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

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Extended results for El Salvador
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:
  - 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)
El Salvador: Daily Deaths per Million People

El Salvador
El Salvador: 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)
El Salvador: Estimates of $R_0(t)$

El Salvador

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
El Salvador: Percent Currently Infectious

El Salvador
Peak I/N = 0.08%  Final I/N = 0.04%  $\delta=0.010$  $\theta=0.10$  $\gamma=0.20$
El Salvador: Growth Rate of Daily Deaths over Past Week (percent)

El Salvador

\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Notes on Interpreting Results
Guided 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 $R_0(t) =$ 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 $\alpha = 0$)
El Salvador (7 days): Daily Deaths per Million People ($\alpha = 0.05$)

El Salvador

$R_0 = 1.4/0.8/0.9$, $\delta = 0.010$, $\alpha = 0.05$, $\theta = 0.1$, $\%$ Infect = 1/1/1

DATA THROUGH 11-SEP-2020
El Salvador (7 days): Cumulative Deaths per Million (Future, $\alpha = 0.05$)

El Salvador

$R_0=1.4/0.8/0.9 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}= 1/1/1$

DATA THROUGH 11-SEP-2020
El Salvador (7 days): Cumulative Deaths per Million, Log Scale \( (\alpha = .05) \)

\[ R_0 = 1.4/0.8/0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1 \]
Robustness to Mortality Rate, $\delta$
El Salvador: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

El Salvador

$R_0 = 1.4/0.8/0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1$

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

El Salvador

$R_0 = 1.4/0.8/0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1$

DATA THROUGH 11-SEP-2020
El Salvador: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

El Salvador

$R_0 = 1.4/0.8/0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1$

DATA THROUGH 11-SEP-2020

Cumulative deaths per million people


$\delta = 0.008$
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
El Salvador: Re-Opening ($\alpha = .05$)

El Salvador

$R_0(t)$=0.8, $R_0$ (suppress)=1.0, $R_0(25/50)$=1.1/1.4, $\delta = 0.010$, $\alpha=0.05$

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

El Salvador

$R_0(t)=0.8,$  $R_0(\text{suppress})=1.0,$  $R_0(25/50)=1.1/1.4,$  $\delta = 0.010,$  $\alpha=0.00$
Results for alternative parameter values
El Salvador (7 days): Daily Deaths per Million People ($\alpha = 0$)

El Salvador

$R_0=1.4/0.8/0.8 \; \delta = 0.010 \; \alpha=0.00 \; \theta=0.1 \; \%\text{Infect}= 1/ 1/ 1$

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

El Salvador

$R_0 = 1.4/0.8/0.8$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%$Infect = 1/1/1

Data through 11-Sep-2020
El Salvador (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

El Salvador

$R_0 = 1.4/0.8/0.8 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1$

New York City

Italy
El Salvador: Daily Deaths per Million People ($\delta = 0.8\%$)

El Salvador

$R_0=1.4/0.8/0.9 \quad \delta = 0.008 \quad \theta=0.1 \quad \gamma=0.2 \quad \%\text{Infect} = 1/2/2$
El Salvador: Cumulative Deaths per Million ($\delta = 0.8\%$)

El Salvador

$R_0 = 1.4/0.8/0.9$ $\delta = 0.008$ $\theta = 0.1$ $\gamma = 0.2$ %Infect = 1/2/2
El Salvador: Daily Deaths per Million People ($\delta = 1.2\%$)

El Salvador

$R_0 = 1.4/0.8/0.9$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect = 1/1/1
El Salvador: Cumulative Deaths per Million ($\delta = 1.2\%$)

El Salvador

$R_0 = 1.4/0.8/0.9$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $\%$ Infect = 1/1/1
El Salvador: Daily Deaths per Million People ($\gamma = .2 / .15$)

El Salvador

$R_0 = 1.4 / 0.8 / 0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1 / 1 / 1$

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

DATA THROUGH 11-SEP-2020

El Salvador

$R_0=1.4/0.8/0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad %\text{Infect}= 1/1/1$

$\gamma = 0.25$
El Salvador: Daily Deaths per Million People ($\theta = .1/.07/.2$)

Data through 11-Sep-2020

$R_0=1.4/0.8/0.9$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect= 1/1/1
El Salvador: Cumulative Deaths per Million People ($\theta = .1 / .07 / .2$)

El Salvador

$R_0 = 1.4/0.8/0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1$

DATA THROUGH 11-SEP-2020

Cumulative deaths per million people
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)
El Salvador: Daily Deaths, Actual and Smoothed

El Salvador: Daily deaths, $d$

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

El Salvador: Delta $d$

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

El Salvador: Delta (Δd)

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