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

Jesús Fernández-Villaverde and Chad Jones

Extended results for Monaco
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:
  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)
Monaco: Daily Deaths per Million People

Monaco

Daily deaths per million people

2020
Monaco: 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 $t \left( \frac{\beta_t}{\gamma} \right)$</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)
Monaco: Estimates of $R_0(t)$

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

Peak I/N = 0.29%  Final I/N = 0.15%  \( \delta = 0.010 \)  \( \theta = 0.10 \)  \( \gamma = 0.20 \)
Monaco: Growth Rate of Daily Deaths over Past Week (percent)

Monaco
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
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:
  - 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 $\alpha = 0$)
Monaco (7 days): Daily Deaths per Million People ($\alpha = .05$)

Monaco

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

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

Monaco

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

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

Monaco

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

New York City

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

Monaco

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

DATA THROUGH 24-AUG-2020
Monaco: Daily Deaths per Million People ($\delta = \frac{1}{12}/\frac{1}{8}/\frac{1}{12}$)

Monaco

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

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

Monaco

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

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people

Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  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 $R_0 = “normal”$
– Purple: we move 50% of the way from $R_0(today)$ back to initial $R_0 = “normal”$

NOTE: Lines often cover each other up
Monaco: Re-Opening ($\alpha = .05$)

Monaco

$R_0(t)=0.2$, $R_0(\text{suppress})=1.0$, $R_0(25/50)=0.7/1.1$, $\delta = 0.010$, $\alpha=0.05$
Monaco: Re-Opening ($\alpha = 0$)

Monaco
$R_0(t)=0.2$, $R_0^{\text{suppress}}=1.0$, $R_0^{(25/50)}=0.7/1.1$, $\delta = 0.010$, $\alpha=0.00$
Results for alternative parameter values
Monaco (7 days): Daily Deaths per Million People ($\alpha = 0$)

Monaco

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

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

Monaco

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

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

Monaco

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

New York City

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

Monaco

$R_0 = 1.5/0.2/0.2 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 2/2/2$

SOME ERRORS IN ESTIMATION...
Monaco: Cumulative Deaths per Million ($\delta = 0.8\%$)

Monaco

$R_0 = 1.5/0.2/0.2$  \( \delta = 0.008 \)  \( \theta = 0.1 \)  \( \gamma = 0.2 \)  \% Infect = 2/2/2

SOME ERRORS IN ESTIMATION...
Monaco: Daily Deaths per Million People ($\delta = 1.2\%$)

Monaco

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

SOME ERRORS IN ESTIMATION...
Monaco: Cumulative Deaths per Million ($\delta = 1.2\%$)

Monaco

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

SOME ERRORS IN ESTIMATION...
Monaco: Daily Deaths per Million People ($\gamma = 0.2 / 0.15$)

Monaco

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

DATA THROUGH 24-AUG-2020
Monaco: Cumulative Deaths per Million $\gamma = 0.2/0.15$

Monaco

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

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people

Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  Jan

2020

$\gamma = 0.15$

$\gamma = 0.2$
Monaco: Daily Deaths per Million People ($\theta = .1/.07/.2$)

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

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

DATA THROUGH 24-AUG-2020

Monaco

$R_0=1.5/0.2/0.2$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$ Infect $= 1/1/1$  $\theta = 0.07$

$\theta = 0.1$

$\theta = 0.2$
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)
Monaco: Daily Deaths, Actual and Smoothed

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

Monaco: Delta d
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Monaco: Change in (Change in Smoothed Daily Deaths)

Monaco: Delta (Delta d)

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