Effective Lockdown and Role of Hospital-Based COVID-19 Transmission in Some Indian States: An Outbreak Risk Analysis

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Several reports in India indicate hospitals and quarantined centers are COVID-19 hotspots. To study the transmission occurring from the hospitals and as well as from the community, we developed a mechanistic model with a lockdown effect. Using daily COVID-19 cases data from six states and overall India, we estimated several important parameters of our model. Moreover, we provided an estimation of the effective ($R_T$), the basic ($R_0$), the community ($R_C$), and the hospital ($R_H$) reproduction numbers. We forecast COVID-19 notified cases from May 3, 2020, till May 20, 2020, under five different lockdown scenarios in the seven locations. Our analysis suggests that 65% to 99% of the new COVID-19 cases are currently asymptomatic in those locations. Besides, about 1–16% of the total COVID-19 transmission are currently occurring from hospital-based contact and these percentage can increase up to 69% in some locations. Furthermore, the hospital-based transmission rate ($\beta_2$) has significant positive (0.65 to 0.8) and negative (-0.58 to -0.23) correlation with $R_0$ and the effectiveness of lockdown, respectively. Therefore, a much larger COVID-19 outbreak may trigger from the hospital-based transmission. In most of the locations, model forecast from May 3, 2020, till May 20, 2020, indicates a two-times increase in cumulative cases in comparison to total observed cases up to April 29, 2020. Based on our results, we proposed a containment policy that may reduce the threat of a larger COVID-19 outbreak in the future.

KEY WORDS: COVID-19; effective lockdown policy; ensemble model forecast; hospital-based transmission; outbreak risk analysis

1. INTRODUCTION

Coronavirus disease of 2019 (COVID-19) was first observed in Wuhan, China and rapidly spread across the globe in a short duration (Wang et al., 2020). World Health Organization (WHO) declared COVID-19 as pandemic after assessing its various characteristics (WHO, 2020b). As of April 29, 2020, over 3 million cases and over 200,000 deaths due to COVID-19 have been reported across the globe (COVID-19 Tracker [CT], 2020a). In India, the first confirmed case of COVID-19 was reported on January 30, 2020 (WHO, 2020a), a student from Kerala studying in a university in Wuhan (India Today, 2020d). As of April 29, 2020, 33,065 confirmed cases and 1,079 deaths due to COVID-19 have been reported in India (CT, 2020b).

According to a daily monitoring report published by WHO, 22,073 healthcare workers across 52 countries have been tested positive for COVID-19 (WHO, 2020c). The report also noted that the number provided may be an underestimation as there is no...
systematic reporting of infections among the healthcare workers (WHO, 2020c). Some recent reports from different states of India indicate that a high percentage of COVID-19 transmission is currently occurring due to hospital-based contacts (Economic Times [ET], 2020a; India Today, 2020a; New Delhi Television Ltd [NDTV], 2020a; The Hindu [TH], 2020; The Print (TP, 2020)). The doctors, nurses, and other health workers are most vulnerable as they are in close proximity with COVID-19 patients (ET, 2020a; India Today, 2020a; NDTV, 2020a, 2020b; TP, 2020). Close relatives of notified COVID-19 patients in quarantine centers may also be at risk of getting infection. In addition, the journalists who are continuously visiting hospitals and quarantine centers to get updated reports on COVID-19 may also be at risk of getting infected (India TV, 2020; Scroll.in (SI, 2020). Therefore, a significant percentage of susceptible population in the community may be exposed to COVID-19 infection occurring from the contacts with patents in hospitals and quarantine centers.

Currently there is no vaccine and effective medicine available for COVID-19 in India. Therefore, to break the transmission chain of COVID-19, the government had implemented a full nationwide lockdown (home-quarantined the community) starting from March 25 to April 14, 2020. However, in a large country like India with such diverse and huge population, lockdown all over the nation may not be a very feasible and effective solution. Moreover, a lockdown already has a huge impact on the Indian economy, especially on the short-scale industries (ET, 2020d; India Today, 2020b). To partially overcome this economic crisis as well reducing COVID-19 transmission, Government has proposed some amendments (known as cluster containment strategy) on the lockdown rules from April 20, 2020 (ET, 2020c; Financial Express [FE], 2020b). In these revised rules, the government has provided some relaxation in current rules by dividing different districts of the various states into three zones, namely red (hotspot), orange (limited human movement), and green (economic activity) depending on the number of COVID-19 cases (Business Today, 2020; ET, 2020c; FE, 2020b). However, question remains whether this cluster containment strategy might be successful in reducing COVID-19 transmission or not? If not, then what could be other alternative solutions to reduce COVID-19 transmission? These question can only be answered by studying the dynamics and prediction of a mechanistic mathematical model for COVID-19 transmission and testing the results in real situation (Moghadas et al., 2020; Tang et al., 2020; Sardar et al., 2020b, 2020a)

In this article, we formulated a mechanistic model on COVID-19 with community as well as hospital-based transmission to study the lockdown effect. We assumed that patients from the hospitals and quarantine centers can only be in contact with a small fraction of the susceptible population from the community. Furthermore, we assume different transmission rates for the community and the hospital-based infection. In the mechanistic model, we have incorporated the lockdown effect through home quarantine of a certain percentage of susceptible population from the community. Using the daily notified COVID-19 cases from six states (Maharashtra, Delhi, Madhya Pradesh, Rajasthan, Gujarat, and Uttar Pradesh) and overall India, we estimated several important parameters of the mechanistic model. Furthermore, we estimated the basic ($R_0$), the community ($R_C$), and the hospital ($R_H$) reproduction numbers for the seven locations under study. To obtain a reliable forecast of future COVID-19 notified cases in the above-mentioned locations, we used a hybrid statistical model that can efficiently capture fluctuations in the daily time series data. A Bayesian model averaging technique based on DRAM algorithm is used to ensemble our mechanistic mathematical model with the hybrid statistical model. Using the ensemble model, we forecast COVID-19 notified cases (daily and cumulative) from May 3 to May 20, 2020, under five different lockdown scenarios in the seven locations. To determine an effective lockdown policy, we carried out a global sensitivity analysis of four epidemiologically measurable and controllable parameters on the lockdown effect (number of cases reduction) and as well as on $R_0$.

2. METHOD

The mechanistic model we developed in this article is an extension of an SEIR model with additional asymptomatic, hospitalized, and notified and lockdown population (see Fig. 1 and Supporting Information Eqn S1 and S2). We assumed that hospitalized and notified infected population can only be in contact with a small fraction ($\rho$) of the susceptible population from the community (see Fig 1 and Table I). Recently, Lee et al. (2020) showed that the viral load in the symptomatic and the asymptotically infected are similar. Therefore, we assumed that they transmit the disease at the same rate $\beta_1$ (see Fig. 1 and Table I). We also assumed different
Table I: Parameters with Their Respective Epidemiological Information for the Mechanistic ODE Model (see Fig. 1 and Supporting Information) for COVID-19

| Parameters | Biological Meaning | Value/Ranges | Reference |
|------------|--------------------|--------------|-----------|
| \( \Pi = \mu \times N(0) \) | Recruitment rate of human population | Differs over states | - |
| \( \frac{1}{\mu} \) | Average life expectancy at birth | Differs over states | Niti Aayog (2020) |
| \( \beta_1 \) | Average transmission rate of a symptomatic and asymptomatic COVID-19 infected | (0–500) days | Estimated |
| \( \beta_2 \) | Average transmission rate of a notified & hospitalized COVID-19 infected | (0–500) days | Estimated |
| \( \rho \) | Fraction of the susceptible population that are exposed to hospital-based transmission | 0–0.2 | Estimated |
| \( \frac{1}{\tau} \) | COVID-19 incubation period | (1–14) days | Estimated |
| \( \frac{1}{\kappa} \) | Fraction of the COVID-19 exposed population that become symptomatic infected | 0–1 | Estimated |
| \( \gamma_1 \) | Average recovery rate of symptomatic infection | \((\gamma_1 - 1)\text{day}^{-1}\) | Estimated |
| \( \gamma_2 \) | Average recovery rate of asymptomatic infection | \((\gamma_2 - 1)\text{day}^{-1}\) | Estimated |
| \( \tau \) | Average hospitalization rate for the COVID-19 symptomatic individuals | (0–1) day\(^{-1}\) | Estimated |
| \( \delta \) | Average death rate due to COVID-19 infection in hospital | Differs over states | CT (2020b) |
| \( \gamma_3 \) | Average recovery rate of the notified & hospitalized populations | Differs over states | CT (2020) |
| \( l \) | Average lockdown rate | \((0-0.9)\text{day}^{-1}\) | Estimated |
| \( \frac{1}{\omega} \) | Current lockdown period in India | 40 days | TOI (2020); FE (2020a) |

Fig 1. A Flow diagram of the mechanistic ODE model with hospital-based COVID-19 transmission and lockdown effect. Different class of population shown in this figure are: S: Susceptible population; E: Exposed population; \( I_S \): COVID-19 symptomatic infected population; \( I_A \): COVID-19 asymptomatic infected population; H: Notified & Hospital individuals suffering from COVID-19 infection; R: COVID-19 recovered population; and L: Home quarantined susceptible population during lockdown, respectively. Two arrows from \( I_S, I_A \), and H to S represent that susceptible population can get infection in contact with these populations (\( I_S, I_A \), and H), whereas a single arrow from S to E represents the flow of new infection from susceptible to the exposed class. Epidemiological information of the parameters shown in this figure are provided in Table I.

Transmission rates (\( \beta_1 \) and \( \beta_2 \), respectively) for community and hospital-based infection. As it is very difficult to detect asymptotically infected in the community therefore, we assumed that only a fraction of symptomatically infected population was being notified and hospitalized by COVID-19 testing at a rate, \( \tau \) (see Fig. 1 and Table I). The disease related deaths are considered only for the notified and hospitalized population at a rate \( \delta \). We incorporated lockdown effect in our model (see Fig. 1 and Supporting Information Eqn S2) by home quarantined a fraction of susceptible population at a rate \( l \). We also assumed that after the current lockdown period (\( \frac{1}{\omega} = 40 \) days) the home quarantined individuals will return to the general susceptible population (see Fig. 1 and Supporting Information Eqn S2). Moreover, we assumed that the home quarantined individuals do not mix with the general population (see Fig. 1 and Supporting Information Eqn S2) that is, this class of individuals do not contribute in disease transmission. A flow diagram and the information on our mechanistic ODE model parameters are provided in Fig. 1 and Table I, respectively.

The mechanistic ODE model (see Fig. 1 and Supporting Information Eqn S1 and S2) we are using for this study may be efficient in capturing overall trend of the time-series data and the transmission dynamics of COVID-19. However, as solution of the ODE model is always smooth therefore, our mechanistic model may not be able to capture fluctuations occurring in the daily time-series data. Several complex factors like lockdown, symptomatic, asymptomatic,
hospital transmission, awareness, rapid testing, preventive measures, and so on may influence the variations in daily COVID-19 time-series data. Therefore, it is an extremely challenging job to fit and long-term forecast using this daily time-series data. To resolve this issue, we considered a hybrid statistical model, which is a combination of five forecasting models namely, auto-regressive integrated moving Average model (ARIMA); exponential smoothing state space model (ETS); theta method model (THETAM); exponential smoothing state space model with box-cox transformation, ARMA errors, trend and seasonal components (TBATS); and neural network time series forecasts (NNETAR). Finally, the hybrid statistical model and the mechanistic ODE model (see Fig. 1 and Supporting Information Eqn S1 and S2) are combined together by a post-processing Bayesian model averaging (BMA) technique, which we discussed later in the article.

We used daily confirmed COVID-19 cases from Maharashtra (MH), Delhi (DL), Madhya Pradesh (MP), Rajasthan (RJ), Gujarat (GJ), Uttar Pradesh (UP) and overall India (IND) for the time period March 14–April 14, 2020 (MH), March 14–April 18, 2020 (DL), March 20–April 17, 2020 (MP), March–April 18, 2020 (RJ), March 19–April 16, 2020 (GJ), March 14–April 18, 2020 (UP), and March 2–April 19, 2020 (IND) for our study. As of April 29, 2020, these referred six states contribute to 74% of the total COVID-19 notified cases in India (CT, 2020b). Confirmed daily COVID-19 cases from the mentioned seven locations are collected from CT (2020b). State-wise population data are taken from The Unique Identification Authority of India (UIDAI) (2020).

We estimated several epidemiologically important parameters (see Table I) by calibrating our mathematical model (see Fig. 1 and Supporting Information Eqn S1 and S2) to the daily notified COVID-19 cases from the seven locations. As some initial conditions of our mathematical model (see Fig. 1 and Supporting Information Eqn S1 and S2) are also unknown therefore, we prefer to estimate these initial conditions from the data (see Supporting Information Table S1). In lockdown 1.0, the Indian government implemented a 21 days nationwide full lockdown (home quarantined the community) starting from March 25–April 14, 2020 (ET, 2020b) and then extend the lockdown period up to May 2, 2020 (lockdown 2.0) (Times of India [TOI], 2020); FE, 2020a). Therefore, the daily COVID-19 time series data contain the effect of with and without lockdown scenario, therefore, we prefer to use a combination of two mathematical models (without and with lockdown) for calibration. An elaboration on the combination technique of the mathematical models without and with lockdown is provided below:

- We first use the mechanistic model without lockdown (see Eqn S1 in Supporting Information) starting from the first date of the daily COVID-19 data up to end of March 24, 2020 for the seven locations MH, DL, MP, RJ, GJ, UP, and IND, respectively.
- Using values of the state variables of the model without lockdown (see Eqn S1 in Supporting Information method) onset of March 24, 2020 as initial condition, we run the mechanistic model with lockdown (see Fig. 1 and Model S2 in Supporting Information) up to the end date of the daily COVID-19 data for the mentioned seven locations.

The nonlinear least square function “lsqnonlin” in the MATLAB-based optimization toolbox is called to fit the simulated and observed daily COVID-19 notified cases in the seven locations mentioned earlier. Bayesian-based “DRAM” algorithm (Haario et al., 2006) is used to sample the epidemiologically unknown parameters and initial conditions (see Table II and Table S1 in Supporting Information) of the mathematical models combination without and with lockdown (see Fig. 1 and Supporting Information Eqn S1 and S2). The details on mechanistic model fitting are provided in Sardar and Saha (2017).

Calibration of the hybrid statistical model for the mentioned seven states is done using the R package “forecastHybrid” (Shaub & Ellis, 2020). First, we fitted the individual models ARIMA, ETS, THETAM, TBATS, and NNETAR by calling the functions “auto.arima,” “ets,” “thetam,” “tbats,” and “nneta,” respectively. The results generated from each of the above models are combined with equal weights to determine the hybrid statistical model. Equal weight among the five individual models is taken as it generates a robust result (see Table S3 in Supporting Information) for the hybrid statistical model (Lemke & Gabrys, 2010).

Post-processing Bayesian model averaging technique for combining the mechanistic model (see Fig. 1 and Supporting Information S1 and S2) and the hybrid statistical model is based on “DRAM” algorithm (Haario et al., 2006). Let $Y^{ODE} = \{y_j^{ODE}\}_{j=1}^n$ and $Y^{HBD} = \{y_j^{HBD}\}_{j=1}^n$ be $n$ simulated
observations from our mechanistic ODE model and the hybrid statistical model, respectively, and let \( \hat{Y} = \{ \hat{y}_{ij} \}_{j=1}^n \) be \( n \) observation from the data. Then

\[
Y^E = \omega_1 Y^{ODE} + \omega_2 Y^{HBD},
\]

is our ensemble model, where the weights \( \omega_1 \) and \( \omega_2 \) satisfy the constraints

\[ \Delta = \{ \omega_1, \omega_2 \geq 0 : \omega_1 + \omega_2 = 1 \} . \]

We assume \( \omega_1 \) and \( \omega_2 \) follows Gaussian proposal distribution. Then the error sum of square function (Haario et al., 2006) is defined as:

\[
SS(\hat{\theta}) = \sum_{i=1}^n (\hat{Y} - Y^E(\hat{\theta}))^2
\]

Posterior distribution of the weights \( \hat{\omega} = (\hat{\omega}_1, \hat{\omega}_2) \) for the ensemble model (1) is generated using Bayesian-based “DRAM” algorithm (Haario et al., 2006) (see Table S2 and Fig. S23–S29 in Supporting Information).

To save the countries short-scale industries and the agricultural sectors, the Indian government has proposed some amendments on current lockdown rules from April 20, 2020 (ET, 2020c; FE, 2020b). In these revised rules, Government has provided some relaxation in current rules by dividing different districts of the various states into three red (hotspot), orange (limited human movement), and green (economic activity) zones depending on the number of COVID-19 cases (BT, 2020; ET, 2020c; FE, 2020b). Implementation of these new rules in our mechanistic models combination (see Fig. 1 and Supporting Information Eqn S1 and S2) are based on the following assumptions:

- **Lockdown rule will be relaxed from April 20, 2020 in those states where the current estimate of the lockdown rate (see Table II) is higher than a threshold value. This relaxation in lockdown is based on the fact that locations where lockdown are strictly implemented before April 20, 2020 are likely to have more impact on the economic growth.**
- **Lockdown rule will be more intensive from April 20, 2020 in those states where the current estimate of the lockdown rate (see Table II) is below a threshold value. This assumption is made because locations where lockdown is not implemented properly before April 20, 2020 are likely to have more red (hotspot) zones.**
Note that 50% lockdown success is taken as the threshold value for our study. Here, 50% lockdown success in Delhi means that 50% of the susceptible population in this state is successfully home-quarantined during the period March 25–April 20, 2020.

Insensitivity and relaxation in lockdown are measured in a same scale namely 10%, 20%, and 30% increment or decrement on the current estimate of lockdown rate (see Table II).

Following the above assumptions and using our ensemble model (1), we provided a forecast of notified COVID-19 cases (daily and cumulative) for the seven locations during May 3–May 20, 2020. As COVID-19 notified cases are continuously rising in the mentioned seven locations therefore, it is more likely that lockdown period will be extended beyond May 3, 2020. Therefore, forecast using the ensemble model (1) during the mentioned time duration in those seven locations are based on the following scenarios:

(A1) Using our mechanistic models combination (see Fig. 1 and Supporting Information Eqn S1 and S2) and the current estimate of the lockdown rates (see Table II), we forecast notified COVID-19 cases up to May 20, 2020. This forecast is combined together with the results obtain from the hybrid statistical model by using our ensemble model (1).

(A2) Using our mechanistic models combination (see Fig. 1 and Supporting Information Eqn S1 and S2) and the current estimate of the lockdown rates (see Table II), we forecast notified COVID-19 cases up to April 20, 2020. From April 21–May 20, 2020, forecast are made using 10% increment or decrement (depending on the state) in the estimate of current lockdown rate.

This forecast is combined together with the results obtain from the hybrid statistical model by using our ensemble model (1).

(A3) We followed same procedure as scenario (A2) with 20% increment or decrement (depending on the state) in the estimate of current lockdown rate from April 21–May 20, 2020 to obtain the forecast for the mentioned time duration.

(A4) In this case also, we followed same procedure as scenario (A2) with 30% increment or decrement (depending on the state) in the estimate of current lockdown rate from April 21–May 20, 2020 to obtain the forecast for the mentioned time duration.

(A5) We followed same procedure as the scenario (A1) up to May 2, 2020. Forecast for the time period May 3–May 20, 2020 are made with no lockdown.

As, we assumed that lockdown individuals do not mixed with the general population therefore, the basic reproduction number ($R_0$) with and without lockdown (see Fig. 1 and Supporting Information Eqn S1 and S2) are equal (Van den Driessche & Watmough, 2002):

$$R_0 = \frac{\beta_1 k \sigma}{(\mu + \sigma)(\gamma_1 + \mu + \tau)} + \frac{\beta_1 (1 - k)\sigma}{(\mu + \gamma_2)(\mu + \sigma)} + \frac{\beta_2 k \rho \sigma \tau}{(\mu + \sigma)(\delta + \gamma_2 + \mu)(\gamma_1 + \mu + \tau)}$$

In the expression of $R_0$, sum of first two term indicate the community infection occurring from symptomatically and asymptomatically infected population. The third term in $R_0$ specifies the hospital-based COVID-19 transmission. To distinguish the community and hospital-based COVID-19 transmission, we defined the community reproduction number ($R_C$), and the hospital reproduction number ($R_H$) as follows:

$$R_C = \frac{\beta_1 k \sigma}{(\mu + \sigma)(\gamma_1 + \mu + \tau)} + \frac{\beta_1 (1 - k)\sigma}{(\mu + \gamma_2)(\mu + \sigma)}$$

and

$$R_H = \frac{\beta_2 k \rho \sigma \tau}{(\mu + \sigma)(\delta + \gamma_2 + \mu)(\gamma_1 + \mu + \tau)}$$

Using estimated values of epidemiologically unknown parameters (see Table II), we estimated $R_0$, $R_C$, and $R_H$ for the mentioned seven locations.

The effective reproductive number ($R_T$) indicates the average number of secondary cases produced per infected person in a population made up of both susceptible and nonsusceptible hosts (Rothman et al., 2008). $R_T$ provides information about the severity of a disease over different time points and plays a vital role in control measures (Sardar et al., 2015). For example, $R_T > 1$ signifies that number of new incidences has an increasing trend, whereas $R_T = 1$ implies the disease become endemic in the population, and $R_T < 1$ signifies that number of new cases will have a decreasing trend. We estimated $R_T$ using our ensemble model (1) projected COVID-19 new
cases data under two lockdown scenarios (A1 and A5) during the period April 21–May 20, 2020 by using the following equation derived from the renewal equation of a birth process (Pinho et al., 2010; Sardar et al., 2015):

$$R_T = \frac{b(t)}{\int_0^\infty b(t-a)g(a)\,da},$$

where, the term $b(t)$ corresponds to the number of new cases at the $t$th day and the term $g(\cdot)$ is the generation interval distribution for a disease. We derive the expression of the generation interval distribution $g(t)$ from the COVID-19 mechanistic model (see Fig. 1 and Eqn S2 in Supporting Information) by applying the method discussed in (Pinho et al, 2010; Wallinga & Lipsitch, 2007). The rates of leaving the exposed and infectious compartments are indicated by $b_1$, $b_2$, $b_3$, and $b_4$. These quantities are constant and extracted from our model (see Fig. 1 and Eq S2 in Supporting Information) as $b_1 = \mu + \sigma$, $b_2 = \mu + \gamma_1 + \tau$, $b_3 = \mu + \gamma_2$, and $b_4 = \mu + \gamma_3 + \delta$. Moreover, the generation interval distribution is the convolution of four exponential distributions with a mean $M = \frac{1}{\beta_1} + \frac{1}{\beta_2} + \frac{1}{\beta_3} + \frac{1}{\beta_4}$. Following (Akkouchi, 2008; Pinho et al., 2010), the expression for the convolution is provided below:

$$g(t) = \sum_{i=1}^{4} \frac{b_1b_2b_3b_4 \exp(-b_1t)}{\prod_{j=1, j\neq i}^{4} (b_j - b_i)}$$

with $t \geq 0$. The validity of the above relation (3) holds for a minimum threshold value of the force of infection $\Lambda$, defined as $\Lambda > \min \{ -b_1, -b_2 - b_3, -b_4 \}$ (Pinho et al., 2010; Wallinga & Lipsitch, 2007).

Constructing an effective policy on future lockdown in a region will require some relation between effect of lockdown (number of COVID-19 case reduction) with some important epidemiologically measurable and controllable parameters. Our mechanistic ODE model (see Fig. 1 and Supporting Information Eqn S2) has several important parameters and among them measurable and controllable parameters are $\beta_2$: average rate of transmission occurring from hospitalized and notified contacts (it can be controllable by following WHO guidelines); $\rho$: fraction of susceptible population from the community that are exposed to notified and hospitalized contacts (it also can be minimized by following proper guidelines from WHO); $\kappa$: fraction of infected that are symptomatic (rapid COVID-19 testing can provide an accurate estimate); $\tau$: notification and hospitalization rate of symptomatic infected population (it also depend on number of COVID-19 testing). We perform a global sensitivity analysis (Marino et al., 2008) to determine the effect of these parameters on the lockdown effect and on the basic reproduction number ($R_0$), respectively. The effect of lockdown is measured in terms of differences in the total number of COVID-19 cases that occurred during May 3–May 20, 2020 under the lockdown scenarios (A1) and (A5), respectively. We draw 500 samples from the biologically feasible ranges of the mentioned four parameters (see Table I) using Latin hypercube sampling (LHS) technique. Other epidemiologically known and unknown parameters during simulation of the mechanistic model are taken from Table I and Table II, respectively. Partial rank correlation coefficients (PRCC) and its corresponding $p$-value are evaluated to determine the effect of these mentioned four parameters on the lockdown effect and the basic reproduction number ($R_0$), respectively.

### 3. RESULTS AND DISCUSSION

Testing of the three models (the mechanistic ODE model, the hybrid statistical model, and the ensemble model) on daily notified COVID-19 cases from MH, DL, MP, RJ, GJ, UP, and IND are presented in Fig. 2. Based on the performance on testing data from the seven locations, we estimated the weights ($w_1$ and $w_2$) for our ensemble model (1) (see Table S2 in Supporting Information). Our result suggests that the mechanistic ODE model (see Fig. 1 and Supporting Information Eqn S1 and S2) displayed a better performance in RJ, UP, and IND compared to the hybrid statistical model (see Table S2 in Supporting Information). For rest of the locations (MH, DL, MP, and GJ), the hybrid statistical model has performed better than the mechanistic ODE model in terms of capturing the trend of the time-series data (Table S2 in Supporting Information). The ensemble model (1), which is derived from a combination of the mechanistic ODE and the hybrid statistical model respectively, has provided a robust result in all of these mentioned seven locations in terms of capturing time-series data trend (see Fig. 2).

The estimates of different parameters of the mechanistic ODE model (Fig. 1 and Supporting Information Eqn S1 and S2) suggests that currently in the seven locations (MH, DL, MP, RJ, GJ, UP, and IND) the community infection is mainly dominated
by contribution from the asymptomatically infected population (Table II). Among the seven locations, the lowest percentage of symptomatic infection in the community is found in RJ (about 0.1%) and the highest percentage is found in IND (about 35%) (Table II). Our estimates suggest that currently in the seven locations, the notification and hospitalization rate of symptomatically infected population is about 0.2–23% (Table II). Therefore, most of the COVID-19 infections in the seven mentioned locations are currently undetected. Our result agrees with the recent report by the Indian Council of Medical Research (ICMR) (India Today, 2020c). Our estimates of the lockdown rate for the mentioned seven locations, suggest that lockdown is properly implemented in the two metro cities DL and MH. Also, in overall India (IND) lockdown is properly implemented. In these three locations (MH, DL, and IND), about 61–77% of the total susceptible population may be successfully home quarantined during the present lockdown period (Table II). However, for rest of the locations, our results suggest that lockdown may not be successful as about 11–49% of the total susceptible population may be isolated (home quarantined) during the current lockdown period in MP, RJ, GJ, and UP, respectively (Table II). In the seven locations, we found that about 1–9% of the total susceptible populations may be exposed to hospital (notified and hospitalized population) related contacts (Table II).

Considering the fact that estimates of the average hospital-based transmission rates for the seven locations are very high (Table II), therefore, a significant amount of COVID-19 infection in these seven locations may be currently occurring due to notified and hospitalized infected related contacts. These findings can be further justified by analyzing the estimates of the basic ($R_0$), community ($R_C$) and hospitalized ($R_H$) reproduction numbers for the mentioned seven locations (see Table III). Except for the RJ, in the remaining six locations, we found that about 1–16% of the total COVID-19 transmission currently occurring is from notified and hospitalized infected population.
related contacts (see Table III). These figures can be increased up to 69% if proper measures are not taken in MH, DL, MP, GJ, UP, and IND, respectively, (see Table III). This is a worrisome situation as higher value of the hospital-based transmission rate in these six locations (Table II) indicates that there may be super-spreading incidents occurring from hospital-based contacts. In RJ, low contribution of $R_0$ on $R_0$ (see Table III) may be due to existence of low percentage of the symptomatically infected population in the community (Table II) and that leads to low percentage of notified and hospitalized COVID-19 cases.

For further investigation on super-spreading events, we carried a global uncertainty and sensitivity analysis of some epidemiologically measurable and controllable parameters from our mechanistic ODE model (Fig. 1 and Supporting Information Eqn S1 and S2) namely, $\beta_2$ : average rate of transmission occurring from notified and hospitalized based contact (it can be controllable following the WHO guidelines (Europe World Health Organization [EWHO], 2020)), $\rho$ : fraction of susceptible population that are exposed to hospital-based contact (it can be reduced by following proper guidelines from the WHO (EWHO, 2020)), $\kappa$ : fraction of the newly infected that are symptomatic (Rapid COVID-19 testing can provide an accurate estimate), $\tau$ : hospitalization and notification rate of symptomatic infected population (it also depend on number of COVID-19 testing) on the basic reproduction number ($R_0$). Partial rank correlation coefficients (PRCC) and its corresponding $p$-value suggested that all these four parameters have significant positive correlation with $R_0$ (see Fig. 6 and Fig. S17 to Fig. S22 in Supporting Information). Furthermore, high positive correlation of $\rho$ on $R_0$ indicate that small increase in the percentage of susceptible population from the community that are exposed hospital-based transmission will lead to significant increase in COVID-19 infection. Considering the fact that estimated value of $\beta_2$ (see Table II) in the seven locations are very high (much higher than community transmission rate), therefore, a small increase in $\rho$ may leads to a larger COVID-19 outbreak in those seven locations. Therefore, until and otherwise any preventive measures are taken in these locations, a larger COVID-19 outbreak may trigger from hospitals and quarantine centers.

Using the ensemble model (1), we forecast daily as well as total COVID-19 cases under five different lockdown scenarios in the mentioned seven locations, from May 3–May 20, 2020, (see Fig. 3, Table IV and Fig. S1 to Fig. S6 in Supporting Information). Spatial distribution of the projected COVID-19 cases under different lockdown scenarios in the six states of India during the mentioned projection period are provided in Fig. 4 and Fig. S7–S10 in Supporting Information. Comparing the projected total COVID-19 cases during May 3–20, 2020, (see Table IV) with the total observed cases (CT, 2020b) during March 2–April 29, 2020, we found about double increase in the total cases in MH, MP, GJ, UP, and IND, respectively. In summary, our forecast result suggest that in the coming two weeks a significant

Table III. Estimates of the Basic, the Community and the Hospital Reproduction Numbers. The Epidemiologically Known and Unknown Parameters of the Mechanistic ODE model (see Fig. 1 and Supporting Information) During the Estimation of the Different Reproduction Numbers are Taken from Table I and Table II, Respectively. Respective Subscripts MH, DL, MP , RJ, GJ, UP , and IND are same as Table II. All Data are Given in the Format Estimate (95% CI)

| Region | $R_0$ | $R_C$ | $\% R_0$ | $R_H$ | $\% R_0$ |
|--------|-------|-------|----------|-------|----------|
| MH     | 2.37  | 2.309 | 97.37    | 0.0623| 2.63     |
|        | (2.095–4.005) | (1.542–3.894) | (55.46–99.93) | (0.0019–1.254) | (0.1–44.54) |
| DL     | 2.54  | 2.37  | 93.46    | 0.1658| 6.53     |
|        | (1.37–5.52) | (0.934–5.49) | (56.91–99.95) | (0.0016–0.8236) | (0.048–43.09) |
| MP     | 2.497 | 2.467 | 98.82    | 0.0296| 1.18     |
|        | (2.21–6.11) | (1.68–5.63) | (49.22–99.81) | (0.0062–2.045) | (0.19–50.78) |
| RJ     | 1.43  | 1.42  | 99.46    | 0.01   | 0.54     |
|        | (1.42–3.78) | (1.405–3.76) | (94.40–100) | (0–0.068) | (0–3.66) |
| GJ     | 1.835 | 1.706 | 93.02    | 0.128  | 6.98     |
|        | (1.51–4.86) | (0.895–3.72) | (31.4–99.56) | (0.0083–2.68) | (0.43–68.60) |
| UP     | 1.46  | 1.22  | 84       | 0.233  | 16       |
|        | (1.35–3.14) | (0.787–2.88) | (39.21–99.96) | (0.001–1.47) | (0.039–60.79) |
| IND    | 2.81  | 2.56  | 91.28    | 0.245  | 8.72     |
|        | (2.15–4.94) | (1.92–4.86) | (84.63–99.84) | (0.0048–0.388) | (0.16–15.37) |
increase in cases may be observed in most of these locations.

Estimation of the effective reproduction number ($R_T$) under two lockdown scenarios (A1 and A5) for the seven locations during the period April 21–May 20, 2020 (see Fig. 5 and Fig. S11 to Fig. S16 in Supporting Information) suggest that except for RJ, all other six locations the cases will increase with or without lockdown ($R_T > 1$). However, in RJ, values of $R_T$ were found to be below unity under lockdown scenario (A1) and found to be greater than unity (After May 18, 2020) under lockdown scenario (A5) (see Fig. S14 in Supporting Information). Therefore, if the current lockdown rate is maintained after April 21, 2020 then COVID-19 cases in RJ may gradually decrease in the coming days.

To determine which epidemiologically measurable and controllable parameters are most influencing, we carried out a global uncertainty analysis of $\beta_2$, $\rho$, $\kappa$, and $\tau$ on the lockdown effect. The lockdown effect is measured in terms of differences in the total number of COVID-19 cases during May 3–May 20, 2020, in the seven locations under the lockdown scenarios (A1) and (A5), respectively (see Section 2 for details). For MH, PRCC and its corresponding $p$-value suggested that all these four parameters have significant influence on the lockdown effect (see Fig. S17 in Supporting Information). Furthermore, significant negative correlation of $\beta_2$, and $\rho$ with the lockdown effect (see Fig. S17 in Supporting Information) suggested that only home quarantined the community may not be sufficient to reduce COVID-19 transmission in MH. Government and the policymakers may also have to focus on reducing the transmission occurring from hospital premises based on the guidelines from the WHO (EWHO, 2020). For DL, PRCC and its corresponding $p$-value suggested that $\beta_2$, $\rho$, and $\kappa$ are the main parameters that are influencing the lockdown effect (see Fig. S18 in Supporting Information). Moreover, significant negative correlation of $\beta_2$ and $\rho$ with the lockdown effect and as well as significant positive correlation of $\kappa$ with the lockdown effect (see Fig. S18 in Supporting Information) implies that an effective lockdown policy in DL may be a combination of lockdown in the community, contact tracing of COVID-19 cases, and with some effort in reducing hospital-based transmission following WHO guidelines (EWHO, 2020). For MP, PRCC and its corresponding $p$-value suggested that $\kappa$ and $\tau$ have high positive correlation with the lockdown effect (see Fig. S19 in Supporting Information). Furthermore,
Fig 4. Spatial distribution of total number of COVID-19 cases during May 3, 2020 till May 20, 2020 in the six states namely, Maharashtra (MH), Delhi (DL), Madhya Pradesh (MP), Rajasthan (RJ), Gujarat (GJ), and Uttar Pradesh (UP), under the lockdown scenario (A1). We used the following color clustering of the cases: Green (1,000–1,500), Purple (1,501–3,000), Blue (3,001–5,000), Yellow (5,001–7,000), Orange (7,001–12,000), and Red (12,001–24,000).
Table IV. Ensemble Model (1) Forecast of the Total Notified COVID-19 Cases During May 3–May 20, 2020. Respective Subscripts MH, DL, MP, RJ, GJ, UP, and IND are same as Table II. Regions Where, Current Lockdown Rate (↓) implies the Ensemble Model (1) Projections for the Scenarios (A2) to (A4) with 10%, 20% and 30% Decrement in the Current Estimate of Lockdown Rate (see Table II) during the Mentioned Period, whereas Current Lockdown Rate (↑) Implies the Ensemble Model (1) Projections for the Scenarios (A2) to (A4) with 10%, 20% and 30% Increment in the Current Estimate of Lockdown Rate (see Table II) During the Mentioned Period. Scenario (A1) Implies the Ensemble Model (1) Forecast with the Current Estimate of the Lockdown Rate (see Table II) During May 3–May 20, 2020. Finally, Scenario (A5) Implies the Ensemble Model (1) Forecast with no Lockdown During May 3–May 20, 2020. All Data are Provided in the Format Estimate (95% CI)

| Region | Current lockdown rate | Scenario A1 | Scenario A2 | Scenario A3 | Scenario A4 | Scenario A5 |
|--------|-----------------------|-------------|-------------|-------------|-------------|-------------|
| MH     | ↓                     | 16,790      | 17,410      | 18,147      | 19,036      | 23,000      |
|        |                       | (16,056−18,727) | (16,499−19,812) | (17,026−21,101) | (17,662−22,656) | (20,499−29,596) |
| DL     | ↓                     | 2,642       | 1,840       | 2,693       | 2,729       | 2,886       |
|        |                       | (1,791−3,294) | (1,337−3,297) | (1,901−3,300) | (1,979−3,304) | (2,319−3,320) |
| MP     | ↑                     | 4,036       | 3,924       | 3,825       | 3,738       | 5,058       |
|        |                       | (3,599−4,578) | (3,531−4,410) | (3,472−4,263) | (3,419−4,134) | (4,216−6,101) |
| RJ     | ↑                     | 1,184       | 1,156       | 1,133       | 1,114       | 1,138       |
|        |                       | (654−1,624) | (611−1,608) | (576−1,595) | (547−1,585) | (858−1,699) |
| GJ     | ↑                     | 7,707       | 7,444       | 7,206       | 6,990       | 9,337       |
|        |                       | (7,689−12,589) | (7,427−11,991) | (7,191−11,451) | (6,976−10,961) | (9,312−16,292) |
| UP     | ↑                     | 5,599       | 5,383       | 5,184       | 4,999       | 7,217       |
|        |                       | (3,656−6,478) | (3,564−6,206) | (3,479−5,954) | (3,401−5,722) | (4,343−8,517) |
| IND    | ↓                     | 38,134      | 40,278      | 42,824      | 45,896      | 57,159      |
|        |                       | (36,550−45,296) | (38,877−46,612) | (41,640−48,174) | (44,975−50,059) | (56,971−57,201) |

**Fig 5.** Effective reproduction number ($R_T$) under two lockdown scenarios (A1 and A5) for the period April 21–May 20, 2020 for India.

$\rho$ has significant negative correlation with the lockdown effect (see Fig. S19 in Supporting Information). Therefore, an effective lockdown policy in MP may be a strict implementation of lockdown in the red and orange zones, rapid COVID-19 testing in the community and reducing hospital-based transmission by following guidelines from WHO (EWHO, 2020). For RJ, PRCC and its corresponding $p$-value suggested that only $\kappa$ has a significant positive correlation with the lockdown effect (see Fig. S20 in Supporting Information). No significant correlation with hospital-based parameters may be due to existence of low percentage of the symptomatically infected population in the community (see Table II) and that leads to low percentage of notified and hospitalized based COVID-19 transmission. Therefore, RJ Government may focus more on contact tracing in the community with relaxation given in the Green and Orange zones to increase the percentage of symptomatically infected in the community. For GJ, PRCC and its cor-
Fig 6. Effect of uncertainty of four epidemiologically measurable and controllable parameters of the mechanistic ODE model (see Fig. 1, Table I and method section) on the effect of lockdown and the basic reproduction number ($R_0$). Lockdown effect is measured in terms of the differences in total number of COVID-19 cases occurred during May 3–May 20, 2020 in India under the lockdown scenarios (A1) and (A5), respectively (see method section). Effect of Uncertainty of these four parameters on the two mentioned responses are measured using Partial Rank Correlation Coefficients (PRCC). 500 samples for each parameter were drawn using Latin hypercube sampling techniques (LHS) from their respective ranges provided in Table I.

The corresponding $p$-value suggested that all these four parameters have significant influence on the lockdown effect (see Fig. S21 in Supporting Information). Furthermore, significant negative correlation of $\beta_2$, and $\rho$ with the lockdown effect (see Fig. S21 in Supporting Information) indicate that only home quarantining the community may not be sufficient to reduce COVID-19 transmission in GJ. Government of GJ and policymakers may also have to focus on reducing the transmission occurring from hospital premises based on the guidelines from the WHO (EWHO, 2020). For UP, PRCC and its corresponding $p$-value suggested that $\beta_2$, $\rho$, and $\kappa$ are the main parameters that are influencing the lockdown effect (see Fig. S22 in Supporting Information). Moreover, significant negative correlation of $\beta_2$ and $\rho$ with the lockdown effect and as well as significant positive correlation of $\kappa$ with the lockdown effect (see Fig. S22 in Supporting Information) implies that an effective lockdown policy in UP may be a combination of lockdown (relaxation in Green zone), contact tracing in community with effort in reducing hospital-based transmission following the WHO guidelines (EWHO, 2020). Finally for IND, PRCC and its corresponding $p$-value suggested that $\beta_2$ and $\rho$ are the main parameters that are most influencing the lockdown effect (see Fig. 6).

Therefore, only home quarantining the community may not be sufficient to reduce COVID-19 transmission in IND. Government of IND and the policymakers may also have to focus on reducing the transmission occurring from hospital premises based on the guidelines from the WHO (EWHO, 2020).

4. CONCLUSION

Our analysis of the mechanistic model with hospital-based COVID-19 transmission suggest that most of the new infections occurring in India as well as most of the states are currently undetected. Furthermore, a global sensitivity analysis of two epidemiologically controllable parameters from the hospital-based transmission on the basic reproduction number ($R_0$), indicate that if appropriate preventive measures are not taken immediately, a much larger COVID-19 outbreak may trigger due to the transmission occurring from the hospitalized and notified based contacts. Moreover, our ensemble forecast model (1) predicted a substantial percentage of increase in the COVID-19 notified cases during May 3–May 20, 2020, (see Table IV) in most of these locations. In RJ, trend of the forecast data (see Fig. S4 in Supporting Information) during May 3–May 20, 2020, is showing a decreasing trend. This may be due to low number of hospitalized and reported cases in this state (see Table II). However, cases may rise in RJ if relaxation in lockdown is applied. Furthermore, trend of the forecast data in IND (see Fig. 3) during May 3–May 20, 2020 indicates the fact that reaching the peak of the COVID-19 epidemic curve may be a long way ahead for India. Finally, based on our results of global sensitivity analysis of the four important epidemiologically measurable and controllable parameters on the lockdown effect, we are suggesting the following policy that may reduce the threat of a larger COVID-19 outbreak in the coming days.
4.1. Effective Lockdown Policy

Dividing different states into three clusters (red, orange, and green) with extensive lockdown in red zones and providing relaxation in orange and green zones of a state will increase the percentage of symptomatically infected in these two zones (orange, and green). From our sensitivity analysis results, the lockdown will be effective in those locations where higher percentage of symptomatic infection exist in the population. Therefore, the government has to shift some orange or green zones under the red zones or move some red zones under the orange or green zones depending upon the percentage of symptomatic infection of those locations. However, from time-to-time COVID-19 testing is needed in these zones to get better result out of this cluster lockdown policy. Furthermore, COVID-19 testing will increase the number of notified and hospitalized cases over the states. Also from our results, lockdown effectiveness has a negative correlation with the hospital-based transmission rate ($\beta_2$) and fraction of the susceptible population that is exposed to hospital-based contact ($\rho$). Therefore, reducing these two parameters will increase the effectiveness of the lockdown in those seven locations. To reduce the hospitalized and notified based contacts, an efficient disaster management team is required. They will continuously monitor the situations in different hospitals and quarantine centers across India. This team must ensure that proper safety measures are being followed based on the guidelines provided by ICMR and WHO (WHO, 2020a).

There are few limitations of this current study and may be improved in future. We assumed that home quarantined population do not mix with the infected individuals from the community. This is a very crude approximation because in such a huge country like India with such a dense population there is always a possibility that a certain percentage of population under the lockdown can get infection from the community. In addition to this fact, there is a possibility of cross infection within the home quarantined population. This assumption will lead to more compartments (exposed under lockdown, symptomatic under lockdown, and asymptomatic under lockdown) and thus make our model more complex. Moreover, currently there is little evidence of air-borne transmission of COVID-19 in some regions (Morawska & Milton, 2020). However, this alternative air-borne transmission route is not considered in our model. Adding all these components in our mechanistic model may produce some rich dynamical properties like backward bifurcation, hopf-bifurcation, and so on. We shall explore these factors in our future studies.

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CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1: Estimated uninformative initial conditions for the mechanistic ODE model combinations (S-1) & (S-2).

Table S2: Weight estimates for the mechanistic ODE model combinations (S-1) & (S-2) and the Hybrid statistical model (see main text), respectively.

Table S3: Goodness of fit (RMSE and MAE) of the Hybrid statistical model (see main text) for the test data from MH, DL, MP, RJ, GJ, UP, and IND, respectively. Respective subscripts MH, DL, MP, RJ, GJ, UP, and IND are same as Table S1.

Fig. S1: Ensemble model (see main text) forecast for the daily notified COVID-19 cases in Maharashtra during May 3, 2020 till May 20, 2020 under five different lockdown scenarios.

Fig. S2: Ensemble model (see main text) forecast for the daily notified COVID-19 cases in Delhi during May 3, 2020 till May 20, 2020 under five different lockdown scenarios.

Fig. S3: Ensemble model (see main text) forecast for the daily notified COVID-19 cases in Madhya Pradesh during May 3, 2020 till May 20, 2020 under five different lockdown scenarios.

Fig. S4: Ensemble model (see main text) forecast for the daily notified COVID-19 cases in Rajasthan during May 3, 2020 till May 20, 2020 under five different lockdown scenarios.

Fig. S5: Ensemble model (see main text) forecast for the daily notified COVID-19 cases in Gujarat during May 3, 2020 till May 20, 2020 under five different lockdown scenarios.

Fig. S6: Ensemble model (see main text) forecast for the daily notified COVID-19 cases in Uttar Pradesh during May 3, 2020 till May 20, 2020 under five different lockdown scenarios.

Fig. S7: Spatial distribution of total number of COVID-19 cases during May 3, 2020 till May 20, 2020 in the six states namely, Maharashtra (MH), Delhi (DL), Madhya Pradesh (MP), Rajasthan (RJ), Gujarat (GJ), and Uttar Pradesh (UP), under the lockdown scenario (A2). We used the following colour clustering of the cases: Green (1000 - 1500), Purple (1501 - 3000), Blue (3001 - 5000), Yellow (5001 - 7000), Orange (7001 - 12000), and Red (12001 - 24000).

Fig. S8: Spatial distribution of total number of COVID-19 cases during May 3, 2020 till May 20, 2020 in the six states namely, Maharashtra (MH), Delhi (DL), Madhya Pradesh (MP), Rajasthan (RJ), Gujarat (GJ), and Uttar Pradesh (UP), under the lockdown scenario (A3). Colour clustering of the cases are same as Fig. S7.

Fig. S9: Spatial distribution of total number of COVID-19 cases during May 3, 2020 till May 20, 2020 in the six states namely, Maharashtra (MH), Delhi (DL), Madhya Pradesh (MP), Rajasthan (RJ), Gujarat (GJ), and Uttar Pradesh (UP), under the lockdown scenario (A4). Colour clustering of the cases are same as Fig. S7.

Fig. S10: Spatial distribution of total number of COVID-19 cases during May 3, 2020 till May 20, 2020 in the six states namely, Maharashtra (MH), Delhi (DL), Madhya Pradesh (MP), Rajasthan (RJ), Gujarat (GJ), and Uttar Pradesh (UP), under the lockdown scenario (A5). Colour clustering of the cases are same as Fig. S7.

Fig. S11: Effective reproduction number (RT) under two lockdown scenarios (A1 & A5) for the period April 21, 2020 till May 20, 2020 for Maharashtra.

Fig. S12: Effective reproduction number (RT) under two lockdown scenarios (A1 & A5) for the period April 21, 2020 till May 20, 2020 for Delhi.

Fig. S13: Effective reproduction number (RT) under two lockdown scenarios (A1 & A5) for the period April 21, 2020 till May 20, 2020 for Madhya Pradesh.

Fig. S14: Effective reproduction number (RT) under two lockdown scenarios (A1 & A5) for the period April 21, 2020 till May 20, 2020 for Rajasthan.

Fig. S15: Effective reproduction number (RT) under two lockdown scenarios (A1 & A5) for the period April 21, 2020 till May 20, 2020 for Gujarat.

Fig. S16: Effective reproduction number (RT) under two lockdown scenarios (A1 & A5) for the period April 21, 2020 till May 20, 2020 for Uttarakhand.

Fig. S17: Effect of uncertainty of four epidemiologically measurable and controllable parameters of the mechanistic ODE model (see Table I and Fig.1 in the
main text) on the effect of lockdown and the basic reproduction number (R0).

**Fig. S18**: Effect of uncertainty of four epidemiologically measurable and controllable parameters of the mechanistic ODE model (see Table I and Fig.1 in the main text) on the effect of lockdown and the basic reproduction number (R0).

**Fig. S19**: Effect of uncertainty of four epidemiologically measurable and controllable parameters of the mechanistic ODE model (see Table I and Fig.1 in the main text) on the effect of lockdown and the basic reproduction number (R0).

**Fig. S20**: Effect of uncertainty of four epidemiologically measurable and controllable parameters of the mechanistic ODE model (see Table I and Fig.1 in the main text) on the effect of lockdown and the basic reproduction number (R0).

**Fig. S21**: Effect of uncertainty of four epidemiologically measurable and controllable parameters of the mechanistic ODE model (see Table I and Fig.1 in the main text) on the effect of lockdown and the basic reproduction number (R0).

**Fig. S22**: Effect of uncertainty of four epidemiologically measurable and controllable parameters of the mechanistic ODE model (see Table I and Fig.1 in the main text) on the effect of lockdown and the basic reproduction number (R0).

**Fig. S23**: Posterior distribution of the weights for the mechanistic ODE model combinations (S-1) & (S-2) and the Hybrid statistical model (see main text), respectively for Maharashtra.

**Fig. S24**: Posterior distribution of the weights for the mechanistic ODE model combinations (S-1) & (S-2) and the Hybrid statistical model (see main text), respectively for Delhi.

**Fig. S25**: Posterior distribution of the weights for the mechanistic ODE model combinations (S-1) & (S-2) and the Hybrid statistical model (see main text), respectively for Madhya Pradesh.

**Fig. S26**: Posterior distribution of the weights for the mechanistic ODE model combinations (S-1) & (S-2) and the Hybrid statistical model (see main text), respectively for Rajasthan.

**Fig. S27**: Posterior distribution of the weights for the mechanistic ODE model combinations (S-1) & (S-2) and the Hybrid statistical model (see main text), respectively for Gujarat.

**Fig. S28**: Posterior distribution of the weights for the mechanistic ODE model combinations (S-1) & (S-2) and the Hybrid statistical model (see main text), respectively for Uttar Pradesh.

**Fig. S29**: Posterior distribution of the weights for the mechanistic ODE model combinations (S-1) & (S-2) and the Hybrid statistical model (see main text), respectively for India.