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

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Extended results for San Marino
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)
San Marino: Daily Deaths per Million People

San Marino
San Marino: 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)
San Marino: Estimates of $R_0(t)$

San Marino

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

San Marino
Peak I/N = 2.47%  Final I/N = 0.28%  δ = 0.010  θ = 0.10  χ = 0.20
San Marino: Growth Rate of Daily Deaths over Past Week (percent)

San Marino
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
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:

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

     $\Rightarrow \alpha \approx .05$

     \[R_0 \text{ declines by 5 percent for each new daily death, or rises by 5 percent when daily deaths decline}\]

- 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 $\alpha = 0$)
San Marino (7 days): Daily Deaths per Million People ($\alpha = .05$)

San Marino

$R_0 = 2.3/0.5/0.5 \: \delta = 0.010 \: \alpha = 0.05 \: \theta = 0.1 \: \%\text{Infect} = 13/13/13$

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

San Marino

$R_0=2.3/0.5/0.5$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%\text{Infect}=13/13/13$

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

San Marino

$R_0 = 2.3/0.5/0.5$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%\text{Infect} = 13/13/13$
Robustness to Mortality Rate, $\delta$
San Marino: Cumulative Deaths per Million ($\delta = 0.01 / 0.008 / 0.012$)

San Marino

$R_0 = 2.3/0.5/0.5 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 13/13/13$

DATA THROUGH 24-AUG-2020
San Marino: Daily Deaths per Million People ($\delta = .01/.008/.012$)

San Marino

$R_0 = 2.3/0.5/0.5$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect=13/13/13

DATA THROUGH 24-AUG-2020
San Marino: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

San Marino

$R_0 = 2.3/0.5/0.5 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% InFect = 13/13/13$

DATA THROUGH 24-AUG-2020

$\delta = 0.008$
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
San Marino: Re-Opening \((\alpha = .05)\)

San Marino

\[ R_0(t)=0.5, \quad R_0(\text{suppress})=1.1, \quad R_0(25/50)=0.9/1.4, \quad \delta = 0.010, \quad \alpha=0.05 \]
San Marino: Re-Opening ($\alpha = 0$)

San Marino

$R_0(t)=0.2$, $R_0(\text{suppress})=1.1$, $R_0(25/50)=0.7/1.2$, $\delta = 0.010$, $\alpha=0.00$
Results for alternative parameter values
San Marino (7 days): Daily Deaths per Million People ($\alpha = 0$)

San Marino

$R_0=2.3/0.2/0.2$  $\delta = 0.010$  $\alpha=0.00$  $\theta=0.1$  $\%\text{Infected}=13/13/13$

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

San Marino

$R_0 = 2.3/0.2/0.2$  $\delta = 0.010$  $\alpha=0.00$  $\theta=0.1$  $\%Infect=13/13/13$

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

San Marino

$R_0=2.3/0.2/0.2$  $\delta = 0.010$  $\alpha=0.00$  $\theta=0.1$  %Infect=13/13/13
San Marino: Daily Deaths per Million People ($\delta = 0.8\%$)

San Marino

$R_0 = 2.3/0.5/0.5 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 16/16/16$

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

San Marino

$R_0 = 2.3/0.5/0.5 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect}=16/16/16$

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

San Marino
$R_0=2.3/0.4/0.4$  $\delta = 0.012$  $\theta=0.1$  $\gamma=0.2$  $\%\text{Infect}=11/11/11$

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

San Marino

$R_0=2.3/0.4/0.4$  $\delta = 0.012$  $\theta=0.1$  $\gamma=0.2$  $\%Infect=11/11/11$

SOME ERRORS IN ESTIMATION...
San Marino: Daily Deaths per Million People ($\gamma = .2/.15$)

San Marino

$R_0 = 2.3/0.5/0.5 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 13/13/13$

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

San Marino

$R_0 = 2.3/0.5/0.5$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $%\text{Infect}=13/13/13$

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

San Marino

$R_0 = 2.3/0.5/0.5$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%Infect = 13/13/13$

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

San Marino
$R_0=2.3/0.5/0.5$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect=13/13/13

DATA THROUGH 24-AUG-2020

$\theta = 0.07$
$\theta = 0.1$
$\theta = 0.2$
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)
San Marino: Change in Smoothed Daily Deaths

San Marino: Delta $d$

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

San Marino: Delta (Delta d)
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]