Estimating and Simulating a SIRD Model of COVID-19 for Many Countries, States, and Cities

Jesús Fernández-Villaverde and Chad Jones

Extended results for South Carolina
Based on data through August 24, 2020
Outline of Slides

• Basic data from Johns Hopkins CSSE (raw and smoothed)
• Brief summary of the model
• Baseline results ($\delta = 1.0\%, \gamma = 0.2, \theta = 0.1$)
• Simulation of re-opening – possibilities for raising $R_0$
• Results with alternative parameter values:
  o Lower mortality rate, $\delta = 0.8\%$
  o Higher mortality rate, $\delta = 1.2\%$
  o Infections last longer, $\gamma = 0.15$
  o Cases resolve more quickly, $\theta = 0.2$
  o Cases resolve more slowly, $\theta = 0.07$
• Data underlying estimates of $R_0(t)$
Underlying data from Johns Hopkins CSSE

- Raw data
- Smoothed = 7 day centered moving average
- No “excess deaths” correction (change as of Aug 6 run)
South Carolina: Daily Deaths per Million People

Daily deaths per million people

South Carolina

Apr  May  Jun  Jul  Aug  2020
South Carolina: Daily Deaths per Million People (Smoothed)
Brief Summary of Model

- See the paper for a full exposition
- A 5-state SIRDC model with a time-varying $R_0$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta$</td>
<td>1.0%</td>
<td>Mortality rate from infections (IFR)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.2</td>
<td>Rate at which people stop being infectious</td>
</tr>
<tr>
<td>$\theta$</td>
<td>0.1</td>
<td>Rate at which cases (post-infection) resolve</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.05</td>
<td>Rate at which $R_0(t)$ decays with daily deaths</td>
</tr>
<tr>
<td>$R_0$</td>
<td>...</td>
<td>Initial base reproduction rate</td>
</tr>
<tr>
<td>$R_0(t)$</td>
<td>...</td>
<td>Base reproduction rate at date $t$ ($\beta_t/\gamma$)</td>
</tr>
</tbody>
</table>
Estimates of Time-Varying $R_0$

– Inferred from daily deaths, and
– the change in daily deaths, and
– the change in (the change in daily deaths)
(see end of slide deck for this data)
South Carolina: Estimates of $R_0(t)$

South Carolina

$\delta = 0.010$  $\theta = 0.10$  $\gamma = 0.20$
South Carolina: Percent Currently Infectious

South Carolina
Peak I/N = 0.50%  Final I/N = 0.30%  δ = 0.010  θ = 0.10  γ = 0.20
South Carolina: Growth Rate of Daily Deaths over Past Week (percent)

South Carolina

\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Notes on Interpreting Results
Guide to Graphs

• **Warning:** Results are often very uncertain; this can be seen by comparing across multiple graphs. See the original paper.

• 7 days of forecasts: Rainbow color order!
  ROY-G-BIV (old to new, low to high)
  - Black = current
  - Red = oldest, Orange = second oldest, Yellow = third oldest...
  - Violet (purple) = one day earlier

• For robustness graphs, same idea
  - Black = baseline (e.g. $\delta = 1.0\%$)
  - Red = lowest parameter value (e.g. $\delta = 0.8\%$)
  - Green = highest parameter value (e.g. $\delta = 1.2\%$)
How does $R_0$ change over time?

- Inferred from death data when we have it
- For future, two approaches:
  1. Alternatively, we fit this equation:

\[
\log R_0(t) = a_0 - \alpha(Daily\ Deaths)
\]

\[\Rightarrow \alpha \approx .05\]

$R_0$ declines by 5 percent for each new daily death, or rises by 5 percent when daily deaths decline.

- Robustness: Assume $R_0(t) =$ final empirical value. Constant in future, so no $\alpha$ adjustment $\rightarrow \alpha = 0$
Repeated “Forecasts” from the past 7 days of data

- After peak, forecasts settle down.
- Before that, very noisy!
- If the region has not peaked, do not trust
- With $\alpha = .05$ (see robustness section for $\alpha = 0$)
South Carolina (7 days): Daily Deaths per Million People ($\alpha = .05$)

South Carolina

$R_0$=1.2/1.0/1.1 $\delta = 0.010$ $\alpha=0.05$ $\theta=0.1$ $\%$Infect= 6/7/12

DATA THROUGH 24-AUG-2020
South Carolina (7 days): Cumulative Deaths per Million (Future, $\alpha = 0.05$)

South Carolina

$R_0 = 1.2/1.0/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad %Infect = 6/7/12$

DATA THROUGH 24-AUG-2020
South Carolina (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = \frac{1}{2}/1.0/1.1$)

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deaths</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>16</td>
<td>32</td>
<td>64</td>
<td>128</td>
<td>256</td>
<td>512</td>
<td>1024</td>
<td>2048</td>
</tr>
</tbody>
</table>

New York City
Italy

$R_0 = 1.2/1.0/1.1$, $\delta = 0.010$, $\alpha = 0.05$, $\theta = 0.1$, $\%$ Infection $= 6/7/12$
Robustness to Mortality Rate, $\delta$
South Carolina: Cumulative Deaths per Million \( (\delta = 0.01/0.008/0.012) \)

South Carolina

\[ R_0 = 1.2/1.0/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 6/7/12 \]

DATA THROUGH 24-AUG-2020
South Carolina: Daily Deaths per Million People ($\delta = .01/.008/.012$)

South Carolina

$R_0 = 1.2/1.0/1.1$  \( \delta = 0.010 \)  \( \alpha = 0.05 \)  \( \theta = 0.1 \)  \%Infect= 6/7/12

DATA THROUGH 24-AUG-2020
South Carolina: Cumulative Deaths per Million ($\delta = \, .01/\,.008/\,.012$)

South Carolina

$R_0 = 1.2/1.0/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/7/12$

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people
Reopening and Herd Immunity

– **Black**: assumes $R_0(\text{today})$ remains in place forever
– **Red**: assumes $R_0(\text{suppress}) = 1/s(\text{today})$
– **Green**: we move 25% of the way from $R_0(\text{today})$ back to initial $R_0 = “normal”$
– **Purple**: we move 50% of the way from $R_0(\text{today})$ back to initial $R_0 = “normal”$

NOTE: Lines often cover each other up
South Carolina: Re-Opening ($\alpha = .05$)

South Carolina

$R_0(t)=1.0$, $R_0\text{(suppress)}=1.1$, $R_0(25/50)=1.3/1.5$, $\delta = 0.010$, $\alpha=0.05$
South Carolina: Re-Opening ($\alpha = 0$)

South Carolina

$R_0(t)=1.0, \ R_0(\text{suppress})=1.1, \ R_0(25/50)=1.3/1.5, \ \delta = 0.010, \ \alpha=0.00$
Results for alternative parameter values
South Carolina (7 days): Daily Deaths per Million People ($\alpha = 0$)

South Carolina

$R_0=1.2/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 6/7/9$

DATA THROUGH 24-AUG-2020
South Carolina (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

South Carolina

$R_0 = 1.2/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%$ Infect = 6/7/9

DATA THROUGH 24-AUG-2020
South Carolina (7 days): Cumulative Deaths per Million, Log Scale ($\alpha =$)

South Carolina
$R_0=1.2/1.0/1.0$ $\delta = 0.010$ $\alpha=0.00$ $\theta=0.1$ $\%$Infect$=6/7/9$
South Carolina: Daily Deaths per Million People ($\delta = 0.8\%$)

North Carolina

$R_0 = 1.2/1.1/1.2 \; \delta = 0.008 \; \theta = 0.1 \; \gamma = 0.2 \; \%\text{Infect} = 7/9/15$
South Carolina: Cumulative Deaths per Million ($\delta = 0.8\%$)

South Carolina

$R_0 = 1.2/1.1/1.2$  $\delta = 0.008$  $\theta=0.1$  $\gamma=0.2$  $\%$Infect= 7/9/15

Cumulative deaths per million people

Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  2020
South Carolina: Daily Deaths per Million People ($\delta = 1.2\%$)

South Carolina

$R_0 = 1.2/1.0/1.1 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 5/6/10$
South Carolina: Cumulative Deaths per Million ($\delta = 1.2\%$)

South Carolina

$R_0 = 1.2/1.0/1.1$  $\delta = 0.012$  $\theta=0.1$  $\gamma=0.2$  $\%Infect=5/6/10$
South Carolina: Daily Deaths per Million People ($\gamma = .2/.15$)

South Carolina

$R_0 = 1.2/1.0/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 6/7/12$

DATA THROUGH 24-AUG-2020

Daily deaths per million people

Apr      May      Jun      Jul      Aug      Sep      Oct      Nov      Dec      Jan

2020
South Carolina: Cumulative Deaths per Million $\gamma = 0.2/0.15$)

South Carolina

$R_0=1.2/1.0/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%Infect=6/7/12$

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people

Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  Jan

2020

$\gamma = 0.2/0.15$
South Carolina: Daily Deaths per Million People ($\theta = .1/.07/.2$)

South Carolina

$R_0 = 1.2/1.0/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/7/12$

DATA THROUGH 24-AUG-2020

Daily deaths per million people

Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  Jan  2020
South Carolina: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

South Carolina

$R_0 = 1.2/1.0/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect$ = 6/7/12$

DATA THROUGH 24-AUG-2020
Data Underlying Estimates of Time-Varying $R_0$

– Inferred from daily deaths, and
– the change in daily deaths, and
– the change in (the change in daily deaths)
South Carolina: Daily Deaths, Actual and Smoothed

South Carolina: Daily deaths, $d$

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
South Carolina: Change in Smoothed Daily Deaths

South Carolina: Delta $d$

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
South Carolina: Change in (Change in Smoothed Daily Deaths)

South Carolina: Delta (Δ = 0.010, θ = 0.10, γ = 0.20)

Graph showing the change in smoothed daily deaths from February to August 2020.