Situational awareness and forecasting

FHI COVID-19 modelling team

14 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 kommune
- Mobility data for inter-kommune movements (Telenor mobile phone data)
- Infection transmission model

The model produces estimates of the current epidemiological situation at the kommune, 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 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 13. It accounts for the changes in the movement patterns between municipalities that have occurred since March 12.

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 is calibrated to hospitalization data (number of occupied beds) until March 20; R_{eff} from March 21 until today. We weight the last days (from March 28) more than the first days. We use a distribution of all reproduction numbers to guarantee appropriate uncertainty of their estimates. However, uncertainties related to the model parameters, as well as the transient period in week 11 imply that reported effective reproductive values should be interpreted with caution. We notice that our prediction of intensive care beds are too high compared to current data. We will update the parameters related to permanence in hospital and ICU as soon as NPR data will be linked with MSIS.

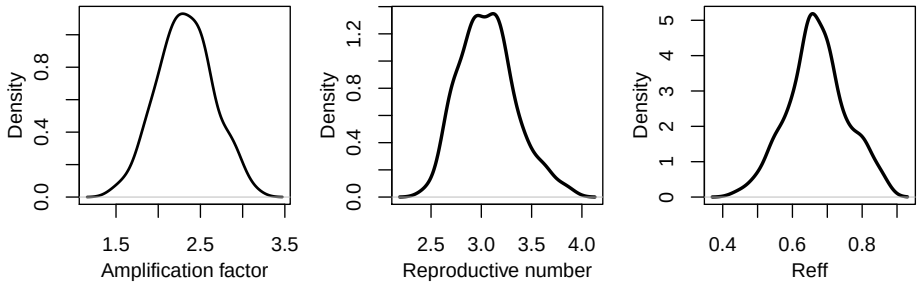
1 Estimated Reproductive Numbers

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

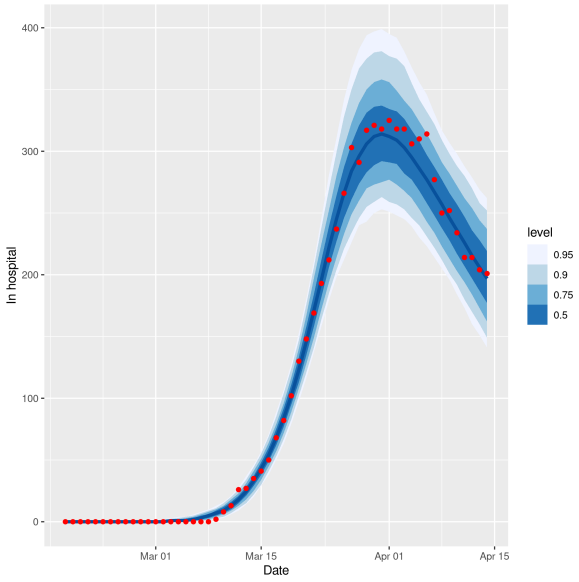
Table 1: Calibration results

Parameter	Mean	Median	Confidence interval (95 %)
Amplification factor	2.32	2.33	(1.71-2.96)
Ro	3.06	3.06	(2.64-3.64)
Reff	0.67	0.65	(0.5-0.85)

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, 2020-04-14

Region	Total	Symptomatic	No. confirmed	Fraction reported	Min. fraction
Norway	44581 (36924; 53021)	27297 (22884; 32151)	6566	15%	12%
Agder	2742 (1924; 3794)	1677 (1181; 2308)	266	10%	7%
Innlandet	2275 (1512; 3237)	1381 (910; 1954)	398	17%	12%
Møre og Romsdal	881 (554; 1296)	545 (338; 806)	117	13%	9%
Nordland	724 (412; 1169)	443 (247; 714)	95	13%	8%
Oslo	10311 (8436; 12541)	6274 (5124; 7602)	1960	19%	16%
Rogaland	5950 (4506; 7564)	3642 (2790; 4637)	380	6%	5%
Troms og Finnmark	1299 (608; 2537)	791 (367; 1554)	197	15%	8%
Trøndelag	1999 (1280; 2779)	1224 (808; 1713)	403	20%	15%
Vestfold og Telemark	3643 (2477; 5589)	2216 (1525; 3368)	247	7%	4%
Vestland	4763 (3426; 6405)	2905 (2087; 3885)	684	14%	11%
Viken	9994 (7999; 12342)	6198 (4996; 7579)	1810	18%	15%

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.

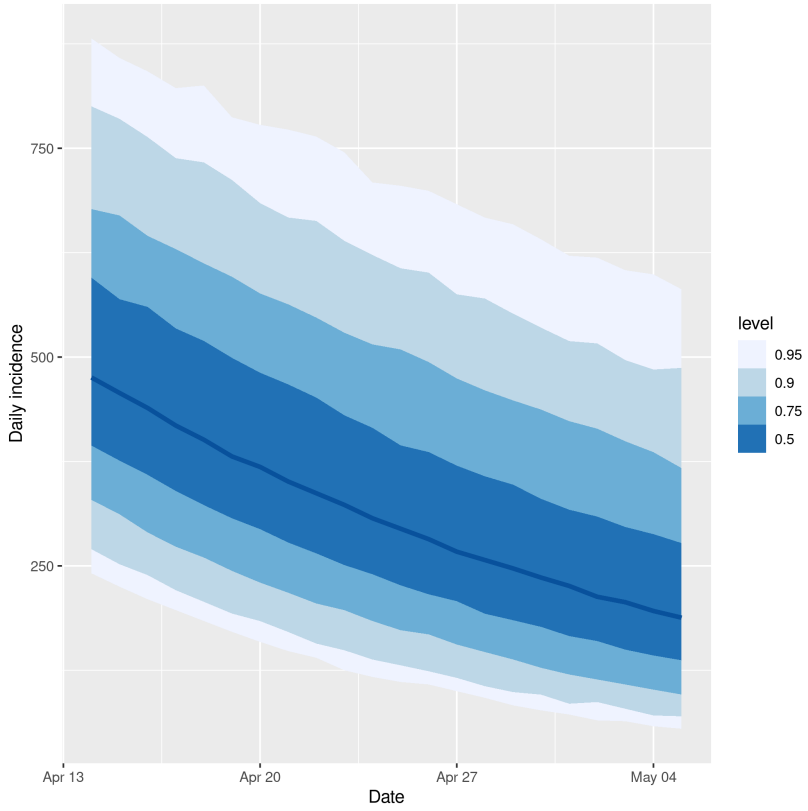


Table 3: Predicted incidence per day.

Region	1 week prediction (21 April)	2 weeks prediction (28 April)	3 weeks prediction (05 May)
Norway	381 (146-772)	289 (91-667)	221 (55-581)
Agder	24 (7-53)	18 (3-46)	14 (2-40)
Innlandet	26 (8-54)	20 (4-46)	15 (2-40)
Møre og Romsdal	9 (1-22)	7 (1-19)	5 (0-17)
Nordland	7 (1-19)	5 (0-15)	4 (0-14)
Oslo	62 (22-131)	47 (13-110)	35 (7-98)
Rogaland	48 (17-100)	36 (9-85)	28 (6-72)
Troms og Finnmark	11 (1-26)	8 (1-22)	6 (0-18)
Trøndelag	19 (5-42)	14 (2-36)	11 (1-30)
Vestfold og Telemark	31 (10-65)	24 (5-58)	18 (3-46)
Vestland	42 (14-88)	32 (8-73)	25 (5-64)
Viken	104 (39-209)	79 (23-179)	60 (14-161)

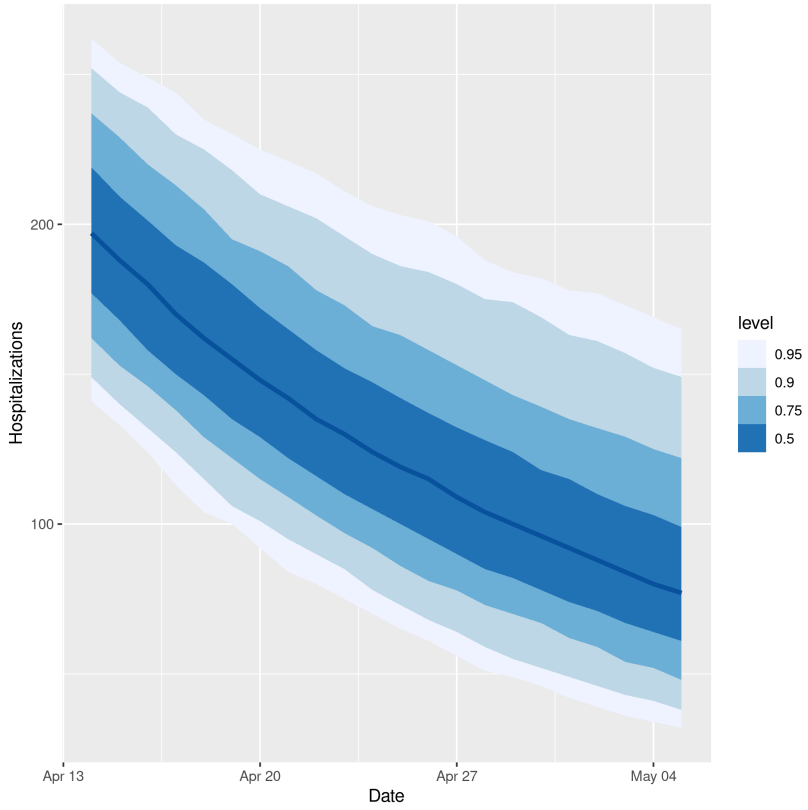
4 Predicted hospitalisation, next three weeks, including ICU

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

Region	1 week prediction (21 April)	2 weeks prediction (28 April)	3 weeks prediction (05 May)
Norge	145 (81-224)	109 (49-193)	83 (30-169)
Agder	9 (1-20)	7 (1-16)	5 (0-14)
Innlandet	10 (1-21)	8 (1-18)	6 (0-17)
Møre og Romsdal	3 (0-10)	3 (0-8)	2 (0-7)
Nordland	3 (0-9)	2 (0-8)	2 (0-7)
Oslo	27 (11-49)	18 (5-38)	12 (1-28)
Rogaland	18 (5-33)	13 (3-28)	10 (1-23)
Troms og Finnmark	4 (0-13)	3 (0-10)	2 (0-9)
Trøndelag	7 (0-15)	5 (0-13)	4 (0-12)
Vestfold og Telemark	14 (3-29)	10 (2-23)	8 (0-20)
Vestland	16 (5-32)	12 (3-26)	9 (1-23)
Viken	34 (16-59)	28 (9-56)	23 (6-50)

Yesterday's real value for Norway: 201

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



Similar table and figure for each fylke available on request.

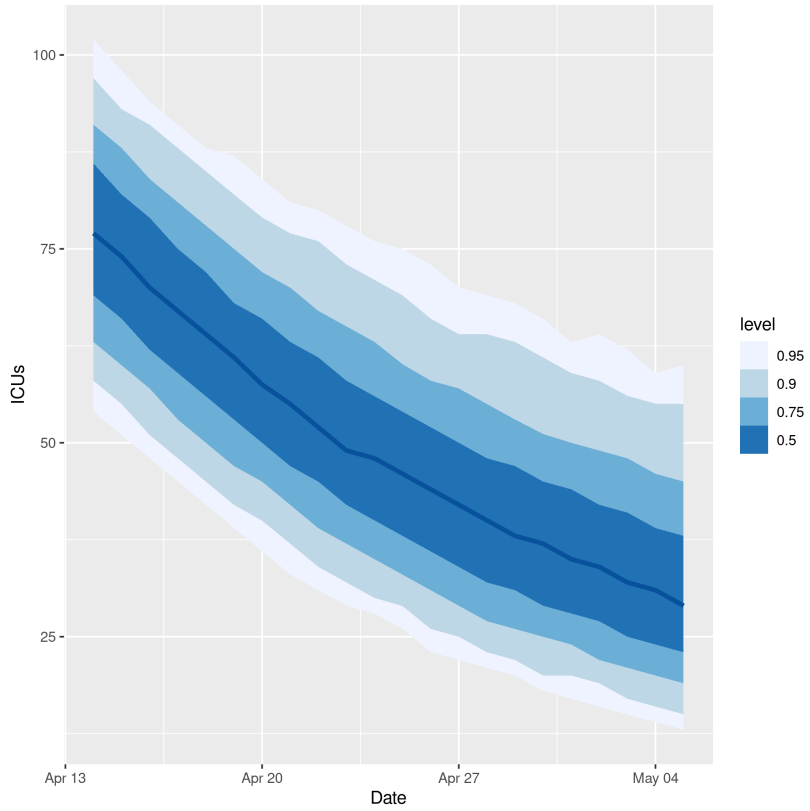
5 Predictive intensive care beds: next three weeks

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

Region	1 week prediction (21 April)	2 weeks prediction (28 April)	3 weeks prediction (05 May)
Norge	56 (33-81)	41 (21-69)	31 (13-60)
Agder	3 (0-8)	2 (0-6)	2 (0-5)
Innlandet	4 (0-9)	3 (0-7)	3 (0-7)
Møre og Romsdal	1 (0-4)	1 (0-3)	1 (0-3)
Nordland	1 (0-4)	1 (0-3)	1 (0-3)
Oslo	10 (4-18)	7 (2-14)	5 (0-10)
Rogaland	7 (2-13)	5 (1-11)	4 (0-9)
Troms og Finnmark	2 (0-5)	1 (0-4)	1 (0-4)
Trøndelag	3 (0-6)	2 (0-5)	2 (0-5)
Vestfold og Telemark	6 (1-12)	4 (1-9)	3 (0-8)
Vestland	6 (2-13)	5 (1-10)	3 (0-8)
Viken	13 (6-22)	10 (3-20)	8 (2-18)

Yesterday's real value for Norway: 53

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



Similar table and figure for each 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).

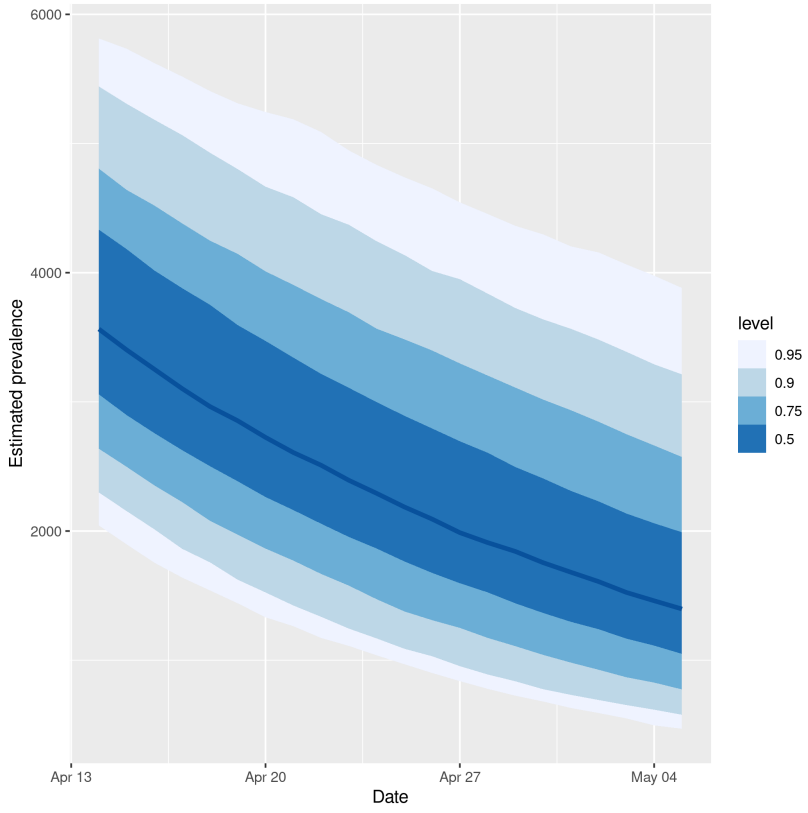
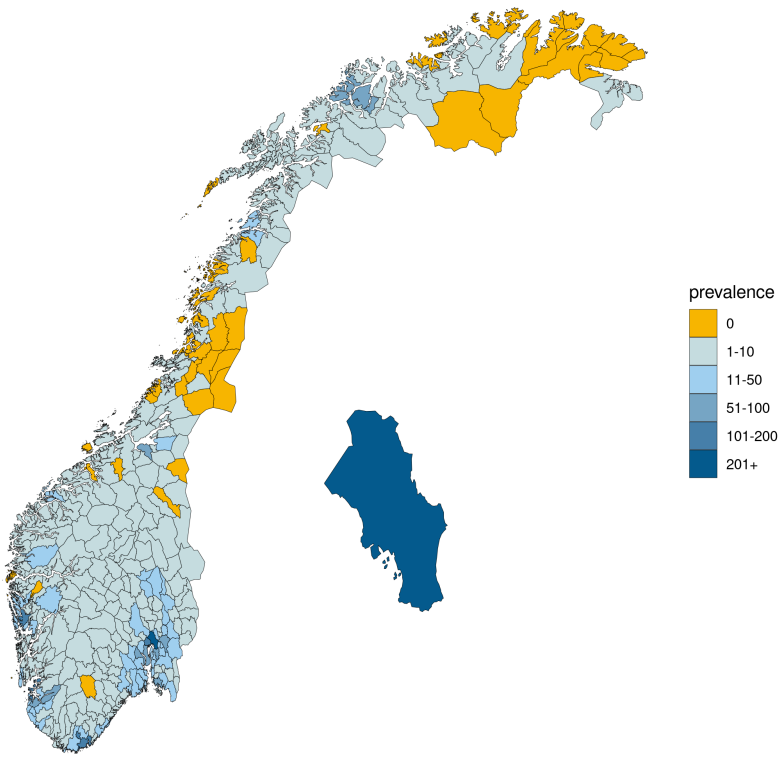


Table 6: Predicted prevalence. Number of infectious individuals (asymptomatic plus pre-symptomatic plus symptomatic) per day. Means and 95 perc. CI for three weeks prediction.

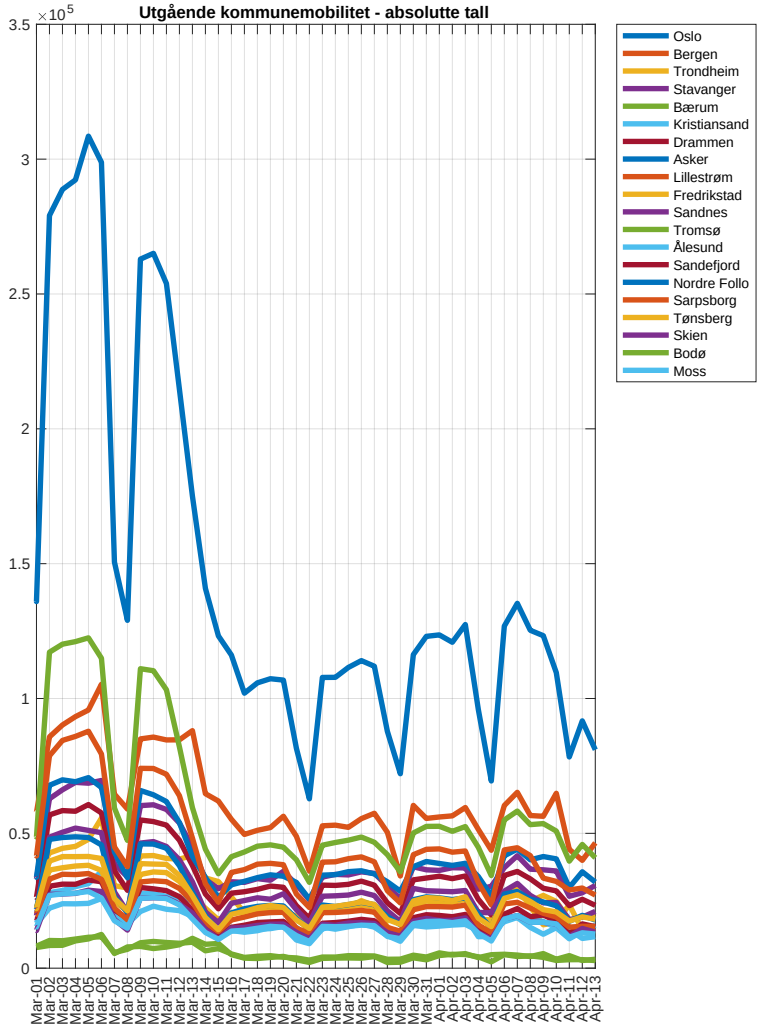
Region	Mean, 21 April	Mean, 28 April	Mean, 05 May	low CI, 05 May	high CI, 05 May
Norway	2782	2107	1605	467	3882
Agder	172	131	101	22	251
Innlandet	186	142	109	27	256
Møre og Romsdal	62	48	37	6	102
Nordland	49	38	29	4	84
Oslo	453	342	259	73	632
Rogaland	351	265	201	54	462
Troms og Finnmark	78	59	45	8	113
Trøndelag	137	105	79	17	197
Vestfold og Telemark	224	170	130	33	309
Vestland	305	232	178	49	433
Viken	763	577	438	127	1042

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



7 Mobility between kommuner

Number of trips out from each kommune during each day, based on Telenor mobility data. We have observed a large reduction in inter-kommune 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.



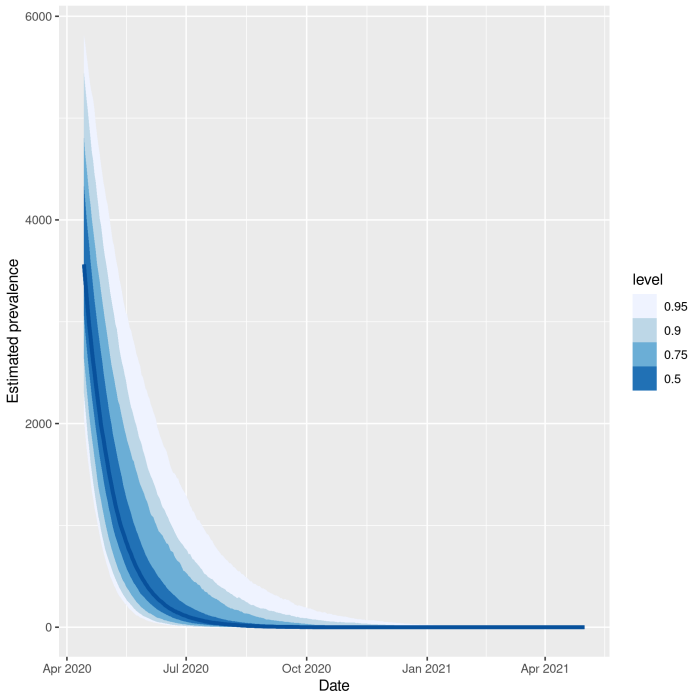
Percentage reduction in total mobility out from each kommune: Monday April 6th is compared to Monday March 2, which is the last Monday before interventions (March 12), etc.

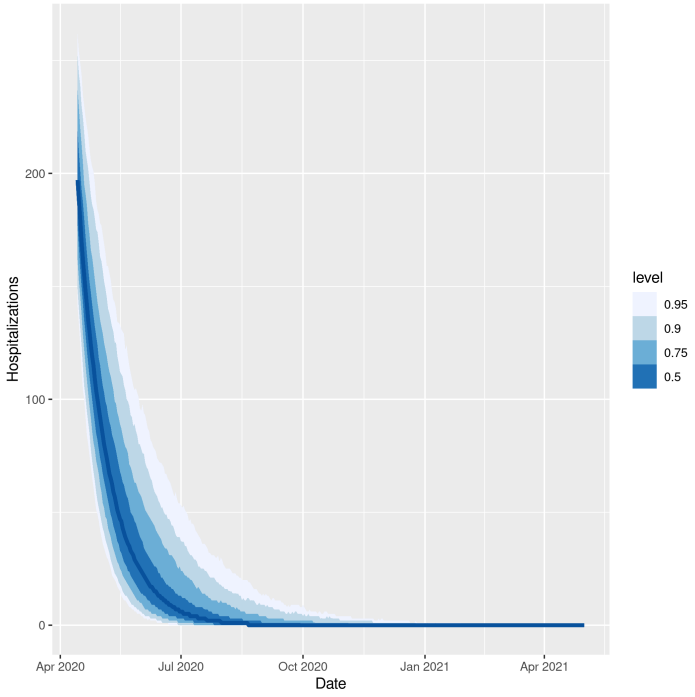
	Man_06	Tirs_07	Ons_08	Tors_09	Fre_10
Hele Norge	34%	32%	40%	44%	44%
Oslo	55%	53%	57%	60%	63%
Bergen	30%	28%	39%	41%	38%
Trondheim	37%	33%	49%	66%	69%
Stavanger	41%	37%	47%	47%	48%
Bærum	53%	52%	56%	56%	55%
Kristiansand	34%	32%	40%	45%	58%
Drammen	40%	39%	43%	51%	50%
Asker	39%	37%	42%	41%	39%
Lillestrøm	44%	47%	51%	62%	59%
Fredrikstad	28%	23%	34%	29%	31%
Sandnes	41%	38%	48%	53%	51%
Tromsø	40%	49%	55%	63%	77%
Ålesund	23%	21%	37%	48%	41%
Sandefjord	34%	29%	39%	40%	45%
Nordre Follo	42%	41%	47%	49%	49%
Sarpsborg	28%	30%	36%	42%	42%
Tønsberg	35%	34%	40%	48%	48%
Skien	33%	29%	38%	41%	42%
Bodø	50%	52%	60%	53%	71%
Moss	33%	29%	39%	40%	37%

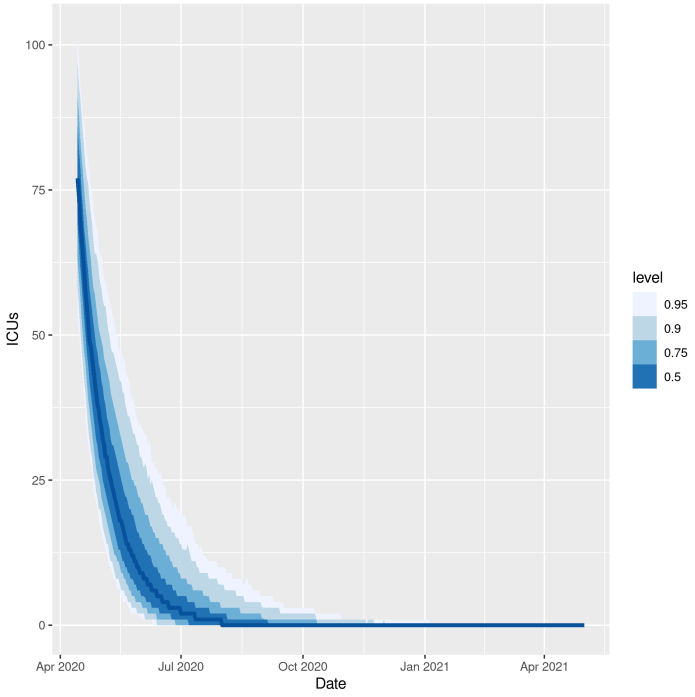
8 Long-term prediction results

Predicted daily number of COVID-19 patients in hospital and ICU in Norway until the end April, 2021, in addition to prevalence. The figures are made using 10 runs of each of the 100 candidate models, where the R_{eff}, from the March 15 and onward ranges between 0.45 and 0.85, with interquartile range 0.60-0.70 and median 0.65.

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



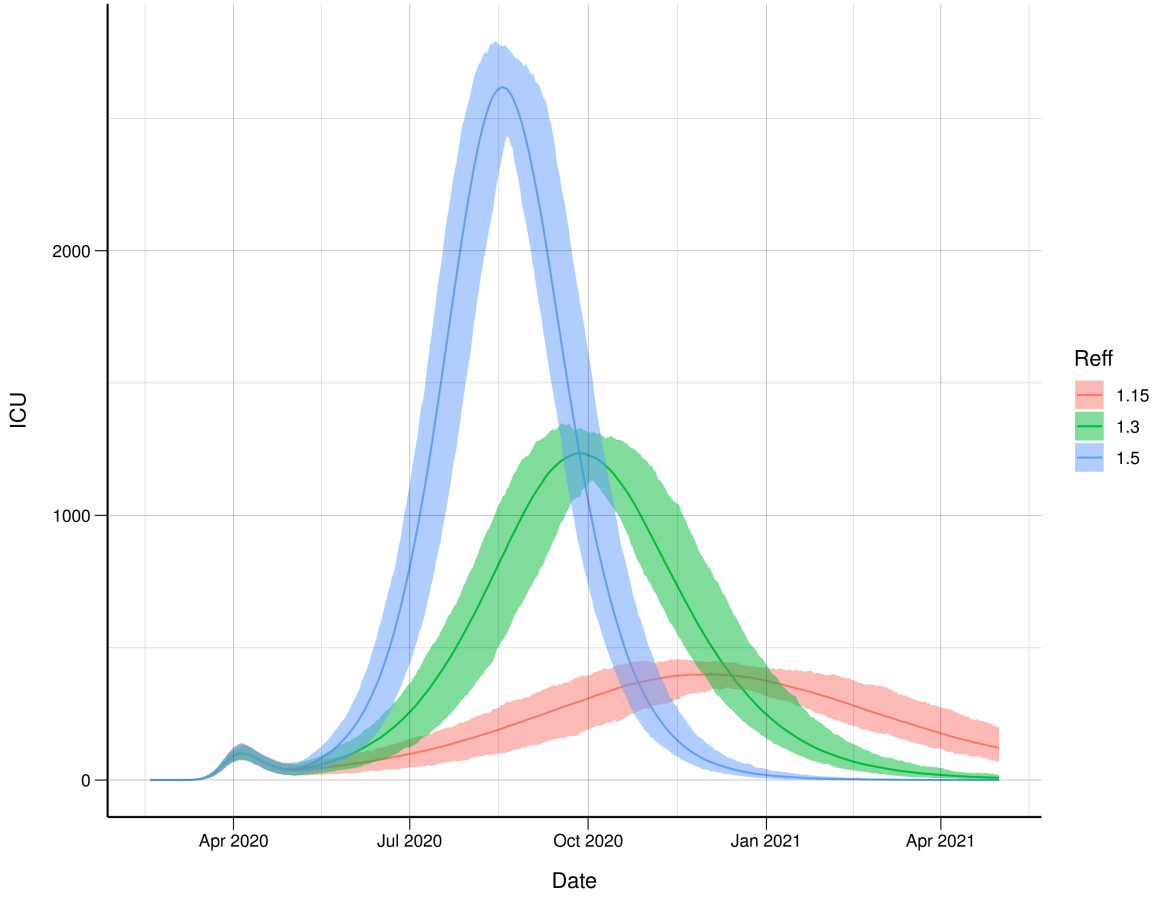




None of the simulations exceeded the surge capacity need of **500 ICU** beds.

9 Long-term scenario results

Here we show how the epidemics will develop, from the current situation, if the reproductive number would increase to $1.15, 1.3$ and 1.5 respectively. We show the daily number of covid-19 patients in ICU.

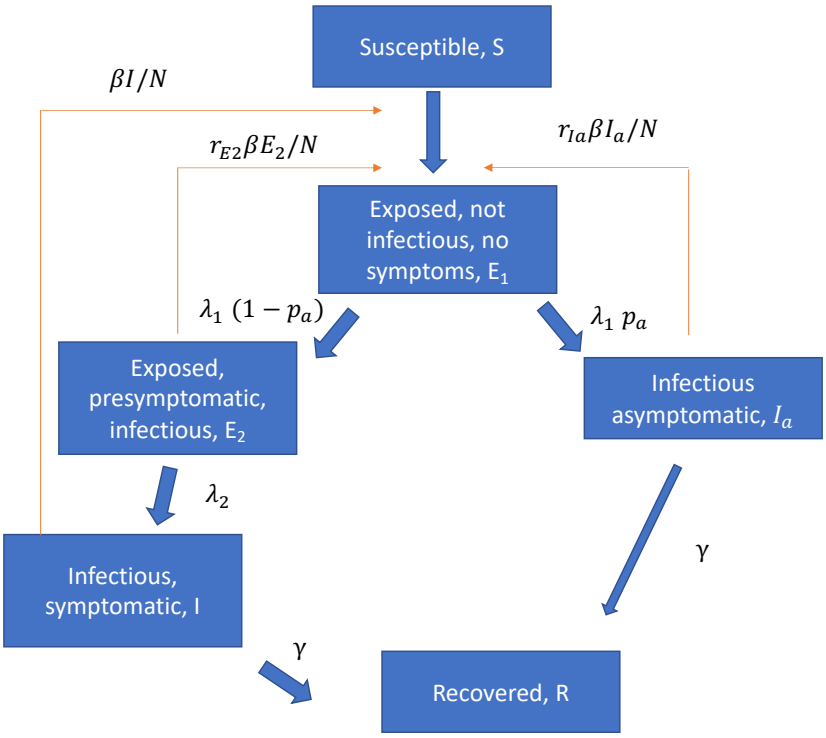


Model

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 kommuner, and local transmission within each kommune. In this way, the model can simulate the spread of COVID-19 within each kommune, 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 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 ICU 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.

Reproduction number and calibration

We estimate the reproduction number R_0 so that the predicted mean number of hospitalized individuals is closest to the true number of hospitalized individuals, from March 10 until March 20. Restrictions introduced on March 12 require a change in the effective reproduction number. The effective reproductive number R_{eff} is active from March 15 until today, and in the future when we predict. R_0 is calibrated to hospitalisation data (number of occupied beds) until March 20; R_{eff} from March 21 until today. We weight the last days (from March 28) more than the first days. We estimate R_0 by selecting the 100 best R_0s out of 10000 random candidates (each simulated 10 times). For these 100 best, we find by grid search the R_{eff} that fit best the hospitalisation data. Then we run 10 simulations of the future for each of these 100 best (R_0, R_{eff}).

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.

- **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.
- **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 β. 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.

Parameters used today

Table 7: Assumptions I

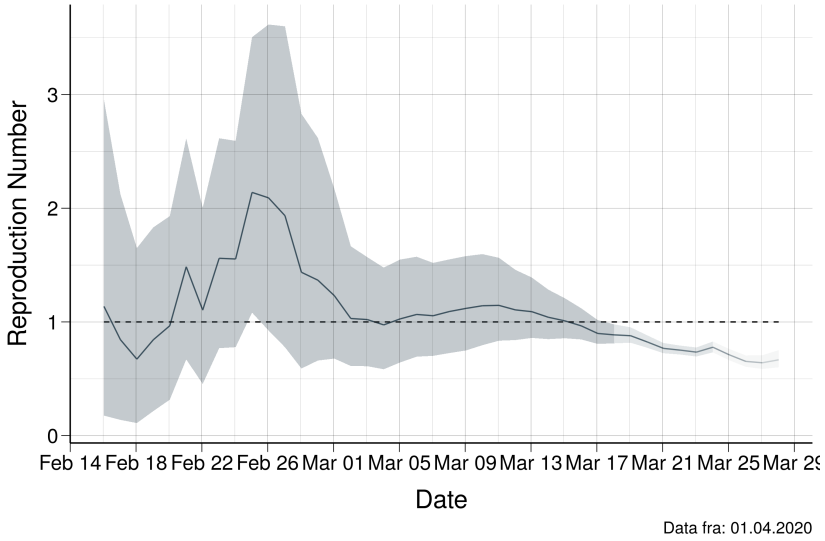
Assumptions	Mean	Distribution	Reference
Seeding			
Scaling factor on imported cases	Min. 1.49 1st Qu. 2.11 Median 2.33 Mean 2.32 3rd Qu. 2.53 Max. 3.14	random	Calibrated to hospitalizations together with R_0
Telenor coverage	48%		https://ekomstatistikken.nkom.no//statistics/
Model parameters			
Exposed 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. 2.46 1st Qu. 2.88 Median 3.06 Mean 3.06 3rd Qu. 3.22 Max. 3.86	random	Calibrated to hospitalizations
R_{eff}, from 15 March until today	Min. 0.45 1st Qu. 0.60 Median 0.65 Mean 0.67 3rd Qu. 0.70 Max. 0.85	random	Calibrated to hospitalizations

Table 8: Assumptions II

Assumptions	Mean	Distribution	Reference
Healthcare			
Time sympt. onset to hospitalisation	8 days	Poisson	
Fraction asymptomatic infections	40%	Fixed	Mizumoto et al 2020 20% for the old population, Diamond Princess
% symptomatic and asymptomatic infections requiring hospitalization: 0-9 years 10 - 19 years 20 - 29 years 30 - 39 years 40 - 49 years 50 - 59 years 60 - 69 years 70 - 79 years 80+ years	 0.00% 0.013% 0.37% 1.13% 1.43% 2.73% 3.93% 5.53% 5.33%	Fixed	Verity et al 2020 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.
% hospitalized patients requiring ICU 0-9 years 10 - 19 years 20 - 29 years 30 - 39 years 40 - 49 years 50 - 59 years 60 - 69 years 70 - 79 years 80+ years	 5% 5% 5% 5% 6.3% 12.2% 27.4% 43.2% 70.9%	Fixed	Verity et al 2020
Overall hospitalization risk	1.9%	Fixed	Verity et al 2020 (adapted to Norwegian population)
Normal hospitalization length	8 days	Poisson	Ferguson et al 2020
Time in hospital before ICU	4 days	Poisson	Ferguson et al 2020, Expert opinion
Time in ICU	12 days	Poisson	Ferguson et al 2020, Expert opinion
Mobile phone mobility			
Until April 13	Measured Telenor mobility		
Data used in the predictions	April 7	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 bellow 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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