

# Situational awareness and forecasting

FHI COVID-19 modelling team

20 April 2020

## What this report contains:

This report presents results based on a mathematical model describing the geographical spread of COVID-19 in Norway. The model consists of three layers:

- Population structure in each municipality
- Mobility data for inter-municipality movements (Telenor mobile phone data)
- Infection transmission model

The model produces estimates of the current epidemiological situation at the municipality, county (fylke) and national levels, a forecast of the situation for the next three weeks and a long term prediction.

### How we calibrate the model:

The model is fitted to Norwegian COVID-19 hospitalization prevalence data since March 10 until today. We seed new infections into the model using imported COVID-19 cases in Norway from February 26 until March 18.

### How you should interpret the results:

The model is stochastic (random). To predict the probability of various outcomes, we run the model many times. We present the results in terms of mean values, 95% confidence intervals, median and interquartile ranges. We underline that the confidence bands presented might be broader: First, there are uncertainties related to the natural history of SARS-CoV-2, including the importance of asymptomatic and presymptomatic infection. Second, there are uncertainties related to the timing of hospitalization relative to symptom onset, the severity of the COVID-19 infections by age, and the duration of hospitalization and ventilator treatment in ICU. These uncertainties are not fully explored in the present results. We will update the model parameters in accordance with new evidence and local data as they becomes available and results can change also significantly. See more details at the end of this report.

The mobility data is updated until April 15. It accounts for the changes in the movement patterns between municipalities that have occurred since start of the epidemics.

In the forecasting, we use the reproduction numbers that fit the hospitalization data best. The basic reproductive number,  $R_0$ , is used until March 14. A new effective reproductive number,  $R_{eff}$ , acts from March 15 until today, and in the future when we predict.  $R_0$  and  $R_{eff}$  are calibrated to hospitalization data (number of occupied beds) until today. Estimates of  $R_0$  and  $R_{eff}$  are uncertain, and we use their distribution to guarantee appropriate uncertainty of their estimates of our predictions. However, uncertainties related to the model parameters, as well as the transient period in week 11 and week 17, imply that reported effective reproductive values should be interpreted with caution. We will update the parameters related to permanence in hospital and ICU as soon as NPR data will be linked with MSIS.

Note that, in this report, the term patient in ventilator treatment includes only those patients that require either invasive mechanical ventilation or ECMO (Extracorporeal membrane oxygenation).

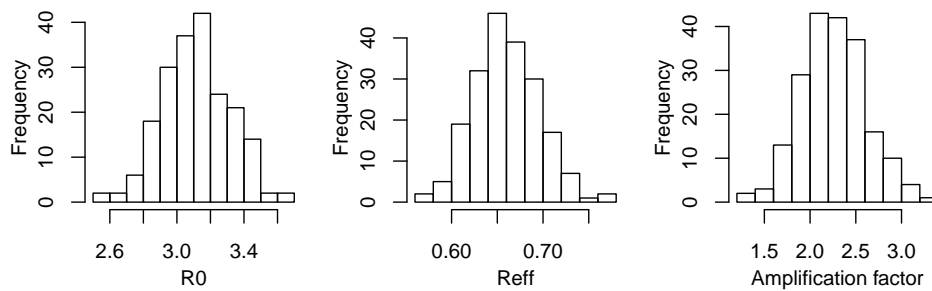
# 1 Estimated Reproductive Numbers

Calibration of our model with hospitalisation data leads to the following estimates:

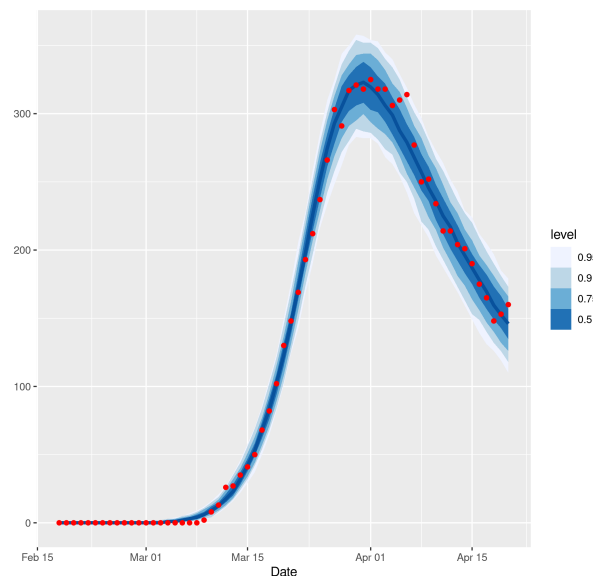
Table 1: Calibration results

Parameter	Mean	Median	Confidence interval (95 %)
Amplification factor	2.26	2.26	(1.6-2.97)
$R_0$	3.11	3.11	(2.75-3.49)
$R_{eff}$	0.66	0.66	(0.6-0.73)

Estimated densities of these three parameters are plotted below:



Our model estimates the number of hospitalised Covid-19 patients, plotted below with blue median and interquartile bands, which are compared with the actual hospitalisation data, in red. The uncertainty captures the uncertainty in the calibrated parameters in addition to the stochastic elements of our model.



True total number of hospitalisations (red) and predicted values (blue)

## 2 Estimated cumulative number of infected individuals

Table 2: Estimated cumulative number of infections, 2020-04-20

Region	Total	Symptomatic	No. confirmed	Fraction reported	Min. fraction
Norway	46585 (42330; 50382)	28549 (26038; 30720)	7113	15%	14%
Agder	2873 (2230; 3702)	1759 (1371; 2297)	292	10%	8%
Innlandet	2436 (1768; 3337)	1479 (1078; 2043)	412	17%	12%
Møre og Romsdal	920 (591; 1305)	570 (365; 827)	118	13%	9%
Nordland	763 (462; 1152)	467 (282; 692)	109	14%	9%
Oslo	10677 (9305; 11994)	6504 (5694; 7315)	2156	20%	18%
Rogaland	6262 (5041; 7660)	3836 (3096; 4657)	392	6%	5%
Troms og Finnmark	1410 (782; 2545)	857 (468; 1525)	223	16%	9%
Trøndelag	2128 (1554; 2752)	1307 (932; 1683)	420	20%	15%
Vestfold og Telemark	3700 (2739; 4998)	2258 (1682; 3019)	261	7%	5%
Vestland	5020 (3768; 6504)	3063 (2316; 3970)	795	16%	12%
Viken	10396 (8837; 11842)	6450 (5466; 7263)	1933	19%	16%

Fraction reported=Number confirmed/number predicted; Minimal fraction reported=number confirmed/upper CI

### 3 Predicted incidence of infected individuals, next three weeks

Predicted incidence (asymptomatic and symptomatic) for Norway per day, with confidence intervals.

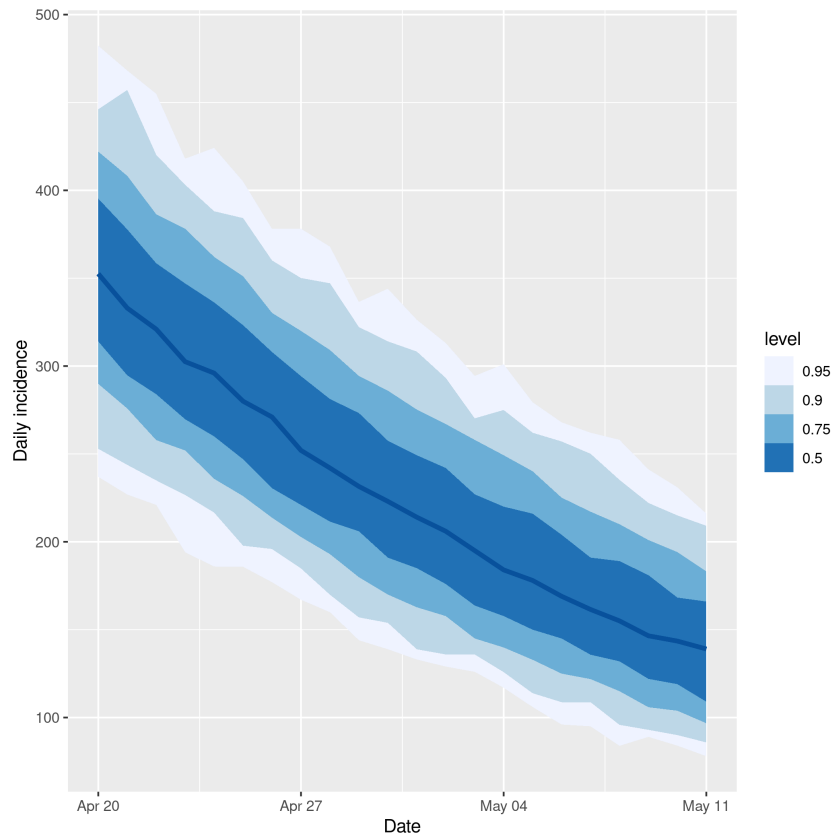


Table 3: Predicted incidence per day.

Region	1 week prediction (27 April)	2 weeks prediction (04 May)	3 weeks prediction (11 May)
Norway	259 (167-378)	190 (115-301)	140 (78-216)
Agder	16 (6-32)	12 (5-24)	9 (2-20)
Innlandet	18 (7-31)	14 (5-28)	11 (2-23)
Møre og Romsdal	6 (0-14)	4 (0-11)	3 (0-9)
Nordland	5 (0-11)	4 (0-9)	3 (0-8)
Oslo	42 (23-66)	31 (15-54)	23 (10-42)
Rogaland	33 (17-54)	24 (11-44)	17 (6-34)
Troms og Finnmark	8 (2-17)	6 (0-13)	4 (0-11)
Trøndelag	14 (5-23)	10 (3-20)	8 (2-16)
Vestfold og Telemark	21 (10-36)	16 (6-30)	12 (4-22)
Vestland	29 (14-49)	21 (9-40)	16 (5-29)
Viken	71 (45-107)	52 (26-87)	39 (18-66)

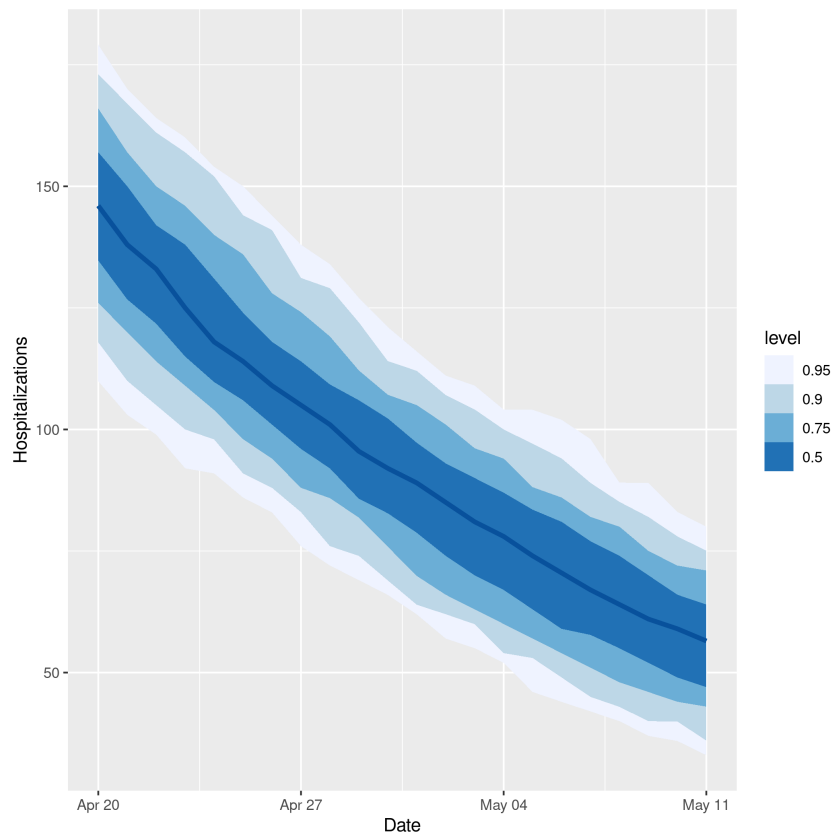
## 4 Predicted hospitalisation, next three weeks, including patients in ventilator treatment

Table 4: Number of hospitalisation beds occupied by Covid-19 patients.

Region	1 week prediction (27 April)	2 weeks prediction (04 May)	3 weeks prediction (11 May)
Norge	105 (70-143)	77 (49-109)	56 (32-83)
Agder	7 (1-15)	5 (0-13)	3 (0-10)
Innlandet	7 (1-15)	6 (0-14)	4 (0-10)
Møre og Romsdal	3 (0-8)	2 (0-7)	1 (0-5)
Nordland	2 (0-7)	2 (0-6)	1 (0-5)
Oslo	20 (9-34)	13 (4-26)	8 (1-18)
Rogaland	13 (4-24)	9 (1-18)	6 (0-16)
Troms og Finnmark	3 (0-10)	2 (0-9)	2 (0-7)
Trøndelag	5 (0-12)	4 (0-10)	3 (0-8)
Vestfold og Telemark	10 (1-21)	7 (1-18)	5 (0-14)
Vestland	12 (3-23)	8 (1-19)	6 (0-14)
Viken	24 (11-38)	20 (7-32)	15 (5-28)

Yesterday's real value for Norway: 160

Predicted daily number of COVID-19 patients in hospital in Norway (95% confidence intervals and interquartile range), next three weeks, including patients ventilator treatment.



Similar table and figure for each county (fylke) available on request.

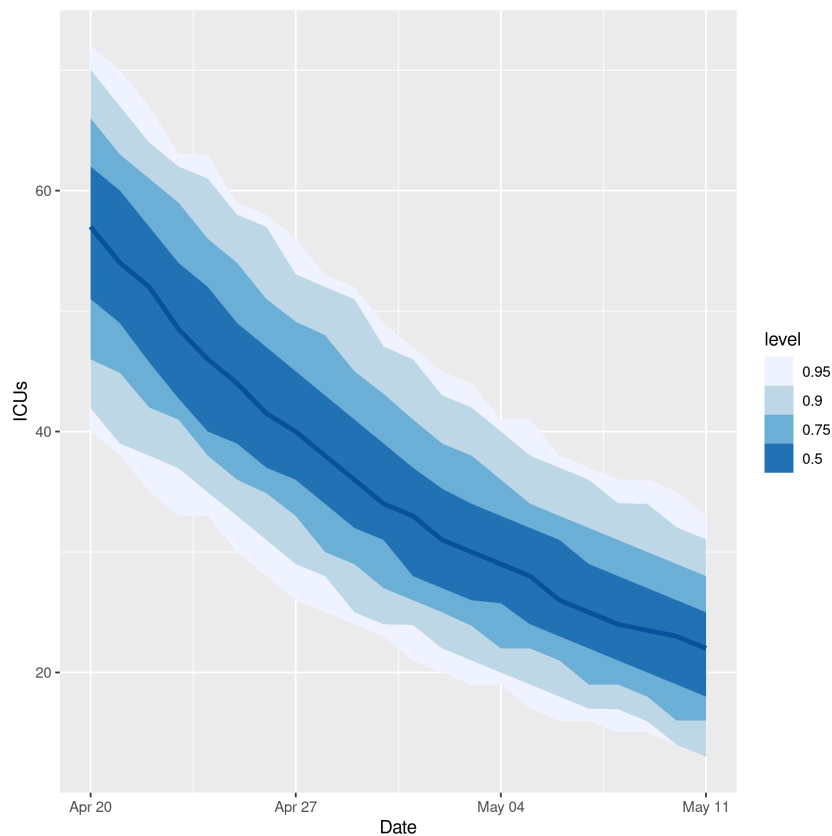
## 5 Predictive number of patients in ventilator treatment: next three weeks

Table 5: Number of ICU beds occupied by Covid-19 patients.

Region	1 week prediction (27 April)	2 weeks prediction (04 May)	3 weeks prediction (11 May)
Norge	40 (26-56)	29 (19-41)	22 (13-33)
Agder	3 (0-6)	2 (0-6)	1 (0-4)
Innlandet	3 (0-7)	2 (0-6)	2 (0-4)
Møre og Romsdal	1 (0-3)	1 (0-3)	1 (0-2)
Nordland	1 (0-3)	1 (0-3)	0 (0-2)
Oslo	7 (3-13)	5 (1-10)	3 (0-7)
Rogaland	5 (1-10)	3 (0-7)	2 (0-6)
Troms og Finnmark	1 (0-4)	1 (0-3)	1 (0-3)
Trøndelag	2 (0-5)	1 (0-4)	1 (0-3)
Vestfold og Telemark	4 (0-8)	3 (0-7)	2 (0-6)
Vestland	5 (1-10)	3 (0-8)	2 (0-6)
Viken	9 (4-15)	7 (2-12)	6 (2-11)

Yesterday's real value for Norway: 43

Predicted daily number of COVID-19 patients in ventilator treatment in Norway (95% confidence intervals and interquartile range), next three weeks.



Similar table and figure for each county (fylke) available on request.

## 6 Predicted prevalence of infectious individuals, next three weeks:

Predicted daily prevalence of asymptomatic, presymptomatic and symptomatic individuals, aggregated, whole Norway, (95% confidence interval).

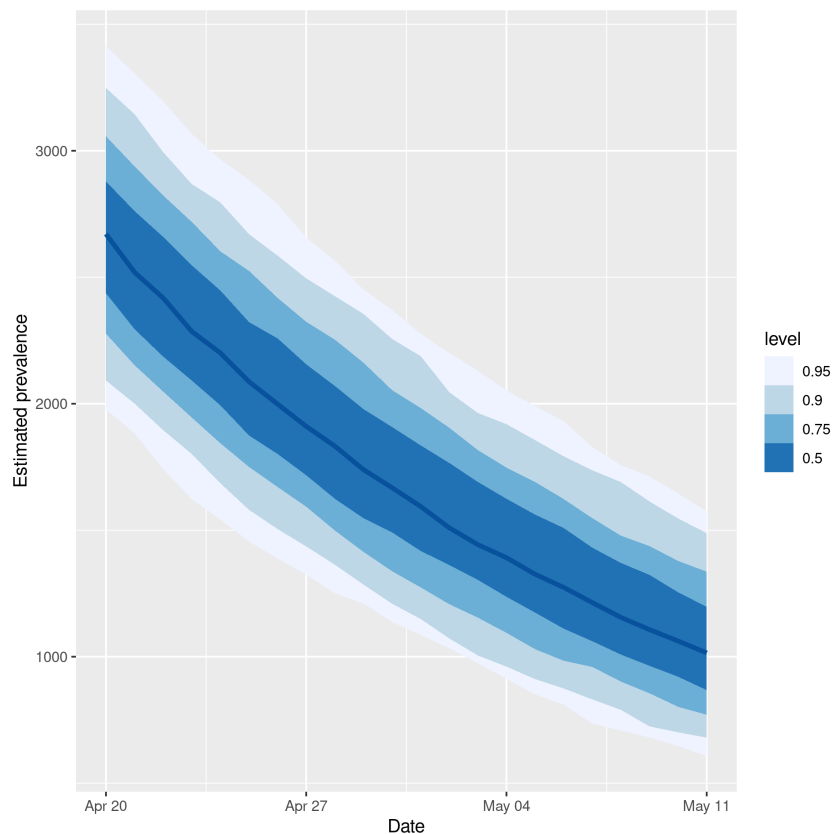
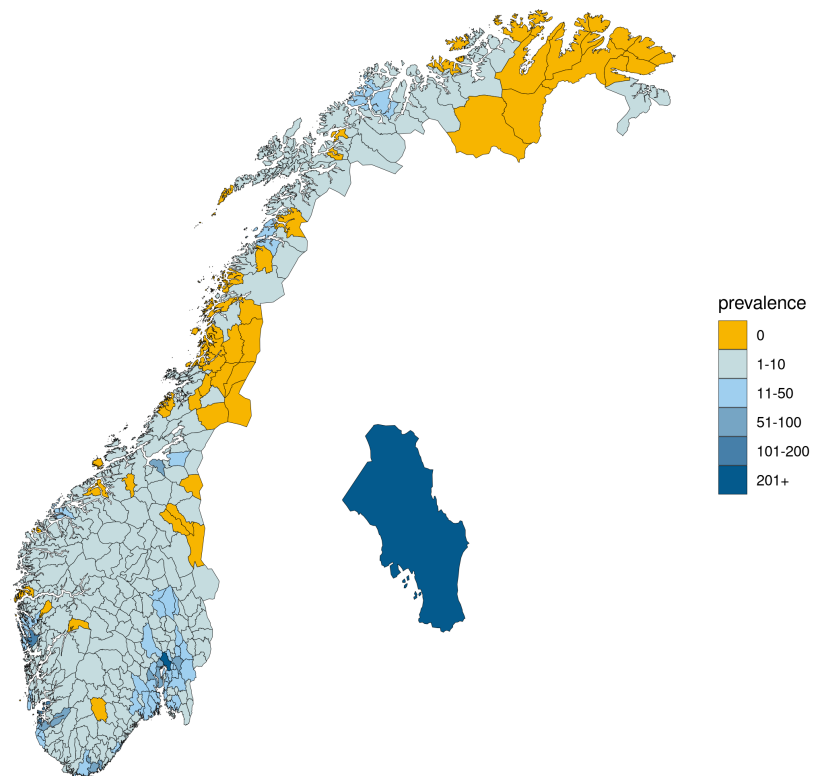


Table 6: Predicted prevalence. Number of infectious individuals (asymptomatic plus pre-symptomatic plus symptomatic) per day. Means and 95 perc. CI for three weeks prediction.

Region	Mean, 27 April	Mean, 04 May	Mean, 11 May	low CI, 11 May	high CI, 11 May
Norway	1937	1418	1039	590	1575
Agder	120	89	67	27	127
Innlandet	135	101	76	33	139
Møre og Romsdal	43	31	23	6	54
Nordland	34	25	18	4	39
Oslo	310	227	166	84	269
Rogaland	246	178	130	73	216
Troms og Finnmark	58	42	31	10	65
Trøndelag	98	72	53	25	94
Vestfold og Telemark	155	115	84	44	154
Vestland	213	155	114	55	198
Viken	528	386	281	151	443

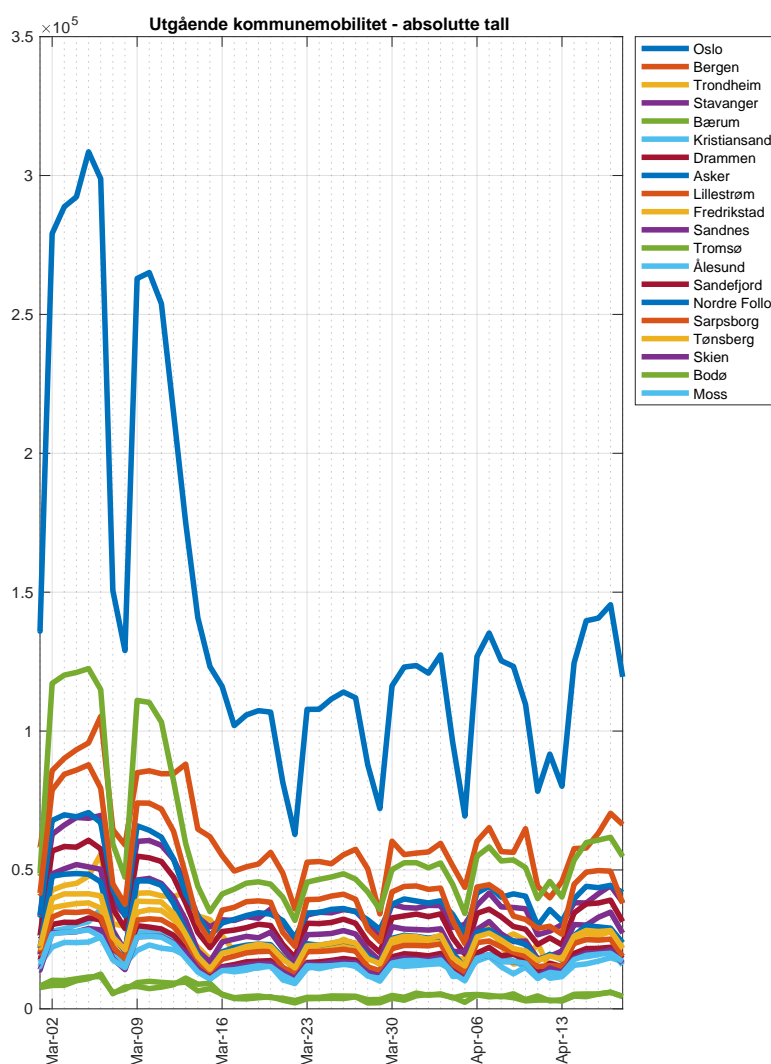
Map of predicted prevalence. Number of infectious individuals (asymptomatic plus presymptomatic plus symptomatic) today in each municipality.





## 7 Mobility between municipalities

Number of trips out from each municipality during each day, based on Telenor mobility data. We have observed a large reduction in inter-municipality mobility in week 11 (around March 11), with a minimum reached on Tuesday 17 March. The reduction with respect to the weeks before (for example week 10) is on average 50%. Thereafter, we observe a slight increasing trend: in Oslo, for example, out-mobility has increased of roughly 2% per day in the last three weeks. Weekends still have a lower mobility, indicating that there is still some commuting-to-job during weekdays.



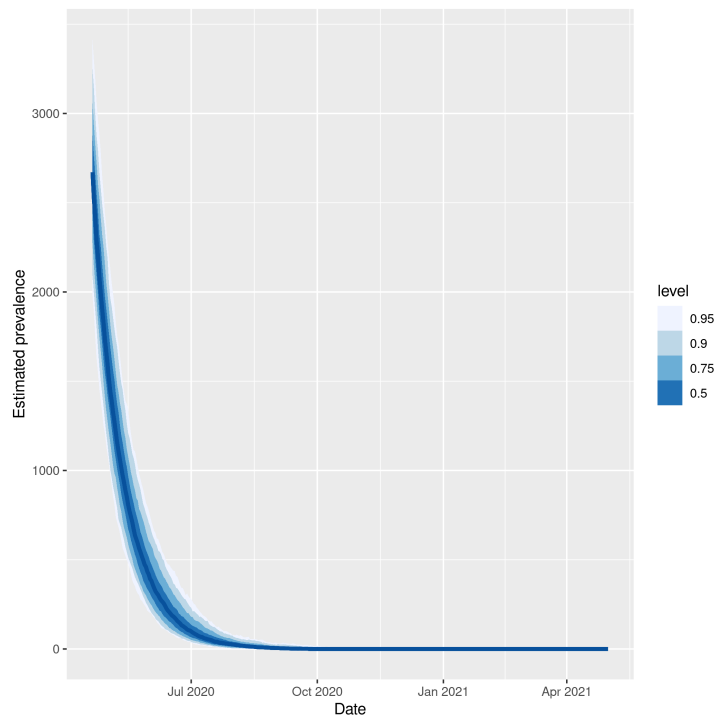
Percentage reduction in total mobility out from each municipality: Monday April 6th is compared to Monday March 2, which is the last Monday before interventions (March 12), etc.

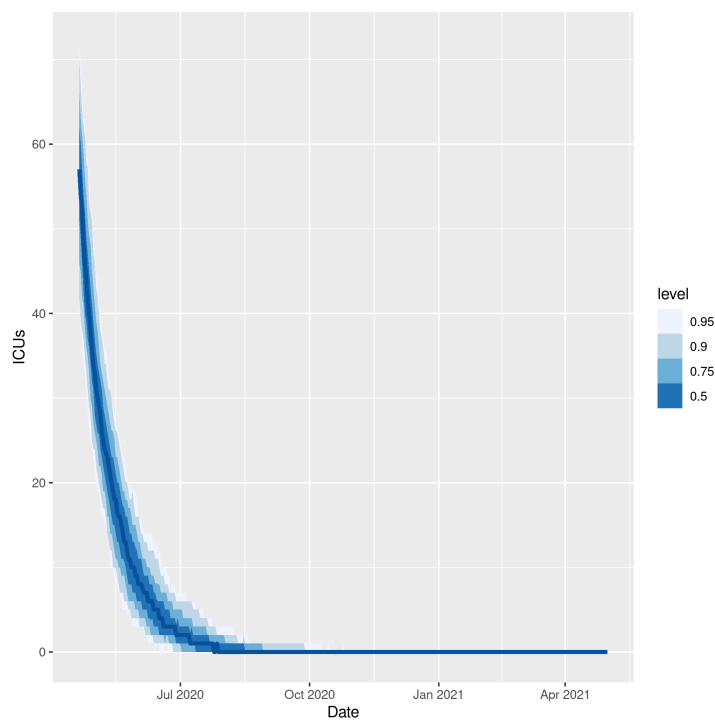
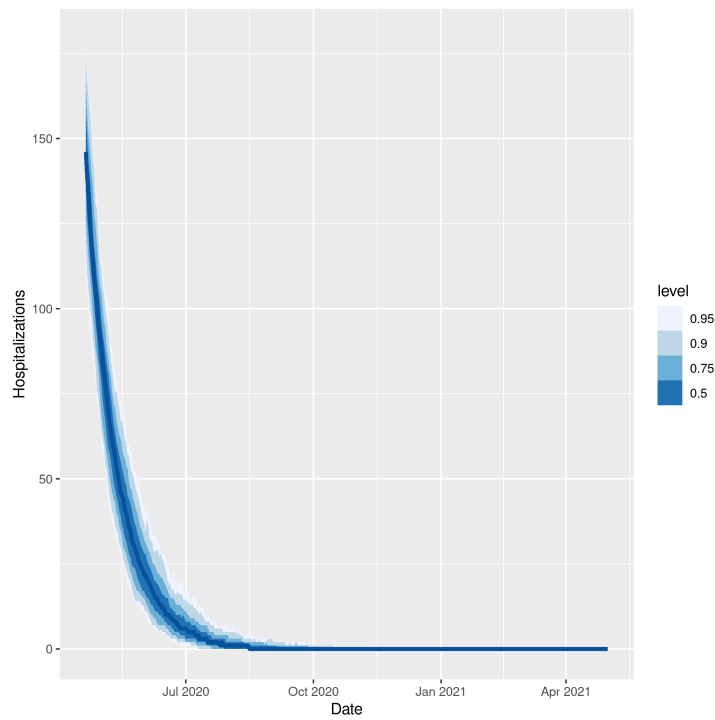
	Man_13	Tirs_14	Ons_15	Tors_16	Fre_17
Hele Norge	52%	38%	35%	35%	32%
Oslo	71%	57%	52%	54%	51%
Bergen	47%	36%	38%	34%	33%
Trondheim	68%	45%	45%	45%	50%
Stavanger	52%	42%	45%	40%	36%
Bærum	66%	55%	51%	50%	46%
Kristiansand	44%	36%	38%	38%	41%
Drammen	59%	41%	35%	37%	32%
Asker	54%	43%	36%	38%	34%
Lillestrøm	66%	47%	43%	43%	38%
Fredrikstad	47%	31%	28%	28%	22%
Sandnes	57%	40%	42%	35%	31%
Tromsø	67%	46%	57%	51%	53%
Ålesund	48%	34%	32%	29%	29%
Sandefjord	50%	36%	30%	33%	31%
Nordre Follo	63%	46%	39%	39%	36%
Sarpsborg	54%	32%	28%	30%	24%
Tønsberg	55%	37%	32%	33%	31%
Skien	52%	33%	27%	30%	25%
Bodø	68%	48%	50%	53%	48%
Moss	53%	36%	31%	31%	23%

## 8 Long-term prediction results

Predicted daily number of COVID-19 patients in hospital and receiving ventilator treatment in Norway until the end April, 2021, in addition to prevalence. The figures are made using 1 runs of each of the 200 candidate models, where the  $R_{eff}$  is varying accordingly.

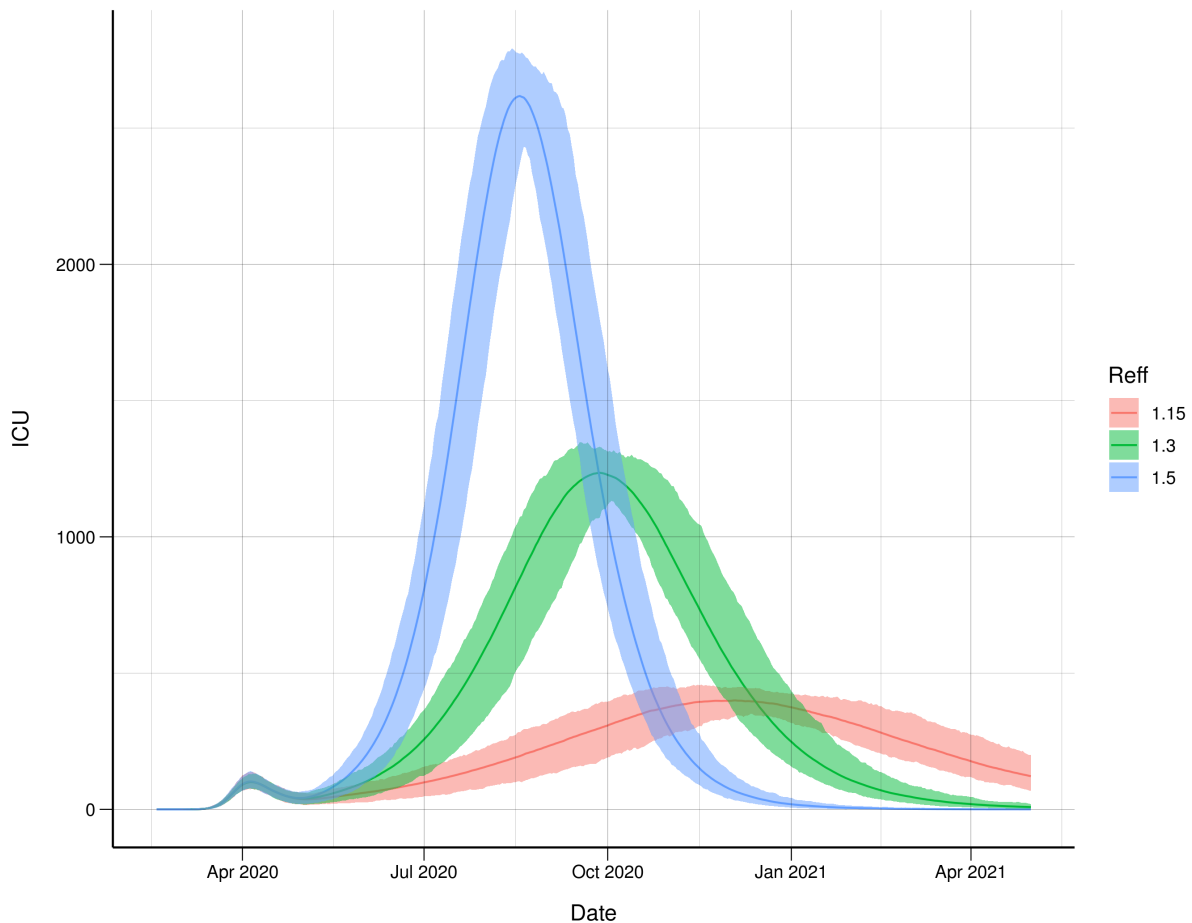
The confidence intervals reflected on the plots are two tailed around the median, and therefore the upper 95 % level shows the 97.5 % boundary.





## 9 Long-term scenario results

Here we show how the epidemics will develop, from April 13<sup>th</sup> if the reproductive number would increase to 1.15, 1.3 and 1.5 respectively. We show the daily number of covid-19 patients with ventilator treatment.

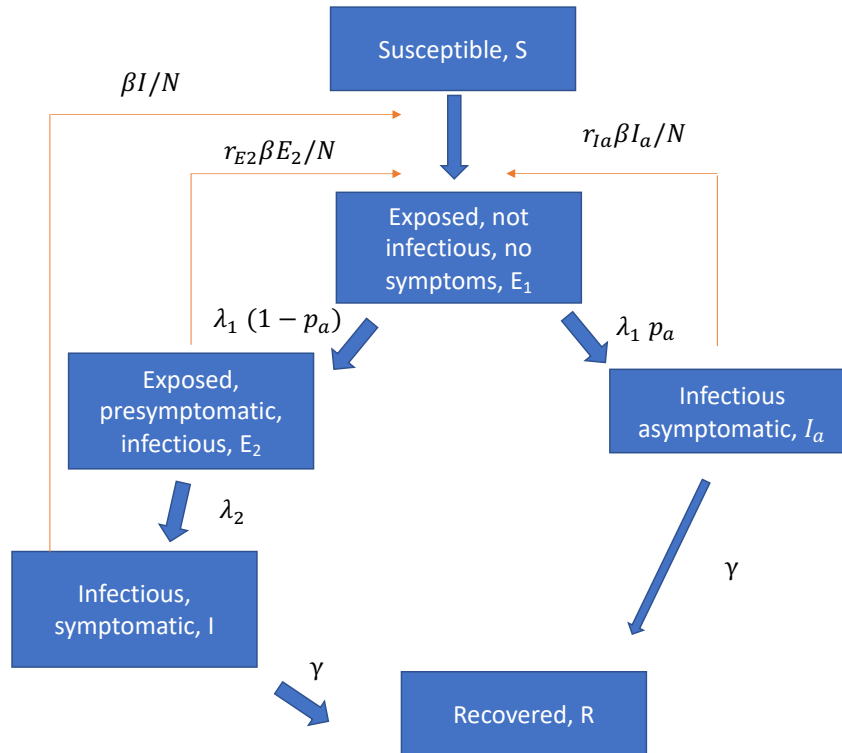


## Model

We use a metapopulation model to simulate the spread of COVID-19 in Norway in space and time. The model consists of three layers: the population structure in each municipality, information about how people move between different municipalities, and local transmission within each municipality. In this way, the model can simulate the spread of COVID-19 within each municipality, and how the virus is transported around in Norway.

### Transmission model

We use an SEIR (Susceptible-Exposed-Infected-Recovered) model without age structure to simulate the local transmission within each area. Mixing between individuals is assumed random. Demographic changes due to births, immigration, emigration and deaths are not considered. The model distinguishes between asymptomatic and symptomatic infection, and we consider presymptomatic infectiousness among those who develop symptomatic infection. In total, the model consists of 6 disease states: Susceptibles (S), Exposed, infected, but not infectious (E), Presymptomatic infected (E2), Symptomatic infected (I), Asymptomatic infected (Ia), and Recovered, either immune or dead (R). A schematic overview of the model is shown below:



### Movements between municipalities:

We use 6-hourly mobility matrices from Telenor to capture the movements between municipalities. The matrices are scaled according to the overall Telenor market share in Norway, estimated at 48%. Since week 8, we use the actual daily mobility matrices to simulate the past. In this way, alterations in the mobility pattern will be incorporated in our model predictions. To predict future movements, we use the latest weekday measured by Telenor. We follow closely the development in the mobility matrices, and weekend patterns will be introduced if needed.

## Healthcare utilization

Based on the estimated daily incidence data from the model and the population age structure in each municipality, we calculated the hospitalization using a weighted average. The hospitalization is assumed delayed relative to symptom onset. We calculate the number of patients admitted to ventilator treatment from the patients in hospital using age adjusted probabilities and an assumed delay.

## Seeding

At the start of each simulation, we locate 5.367.580 people in the municipalities of Norway according to data from SSB per January 1. 2020. All confirmed Norwegian imported cases with information about residence municipality and test dates are used to seed the model, until 18th March. For each case, we add an additional random number of infectious individuals, in the same area and on the same day, to account for asymptomatic imported cases who were not tested or others missed. This is called amplification factor.

## Reproduction number and calibration

We assume a reproduction number  $R_0$  until March 14 and a new effective reproduction number  $R_{eff}$  active from March 15 until today, and in the future when we predict. We estimate the reproduction numbers  $R_0$  and  $R_{eff}$  so that the predicted number of hospitalized individuals is closest to the true number of hospitalized individuals, from March 10 until today. Restrictions introduced on March 12 require a change in the effective reproduction number. We use a method called sequential ABC which tests thousands of combinations of  $R_0$ ,  $R_{eff}$  and the amplification factor, to determine the 200 ones that lead to the best fits of hospitalisations. Then we run 1 simulation of the future for each of these 200 best parameters.

## Update notes: what is new in this report.

Here we list aspects of the model or of the input parameters which have changed compared to previous reports, and we explain the reason for these changes. Some changes will have big effects on some of our estimates.

- 14 April: **Hospitalisation risk:** Our model requires the specification of the proportion of symptomatic and asymptomatic patients requiring hospitalisation. Previously we used estimates from Verity et al. (2020) based on Chinese data, adapted to the Norwegian demography, and to the reduced mobility of elderly patients living in elderly homes. We summarised this proportion to be 5.6%. Under these assumptions, our model estimates a cumulative number of infected individuals of ca. 14.000. As we have had ca 135 confirmed deaths in Norway, this corresponds to an Infection Fatality Ratio (IFT) of roughly 1%. However, international studies indicate that the IFT should be around 0.3% (<https://www.cebm.net/covid-19/global-covid-19-case-fatality-rates/>). We therefore calibrate our model to this IFT (in addition to calibrate the model to the hospitalisation data), by adjusting the hospitalisation risk in our model, reducing it by a third, to 1.85%. The effect of this change is visible on the estimated cumulative number of infected individuals, which is now approximately 45.000. A further effect of this change is that the reproductive numbers are different, with  $R_0$  larger and  $R_{eff}$  smaller than before, when we had a higher hospitalisation risk.
- 14 April: **Change point for the reproductive number:** On March 12, a number of contact restrictions were implemented. During that week 11, mobility was reduced significantly, and appears to stabilize on Monday March 16th. Between the 11th and 16th of March we expect a reduction of the reproduction rate. We model this change as a sudden jump from a first reproduction rate  $R_0$  to a second and lower reproduction rate  $R_{eff}$ , through a change in the model parameter  $\beta$ . We have chosen Monday March 15 as the changepoint for the reproductive number because it gives the best fit to the hospitalisation data. If we move the changepoint to March 14, or assume a

continuous linear reduction during week 11, the fit deteriorates. We also notice that the best changepoint depends on the assumed time between symptoms appearance and hospitalisation, which is assumed to have mean 8 days in this report. The optimal changepoint also depends on the assumed hospitalisation risk.

- 20 April: **Change in parameter estimation method:** We use sequential ABC instead that iterative parameter calibration. Estimation of the reproduction numbers and of the amplification factor in seeding of the epidemic at the start is done using Approximate Bayesian Computation (ABC), as described in Engebretsen et al. (2020): <https://www.medrxiv.org/content/10.1101/2020.03.11.20033555v1>. Sequential ABC avoids to calibrate  $R_0$  first on part of the data and then, given the best values of such  $R_0$ , to find the best fitting  $R_{eff}$ , which might not lead to optimal estimation and is based on more ad-hoc choices. We also do not weight the last part of the data more than the rest. Sequential ABC takes more time to run: therefore the daily report might use only the hospitalisation until yesterday.



## Parameters used today

Table 7: Assumptions I

Assumptions	Mean	Distribution	Reference
<b>Seeding</b>			
Scaling factor on imported cases	Min. 1.37 1st Qu. 2.01 Median 2.26 Mean 2.26 3rd Qu. 2.48 Max. 3.23	random	Calibrated to hospitalizations together with $R_0$
Telenor coverage	48%		<a href="https://ekomstatistikken.nkom.no/">https://ekomstatistikken.nkom.no/</a>
<b>Model parameters</b>			
Exposed period ( $1/\lambda_1$ )	3 days	Exponential	Fraser et al. Not published
Pre-symptomatic period ( $1/\lambda_2$ )	2 days	Exponential	Fraser et al. Not published
Symptomatic infectious period ( $1/\mu$ )	5 days	Exponential	Fraser et al. Not published
Asymptomatic, infectious period ( $1/\mu$ )	5 days	Exponential	Fraser et al. Not published
Infectiousness asympt. ( $r_{I_a}$ )	0.1	Fixed	Fraser et al. Not published
Infectiousness presymp ( $r_{E_2}$ )	1.25	Fixed	Fraser et al. Not published
Prob. asymptomatic infection ( $p_a$ )	0.4		Fraser et al. Not published
$R_0$ (until March 14)	Min. 2.59 1st Qu. 2.97 Median 3.11 Mean 3.12 3rd Qu. 3.25 Max. 3.66	random	Calibrated to hospitalizations
$R_{eff}$ , from 15 March until today	Min. 0.57 1st Qu. 0.64 Median 0.66 Mean 0.66 3rd Qu. 0.68 Max. 0.77	random	Calibrated to hospitalizations

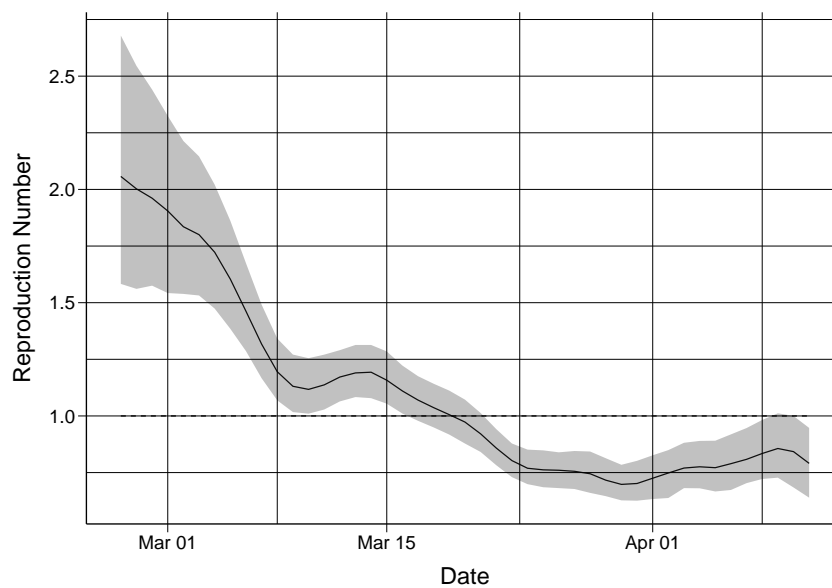
Table 8: Assumptions II

Assumptions	Mean	Distribution	Reference
<b>Healthcare</b>			
Time sympt. onset to hospitalisation	8 days	Poisson	
Fraction asymptomatic infections	40%	Fixed	<a href="#">Mizumoto et al 2020</a> 20% for the old population, Diamond Princess
% symptomatic and asymptomatic infections requiring hospitalization:			<a href="#">Verity et al 2020</a> corrected for: % of elderly living in of elderly living in Norway (last two age groups). Also corrected by 1/3 to account for severity in comparison with the expected fatality rate.
0-9 years	0.00%	Fixed	
10 - 19 years	0.013%		
20 - 29 years	0.37%		
30 - 39 years	1.13%		
40 - 49 years	1.43%		
50 - 59 years	2.73%		
60 - 69 years	3.93%		
70 - 79 years	5.53%		
80+ years	5.33%		
% hospitalized patients requiring ICU			
0-9 years	5%	Fixed	<a href="#">Verity et al 2020</a>
10 - 19 years	5%		
20 - 29 years	5%		
30 - 39 years	5%		
40 - 49 years	6.3%		
50 - 59 years	12.2%		
60 - 69 years	27.4%		
70 - 79 years	43.2%		
80+ years	70.9%		
Overall hospitalization risk	1.9%	Fixed	<a href="#">Verity et al 2020</a> (adapted to Norwegian population)
Normal hospitalization length	8 days	Poisson	<a href="#">Ferguson et al 2020</a>
Time in hospital before ICU	4 days	Poisson	<a href="#">Ferguson et al 2020</a> , Expert opinion
Time in ICU	12 days	Poisson	<a href="#">Ferguson et al 2020</a> , Expert opinion
<b>Mobile phone mobility</b>			
Until April 18	Measured Telenor mobility		
Data used in the predictions	April 15	Fixed	Corrected to preserve population

## Supplementary analysis: Instantaneous Reproduction Number based on lab-confirmed cases only, EpiEstim

These following results are based on confirmed cases and should be interpreted very carefully due to the multiple changes in testing criteria during this period. During the early part of the period, testing was mainly based on travel to areas with an ongoing outbreak, while the last two weeks have changed to testing people with an acute respiratory infection. The fact that the reproduction number is close to or below one corresponds to the break in the exponential growth in confirmed cases. The last two weeks have seen a fairly constant rate of new confirmed cases.

Using the date of onset of the confirmed cases from the outbreak registry we estimate the instantaneous reproduction number using the procedure outlined in Thompson et Al (2019). This method, implemented in the EpiEstim R-package uses a Bayesian method to estimate the instantaneous reproduction number smoothed over a sliding window of 7 days. For data without onset date, we estimate an onset date by subtracting 7 days, which is the mean delay between the date of onset and reporting date in the data, from the reporting date. The serial interval was assumed at 5 days with uncertainty; the serial interval refers to the time between symptom onset between successive cases in a chain of transmission (see <https://www.medrxiv.org/content/10.1101/2020.02.03.20019497v2>). To account for censoring of observations with onset dates in the last few days we correct the observed data by the mean of a negative binomial distribution with observation probability given by the empirical cumulative distribution of the onset to reporting date distributions. Due to this correction, the results from the last few days should be interpreted with caution. These dates are indicated by the weaker colours.



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