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

Jesús Fernández-Villaverde and Chad Jones

Extended results for Dominican Republic
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 \((\delta = 1.0\%, \quad \gamma = 0.2, \quad \theta = 0.1)\)
- Simulation of re-opening – possibilities for raising \(R_0\)
- Results with alternative parameter values:
  - Lower mortality rate, \(\delta = 0.8\%\)
  - Higher mortality rate, \(\delta = 1.2\%\)
  - Infections last longer, \(\gamma = 0.15\)
  - Cases resolve more quickly, \(\theta = 0.2\)
  - 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)
Dominican Republic: 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)
Dominican Republic: Estimates of $R_0(t)$

Dominican Republic

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
Dominican Republic: Percent Currently Infectious

Dominican Republic
Peak I/N = 0.11%  Final I/N = 0.11%  δ = 0.010  θ = 0.10  γ = 0.20
Dominican Republic: 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:
  - 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 $\alpha = 0$)
Dominican Republic (7 days): Daily Deaths per Million People ($\alpha = .05$)

**Dominican Republic**

$R_0 = 1.2/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $%\text{Infect} = 2/3/4$

DATA THROUGH 11-SEP-2020
Dominican Republic (7 days): Cumulative Deaths per Million (Future, α)

Dominican Republic

$R_0 = 1.2/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 2/3/4$

DATA THROUGH 11-SEP-2020

Cumulative deaths per million people

Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan 2020
Dominican Republic (7 days): Cumulative Deaths per Million, Log Scale

Dominican Republic

$R_0 = 1.2/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 2/3/4$
Robustness to Mortality Rate, $\delta$
Dominican Republic: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

Dominican Republic

$R_0 = 1.2/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect$ = 2/3/4$

DATA THROUGH 11-SEP-2020
Dominican Republic: Daily Deaths per Million People ($\delta = 0.01/0.008/0.012$)

Dominican Republic

$R_0 = 1.2/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 2/3/4

DATA THROUGH 11-SEP-2020
Dominican Republic: Cumulative Deaths per Million ($\delta = .01/0.008/0.012$)

Dominican Republic

$R_0=1.2/1.0/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 2/3/4

DATA THROUGH 11-SEP-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
Dominican Republic: Re-Opening ($\alpha = .05$)

Dominican Republic

$R_0(t) = 1.0$, $R_0(\text{suppress}) = 1.0$, $R_0(25/50) = 1.2/1.5$, $\delta = 0.010$, $\alpha = 0.05$

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

Dominican Republic

\[ R_0(t)=1.0, \ R_0(\text{suppress})=1.0, \ R_0(25/50)=1.3/1.5, \ \delta = 0.010, \ \alpha=0.00 \]

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

Dominican Republic

$R_0 = 1.2/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 2/3/4$

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

<table>
<thead>
<tr>
<th>Cumulative deaths per million people</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

Dominican Republic

$R_0 = 1.2/1.0/1.0 \ \delta = 0.010 \ \alpha = 0.00 \ \theta = 0.1 \ \%Infect = 2/3/4$

DATA THROUGH 11-SEP-2020
Dominican Republic (7 days): Cumulative Deaths per Million, Log Scale

Dominican Republic

$R_0 = 1.2/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 2/3/4$
Dominican Republic: Daily Deaths per Million People ($\delta = 0.8\%$)

Dominican Republic

$R_0 = 1.2/1.0/1.0$ \hspace{1em} $\delta = 0.008$ \hspace{1em} $\theta = 0.1$ \hspace{1em} $\gamma = 0.2$ \hspace{1em} $\%\text{Infect} = 3/3/5$
Dominican Republic: Cumulative Deaths per Million (δ = 0.8%)
Dominican Republic: Daily Deaths per Million People ($\delta = 1.2\%$)

Dominican Republic

$R_0 = 1.2/1.0/1.0$  \  $\delta = 0.012$  \  $\theta = 0.1$  \  $\gamma = 0.2$  \  %Infect = 2/2/3
Dominican Republic: Cumulative Deaths per Million ($\delta = 1.2\%$)

Dominican Republic

$R_0=1.2/1.0/1.0$  \( \delta = 0.012 \)  \( \theta=0.1 \)  \( \gamma=0.2 \)  \%Infect= 2/2/3
Dominican Republic: Daily Deaths per Million People ($\gamma = .2/.15$)

Dominican Republic

$R_0 = 1.2/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%\text{Infect} = 2/3/4$

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

Dominican Republic

$R_0=1.2/1.0/1.0$ $\delta = 0.010$ $\alpha=0.05$ $\theta=0.1$ \%Infect= 2/3/4

DATA THROUGH 11-SEP-2020

Cumulative deaths per million people

Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

2020
Dominican Republic: Daily Deaths per Million People ($\theta = .1 / .07 / .2$)

Dominican Republic

$R_0 = 1.2/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%Infect = 2/3/4$

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

Dominican Republic

$R_0=1.2/1.0/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 2/ 3/ 4

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)
Dominican Republic: Daily Deaths, Actual and Smoothed

Dominican Republic: Daily deaths, $d$

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

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

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