NIPH
Norwegian Institute of Public Health

Situational awareness and forecasting for Norway

FHI COVID-19 modelling team

Week 53, 30 December 2020

Highlights:

- This report is a shortened version of the modelling report including only national results.
- **National epidemiological situation:** Our models evaluate the present situation as worsening with a clear increasing trend since the start of December. The effective reproduction number R_{10} acting in our changepoint model from 15 December is estimated to be 1.29 (median, 95% CI 0.91-1.66). The estimated probability that R_{10} is larger than 1 is 94%. The SMC model estimates the 7-days averaged effective reproduction number one week ago to be 1.33 (95% CI 1.02-1.68). In this model, the estimated probability that the daily reproduction number one week ago was above 1 is 99%. In comparison, the averaged effective reproduction number obtained from running the SMC model one week ago was 1.04 (95% CI 0.78- 1.35) with probability that Reff > 1 at 59%. Since the start of the epidemic, we estimate that in total 102.000 (95% CI 88.000- 116.000) persons in Norway have been infected. The current estimate of the detection probability is stable around $\tilde{5}0\%$.
- **National forecasting:** In one week, we estimate 1.400 new cases per day (median; 95%CI 550-2.770), and a prevalence (total number of infected people in Norway) of 7.750 (median; 95% CI 3.600-14.000). Hospitalisations in one week are estimated to be 165 (median 95% CI 115-226) and patients on ventilator treatment are estimated to be 23 (median 95% CI 13-33); the corresponding three-week projections are (95% CI 98 - 534) and (95% CI 14 - 68).
- **Telenor mobility data, local mobility and foreign roamers:** Inter-municipality mobility, measured as outgoing mobility of mobile phones from each municipality has declined over the last weeks. In week 53 the relative weekly mobility in Norway was at 62% compared to week 10 right before the lockdown, but with significant variations between municipalities across the country. In week 50, the corresponding inter-municipality mobility was at 87%. Analysis of foreign roamers shows that the number of visitors has dropped around 1/3 compared to the end of November.Polish and Lithuanian roamers show high visiting levels throughout 2020, but the levels have fallen sharply in late December. Roamers from England show an increasing trend since October, in particular in Oslo.

What this report contains:

This report presents results based on a mathematical infectious disease 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 (SEIR-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. We run three different models built on the same structure indicated above: (1) a national changepoint model, (2) a regional changepoint model and (3) a national Sequential Monte Carlo model, named SMC model.

How we calibrate the model: The national changepoint model is fitted to Norwegian COVID-19 hospital incidence data from March 10 until yesterday, and data on the laboratory-confirmed cases from May 1 until yesterday. We do not use data before May 1, as the testing capacity and testing criteria were significantly different in the early period.
Note that the results of the national changepoint model are not a simple average or aggregation of the results of the regional changepoint model because they use different data. The estimates and predictions of the regional model are more uncertain than those of the national model. The regional model has more parameters to be estimated and less data in each county; lack of data limits the number of changepoints we can introduce in that model. In the regional changepoint model, each county has its own changepoints and therefore a varying number of reproduction numbers. Counties where the data indicate more variability, have more changepoints.
The national SMC model is also calibrated both to the hospitalisation incidence data (same data as described above) and the laboratory-confirmed cases.

Telenor mobility data: The mobility data account for the changes in the movement patterns between municipalities that have occurred since the start of the epidemic.

How you should interpret the results: The model is stochastic. To predict the probability of various outcomes, we run the model many times in order to represent the inherent randomness.
We present the results in terms of mean values, 95% confidence intervals, medians, and interquartile ranges. We emphasise that the confidence bands might be broader than what we display, because there are several sources of additional uncertainty which we currently do not fully explore: firstly, there are uncertainties related to the natural history of SARS-CoV-2, including the importance of asymptomatic and presymptomatic infection. Secondly, there are uncertainties related to the timing of hospitalisation relative to symptom onset, the severity of the COVID-19 infections by age, and the duration of hospitalisation and ventilator treatment in ICU. We continue to update the model assumptions and parameters in accordance with new evidence and local data as they become available. A full list of all updates can be fount at the end of this report.
Estimates of all reproduction numbers are uncertain, and we use their distribution to assure appropriate uncertainty of our predictions. Uncertainties related to the model parameters imply that the reported effective reproductive numbers should be interpreted with caution.

When we forecast beyond today, we use the most recent reproduction number for the whole future, if not explicitly stated otherwise.

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

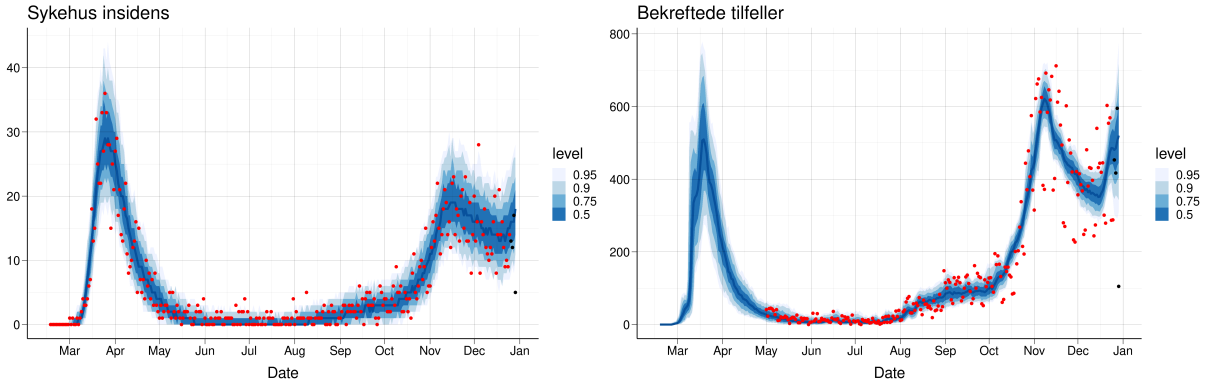
1 Estimated national reproduction numbers

Calibration of our national changepoint model to hospitalisation incidence data and test data leads to the following estimates provided in table 1. Figure 1 shows the estimated daily number of COVID-19 patients admitted to hospital (1a) and the estimated daily number of laboratory-confirmed SARS-CoV-2 cases (1b), with blue medians and interquantile bands, which are compared to the actual true data, provided in red. The uncertainty captures the uncertainty in the calibrated parameters in addition to the stochastic elements of our model and the variability of other model parameters.

Table 1: Calibration results

Reff	Period
3.08/3.09(2-3.99)	From Feb 17 to Mar 14
0.52/0.53(0.41-0.64)	From Mar 15 to Apr 19
0.58/0.57(0.11-1.1)	From Apr 20 to May 10
0.63/0.6(0.1-1.11)	From May 11 to Jun 30
0.69/0.71(0.07-1.43)	From Jul 01 to Jul 31
1.05/1.06(0.71-1.44)	From Aug 01 to Aug 31
0.95/0.96(0.75-1.19)	From Sep 01 to Sep 30
1.28/1.27(0.99-1.51)	From Oct 01 to Oct 25
1.43/1.42(1.12-1.69)	From Oct 26 to Nov 04
0.89/0.89(0.84-0.94)	From Nov 05 to Dec 14
1.29/1.3(0.91-1.66)	From Dec 15

Median/Mean (95% credible intervals)

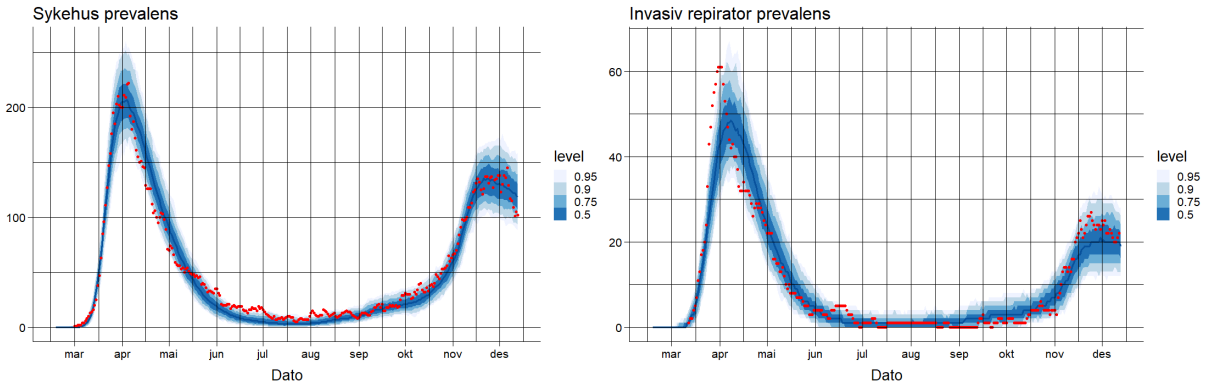


(a) Hospital admissions

(b) Test data

Figure 1: A comparison of true data (red) and predicted values (blue) for hospital admissions and test data. The last four data points (black) are assumed to be affected by reporting delay. B) Comparison of our simulated number of positive cases, with blue median and interquartile bands to the actual true number of positive cases, provided in red. The uncertainty captures the uncertainty in the calibrated parameters, in addition to the stochastic elements of our model and the variability of other model parameters. Note that we do not capture all the uncertainty in the test data–our blue bands are quite narrow. This is likely because we calibrate our model parameters on a 7-days moving average window of test data, instead of daily. This is done to avoid overfitting to random daily variation. Moving averages over 7 days are less variable than the daily data.

In figure 2, we show how our national model fits the national hospital prevalence data (2a) and the daily number of patients receiving ventilator treatment (2b). Those data sources are not used to estimate the parameters, and can therefore be seen as a validation of the model assumptions.



(a) Hospital prevalence

(b) Ventilator prevalence

Figure 2: A comparison of true data (red) and predicted values (blue) for hospital and respirator prevalence.

1.1 National SMC-model: Estimated daily reproduction numbers

In the SMC-model, we allow for estimation of a different reproduction number for each day t. To reduce spurious fluctuation, we report a 7-days moving average, $R(t)$, representing the average reproduction number for the whole week before day t. However, until March 8 we keep the reproduction number constant. By assuming a time varying reproduction number $R(t)$, we can detect changes without introducing explicit changepoints. Thus, we can easier detect unexpected changes.

The SMC model uses the daily number of new admissions to hospital and the daily number of positive and negative lab-confirmed tests, to estimate all its parameters. Because of the time between infection and the possibility to be detected as positive by a test, and because if a delay in reporting tests, the data contain information on the transmissibility until a week before the end of the data (today).

The parameters π_0 and π_1 related to the probability to detect a positive case by testing are estimated off-line.

The figure below shows the SMC estimate of the 7-day-average daily reproduction number $R(t)$ from the start of the epidemic in Norway and until today. In the figure we plot the 95% confidence interval and quantiles of the estimated posterior distribution of $R(t)$.

1.1 National SMC-model: Estimated daily reproduction numbers

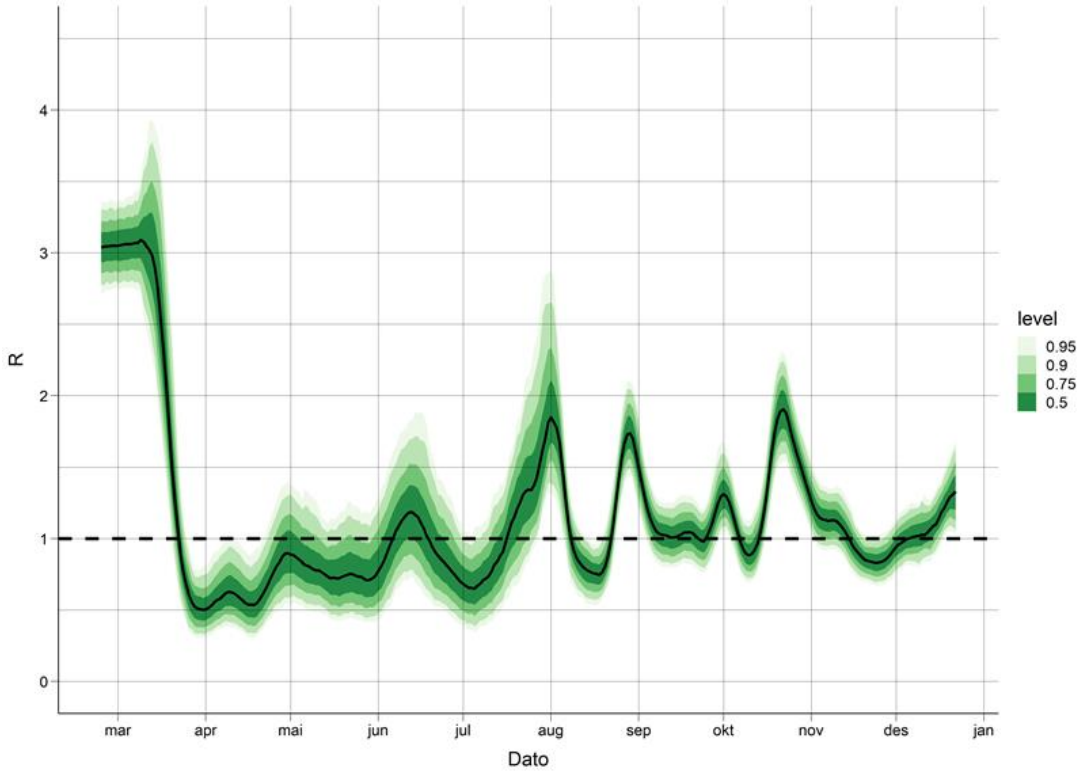


Figure 3: R(t) estimates using a Sequential Monte Carlo approach calibrated to hospitalisation incidence and test data. The large uncertainty during the last 7 days reflects the lack of available data due to the transmission delay, test delay, time between symptoms onset and hospitalisation. The green band shows the 95% posterior credibility interval. We observe that $R(t)$ dropped below 1 in the middle of March, corresponding to the implementation of the lockdown. It remained stable around 0.5 until the end of April, when it increased to 1 in the beginning of May. It then kept oscillating below and above 1, in accordance with increases and decreases of the number of new hospitalisations and number of positive test cases. $R(t)$ is sensitive to these oscillations in the data. We observe the steep increase in October and the a decrease concomitant to the first package of interventions in Norway and in the main cities. This intervention led to a decrease in the estimated reproduction number. The decrease seems to stabilise in the first days of November, when a second set of contact-reducing interventions have been decided, after which $R(t)$ drops again. As we use test data only from 1 August, the credibility interval becomes more narrow thereafter.

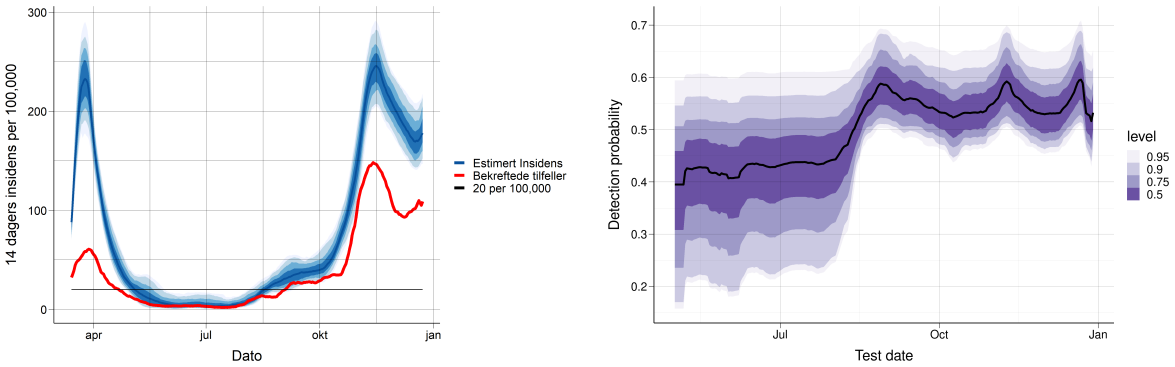
2 National estimate of cumulative (total) number of infections

The national changepoint model estimates the total number of infections and the symptomatic cases that have occurred (Table 2).
Figure 4a shows the modelled expected daily incidence (blue) and the observed daily number of laboratory-confirmed cases (red). When simulating the laboratory-confirmed cases, we also model the detection probability for the infections (both symptomatic, presymptomatic and asymptomatic), Figure 4b. There are two differences between this estimate of the detection probability and the previous one provided in figure 4a. In figure 4b, we calibrate our model to the true number of positive cases, instead of using the test data directly. Furthermore, in figure 4a we use a parametric model to estimate the detection probability that depends on the true total number of tests performed.

Table 2: Estimated cumulative number of infections, 2020-12-29

Region	Total	No. confirmed	Fraction reported	Min. fraction
Norway	101676 (87944; 115670)	48278	47%	42%

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



(a) Number of laboratory-confirmed cases vs model-based estimated number of new infected individuals

(b) Estimated detection probability for an infected case per calendar day

Figure 4

3 National 3-week predictions: Prevalence, Incidence, Hospital beds and Ventilator beds

The national changepoint model estimates the prevalence and daily incidence of infected individuals (asymptomatic, presymptomatic and symptomatic) for the next three weeks, aggregated to the whole of Norway (table 3). In addition, the table shows projected national prevalence of hospitalised patients (hospital beds) and prevalence of patients receiving ventilator treatment (ventilator beds). The projected epidemic and healthcare burden are illustrated in figure 5.

Table 3: Estimated national prevalence, incidence, hospital beds and ventilator beds. Median/Mean (CI)

	1 week prediction (Jan 05)	2 week prediction (Jan 12)	3 week prediction (Jan 19)
Prevalence	7748/7192 (3579-14024)	10201/9050 (3262-22055)	13628/11417 (2892-34554)
Daily incidence	1408/1270 (547-2768)	1863/1610 (487-4365)	2511/2034 (453-6845)
Hospital beds	165/162 (115-226)	206/194 (109-360)	265/242 (98-534)
Ventilator beds	23/22 (13-33)	27/26 (14-43)	35/33 (14-68)

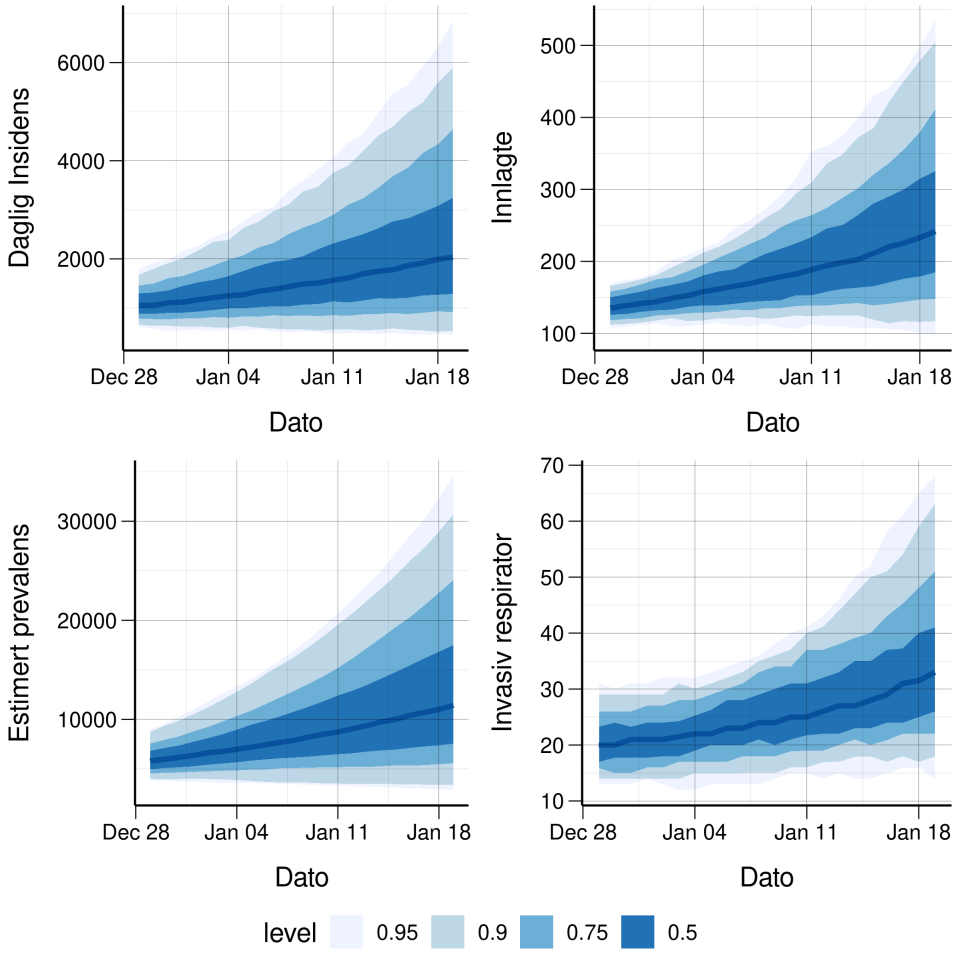


Figure 5: National 3 week predictions for incidence (top left), prevalence (bottom left), hospital beds (top right) and ventilator beds (bottom right)

4 National long-term scenarios: Prevalence, Hospital beds and Ventilator beds

Results from 12-month scenario of the calibrated national changepoint model, showing expected prevalence (Figure 6a), hospital beds (Figure 6b) and ventilator beds (Figure 6c), in the case where the transmissibility stays the same as today. The figures are made using the 200 candidate models, where the reproductive numbers are varying according to their estimated uncertainty as of today. The confidence intervals shown in the plots are two-tailed around the median, and therefore the upper 95% level shows the 97.5% boundary. Note that age-specific attack rate after 21 days of projection is assumed to follow the demography in each county, instead of being informed by the current age-distribution of the laboratory-confirmed cases.

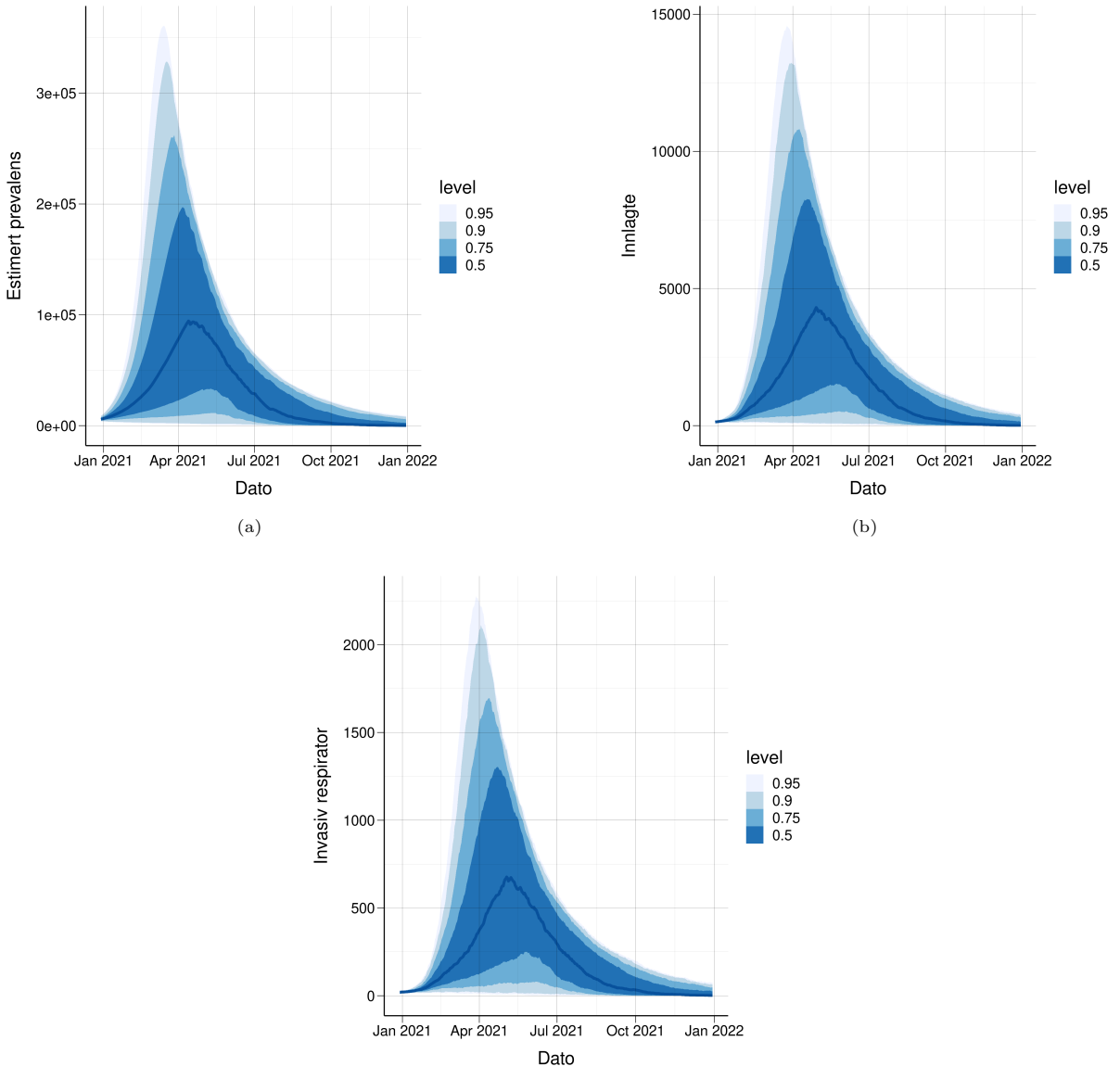


Figure 6: Long-term predictions for prevalence (a),hospital beds (b) and ventilator beds (c)

The probability of a surge capacity need above **500 ICU** ventilator beds is **65.5 %**. We estimate the

probability of a surge capacity need above **1000 ICU** beds to be equal to **41.5 %**.

5 National scenario-based long-term predictions: Hospital beds and Ventilator beds

Here we show how the epidemic estimated from the national changepoint model will develop under three assumed epidemiological scenarios, by fixing the effective reproduction number to be 1.1, 1.2 or 1.3, from today. We show the daily number of COVID-19 patients in hospital, including patients receiving ventilator treatment, (Figure 7, and the daily number of patients on ventilator treatment, figure 8. Note that age-specific attack rate after 21 days of projection is assumed to follow the demography in each county, instead of being informed by the current age-distribution of the laboratory-confirmed cases. Additional information about the total attack rate (cumulative incidence) and healthcare burden and surge capacity for these scenarios are provided in Table 4.

Table 4: Predicted numbers of total infected, total number of hospitalisations, total number needing ventilator treatment, and the predicted peak number in ward (not in respirator), hospitalised (both with and without ventilator treatment) and ventilated treatments based on three different scenarios with R effective equal to 1.1, 1.2 and 1.3.

	Reff=1.1	**Reff=1.2**	**Reff=1.3**
Total:			
Attack rate (infected)	903.000(863.000 - 936.000)	1.640.000(1.620.000 - 1.650.000)	2.230.000(2.220.000 - 2.250.000)
Hospitalisations	28.100(26.800 - 29.100)	51.200(50.500 - 51.800)	70.000(69.400 - 70.600)
Patients on ventilator	2.450(2.310 - 2.560)	4.400(4.310 - 4.530)	6.010 (5.910 - 6.130)
At peak			
Hospital beds, excl. vent.	617(561 - 679)	1.950(1.870 - 2.050)	3.920(3.810 - 4.010)
Hospital beds, incl. vent.	724(662 - 793)	2.300(2.210 - 2.410)	4.630(4.500 - 4.730)
Ventilator beds	122(108 - 137)	370(347 - 396)	731(697 - 776)

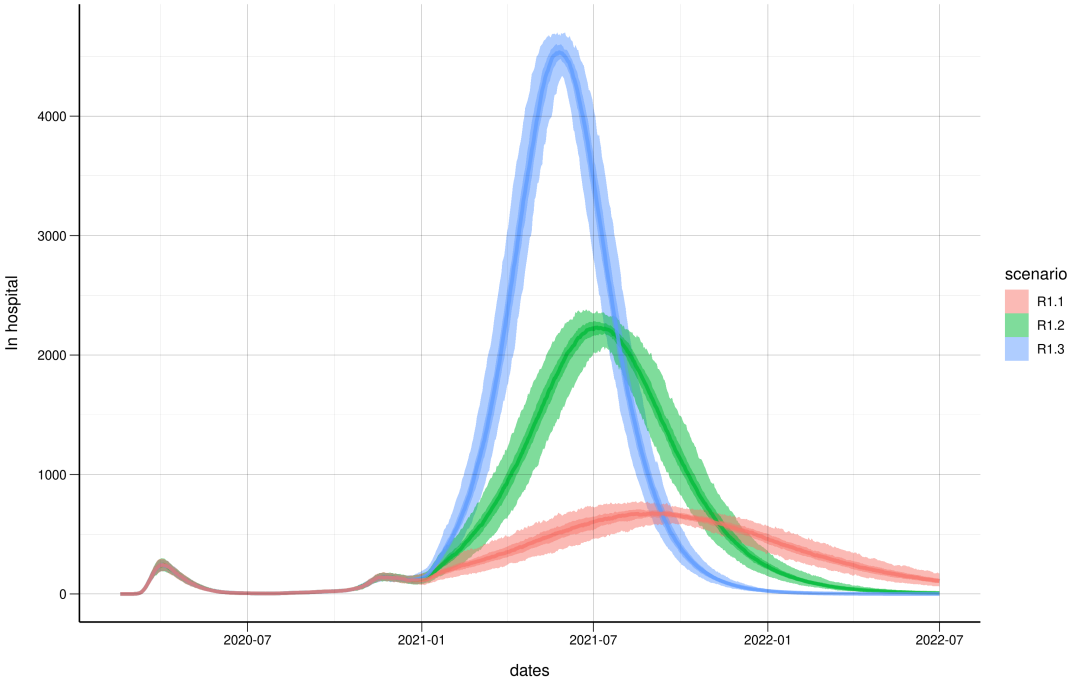


Figure 7: Predicted number of COVID-19 patients in hospital based on three different scenarios with R effective equal to 1.1, 1.2 and 1.3. Shaded areas show interquartile range and 95% confidence interval around the median.

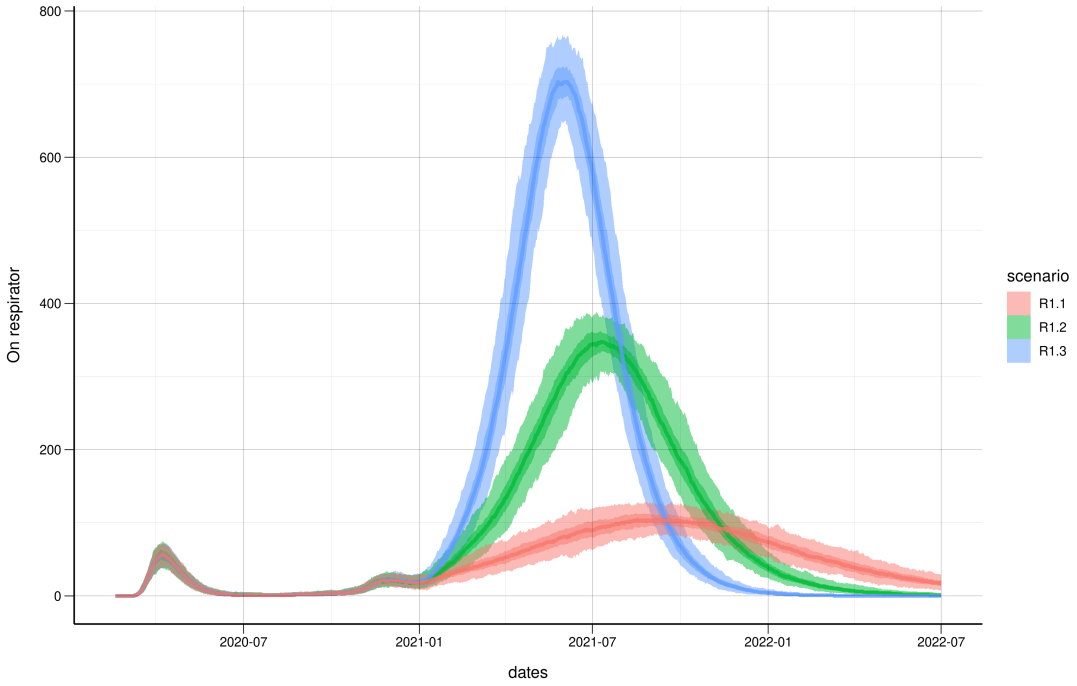


Figure 8: Predicted number of COVID-19 patients needing ventilator treatment based on three different scenarios with R effective equal to 1.1, 1.2 and 1.3. Shaded areas show interquartile range and 95% confidence interval around the median.

13 Mobility data

Number of trips out from each municipality during each day is based on Telenor mobility data. We observed a large reduction in inter-municipality mobility in March (with minimum reached on Tuesday 17 March), and thereafter we see an increasing trend in the mobility lasting until vacation time in July. The changes in mobility in July coincides with the three-week "fellesferie" in Norway, and during August the mobility resumes approximately the same levels as pre-vacation time. There is however a significant local variation.

The reference level is set to 100 on March 2nd 2020 for all the figures in this section, and we plot the seven-day, moving average of the daily mobility. Figure 22 shows an overview of the mobility since March for the largest municipalities in each county, and Figure 23 shows the total mobility out from all municipalities in each county, including Oslo. Figure 24 and 25, zooms in on mobility from August 31, for municipalities and counties, respectively.

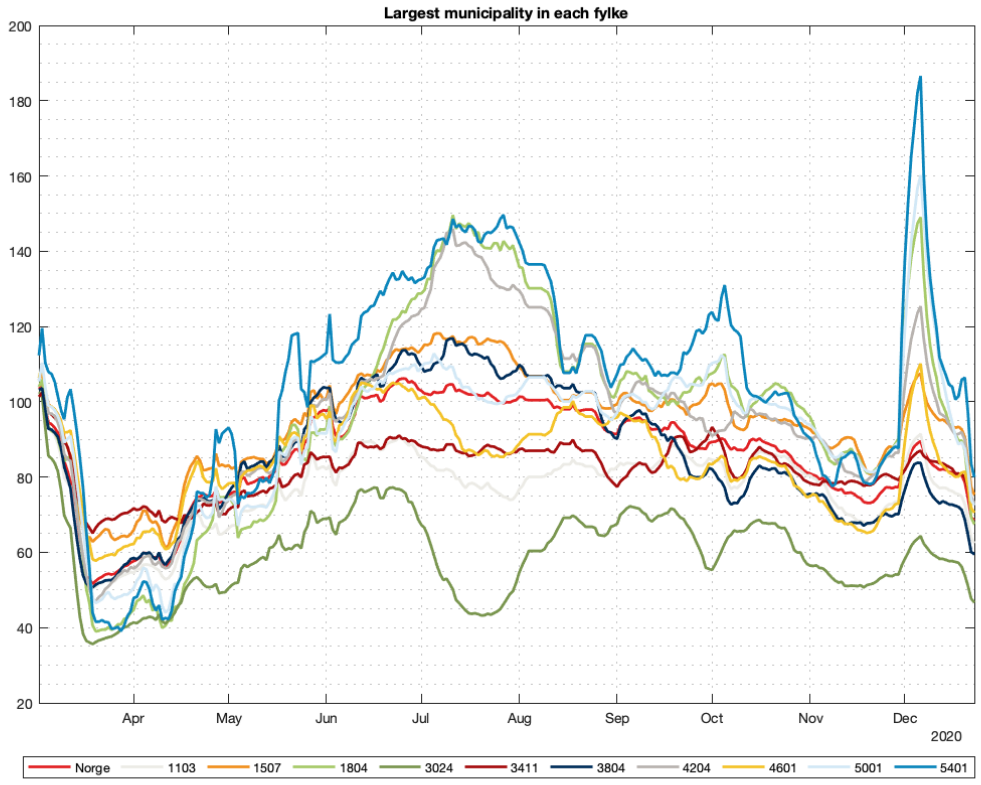


Figure 22: Mobility for selected municipalities for all of 2020: Nationally (Norge), Stavanger (1103), Ålesund (1507), Bodø (1804), Bærum (3024), Ringsaker (3411), Sandefjord (3804), Kristiansand (4204), Bergen (4601), Trondheim (5001), Tromsø (5401).

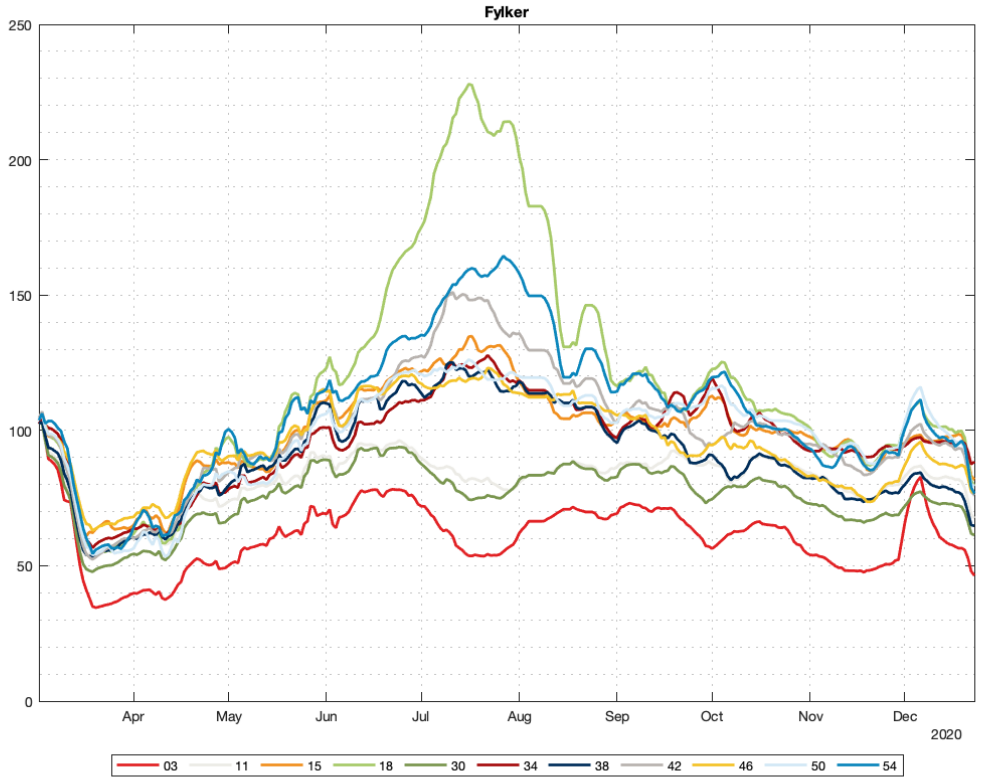


Figure 23: Mobility for fylker for all of 2020: Oslo (03), Rogaland (11), Møre og Romsdal (15), Nordland (18), Viken (30), Innlandet (34), Vestfold og Telemark (38), Agder (42), Vestland (46), Trøndelag (50), Troms og Finmark (54).

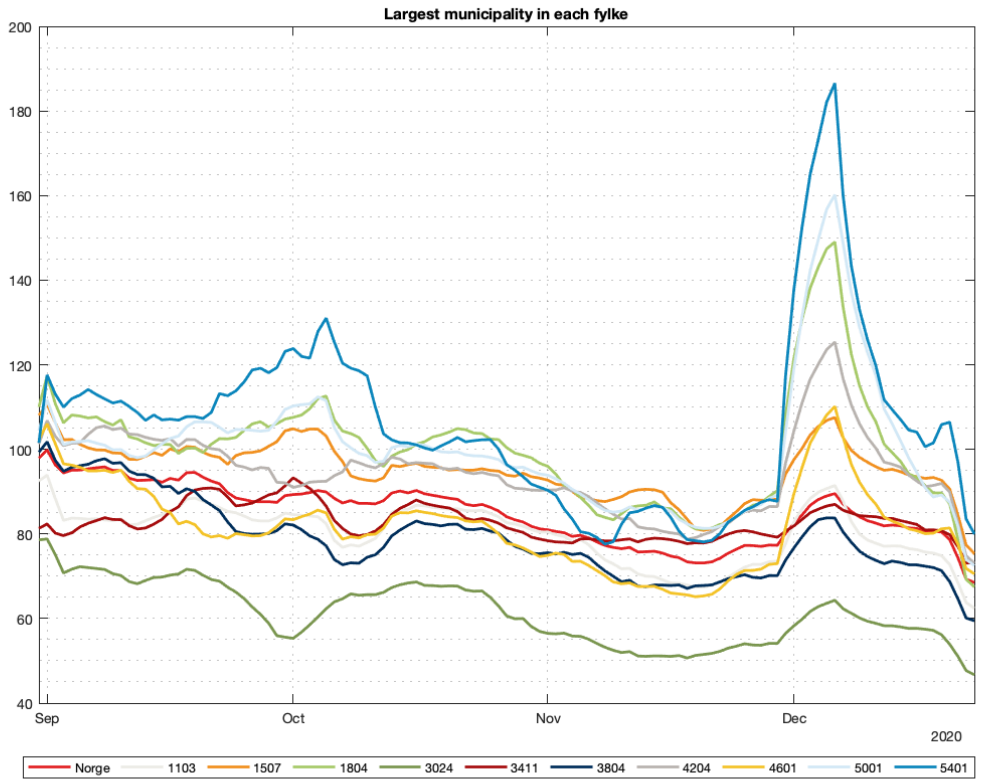


Figure 24: Zoom: Mobility from August 31 and onwards: Nationally (Norge), Stavanger (1103), Ålesund (1507), Bodø (1804), Bærum (3024), Ringsaker (3411), Sandefjord (3804), Kristiansand (4204), Bergen (4601), Trondheim (5001), Tromsø (5401).

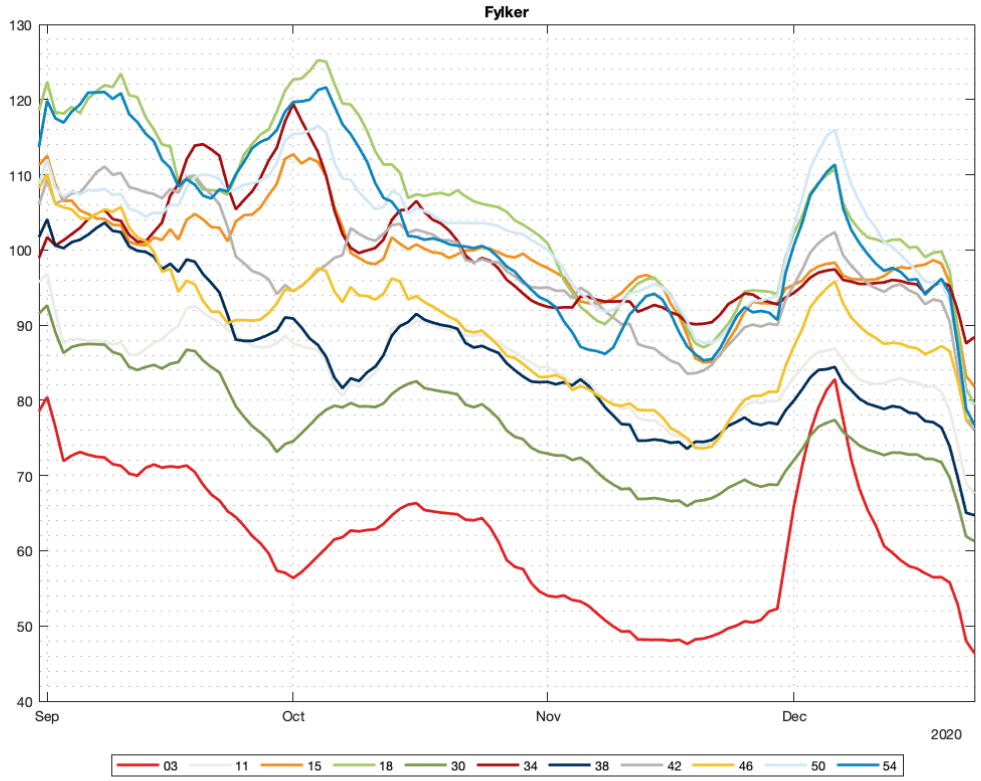


Figure 25: Zoom: Mobility from August 31 and onwards, per fylker: Oslo (03), Rogaland (11), Møre og Romsdal (15), Nordland (18), Viken (30), Innlandet (34), Vestfold og Telemark (38), Agder (42), Vestland (46), Trøndelag (50), Troms og Finnmark (54).

	49	50	51	52	53
Norge	80.2	87.0	81.9	74.4	62.0
Stavanger	77.7	87.8	77.1	68.5	53.8
Ålesund	94.2	102.7	94.7	84.5	70.8
Bodø	108.0	133.7	97.2	78.7	63.7
Bærum	56.5	62.3	58.0	51.1	37.0
Ringsaker	80.6	85.6	83.1	77.0	70.4
Sandefjord	73.8	80.5	73.2	64.7	50.8
Kristiansand	96.8	116.7	95.8	82.5	63.5
Bergen	81.5	102.9	82.3	77.5	60.9
Trondheim	104.2	148.8	102.0	81.8	60.8
Tromsø	117.4	160.1	107.0	97.0	71.1

Table 14: Municipalities

	49	50	51	52	53
Oslo	59.0	77.5	58.8	52.8	34.0
Rogaland	81.5	85.3	83.0	74.1	58.9
Møre og Romsdal	94.9	96.6	97.7	89.6	77.9
Nordland	99.1	106.2	101.4	89.3	75.8
Viken	70.6	75.8	73.0	66.2	53.6
Innlandet	93.7	96.0	95.9	91.9	91.5
Vestfold og Telemark	78.7	82.4	79.1	69.6	57.5
Agder	93.4	99.3	95.4	84.0	68.9
Vestlandet	84.6	92.9	87.5	82.5	71.5
Trøndelag	98.7	112.1	99.4	87.1	72.6
Troms og Finnmark	96.9	105.5	97.1	87.0	72.8

Table 15: Counties

Weekly mobility for Norway and selected municipalities is displayed in Tables 14 and mobility for counties is displayed in 15. The percentages in the tables are to be interpreted towards the reference level of 100% for week 10 in March 2020. The color-coding encodes the following: 'Green' monotonic decrease in mobility, 'Yellow' almost monotonic decrease or flat mobility trend, 'Red' increasing mobility.

13.1 Foreign roamers on Telenor's network in Norway

An analysis of foreign roamers in Norway for 2020 has been carried out, to better understand the potential virus importation. In Figure 26 the total number of roamers per day per county are displayed. We can see an approximate 40% drop in the number of visiting roamers after the lock-down in March. The number of visiting roamers recover during the Summer, and there is a spike of visitors in August followed by a drop again. During October the levels of visiting, foreign roamers to Norway have reached quite high levels, just 10% short of the all-year high, and Oslo and Viken have seen big increases in visitors. The level seems to have stabilised.

Figure 27 showcases the levels of roamers from four different countries: Poland, Denmark, Lithuania and Germany, and the figure illustrates where in Norway the roamers of the given nationality are staying in each day. For example, the Polish roamers are typically going to the cities, Oslo, Bergen, Trondheim, and Stavanger, and they show quite high visiting levels during all of 2020. The visiting-levels in October are all-time highs for 2020. In comparison, thefre are many Danish roamers early in 2020, and levels drop after the lock-down, with a visiting spike during July followed by a drop after Summer. German roamers show the same behaviour, but at lower, absolute levels. Lithuanian visitors show a similar patterns as the Polish visitors.

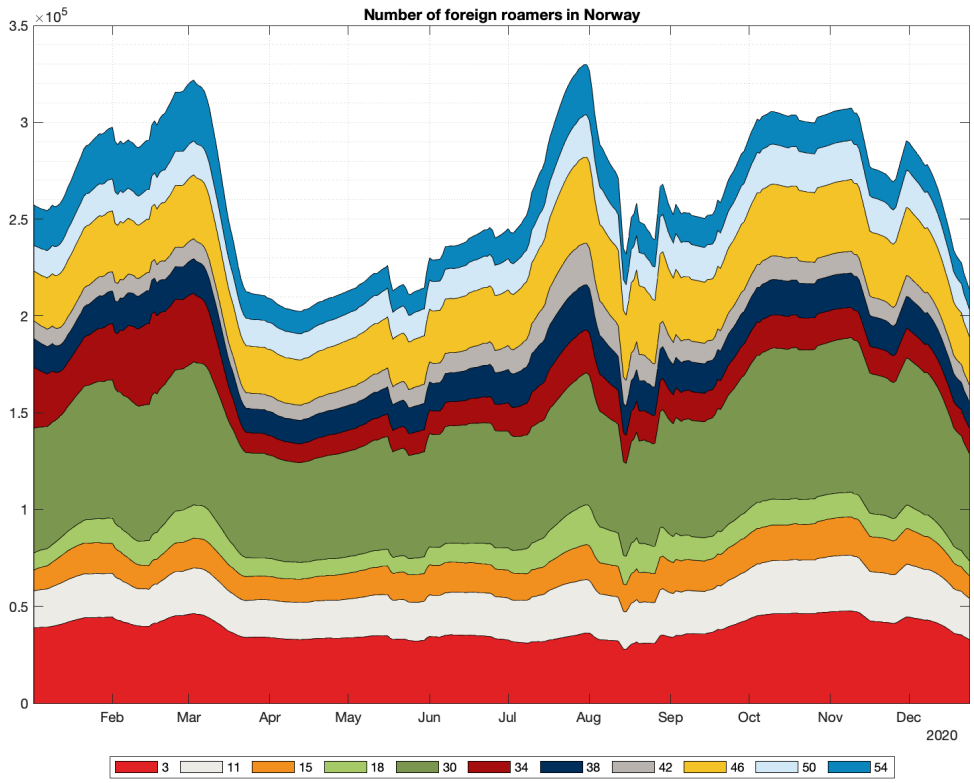


Figure 26: The total number of foreign roamers in Norway broken down on different fylker: Oslo (3), Rogaland (11), Møre og Romsdal (15), Nordland (18), Viken (30), Innlandet (34), Vestfold og Telemark (38), Agder (42), Vestland (46), Trøndelag (50), Troms og Finmark (54).

13.1 Foreign roamers on Telenor's network in Norway

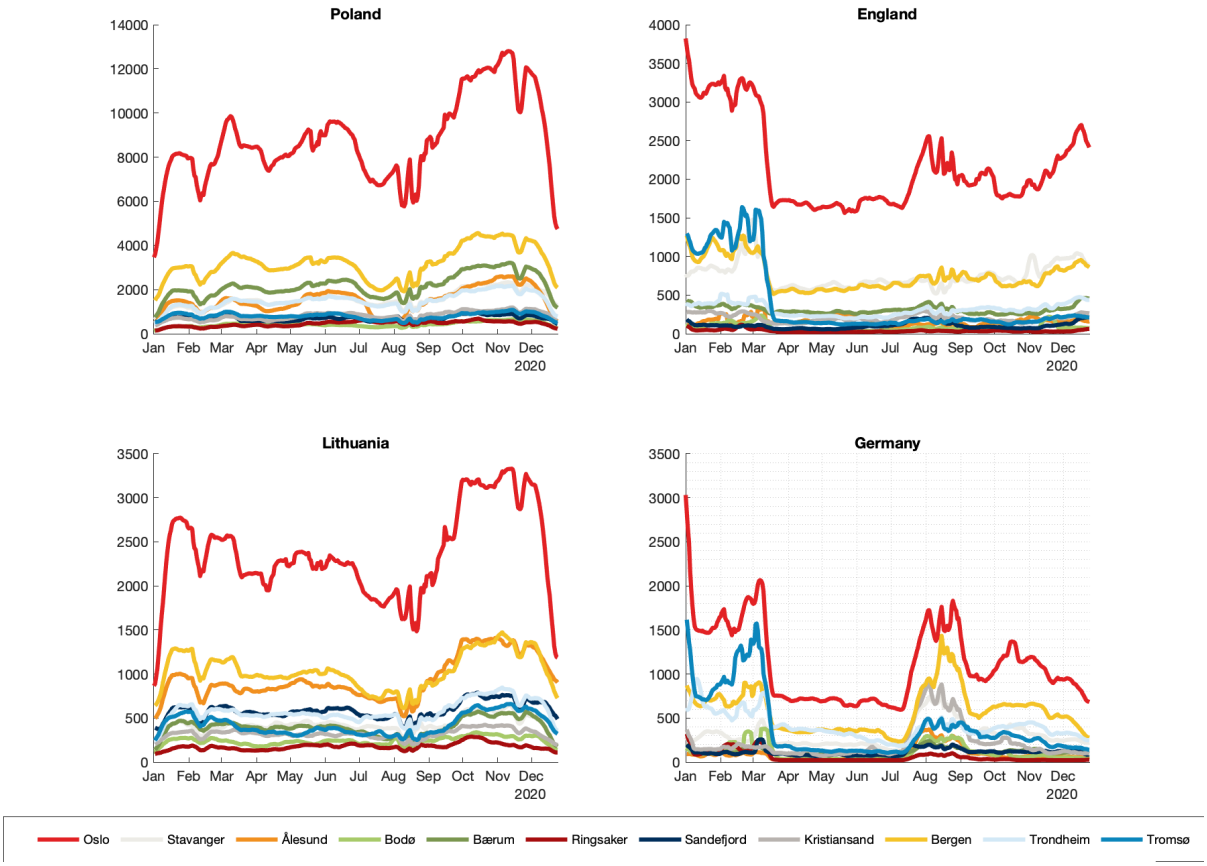


Figure 27: Roamers from Poland, England, Lithuania and Germany, broken down on the the largest municipalities in each fylke.

14 Methods

14.1 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.

14.1.1 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 within each area is assumed to be 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: Susceptible (S), Exposed, infected, but not infectious (E_1), Presymptomatic infected (E_2), Symptomatic infected (I), Asymptomatic infected (I_a), and Recovered, either immune or dead (R). A schematic overview of the model is shown in figure 28.

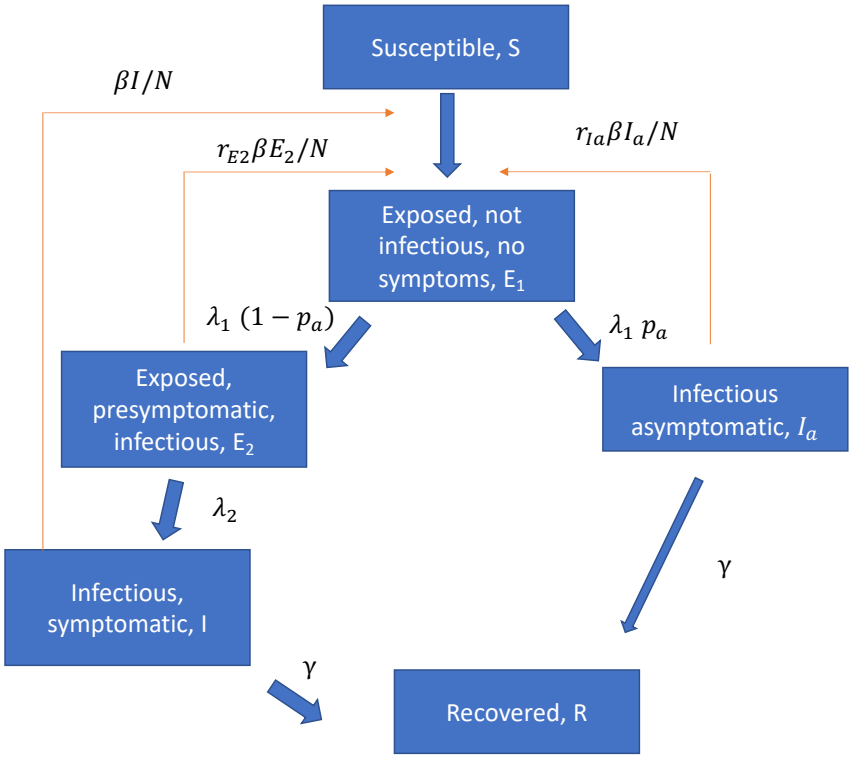


Figure 28: Schematic overview of the model.

14.2 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 to be 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, regularised to be balanced in total in- and outgoing flow for each municipality.

14.3 Healthcare utilisation

Based on the estimated daily incidence data from the model and the population age structure in each municipality, we calculated the hospitalisation using a weighted average. We correct these probabilities by a factor which represents the over or under representation of each age group among the lab confirmed positive cases. The hospitalisation is assumed to be delayed relative to the 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.

14.4 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, using the data available until yesterday. 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 otherwise missed. We denote this by the amplification factor.

14.5 Calibration

Estimation of the parameters of the model: the reproduction numbers, the amplification factor for the imported cases, the parameters of the detection probability and the delay between incidence and test, is done using Sequential Monte Carlo Approximate Bayesian Computation (SMC-ABC), as described in Engebretsen et al. (2020): https://royalsocietypublishing.org/doi/10.1098/rsif.2019.0809, where the algorithm can be found in the supplement.

The idea behind ABC is to try out different parameter sets, simulate using these, then compare how much the simulations deviate from the observations in terms of summary statistics. We thus test millions of combinations of $R_0, R_1, R_2, R_3, R_4, R_5, R_6, R_7, R_8, R_9, R_10$, the amplification factor, and the parameters for the positive tests, to determine the ones that lead to the best fits to the true number of hospitalised individuals, from March 10 until the last available data point, and the laboratory-confirmed COVID-19 cases from May 1 until the latest available data point.

In the ABC procedure we thus use two summary statistics, one is the distance between the simulated hospitalisation incidence and the observed incidence, and the other is the distance between the observed number of laboratory-confirmed cases and the simulated ones. As the two summary statistics are not on the same scale, we use two separate tolerances in the ABC-procedure, ensuring that we get a good fit to both data sources.

14.5.1 Calibration to hospitalisation data

In order to calibrate to the hospitalisation data, we need to simulate hospital incidence. The details on how we simulate hospitalisations are described in Section 14.3, using the parameters provided in Section 15, which are estimated from individual-level Norwegian data, and updated regularly. As our distance measure, we calculate the squared distance over each time point and each county.

14.5.2 Calibration to test data

We include the laboratory-confirmed cases in the calibration procedure, as these contain additional information about the transmissibility, and the delay between transmission and testing is shorter than the delay between transmission and hospitalisation. Therefore, we simulate also the number of detected positive cases in our model. We assume that the number of detected positive cases can be modelled as a binomial process of the simulated daily total incidence of symptomatic and asymptomatic cases, with a

success probability π_t, which changes every day. We also assume a delay d between the day of test and the day of transmission.

The data on the number of positive cases are more difficult to use, as the test criteria and capacity have changed multiple times. We take into account these changes by using the total number of tests performed on each day, as a good proxy of capacity and testing criteria. Moreover, we choose not to calibrate to the test data before May 1, because the test criteria and capacity were so different in the early period. The detection probability is modelled as

$$\pi_t = \exp(\pi_0 + \pi_1 \cdot k_t)/(1 + \exp(\pi_0 + \pi_1 \cdot k_t)),$$

where k_t is the number of tests actually performed on day t, and π_0 and π_1 are two parameters that we estimate, assuming positivity of π_1. We also estimate the delay d. We choose to use a 7-days backwards moving average for the covariate k_t. To calculate the distance between the observed number of positive tests and the simulated ones we also use a 7-days backwards moving average. We do this to take into account potential day-of-the-week-effects. For example, it could well be that the testing criteria are different on weekends and weekdays. However, using instead the number of tests and calibrating on a daily basis would lead to a larger day-to-day variance. This is likely why we find that the uncertainty in the simulated positive cases seems somewhat too low, and that we do not capture all the variance in the daily test data. Moreover, the binomial assumption could be too simple, and a beta-binomial distribution would allow more variance. A limitation of our current model for the detection probability, is that we only capture the changes in the test criteria that are captured in the total number of tests performed.

14.6 Specifications for the national changepoint model

In the national changepoint model, we assume a first reproduction number R_0 until March 14, a second reproduction number R_1 until April 19, a third reproduction number R_2 until May 10, a fourth reproduction number R_3 until June 30, R_4 until July 31, R_5 until August 31, R_6 from September 1 until September 30, R_7 from October 1 until October 26, R_8 until November 4, a tenth reproduction number R_9 until November 14, and an 11th reproduction number from November 15 until today. This last reproduction number is used for the future. The changepoints follow the changes in restrictions introduced. In the calibration procedure, we obtain 200 parameter sets that we use to represent the distributions of parameters.

After we have obtained the estimated parameters, we run the model with these 200 parameter sets again, from the beginning until today, plus three weeks into the future (or for an additional year). In this way, we obtain different trajectories of the future, allowing us to investigate different scenarios, with corresponding uncertainty.

14.7 Specifications for the regional changepoint model

In the regional changepoint model, each county has its own reproduction numbers, assumed constant in different periods, just like the national changepoint model. As there are more parameters in the regional changepoint model, we obtain 1000 parameter sets in the ABC-SMC.

Calibrating regional reproduction numbers is a more difficult estimation problem than calibrating national reproduction numbers, as we have a lot more parameters, and in addition less data in each county. Therefore, we cannot include the same amount of changepoints in the regional model as we can for the national model. Currently we assume five changepoints (six reproduction numbers) for Viken, Oslo, Vestland (the three largest counties of Norway), and four changepoints (five reproduction numbers) in all other counties.

After we have obtained the estimated parameters, we run the model with these 1000 parameter sets again, from the beginning until today, plus three weeks into the future (or for an additional year). In this way, we obtain different trajectories of the future, allowing us to investigate different scenarios, with corresponding uncertainty.

15 Parameters used today

Figures 29 and 30 indicate which assumptions we make in our model, related to hospitalisation. We obtained data from the Norwegian Pandemiregister. These estimates will be regularly updated, on the basis of new data.

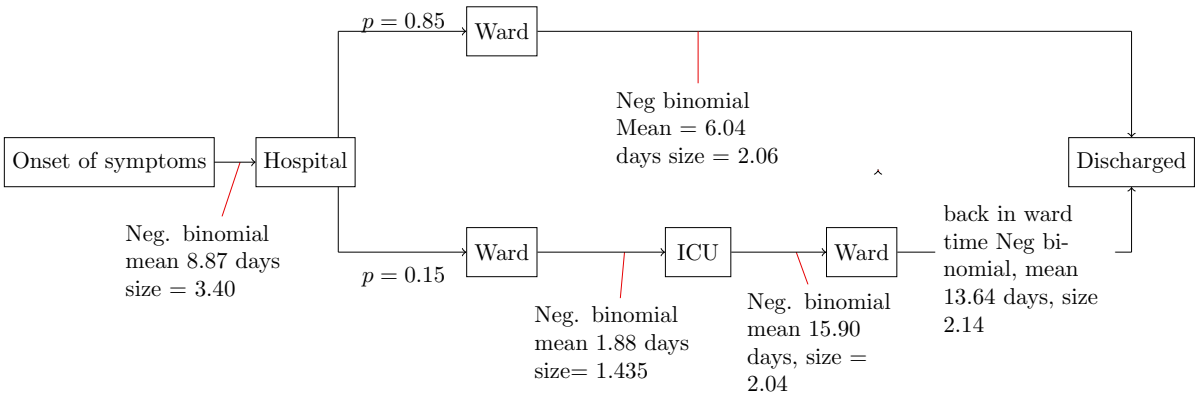


Figure 29: Hospital assumptions and parameters used before 1 August

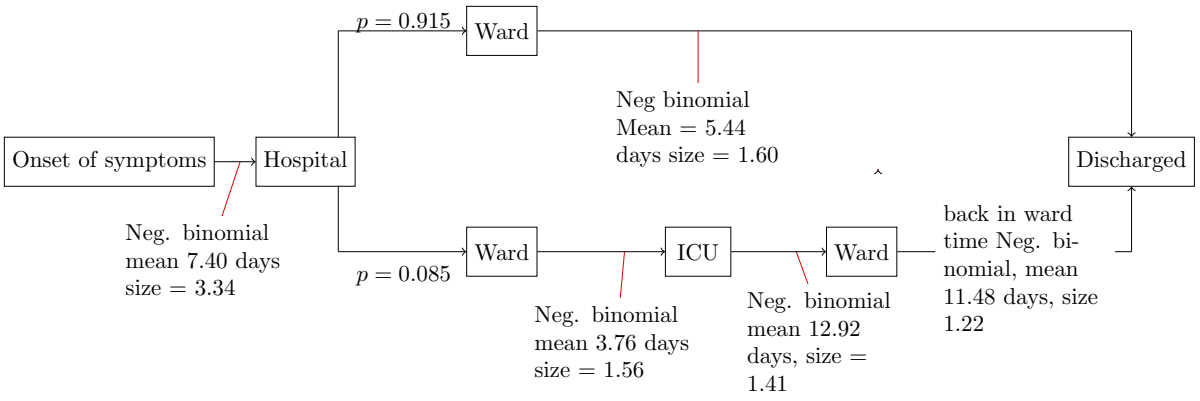


Figure 30: Hospital assumptions and parameters used after 1 August

Table 16: Estimated parameters

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	Period
R0s	1.778	2.811	3.083	3.086	3.426	4.184	Until March 14
R1s	0.372	0.483	0.524	0.527	0.57	0.688	From March 15 to April 19
R2s	0.018	0.394	0.584	0.57	0.751	1.196	From April 20 to May 10
R3s	0.009	0.411	0.63	0.608	0.827	1.364	From May 11 to June 30
R4s	0.001	0.46	0.691	0.714	0.989	1.555	From July 1 to July 31
R5s	0.613	0.944	1.051	1.067	1.174	1.529	From Aug 1 to Aug 31
R6s	0.554	0.902	0.951	0.964	1.03	1.325	From Sept 1 to Sept 30
R7s	0.925	1.196	1.29	1.278	1.368	1.788	From Oct 1 to Oct 25
R8s	0.957	1.315	1.439	1.431	1.553	1.807	From Oct 26 to Nov 4
R9s	0.842	0.882	0.898	0.9	0.919	0.967	From Nov 5 to Nov 14
R10s	0.818	1.183	1.312	1.317	1.457	1.79	From Nov 15
AMPs	1.03	1.569	1.867	1.925	2.259	3.186	-
π_0	-2.078	-0.912	-0.476	-0.585	-0.203	0.556	-
π_1	5.5e-07	3.2e-05	5.5e-05	6.5e-05	9.5e-05	1.9e-04	-
delays	0	1	2	1.82	3	4	-

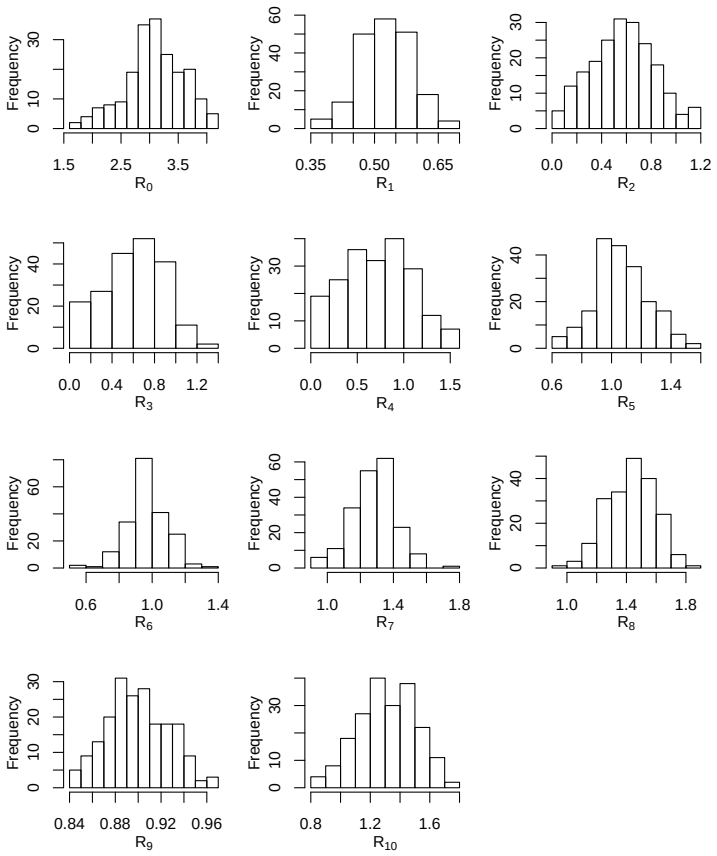


Figure 31: Estimated densities of the reproduction numbers. National model

Table 17

R	Parameter	County	From	To	Pr(R>1)
3.91 (2.92-4.95)	R0	Oslo	2020-02-17	2020-03-14	1
2.67 (1.79-3.61)	R0	Rogaland	2020-02-17	2020-03-14	1
3.85 (2.1-5.61)	R0	Møre og Romsdal	2020-02-17	2020-03-14	1
3.13 (1.26-5.23)	R0	Nordland	2020-02-17	2020-03-14	0.99
3.88 (2.97-4.81)	R0	Viken	2020-02-17	2020-03-14	1
3.31 (1.89-4.6)	R0	Innlandet	2020-02-17	2020-03-14	1
2.78 (1.63-4.72)	R0	Vestfold og Telemark	2020-02-17	2020-03-14	1
2.99 (2.04-3.93)	R0	Agder	2020-02-17	2020-03-14	1
3.56 (2.56-4.78)	R0	Vestland	2020-02-17	2020-03-14	1
3.16 (1.44-5.11)	R0	Trøndelag	2020-02-17	2020-03-14	0.99
2.71 (1.64-4.3)	R0	Troms og Finnmark	2020-02-17	2020-03-14	1
0.8 (0.63-0.97)	R1	Oslo	2020-03-15	2020-04-19	0.01
0.48 (0.14-0.96)	R2	Oslo	2020-04-20	2020-06-19	0.02
0.89 (0.57-1.21)	R3	Oslo	2020-06-20	2020-08-31	0.24
1.42 (1.32-1.52)	R4	Oslo	2020-09-01	2020-11-04	1
0.94 (0.75-1.12)	R5	Oslo	2020-11-05	2020-11-21	0.25
0.84 (0.5-1.15)	R6	Oslo	2020-11-22		0.18
0.09 (0-0.28)	R1	Rogaland	2020-03-15	2020-04-19	0
0.59 (0.21-0.94)	R2	Rogaland	2020-04-20	2020-08-31	0.01
0.84 (0.66-1.05)	R3	Rogaland	2020-09-01	2020-11-04	0.07
0.89 (0.6-1.16)	R4	Rogaland	2020-11-05		0.23
0.81 (0.56-1.04)	R1	Møre og Romsdal	2020-03-15	2020-04-19	0.06
0.77 (0.44-0.97)	R2	Møre og Romsdal	2020-04-20	2020-08-31	0.01
0.95 (0.65-1.3)	R3	Møre og Romsdal	2020-09-01	2020-11-04	0.35
0.48 (0.09-0.91)	R4	Møre og Romsdal	2020-11-05		0.01
0.64 (0.32-1.01)	R1	Nordland	2020-03-15	2020-04-19	0.03
0.45 (0.21-0.67)	R2	Nordland	2020-04-20	2020-08-31	0
0.68 (0.32-1.06)	R3	Nordland	2020-09-01	2020-11-04	0.05
1.25 (0.71-1.71)	R4	Nordland	2020-11-05		0.84
0.3 (0.07-0.58)	R1	Viken	2020-03-15	2020-04-19	0
0.81 (0.49-1.1)	R2	Viken	2020-04-20	2020-06-19	0.12
0.73 (0.44-1.02)	R3	Viken	2020-06-20	2020-08-31	0.04
1.18 (1.05-1.31)	R4	Viken	2020-09-01	2020-11-04	1
0.98 (0.82-1.15)	R5	Viken	2020-11-05	2020-11-21	0.4
1.3 (1.01-1.51)	R6	Viken	2020-11-22		0.98

Mean and 95% credible intervals

Table 18

R	Parameter	County	From	To	Pr(R>1)
0.44 (0.16-0.79)	R1	Innlandet	2020-03-15	2020-04-19	0
0.98 (0.82-1.13)	R2	Innlandet	2020-04-20	2020-08-31	0.38
0.87 (0.63-1.11)	R3	Innlandet	2020-09-01	2020-11-04	0.15
0.97 (0.66-1.24)	R4	Innlandet	2020-11-05		0.43
0.5 (0.2-0.74)	R1	Vestfold og Telemark	2020-03-15	2020-04-19	0
0.46 (0.22-0.85)	R2	Vestfold og Telemark	2020-04-20	2020-08-31	0
0.84 (0.52-1.25)	R3	Vestfold og Telemark	2020-09-01	2020-11-04	0.16
0.43 (0.12-0.74)	R4	Vestfold og Telemark	2020-11-05		0
0.44 (0.15-0.87)	R1	Agder	2020-03-15	2020-04-19	0
0.58 (0.3-0.86)	R2	Agder	2020-04-20	2020-08-31	0
1.06 (0.49-1.36)	R3	Agder	2020-09-01	2020-11-04	0.71
0.57 (0.14-1.06)	R4	Agder	2020-11-05		0.04
0.55 (0.3-0.76)	R1	Vestland	2020-03-15	2020-04-19	0
0.9 (0.6-1.11)	R2	Vestland	2020-04-20	2020-08-16	0.2
1.04 (0.46-1.58)	R3	Vestland	2020-08-17	2020-09-09	0.56
1.29 (1.1-1.55)	R4	Vestland	2020-09-10	2020-11-04	1
0.42 (0.18-0.65)	R5	Vestland	2020-11-05		0
0.59 (0.32-0.86)	R1	Trøndelag	2020-03-15	2020-04-19	0
0.52 (0.3-0.78)	R2	Trøndelag	2020-04-20	2020-08-31	0
0.91 (0.37-1.25)	R3	Trøndelag	2020-09-01	2020-11-04	0.36
0.83 (0.41-1.43)	R4	Trøndelag	2020-11-05		0.19
0.85 (0.34-1.15)	R1	Troms og Finnmark	2020-03-15	2020-04-19	0.22
0.32 (0.03-0.87)	R2	Troms og Finnmark	2020-04-20	2020-08-31	0
1.12 (0.71-1.44)	R3	Troms og Finnmark	2020-09-01	2020-11-04	0.75
0.96 (0.6-1.33)	R4	Troms og Finnmark	2020-11-05		0.41
2.04 (1.26-2.53)	AMP factor	All			-

Mean and 95% credible intervals

Table 19: Hospitalisation probabilities (1/2)

	Until 2020-05-01	Until 2020-06-01	Until 2020-07-01	Until 2020-08-01
0-9 years	0.0002	0.0005	0.001	0.0005
10 - 19 years	0.001	0.001	0.001	0.001
20 - 29 years	0.006	0.007	0.009	0.010
30 - 39 years	0.014	0.019	0.016	0.014
40 - 49 years	0.018	0.016	0.015	0.013
50 - 59 years	0.040	0.032	0.025	0.030
60 - 69 years	0.053	0.030	0.031	0.035
70 - 79 years	0.075	0.048	0.022	0.041
80+ years	0.328	0.120	0.145	0.040

Table 20: Hospitalisation probabilities (2/2)

	Until 2020-09-01	Until 2020-10-01	Until 2020-11-01	From 2020-11-01
0-9 years	0.0004	0.0004	0.0004	0.001
10 - 19 years	0.001	0.001	0.001	0.002
20 - 29 years	0.015	0.012	0.011	0.007
30 - 39 years	0.011	0.014	0.014	0.013
40 - 49 years	0.011	0.013	0.015	0.016
50 - 59 years	0.022	0.024	0.027	0.027
60 - 69 years	0.015	0.030	0.031	0.036
70 - 79 years	0.025	0.033	0.033	0.038
80+ years	0.038	0.096	0.076	0.123

Table 21: Assumptions

Assumptions	Mean	Distribution	Reference
Mobile Mobility Data			
Telenor coverage	48%		https://ekomstatistikken.nkom.no/
Data updated	December 26th		
Data used in the predictions	December 21th	Fixed	Corrected to preserve population
Model parameters			
Exposed period ($1/\lambda_1$)	3 days	Exponential	Feretti et al 2020
Pre-symptomatic period ($1/\lambda_2$)	2 days	Exponential	Feretti et al 2020
Symptomatic infectious period ($1/\gamma$)	5 days	Exponential	Feretti et al 2020
Asymptomatic, infectious period ($1/\gamma$)	5 days	Exponential	Feretti et al 2020
Infectiousness asympt. (r_{I_a})	0.1	Fixed	Feretti et al 2020
Infectiousness presymp (r_{E_2})	1.25	Fixed	guided by Feretti et al 2020
Prob. asymptomatic infection (p_a)	0.4		Feretti et al 2020
Healthcare			
Time sympt. onset to hospitalisation	8.87 days (before August 1st)/ 7.40 (After August 1st)	Neg. binomial	
Fraction asymptomatic infections	40%	Fixed	Mizumoto et al 2020 20% for the old population, Diamond Princess
% symptomatic and asymptomatic infections requiring hospitalization:		Fixed	Salje et al 2020 corrected for: % of elderly living in elderly homes in Norway (last two age groups) and corrected for presence among positive tested since May 1. Corrected values available in tables 19 and 20
0-9 years	0.1%		
10 - 19 years	0.1%		
20 - 29 years	0.5%		
30 - 39 years	1.1%		
40 - 49 years	1.4%		
50 - 59 years	2.9%		
60 - 69 years	5.8%		
70 - 79 years	9.3%		
80+ years	22.3%		
% hospitalized patients requiring ICU		Fixed	Estimated from "Beredskapsregistret BeredtC19"
Feb - July	15.1%		
August -	8.5%		
Probability that an admission has been reported on Monday		Fixed	Estimated from "Beredskapsregistret BeredtC19"
From Sunday	32%		
From Saturday	49%		
From Friday	68%		
From Thursday	86%		
Probability that an admission has been reported		Fixed	Estimated from "Beredskapsregistret BeredtC19"
From one day before	53%		
From two days before	77%		
From three days before	82%		
From four days before	91%		
Probability that a positive laboratory test has been reported		Fixed	Estimated from MSIS
From one day before	6.7%		
From two days before	59%		
From three days before	90%		
From four days before	97%		
Probability that a negative laboratory test has been reported		Fixed	Estimated from MSIS
From one day before	16%		
From two days before	74%		
From three days before	92%		
From four days before	98%		

Supplementary analysis: EpiEstim estimation of reproduction number based on laboratory-confirmed cases

To complement the results of the metapopulation model, we present estimates of the temporal evolution of the reproduction number in Norway based on an analysis of laboratory-confirmed cases. The primary purpose of this analysis is to provide a more comprehensive perspective on the epidemic situation, taking into account several data sources.
The hospitalisation data are a less biased information source for the number of infections compared to case data because the testing criteria in Norway has changed. For this reason, the present results should be interpreted with caution. During the early part of the period, testing of individuals was mainly based on travel history to areas with an ongoing outbreak. Since the middle of March, testing is recommended for people with an acute respiratory infection. From early May, the testing criteria have been expanded to include less severe symptoms. The analysis of laboratory-confirmed cases does not take into account the effect of imported cases during the early outbreak in Norway; the early results are less reliable than later results when the impact of importations is negligible.

EpiEstim method and assumptions: 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 approach to estimate the instantaneous reproduction number smoothed over a sliding window of 5 days, see figure 32. For the results to be comparable to those of the metapopulation model, we use the same natural history parameters. We estimate the date of infection for each confirmed case by first estimating the date of symptom onset and then subtracting 5 days for the incubation period. We estimate the date of symptom onset from the empirical delay between onset and testing in the first reported cases. For each case, we draw 100 possible onset dates from the delay distribution; this gives us 100 epi-curves that we use to estimate the reproduction number. The displayed results are the combined results from all these 100 simulated epi-curves. The serial interval was assumed to be 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 are uncertain, as indicated by increasing credible intervals.

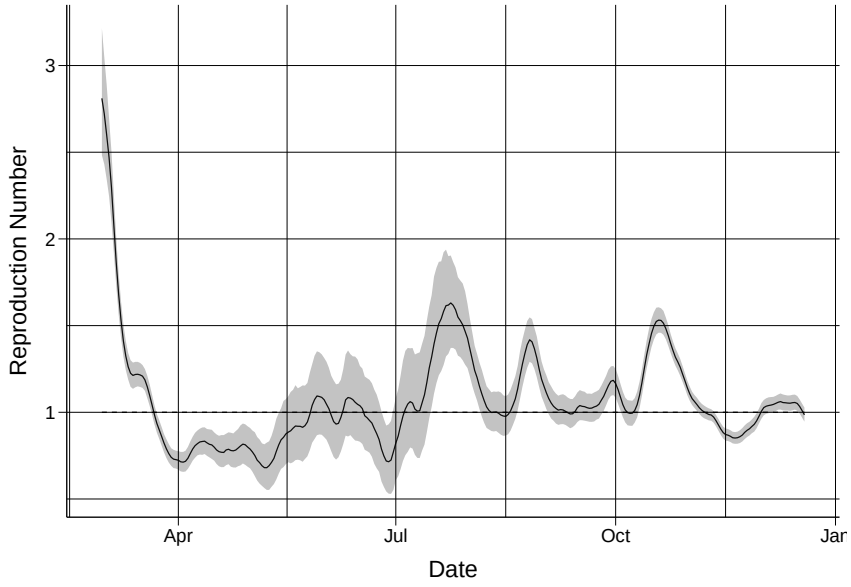


Figure 32: Reproduction number estimated using the R package EpiEstim.

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