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

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Extended results for Brazil
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)
Brazil: Daily Deaths per Million People
Brazil: 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>$\ldots$</td>
<td>Initial base reproduction rate</td>
</tr>
<tr>
<td>$R_0(t)$</td>
<td>$\ldots$</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)
Brazil: Estimates of $R_0(t)$

\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Brazil: Percent Currently Infectious

Peak I/N = 0.25%   Final I/N = 0.16%   δ=0.010   θ=0.10   γ=0.20
Brazil: Growth Rate of Daily Deaths over Past Week (percent)

\[
\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20
\]
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:

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

\[\Rightarrow \alpha \approx 0.05\]

$R_0$ 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 $\alpha = 0$)
Brazil (7 days): Daily Deaths per Million People ($\alpha = .05$)

Brazil

$R_0 = 1.3/0.9/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $%\text{Infect} = 6/7/8$

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

Brazil

$R_0 = 1.3/0.9/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect $= 6/7/8$

DATA THROUGH 11-SEP-2020
Brazil (7 days): Cumulative Deaths per Million, Log Scale (α = .05)

Brazil

$R_0 = 1.3 / 0.9 / 1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/7/8$

Cumulative deaths per million people

New York City

Italy

Robustness to Mortality Rate, $\delta$
Brazil: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Brazil

$R_0=1.3/0.9/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 6/7/8

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

Brazil

$R_0 = 1.3/0.9/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect $= 6/7/8$

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

Brazil

$R_0=1.3/0.9/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%Infect=6/7/8$
Reopening and Herd Immunity

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

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

Brazil

$R_0(t)=0.9, \ R_0(\text{suppress})=1.1, \ R_0(25/50)=1.2/1.5, \ \delta = 0.010, \ \alpha=0.05$

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

Brazil

$R_0(t)=0.9, \ R_0({\text{suppress}})=1.1, \ R_0(25/50)=1.2/1.4, \ \delta = 0.010, \ \alpha=0.00$

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

Brazil

$R_0 = 1.3/0.9/0.9 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 6/7/7$

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

Brazil

$R_0=1.3/0.9/0.9$  $\delta = 0.010$  $\alpha=0.00$  $\theta=0.1$  %Infect= 6/ 7/ 7

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

Brazil

$R_0 = 1.3/0.9/0.9$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  %Infect = 6/7/7

New York City

Italy

Cumulative deaths per million people

Brazil: Daily Deaths per Million People ($\delta = 0.8\%$)

Brazil

$R_0 = 1.3/0.9/1.1 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 8/9/10$
Brazil: Cumulative Deaths per Million ($\delta = 0.8\%$)

Brazil

$R_0 = 1.3/0.9/1.1$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect = 8/9/10
Brazil: Daily Deaths per Million People ($\delta = 1.2\%$)

Brazil

$R_0 = 1.3/0.9/1.0 ~ \delta = 0.012 ~ \theta = 0.1 ~ \gamma = 0.2 ~ \text{%Infect} = 5/6/6$
Brazil: Cumulative Deaths per Million ($\delta = 1.2\%$)

Brazil

$R_0=1.3/0.9/1.0$  $\delta = 0.012$  $\theta=0.1$  $\gamma=0.2$  $\%$Infect= 5/ 6/ 6
Brazil: Daily Deaths per Million People ($\gamma = .2/.15$)

Brazil

$R_0 = 1.3/0.9/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/7/8$

DATA THROUGH 11-SEP-2020
Brazil: Cumulative Deaths per Million $\gamma = 0.2/0.15$

Brazil

$R_0 = 1.3/0.9/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infected = 6/7/8

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

Brazil

$R_0 = 1.3/0.9/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/7/8$

DATA THROUGH 11-SEP-2020
Brazil: Cumulative Deaths per Million People ($\theta = 0.1 / 0.07 / 0.2$)

Brazil

$R_0 = 1.3 / 0.9 / 1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$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)
Brazil: Daily Deaths, Actual and Smoothed

Brazil: Daily deaths, $d$

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

Brazil: Delta $d$

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

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