Projections of the COVID-19 epidemic in Colorado under different social distancing scenarios

Prepared by the COVID-19 Modeling Group

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SUMMARY

- Social distancing measures implemented in mid-March appear to be slowing the growth of the COVID-19 outbreak in Colorado.
- Due to lags in the data, we anticipate being able to estimate the impact of the state-wide stay at home order implemented March 26 in the coming week.
- The short- and long-term trajectory of COVID-19 in Colorado, including the number of deaths and whether hospital capacity is exceeded, depends, in part, on how well we can reduce the contact rate between infectious and susceptible people.
- High levels of social distancing, sustained throughout April, can not only flatten the curve but bend the curve such that we will see a decline in cases and hospitalizations such that hospital capacity is not exceeded.
- A key question in the days ahead is how phase 2 social distancing (implemented March 26) is actually impacting contact rates and ultimately, the accumulation of cases in Colorado.

INTRODUCTION

This report responds to the urgent need for projections of the impact and course of COVID-19 in Colorado. We use the findings of an epidemic model developed by this team for the State of Colorado to describe the epidemic curve. We developed an age-structured deterministic SEIR (Susceptible, Exposed, Infected, Recovered) model, fit to COVID-19 reported cases in Colorado, in order to estimate the projected number of cases, hospital demand and deaths from COVID-19 in Colorado under different intervention scenarios.

In this report we focus on projecting the impacts of social distancing interventions that were implemented in Colorado in March. One of the key factors that impacts the spread of COVID-19 is the contact rate – the frequency of contact between infectious and susceptible individuals. The central aim of social distancing measures is to reduce the contact rate and slow the spread of infections. For the purpose of this report, we distinguish two phases of social distancing interventions. Phase 1 social distancing interventions include school closures, the closing of bars and restaurants and the closure of ski resorts which were implemented in mid-March. We refer to the state-wide stay at home order, implemented March 26 as Phase 2. Here we describe when we might expect to see the impact of these interventions on COVID-19, estimate the likely impact of phase 1 on the epidemic to date, and project the potential impacts of phase 2 on cases, hospital demand and fatalities in the coming months.

COVID-19 emerged four months ago, and our understanding of the virus and the course of infection is evolving rapidly.

This report should be considered as covering the methods and assumptions underlying our work up to April 6, 2020. Our modeling work is dynamic, however, and the methods will undergo refinements and some assumptions will change as more data are gathered as the pandemic progresses. We will continue to update these models as data accumulate over the course of the pandemic. For the purpose of this report, we assume all social distancing measures are implemented indefinitely, and in later work we will explore their relaxation. Future reports will evaluate the potential impacts of relaxing social distancing measures.

METHODS

Model description. We used a deterministic age-structured susceptible, exposed, infected, recovered (SEIR) model to project the number of people with COVID 19 needing hospitalization, critical care and the number of deaths in Colorado under different intervention scenarios (Figure 1).

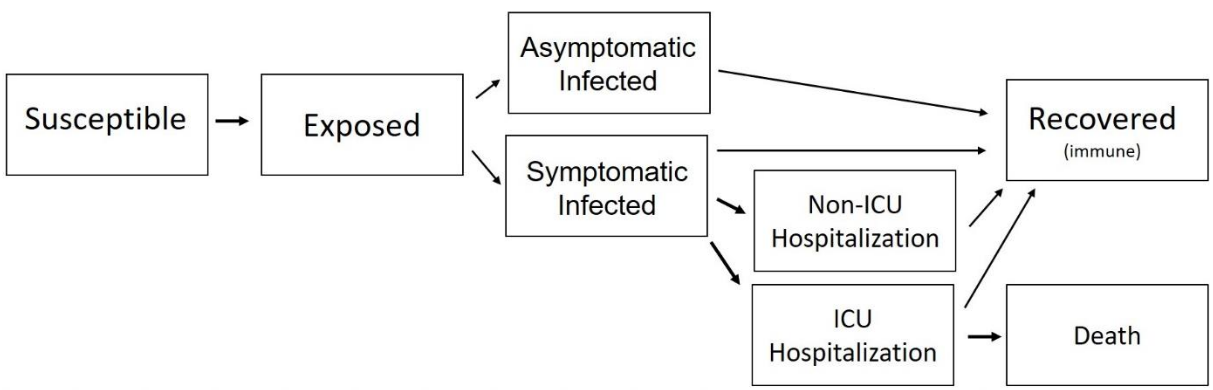

Figure 1. Structure of the deterministic SEIR model used. Infected individuals are separated into asymptomatic and symptomatic individuals. Symptomatic individuals may recover without hospitalization, experience a non-ICU hospitalization or an ICU hospitalization.

Critical assumptions and the basis for making them follow. In this model, we assume exposed individuals incubate infections for 5.1 days before becoming infectious (Lauer et al, Li et al), the infectious period is the same regardless of symptoms and lasts for 8 days (Zou et al) and both are exponentially distributed. Infected individuals can be either asymptomatic or symptomatic. In light of evidence that the probability an infected individual develops symptoms (Davies et al) and the probability a symptomatic individual needs hospitalization is age-dependent (Verity et al), we developed an age-structured model with three separate age compartments (<30, 30-59, 60+). We used Colorado demographic data from 2020, provided by CDPHE, to define age and population structure. We estimated age-dependent probabilities that an infected individual is symptomatic, estimating the product of the age distribution of Colorado within each age-compartment and the age-group-specific symptomatic fraction as shown in Table 1 (Davies et al., personal communication). All individuals have equal probability of exposure and infection, regardless of age. In our model, asymptomatic individuals are assumed to circulate in the population and do not self-isolate. Symptomatic individuals are assumed to self-isolate albeit imperfectly, starting on March 5, the date that the first case of COVID-19 was reported in Colorado (CDPHE). The model assumes the infectiousness of symptomatic individuals is greater than asymptomatic individuals. We note that there is emerging evidence that infectiousness of an individual may vary based on symptom severity (Zou et al), a phenomenon that is not accounted for in our model.

We use the estimates of Verity et al, summarized by Ferguson et al to estimate the proportion of symptomatic cases that will require hospitalization and critical care based on the age structure of the population in the state of Colorado (Table 1). We assume that symptomatic cases will require care 8 days after the onset of symptoms (this is within the range of Linton et al and Tindale et al's estimated ranges). We assume that the average length of hospital stay is 8 days if critical care is not required and 10 days if critical care is required (Ferguson et al). We also assume that no further transmission occurs once the patient enters the hospital. At present, these assumptions are based on experience external to Colorado, but could be replaced as Colorado data become available.

Table 1. Age-specific parameter estimates from the literature, standardized using Colorado population age distribution from CDPHE 2020 estimates

Age Group	Probability of symptoms, given infection (Davies et al.)	Probability of hospitalization given symptoms (Verity et al.)	Probability of needing ICU hospitalization given symptoms (Verity et al.)
0 - 29	0.18	0.006	0.0003
30 - 59	0.47	0.059	0.0045
60 +	0.79	0.207	0.0808

Estimated deaths are based on the probability of death for ICU patients and ICU capacity. We assume 50% of cases in the ICU die, a figure which is consistent with Ferguson et al and roughly the mortality of ARDS cases, generally. Additionally, we assume that once available ICU beds are full, all cases requiring ICU care in excess of availability result in deaths. We estimate ICU bed capacity using the estimated number of beds available in Colorado. We currently assume there are 2,700 ventilator-able ICU beds in the state of Colorado and that 700 are needed for non-COVID 19 patients based on recent estimates of ICU use when elective surgeries are cancelled, allowing for a capacity of 2,000 ICU beds for Covid-19 patients.

Recovered individuals are assumed to remain immune to infection. We assume random population mixing, and that infection probability does not vary by age or sex. There are no additional importations, migration, or deaths in the system.

Model fitting and parameter estimation. We fit the model to Colorado COVID-19 data provided by CDPHE in order to estimate parameter values which may vary regionally and/or for which there is considerable uncertainty in the current literature (Table 2). For example, we estimated the probability that a symptomatic case is detected by the state surveillance system, a parameter that likely varies depending on the surveillance capacities of different state public health systems. For model fitting, we used reported COVID cases through March 31 provided by CDPHE. Due to lags in reporting, making the most recent days unstable, we fit the model to case reports with an onset date of March 26 or earlier. For cases with missing onset date, we estimated onset date as date of report minus seven days in accordance with typical reporting lags for Colorado.

In order to fit the model to observed case-date early in the epidemic, the rate of infection (beta), probability of identifying symptomatic cases (pID), proportion of symptomatic individuals that self-isolated after March 5 (siI), the proportionate increase in transmission comparing symptomatic to asymptomatic infections (lambda), the start date of the epidemic in Colorado and the efficacy of social distancing interventions after March 17th were allowed to vary within pre-specified ranges (Table 1). Best-fitting parameter values were identified via a least-squares cost function minimizing the comparison between the estimated proportion of expected cases that would be detected in the model and the number of confirmed COVID-19 cases in Colorado. The cost function was minimized using a two-stage fitting algorithm in R, first applying a psuedo-random optimization algorithm (Price, 1977) to find a region of minimum difference between the model and the data. The second phase used least-squares optimization applying the Levenberg-Marquardt algorithm (More, 1978).

Table 2. Model parameters estimated by fitting our model to Colorado COVID-19 surveillance data

	Range of possible values and sources	Fitted value
The rate of infection (beta)	0.2 - 0.6 (MIDAS*)	0.413
Proportion of symptomatic individuals that self-isolate after March 5 (siI)	0.3 - 0.8 (Ferguson et al)	0.379
Ratio of infectiousness for symptomatic vs. asymptomatic individuals (lambda)	1.0 - 4.0 (Li et al, Zou et al)	2.268
Probability symptomatic cases are identified by state surveillance (pID)	0.05 - 0.6 (MIDAS*)	0.277
Effectiveness of social distancing interventions implemented March 17	0.1 - 0.6 (see text)	0.45
Date the first infection was introduced in Colorado	Jan 17 – Jan 29 (see text)**	Jan 24

*The range of potential parameter estimate values were obtained from the MIDAS Online COVID-19 compilation of parameter estimates available here.
**The first case of COVID19 reported in Colorado had a symptom onset date of 2/18/2020 and the next three reported cases had a symptom onset date of 2/20/2020. Assuming a 5.1 day incubation period (Lauer et al, Li et al), during this initial phase of the outbreak 85% of cases were unreported (Li et al), and the outbreak has a 5.2 to 6.5 day doubling time (Wu et al, Wu et al), we estimate the first cases arrived between 1/17 to 1/29/2020. At present, it is unclear if the Colorado outbreak is due to a single or multiple importation events.

Estimating the impact of social distancing. We used the above model to estimate the impact of current social distancing scenarios on the shape of the epidemic including the timing and magnitude of peaks in hospital utilization, and the cumulative number of deaths. The growth of an epidemic can be defined, in part, by the basic reproductive number (R_0), which is the expected number of cases directly generated by one case in a population where all individuals are susceptible to infection. In a simple epidemic model, R_0 is a function of the contact rate (*c*, the rate at which an infected individual contacts susceptible individuals), the transmission probability (*h*, the probability a contact between an infected and susceptible individual results in an infection), and the duration of infectiousness (d, the average number of days an individual is infectious). Social distancing measures generally aim to lower the contact rate, and thereby reduce the number of new cases generated by a single case, slowing the growth of the epidemic (Figure 3). If R_0 is reduced below one, the number of infections declines.

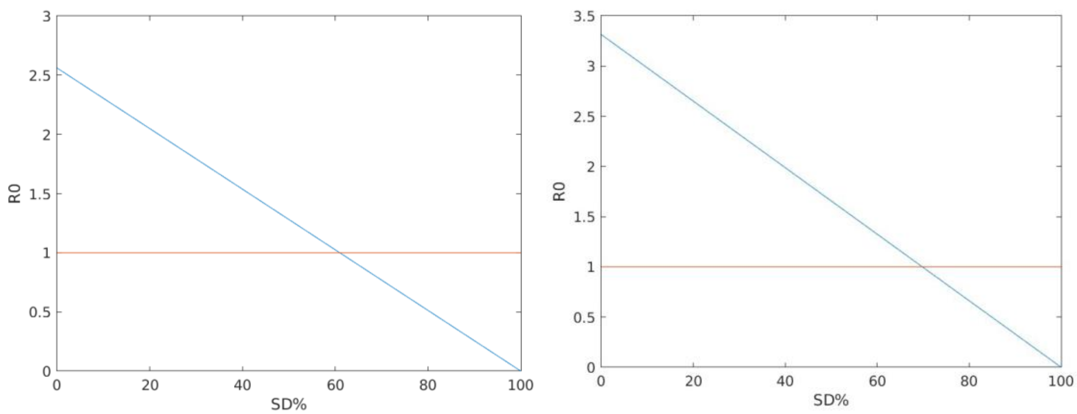

Figure 3. The relationship between social distancing, modeled as a percent reduction in the contact rate, and the average number of new infections directly generated by an infected person (R_0) for two different population models. On the left is the simpler model which does not partition the infected categories by age. On the right is the plot of R0 vs. Social Distancing (SD%) for a model with the infected populations separated into 3 distinct age groups. The message in both figures Is that the social distancing must reduce contacts by over 60%-70% or the epidemic will not decrease over time.

Social distancing of this magnitude has not been previously implemented and we do not yet know how these measures will impact contact rates and ultimately, the spread of SARS-CoV-2. In Colorado, social distancing orders were rolled out over a two-week period. On 3/14 Colorado ski resorts were closed. By 3/16/2020, many Colorado school districts had closed. On 3/17/2020, an executive order was issued closing all restaurants, bars, theaters and casinos in the state. And on 3/26/2020 a state-wide stay at home order was issued. Here, we distinguish two phases of social distancing interventions: phase 1 interventions were assigned a start date of March 17, and phase 2, which presumably resulted in greater social distancing, was assigned a start date of March 26.

The impact of social distancing measures on COVID-19 cases and fatalities will not be observed immediately due to natural lags between infection and symptom onset, symptom onset and death, as well as lags in testing (Figure 4). Due to these lags, we anticipate the impacts of phase 1 social distancing to be just recently observable in terms of reported COVID-19 cases and not yet observable in terms of COVID-19 deaths. We anticipate the impacts of phase 2 social distancing measures to be observable in the coming week. For this reason, we used model fitting (described above) to estimate the efficacy of the phase 1 social distancing interventions in terms of the % reduction in contact rates. We then used the best fit model (45% social distancing) as the presumed level of social distancing for phase 1. Because the impact of phase 2 is not yet observable, we modeled scenarios of social distancing as a 50, 60, 70 and 80% percent reduction in the contact rate among people starting March 26 to capture the current uncertainty concerning how stay-in place measures will impact SARS-CoV-2 transmission. We considered indefinite implementation of these measures. Scenarios examining the impact of relaxing social distancing measures will be considered at a future date.

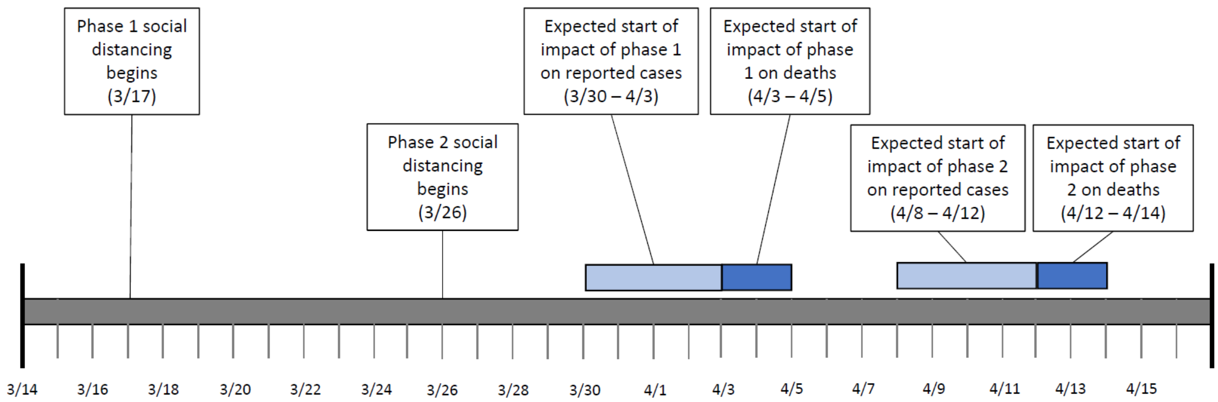

Figure 4. The expected dates when the first impacts of different social distancing measures will be observed in reported COVID-19 cases and deaths. Figure shows the expected timing of observed impacts of phase 1 social distancing which includes the closure of bars, restaurants, theatres and casinos (3/17), many schools (3/16) and ski resorts (3/14), shown here as occurring on 3/17, and phase 2 social distancing corresponding with a state-wide stay at home order, implemented on March 26. These estimates account for an estimated 5.1 day (range 4.5 to 6.0) incubation period (the time between exposure and symptom onset) based on Lauer et al, Li et al , Linton et al; an estimated 5.3 day (95% CI 5.0, 5.6) lag between symptom onset and hospitalization based on analysis of COVID-19 epidemiological data from Xu et al; an 8 day lag between hospitalization and death (Ferguson et al); and an estimated 9.3 day (range 8.5, 11.5 based on reporting lags over the past week) lag between symptom onset and case report based on Colorado COVID-19 surveillance data.

RESULTS

Estimated impact of phase 1 social distancing. Fitting the model to the case data, we find evidence that phase 1 social distancing has yielded an approximately 45% reduction in the contact rate (Figure 5). The current model suggests that, without phase 1 social distancing measures in place, in the 8 days from March 19 through March 26, approximately 1,200 additional cases would have been reported.

Projected impact of phase 2 social distancing. Figures 6 through 8 show the projected number of reported cases, non-ICU hospitalizations and ICU-hospitalizations under different phase 2 social distancing scenarios, starting March 26. The modeled scenarios project that social distancing efficacy of 40% to 60% flattens the curve such that peaks in infections, non-ICU hospitalizations and ICU demand occurs later, and the peak is smaller than the no social distancing scenario, with more effective social distancing yielding lower peaks and more time to prepare (Table 4). However, in each of these scenarios, ICU capacity is expected to be exceeded (Table 3). Notably, the 80% social distancing scenario shows a decline in cases in the next month, suppressing the contact rate such that the epidemic peaks and declines in the month of April while social distancing measures are maintained. In the 70% and 80% social distancing scenarios, ICU capacity is not projected to be exceeded, resulting in far fewer projected deaths (Table 5).

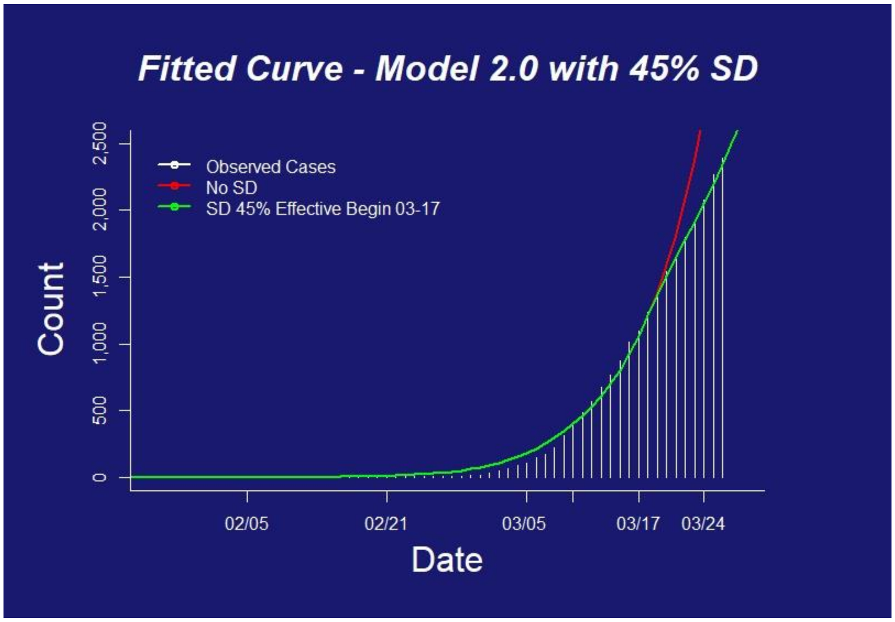

Figure 5. The fit of the age-structured SEIR model to reported COVID-19 cases through March 31 (data provided by CDPHE). The best-fit curve, showing social distancing efficacy of 45% starting March 17 (green line) and a curve showing no social distancing (red line) are shown. Due to lags in reporting, making the most recent days unstable, we fit the model to case reports and hospitalizations with an onset date of March 26 or earlier. This will be updated on an ongoing basis.

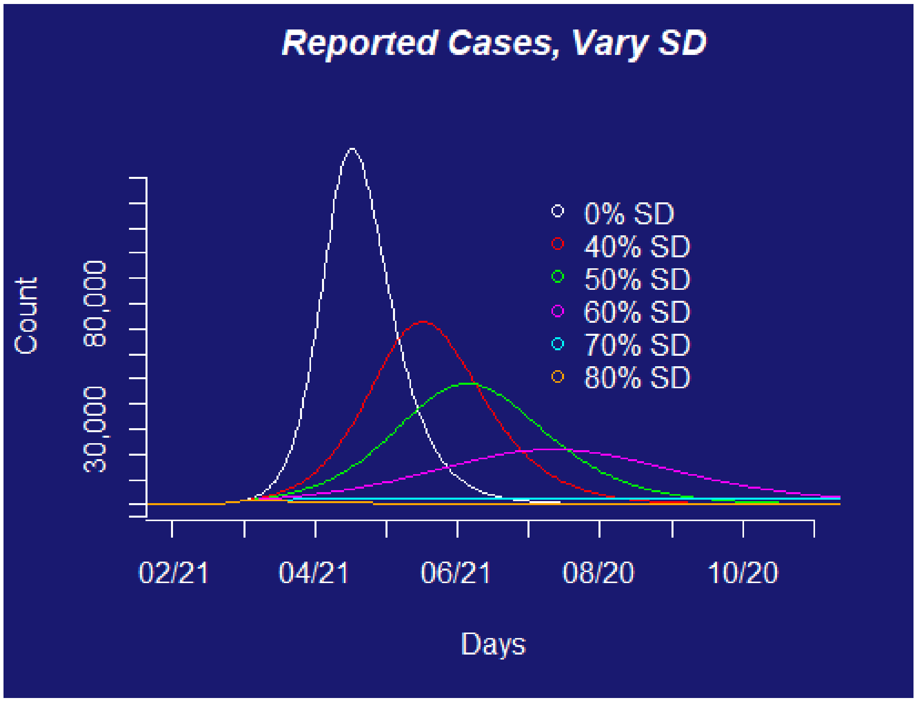

Figure 6. Projected number of observed cases under different levels of phase 2 social distancing, starting March 26. All scenarios include phase 1 social distancing starting March 17 modeled as a 45% reduction in the contact rate.

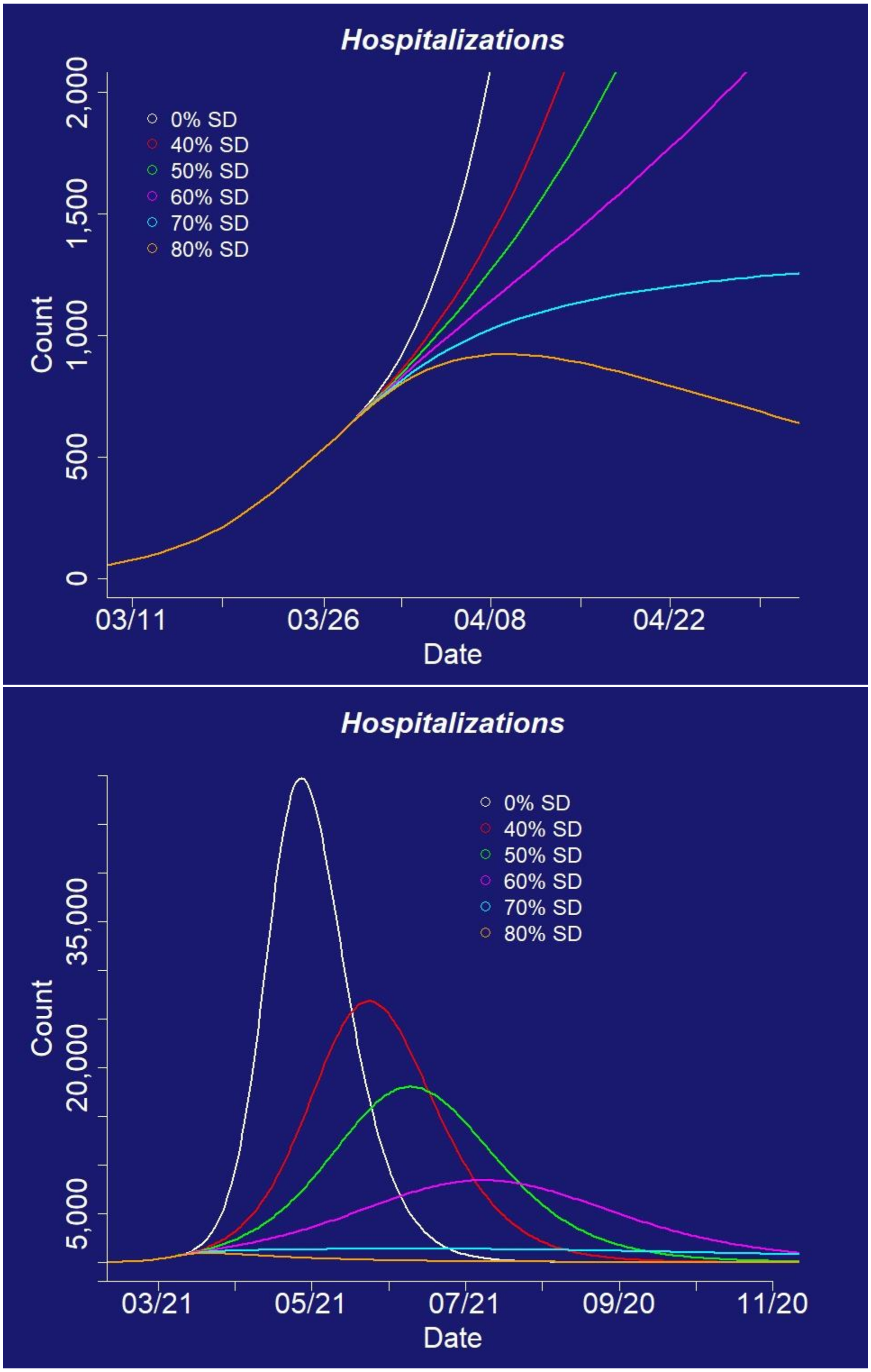

Figure 7. Projected COVID-19 non-ICU hospital demand in the short-term (top panel) and long term (bottom panel) under different levels of phase 2 social distancing, starting March 26. All scenarios include phase 1 social distancing starting March 17 modeled as a 45% reduction in the contact rate.

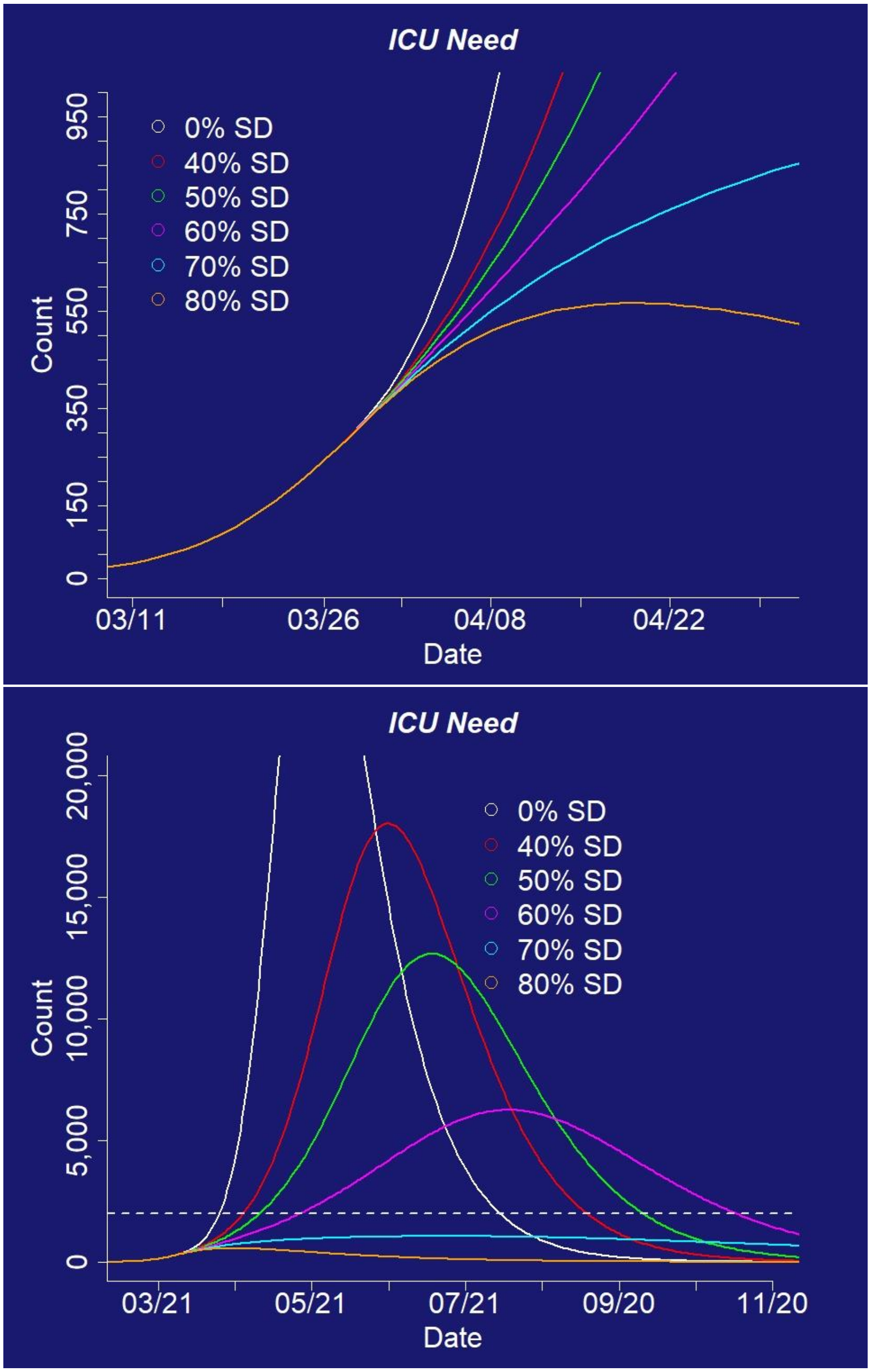

Figure 8. Projected COVID-19 ICU demand in the short-term (top panel) and long-term (bottom panel) under different levels of phase 2 social distancing, starting March 26. Dashed line in the bottom panel indicates Colorado's estimated COVID-19 ICU capacity of 2,000 beds, reflecting an estimated 2700 ICU beds, 700 of which are occupied by non-COVID-19 patients. All scenarios include phase 1 social distancing starting March 17 modeled as a 45% reduction in the contact rate.

Table 3. Approximate dates where ICU threshold of 2,000 bed capacity is reached under different phase 2 social distancing scenarios. All scenarios include phase 1 social distancing starting March 17 modeled as a 45% reduction in the contact rate.

Phase 2 Social Distancing Scenarios	**Approximate date ICU threshold (2,000 beds) is reached**
0% Efficacy	April 13
40% Efficacy	April 23
50% Efficacy	April 29
60% Efficacy	May 15
70% Efficacy	N/A
80% Efficacy	N/A

Table 4. Estimated timing of the peak number of infections and peak number of hospitalizations. Model assumes social distancing begins March 17 at 45% efficacy and then is changed on March 26th to varying efficacies shown in the table and remains in place indefinitely.

	Peak Infections		Peak non-ICU hospitalizations***		Peak ICU hospitalizations	
Phase 2 Social Distancing Scenarios	Num.*	Date	Num.*	Date	Num*	Date
0% Efficacy	222,643	5/8/2020	49,887	5/11/2020	29,944	5/16/2020
40% Efficacy	138,139	6/13/2020	26.857	6/09/2020	18,046	6/17/2020
50% Efficacy	104,738	7/9/2020	17,971	6/28/2020	12,647	7/06/2020
60% Efficacy	64,613	9/14/2020	8,246	8/03/2020	6,133	8/13/2020
80% Efficacy	2,386	4/01/2020	557	4/03/2020	339	4/13/2020

*Number of infections, non-ICU hospitalizations and ICU hospitalizations at the peak date indicated.
***Peak and cumulative ICU hospitalizations is the estimated number of needed ICU beds. These may be in excess of capacity at peak times. The 0% efficacy is used to determine the consequences of distancing.

Table 5. Estimated cumulative number of COVID-19 deaths, non-ICU and ICU hospitalizations. Model assumes social distancing begins March 17 at 45% efficacy and then is changed on March 26th to varying efficacies shown in the table and remains in place indefinitely.

	Cumulative deaths*		Cumulative non-ICU hospitalizations		Cumulative ICU bed need**	
	As of 6/1/2020	As of 1/1/2021	As of 6/1/2020	As of 1/1/2021	As of 6/1/2020	As of 1/1/2021
0% Efficacy	73,162	80,260	239,501	256,074	127,195	160,519
40% Efficacy	29,783	68,827	101,082	219,612	48,282	137,656
50% Efficacy	13,828	60,089	50,185	191,844	24,235	120,211
60% Efficacy	4,516	43,158	20,480	139,430	10,365	86,828
80% Efficacy	1,030	1,406	3,836	4,487	2,232	2,811

*We assume 50% of cases in the ICU die, a figure which is consistent with Ferguson et al and roughly the mortality of ARDS cases, generally. Additionally, we assume that once available ICU beds are full, all cases requiring ICU in excess of availability result in deaths. Cumulative death estimate assumes the number of available beds with ventilator-capacity in the ICU is 2000.
**Peak and cumulative ICU hospitalizations is the estimated number of needed ICU beds. These may be in excess of capacity at peak times.

DISCUSSION AND CONCLUSIONS

Our findings suggest the phase 1 social distancing has had an impact on the number of cases being reported in Colorado. The short- and long-term trajectory of COVID-19 in Colorado, including the number of deaths and whether hospital capacity is exceeded, depends on the efficacy of phase 2 social distancing over the coming month. Our models suggest high levels of social distancing sustained over the coming month can not only flatten the curve but bend the curve such that we see a decline in cases and hospitalizations and do not exceed hospital capacity. Because we cannot yet observe the impact of the state-wide stay at home order in the epidemiological data, we modeled a set of scenarios describing the potential efficacy of social distancing. A key question in the days ahead is how phase 2 social distancing is actually impacting contact rates and ultimately, the accumulation of cases in Colorado.

In modeling social distancing scenarios, we assumed they impact all populations essentially evenly. However, changes in contact rate may not be uniform across the population – essential workers, homeless populations may be more vulnerable populations in need of special considerations. We also made the strong assumption that once a COVID-19 patient enters the hospital, no further spread of infection occurs. In reality, we know that health care workers have become infected with COVID-19 with serious, and sometimes fatal, consequences. Slowing the rate of infections such that hospital capacity is not exceeded, can help improve the likelihood that healthcare workers have access to personal protective equipment and hospitals are able to adhere to infection control protocols. Lastly, it is not currently understood whether the transmission of SARS-CoV-2 varies seasonally but if it does, this may impact long-term projects of infections (National Academics of Medicine), which is not currently accounted for in our models.