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

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Extended results for Belize
Based on data through October 9, 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)
Belize: Daily Deaths per Million People

- May
- Jun
- Jul
- Aug
- Sep
- Oct 2020

Daily deaths per million people

Belize
Belize: 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)
Belize: Estimates of $R_0(t)$

Belize

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

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

$$\Rightarrow \alpha \approx .05$$

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

Belize

$R_0 = 1.4/1.2/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%\text{Infect} = 1/3/14$

DATA THROUGH 09-OCT-2020
Belize (7 days): Cumulative Deaths per Million (Future, $\alpha = .05$)

DATA THROUGH 09-OCT-2020

Belize

$R_0 = 1.4/1.2/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 1/3/14
Belize (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0.05$)

$R_0 = 1.4/1.2/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/3/14$
Robustness to Mortality Rate, $\delta$
Belize: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

R$_0 = 1.4/1.2/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 1/3/14

DATA THROUGH 09-OCT-2020
Belize: Daily Deaths per Million People \((\delta = .01/.008/.012)\)

\[ R_0 = 1.4/1.2/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/3/14 \]

DATA THROUGH 09-OCT-2020
Belize: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Belize

$R_0=1.4/1.2/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 1/3/14

DATA THROUGH 09-OCT-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 $R_0 = \text{“normal”}$
– 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
Belize: Re-Opening ($\alpha = 0.05$)

Belize

$R_0(t)=1.2$, $R_0\text{(suppress)}=1.0$, $R_0(25/50)=1.4/1.6$, $\delta = 0.010$, $\alpha=0.05$

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

Belize

$R_0(t)=1.3, \ R_0(\text{suppress})=1.1, \ R_0(25/50)=1.5/1.6, \ \delta = 0.010, \ \alpha=0.00$

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

Belize

$R_0 = 1.4/1.3/1.3$  \(\delta = 0.010\)  \(\alpha = 0.00\)  \(\theta = 0.1\)  \%Infect = 1/5/40

DATA THROUGH 09-OCT-2020
Belize (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

DATA THROUGH 09-OCT-2020

\[ R_0 = 1.4/1.3/1.3 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 1/5/40 \]
Belize (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

Belize

$R_0 = 1.4/1.3/1.3 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 1/5/40$

New York City

Italy
Belize: Daily Deaths per Million People \((\delta = 0.8\%)\)

\[ R_0 = 1.4/1.2/1.2 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \% \text{Infect} = 2/4/16 \]
Belize: Cumulative Deaths per Million ($\delta = 0.8\%$)

Belize

$R_0 = 1.4/1.2/1.2$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%$ Infect = 2/4/16
Belize: Cumulative Deaths per Million ($\delta = 1.2\%$)

Belize

$R_0 = 1.4/1.2/1.1$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  %Infect = 1/3/12
Belize: Daily Deaths per Million People ($\gamma = .2/.15$)

DATA THROUGH 09-OCT-2020
Belize: Cumulative Deaths per Million $\gamma = .2/.15$)

Belize

$R_0=1.4/1.2/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect$=1/3/14$

$\gamma = 0.15$

$\gamma = 0.2$

DATA THROUGH 09-OCT-2020

Cumulative deaths per million people

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

R$_0$=1.4/1.2/1.1  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 1/3/14

DATA THROUGH 09-OCT-2020
Belize: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

Belize $R_0=1.4/1.2/1.1$, $\delta = 0.010$, $\alpha=0.05$, $\theta=0.1$, %Infect$=1/3/14$

DATA THROUGH 09-OCT-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)
Belize: Daily Deaths, Actual and Smoothed

Belize: Daily deaths, d

\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Belize: Change in Smoothed Daily Deaths

Belize: Delta $d$

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

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