

# Final Year Project

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January 31, 2021

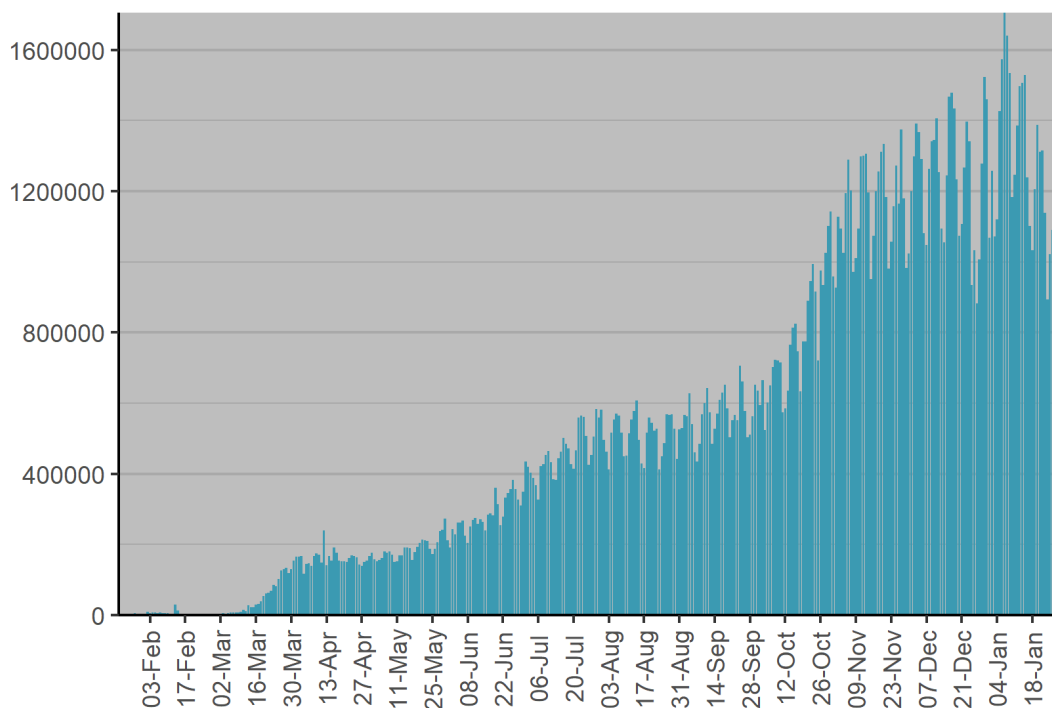
## Abstract

We construct a various models of the Covid-19 pandemic over various periods of 2020. We first construct simple model of a the epidemic by using a recurrence equation. We also add a periodic complexity to these simpler models. We then use more statistical methods, modelling using time series forecasting methods such as HoltWinters and ARIMA methods. All of this is with the aim of predicting the course of the epidemic.

## 1 Introduction

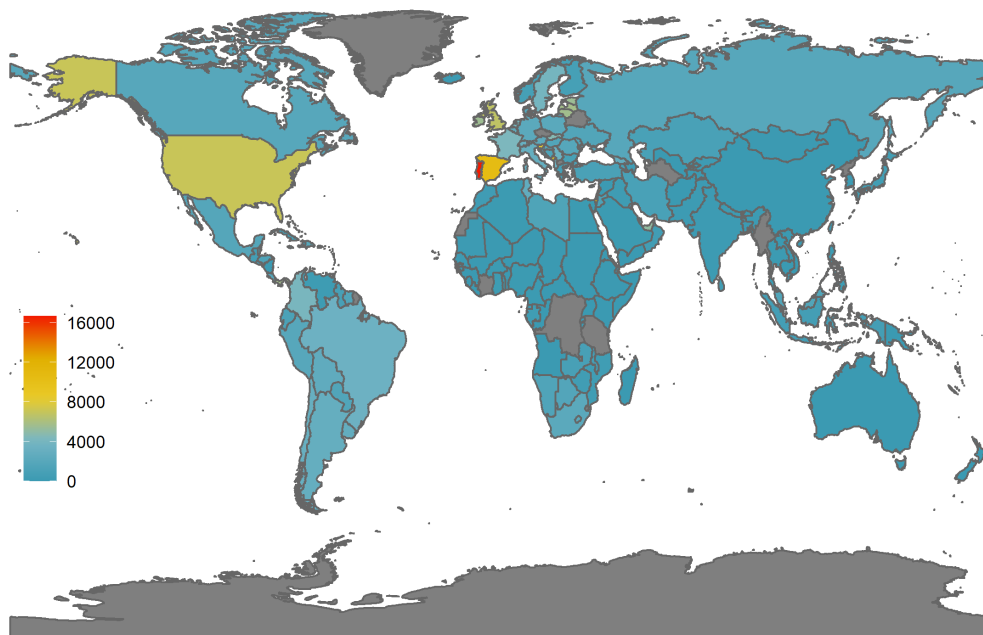
The Coronavirus disease (COVID-19) was first characterized by the World Health Organisation as pandemic on 11th March 2020 [11]. The outbreak has affected almost every aspect of human life throughout 2020, and is expected to continue for much of 2021.

Global Total =203,513,382 as at January 30, 2021

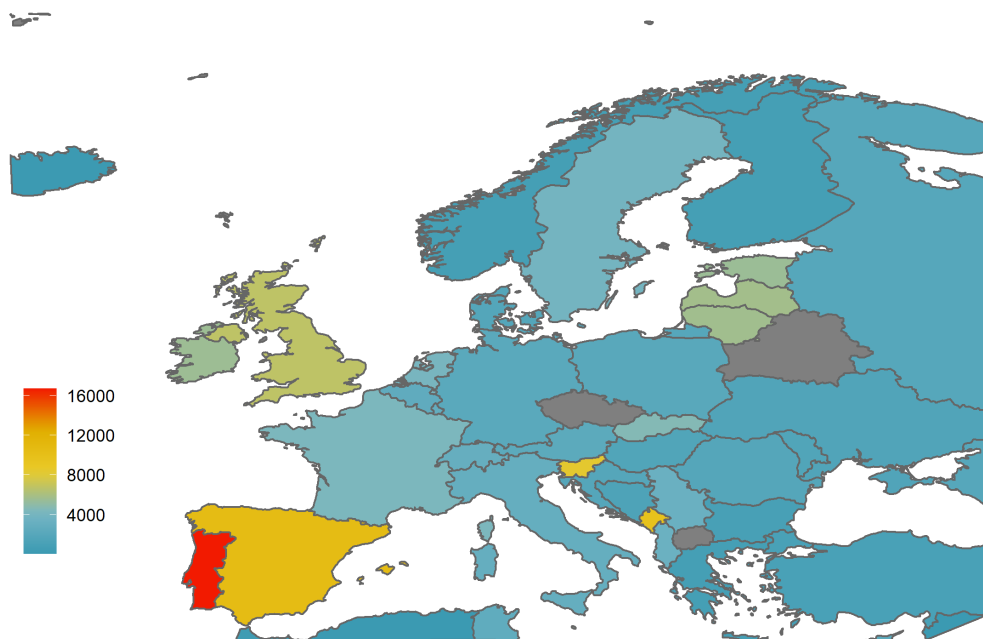


We can map the cumulative number of cases per 100,000 population for each country to see the varying severity of disease spread.

Total cases per 1 million population by country  
From January 15, 2021 to January 28, 2021



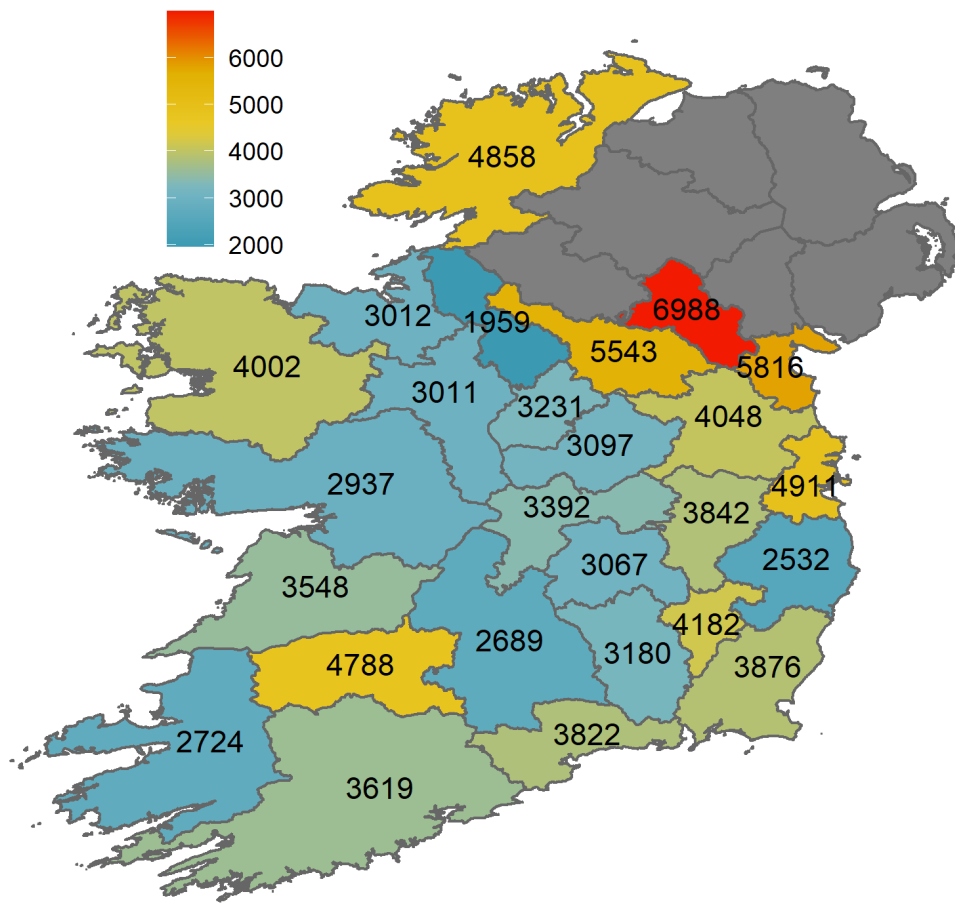
Europe is experiencing an especially high number of cases, proportionally, as well as the US.  
Total cases per 1 million population by country  
From January 15, 2021 to January 28, 2021



More locally, we see that Ireland also has a clear variation in concentration of cases to date, with Donegal and much of Leinster experiencing sometimes twice as many cases per 100,000 population as the rest of the country.

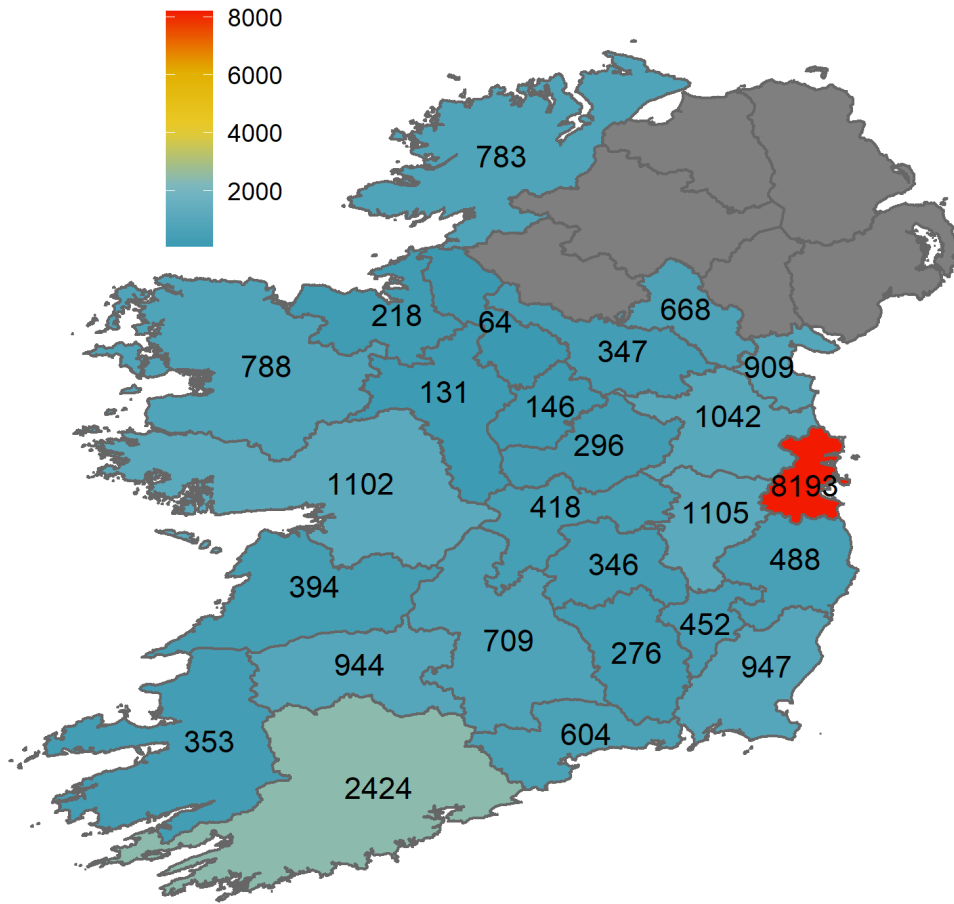
# Cases in Ireland per 100,000 population by county

Cumulative, up to January 28, 2021



## Cases in Ireland by county

From January 15, 2021 to January 28, 2021



This project is based on the work in [12], where I attempt to reconstruct the recurrence relation to model the pandemic. This largely mathematical model (based on practical assumptions), but of course does not fit well in the long run. It is efficient at explaining singular phases of the pandemic, and calculating the infamous  $R_0$  number, defined below, from [2].

**Definition.** The number  $R_0$  is called the *basic reproduction number* and is unquestionably the most important quantity to consider when analyzing any epidemic model for an infectious disease. Each infective individual can be expected to infect  $R_0$  individuals.

## 2 Mathematical Model

As per the base and periodic models shown in [12].

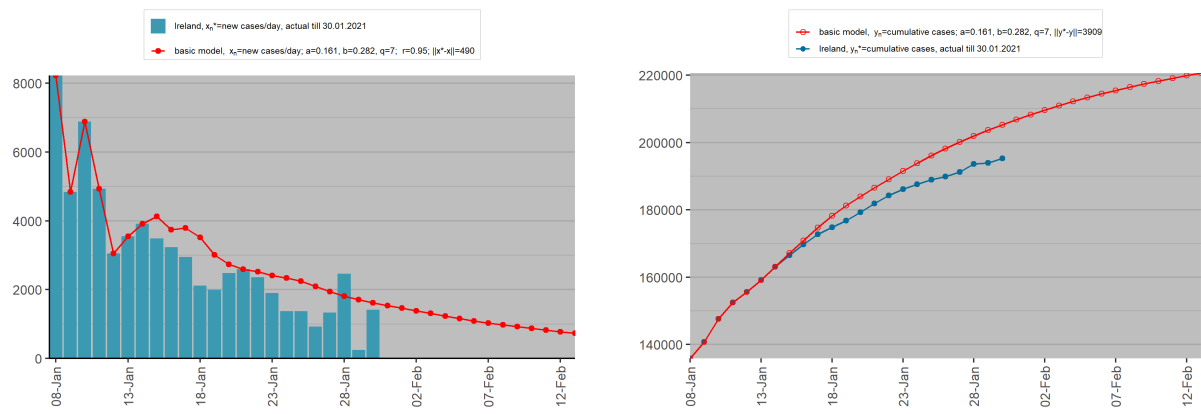
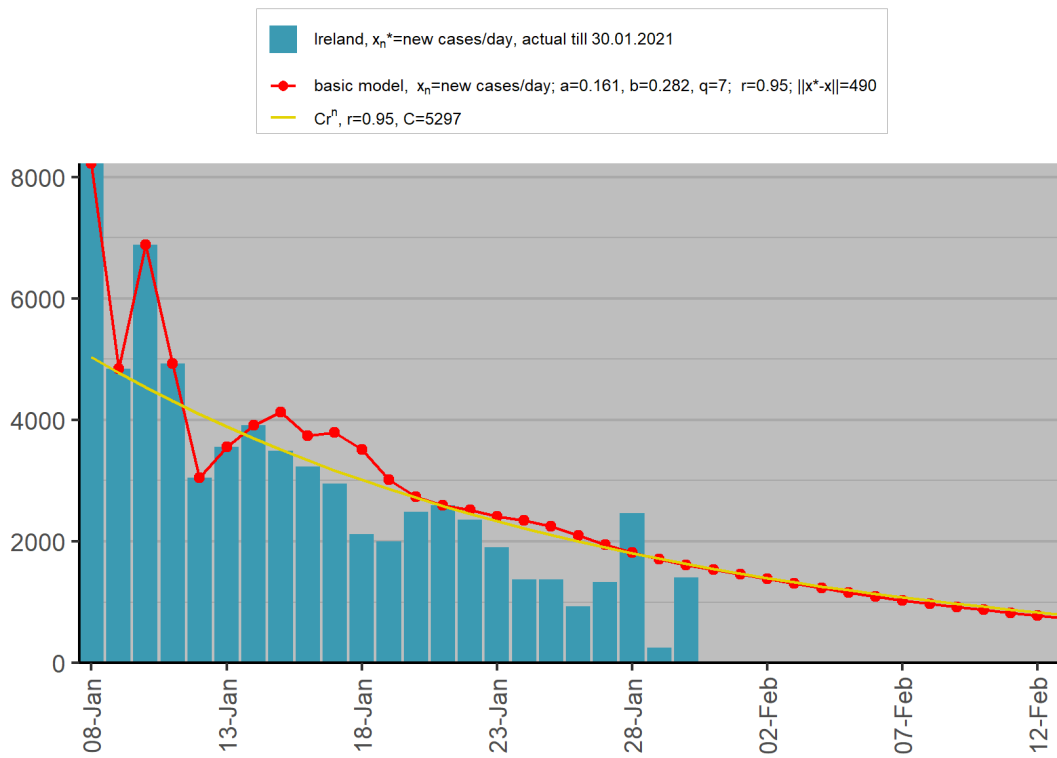
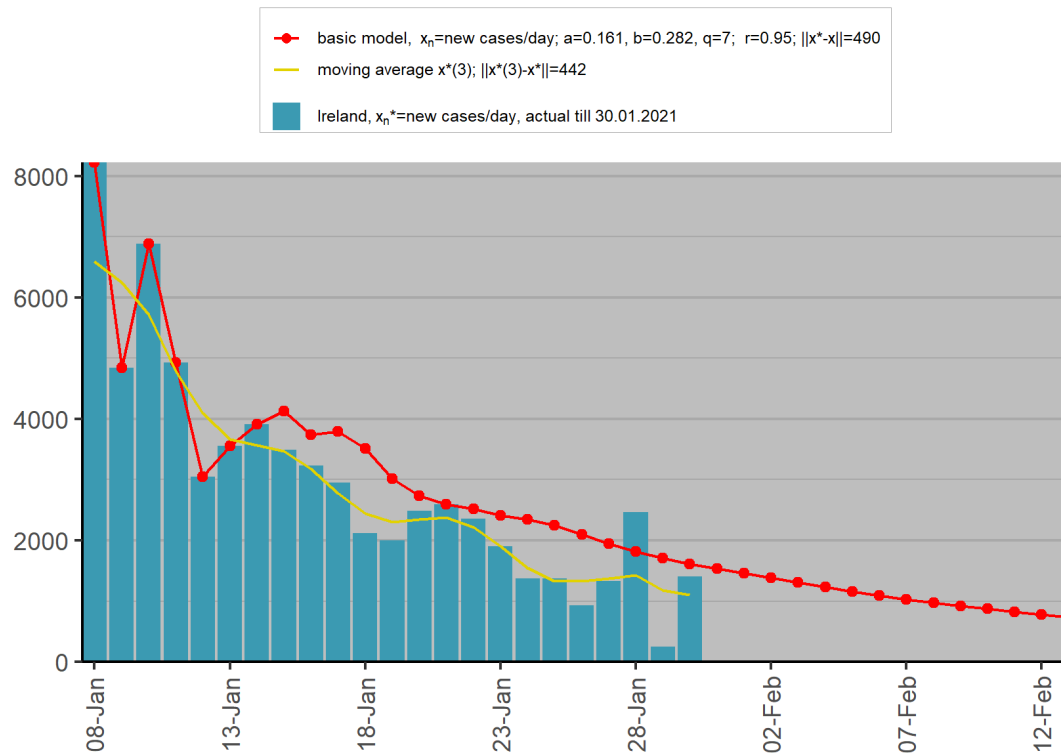


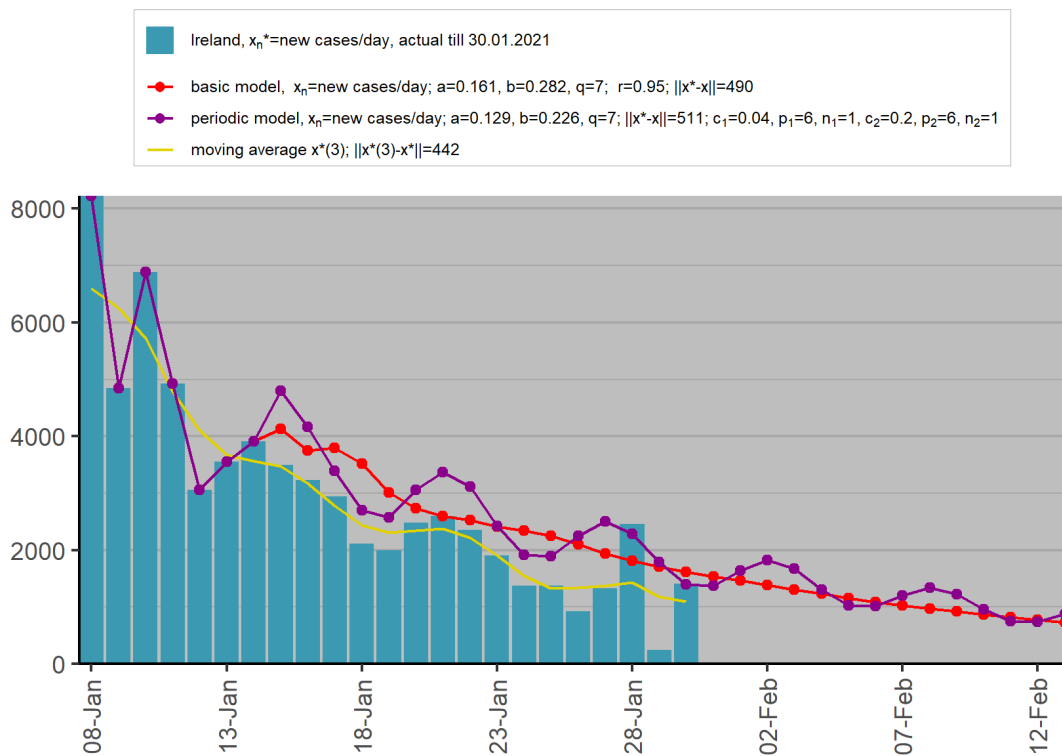
Figure 1: Basic modelsl, Ireland

## 2.1 Base model





## 2.2 Periodic model



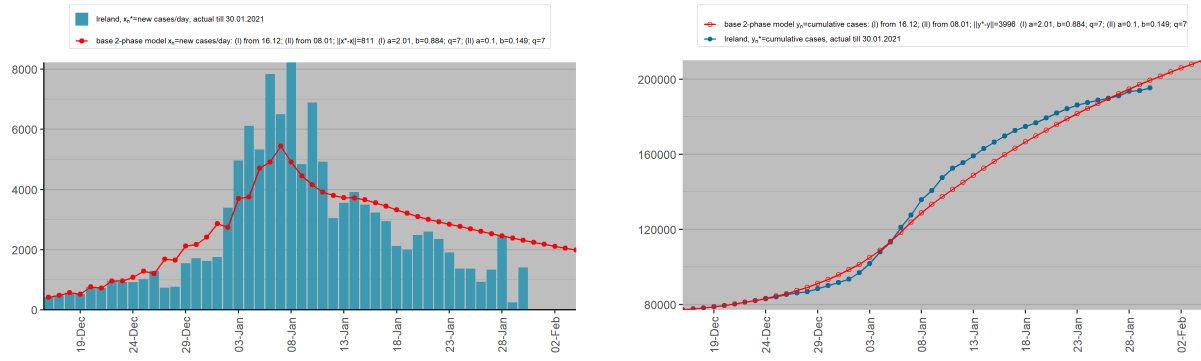


Figure 2: Multi-phase model, Ireland

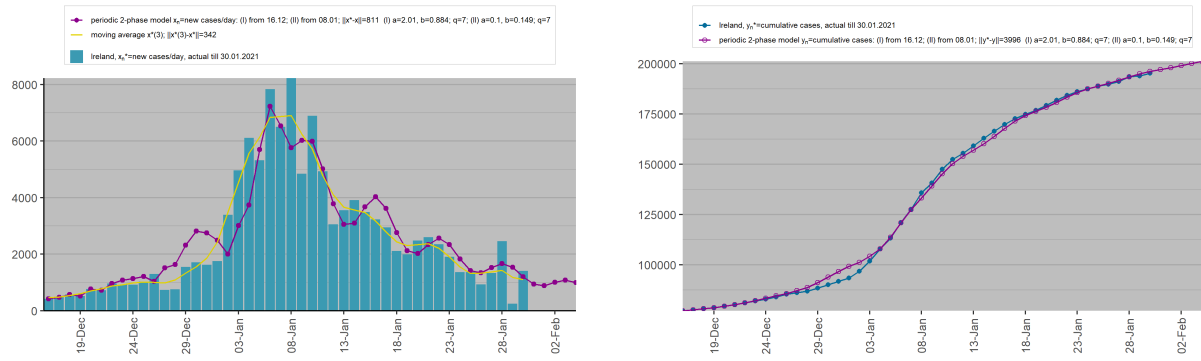


Figure 3: Multi-phase periodic model, Ireland

## 2.3 Multi-phase model

# 3 Theorems

## 3.1 Model Assumptions

- (I) Any infected person becomes ill (symptomatic) and infectious on the  $q$ -th day after infection.<sup>1</sup>
- (A) During each day, each ill person unconfined infects on average  $a$  other persons.
- (B) During each day, a fraction  $b$  of ill people loose gets isolated (hospitalized or otherwise) and withdrawn from a further spread of the epidemic.

Many models use a set of differential equations for to describe the movement of people between *groups* or *compartments*[14, 4, 10]. The SIR (Susceptible–Infectious–Recovered) model, the most frequently used model in epidemiology, uses a set of 3 such differential equations [3, 5].

Our main mathematical model (and even some of the statistical models) make use recurrence equations, which have some correspondence to differential equations [1].

## 3.2 Notation

- $x_n$  - the number of infected people that are detected and isolated during the day  $n$ ;
- $y_n$  – the cumulative number of detected cases from the beginning of epidemic by the beginning of the day  $n$ ;

<sup>1</sup>The number of days before an infected person becomes infectious is called the latent period, and before he/she becomes symptomatically ill – the incubation period. Here we assume for simplicity that these two periods are equal.

- $z_n$  – the number of ill people at large by the beginning of the day  $n$  (that is, those who were infected at least  $q$  days ago and stay unisolated);
- $u_n$  – the number of people newly infected during the day  $n$ .

We will obtain the following relation between the leading root  $r$  and the basic reproductive rate  $R_0$  that is a main characteristic of an epidemic in epidemiology:

$$r \approx R_0^{\frac{1}{2q}}. \quad (1)$$

Recurrence relation for  $z_n$ :

$$z_{n+1} = z_n - x_n + u_{n-q}. \quad (2)$$

Using  $x_n = bz_n$  we obtain the following equation for  $x_n$ :

$$x_{n+1} = (1 - b)x_n + ax_{n-q}. \quad (3)$$

We let the model equal the actual data for the first  $q + 1$  days

$$x_n = x_n^* \text{ for } n = 0, 1, \dots, q, \quad (4)$$

To fit our model we optimize against the normalized 1-norm:

$$\|x - x^*\| := \frac{1}{N+1} \sum_{n=0}^N |x_n - x_n^*|, \quad (5)$$

Similarly we define  $\|y - y^*\|$

In order to determine values  $a, b, q$ , we want to minimize both

$$\|x - x^*\| \text{ and } \|y - y^*\| \quad (6)$$

### 3.2.1 Why minimize both diatances?

Do 3 pairs of plots: -  $x_n/y_n$  for just x-norm -  $x_n/y_n$  for just y-norm -  $x_n/y_n$  for both x-norm and y-norm

### 3.2.2 Recurrence equation

This is our general linear recurrence equation with constant coefficients:

$$x_{n+1} = a_0x_n + a_1x_{n-1} + a_2x_{n-2} + \dots + a_qx_{n-q} \quad (7)$$

The characteristic polynomial of 7

$$f(\lambda) = \lambda^{q+1} - a_0\lambda^q - a_1\lambda^{q-1} - a_2\lambda^{q-2} - \dots - a_{q-1}\lambda - a_q. \quad (8)$$

**Definition 1.** A root  $\lambda$  of  $f$  with the maximal absolute value  $|\lambda|$  will be referred to as a leading root of the general linear recurrence relation 7.

## 3.3 Theorems

**Theorem 1.** Let  $a_k \geq 0$  for all  $k \in \{0, \dots, q\}$  and  $a_{k_0} > 0$  for some  $k_0 \in \{0, \dots, q\}$ .

- (Cauchy, 1829) The polynomial  $f(\lambda)$  from 8 has exactly one positive real root  $r$ . Besides, the root  $r$  is simple and, for any other root  $\lambda \in \mathbb{C}$ , we have  $|\lambda| < r$ . Consequently,  $r$  is the leading root of 7.
- For any positive solution  $x_n$  of 7, there exists  $C > 0$  such that

$$x_n \sim Cr^n \text{ as } n \rightarrow \infty. \quad (9)$$

It follows from 9 that if  $r < 1$  then the epidemic fades away, whereas if  $r > 1$  then it spreads unlimited.



**Proof:**

(a) Although this statement is not new, we give here the proof as it is quite simple and a part of the argument will be used below. The equation  $f(\lambda) = 0$  is equivalent to

$$0 = \lambda^{q+1} - a_0\lambda^q - a_1\lambda^{q-1} - a_2\lambda^{q-2} - \dots - a_{q-1}\lambda - a_q$$

dividing across by  $\lambda^{q+1}$

$$= 1 - \frac{a_0}{\lambda} - \frac{a_1}{\lambda^2} - \frac{a_2}{\lambda^3} - \dots - \frac{a_{q-1}}{\lambda^q} - \frac{a_q}{\lambda^{q+1}}$$

And so

$$1 = \underbrace{\frac{a_0}{\lambda} + \frac{a_1}{\lambda^2} + \frac{a_2}{\lambda^3} + \dots + \frac{a_{q-1}}{\lambda^q} + \frac{a_q}{\lambda^{q+1}}}_{g(\lambda)} \quad (10)$$

Since  $a_{k_0} > 0$  for some  $k_0$ , and the remaining  $a_k$  are non-negative,  $g(\lambda)$  is strictly monotone decreasing in  $\lambda > 0$  (if  $c\lambda$  is increasing, then  $\frac{c}{\lambda}$  is decreasing), and we have the limits

- $\lim_{\lambda \rightarrow 0^+} g(\lambda) = +\infty$
- $\lim_{\lambda \rightarrow +\infty} g(\lambda) = 0^+$

Hence, there is exactly one positive value  $\lambda = r$  that satisfies this  $g(r) = 1$ , that is,

$$1 = \frac{a_0}{r} + \frac{a_1}{r^2} + \frac{a_2}{r^3} + \dots + \frac{a_{q-1}}{r^q} + \frac{a_q}{r^{q+1}}.$$

Now, let  $\lambda \in \mathbb{C} \setminus \{0\}$  be another root of  $f$ . We obtain from 10 (using the triangle inequality) that

$$1 \leq \frac{a_0}{|\lambda|} + \frac{a_1}{|\lambda|^2} + \frac{a_2}{|\lambda|^3} + \dots + \frac{a_{q-1}}{|\lambda|^q} + \frac{a_q}{|\lambda|^{q+1}}$$

And so  $g(r) \leq g(|\lambda|)$  which implies  $|\lambda| \leq r$  by the definition of decreasing functions.

We next need to show that the root  $r$  is simple. Denote by  $r'$  the largest non-negative root of the derivative  $f'(\lambda)$  that exists for the following reason. If  $a_k > 0$  for some  $k < q$  then the polynomial  $\frac{1}{q+1}f'(\lambda)$  satisfies the hypotheses of the present theorem and, by the above argument,  $f'(\lambda)$  has exactly one positive root, that is  $r'$ . If  $a_k = 0$  for all  $k < q$  then  $f'(\lambda) = (q+1)\lambda^q$  has the only root 0, and, hence,  $r' = 0$ .

Let us verify that  $r' < r$ , which will also imply that  $r$  is simple. If  $r' = 0$  then it is clear. If  $r' > 0$  then it follows from  $f'(r') = 0$  that

$$\begin{aligned} f'(\lambda) &= (q+1)\lambda^q - qa_0\lambda^{q-1} - (q-1)a_1\lambda^{q-2} - (q-2)a_2\lambda^{q-3} - \dots - a_{q-1} - 0 \\ \frac{1}{q+1}f'(\lambda) &= \lambda^q - \frac{q}{q+1}a_0\lambda^{q-1} - \frac{q-1}{q+1}a_1\lambda^{q-2} - \frac{q-2}{q+1}a_2\lambda^{q-3} - \dots - \frac{1}{q+1}a_{q-1} \\ \frac{1}{q+1}f'(r') &= (r')^q - \frac{q}{q+1}a_0(r')^{q-1} - \frac{q-1}{q+1}a_1(r')^{q-2} - \frac{q-2}{q+1}a_2(r')^{q-3} - \dots - \frac{1}{q+1}a_{q-1} \\ 0 &= (r')^q - \frac{q}{q+1}a_0(r')^{q-1} - \frac{q-1}{q+1}a_1(r')^{q-2} - \frac{q-2}{q+1}a_2(r')^{q-3} - \dots - \frac{1}{q+1}a_{q-1} \\ (r')^q &= \frac{q}{q+1}a_0(r')^{q-1} + \frac{q-1}{q+1}a_1(r')^{q-2} + \frac{q-2}{q+1}a_2(r')^{q-3} + \dots + \frac{1}{q+1}a_{q-1} \\ &\text{dividing both sides by } (r')^q > 0 \end{aligned}$$

$$\begin{aligned} 1 &= \frac{qa_0}{(q+1)r'} + \frac{(q-1)a_1}{(q+1)(r')^2} + \dots + \frac{a_{q-1}}{(q+1)(r')^q} \\ &= \left(\frac{q+1-1}{q+1}\right) \frac{a_0}{r'} + \left(\frac{q+1-2}{q+1}\right) \frac{a_1}{(r')^2} + \dots + \left(\frac{q+1-q}{q+1}\right) \frac{a_{q-1}}{(r')^q} \\ &= \left(1 - \frac{1}{q+1}\right) \frac{a_0}{r'} + \left(1 - \frac{2}{q+1}\right) \frac{a_1}{(r')^2} + \dots + \left(1 - \frac{q}{q+1}\right) \frac{a_{q-1}}{(r')^q} \\ &< \frac{a_0}{r'} + \frac{a_1}{(r')^2} + \dots + \frac{a_{q-1}}{(r')^q} \end{aligned}$$

So  $g(r') > 1$ , but  $g(r) = 1$

$\implies g(r') > g(r) \implies r' < r$  by the definition of decreasing functions.

- (b) Let  $\lambda_1, \lambda_2, \dots$  be all other distinct roots of  $f$  apart from  $r$  (so that  $\lambda_k$  are negative or imaginary). Any solution  $x_n$  of 7 has the form

$$x_n + Cr^n + \tilde{x}_n \quad (11)$$

where  $\tilde{x}_n$  is a linear combination of the functions  $n^j \lambda_k^n$ . Since by (a) we have  $|\lambda_k| < r$ , it follows that

$$|\tilde{x}_n| = o(r^n) \text{ as } n \rightarrow \infty \quad (12)$$

Since  $x_n > 0$ , it follows from 11 and 12 that  $C \geq 0$ . Let us verify that  $C > 0$ , which will finish the proof. It is tempting to say that if  $C = 0$  then  $x_n = \tilde{x}_n$  is a linear combination of terms of the form  $n^j \rho^n \sin(\phi n)$  and  $n^j \rho^n \cos(\phi n)$  and, therefore, cannot stay positive. However, it is not easy to make this argument rigorous because different roots of  $f$  may have the same absolute value  $\rho$  and an uncontrollable cancellation of the terms can occur. We employ here a different, simpler approach that takes advantage of nonnegative coefficients  $a_k$ . To that end, consider a new sequence

$$X_n = \frac{x_n}{r^n}.$$

This satisfies the equation

$$X_{n+1} = A_0 X_0 + A_1 X_{n-1} + \dots + A_q X_{n-q} \quad (13)$$

with  $A_k = \frac{a_k}{r^{k+1}}$ . Since  $r$  is a root of  $f$ , we have

$$\begin{aligned} A_0 + A_1 + \dots + A_q &= \frac{a_0}{r^1} + \frac{a_1}{r^2} + \dots + \frac{a_q}{r^{q+1}} \\ &= g(r) \end{aligned}$$

This implies, by 10, and  $g(r) = 1$  that

$$A_0 + A_1 + \dots + A_q = 1 \quad (14)$$

Set  $c := \min(X_1, \dots, X_{q+1}) > 0$  since  $x_n$  have positive initial values. Then we obtain from 13 and 14 by induction that  $X_n \geq c$  for all  $n \in \mathbb{N}$ , which implies

$$x_n \geq cr^n$$

as required. □

**Theorem 2.** Let  $a_k \geq 0$  for all  $k = 0, \dots, q$ . Denote  $a = a_1 + \dots + a_q, b = 1 - a_0$  and assume that  $a > 0, b > 0$ .

(a) We have the equivalences:  $r < 1 \iff a < b$  and  $r > 1 \iff a > b$ .

(b) Let  $m \geq 1$  be such that  $a_1 = \dots = a_{m-1} = 0$  and  $a_m > 0$ . Then

$$\min \left( 1, \left( \frac{a}{b} \right)^{1/m} \right) \leq r \leq \max \left( 1, \left( \frac{a}{b} \right)^{1/m} \right) \quad (15)$$

**Remark 1.** Although there are in the literature plenty of estimates of the leading roots of polynomial (see, for example, [2]), none of them seems to imply 15. The latter is very useful for a basic model as we will see below in an example.

**Proof:**

(a) We have

$$\begin{aligned} f(1) &= 1 - a_0 - a_1 - \dots - a_q \\ &= \underbrace{(1 - a_0)}_b - \underbrace{(a_1 + \dots + a_q)}_a \\ &= b - a \end{aligned}$$

We know  $f$  is increasing.

So if  $r < 1$ , we have  $f(1) > 0$  and then  $b - a > 0 \implies a < b$ .

And if  $r > 1$ , we have  $f(1) < 0$  and then  $b - a < 0 \implies a > b$

(b)  $f(r) = 0$  is equivalent to

$$r^{q+1} - a_0 r^q - a_1 r^{q-1} - a_2 r^{q-2} - \dots - a_{q-1} r - a_q = 0$$

But any  $a_1, \dots, a_{m-1}$  are all zero

$$\implies r^{q+1} - a_0 r^q - a_m r^{q-m} - a_{m+1} r^{q-m-1} - \dots - a_{q-1} r - a_q = 0$$

$$\implies r^{q+1} - (1 - b) r^q - a_m r^{q-m} - \dots - a_q = 0$$

$$\implies r^{q+1} - r^q + b r^q - a_1 r^{q-m} - \dots - a_q = 0$$

$$\implies r^{q+1} - r^q = -b r^q + a_m r^{q-m} + \dots + a_q$$

If  $r > 1$  then  $r^{q+1} > r^q$  and so  $r^{q+1} - r^q > 0$

and so

$$0 < -b r^q + a_m r^{q-m} + \dots + a_q$$

$$\implies b r^q < a_m r^{q-m} + \dots + a_q$$

$$\leq a_m r^{q-m} + \dots + a_q r^{q-m}$$

$$= (a_m + \dots + a_q) r^{q-m}$$

$$= a r^{q-m}$$

$$\text{So } b r^q < a r^{q-m} \iff r^m = \frac{a}{b} \iff r < \left(\frac{a}{b}\right)^{1/m}$$

And if  $r < 1$  we get  $r < \left(\frac{a}{b}\right)^{1/m}$ .

We can combine both cases with  $a \leq \max((1, a))$  and  $a \geq \min(1, a)$  to get 15, as required. □

**Lemma 3.** For the model described by equation 7 we have

$$R_0 = \frac{a}{b}$$

**Proof:** Let  $u$  be the number of people infected on some day, say 0. On the day  $k = 1, \dots, q$  the number  $c_k u$  of them become ill and can infect other people. On the day  $k + 1$  they infect  $a c_k u$  people while  $b c_k u$  of them get isolated. On the day  $k + 1$ , the remaining  $(1 - b) c_k u$  people infect further  $a(1 - b) c_k u$  people. Continuing this way, we obtain that this group of  $c_k u$  people infects in total

$$a c_k u + a(1 - b) c_k u + a(1 - b)^2 c_k u + \dots = a c_k u \sum_{n=0}^{\infty} (1 - b)^n = \frac{a c_k u}{1 - (1 - b)} = \frac{a}{b} c_k u$$

since  $0 < 1 - b < 1$ .

other people.

Hence, the initial group of  $u$  people infects in total

$$\sum_{k=0}^q \frac{a}{b} c_k u = \frac{a}{b} u \sum_{k=0}^q c_k = \frac{a}{b} u$$

So we know  $R_0$  is the unit reproduction number per infected person ( $u = 1$ ).

And so we get the result  $R_0 = \frac{a}{b}$  as required. □

Suppose there are  $N$  observations.

Initial step:

$$L_s = \frac{1}{s} \sum_{i=1}^s y_i$$

$$b_s = \frac{1}{s} \left[ \frac{y_{s+1} - y_1}{s} + \frac{y_{s+2} - y_2}{s} + \dots + \frac{y_{2s} - y_s}{s} \right]$$

$$S_i = \frac{y_i}{L_s}, \quad i = 1, \dots, s$$

and choose parameters  $0 \leq \alpha \leq 1$ ,  $0 \leq \beta \leq 1$  and  $0 \leq \gamma \leq 1$

Then compute for  $s < t \leq N$ :

$$\begin{aligned} \text{Level} \quad L_t &= \alpha \frac{y_t}{S_{t-s}} + (1 - \alpha)(L_{t-1} + b_{t-1}) \\ \text{Trend} \quad b_t &= \beta(L_t - L_{t-1}) + (1 - \beta)b_{t-1} \\ \text{Seasonal} \quad S_t &= \gamma \frac{y_t}{L_t} + (1 - \gamma)S_{t-s} \\ \text{Forecast} \quad F_{t+1} &= (L_t + b_t)S_{t+1-s} \end{aligned}$$

For subsequent observations,

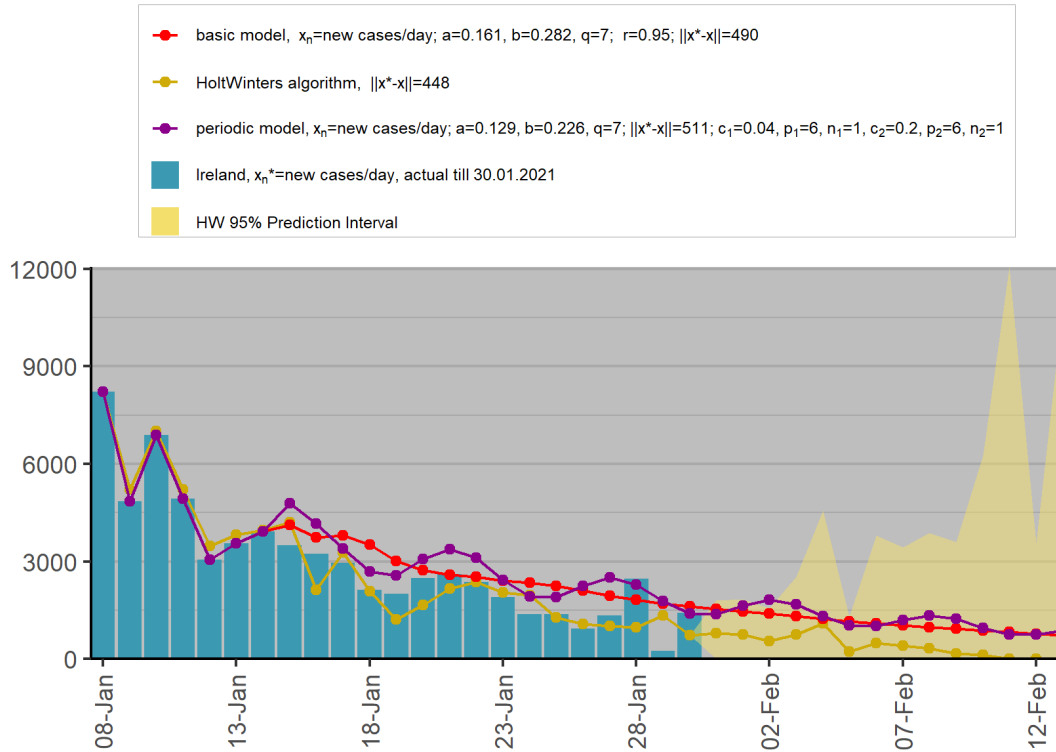
$$F_{N+k} = (L_N + k \cdot b_N)S_{N+k-s}$$

Figure 4: Seasonal Holt Winter's Multiplicative Model Algorithm (denoted SHW<sub>x</sub>)

## 4 Statistical Models

Primary source for this was Hyndman-et-al-2018

### 4.1 Holt-Winters' seasonal method



### 4.2 ARIMA models

ARIMA( $p, d, q$ )( $P, D, Q$ )<sub>s</sub> is defined as

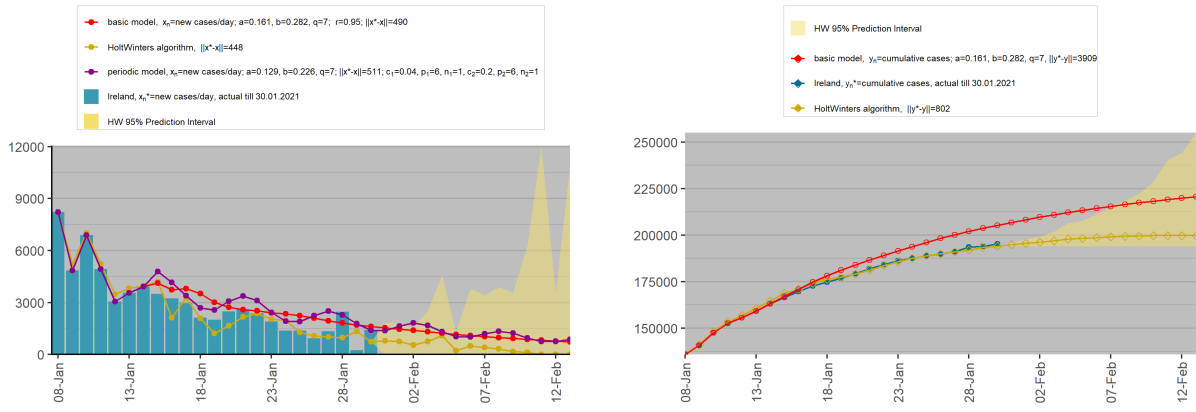


Figure 5: HoldWinters model, Ireland

$$\underbrace{(1 - \phi_1 B - \phi_2 B^2 - \dots - \phi_p B^p)}_{AR(p)} \underbrace{(1 - \beta_1 B^s - \beta_2 B^{2s} - \dots - \beta_P B^{Ps})}_{AR_s(P)} \underbrace{(1 - B)^d}_{I(d)} \underbrace{(1 - B^s)^D}_{I_s(D)} y_t = c + \underbrace{(1 - \psi_1 B - \psi_2 B^2 - \dots - \psi_q B^q)}_{MA(q)} \underbrace{(1 - \theta_1 B^s - \theta_2 B^{2s} - \dots - \theta_Q B^{Qs})}_{MA_s(Q)} \epsilon_t \quad (16)$$

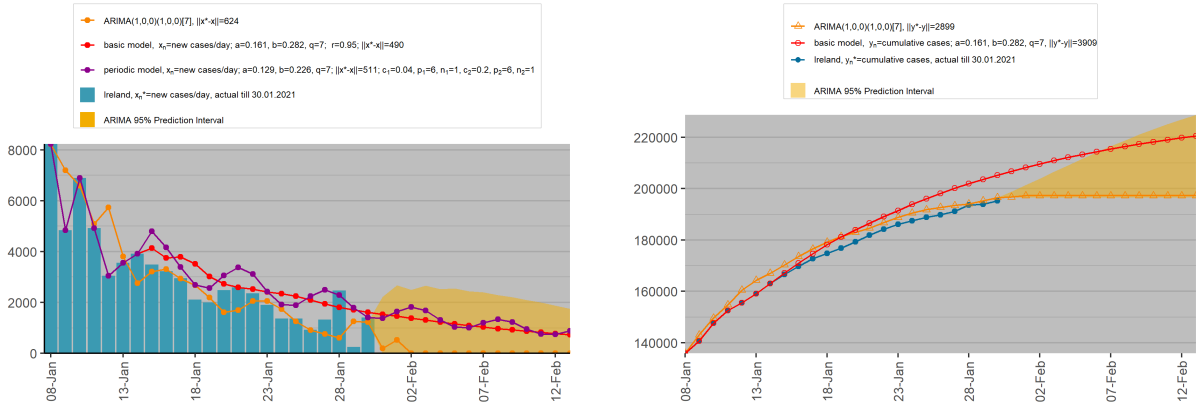
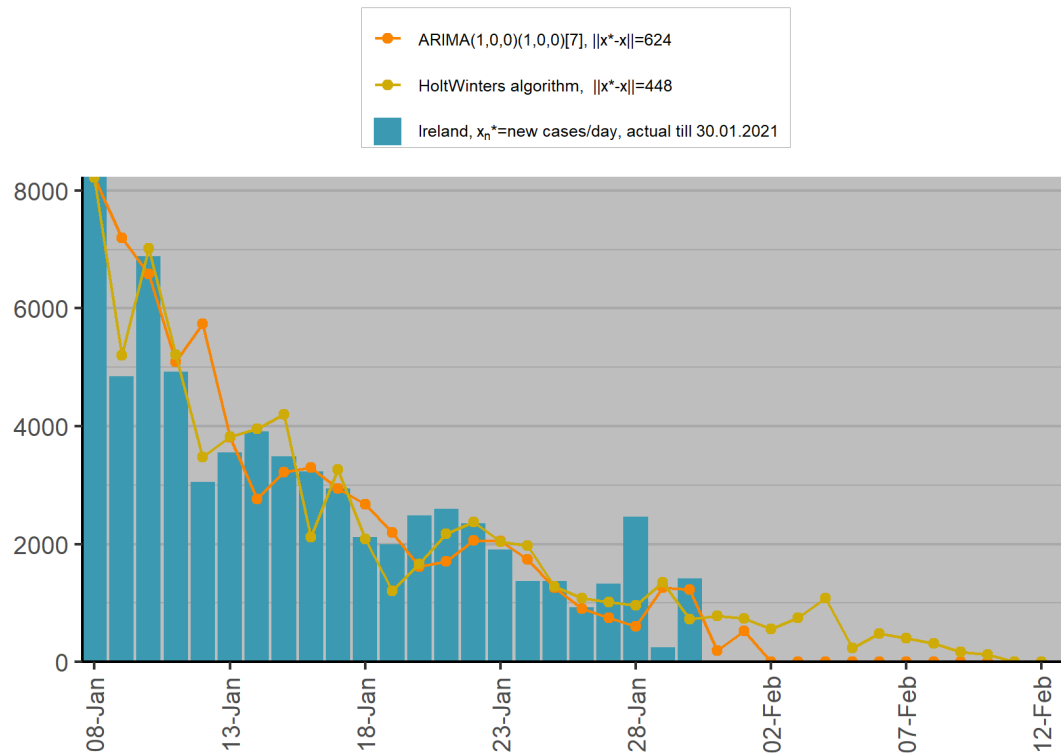


Figure 6: ARIMA model, Ireland



### 4.3 Neural network models

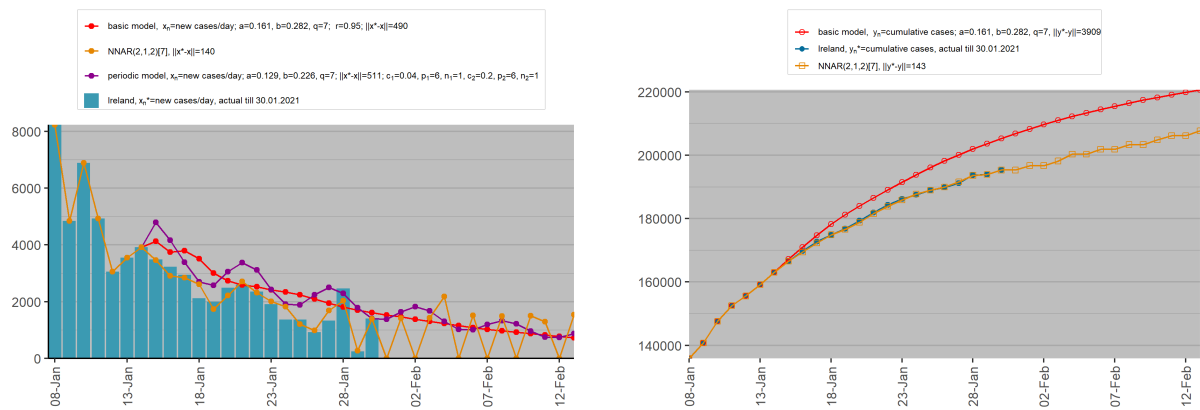


Figure 7: Neural Network model, Ireland

## 5 R Code and Data Sources

Much of the code was written from scratch for this project, or is a close to direct translation of the formulas described in papers such as

### 5.1 Plotting and colour

wesanderson [15]

## 5.2 Shapefiles

Ireland Counties [7]  
World [13]

## 5.3 Datasets

Country-based data

Originally used data from [9], but the ECDC switched from a daily to a weekly update from 14 December 2020. Therefore, I have chosen to use the data from [8], which has remained daily  
Ireland cases by county are from [6]

## References

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