Update to Analysis & Projections of the COVID-19 Pandemic

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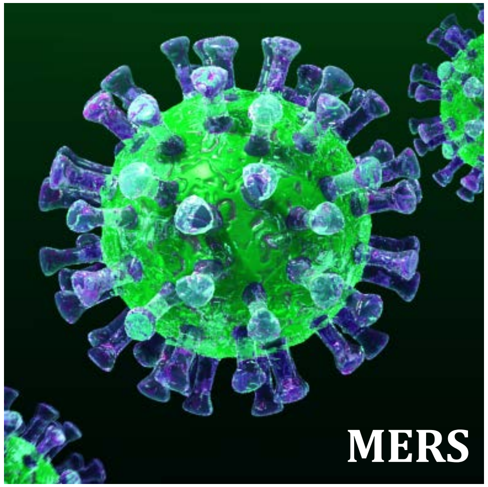
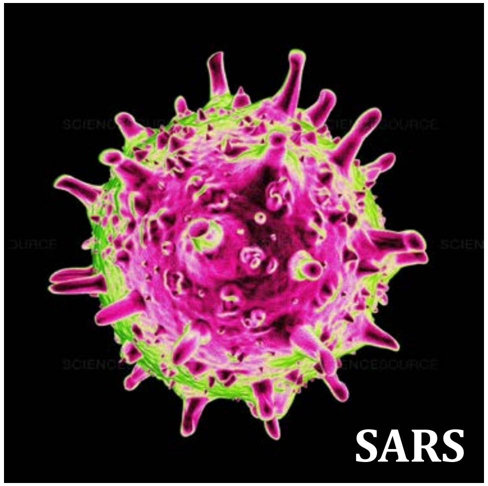
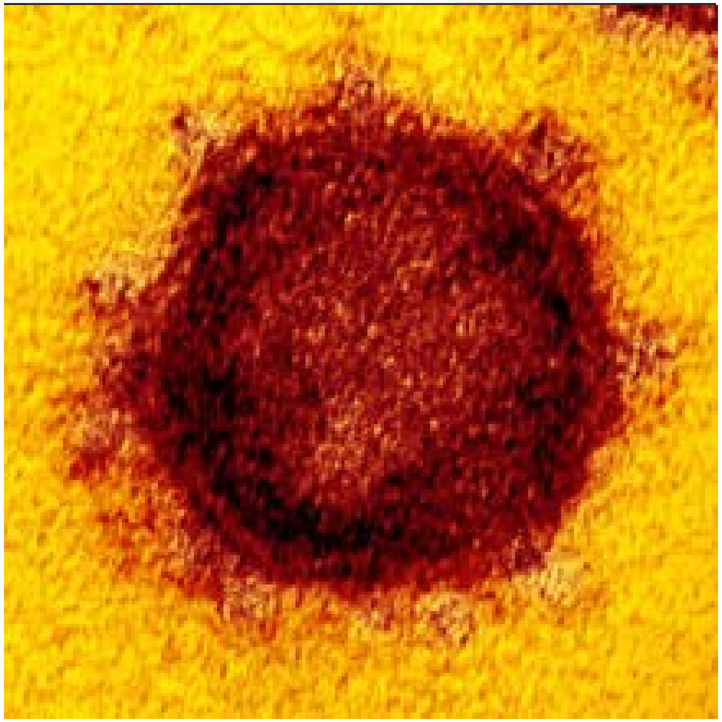
March 14, 2020







COVID-19

Outline

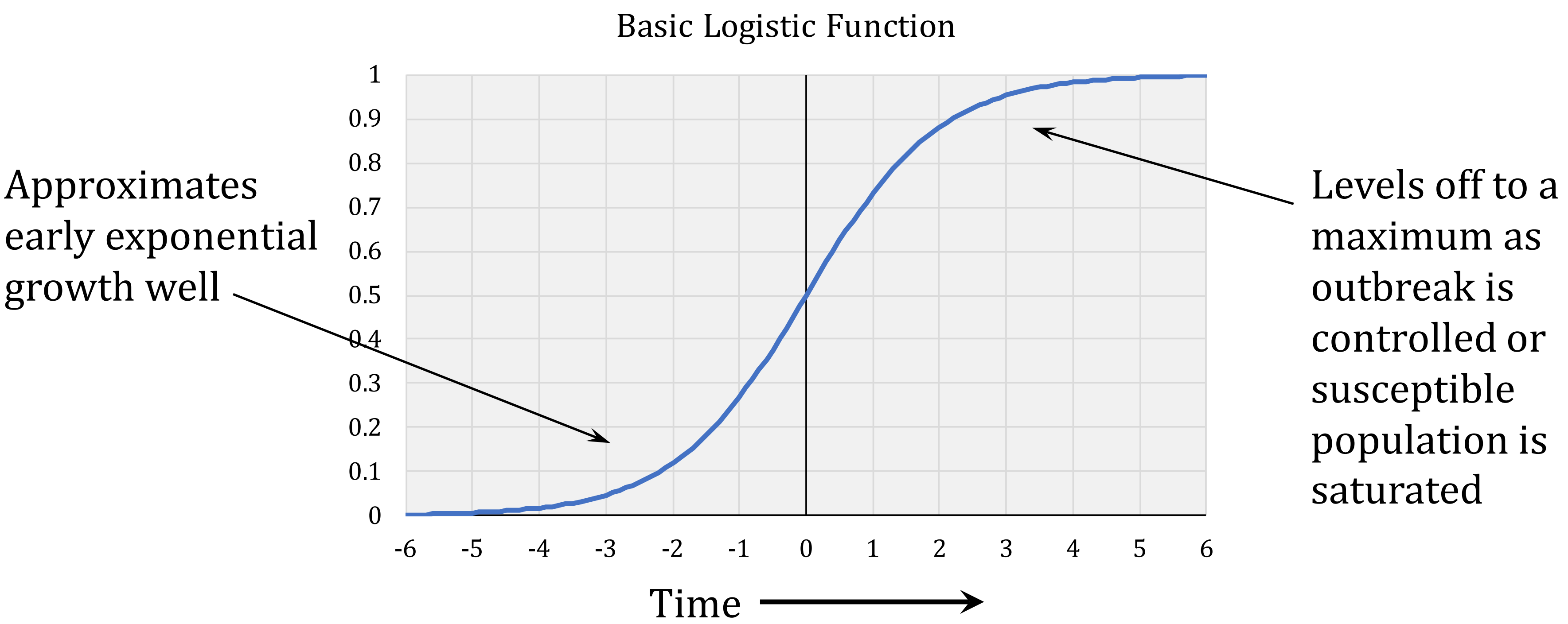
- Introduction to the outbreak & logistic model
- Results of global models for cases & deaths
- Selected individual country models
- Fatality rate estimates
- Conclusions (not really, conclusions is an overstatement)
- Appendix on the math

COVID-19 Analysis

- Outbreak began in December in Wuhan China
- Characteristics believed to be
  - Easier to spread than SARS & MERS
  - Less fatal than SARS & MERS
- Data collected from government reports, John Hopkins and Worldometer data aggregation web sites.
- Based on these data, can we estimate:
  - When will the outbreak be controlled?
  - How many outbreaks are there?
  - How many will be afflicted?
  - What is the fatality rate?
- Approach – develop and fit logistic models to the outbreak data

Logistic Function

- The most general form is: $y = \dfrac{1}{1 + e^{-x}}$

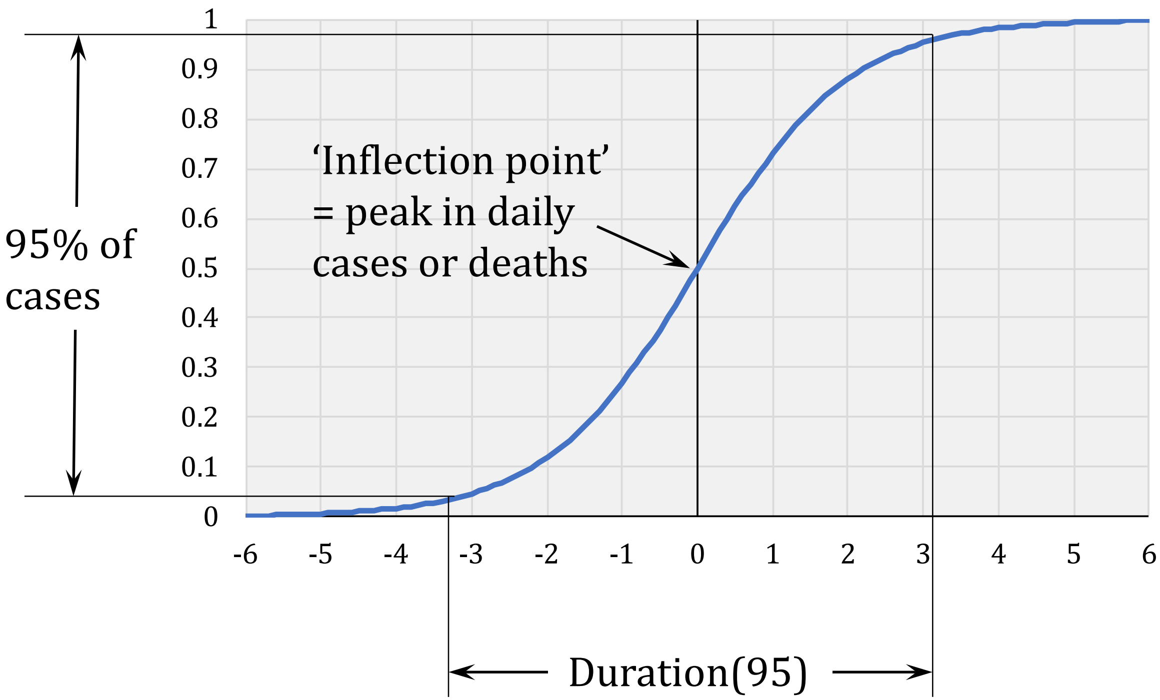


- Useful in modeling disease outbreaks; the form used in this analysis is:

$$N(t) = \frac{N_0}{1 + \delta e^{kt^{\lambda}}}$$

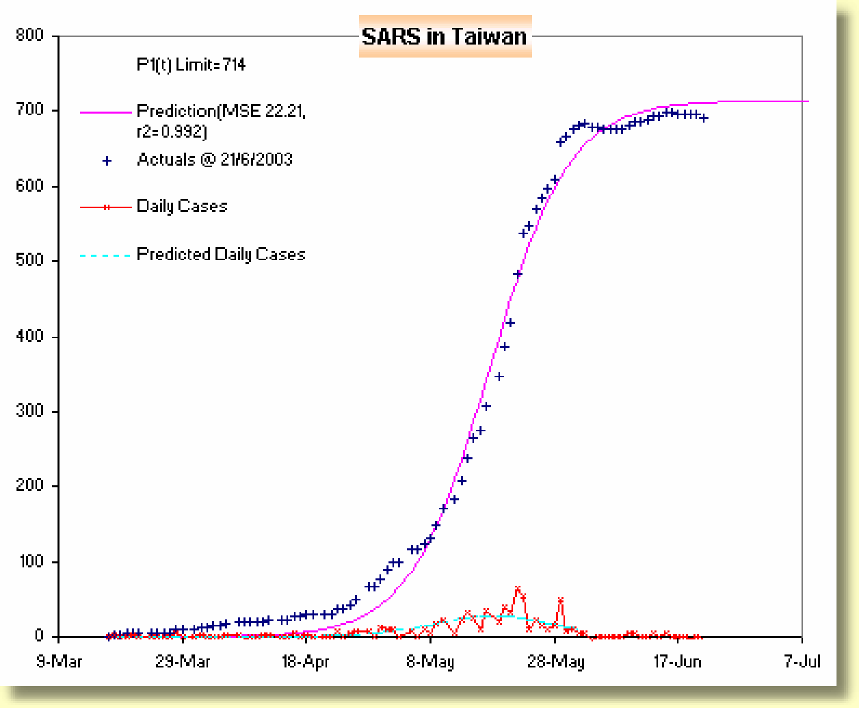
Duration(95)

- The calculated model output of duration(95) is the time predicted to transpire over the development of the central 95% of cases. It is an estimate of the duration of the 'main' part of the outbreak.



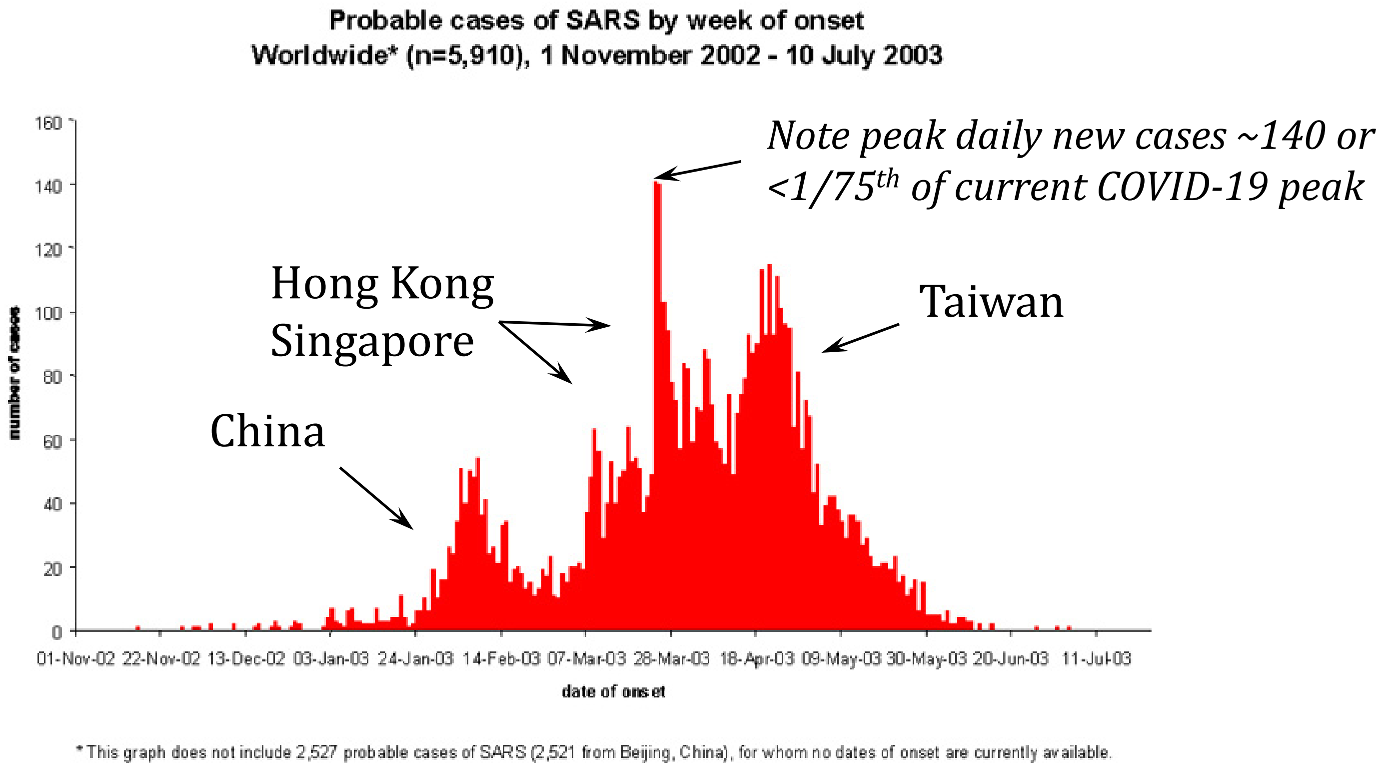
- Useful in comparing outbreaks; however, it is very uncertain before inflection of the curve (0 on this graph)

Logistic Modeling of Taiwan SARS Outbreak



- Reasonably good model of the progression of SARS in Taiwan in 2003
- Logistic model fits cumulative data; its derivative with respect to time estimates daily data
- Note that during the SARS outbreak in Taiwan, it took about 60 days to grow to 700 cases – compare to COVID-19, where Italy had growth of over 2,500 new cases *yesterday*

Daily Data, Global SARS Outbreak

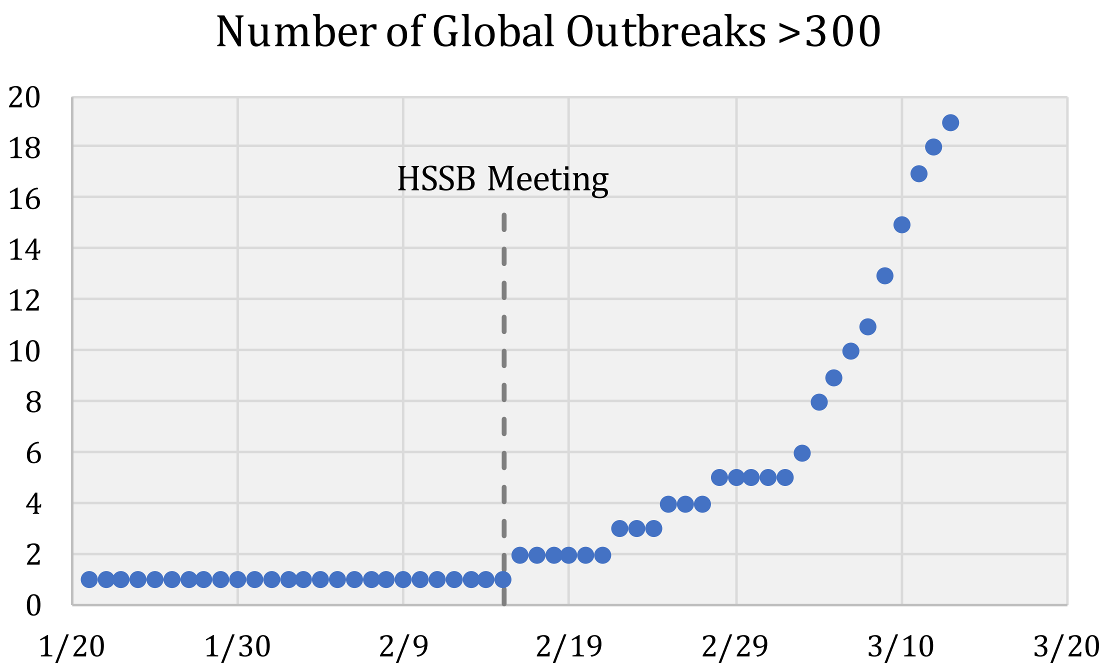


- Multiple outbreaks, each of which can be represented with a logistic model

COVID-19 Modeling

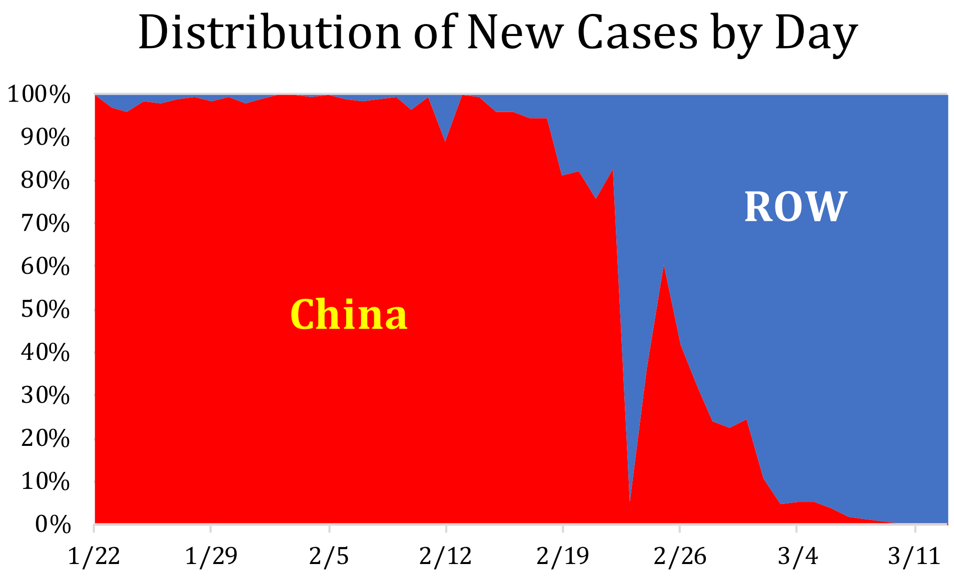
- Laboratory and Clinically Diagnosed Data issues
  - On February 12th, Hubei province changed the definition of a 'case' of COVID-19 to include both clinically-diagnosed (CD) and laboratory-diagnosed (LD) cases. Previously only LD cases were included. This created a single-day surge of >14,000 new cases, many of which were identified in earlier periods.
  - On February 14th, Hubei province announced that they had double-counted some cases and removed ~1000 cases and ~100 deaths to correct the error
- In order to have a consistent data set over time, only LD data are modeled

Remember When There Was Just One?



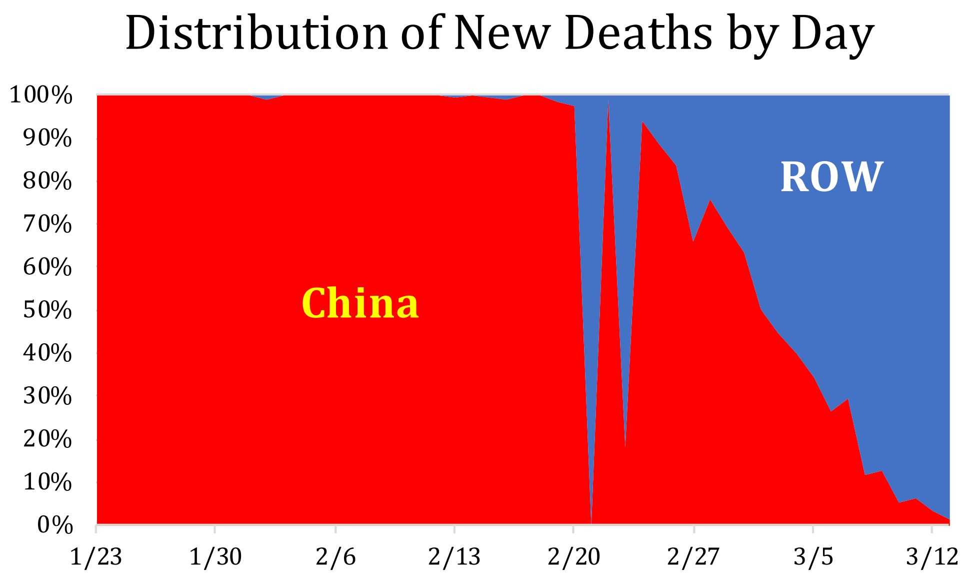
Outbreaks:
- China
- Diamond Princess
- Korea
- Italy
- Iran
- France
- Japan
- Germany
- US
- Spain
- Switzerland
- UK
- Netherlands
- Sweden
- Norway
- Denmark
- Belgium
- Austria
- Qatar

- There are 19 outbreaks with over 300 identified cases as of 3/13.
- 4 weeks ago, there was *one*

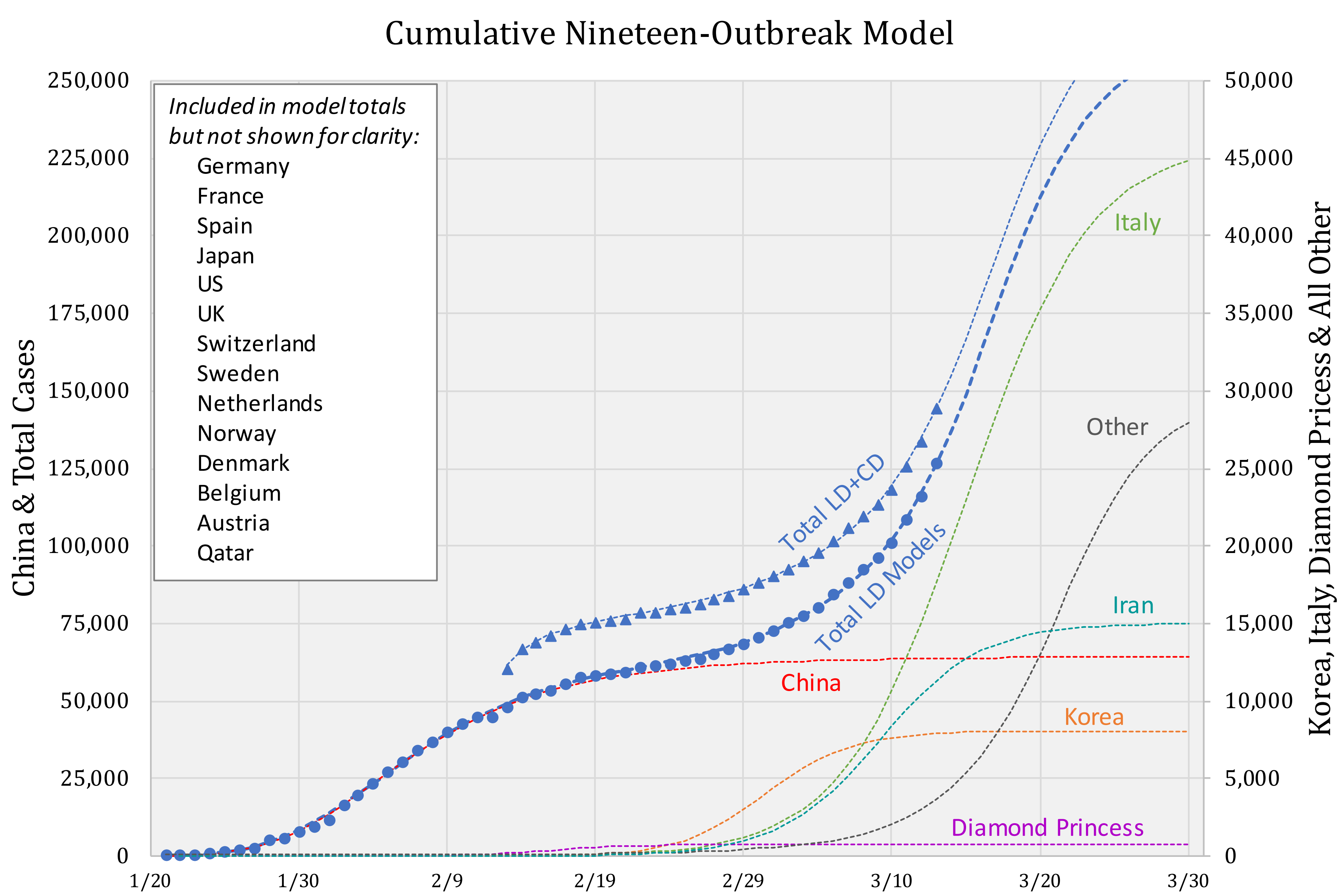


Since 3/1, >90% of the new cases each day have occurred outside of China

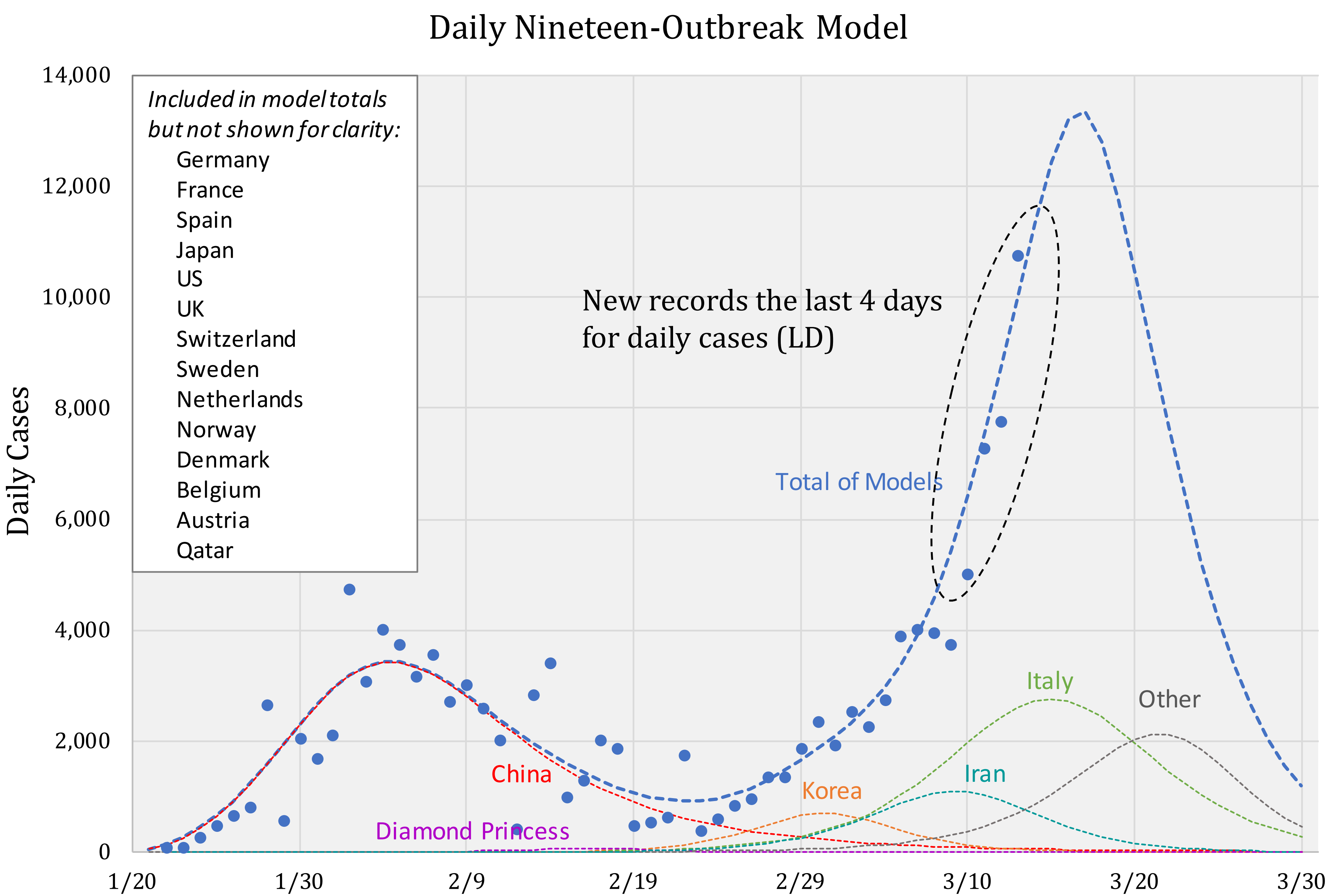
ROW = Rest of World



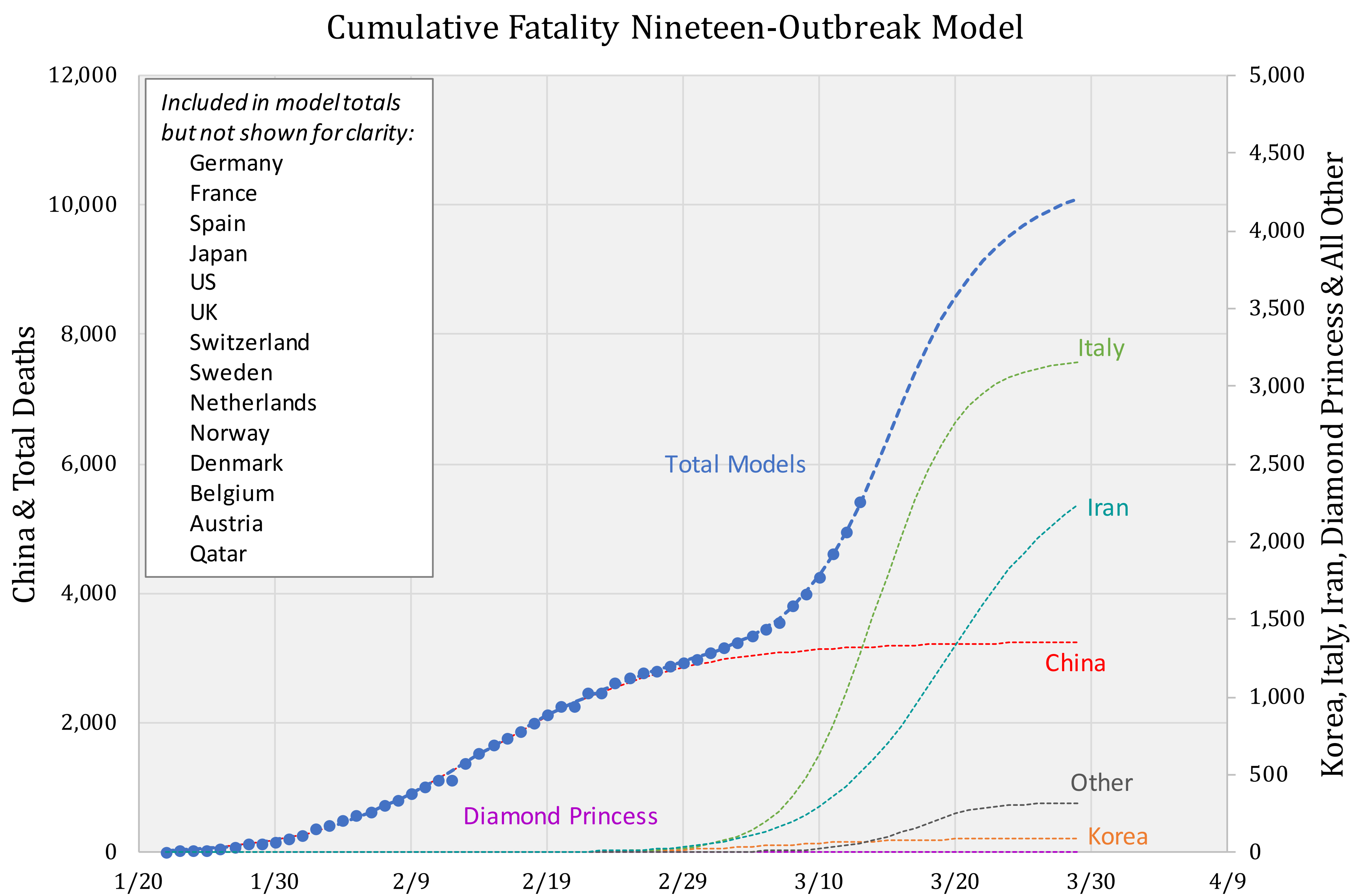
Since 3/9, >90% of the new deaths each day have occurred outside of China



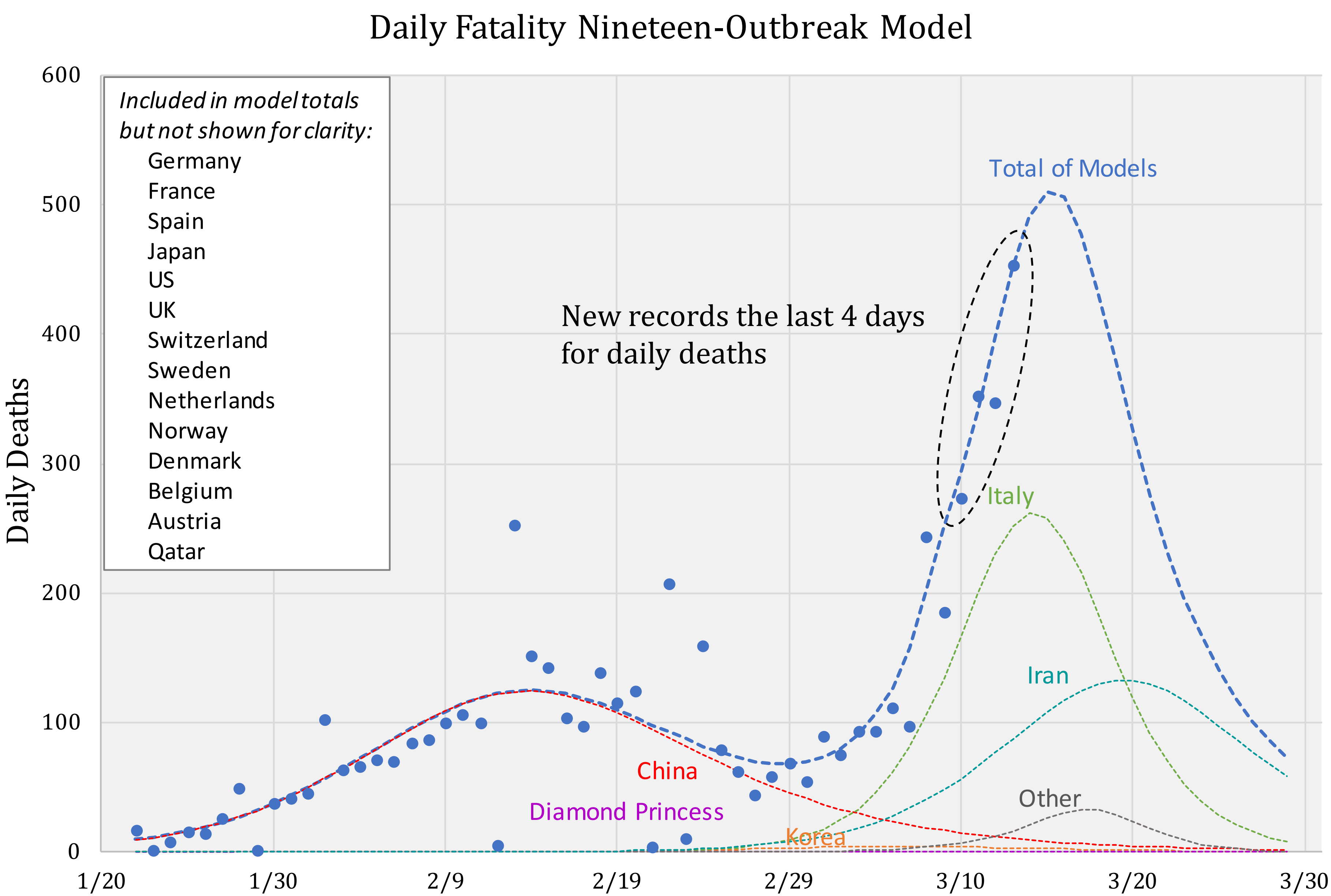
Cumulative Nineteen-Outbreak Model
China & Total Cases
Korea, Italy, Diamond Pricess & All Other
250,000
225,000
200,000
175,000
150,000
125,000
100,000
75,000
50,000
25,000
0
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
1/20
1/30
2/9
2/19
2/29
3/10
3/20
3/30
Included in model totals but not shown for clarity:
Germany
France
Spain
Japan
US
UK
Switzerland
Sweden
Netherlands
Norway
Denmark
Belgium
Austria
Qatar
Total LD+CD
Total LD Models
Italy
Other
Iran
China
Korea
Diamond Princess



Daily Nineteen-Outbreak Model
Daily Cases
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1/20
1/30
2/9
2/19
2/29
3/10
3/20
3/30
Included in model totals
but not shown for clarity:
Germany
France
Spain
Japan
US
UK
Switzerland
Sweden
Netherlands
Norway
Denmark
Belgium
Austria
Qatar
New records the last 4 days
for daily cases (LD)
Total of Models
Italy
Other
Iran
Korea
China
Diamond Princess



Cumulative Fatality Nineteen-Outbreak Model
Included in model totals but not shown for clarity:
Germany
France
Spain
Japan
US
UK
Switzerland
Sweden
Netherlands
Norway
Denmark
Belgium
Austria
Qatar
Total Models
Italy
Iran
China
Other
Korea
Diamond Princess
China & Total Deaths
Korea, Italy, Iran, Diamond Princess & All Other
0
2,000
4,000
6,000
8,000
10,000
12,000
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
1/20
1/30
2/9
2/19
2/29
3/10
3/20
3/30
4/9

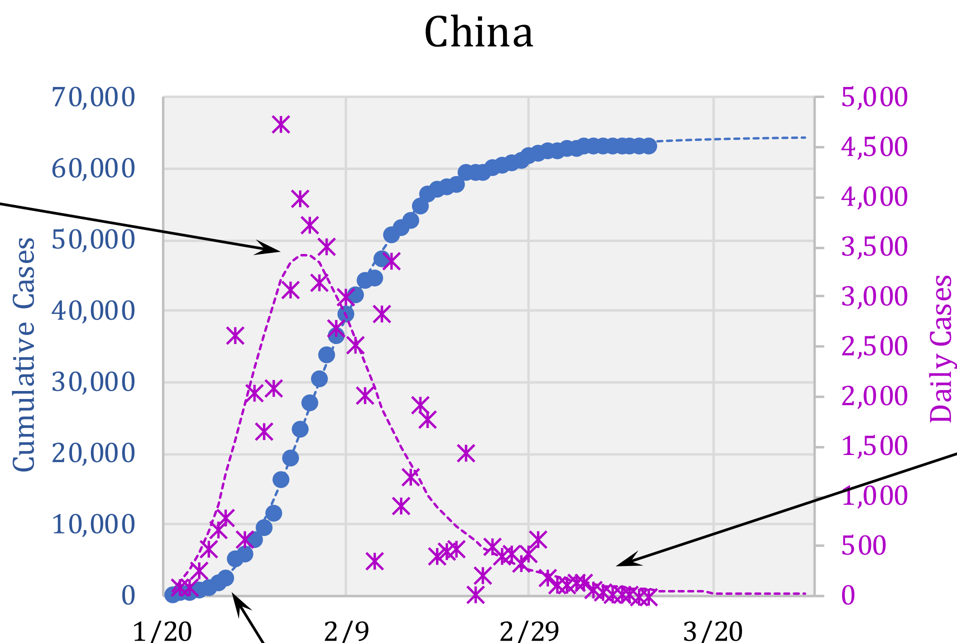


Daily Fatality Nineteen-Outbreak Model
Daily Deaths
600
500
400
300
200
100
0
1/20
1/30
2/9
2/19
2/29
3/10
3/20
3/30
Included in model totals
but not shown for clarity:
Germany
France
Spain
Japan
US
UK
Switzerland
Sweden
Netherlands
Norway
Denmark
Belgium
Austria
Qatar
Total of Models
New records the last 4 days
for daily deaths
Italy
Iran
China
Diamond Princess
Korea
Other

China Model – What Can We Learn…

- Settling out a little above where predicted last month (~64k)
- Peak – 2/5/2020
- Duration(95) – 39 days

Peak in daily cases ~2/5 or 12 days after shutdown



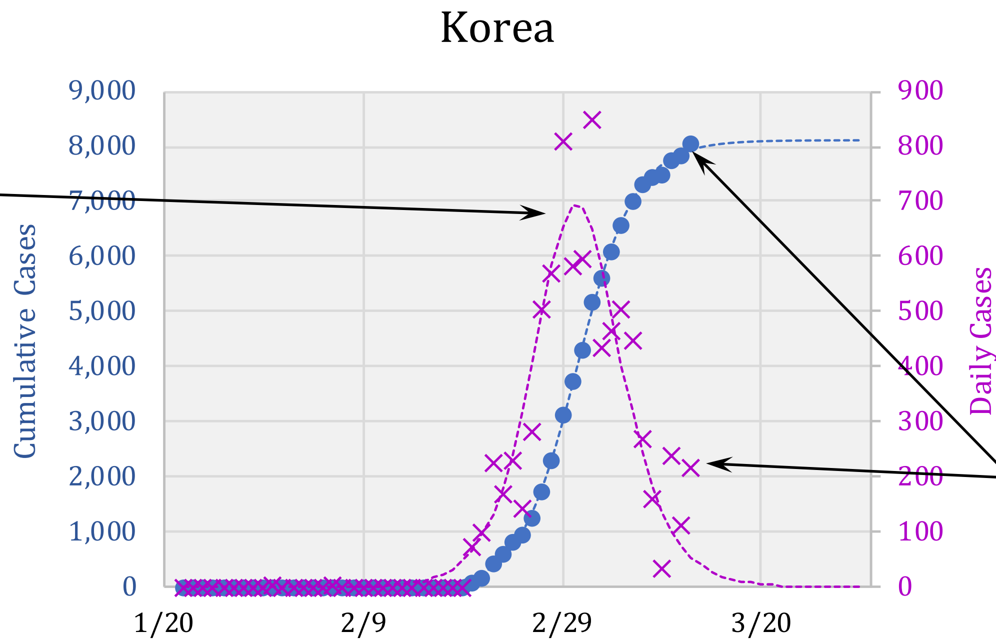
Long 'tail' on daily cases; growth continues to slow but not stop. This asymmetry is why (λ) is needed in the model. For China, $\lambda \approx 0.2$ vs. symmetry if $\lambda = 1$

Wuhan city & Hubei province shut down and isolated ~1/23-24 at 500-1000 identified cases

Korea Model

- Predicted total cases: 8-9k
- Peak – 3/2/2020
- Duration(95) – 21 days

No society-wide lockdown; focus on exhaustive testing and case-tracking appears to be successful

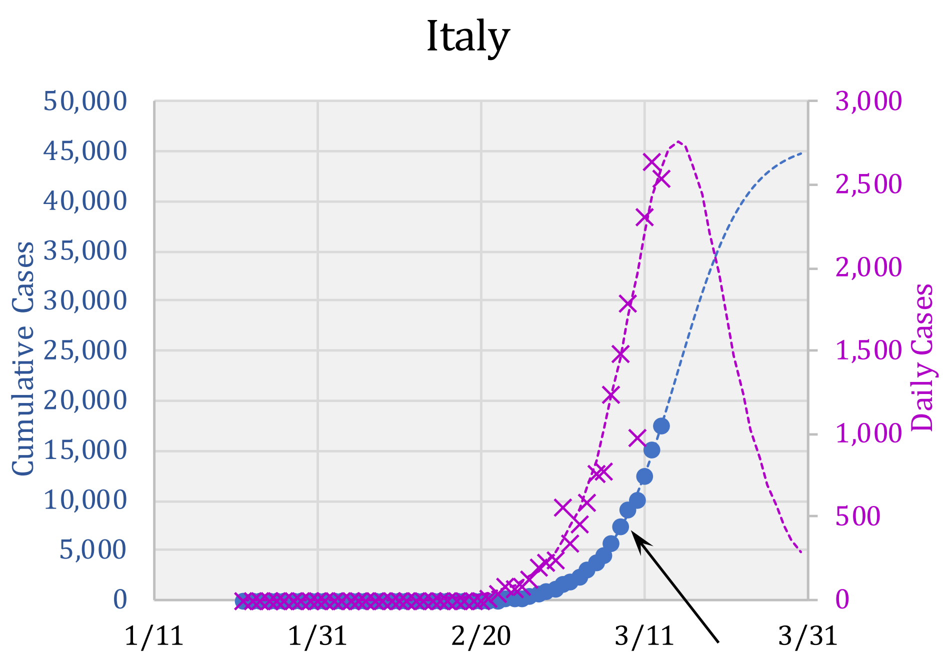


Right now, daily model is fairly symmetric with $\lambda \approx 0.8$. Is yesterday's uptick in cases a sign of asymptotic slowing like China?

Italy Model – No Inflection Yet

- Predicted total cases: 45-50k
- Peak – 3/16/2020
- Duration(95) – 31 days

Note: Quantitative predictions from the model are much more uncertain before daily peak occurs



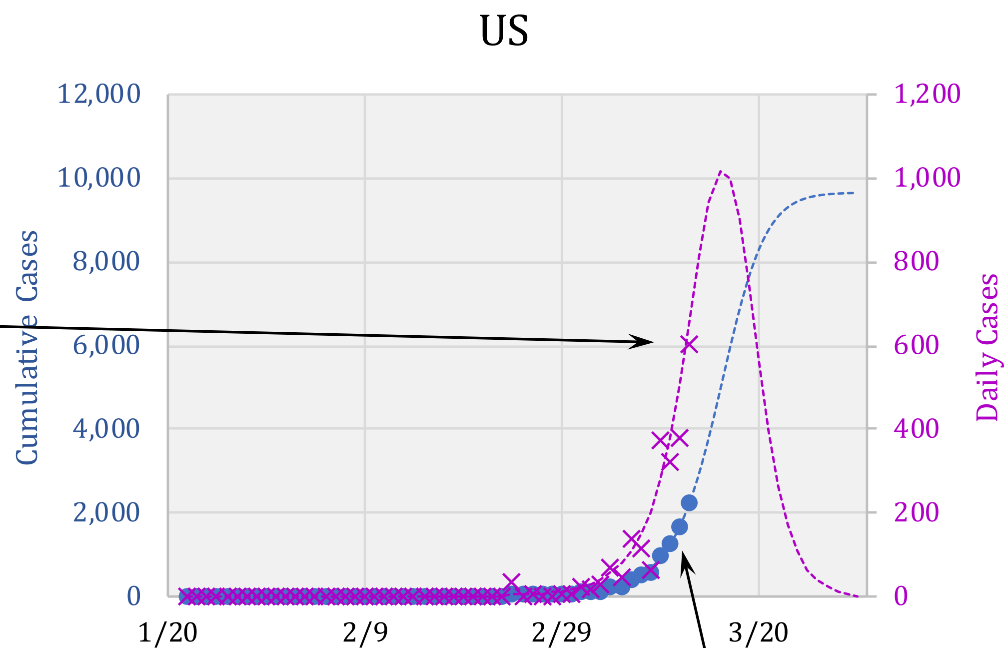
Lombardy & Italy shut down and isolated 3/8-9. Based on Hubei, cases would peak 3/20-21. Shutdown at ~7k cases or ~10 × Hubei

US Model – No Inflection Yet

- Predicted total cases: 10-11k
- Peak – 3/17/2020
- Duration(95) – 18 days

Note: Quantitative predictions from the model are much more uncertain before daily peak occurs

Far from the peak – don't believe the quantitative predictions



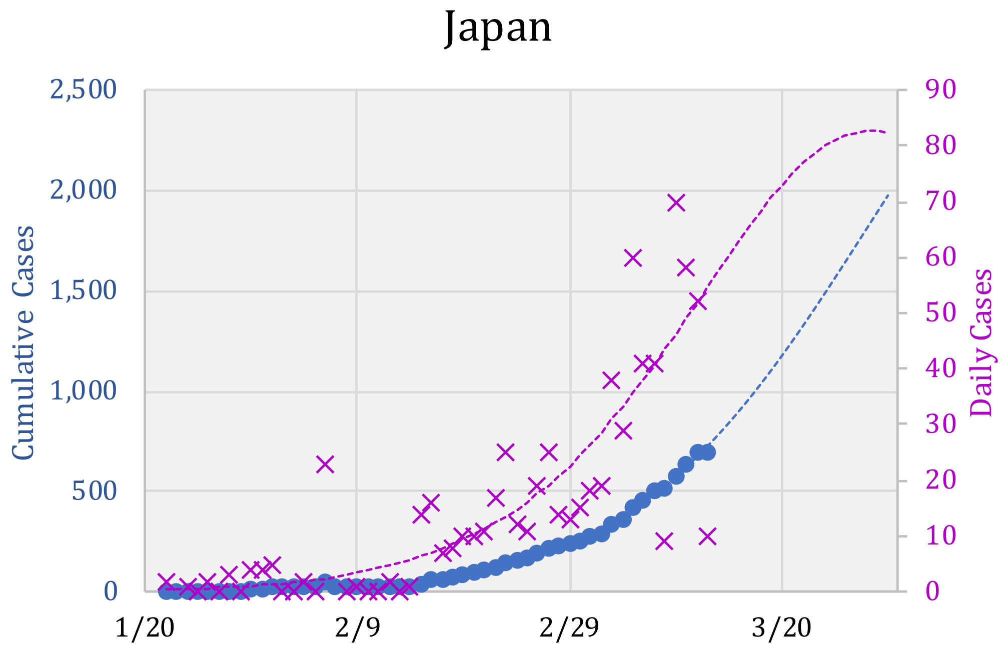
To date the US has neither the extensive shutdown/isolation nor exhaustive testing/tracking that have been employed elsewhere

Ad hoc shutdowns of schools, sports leagues, public gatherings with variation by jurisdiction 3/10-12. Based on Hubei peak ~3/23. "Shutdown(?)" at ~2k cases or ~ 3 × Hubei

Japan Model – What's Up With That?

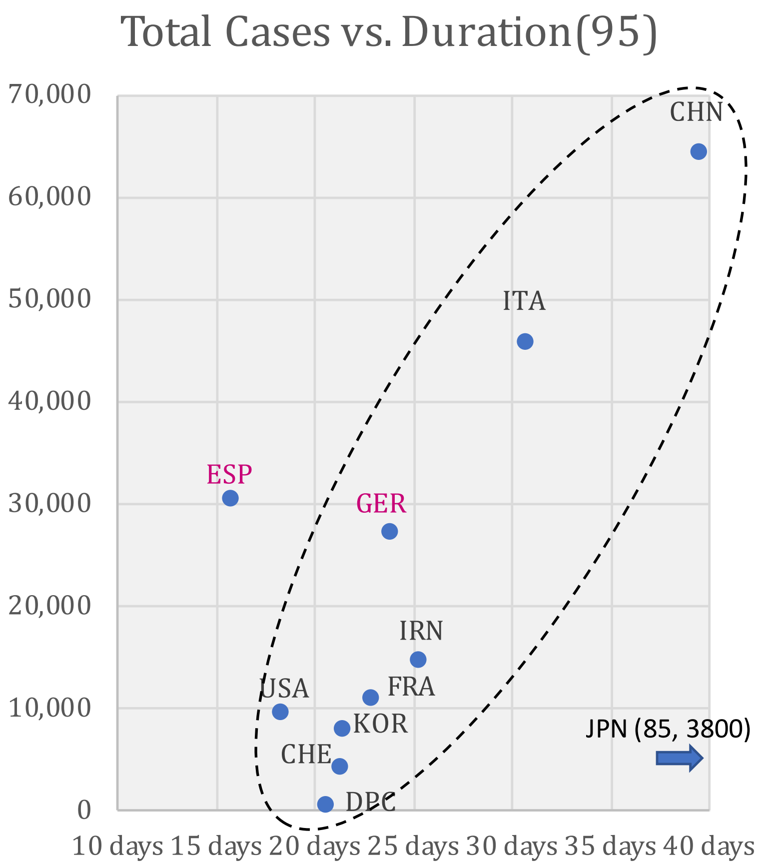
- Predicted total cases: 4-5k
- Peak – 3/29/2020
- Duration(95) – 85 days(!)

Note: Quantitative predictions from the model are much more uncertain before daily peak occurs



I don't have an explanation for the slow, steady growth of cases in Japan. Somehow it is neither accelerating much nor leveling out. Remaining manageable but could be difficult (or risky) to maintain

Duration(95) and Cases



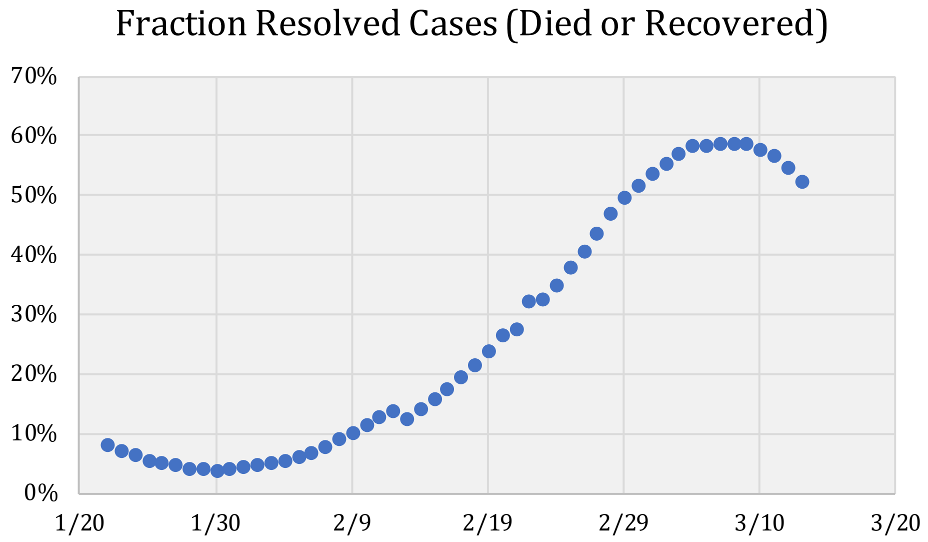
Countries tripping the 'circuit breaker' in their model are shown in **red**. The circuit breaker constrains N_0 to 10× the current cases to deal with the effect of noise in the data early in an outbreak

JPN ⊗

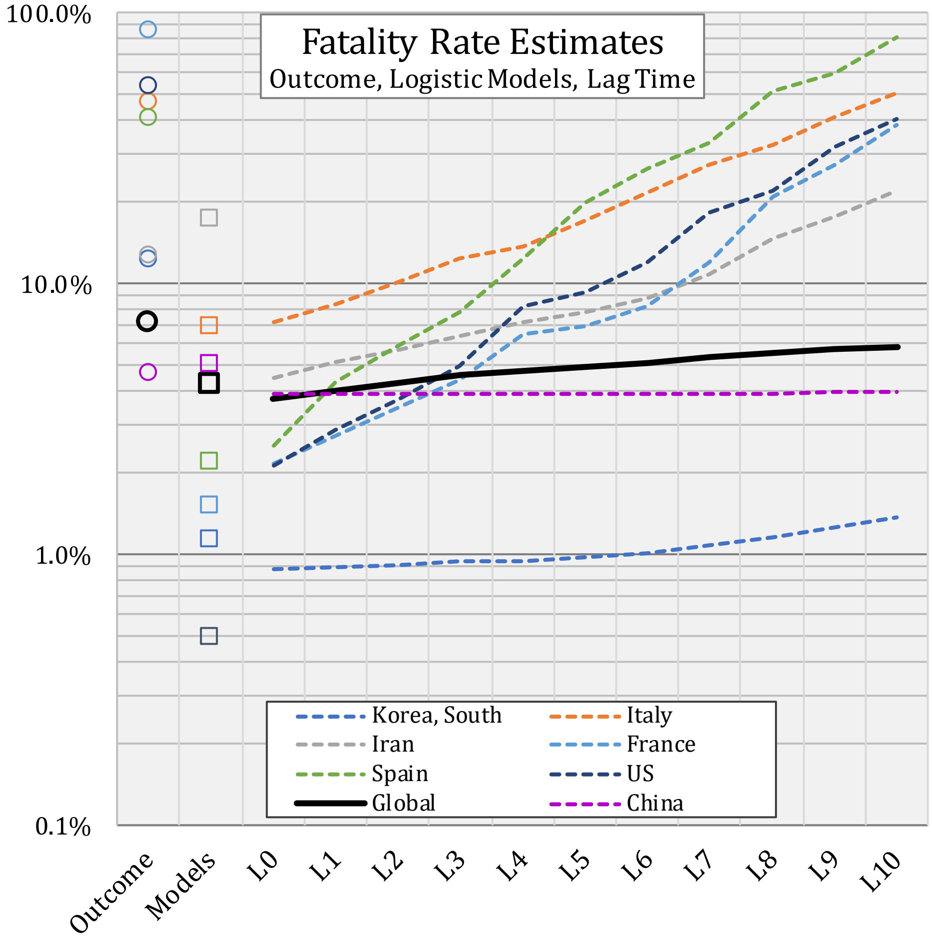
Most of the countries fall into a correlated grouping of duration vs. cases with exception of Japan which is a huge outlier

Fatality Rate

- Simplistic current fatality rate is 3.7% (deaths/cases)
- This is an underestimate until the outbreak is over; it would only be correct if *all* current cases recovered with no more fatalities (~70k active cases)
- Deaths lag identification of a case; an individual dying today became a case before today. The mean lag time can improve estimates during the course of an outbreak
- Lag time between logistic-modelled inflection in cases and deaths is ~7 days



Fatality Rate Estimates



- Outcome rate is deaths/(recovered+died) – global ~7%
- Modelled logistic constants estimate an overall fatality rate of ~4.2%
- Lag times (L0 to L10, 'L*N*') are (deaths today)/(cases N days ago)
  - Lines are sloped when daily cases are growing rapidly increasing the impact of lag time
  - Lines flatten out (Korea, China) when the outbreak flattens out
- Why is Korea so displaced? My hypothesis is that the testing was so comprehensive that they successfully identified a greater fraction of total cases than other countries, reducing the apparent fatality rate

Overall fatality rate estimated between 3.5 and 6%

Note that if the world tested everyone like Korea, it could be much lower purely as a result of the math

Conclusion - Inferences from the Modelling

- When will the outbreak be controlled?
  - Models suggest the China, Diamond Princess, and Korea outbreaks are now under control, based on inflection in both cases and deaths. None of the other 16 modeled outbreaks have inflected in both.
- How many outbreaks are there?
  - Currently modeling 19 based on the arbitrary definition of 300 cases.
  - Global outbreaks have been rapidly and steadily increasing in number for the last 4 weeks. It seems likely there will be more.
- How many will be afflicted?
  - With no more outbreaks and the current outbreaks brought under control from now (questionable assumptions) the model estimates a global total of ~300,000 cases & 13,000 deaths. The model is NOT good at predicting who will end up like Korea and who will end up like Italy, especially at this point in the outbreaks. It also cannot forecast the probability of more outbreaks, just the course of outbreaks that have been identified.
- What is the fatality rate?
  - Estimated between 3.5 and 6% based on models, outcomes, and lag times
  - Less deadly than SARS (~10%) and MERS (~30%)

Appendix – Equations Used

- Basic model of cumulative cases or deaths as a function of time

$$N(t) = \frac{N_0}{\left(1 + \delta e^{kt^{\lambda}}\right)}$$

This is fit to the actual data to estimate values for N_0, δ, k, λ

- Modeled estimate of daily cases or deaths

$$\frac{dN(t)}{dt} = -\frac{N_0 \delta k \lambda e^{kt^{\lambda}} t^{\lambda-1}}{\left(1 + \delta e^{kt^{\lambda}}\right)^2}$$

- Solve this for (t) to determine the inflection point; peak time for cases or deaths per day (I haven't found a closed-form solution)

$$\frac{k\lambda t^{\lambda} + \lambda - 1}{k\lambda t^{\lambda} - \lambda + 1} - \delta e^{kt^{\lambda}} = 0$$

- This is the expression for calculating the duration for the accumulation of the middle fraction (ϕ) of cases or deaths

$$\mathrm{dur}(\phi) = \frac{\left[\ln\left(\frac{1-\phi}{\delta(1+\phi)}\right)\right]^{\frac{1}{\lambda}} - \left[\ln\left(\frac{1+\phi}{\delta(1-\phi)}\right)\right]^{\frac{1}{\lambda}}}{k^{\frac{1}{\lambda}}} \qquad \mathrm{dur}(95) = \frac{\left[\ln\left(\frac{1}{39\delta}\right)\right]^{\frac{1}{\lambda}} - \left[\ln\left(\frac{39}{\delta}\right)\right]^{\frac{1}{\lambda}}}{k^{\frac{1}{\lambda}}}$$

Appendix: Fit and Calculated Parameters of Outbreak Case Models

Parameter	**China**	**Korea**	**Italy**	**D.P. Ship**	**Iran**	**France**	**Germany**	**Spain**	**Japan**	**US**
N_0	64,576	8,093	46,088	746	15,003	11,099	27,450	30,590	3,866	9,675
δ	5.30E+07	5.62E+07	6.32E+05	5.29E+02	1.37E+05	1.27E+05	9.95E+05	2.32E+06	5.24E+03	3.14E+03
k	-1.00E+01	-9.01E-01	-2.55E-01	-3.35E-02	-1.03E-01	-2.57E-02	-6.08E-02	-9.64E-03	-4.55E-01	-6.49E-05
λ	2.00E-01	8.01E-01	9.88E-01	1.59E+00	1.22E+00	1.53E+00	1.33E+00	1.82E+00	6.92E-01	2.91E+00
r^2	0.9999	0.9997	0.9990	0.9987	0.9949	0.9962	0.9925	0.9881	0.9978	0.9973
Peak	02/05/20	03/02/20	03/16/20	02/17/20	03/09/20	03/16/20	03/20/20	03/17/20	03/29/20	03/17/20
dur(0.95)	39 days	21 days	31 days	20 days	25 days	23 days	24 days	16 days	85 days	18 days

Parameter	Switzerland	UK	Netherlands	Sweden	Norway	Denmark	Belgium	Austria	Qatar
N_0	4,484	3,039	1,455	1,947	2,831	924	1,115	3,020	495
δ	9.84E+03	2.24E+03	6.52E+04	2.73E+04	6.72E+04	1.56E+07	1.92E+05	7.82E+04	1.58E+05
k	-1.50E-03	-4.83E-04	-8.54E-03	-2.34E-03	-2.23E-03	-1.91E-04	-3.21E-02	-2.72E-03	-8.54E-05
λ	2.17E+00	2.40E+00	1.81E+00	2.10E+00	2.13E+00	2.89E+00	1.49E+00	2.06E+00	3.00E+00
r^2	0.9943	0.9932	0.9935	0.9957	0.9903	0.9959	0.9762	0.9862	0.8688
Peak	03/17/20	03/17/20	03/13/20	03/15/20	03/15/20	03/12/20	03/14/20	03/18/20	03/13/20
dur(0.95)	21 days	23 days	19 days	19 days	17 days	8 days	22 days	18 days	11 days