases, and execute rigorous non-pharmaceutical interventions before successful vaccination development.

Introduction

As a severe acute respiratory syndrome coronavirus, COVID–19 has spread to various countries in the three months since the Wuhan outbreak due to its high infectiousness and the lack of effective drugs, which has led to disastrous social and economic difficulties. According to the World Health Organization, more than five million confirmed cases have been recorded worldwide as of May 29, 2020, indicating that the prevention and control of COVID–19 has reached an urgent point. Considering the globalizing trend of the epidemic, it is imperative to take into account the influence of human mobility on epidemic growth. The traditional SEIR (susceptible-exposed-infected-removed) model that applies in isolated regions may become no longer appropriate to simulate the epidemic changes in a global environment as it ignores the imported cases which pose an increasing risk for each country.1

Most previous studies either have simulated scenarios in which the epidemic grows under different governmental interventions without considering human mobility, or have considered human mobility but without taking governmental responses into account.2,3 We searched PubMed for articles published in English as of May 29, 2020, with the keywords “COVID–19” in title, keywords “isolation” and “SEIR” in the title or abstract, and totally seven studies were retrieved, but none of them consider regional human mobility; then, we searched with the keywords “COVID–19” in title, keywords “isolation” and “modelling” in the title or abstract, four studies were retrieved, only one of them, published online on May 4, 2020, combines the isolation, social-distancing, and regional human mobility in China.4

Thus, this study fills the gap by combining the traditional SEIR model with both non-pharmaceutical governmental interventions, including social-distancing and isolation of suspected cases, with the human mobility between Wuhan, Hubei Province excluding Wuhan, other provinces of mainland China, and thirteen Western countries (Switzerland, Sweden, Austria, France, United Kingdom, Germany, Italy, Spain, Norway, Netherlands, Belgium, Denmark). Consequently, this may lead to a less biased prediction or simulation from a more comprehensive global perspective.

We have compared the intervention differences between Chinese and Western regions in terms of social-distancing and suspected-cases isolation, and reproduced and predicted epidemic trajectories both controlling for under-reporting or not, and finally we have simulated various scenarios to predict new epidemic trajectories under new conditions. These included, how the epidemic trajectories of Western countries would change if interventions were executed in the same way as Wuhan from different time-points or banned all international human mobility thoroughly from different time-points, and how the epidemic trajectories of Western countries or China would grow naturally if there were no or less non-pharmaceutical interventions in effect. Overall, this study complements modelling studies on the dynamic trajectory of COVID–19 and provides a tool for policy-simulation which can assist countries around the world in evaluating previous interventions and deciding the right time, region, and degree of future interventions, from social-distancing, suspected-case isolation, to mobility bans.

Results

Trajectories of region-specific time-variant reproduction numbers

Fig. 2 displays the trajectories of region-specific time-variant reproduction numbers for fifteen regions (Wuhan, Hubei Province excluding Wuhan, Switzerland, Sweden, Austria, France, the United Kingdom, Germany, Spain, Italy, Norway, the Netherlands, Belgium, Denmark, and the United States), not controlling for under-reporting. After shutdown in Wuhan, the reproduction number in Wuhan greatly declined from 6.982 (95% CI, 2.558-14.668) on January 23, 2020 to 1.130 (95% CI, 0.289-3.279) on February 7, 2020. And for almost all Western countries, the reproduction numbers peaked in March, and then declined gradually. For example, in the United States, R0 declined from 12.510 (95% CI, 5.606-39.015) on March 10, 2020 to 1.909 (95% CI, 0.336-4.303) on March 30, 2020, then to 1.113 (95% CI, 0.051-5.216) on May 1, 2020. Region-specific time-variant reproduction numbers for fifteen regions controlling for under-reporting have been drawn in Fig. 3.

Trend plots of region-specific time-variant social-distancing rate, suspected-cases isolation rate, work-resumption rate and accumulated imported cases from abroad

Trend plots of region-specific time-variant social-distancing rate, suspected-cases isolation rate, work-resumption rate, and accumulated imported cases (not controlling for under-reporting) are drawn in Fig. 4. In Fig. 4 (A) and (B), during most time from January 23, 2020 to April 1, 2020, days needed for an individual to become fully socially-distanced in Wuhan are less than Chinese average, followed by Western average, and then by the United States, suggesting a higher social-distancing rate in Wuhan; similarly, days needed for a socially-distanced individual to resume work in Wuhan are more than Chinese average, followed by Western average, and then by the United States, suggesting a lower work-resumption rate in Wuhan. However, the social-distancing rate in the United States
is gradually increasing, suggesting the government is making every efforts to expand the social distancing of citizens. It is not surprising to see that work-resumption rate in Wuhan increases gradually since early March, suggesting a refigring epidemic and a progressing work resumption in Wuhan to reinvigorate the economy. The result in Fig. 4 (C), further supports previous discoveries: more susceptible people in Wuhan were social-distanced since early February, than that of Chinese average, followed by Western average and the United States. As shown in Fig. 4 (D), the isolation rate of suspected cases in Wuhan is consistently higher than Chinese and Western average (i.e. the number of days needed for isolation are less), indicating a more efficient epidemiological contract tracing. Proportion of isolated cases in whole population peaked earlier and higher for Wuhan than for Western average and the United States (Fig. 4 (E)), and proportion of isolated cases in suspected cases also grew more rapidly for Wuhan, where about 95% suspected cases had been isolated on April 1 (Fig. 4 (F)). Finally, the first three Western countries with most accumulated imported cases from other Western countries are respectively the United Kingdom, Germany, and Spain, with 3258 (95% CI, 652-188472), 2859 (95% CI, 552-181195), and 2739 (95% CI, 519-166091) imported cases by May 1, 2020, respectively (Fig 4 (G)). Trend plots yet controlling for under-reporting are drawn in Fig. 5. Most discoveries remain consistent except the social-distancing rate of the United States becomes higher. Accumulated imported cases for the United Kingdom drastically increases to 16312 (95% CI, 1704-180594) by May 1 (Fig 5 (G)) after controlling for under-reporting.

**Discussion**

We develop an extended stochastic meta-population model based on real data from December 10, 2019 to May 1, 2020, considering real human mobility in 45 regions (including 32 Chinese regions and 13 Western countries). Differences in the effects of NPI are explored between China and Western countries, including social-distancing and isolation of suspected cases. We find a higher social-distancing rate and a lower work-resumption rate in Wuhan during the time from the shutdown of Wuhan to mid-March, which leads to a higher socially-distanced proportion of Wuhan. Similarly, the suspected-cases isolation rate in Wuhan is higher than the Chinese average and the Western average during most time, leading to a higher proportion of isolated cases in both the urban population and suspected cases (Fig. 4 and Fig. 5). We believe the differentiation between Wuhan and the Western average in the effects of NPI results from stricter governmental regulations in Wuhan. In the trajectory prediction (Fig. 6), we discover that after controlling for under-reporting, the individuals infected but not hospitalized in Western countries on a given day would grow drastically, and as most of them would keep infecting others before self-recovery or death, the real infected cases may be far beyond what have been reported. Through the scenario simulations, we conclude that the sooner the Western governments adopt the same level of NPI as Wuhan in China, the sooner the epidemic can be controlled (Fig. 7). In addition, we find that for most Western countries, the earlier international human-mobility ban are implemented, the earlier the epidemic can be controlled (Fig. 8), suggesting the effectiveness of mobility bans. However, we do find that for the United States, mobility bans always lead to more local cases. Finally, we test the effectiveness of non-pharmaceutical interventions, and discover that without such interventions, the epidemic in Western countries could grow up by hundreds of times (Fig. 9), strongly supporting the necessity and significance of non-pharmaceutical interventions, especially before any vaccine inventions, and our demonstrations of the effectiveness of social distancing and isolation are consistent with previous research.
Considering the COVID-19 epidemic is quickly developing into a global crisis, it is urgent to develop a more open model to understand the transmission dynamics of the epidemic from a global perspective.\textsuperscript{24} The extended stochastic meta-population model of the present study can help evaluate the effectiveness of controlling measures executed in the past, predict the outbreak proclivity for different regions in the future, and also help determine the most effective and economical time and place to execute interventions by visualizing the regional and time differences of intervention effects. In summary, by combining regional mobility and governmental interventions, this model could guide decision-makers in medical-resources allocation and intervention-strategies design.

During this emergency public health crisis, China has shown a strong response capacity and intervention effectiveness, and the reasons behind are worth discussing. It is widely recognized that since the early outbreak of COVID-19 in January 2020 in Wuhan, the local government has adopted many controlling policies such as closing the city on January 23, 2020, banning almost all personnel exchange, and suspending work, school, and public transport.\textsuperscript{29} In addition, on the same day, the Chinese government announced that China had entered a national emergency response state and adopted a series of nationwide strict and large-scale controlling measures.\textsuperscript{30} Being able to control epidemics through rigorous policies in a short period of time is undoubtedly an important experience that China could give to the international society to combat the epidemic.

There are still some limitations for this study. Firstly, due to data availability, daily human mobility data between Western countries are inferred from the monthly or seasonal data of 2019, which could bring bias to the prediction of future epidemic growth and the simulation of mobility bans. However, the overall trend of prediction would not be affected; Secondly, as the result shows, prediction of future total number of reported confirmed cases may change greatly after controlling for under-reporting, like that of the United States. Thus, if there are any significant under-reporting on real data, then the prediction of future cases could be underestimated, and although we have attempted to control for under-reporting in trajectory prediction, the under-reporting degree we used may still be biased as they were estimated without taking into account age-distribution of each country.\textsuperscript{24} Thirdly, we have not considered population demographics and meteorological conditions, which should be integrated in a more realistic model;\textsuperscript{28} Finally, as we included only thirteen Western countries in the model, more countries should be included to reflect a more globalized perspective.

**Methods**

**Model structure**

The model structure is displayed in Fig. 1. We stratify the natural infective process into four stages: susceptible individuals, exposed infected individuals in the incubation period, symptomatic infected individuals, and removed individuals (who either recovered or died). Susceptible individuals are those who have not been infected before and are vulnerable to infection, in which they would become exposed infected individuals. After an incubation period of 6-4 days for coronavirus,\textsuperscript{5} exposed infected individuals, if not isolated, will develop into symptomatic infected individuals. After a symptom-onset period of 3-8 days,\textsuperscript{6} symptomatic infected individuals, if not isolated, would be hospitalized and get tested. A proportion of hospitalized cases would die within an average period of 14-7 days (for non-survivors of coronavirus since hospitalization), and the rest recover within an average period of 18-2 days (for survivors of coronavirus since hospitalization).\textsuperscript{7} The individuals who recover are assumed to gain immunity and would not be infected again. In our model we assume that healthcare facilities like negative pressure isolation wards and personal protective equipment (PPE) for medical staff are abundant, so that no further infection would occur once infected individuals are hospitalized or isolated. To take asymptomatic cases into account, we assume 7-5\% of cases would be asymptomatic before recovery,\textsuperscript{8} who will remain at the stage of exposed infected individuals and keep infecting others with the same infectiousness of symptomatic cases until being isolated or self-recovered.\textsuperscript{9} Before being reported, exposed infected individuals or symptomatic infected individuals are suspected cases.

After individuals are hospitalized, official reporting will be performed. Considering the average testing and official reporting speeds for Wuhan were different before and after January 27, 2020, we assume days required for reporting individual cases in China are 4-5 days and 2-8 days before and after January 27, 2020.\textsuperscript{5} For western countries, considering the difficulty in confirming unknown COVID-19 cases before the Wuhan outbreak, we assume the reporting rate would gradually linearly accelerate to 4-5 days by February 19, and then linearly accelerate to 2-8 days by March 8, to reflect a growth of public awareness and government response. Delays are accounted for between infection, symptom onset, hospitalization, and recovery, by dividing the corresponding processes into two compartments.\textsuperscript{10} Given the possibility of COVID-19 infection during the late incubation period, we assume cases would be infectious since the second phase of exposed infection.\textsuperscript{11}

We integrate human mobility process into traditional SEIR model to consider daily human mobility, through which susceptible individuals, exposed infected individuals in an incubation period, and symptomatic infected individuals could be exported freely between regions from December 10, 2019 to January 23, 2020, the time of the shutdown in Wuhan. However, after the shutdown in Wuhan, we assume only susceptible individuals and exposed infected individuals could travel freely by precisely screening symptomatic infected individuals.

For governmental interventions, besides the estimation and drawing of region-specific time-variant reproduction numbers, we estimate rates of region-specific time-variant social distancing, work resumption, and isolation based on extended SEIR model by fitting random walk process containing 2000 operators to the real total confirmation data for each region.

Susceptible individuals could expand their social distancing to the extent that they would not be infected, at a social-distancing rate, and similarly, individuals who have social-distanced themselves could resume work at a work-resumption rate and become susceptible individuals again. Exposed infected individuals and symptomatic infected individuals could be isolated at a region-specific time-variant rate. Once isolated, we assume that the individual would not infect others any more. We set the isolation period as seven days, as per the guidance from Public Health England, who suggest that people with COVID-19-like
symptoms should self-isolate themselves for a seven-days medical observation since the time of symptom onset. After isolation, if still do not recover, the isolated individuals will be hospitalized, tested, and reported. The asymptomatic cases could also be isolated through contact tracing. As Wuhan governmental interventions such as travel bans, social distancing, school and workplace closure, and contact tracing, mainly started on January 23, 2020. Thus, we assume no isolation or social distancing effects exist before January 23 for both China and Western regions. A comparison of the moving trend of these parameters has been done between the Wuhan level, the Chinese average level, the United States level, and the Western average level.

Data sources and processing

Previous studies reported that the Coronavirus firstly emerged in Wuhan, China in early December, 2019. Thus, for Wuhan, Hubei Province excluding Wuhan, and other provinces in mainland China, data outlining total daily confirmed cases of COVID-19 were collected from December 10, 2019 to May 1, 2020, from the National Health Commission of the People’s Republic of China and the Health Commissions of distinct provinces. For each selected Western country, data for the total number of daily confirmed cases were collected from the daily situation reports of the World Health Organization for the same period. These data were fit in the extended stochastic meta-population model to estimate the dynamic trajectories of region-specific time-variant parameters, which would be the base for further scenario simulations.

Daily human mobility data between Wuhan, Hubei Province excluding Wuhan, and other provinces in mainland China were collected from the Baidu Migration Platform. That from December 10, 2019 to January 1, 2020 was backwards inferred as 50% of the mobility on January 1, 2020, which is moderately lower than the huge migration flows during the Chinese Spring Festival at the beginning of 2020.

Daily human mobility data between 13 Western countries (Switzerland, Sweden, Austria, France, the United Kingdom, Germany, Spain, Italy, Norway, the Netherlands, Belgium, Denmark and the United States) and between Western countries and Wuhan, Hubei Province excluding Wuhan, and other provinces in mainland China are inferred from seasonal flight data in 2019 from the European Union’s air passenger transport report of 12 European countries and origin and destination flight survey data from the Department of Transportation of the United States.

Mobility data between Chinese regions and Western regions have been further corrected before application. First, based on daily flight statistics reports from Flight Manager, from January 21, 2020 to March 19, 2020, to reduce the threat of epidemic spread, foreign airline companies substantially decreased daily numbers of international inbound and outbound flights in China by 87% on average compared with the average level before January 21, 2020. Second, to control the growth of imported cases from abroad and avoid a second outbreak, the Civil Aviation Administration of China (CAAC) twice declared it would reduce the number of international flights, once on March 20, 2020 and again on March 26, 2020. This is estimated to have decreased the number of international flights into and out of China by 37% and 85%, respectively. Moreover, since March 16, 2020, to counter the spread of the novel coronavirus, the European Union passed a travel ban to restrict non-essential travel from non-EU countries into Europe, so the human mobility data between the United States and European countries after March 16, 2020 are assumed to be 1% of the original.

Trajectory predictions and scenario simulations

Trajectories of total reported cases, individuals infected but not hospitalized, new cases reported, total deaths, and new recoveries every day have been estimated for Wuhan, Hubei Province excluding Wuhan, and thirteen Western countries, from December 10, 2020 to June 26, 2020, not controlling for under-reporting. After controlling for under-reporting, two another trajectories of total reported cases and individuals infected but not hospitalized are estimated. The under-reporting rate of each country is based on a previous study which estimated under-reporting for China (24%) and numerous Western countries (Switzerland 22%, Sweden 6-3%, Austria 29%, France 5-1%, The United Kingdom 4-8%, Germany 25%, Spain 8-5%, Italy 7-3%, Norway 40%, The Netherlands 7-4%, Belgium 5-4%, Denmark 18%, and United States 13%).

In the simulation part, we have simulated three scenarios. First, to understand whether the rigorous strategy of Wuhan is more effective in curbing the spread of the epidemic, we examine a scenario where Western governments, from several time-points, simultaneously carry out intervention strategies in the same way as Wuhan, which is calculated as the average level of Wuhan in social-distancing and suspected-cases isolation during the first month after the shutdown in Wuhan. Second, to understand the significance of controlling imported cases from abroad in containing the epidemic, we have simulated a scenario where Western countries, from several time-points, simultaneously close their borders completely and ban all inbound or outbound mobility. Finally, we have simulated a scenario where less non-pharmaceutical interventions are in effect in China or Western countries to see how the epidemic would grow naturally without interventions.

Considering the COVID-19 epidemic may be already spreading globally since December, 2019 the model was seeded with 2, 1, and 0·1 initial symptomatic infected individuals in Wuhan, Hubei Province excluding Wuhan, and in other Chinese provinces and Western countries on December 10, 2019, with twice the number of exposed infected individuals.

Declarations

Data and code availability

Data and code are available from the corresponding author upon reasonable request.

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We thank Baidu Migration Platform for providing human mobility data within China.
Author contributions

T.Y. and J.D. conceptualized and designed this study. T.Y. Y.L., W.D., W.Z. and J.D. designed the methodology, collected data, and interpreted the results. Y.L. and W.D. analyzed data and visualized results. T.Y. and Y.L. wrote the manuscript. All authors have reviewed and approved this manuscript.

Competing interests

We declare no competing interests.

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**Figures**

Figure 1

Model structure
Region-specific time-variant reproduction numbers for fifteen regions, not controlling for under-reporting. The horizontal black imaginary line represents $R_0$ at 1, the vertical black line represents January 23, 2020, the date of the shutdown in Wuhan, and the blue area on the right side of the picture represents the predicted period from May 1 to June 26, 2020.
Figure 3

Region-specific time-variant reproduction numbers for fifteen regions, controlling for under-reporting. The horizontal black imaginary line represents R0 at 1, the vertical black line represents January 23, 2020, the date of the shutdown in Wuhan, and the blue area on the right side of the picture represents the predicted period from May 1 to June 26, 2020.
Figure 4

Social-distancing rate trajectories for Wuhan, the Chinese average, the United States, and the Western average (a); Work resumption rate trajectories for Wuhan, the Chinese average, the United States, and the Western average (b); Proportion of socially-distanced people in susceptible population for Wuhan, the Chinese average, the United States, and the Western average (c); Isolation rate trajectories for Wuhan, the Chinese average, and the Western average (d); Proportion of population getting isolated in Wuhan, the Chinese average, the United States, and the Western average (e); Proportion of suspected cases getting isolated in Wuhan, the Chinese average, the United States, and the Western average (f); Accumulated imported cases from other Western countries (g). Under-reporting are not controlled for.

Figure 5
Social-distancing rate trajectories for Wuhan, the Chinese average, the United States, and the Western average (a); Work resumption rate trajectories for Wuhan, the Chinese average, the United States, and the Western average (b); Proportion of socially-distanced people in susceptible population for Wuhan, the Chinese average, the United States, and the Western average (c); Isolation rate trajectories for Wuhan, the Chinese average, and the Western average (d); Proportion of population getting isolated in Wuhan, the Chinese average, the United States, and the Western average (e); Proportion of suspected cases getting isolated in Wuhan, the Chinese average, the United States, and the Western average (f); Accumulated imported cases from other Western countries (g). Under-reporting are controlled for.

Figure 6

Epidemic trajectories of Wuhan, Hubei Province excluding Wuhan, and thirteen Western countries. Total number of confirmed cases reported, controlling for under-reporting (purple curve) and not controlling for under-reporting (blue curve); total number of individuals infected but not hospitalized, controlling for under-reporting (pink curve) and not controlling for under-reporting (cyan curve); new confirmed cases (orange curve), total deaths (red curve), and new recoveries (green curve) every day not controlling for under-reporting; All trajectories are predicted from December 10, 2019 to October 4, 2020, for Wuhan, Hubei Province (excluding Wuhan), and thirteen Western countries (shown in Fig 5), based on total-confirmation real data, all with 50% and 95% CI. Black point refers to historical real total number of confirmed cases reported per day.
Figure 7

Simulations of the first scenario. Curves of different colors represent trajectories of total confirmed cases reported for nine selected Western countries in different occasions where NPI of western countries were executed in the same way as Wuhan from different time points. Different time-points to take action are exhibited in the legend of figure.
Figure 8

Simulations of the second scenario. Curves of different colors represent trajectories of total confirmed cases reported and daily new confirmed cases reported for twelve selected Western countries in different occasions where complete international travel ban were executed from different time points. Different time-points to take complete international travel ban are exhibited in the legend of figure.
Figure 9

Simulations of the third scenario. Curves of different colors represent trajectories of daily new confirmed cases reported for four selected Western countries and China in different occasions where less or none NPI were executed in China or Western countries from January 23, 2020. In subplot A of each Western country (The United States, France, The United Kingdom, Germany), the trajectories in occasion of none NPI in China and in occasion of original route are drawn on the right axis, and similarly in subplot A of China, the trajectories in occasion of none NPI in Western countries and in occasion of original route are drawn on the right axis.