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

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Extended results for Ecuador
Based on data through August 24, 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)
Ecuador: Daily Deaths per Million People

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

Ecuador

$\delta = 0.010 \hspace{0.5cm} \theta = 0.10 \hspace{0.5cm} \gamma = 0.20$
Ecuador: Percent Currently Infectious

Peak I/N = 0.34%  Final I/N = 0.08%  δ = 0.010  θ = 0.10  γ = 0.20
Ecuador: 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:

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

  $\Rightarrow \alpha \approx 0.05$

  $R_0$ 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 $\alpha = 0$)
Ecuador (7 days): Daily Deaths per Million People ($\alpha = 0.05$)

$R_0 = 1.2/1.3/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 4/5/9

DATA THROUGH 24-AUG-2020
Ecuador (7 days): Cumulative Deaths per Million (Future, $\alpha = .05$)

$R_0=1.2/1.3/1.1 \ \delta = 0.010 \ \alpha=0.05 \ \theta=0.1 \ \%Infect= 4/5/9$

DATA THROUGH 24-AUG-2020
Ecuador (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = .05$)

Ecuador

$R_0 = 1.2/1.3/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%\text{Infect} = 4/5/9$

New York City

Italy
Robustness to Mortality Rate, $\delta$
Ecuador: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

$R_0 = 1.2/1.3/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect}= 4/5/9$

DATA THROUGH 24-AUG-2020
Ecuador: Daily Deaths per Million People ($\delta = 0.01/0.008/0.012$)

Ecuador

$R_0 = 1.2/1.3/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect = 4/5/9

DATA THROUGH 24-AUG-2020
Ecuador: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Ecuador

$R_0 = 1.2/1.3/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect $= 4/5/9$

DATA THROUGH 24-AUG-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
Ecuador: Re-Opening ($\alpha = 0.05$)

Ecuador

$R_0(t)=1.3, \ R_0(\text{suppress})=1.1, \ R_0(25/50)=1.5/1.6, \ \delta = 0.010, \ \alpha=0.05$
Ecuador: Re-Opening ($\alpha = 0$)

Ecuador
$R_0(t) = 1.3$, $R_0(\text{suppress}) = 1.1$, $R_0(25/50) = 1.5/1.6$, $\delta = 0.010$, $\alpha = 0.00$
Results for alternative parameter values
Ecuador (7 days): Daily Deaths per Million People ($\alpha = 0$)

Ecuador

$R_0 = 1.2/1.3/1.3$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $%\text{Infect} = 4/6/32$

DATA THROUGH 24-AUG-2020
Ecuador (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

Ecuador

$R_0=1.2/1.3/1.3 \ \delta = 0.010 \ \alpha=0.00 \ \theta=0.1 \ \%Infect=4/6/32$

DATA THROUGH 24-AUG-2020
Ecuador (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

Ecuador

$R_0 = 1.2/1.3/1.3$, $\delta = 0.010$, $\alpha = 0.00$, $\theta = 0.1$, %Infect = 4/6/32

New York City

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

\[ R_0 = 1.2/1.3/1.1 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \% \text{Infect} = 5/6/12 \]
Ecuador: Cumulative Deaths per Million ($\delta = 0.8\%$)

Ecuador

$R_0 = 1.2/1.3/1.1$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%$ Infect = 5/6/12
Ecuador: Daily Deaths per Million People ($\delta = 1.2\%$)

Ecuador

$R_0 = 1.2/1.3/1.1$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $\%$ Infection $= 3/4/8$
Ecuador: Cumulative Deaths per Million ($\delta = 1.2\%$)

Ecuador

$R_0 = 1.2/1.3/1.1$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  %Infect = 3/ 4/ 8
Ecuador: Daily Deaths per Million People ($\gamma = .2/.15$)

Ecuador

$R_0=1.2/1.3/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect= 4/5/9

DATA THROUGH 24-AUG-2020
Ecuador: Cumulative Deaths per Million $\gamma = .2/.15$)

Ecuador

$R_0 = 1.2/1.3/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect $= 4/5/9$

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people

Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  Jan

2020

$\gamma = 0.15$

$\gamma = 0.2$
Ecuador: Daily Deaths per Million People ($\theta = 0.1/0.07/0.2$)

Ecuador

$R_0 = 1.2/1.3/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 4/5/9$

DATA THROUGH 24-AUG-2020
Ecuador: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

DATA THROUGH 24-AUG-2020

Ecuador

$R_0 = 1.2/1.3/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 4/5/9$

$\theta = 0.1$

$\theta = 0.2$

$\theta = 0.07$
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)
Ecuador: Daily Deaths, Actual and Smoothed

Ecuador: Daily deaths, d
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Ecuador: Change in Smoothed Daily Deaths

Ecuador: Delta $d$

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

Ecuador: Delta (Δd)

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