Transmission Dynamics and Estimation of Basic Reproduction Number (R_0) from Early Outbreak of Novel Coronavirus (COVID-19) in India

S. K. Laha, Debasmita Ghosh, D. Ghosh, and B. Swarnakar

Abstract Novel coronavirus (COVID-19) caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is an epidemic declared by the World Health Organization (WHO). Till now in June 13, 2020, the total COVID-19 cases in different countries around the world are 77,56,905 with 4,28,576 deaths and 3,974,422 recovered. The virus has taken spread in India as well, whereas of June 13, 2020, 3,09,603 cases are confirmed with 8,890 deaths and 1,54,330 recovery. It this situation, it is vital to know the potential danger posed by the pandemic and the epidemic trajectory. In this paper, the basic reproduction number (R_0) of COVID-19 from the early epidemic data in India is estimated. The course of the pandemic in India as well as the worst affected seven states in India, namely Maharashtra, Tamil Nadu, Delhi, Gujarat, Uttar Pradesh, Rajasthan and West Bengal is also analyzed. The early outbreak data from the Ministry of Health and Family Welfare (MoHFW), Government of India, are collected for the analysis. The two R packages 'R0' and 'earlyR' to estimate the basic reproduction number are used. An attempt is also made to forecast near-future incidence cases based on statistical methods. The results show that R_0 varies from 1.53 to 3.25 accounting to different methodologies and serial intervals adopted, whereas WHO estimations are from 2 to 2.5. Due to effect of lockdown, the time-dependent reproduction number has reduced to near about 1.22. It is predicted that by July 15, cumulative number of COVID-19 cases may reach around 1.2 million if the current effective reproduction number remains same over the next one month. Finally, it can be concluded that in the coming months, the novel

S. K. Laha (✉) · D. Ghosh · B. Swarnakar
Industrial Service and Research Group, CSIR-Central Mechanical Engineering Research Institute, M.G. Avenue, Durgapur 713209, West Bengal, India
e-mail: sk_laha@cmeri.res.in

D. Ghosh
e-mail: dghosh@cmeri.res.in

B. Swarnakar
e-mail: b.swarnakar@cmeri.res.in

D. Ghosh
Indian Institute of Science Education and Research(IISER), Bhopal, India
e-mail: debasmita18@iiserb.ac.in

C. Chakraborty et al. (eds.), *Internet of Medical Things for Smart Healthcare*, Studies in Big Data 80, https://doi.org/10.1007/978-981-15-8097-0_1

coronavirus will pose a severe challenge to the Indian healthcare system. Thus, it is necessary to predict how the virus may spread so that the healthcare system may be prepared in advance. The time-dependent reproduction number shows the positive effect of lockdown, as this number has gone down.

Keywords Basic reproduction number · Novel coronavirus · Transmission dynamics

1 Introduction

Coronavirus in the form of COVID-19 poses a pandemic threat in most of the countries all over the world in 2020. The COVID-19 is spreading at alarming rate in almost all countries over the globe. It has first originated in Wuhan, Hubei province, Republic of China [1] at the end of December 2019. The 41 cases existing as 'pneumonia of unknown reasons' are reported by the Wuhan Municipal Health Committee [2]. On January 01, 2020, the seafood wholesale market in Wuhan is announced as the epicenter of the outbreak of COVID-19 and is decided to be closed. After few days, human-to-human transmission is reported in Wuhan [3]. In first week of February 2020, the virus outbreak causes more than 24,000 total confirmed cases and 494 deaths and spreads in 25 countries around the world. The outbreak is a major concern in Italy, Spain, Iran followed by England, USA, Russia, UAE, Australia, Canada, Singapore, India and many other countries. The outbreak is increasing day by day and poses a major threat to healthcare system in different countries. Till now in June 13, the total cases in different countries around the world are 7,756,905 with 4,28,576 deaths and 3,974,422 recovery [4]. The most affected states and union territories in India are Maharashtra, Tamil Nadu, Delhi, Gujarat, Uttar Pradesh, Rajasthan and West Bengal. 98% of the patients are having mild symptoms or asymptomatic, and rest 2% are in critical and serious condition of acute respiratory problems. The problem of rapid outbreak in India is also very alarming and spread to almost every states in May 2020. The total no of cases in India up to June 13, 2020 are 3,09,603 with 8,890 deaths and 1,54,330 recovery [5].

The first case of COVID-19 in India is reported in 30 January 2020 in Kerala. There has been a gradual increase in the number of infections (1,251 on March 30, among which 32 deaths and 102 recovered cases). In response, Indian government has implemented international travel bans, Janata curfew and strict lockdown throughout the country from 25th March onward. The major event in connection with COVID-19 outbreak is listed in Table 1.

India is having second highest population after China around the world with very large population density, limited infrastructure and healthcare systems to cater to very large demands of COVID-19 patients. On the other hand, factors like warmer climate as well as humidity [6–9], a large proportion of the young population, and possible immunity due to BCG vaccinations [8], may favor India. Most of the infected patients in India are asymptomatic or mild symptoms, which is quite unusual as compared

Table 1 Key events and decisions taken by Indian government

Dates	Key events
January 30, 2020	First confirmed positive case
March 6, 2020	International passenger screenings at airports
March 12, 2020	First confirmed death
March 13, 2020	Suspension of non-essential traveler visas
March 15, 2020	100 confirmed positive cases
March 22, 2020	One-day Janata curfew Passenger air travel suspended till further notice
March 25, 2020	First national lockdown imposed till April 14
March 28, 2020	1000 confirmed positive cases
March 30, 2020	100 confirmed recoveries
April 2, 2020	Government announces plans to convert trains and stadiums into isolation wards
April 14, 2020	10,000 confirmed Covid-19 cases National lockdown extended till May 3
May 01, 2020	Nationwide lockdown further extended till May 17
May 17, 2020	Nationwide lockdown further extended till May 31
May 29, 2020	Highest number of recovered cases recorded
June 01, 2020 till date	Lockdown to continue in containment zone

to Europeans and North American countries. India is experiencing early lockdown followed by China in view of favorable effect in controlling the final epidemic size. However, considering the huge population (almost 1.35 billion), with high population density, poses significant challenges to mitigate the pandemic situation due to COVID-19 spreading, without affecting economic and social issues. In this context, it is very important to consider the huge demand of healthcare systems (like ICU beds, PPE, ventilator, oxygenerator, etc.) and also enforce social distancing and avoid spreading in a larger scale through community transmission. So the prediction of possible COVID-19 outbreak is very important for formulation of policy-making decision regarding healthcare system lockdown and social distancing. The trend of spread in India is confined in some specific hotspot areas, especially in highly population dense area, where the timely decision of lockdown, social distancing and rapid diagnosis of infected cases play a major role to prevent pandemic situation.

Mathematical modeling is frequently used to predict the outbreaks of different diseases in epidemiology [10, 11]. Infectious disease models under epidemiology aim at understanding the mechanisms that influence the spread of diseases and predicting disease transmission. Mathematical models are popular to evaluate the potential impact of different control measures of pandemic diseases and to guide public health policy decisions of certain union government. Different models used earlier to predict the nature of the out breaks of Ebola pandemic diseases at African countries are reported in different literatures [12–14]. The different models used to predict the pandemic disease outbreak mainly consist of two types of models such as statistical models [15] and mechanistic models [16]. The forecasting of different diseases by mathematical modeling in case of dengue, influenza and chikungunya is reported in different literature [17–19]. In all models, a balance must be shown between obtaining precise forecasts, considering for all uncertainties, both in the data and in the dynamics of transmission.

Mathematical modeling is used to understand the dynamics of the pandemic in its early stages and to predict the rate of spreading from the infector to receiver. The basic reproduction number (R_0) measures the average number of secondary infections generated by primary cases in a fully susceptible population. A schematic diagram of basic reproduction number with a value of 2.0 is shown in Fig. 1

Liu et al. [20] reviewed and listed reproduction numbers reported in literatures in PubMed, bioRxiv and Google Scholar. Twelve studies in the period between January 1, 2020–February 7, 2020, were covered in their paper. It was shown that the estimates of reproduction number range from 1.49 to 6.49, with a mean of 3.28, a median of 2.79 and interquartile range (IQR) of 1.16. They attribute that such a large deviation to the estimation method adopted such as stochastic method, mathematical methods and exponential growth method. Zhang et al. [21] estimated the value of R_0 and probable outbreak dynamics in the Diamond Princess cruise ship.

In this study, data is obtained from Govt. of India, the Ministry of Health and Family Welfare (MoHFW) for the period from 2 March to 1 April to estimate the R_0 of COVID-19 by applying different statistical models. No new cases of COVID-19 have been detected in India from January 31 to 1 March 1, 2020; therefore in the modeling, the number of the samples has been taken from March 2, 2020 onward.

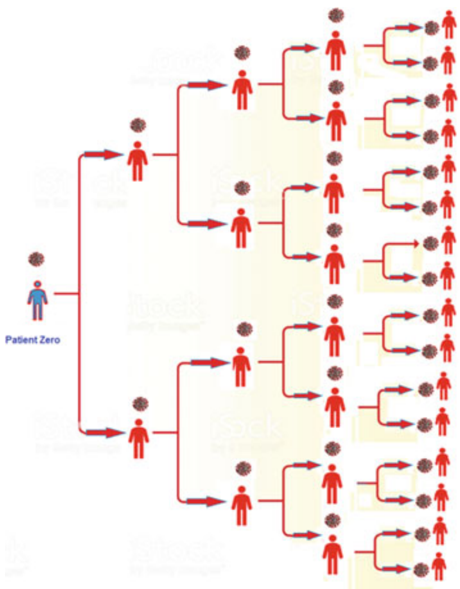


Fig. 1 A schematic diagram of basic reproduction number

The gradual increase of infected cases is observed on March 2, 2020 onward. The ‘projections’ package in R is used to get an idea about the possible epidemic trend in India.

2 Materials and Methods

The incidence data is taken from the Ministry of Health and Family Welfare (MoHFW) of the Government of India and COVID 10 tracker in India [5], which tracks the country-wise COVID-19 cases in India. To estimate the reproduction number, three serial interval (SI) distributions reported in the literature: (1) by Li et al. [22]; (2) by Nishihura et al.; [23] and (3) by Du et al. [24].

Two R packages ‘earlyR’ [25] and ‘R0’ [26, 27] are used to estimate the basic reproduction number (R_0). The ‘earlyR’ package estimates this number using the maximum likelihood (ML) method as illustrated by Cori et al. [28]. The ‘R0’ package uses five different methods to estimate the number: (1) from attack rate, (2) maximum likelihood, (3) exponential growth rate, (4) Bayesian approach and (5) time-dependent reproduction number. In this paper, three methods from the ‘R0’ package: (1) exponential growth rate (EG), (2) maximum likelihood (ML) and (3) time-dependent (TD) reproduction number are used. The maximum likelihood (ML) method of estimation in ‘R0’ package follows the algorithm proposed by White and Pagano [29], whereas the exponential growth rate method follows the paper by Wallinga and Lipsitch [30], and the time-dependent method is proposed by Wallinga and Teunis [31]. Nouvellet et al. [32] presented a simple approach to forecast near-future incidence cases based on a statistical method. In their model, the daily incidence I_t can be approximated by the renewal equation which is assumed to be a Poisson’s process as given by $I_t \sim \text{Pois}\left(R_t \sum_{s=0}^{t} I_{t-s}\omega_s\right)$ where ω is the serial interval and R_t is the instantaneous reproduction rate. Their method is implemented in the R package named ‘projections’ [33].

2.1 Serial Interval

To estimate the reproduction number, it is necessary to know about generation time, which is the time lag between infection in primary cases (infectors) and secondary cases (infectee). It is generally obtained from the serial interval (SI) which is defined as the time lag between the onset of symptoms in primary cases and secondary cases. It is assumed the serial interval has gamma distribution. In the analysis of the early outbreak of novel coronavirus in the form of COVID-19 in the city of Wuhan, China, Li et al. [22] estimated that the SI has a mean of 7.5 days and an SD of 3.4 days. However, Nishiura et al. [23] estimated that the mean and standard deviation of SI are 4.7 days (95% CI: [3.7, 6.0]) and 2.9 days, respectively. They have estimated the parameters based on the dataset of 28 infector/infectee pairs. Du et al. [24] also obtained similar SI distribution, where mean is 3.96 days (95% CI: [3.53, 4.39]) and SD is 4.75 days (95% CI: [4.46, 5.07]). Their dataset consists of 468 COVID-19 transmission events.

3 Results

3.1 Analysis of COVID-19 in India

3.1.1 Epidemic Curve and Preliminary Analysis

The epidemic curve of incidence cases in India from March 2, 2020 to April 1, 2020, is shown in Fig. 2. An exponential model is also fitted to the epidemic curve and is shown in Fig. 2. The fitted curve shows that daily cases are doubling in approximately four days.

3.1.2 Estimation of R_0

Table 2 shows our estimation of R_0 along with the 95% confidence interval for three reported SI data and the R package used in the analysis. The range of estimated values of R_0 is from 1.53 to 3.25 with a mean of 2.18. It seems that the 'R0' package tends to overestimate the reproduction number slightly. Also, the R_0 value estimated with SI mean = 7.5 and 3.4 is higher than that obtained with other SI data. The mean value obtained (i.e., 2.18) in this analysis falls within the WHO recommended value.

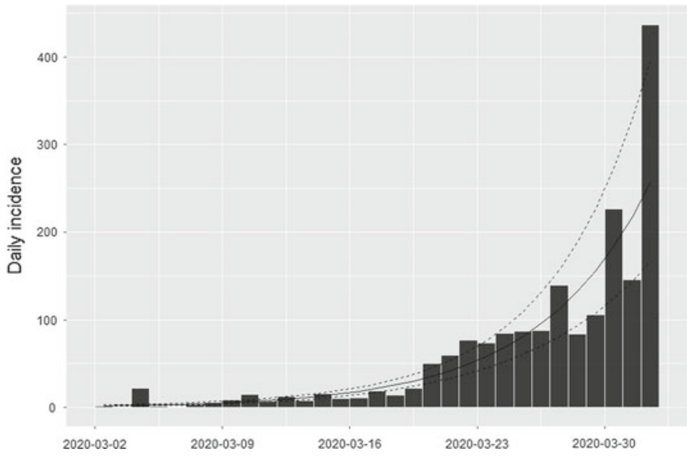


Fig. 2 Epidemic curve of COVID-19 in India (March 02, 2020–April 01, 2020)

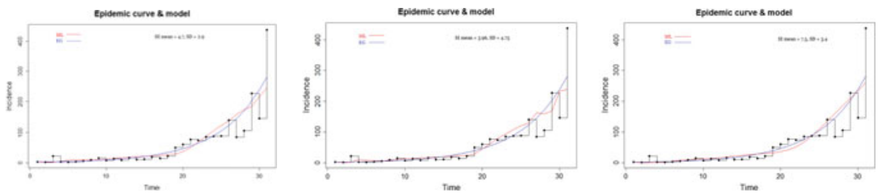
Table 2 Estimation of R_0 with confidence interval

Serial interval (SI) (days)	R_0 [95% confidence interval (CI)]	
SI mean = 4.7, SD = 2.9	ML method, 'R0' package	2.05 [1.92, 2.19]
	EG method, 'R0' package	2.15 [2.08, 2.22]
	ML method, 'earlyR' package	1.53 [1.47, 1.60]
SI mean = 3.96, SD = 4.75	ML method, 'R0' package	1.94 [1.82, 2.07]
	EG method, 'R0' package	1.98 [1.93, 2.04]
	ML method, 'earlyR' package	1.68 [1.60, 1.75]
SI mean = 7.5, SD = 3.4	ML method, 'R0' package	2.99 [2.80, 3.19]
	EG method, 'R0' package	3.25 [3.03, 3.43]
	ML method, 'earlyR' package	2.08 [1.99, 2.18]

Figure 3 shows the daily observed incidence and model predicted incidence using ML and EG methods. This fitted incidence is then used to estimate R_0. It can be seen from Fig. 3 that the predicted model fits quite well to the observed incidence data.

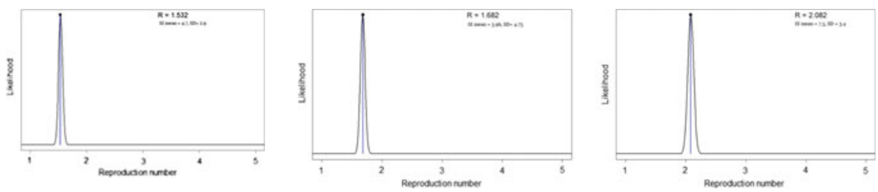
The likely values of the basic reproduction number implemented with the 'earlyR' package are shown in Fig. 4.

As deviations are observed concerning serial interval distribution, a sensitivity analysis of SI on the R_0 value is also carried out. The serial interval is assumed to have gamma distribution. The mean and standard deviation of the SI are varied over a range of 1–7 days and 2–5 days, respectively, and then R_0 numbers are estimated using the ML method. Figure 5a shows three different serial distributions considered



SI mean = 4.7, SD = 2.9   SI mean = 3.96, SD = 4.75   SI mean = 7.5, SD = 3.4

Fig. 3 Observed incidence and model predicted incidence using ML and EG



SI mean = 4.7, SD = 2.9   SI mean = 3.96, SD = 4.75   SI mean = 7.5, SD = 3.4

Fig. 4 Estimation of basic reproduction number (R_0), 'earlyR' package

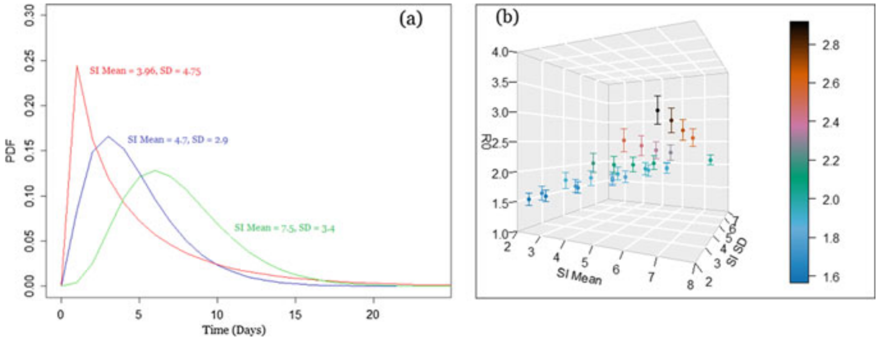


Fig. 5 **a** Serial interval distribution, **b** sensitivity of serial interval distribution to R_0

in the present study. Figure 5b depicts the sensitivity of R_0 to SI mean and standard deviation. From the sensitivity analysis, it can be seen that R_0 has a maximum value of 2.9 when SI mean and SD are seven days and two days, respectively.

Figure 6 shows the time-dependent reproduction number ($R(t)$) over the period from March 14, 2020 to June 10, 2020. The epidemic curve is also shown for this period. The SI mean and the SD are assumed to be 7.5 days and 3.4 days, respectively. The start of lockdown, i.e., March 25, 2020, is also marked on the figure. It can be seen that there is a reduction in reproduction number from April 15 onward, mainly due to the imposition of travel restriction, closure of public places and the imposition

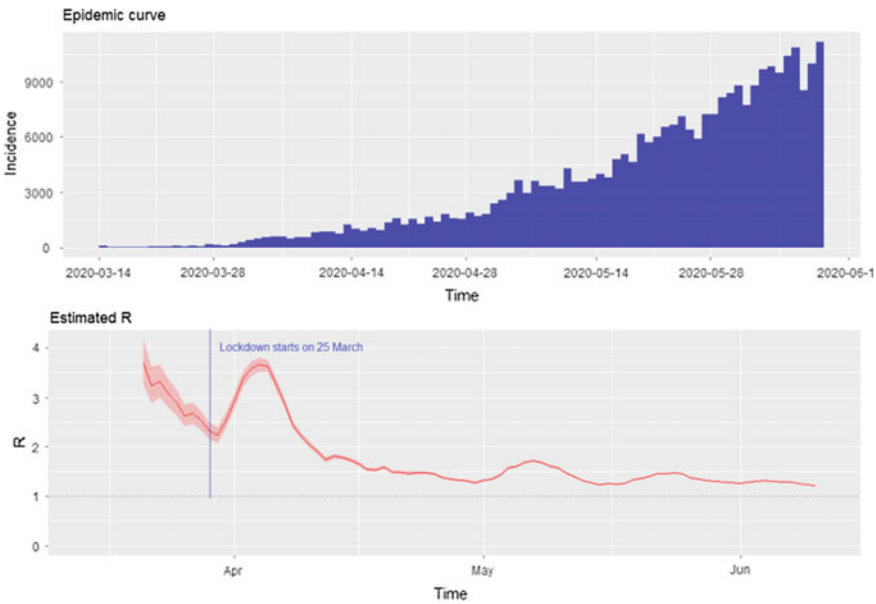


Fig. 6 Epidemic curve and the time-dependent reproduction number in India

of lockdown. For the last twenty days or so, the effective reproduction number has reduced to nearly 1.22 as an effect of the lockdown. However, for containing the spread of the virus, it is necessary to reduce the value of reproduction number below one.

3.2 Forecasting Near-Future Incidences in India

An attempt has been made to forecast near-future incidences up to August 12 using the R package 'projections' developed by Thibaut et al. [33]. The first forty-five days' data starting from March 14 is used for learning the model. Further, during the projection, the reproduction number as given in the renewal equation is assumed to be constant during the projection. This reproduction number is obtained from the average of last seven days of the time-dependent reproduction number, while the serial interval has a mean and standard deviation of 7.5 and 3.4 days, respectively. Figure 7a shows the predicted daily incidences in India from April 28 to August 12. The actual daily incidences from April 28 to June 10 are also shown in Fig. 7a. It can be seen that predicted cases by the present methodology fit quite well with the observed cases. Figure 7b shows the predicted cumulative daily incidences up to August 12. With the present epidemic trajectory, it is estimated that predictions are as follows: On 15 June, cumulative incidences are 305,477 (range: 291,402–319,738); on 25 June, cumulative incidences are 492,903 (range: 469,785–517,156); on 05 July, cumulative incidences are 781,432 (range: 741,211–821,212); on 15 July, cumulative incidences are 1,225,636 (range: 1,159,404–1,289,513); on 25 July, cumulative incidences are 1,909,548 (range: 1,802,053–2,011,688); on 01 August, cumulative incidences are 2,597,702 (range: 2,447,797–2,738,595). It may be noted that these are conservative estimates, assuming the present rate of infection persists. However, if the restrictions of lockdown are eased up, then it is expected that R_0 will increase which will result in more number of COVID-19 cases in India.

3.3 Analysis of COVID-19 in States and UT of India

Analysis of the COVID-19 cases is also carried out for seven worst affected Indian states, namely Maharashtra, Tamil Nadu, Delhi, Gujarat, Uttar Pradesh, Rajasthan and West Bengal. A map of Indian states and the distribution of active COVID-19 cases are shown in Fig. 8. A probable projection of COVID-19 cases in those states is given in Table 3. It may be noted that the predictions are based on the assumption that reproduction number remains same in the prediction horizon which may not be correct particularly for long-term projection.

It may be noted that first 45 days staring from March 14, 2020, is used for future prediction of COVID-19 cases.

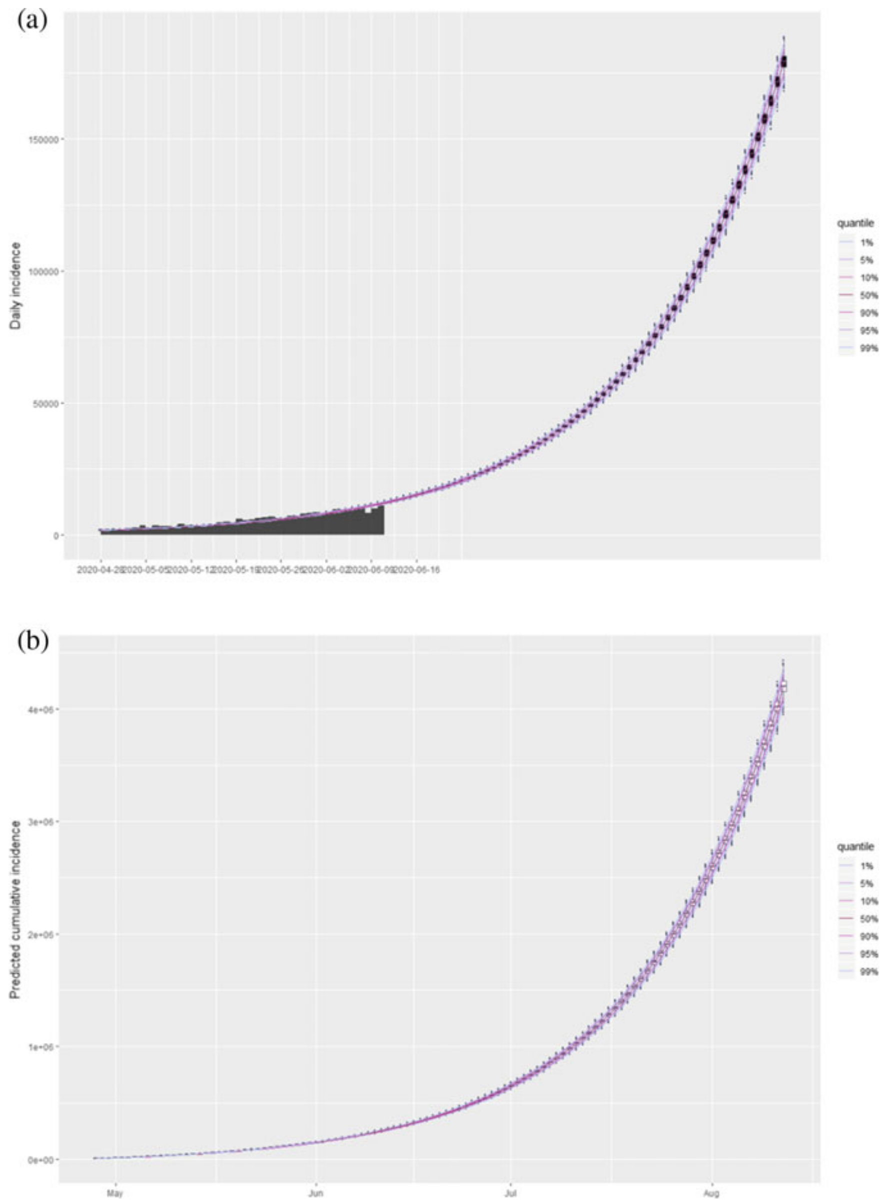


Fig. 7 **a** Predicted daily incidence and actually observed incidence in India, **b** predicted cumulative daily incidence in India

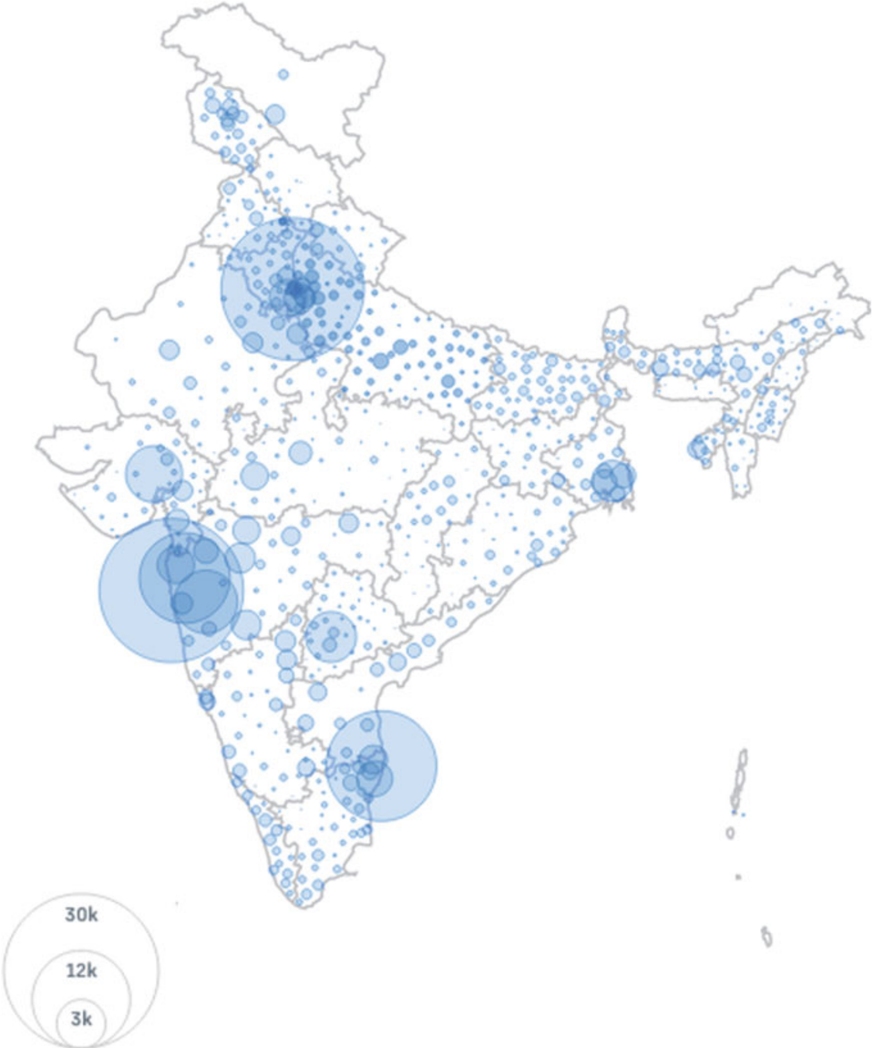


Fig. 8 COVID-19 active cases in India as on June 10, 2020 [5]

Maharashtra

Maharashtra has the highest number of COVID-19 cases in India. As of June 10, total confirmed cases in Maharashtra is 1,04,568 with 51,379 active cases, 49,346 recovered and 3,830 death cases. The epidemic curve and the time-dependent reproduction number in Maharashtra are shown in Fig. 9. However, on a positive note, it can be observed that the effective reproductive number in Maharashtra has reduced to 1.08 on June 10, 2020.

Table 3 Prediction of COVID-19 cases in India and Indian states

Date	India			Maharashtra			Tamil Nadu		
	Mean	Lower	Upper	Mean	Lower	Upper	Mean	Lower	Upper
2020-04-28	1896	1740	2053						
2020-05-03	12,495	12,050	12,952	4258	3986	4493			
2020-05-08	25,570	24,759	26,545	8620	8137	9077	1397	1174	1646
2020-05-13	41,792	40,320	43,395	13,933	13,144	14,658	2497	2044	2985
2020-05-18	61,923	59,630	64,488	20,406	19,236	21,692	4085	3374	4937
2020-05-23	86,897	83,426	90,801	28,290	26,654	30,243	6374	5301	7846
2020-05-28	117,893	113,158	123,070	37,897	35,700	40,623	9677	8035	12,028
2020-06-02	156,355	149,728	162,426	49,602	46,641	53,253	14,442	11,924	18,033
2020-06-07	204,083	195,379	212,843	63,862	59,643	68,735	21,317	17,658	26,902
2020-06-12	263,301	251,309	275,276	81,234	75,701	87,650	31,231	25,795	39,725
2020-06-17	336,792	321,074	352,712	102,404	95,329	110,658	45,538	37,414	57,858
2020-06-22	47,961	407,835	448,972	128,186	118,970	138,726	66,167	54,046	84,404
2020-06-27	541,096	515,459	567,873	159,598	148,018	172,972	95,928	78,153	122,683
2020-07-02	681,469	647,452	715,597	197,861	183,073	214,722	138,852	113,061	178,137
2020-07-07	855,630	811,174	899,752	244,469	225,496	265,685	200,758	163,385	258,080
2020-07-12	1,071,730	1,014,653	1,127,095	301,247	277,250	327,715	290,058	235,918	373,564
2020-07-17	1,339,864	1,267,169	1,409,990	370,415	340,230	402,883	418,865	341,404	539,923
2020-07-22	1,672,591	1,579,711	1,761,329	454,689	417,365	494,771	604,680	492,070	780,292
2020-07-27	2,085,442	1,967,294	2,197,288	557,358	511,271	606,560	872,704	709,482	1,127,071
2020-08-01	2,597,702	2,447,797	2,738,595	682,426	626,142	743,292	1,259,305	1,024,474	1,628,398
2020-08-06	3,233,306	3,043,299	3,409,553	834,789	766,260	910,949	1,816,953	1,477,593	2,352,016

(continued)

Table 3 (continued)

Date	India			Maharashtra			Tamil Nadu		
	Mean	Lower	Upper	Mean	Lower	Upper	Mean	Lower	Upper
2020-08-11	4,021,977	3,781,000	4,241,460	1,020,407	937,085	1,115,301	2,621,322	2,132,404	3,396,833

Date	Delhi			Gujarat			Uttar Pradesh		
	Mean	Lower	Upper	Mean	Lower	Upper	Mean	Lower	Upper
2020-04-28									
2020-05-03	1208	1055	1358						
2020-05-08	2578	2268	2854	1810	1638	1988	1436	1206	1676
2020-05-13	4333	3766	4802	3475	3159	3768	2255	1863	2659
2020-05-18	6586	5676	7420	5254	4780	5691	3209	2631	3764
2020-05-23	9475	8142	10,708	7159	6461	7865	4316	3536	5148
2020-05-28	13,185	11,201	14,990	9198	8255	10,150	5604	4590	6742
2020-06-02	17,947	15,128	20,567	11,382	10,207	12,529	7104	5804	8572
2020-06-07	24,058	20,048	27,567	13,721	12,182	15,241	8847	7252	10,681
2020-06-12	31,900	26,376	36,667	16,226	14,424	18,215	10,874	8799	13,140
2020-06-17	41,968	34,583	48,416	18,906	16,810	21,379	13,233	10,653	16,083
2020-06-22	54,882	45,062	63,611	21,780	19,404	24,860	15,973	12,786	19,355
2020-06-27	71,460	58,536	82,877	24,852	22,005	28,433	19,162	15,268	23,389
2020-07-02	92,731	75,907	107,574	28,145	24,831	32,345	22,869	17,974	27,882
2020-07-07	120,024	98,052	139,199	31,669	27,811	36,474	27,177	21,207	33,085
2020-07-12	155,049	126,217	180,156	35,439	30,834	40,776	32,188	24,930	39,432
2020-07-17	199,996	162,565	232,298	39,477	34,092	45,472	38,016	29,259	46,846

(continued)

Table 3 (continued)

Date	Delhi			Gujarat			Uttar Pradesh		
	Mean	Lower	Upper	Mean	Lower	Upper	Mean	Lower	Upper
2020-07-22	257,687	209,109	299,430	43,801	37,588	50,617	44,795	34,336	55,474
2020-07-27	331,725	268,959	385,103	48,432	41,296	56,085	52,677	40,268	65,502
2020-08-01	426,735	345,574	495,017	53,391	45,393	62,137	61,844	47,260	77,359
2020-08-06	548,664	444,309	636,888	58,700	49,611	68,362	72,507	55,244	91,039
2020-08-10	705,140	570,643	819,369	64,386	54,190	75,218	84,906	64,669	107,040

Date	Rajasthan			West Bengal		
	Mean	Lower	Upper	Mean	Lower	Upper
2020-04-28						
2020-05-03	713	598	837	174	127	222
2020-05-08	1368	1096	1582	499	400	602
2020-05-13	2113	1729	2522	917	726	1159
2020-05-18	2968	2371	3586	1453	1122	1824
2020-05-23	3942	3108	4763	2140	1616	2744
2020-05-28	5057	3976	6168	3023	2188	3882
2020-06-02	6334	4953	7805	4156	2912	5361
2020-06-07	7792	6070	9602	5610	3901	7312
2020-06-12	9458	7309	11,870	7477	5173	9758
2020-06-17	11,365	8666	14,417	9870	6783	12,880
2020-06-22	13,544	10,177	17,422	12,943	8927	16,904
2020-06-27	16,037	12,015	20,843	16,888	11,641	22,140
2020-07-02	18,891	14,146	24,786	21,949	15,110	28,968
2020-07-07	22,149	16,537	29,351	28,443	19,608	37,778

(continued)

Table 3 (continued)

Date	Rajasthan			West Bengal		
	Mean	Lower	Upper	Mean	Lower	Upper
2020-07-12	25,868	19,271	34,615	36,772	25,223	49,052
2020-07-17	30,127	22,248	40,612	47,466	32,734	63,530
2020-07-22	35,015	25,702	47,427	61,185	42,281	81,992
2020-07-27	40,631	29,558	55,631	78,800	54,633	105,528
2020-08-01	47,081	34,078	64,936	101,403	70,349	135,786
2020-08-06	54,500	39,104	75,391	130,410	90,494	174,158
2020-08-11	63,018	44,810	87,472	167,644	116,337	223,809

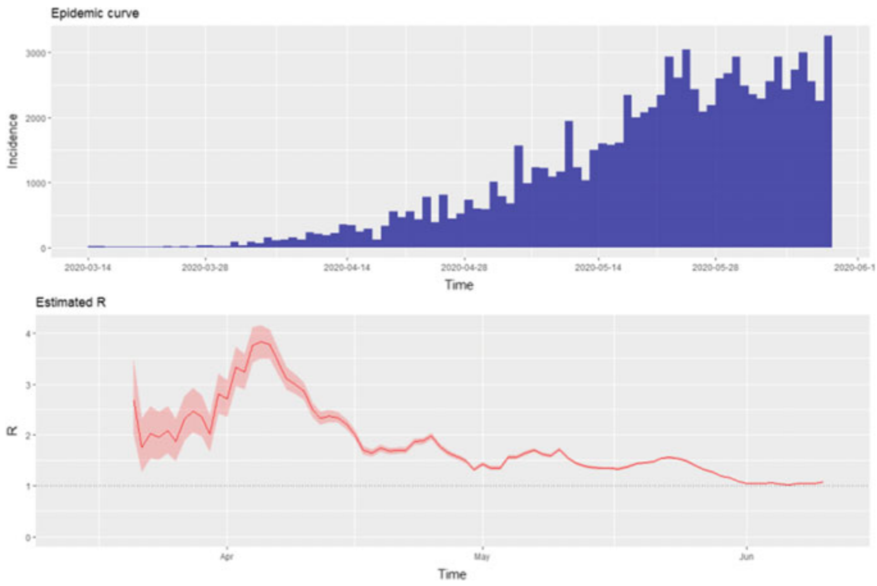


Fig. 9 Epidemic curve and the time-dependent reproduction number in Maharashtra

Figure 10a shows the predicted daily incidences in Maharashtra from April 28 to August 12, whereas Fig. 10b shows the cumulative projection in Maharashtra during that period. The predictions for Maharashtra are as follows: On 30 June, cumulative incidences are 1,81,648 (range: 1,68,149–1,97,195), and on 15 July, cumulative incidences are 3,41,105 (range: 3,13,764–3,70,958).

Tamil Nadu:

Tamil Nadu has second highest number of COVID-19 cases in India. On June 13, Tamil Nadu has observed total 42,687 confirmed cases, 18,881 active cases, 23,490 recovered cases and 397 deaths. Among the worst affected seven states considered in this study, Tamil Nadu has lowest infection death rate. The majority of cases are mainly concentrated in and around of Chennai, which is considered to be the epicenter of Tamil Nadu. However, even after the end of lockdown, the time-dependent reproduction number is still on the higher side. On June 10, 2020, the reproduction number in Tamil Nadu is 1.49 which is higher compared to other Indian states and national average. Also, slight upward trend in the time-dependent reproduction number can be observed (Fig. 11).

Plots indicating future incidences in Tamil Nadu are shown in Figs. 12a and b. It is predicted that cumulative cases may reach 1,19,781 (range: 97,668–1,53,513) on 30 June and 3,61,632 (range: 2,94,560–4,65,707). However, it be noted that such high numbers are predicted for Tamil Nadu can be attributed to higher reproduction number. It is quite possible that actual cases may be much lower, as infection rate may go down due to control measures (Fig. 12).

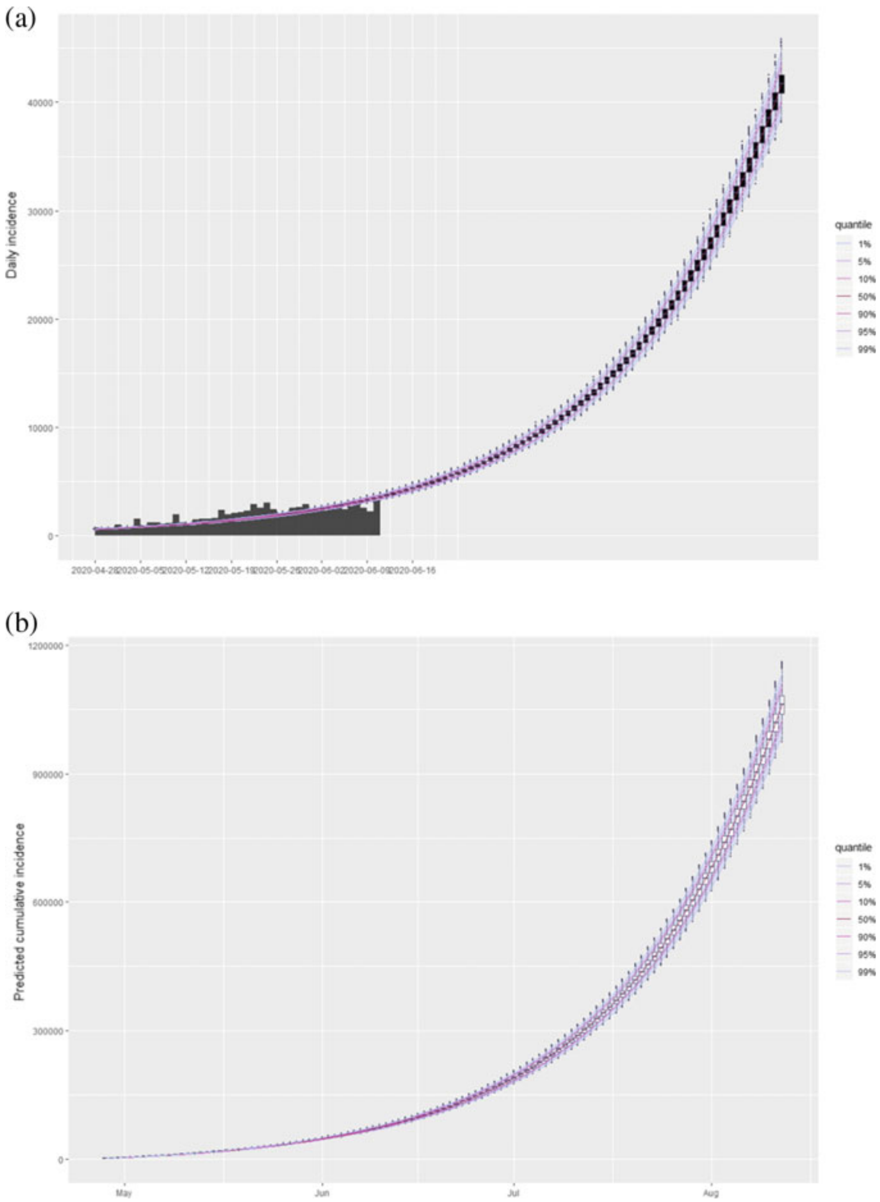


Fig. 10 **a** Predicted daily incidence and actually observed incidence in Maharashtra, **b** predicted cumulative daily incidence in Maharashtra

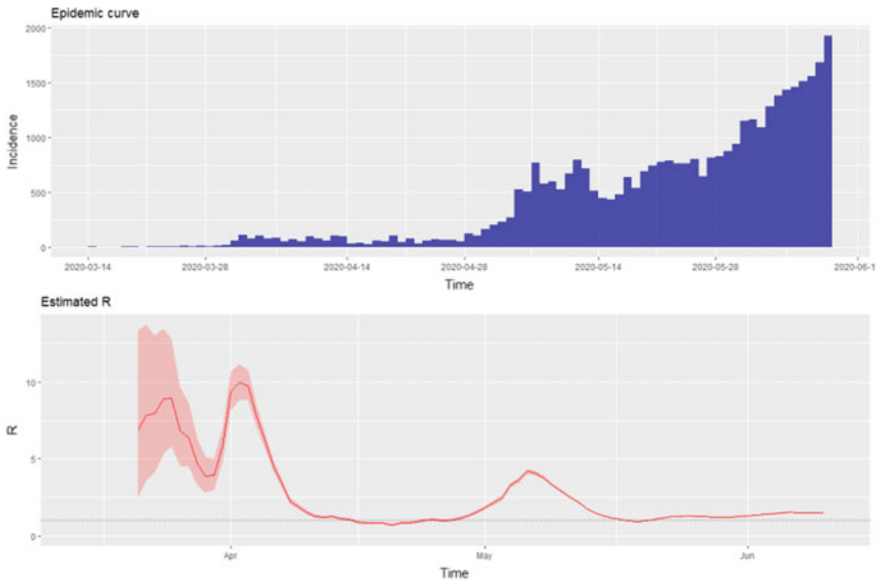


Fig. 11 Epidemic curve and the time-dependent reproduction number in Tamil Nadu

Delhi

Delhi is the third most affected state in India. As on 13 June, there are 3,85,98 confirmed COVID-19 cases with 22,742 active cases, 14,945 recovered cases and 1271 deaths. At the end of 10 June, the time-dependent reproduction number in Delhi is 1.19.

The prediction of future incidences for Delhi is shown in Figs. 14a and b. The predictions for Delhi are as follows: On 30 June, cumulative incidences are 83,585 (range: 68,370–97,017); on 15 July cumulative incidences are 1,80,666 (range: 1,46,961–2,09,867).

Gujarat

There are 23,079 confirmed COVID-19 cases in Gujarat as on June 13, 2020, with 5,739 active cases, 15,891 recovered cases and 1449 deaths. It can be observed from Fig. 15 that the time-dependent reproduction number in Gujarat is 1.24 on June 10, 2020. For a brief period at the last week of May, this number had gone below 1.0, but then again it is increased.

The prediction of future incidences in Gujarat is shown in Figs. 16a and b. From the simulation, it is predicted that cumulative cases in Gujarat may reach 26,802 (range: 23,705–30,779) on 30 June and 37,829 (range: 32,761–43,559) on July 15.

Uttar Pradesh

In Uttar Pradesh, there are 13,118 confirmed cases of COVID-19 resulting in 4,858 active cases, 7,875 recovered and 385 deaths on 13 June. The epidemic curve of

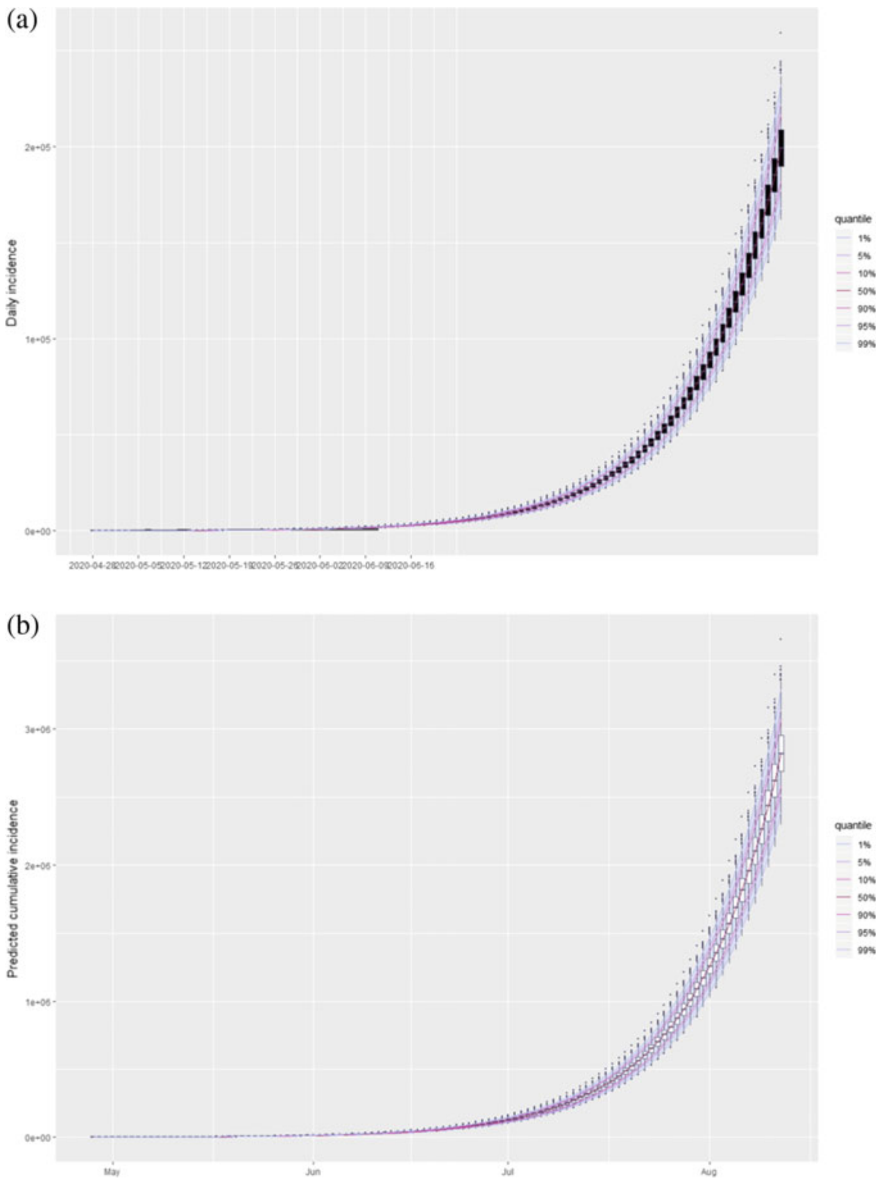


Fig. 12 **a** Predicted daily incidence and actually observed incidence in Tamil Nadu, **b** predicted cumulative daily incidence in Tamil Nadu

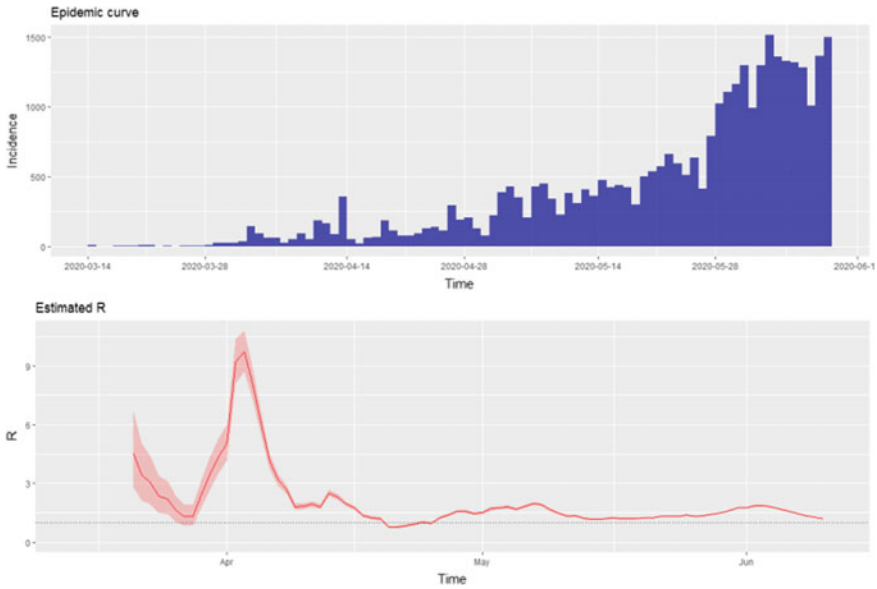


Fig. 13 Epidemic curve and the time-dependent reproduction number in Delhi

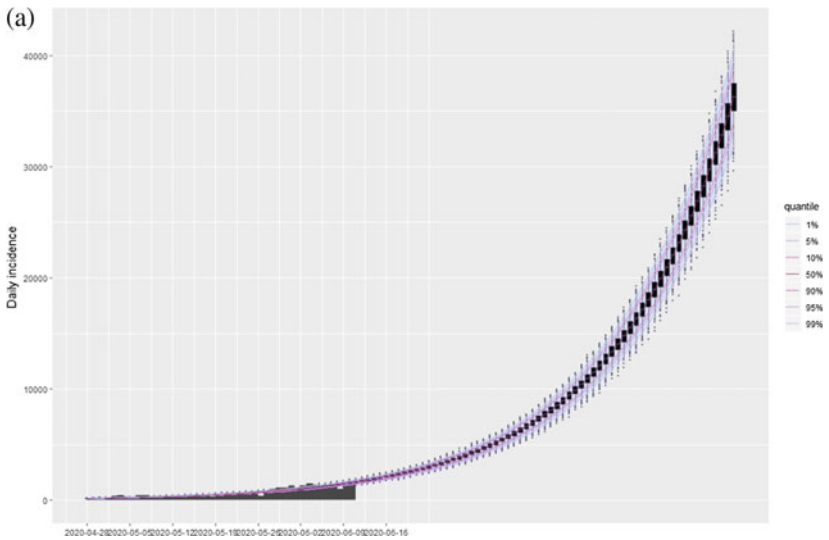


Fig. 14 **a** Predicted daily incidence and actually observed incidence in Delhi, **b** predicted cumulative daily incidence in Delhi

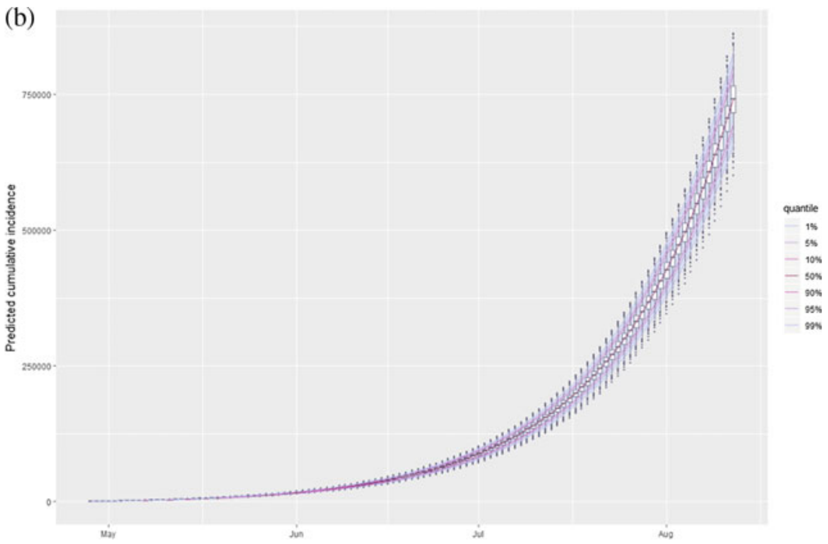


Fig. 14 (continued)

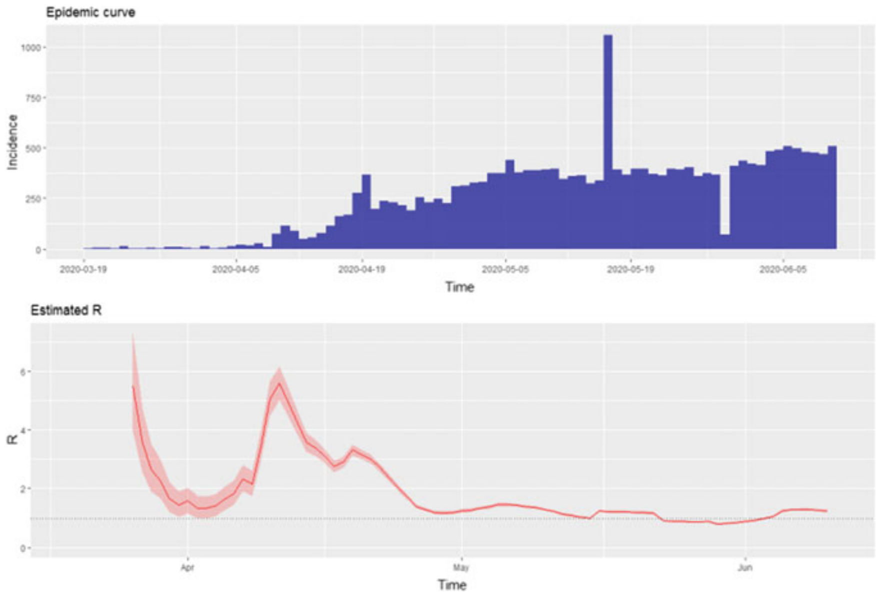


Fig. 15 Epidemic curve and the time-dependent reproduction number in Gujarat

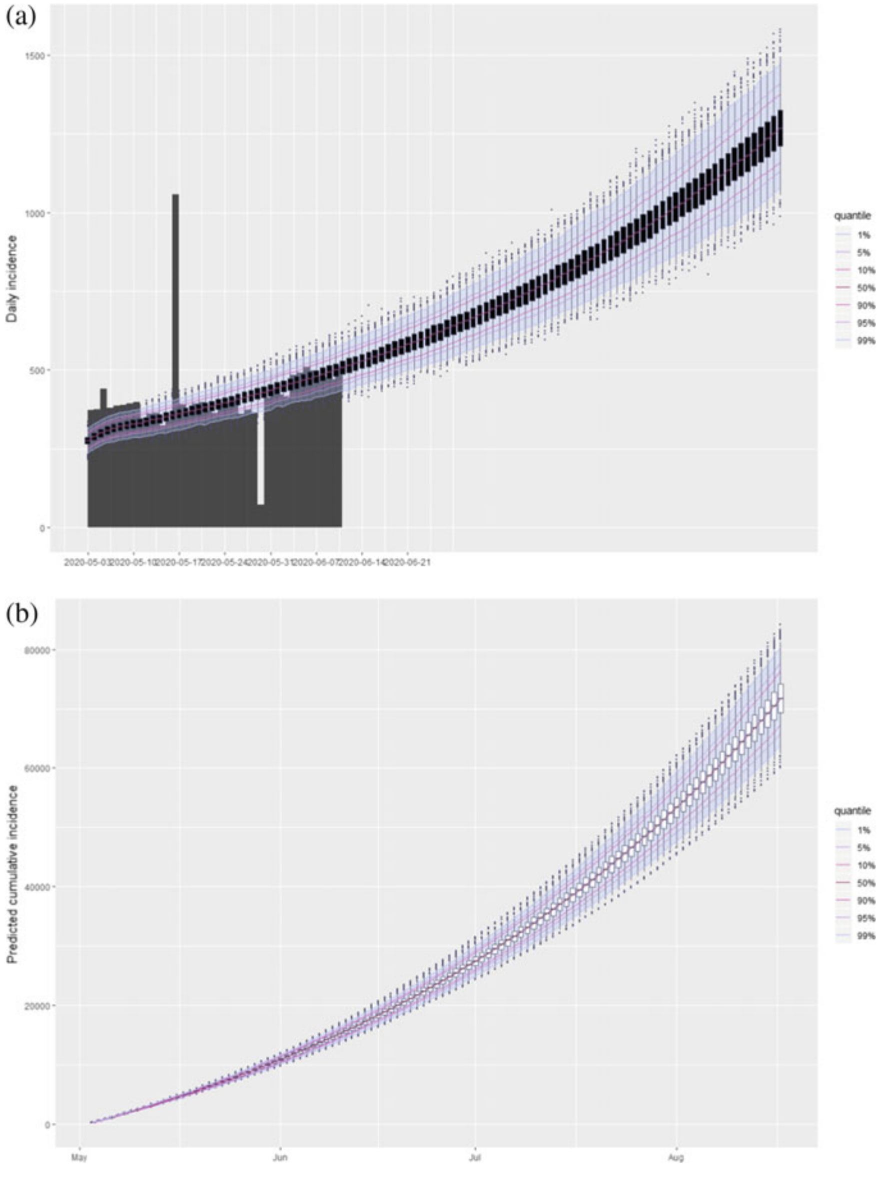


Fig. 16 **a** Predicted daily incidence and actually observed incidence in Gujarat, **b** predicted cumulative daily incidence in Gujarat

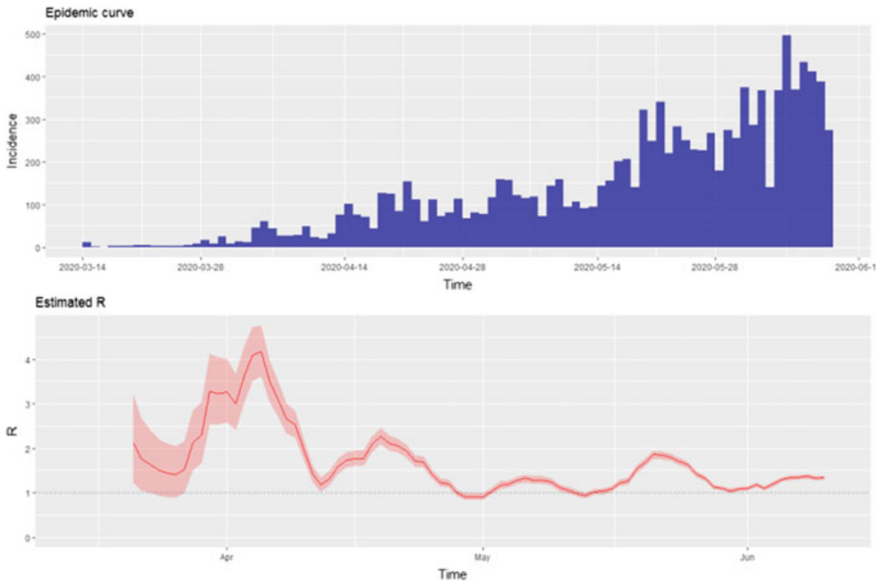


Fig. 17 Epidemic curve and the time-dependent reproduction number in Uttar Pradesh

Uttar Pradesh and the variation of reproduction number with time are shown in Fig. 17. Reproduction number at 10 June is 1.34. Also a slight upward trend in the time-dependent reproduction number can be seen from June 01 onward.

The predicted daily incidence and cumulative incidences in Uttar Pradesh is shown in Fig. 18a and b. It is estimated that is the current rate of infection persists then June 30 and July 15. The predicted value of cumulative cases on July 15 may reach 21,320 [range: 23,705-30,779] and 35,580 [range: 27,453-43,777], respectively.

Rajasthan

For the state of Rajasthan, there are 12,068 confirmed cases of COVID-19 patients along with 2785 active cases, 9011 recovered cases and 272 deaths as on June 13, 2020. The epidemic curve and the time-dependent reproduction number for Rajasthan are shown in Fig. 19. $R(t)$ has downward trend from the week preceding June 01, and on June 10 the value is 1.09.

The predicted daily incidence and cumulative incidences in Rajasthan are shown in Fig. 20a and b, respectively. The predictions for Rajasthan are as follows: On 30 June, cumulative incidences are 17,706 (range: 13,275–23,073); on 15 July, cumulative incidences are 28,354 (range: 20,979–38,153).

West Bengal

West Bengal is one of the highly populous states in India. On June 13, 2020, there are 10698 confirmed cases along with 5693 active cases, 4542 recovered cases and 463 deaths. The epidemic curve and the variation of reproduction number for West

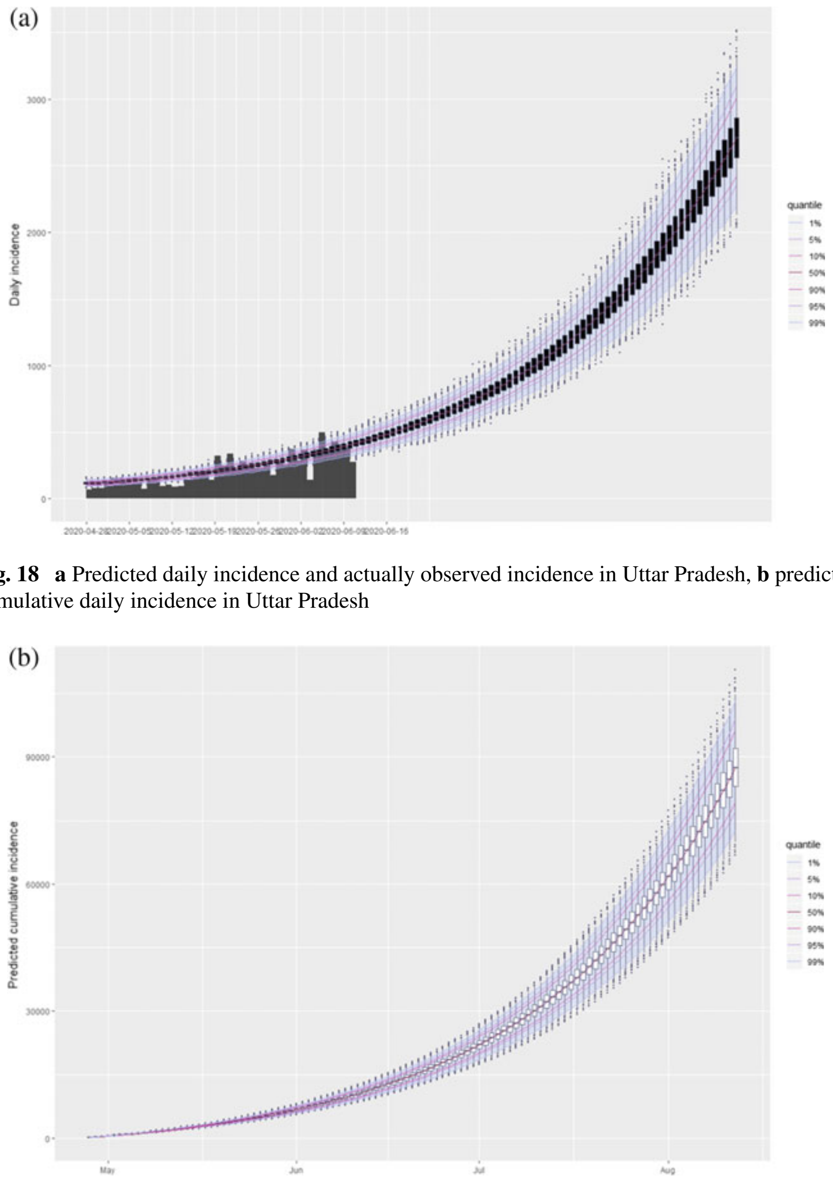


Fig. 18 **a** Predicted daily incidence and actually observed incidence in Uttar Pradesh, **b** predicted cumulative daily incidence in Uttar Pradesh

Fig. 18 (continued)

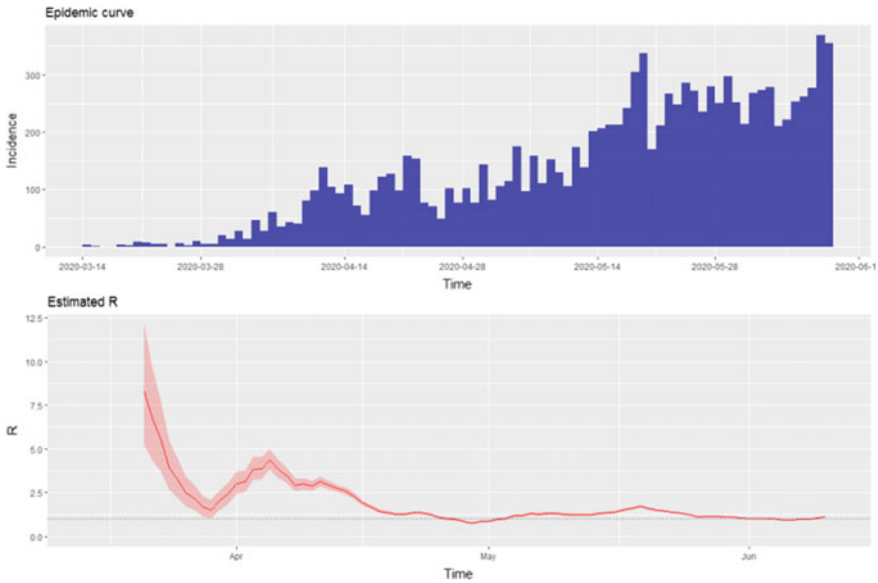


Fig. 19 Epidemic curve and the time-dependent reproduction number in Rajasthan

Bengal are shown in Fig. 21. A downward trend in the reproduction number from 01 June can be observed from the figure. Its value on 10 June is nearly 1.31.

The predicted daily incidence and cumulative incidences in West Bengal are shown in Fig. 22a and b, respectively. The predictions for West Bengal are as follows: On 30 June, cumulative incidences are 19,772 (range: 13,584–26,044); on 15 July, cumulative incidences are 42,864 (range: 29,526–57,359).

4 Discussion

In this study, the basic reproduction number of novel coronavirus (COVID-19) is estimated from the early outbreak of the disease in India. From the results, it is found that the number varies from 1.53 to 3.25 with a mean of 2.18. This variation is due to the method for estimating the number. Also in this study, an attempt is made to predict near-future incidences in India and also in different Indian states. However, it must be noted that these predictions serve as general guidelines rather than absolute certainty. The predictions in India and also in different states help the central and also the state government to formulate the policy for near-future healthcare system in terms of COVID hospitals, doctors, health workers, ICU beds, ventilators, PPE, etc. to fight against COVID-19 pandemic. The predictions also help to take decision regarding further lockdown in hotspot/epicenter area, infrastructure set up for COVID patients, economic and social issues, etc.

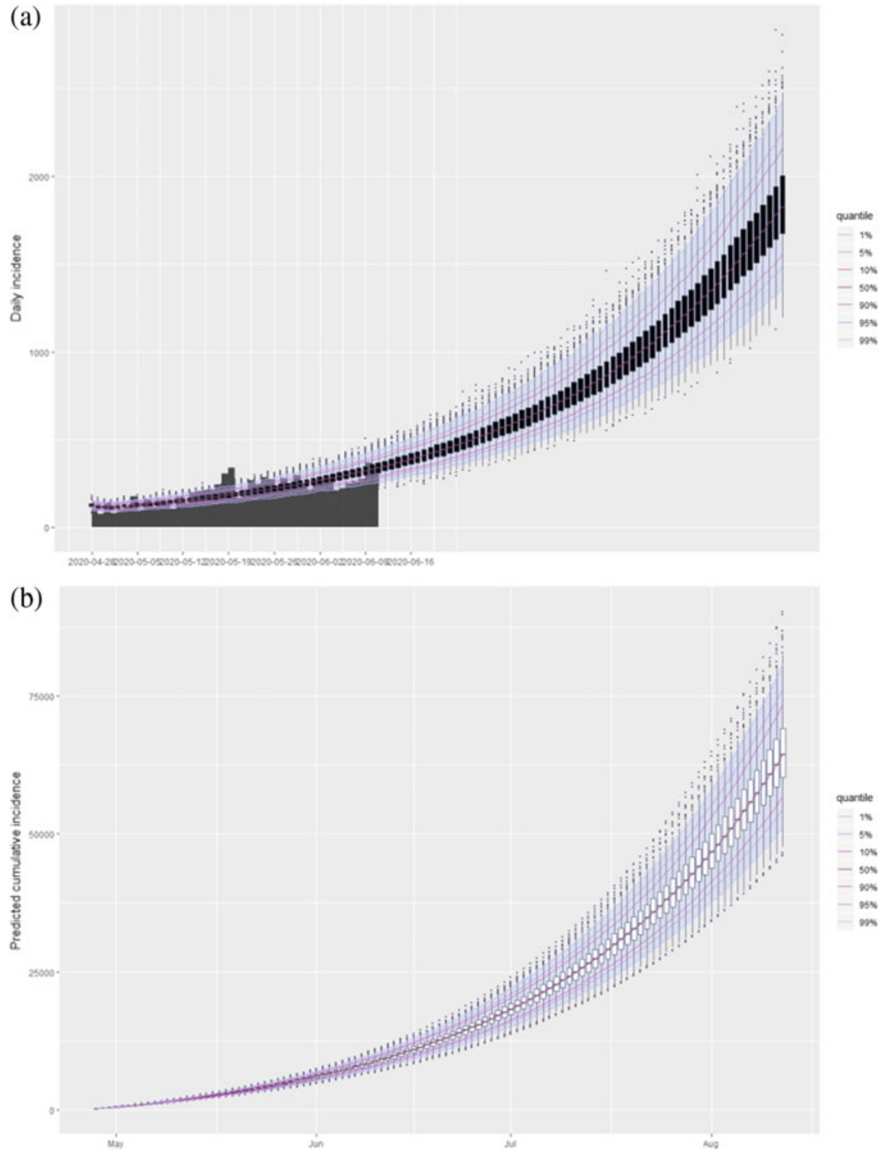


Fig. 20 **a** Predicted daily incidence and actually observed incidence in Rajasthan, **b** predicted cumulative daily incidence in Rajasthan

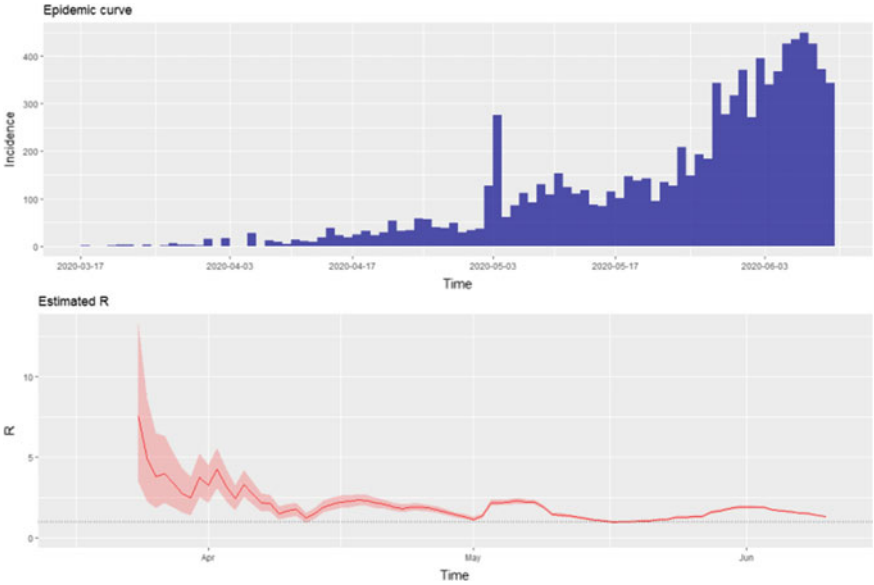


Fig. 21 Epidemic curve and the time-dependent reproduction number in West Bengal

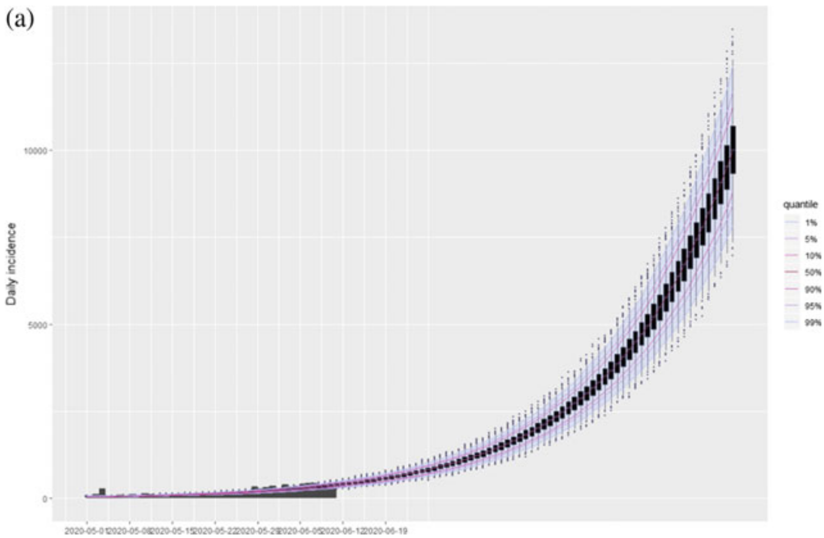


Fig. 22 **a** Predicted daily incidence and actually observed incidence in West Bengal, **b** predicted cumulative daily incidence in West Bengal

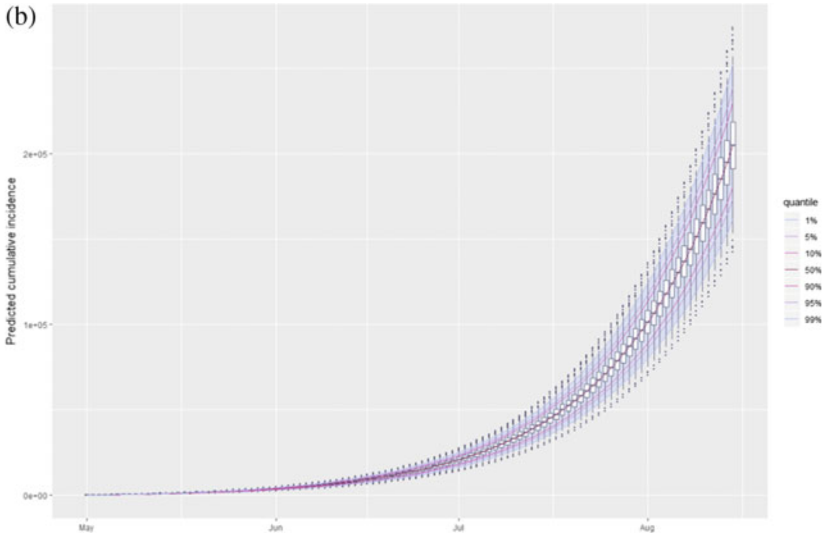


Fig. 22 (continued)

Financial support & sponsorship: None.

Conflicts of Interest: None.

References

1. Li, Q. et al.: Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia. N. Engl. J. Med., (2020)
2. WHO: Pneumonia of unknown cause—China (https://www.who.int/csr/don/05-January- *2020-pneumonia-of-unkown-cause-china/en/; accessed January 30, 2020)*, (2020)
3. Chan, J.F.et al.: A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission: a study of a family cluster. Lancet, (2020)
4. Website:www.Worldometers/ info/coronavirus
5. Data from Ministry of Health and Family Welfare (MoHFW) website(www.mohfw.gov.in) the Government of India and Indian COVID 19 tracker (www. covid19india.org)
6. Ma, Y., Zhao, Y., Liu, J., He, X., Wang, B., Fu, S., Yan, J., Niu, J., Luo, B.: Effects of temperature variation and humidity on the mortality of covid-19 in Wuhan. medRxiv, 2020
7. Araujo, M.B., Naimi, B.: Spread of SARS-CoV-2 Coronavirus likely to be constrained by climate. medRxiv, 2020
8. Salman, S., Salem, M.L.: The mystery behind childhood sparing by COVID-19. Int. J. Cancer Biomed. Res. 10 (3 Apr 2020)
9. Luo, W., Majumder, M., Liu, D., Poirier, C., Mandl, K., Lipsitch, M, Santillana, M.: The role of absolute humidity on transmission rates of the covid-19 outbreak. (2020)
10. Nsoesie, E.O., Brownstein, J.S., Ramakrishnan, N., Marathe, M.V.: A systematicreview of studies on forecasting the dynamics of influenza outbreaks. Influenza. Other. Respir. Viruses. **8**(3), 309–316 (2014)
11. Chretien, J.-P., Riley, S., George, D.B.: Mathematical modeling of the West Africa Ebola epidemic. eLife. **4**, e09186 (2015)

12. WHO Ebola Response Team: Ebola virus disease in West Africa—the first 9 months of the epidemic and forward projections. N. Engl. J. Med. **371**(16), 1481–1495 (2014)
13. WHO Ebola Response Team: West African Ebola epidemic after one year-slowing but not yet under control. N. Engl. J. Med. **372**(6), 584–587 (2015)
14. WHO Ebola Response Team: Ebola virus disease among children in West Africa. New Engl. J. Med. **372**(13), 1274–1277 (2015)
15. Goldstein, E., Cobey, S., Takahashi, S., Miller, J.C., Lipsitch, M.: Predicting the epidemic sizes of influenza A/H1N1, A/H3N2, and B: a statistical method. PLoSMed. **8**(7), e1001051 (2011)
16. Meltzer, M.I., Atkins, C.Y., Santibanez, S., Estimating the future number of cases in the Ebola epidemic—liberia and sierra leone. MMWR Suppl. **63**(3), 1–14 (2014–2015)
17. Influenza Forecasting. http://predict.phiresearchlab.org/flu/index.html (2017)
18. Dengue Forecasting. http://dengueforecasting.noaa.gov/. (2017)
19. Chikungunya Forecasting. http://www.darpa.mil/news-events/ (2017)
20. Liu, Y. et al.: The reproductive number of COVID-19 is higher compared to SARS coronavirus. J. Travel. Med. (2020)
21. Zhang, S. et al.: Estimation of the reproductive number of novel coronavirus (COVID-19) and the probable outbreak size on the Diamond Princess cruise ship: a data-driven analysis. Int. J. Infect. Dis. **93**, 201–204 (2020)
22. Li, Q. et al.: Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia. New England J. Med. (2020)
23. Nishiura, H., Linton, N.M., Akhmetzhanov, A.R.: Serial interval of novel coronavirus (COVID-19) infections. Int. J. Infect. Dis. (2020)
24. Du, Z. et al.: The serial interval of COVID-19 from publicly reported confirmed cases. medRxiv (2020)
25. Jombart, T. et al.: earlyr: Estimation of transmissibility in the early stages of a disease outbreak. Available from: https://cran.r-project.org/package=earlyR
26. Boelle, P.-Y., Obadia, T.: R0: Estimation of R0 and Real-Time Reproduction Number from Epidemics. Available from: https://cran.r-project.org/package=R0
27. Obadia, T., Haneef, R., Boëlle, P.Y.: The R0 package: a toolbox to estimate reproduction numbers for epidemic outbreaks. *BMC* Med. Inf. Decis. Making. **12**(1), 147 (2012)
28. Cori, et al.: A new framework and software to estimate time-varying reproduction numbers during epidemics. Am. J. Epidemiol. **178**(9), 1505–1512 (2013)
29. Forsberg White, L., Pagano, M.: A likelihood-based method for real-time estimation of the serial interval and reproductive number of an epidemic. Stat. Med. **27**(16), 2999–3016 (2008)
30. Wallinga, J., Lipsitch, M.: How generation intervals shape the relationship between growth rates and reproductive numbers. Proc. Roy. Soc. B: Biol. Sci. **274**(1609), 599 (2007)
31. Wallinga, J., Teunis, P.: Different epidemic curves for severe acute respiratory syndrome reveal similar impacts of control measures. Am. J. Epidemiol. **160**(6), 509–516 (2004)
32. Nouvellet, et al.: A simple approach to measure transmissibility and forecast incidence. Epidemics **22**, 29–35 (2018)
33. Thibaut, et al.: Projections: project future case incidence. Available from: https://cran.r-project.org/package=projections