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

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Extended results for Sao Tome and Principe
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:
  - 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)
Sao Tome and Principe: 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)
Sao Tome and Principe: Estimates of $R_0(t)$

Sao Tome and Principe

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
Sao Tome and Principe: Percent Currently Infectious

Sao Tome and Principe
Peak I/N = 0.12%  Final I/N = 0.06%  \(\delta = 0.010\)  \(\theta = 0.10\)  \(\gamma = 0.20\)
Sao Tome and Principe: Growth Rate of Daily Deaths over Past Week

Sao Tome and Principe

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

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

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

$R_0$ 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 $\alpha = 0$)
Sao Tome and Principe (7 days): Daily Deaths per Million People ($\alpha = \ldots$)

**Sao Tome and Principe**

$R_0 = 1.5/0.2/0.2$  
$\delta = 0.010$  
$\alpha = 0.05$  
$\theta = 0.1$  
$%\text{Infect} = 1/1/1$

DATA THROUGH 09-OCT-2020
Sao Tome and Principe (7 days): Cumulative Deaths per Million (Future)

Sao Tome and Principe

$R_0=1.5/0.2/0.2 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}= 1/1/1$

DATA THROUGH 09-OCT-2020
Sao Tome and Principe (7 days): Cumulative Deaths per Million, Log Scale

\[ R_0 = 1.5/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1 \]
Robustness to Mortality Rate, $\delta$
Sao Tome and Principe: Cumulative Deaths per Million \( (\delta = .01/0.008/0.012) \)

Sao Tome and Principe

\[ R_0 = 1.5/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 1/1/1 \]

DATA THROUGH 09-OCT-2020
Sao Tome and Principe: Daily Deaths per Million People ($\delta = .01/.008/.012$)

Sao Tome and Principe

$R_0=1.5/0.2/0.2$ \hspace{1em} $\delta = 0.010$ \hspace{1em} $\alpha=0.05$ \hspace{1em} $\theta=0.1$ \hspace{1em} $\%$Infect$=1/1/1$

DATA THROUGH 09-OCT-2020
Sao Tome and Principe: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

Sao Tome and Principe

$R_0=1.5/0.2/0.2$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 1/ 1/ 1

DATA THROUGH 09-OCT-2020

Cumulative deaths per million people

Reopening and Herd Immunity

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

NOTE: Lines often cover each other up
Sao Tome and Principe: Re-Opening ($\alpha = .05$)

Sao Tome and Principe

$R_0(t)=0.2, \ R_0\ (suppress)=1.0, \ R_0(25/50)=0.7/1.1, \ \delta = 0.010, \ \alpha=0.05$

(Light bars = New York City, for comparison)
Sao Tome and Principe: Re-Opening ($\alpha = 0$)

Sao Tome and Principe

$R_0(t) = 0.2$, $R_0$ (suppress) = 1.0, $R_0(25/50) = 0.7/1.1$, $\delta = 0.010$, $\alpha = 0.00$

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

DATA THROUGH 09-OCT-2020

Sao Tome and Principe

$R_0=1.5/0.2/0.2 \quad \delta = 0.010 \quad \alpha=0.00 \quad \theta=0.1 \quad %Infect=1/1/1$
Sao Tome and Principe (7 days): Cumulative Deaths per Million (Future)

Sao Tome and Principe

$R_0=1.5/0.2/0.2$  $\delta = 0.010$  $\alpha=0.00$  $\theta=0.1$  $\%$Infect= 1/ 1/ 1

DATA THROUGH 09-OCT-2020
Sao Tome and Principe (7 days): Cumulative Deaths per Million, Log Scale

Sao Tome and Principe

$R_0 = 1.5/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1$

New York City

Italy

Cumulative deaths per million people

Sao Tome and Principe: Daily Deaths per Million People (\(\delta = 0.8\%\))

Sao Tome and Principe

\(R_0 = 1.5/0.2/0.2\)  \(\delta = 0.008\)  \(\theta = 0.1\)  \(\gamma = 0.2\)  \(\%\text{Infect} = 1/1/1\)

SOME ERRORS IN ESTIMATION...
Sao Tome and Principe: Cumulative Deaths per Million ($\delta = 0.8\%$)

Sao Tome and Principe

$R_0 = 1.5/0.2/0.2$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%\text{Infect} = 1/1/1$

SOME ERRORS IN ESTIMATION...
Sao Tome and Principe: Daily Deaths per Million People ($\delta = 1.2\%$)

Sao Tome and Principe

$R_0 = 1.5/0.2/0.2 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 1/1/1$

SOME ERRORS IN ESTIMATION...
Sao Tome and Principe: Cumulative Deaths per Million ($\delta = 1.2\%$)

Sao Tome and Principe

$R_0=1.5/0.2/0.2$  $\delta = 0.012$  $\theta=0.1$  $\gamma=0.2$  $\%Infect= 1/ 1/ 1$

SOME ERRORS IN ESTIMATION...
Sao Tome and Principe: Daily Deaths per Million People ($\gamma = .2/.15$)

Sao Tome and Principe

$R_0 = 1.5/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1$

DATA THROUGH 09-OCT-2020
Sao Tome and Principe: Cumulative Deaths per Million $\gamma = .2/1.5$)

$\gamma = 0.15, 0.2$

Sao Tome and Principe

$R_0 = 1.5/0.2/0.2$, $\delta = 0.010$, $\alpha = 0.05$, $\theta = 0.1$, $\%\text{Infect} = 1/1/1$

DATA THROUGH 09-OCT-2020
Sao Tome and Principe: Daily Deaths per Million People ($\theta = .1/.07/.2$)

Sao Tome and Principe

$R_0=1.5/0.2/0.2 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}= 1/1/1$

DATA THROUGH 09-OCT-2020
Sao Tome and Principe: Cumulative Deaths per Million People $(\theta = .1)$

Sao Tome and Principe

$R_0=1.5/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1$

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)
Sao Tome and Principe: Daily Deaths, Actual and Smoothed

Sao Tome and Principe: Daily deaths, \( d \)

\[ \delta = 0.010 \quad \theta=0.10 \quad \gamma=0.20 \]
Sao Tome and Principe: Change in Smoothed Daily Deaths

Sao Tome and Principe: Delta $d$

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
Sao Tome and Principe: Change in (Change in Smoothed Daily Deaths)

Sao Tome and Principe: Delta (Delta d)

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