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

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Extended results for Georgia
Based on data through September 11, 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)
Georgia: Daily Deaths per Million People

Georgia

Daily deaths per million people

Apr May Jun Jul Aug Sep 2020

0 2 4 6 8 10 12
Georgia: Daily Deaths per Million People (Smoothed)

[Graph showing daily deaths per million people from April to September 2020, with a peak in August.]
### 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)
Georgia: Estimates of $R_0(t)$

Georgia

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$

Graph showing the estimates of $R_0(t)$ for Georgia from March to October 2020.
Georgia: Percent Currently Infectious

Georgia

Peak I/N = 0.34%  Final I/N = 0.23%  δ = 0.010  θ = 0.10  γ = 0.20
Georgia: Growth Rate of Daily Deaths over Past Week (percent)

Georgia
\( \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \)
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:

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

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

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

- Robustness: Assume $R_0(t) = \text{final empirical value}$. 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 $\alpha = 0$)
Georgia (7 days): Daily Deaths per Million People (α = .05)

Georgia

$R_0 = 1.6/0.8/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 6/7/8$

DATA THROUGH 11-SEP-2020
Georgia (7 days): Cumulative Deaths per Million (Future, $\alpha = .05$)

Georgia

$R_0=1.6/0.8/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%Infect= 6/7/8$

DATA THROUGH 11-SEP-2020

Cumulative deaths per million people

Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  2020
Georgia (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = .05$)

Georgia

$R_0=1.6/0.8/1.0 \, \delta = 0.010 \, \alpha=0.05 \, \theta=0.1 \, \%Infect= 6/7/8$
Robustness to Mortality Rate, $\delta$
Georgia: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

### Georgia

$R_0 = 1.6/0.8/1.0$  \hspace{1mm} $\delta = 0.010$  \hspace{1mm} $\alpha = 0.05$  \hspace{1mm} $\theta = 0.1$  \hspace{1mm} %Infect = 6/7/8

Data through 11-Sep-2020
Georgia: Daily Deaths per Million People ($\delta = 0.01/0.008/0.012$)

Georgia

$R_0 = 1.6/0.8/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%Infect= 6/7/8$

DATA THROUGH 11-SEP-2020
Georgia: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Georgia

$R_0 = 1.6/0.8/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect}= 6/7/8$

DATA THROUGH 11-SEP-2020

Cumulative deaths per million people

Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan 2020
Reopening and Herd Immunity

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

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

Georgia

$R_0(t)=0.8$, $R_0$ (suppress)=1.1, $R_0(25/50)=1.1/1.4$, $\delta = 0.010$, $\alpha=0.05$

(Light bars = New York City, for comparison)
Georgia: Re-Opening ($\alpha = 0$)

Georgia

$R_0(t)=0.8$, $R_0(\text{suppress})=1.1$, $R_0(25/50)=1.1/1.4$, $\delta = 0.010$, $\alpha=0.00$

(Light bars = New York City, for comparison)
Results for alternative parameter values
Georgia (7 days): Daily Deaths per Million People ($\alpha = 0$)

Georgia

$R_0 = 1.6/0.8/0.8 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infected} = 6/7/7$

DATA THROUGH 11-SEP-2020
Georgia (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

Georgia

$R_0 = 1.6/0.8/0.8 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 6/7/7$

DATA THROUGH 11-SEP-2020
Georgia (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

Georgia

$R_0 = 1.6/0.8/0.8 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \% \text{Infect} = 6/7/7$
Georgia: Daily Deaths per Million People ($\delta = 0.8\%$)

R$_0$ = 1.6/0.9/1.1  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  %Infect = 8/9/9
Georgia: Cumulative Deaths per Million ($\delta = 0.8\%$)

Georgia

$R_0 = 1.6/0.9/1.1 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 8/9/9$
Georgia: Daily Deaths per Million People ($\delta = 1.2\%$)

Georgia

$R_0 = 1.6/0.8/1.0 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect}= 5/6/6$
Georgia: Cumulative Deaths per Million ($\delta = 1.2\%$)

Georgia

$R_0=1.6/0.8/1.0 \; \delta = 0.012 \; \theta=0.1 \; \gamma=0.2 \; \%Infect= 5/6/6$
Georgia: Daily Deaths per Million People ($\gamma = 0.2/0.15$)

Georgia

$R_0 = 1.6/0.8/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect $= 6/7/8$

DATA THROUGH 11-SEP-2020
Georgia: Cumulative Deaths per Million $\gamma = .2/.15$)

Georgia

$R_0 = 1.6/0.8/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%\text{Infected} = 6/7/8$

DATA THROUGH 11-SEP-2020

Cumulative deaths per million people

Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan 2020
Georgia: Daily Deaths per Million People ($\theta = 1/0.07/0.2$)

**Georgia**

$R_0 = 1.6/0.8/1.0$ \hspace{1em} $\delta = 0.010$ \hspace{1em} $\alpha = 0.05$ \hspace{1em} $\theta = 0.1$ \hspace{1em} %Infect = 6/7/8

DATA THROUGH 11-SEP-2020
Georgia: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

R$_0$=1.6/0.8/1.0  $\delta=0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 6/7/8

DATA THROUGH 11-SEP-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)
Georgia: Daily Deaths, Actual and Smoothed

Georgia: Daily deaths, d
\( \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \)
Georgia: Change in Smoothed Daily Deaths

Georgia: Delta d
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Georgia: Change in (Change in Smoothed Daily Deaths)

Georgia: Delta (Delta d)
\[ \delta = 0.010 \quad \theta=0.10 \quad \gamma=0.20 \]