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

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Extended results for Cabo Verde
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)
Cabo Verde: Daily Deaths per Million People

Cabo Verde

Daily deaths per million people

Apr May Jun Jul Aug Sep

2020

0 1 2 3 4 5

Cabo Verde
Cabo Verde: 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>
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</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)
Cabo Verde: Estimates of $R_0(t)$

Cabo Verde

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
Cabo Verde: Percent Currently Infectious

Cabo Verde
Peak I/N = 0.08%  Final I/N = 0.03%  δ = 0.010  θ = 0.10  γ = 0.20
Cabo Verde: Growth Rate of Daily Deaths over Past Week (percent)

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

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

   \[\Rightarrow \alpha \approx 0.05\]

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

Cabo Verde

$R_0=1.4/1.0/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 1/ 1/ 2

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

R$_0$=1.4/1.0/1.0  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 1/ 1/ 2

DATA THROUGH 11-SEP-2020
Cabo Verde (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0.05$)

Cabo Verde
$R_0 = 1.4/1.0/1.0$, $\delta = 0.010$, $\alpha = 0.05$, $\theta = 0.1$, %Infect = 1/1/2

New York City
Italy
Robustness to Mortality Rate, $\delta$
Cabo Verde: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Cabo Verde

$R_0 = 1.4/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%\text{Infect} = 1/1/2$

DATA THROUGH 11-SEP-2020

Cumulative deaths per million people

2020
Cabo Verde: Daily Deaths per Million People ($\delta = 0.01/0.008/0.012$)

Cabo Verde

$R_0=1.4/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/2$

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

Cabo Verde

$R_0=1.4/1.0/1.0 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=1/1/2$

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

Cabo Verde

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

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

Cabo Verde

$R_0(t)=1.0$, $R_0(\text{suppress})=1.0$, $R_0(25/50)=1.2/1.5$, $\delta = 0.010$, $\alpha=0.00$

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

R$_0$=1.4/1.0/1.0  $\delta = 0.010$  $\alpha=0.00$  $\theta=0.1$  %Infect= 1/1/2

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

Cabo Verde  
$R_0 = 1.4/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%\text{Infect} = 1/1/2$

<table>
<thead>
<tr>
<th>Month</th>
<th>Cumulative Deaths per Million People</th>
</tr>
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<tbody>
<tr>
<td>Jun 2020</td>
<td>0</td>
</tr>
<tr>
<td>Jul 2020</td>
<td>0</td>
</tr>
<tr>
<td>Aug 2020</td>
<td>0</td>
</tr>
<tr>
<td>Sep 2020</td>
<td>0</td>
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<tr>
<td>Oct 2020</td>
<td>0</td>
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<tr>
<td>Nov 2020</td>
<td>0</td>
</tr>
<tr>
<td>Dec 2020</td>
<td>0</td>
</tr>
<tr>
<td>Jan 2021</td>
<td>0</td>
</tr>
<tr>
<td>Feb 2021</td>
<td>0</td>
</tr>
<tr>
<td>Mar 2021</td>
<td>0</td>
</tr>
<tr>
<td>Apr 2021</td>
<td>0</td>
</tr>
</tbody>
</table>

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

Cabo Verde

$R_0 = 1.4/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/2$
Cabo Verde: Daily Deaths per Million People \((\delta = 0.8\%)\)

Cabo Verde

\(R_0=1.4/1.0/1.0\) \(\delta = 0.008\) \(\theta=0.1\) \(\gamma=0.2\) \(\%\text{Infect}=1/1/2\)
Cabo Verde: Cumulative Deaths per Million ($\delta = 0.8\%$)

Cabo Verde

$R_0 = 1.4/1.0/1.0$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $%\text{Infect} = 1/1/2$
Cabo Verde: Daily Deaths per Million People ($\delta = 1.2\%$)

Cabo Verde

$R_0=1.4/1.0/1.0$  $\delta = 0.012$  $\theta=0.1$  $\gamma=0.2$  $\%Infect= 1/ 1/ 1$
Cabo Verde: Cumulative Deaths per Million ($\delta = 1.2\%$)

Cabo Verde
$R_0 = 1.4/1.0/1.0$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  %Infect = 1/1/1
Cabo Verde: Daily Deaths per Million People ($\gamma = .2 / .15$)

Cabo Verde

$R_0 = 1.4/1.0/1.0$  $\delta = 0.010$  $\theta = 0.1$  $\gamma = 0.2$  $\%\text{Infect} = 1/1/2$
Cabo Verde: Cumulative Deaths per Million $\gamma = .2/.15$)

Cabo Verde
$R_0=1.4/1.0/1.0$  $\delta = 0.010$  $\theta=0.1$  $\gamma=0.2$  $\%Infect= 1/ 1/ 2$
Cabo Verde: Daily Deaths per Million People ($\theta = .1/.07/.2$)

Cabo Verde

$R_0=1.4/1.0/1.0$  $\delta = 0.010$  $\theta=0.2$  $\gamma=0.2$  $\%$Infect= 1/ 1/ 2
Cabo Verde: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

Cabo Verde

$R_0=1.4/1.0/1.0$  $\delta = 0.010$  $\theta=0.2$  $\gamma=0.2$  %Infect= 1/ 1/ 2
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)
Cabo Verde: Daily Deaths, Actual and Smoothed

Cabo Verde: Daily deaths, d
\( \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \)
Cabo Verde: Change in Smoothed Daily Deaths

Cabo Verde: Delta $d$

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

Cabo Verde: Delta (Delta d)
δ = 0.010  θ=0.10  γ=0.20