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

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

Monaco

Daily deaths per million people

Apr May Jun Jul Aug Sep

-80 -60 -40 -20 0 20 40 60

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 $t$ ($\beta_t/\gamma$)</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)
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%   δ = 0.010   θ = 0.10   γ = 0.20
Monaco: 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:

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

     $\Rightarrow \alpha \approx .05$

     $R_0$ 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 ($\alpha = 0.05$)

\[ R_0 = 1.5/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1 \]
Monaco (7 days): Cumulative Deaths per Million (Future, $\alpha = .05$)

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

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

R$_0$=1.5/0.2/0.2 $\delta = 0.010$ $\alpha=0.05$ $\theta=0.1$ %Infect= 1/ 1/ 1

Cumulative deaths per million people

Monaco

New York City

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

Monaco

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

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

Monaco

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

DATA THROUGH 11-SEP-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 11-SEP-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

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

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

Monaco

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

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

Monaco

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

DATA THROUGH 11-SEP-2020

Monaco
Monaco (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

Monaco

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

DATA THROUGH 11-SEP-2020

Cumulative deaths per million people

Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan 2020
Monaco (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

Monaco

$R_0 = 1.5/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 1/1/1$
Monaco: Daily Deaths per Million People ($\delta = 0.8\%$)

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

SOME ERRORS IN ESTIMATION...
Monaco: 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

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

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

DATA THROUGH 11-SEP-2020

Monaco

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

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Monaco: Cumulative Deaths per Million $\gamma = .2/.15$)

Monaco

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

$\gamma = 0.15$

$\gamma = 0.2$

DATA THROUGH 11-SEP-2020

Cumulative deaths per million people
Monaco: Daily Deaths per Million People ($\theta = .1/.07/.2$)

Monaco

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

DATA THROUGH 11-SEP-2020
Monaco: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

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

DATA THROUGH 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)
Monaco: Daily Deaths, Actual and Smoothed

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

Monaco: Delta (Δd)

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