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An assessment of the potential impact of the Omicron variant of SARS-CoV-2 in Aotearoa New Zealand

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ABSTRACT

New Zealand delayed the introduction of the Omicron variant of SARS-CoV-2 into the community by the continued use of strict border controls through to January 2022. This allowed time for vaccination rates to increase and the roll out of third doses of the vaccine (boosters) to begin. It also meant more data on the characteristics of Omicron became available prior to the first cases of community transmission. Here we present a mathematical model of an Omicron epidemic, incorporating the effects of the booster roll out and waning of vaccine-induced immunity, and based on estimates of vaccine effectiveness and disease severity from international data. The model considers differing levels of immunity against infection, severe illness and death, and ignores waning of infection-induced immunity. This model was used to provide an assessment of the potential impact of an Omicron wave in the New Zealand population, which helped inform government preparedness and response. At the time the modelling was carried out, the date of introduction of Omicron into the New Zealand community was unknown. We therefore simulated outbreaks with different start dates, as well as investigating different levels of booster uptake. We found that an outbreak starting on 1 February or 1 March led to a lower health burden than an outbreak starting on 1 January because of increased booster coverage, particularly in older age groups. We also found that outbreaks starting later in the year led to worse health outcomes than an outbreak starting on 1 March. This is because waning immunity in older groups started to outweigh the increased protection from higher booster coverage in younger groups. For an outbreak starting on 1 February and with high booster uptake, the number of occupied hospital beds in the model peaked between 800 and 3,300 depending on assumed transmission rates. We conclude that combining an accelerated booster programme with public health measures to flatten the curve are key to avoid overwhelming the healthcare system.

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1. Introduction

Since the early stages of the COVID-19 pandemic, New Zealand has used strong border controls to minimise the importation of SARS-CoV-2 into the community from overseas (Baker et al., 2020). In August 2021, New Zealand experienced a community outbreak of the B.1.617.2 (Delta) variant. The outbreak was linked by whole genome sequencing to an ongoing Delta outbreak in the Australian state of New South Wales, and was likely caused by the virus leaking out of a managed isolation and quarantine facility. The outbreak was suppressed with a combination of non-pharmaceutical interventions, increasing levels of vaccination coverage, and ongoing use of managed isolation and quarantine for all international arrivals. By the end of 2021, New Zealand had achieved high vaccination coverage with over 90% of the eligible population having received two doses of the Pfizer/BioNTech BNT162b2 vaccine. The population had very low levels of prior infection, with around 12,600 total community cases since February 2020 out of a population of 5.1 million (0.25%). The health burden of the Delta outbreak was disproportionately felt by Māori and Pacific people (Smith et al., 2021), groups known to be at higher risk from COVID-19 (McLeod et al., 2020; Steyn et al., 2021).

On 26 November 2021, the World Health Organisation designated the B.1.1.529 variant of SARS-CoV-2 a variant of concern, named Omicron (World Health Organisation, 2021). This followed a rapid growth in COVID-19 cases in South Africa driven by the emergence of the new variant (Viana et al., 2022). In many populations, Omicron has exhibited a significant transmission advantage over Delta, at least partly due to a greater ability to infect people who have been vaccinated or previously infected (Pearson et al., 2021). At the time of Omicron's emergence, New Zealand still had strict border controls in place, with all international arrivals required to spend 7 days in government-managed isolation and quarantine. Border restrictions were scheduled to be relaxed in stages, starting from mid January 2022. However, as a result of the emergence and rapid spread of Omicron, these reopening plans were postponed. This delayed the introduction of Omicron into the community, with the first known cases of community transmission reported on 23 January 2022 (Ministry of Health, 2022a). By this time, the 7-day rolling average number of cases associated with the Delta outbreak had reduced to approximately 25 per day with less than 10 cases in hospital.

Delaying the arrival of Omicron into New Zealand bought valuable time to increase vaccine coverage, start the paediatric vaccination programme, which began on 17 January 2022, and roll out booster doses. By 23 January 2022, approximately 77% of New Zealand's population (93% of the eligible population over 12 years old) had received at least two doses of the Pfizer-BioNTech BNT162b2 vaccine, and 19% had received a third dose (Ministry of Health, 2022a), referred to hereafter as a booster. Vaccination of children aged 5–11 years began on 17 January 2022. Booster coverage was higher in older age groups, who were prioritised in the initial vaccination programme and therefore became eligible for the booster earlier. However, Māori tended to receive their primary vaccine course later than non-Māori due to an inequitable vaccine rollout (Waitangi Tribunal Wai, 2575; Whitehead et al., 2021). Hence, given the required four-month interval after the second dose, a low proportion of Māori were eligible for the booster by early 2022.

Given the very large number of cases among international arrivals in managed isolation and quarantine, and the high transmissibility of Omicron (Viana et al., 2022), it was apparent by early January 2022 that it was a matter of time until a border-related outbreak sparked a major epidemic wave in New Zealand. Although experiences of Omicron in other countries serve as useful guides, New Zealand was in a different situation to most other jurisdictions, with a high national vaccination rate, low but rapidly rising levels of booster coverage, and negligible infection-acquired immunity. This paper presents a mathematical model that was used prior to the arrival of Omicron into the New Zealand community to assess the potential impact of an Omicron wave. The model builds on a previously published age-structured stochastic model for the Delta variant (Plank et al., 2021; Steyn et al., 2022), with modified parameters for disease severity and vaccine effectiveness based on international data for Omicron, and generalised to include booster doses and waning of vaccine-induced immunity over time. The model also includes the effects of changing levels of two-dose and three-dose vaccine coverage in different age groups, based on a combination of real data on vaccines administered and projected future uptake.

The results were used to inform government strategy and preparedness in January 2022, including likely demand on the healthcare system and the importance of achieving higher booster coverage. At the time the research was carried out, the date of introduction of Omicron into the New Zealand community was unknown. We therefore explored outcomes for a range of different outbreak start dates and different levels of booster coverage. This allowed the model to explore the interaction between increasing immunity due to the ongoing booster rollout and decreasing immunity due to waning.

2. Methods

We use an age-structured stochastic model for transmission of SARS-CoV-2. This builds on a model that has previously been used to describe New Zealand's Delta outbreak that started from a border-related source in August 2021. With a time-varying control function fitted to data on new daily cases, the model provides a reasonably good fit to cases, hospitalisation and deaths using parameter values for the Delta variant (Plank et al., 2021). Here we generalise the model to include the effects of booster doses and waning of vaccine-induced immunity. We also modify key parameter values to reflect the characteristics of the Omicron variant, as described below. For a complete model specification, see Supplementary Information. Software to run the model is available at https://github.com/michaelplanknz/assessment-of-potential-impact-of-omicron-in-NZ.

2.1. Vaccine coverage

Vaccine coverage by 5-year age band is as per data on doses administered up to 17 January 2022, with the additional assumption that everyone who had received their first dose by 17 January receives their second dose five weeks later. This means that approximately 91% of over-12-year olds are double-vaccinated. Note that model vaccine coverage may be lower than official Ministry of Health statistics because we used the StatsNZ estimated resident population (ERP) as population denominators (see Supplementary Table S1), rather than the health service utilisation (HSU) population, which is typically smaller. As of January 2021, adults become eligible for the booster dose 120 days after receiving their second dose and we assume that either 70% or 90% of adults receive their third dose two weeks after becoming eligible. Vaccination of 5–11-year-olds began on 17 January 2022, with an eight-week interval between the first and second dose. As a simple model of the effects of vaccinating this age group, we assume that there is a 75% uptake over an eight-week period. All vaccine doses are assumed to take effect 14 days after being received.

2.2. Vaccine effectiveness

Vaccine effectiveness of the Pfizer/BioNTech BNT162b2 vaccine is characterised by three model parameters: reduction in risk of infection, risk of hospitalisation, and risk of death. Effectiveness is assumed to wane with time since most recent dose (Table 1) according to estimates by UKHSA (United Kingdom Health Security Agency, 2022a, 2022b, 2022c, 2022d; Andrews et al., 2022). In addition, we assume that effectiveness against infection is the same as effectiveness against symptoms (which is supported by UK data from routine testing of healthcare workers (United Kingdom Health Security Agency, 2022a, 2022b, 2022c, 2022d)), but that there is no additional reduction in transmission for breakthrough infections. This is an optimistic assumption as regards infection prevention, but a pessimistic assumption as regards breakthrough transmission. We assume that effectiveness against death is halfway between effectiveness against hospitalisation and 100%, as vaccines tend to provide better protection against more severe outcomes. These assumptions are broadly consistent with the range of vaccine effectiveness values used by UK SPI-MO modelling groups (Barnard et al., 2021; Keeling & Dyson, 2022; Keeling et al., 2021). In a sensitivity analysis, we investigate an alternative set of vaccine effectiveness parameters from Golding and Lydeamore (2022) based on the model of Khoury et al. (2021) - see Supplementary Table S2.

2.3. Basic reproduction number and generation interval

There is significant uncertainty about the relative contribution of intrinsic transmissibility (as measured by R_0), generation time, and immune evasion to Omicron's transmission advantage over Delta (Pearson et al., 2021). Here we investigate a baseline scenario in which the reproduction number excluding the effects of immunity (R_{EI}) is $R_{EI} = 2.6$ and the mean generation time ($\overline{g}$) is $\overline{g} = 3.3$ days (Abbott et al., 2022; Scientific Pandemic Influenza Group on Modelling, Operational sub-group, 2022). The assumed reproduction number includes the effects of moderate public health measures, such as those required at the red setting of New Zealand's COVID-19 Protection Framework (New Zealand Government, 2021), but assume there is no strict lockdown. Immunity in the population from vaccination and from prior infection reduce the effective reproduction number below the assumed value of R_{EI}. We also consider a high transmission ($R_{EI} = 3.4$, $\overline{g} = 5.05$ days) and a low transmission scenario ($R_{EI} = 2.2$, $\overline{g} = 2.7$ days) (Ferretti et al., 2020; Kim et al., 2022). We do not attempt to model individual public health interventions or restrictions and other combinations of R_{EI} and $\overline{g}$ are possible. We focus on these scenarios as they provide a range of plausible outcomes with case doubling times that are approximately consistent with international observations.

2.4. Disease severity

The assumed risk of hospitalisation and death in five-year age bands for infections in unvaccinated people is shown in Table 2. The risk of hospitalisation is based on the estimates of (Herrera-Esposito & de los Campos, 2021), adjusted as in our previous model by an odds ratio of 2.26 for the Delta variant (Twohig et al., 2021), and additionally adjusted by a hazard ratio of 0.33 reflecting lower intrinsic severity of Omicron relative to Delta (Lewnard et al., 2022; Nyberg et al., 2022; United Kingdom Health Security Agency, 2021). The risk of death is based on estimates of Herrera-Esposito and de los Campos (2021) adjusted by a hazard ratio of 0.3 for Omicron (Ward et al., 2022). Lewnard et al. (2022) found that the risk of death

Table 1
Assumed vaccine effectiveness parameters for Omicron by time since receiving dose 2 or dose 3 of the Pfizer/BioNTech BNT162b2 vaccine (Keeling & Dyson, 2022; United Kingdom Health Security Agency, 2022a, 2022b, 2022c, 2022d).

Vaccine effectiveness	Dose 2				Dose 3			
	2–5 wks	5–10 wks	10–15 wks	15+ wks	2–5 wks	5–10 wks	10–15 wks	15+ wks
Infection	62%	55%	40%	28%	64%	57%	47%	40%
Hospitalisation	83%	80%	75%	72%	92%	88%	83%	79%
Death	92%	90%	88%	86%	96%	94%	92%	90%

Table 2
Hospitalisation and death rates for unvaccinated infected people in five-year age bands.

Age band (years)														
0–4	5–9	10–14	15–19	20–24	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–69	70–74	75+
Proportion of infections causing hospitalisation (%)															
0.31	0.31	0.13	0.20	0.29	0.42	0.61	0.90	1.27	1.87	2.77	3.90	5.65	7.94	11.1	19.9
Proportion of infections causing death (%)															
0.0004	0.0004	0.0004	0.0008	0.002	0.003	0.006	0.011	0.023	0.045	0.087	0.168	0.331	0.635	1.22	4.27

for Omicron cases was 0.19 times the risk of death for Delta cases. However, they did not have sufficient data to adjust this estimate for other covariates. Not controlling for vaccination status and prior infection means this may be an underestimate of the relative risk because Omicron cases are more likely to be breakthrough infections, which tend to be milder.

Note that these hazard ratios describe the intrinsic severity of Omicron relative to Delta. The realised severity is the product of intrinsic severity with vaccine effectiveness against infection and hospitalisation, and the age and vaccination status of the subpopulation that becomes infected. The reduction in realised severity relative to Delta is a model output and may be more than, similar to, or less than the reduction in intrinsic severity (Scientific Pandemic Influenza Group on Modelling, Operational sub-group Chairs, 2021). We assume that the average length of hospital stay for Omicron is 4 days (Abdullah et al., 2021), which is shorter than estimates for the Delta variant.

2.5. Other simplifying assumptions

Immunity from infections that occurred prior to the start of the simulated time period is ignored. This assumption is not likely to have a large effect on model results given that, prior to the arrival of Omicron in the community, New Zealand has had approximately 12,600 confirmed community cases of COVID-19, which is around 0.25% of the total population.

We do not consider the effects of a concurrent outbreak of the Delta variant. This is reasonable given that the number of Delta cases had declined to a 7-day average of around 25 per day. Infection with the Omicron variant is assumed to provide complete protection against re-infection with Omicron for the remainder of the simulation.

Differences in the effectiveness of the AstraZeneca vaccine relative to the Pfizer vaccine are ignored. This is expected to have a negligible effect on population-level outcomes as the number of AstraZeneca vaccines given in New Zealand is very small. Vaccine effectiveness and waning immunity for people who have had one vaccine dose is ignored. This affects a relatively small part of the population.

The effects of seasonality are not included in the model. Simulations are initialised with 500 seed infections introduced over a one-week time period following the specified outbreak start date. This models some initial undetected community transmission and means that model outputs are restricted to seeding events that lead to established community transmission and exclude those that go stochastically extinct. Key model outputs are not highly sensitive to the number of seed infections, though it will affect the timing of the peak.

3. Results

Fig. 2 shows simulated outbreaks starting on 1 January, 1 February, 1 March, 1 April and 1 May 2022 under baseline parameters and assuming 90% of eligible people eventually receive their booster dose. Figs. 3 and 4 show corresponding results for the low transmission and high transmission scenarios. Table 3 shows additional model outputs for the scenarios shown in Figs. 2–4 and an additional set of scenarios where booster uptake eventually reaches 70% of those eligible rather than 90%. Results show the median from $n = 100$ independent model simulations. Because the number of infections is large, the difference between independent realisations of the stochastic model are relatively small. We therefore do not report percentile ranges of simulation because the greater source of uncertainty comes from parameter uncertainty and potential model misspecification.

Given the uncertainty in early January 2022 in some of the parameter values describing the Omicron variant, we benchmarked model outputs against reported data on standardised metrics in different countries, states or regions (Table 4). This shows that the three main scenarios considered in Figs. 2–4 span a range of outcomes realised in different jurisdictions. The low transmission, baseline, and high transmission scenarios compare reasonably closely with outcomes observed in South Australia, London, and New York State respectively (see Table 4 caption for details of data sources).

Across all scenarios investigated, an outbreak starting on 1 February leads to lower peaks and fewer cumulative cases, hospitalisations and deaths than an outbreak starting on 1 January. This is because of the increased level of booster coverage achieved by February/March (Fig. 1). An outbreak starting on 1 March leads to similar outcomes to an outbreak staring on 1 February. Outbreaks starting later (1 April or 1 May) lead to progressively higher peaks and more cumulative cases, hospitalisations and deaths than an outbreak starting on 1 March. This is because the effects of waning immunity, particularly in older age groups who tend to be vaccinated and boosted earlier, start to outweigh the benefits from boosting diminishing number of people in younger groups.

Table 3
Model outputs for the low, baseline and high transmission scenarios with either 70% or 90% eventual uptake of boosters by eligible individuals, and for five different outbreak start dates. Outputs shown are: total number of infections during the simulation; total number of reported cases; total number of hospitalised cases; total number of deaths; peak prevalence (defined as the proportion of the total population newly infected in a 10-day period); peak 7-day average daily reported cases; peak number of hospital beds occupied; time from the first infection to the peak number of daily cases. All results are the median of $n = 100$ independent realisations of the stochastic model.

Start date	Infections	Cases	Hospitalisations	Deaths	Peak prevalence	Peak daily cases	Peak beds	Time to peak (days)
LOW TRANSMISSION (S Australia) - 90% of eligible get boosted								
1 Jan	1,613,000	414,900	12,260	500	8%	9,950	1,140	77
1 Feb	1,497,000	385,600	11,500	460	5%	6,580	790	89
1 Mar	1,673,000	432,300	13,130	520	6%	7,850	960	106
1 Apr	1,817,000	469,700	14,330	570	8%	10,030	1,210	100
1 May	1,902,000	491,500	14,980	590	9%	11,510	1,360	93
LOW TRANSMISSION (S Australia) - 70% of eligible get boosted								
1 Jan	1,849,000	476,600	14,700	610	10%	12,510	1,490	75
1 Feb	1,733,000	447,600	13,780	550	8%	9,730	1,170	81
1 Mar	1,806,000	467,900	14,610	590	8%	10,140	1,250	90
1 Apr	1,941,000	502,800	15,810	630	9%	11,950	1,460	89
1 May	2,033,000	526,200	16,540	660	10%	13,490	1,630	85
MEDIUM TRANSMISSION (London) - 90% of eligible get boosted								
1 Jan	2,664,000	683,300	21,450	950	19%	23,540	2,730	66
1 Feb	2,436,000	625,000	19,300	830	14%	17,600	2,070	71
1 Mar	2,471,000	637,100	20,130	860	14%	17,600	2,120	79
1 Apr	2,608,000	673,600	21,590	910	16%	19,800	2,400	78
1 May	2,731,000	704,500	22,590	950	18%	22,290	2,700	74
MEDIUM TRANSMISSION (London) - 70% of eligible get boosted								
1 Jan	2,811,000	722,900	23,720	1,050	21%	25,750	3,120	66
1 Feb	2,648,000	681,000	21,980	950	17%	21,380	2,590	67
1 Mar	2,638,000	681,200	22,220	950	17%	20,990	2,590	73
1 Apr	2,723,000	704,300	23,250	990	18%	22,410	2,780	73
1 May	2,833,000	732,300	24,210	1,030	20%	24,620	3,040	70
HIGH TRANSMISSION (New York) - 90% of eligible get boosted								
1 Jan	3,481,000	887,400	29,680	1,380	25%	30,820	3,750	70
1 Feb	3,359,000	858,300	28,450	1,320	21%	26,520	3,260	74
1 Mar	3,369,000	863,400	29,250	1,340	21%	26,640	3,360	79
1 Apr	3,464,000	888,700	30,580	1,390	23%	28,460	3,620	79
1 May	3,560,000	914,000	31,600	1,440	25%	30,610	3,880	75
HIGH TRANSMISSION (New York) - 70% of eligible get boosted								
1 Jan	3,596,000	919,400	32,390	1,550	27%	32,950	4,180	69
1 Feb	3,499,000	895,200	30,970	1,440	24%	29,810	3,760	71
1 Mar	3,480,000	894,000	31,410	1,450	24%	29,490	3,780	74
1 Apr	3,538,000	909,800	32,140	1,470	25%	30,640	3,940	73
1 May	3,627,000	931,900	33,040	1,510	26%	32,540	4,200	72

Table 5 compares the baseline model results with various alternative scenarios. Firstly, in a scenario with no booster coverage, all outcomes are significantly worse, emphasising the importance of accelerating the booster roll out in advance of an Omicron wave. Note the model likely underestimates the health impacts in scenarios with no booster and a late outbreak start as we do not model any further waning more than 20 weeks after the second dose. Secondly, in a scenario with an alternative set of vaccine effectiveness estimates (Golding & Lydeamore, 2022), outcomes are worse than the baseline scenario, though the pattern with respect to the outbreak start time remains consistent.

Finally, we investigated the sensitivity of the model to parameters affecting the age distribution of infections. The realised age distribution of cases for the Omicron wave in New Zealand was not known *a priori* and is a product of contact rates between age groups, two-dose and three-dose vaccine coverage by age (which varied through time), and vaccine effectiveness against infection and transmission (which are different for Omicron relative to Delta). We performed model simulations using an adjusted contact matrix with higher contact rates among younger groups, renormalised to give the same R_{EI} as in the baseline scenario (see Supplementary Information). This adjusted contact matrix results in a younger age distribution of cases, which is closer to that observed in New Zealand's Delta outbreak and in Queensland's Omicron wave up to mid January 2022 (Fig. 5). Due to the shift of cases to younger groups, the number of hospitalisations and deaths (Table 5) are significantly lower than under the baseline scenario and slightly lower than under the low transmission scenario with the original contact matrix.

4. Discussion

We have presented a preliminary assessment of the potential impact of the Omicron variant of SARS-CoV-2 in New Zealand. This modelling was carried out before the detection of the Omicron outbreak on 23 January 2022 and simulates outbreaks with a range of different hypothetical start dates. These results should therefore be treated as preliminary estimates

Table 4
International benchmarking of model outputs. Model outputs are shown for the low, medium and high transmission scenarios with a 1 February start date and 90% eventual uptake of booster doses. Data for Australian states is from https://covidlive.com.au; data for UK is from https://coronavirus.data.gov.uk and the Office for National Statistics https://www.ons.gov.uk; data for New York is from Johns Hopkins https://coronavirus.jhu.edu; data for other countries is from Our World in Data https://ourworldindata.org/coronavirus. Vaccination rates are as at 1 January 2022, except for booster rates in Australian states which are for 10 January 2022 (the earliest date for which booster data was available). Stringency index is from the Oxford Coronavirus Government Response Tracker project (Hale et al., 2021) and is a composite measure based on nine response indicators including school closures, workplace closures, and travel bans, rescaled to a value from 0 to 100 (100 = strictest) https://ourworldindata.org/covid-stringency-index.

	Peak prevalence	Peak daily cases per mil. (7d avg)	Peak hospital occupancy per million	% vaccinated 01/01/22 2 dose [3 dose]	Stringency index 7/01/22
Model outputs for 1 Feb start date and 90% eventual booster uptake					
Low transmission	5%	1,300	150		
Baseline	14%	3,400	400		
High transmission	21%	5,200	640		
Selected Australian states					
New South Wales		4,800	350	79% [15%]	
Victoria		4,800	180	79% [14%]	
Queensland		3,300	170	71% [14%]	
South Australia		2,200	170	75% [15%]	
Other selected jurisdictions					
London	9%	3,200	500	70% [44%]	
England	7%	2,800	300	70% [51%]	48.5
Scotland	6%	3,000	300	73% [55%]	
New York		4,400	700	74%	
France		5,200	420 [rising 24/01]	73% [33%]	72.2
Denmark		6,000	140 [rising 24/01]	78% [48%]	35.2
Portugal		4,500	200 [rising 24/01]	90% [29%]	42.6
Ireland		4,800	220	77% [46%]	52.8

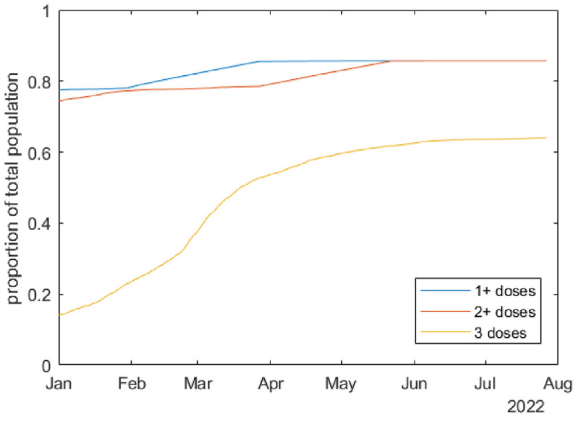

Fig. 1. Modelled proportion of the total population who have received at least one dose, at least two doses, and three doses (under the assumption that 90% of those eligible get a booster dose), plotted by date the immunity takes effect, which is assumed to be 14 days after the vaccine is received.

of potential outcomes, and the relative effect of the booster rollout over time. Work is ongoing to model the unfolding epidemic wave in real time.

4.1. Summary of main findings

For an outbreak starting around 1 February, in scenarios where there is high booster uptake, peak hospital admissions range from 200 to 800 per day, and peak demand for hospital beds ranges from 800 to 3,300 depending on assumed transmission rates. These numbers would put significant strain on hospital capacity, suggesting that public health measures aimed at flattening the curve may be necessary to avoid overwhelming the healthcare system. The Ministry of Health has reportedly said there are around 7,500 inpatient/ward beds in public hospitals, of which around 5,600 were occupied with non-COVID-19 cases in early March 2022 (Martin, 2022). For comparison, the peak COVID-19 hospital occupancy during the Delta outbreak in 2021 was 93 (Ministry of Health, 2021). Note that limiting heath impacts to the lower end of the modelled ranges (i.e. the low transmission scenario) would likely only be possible with an effective public health response.

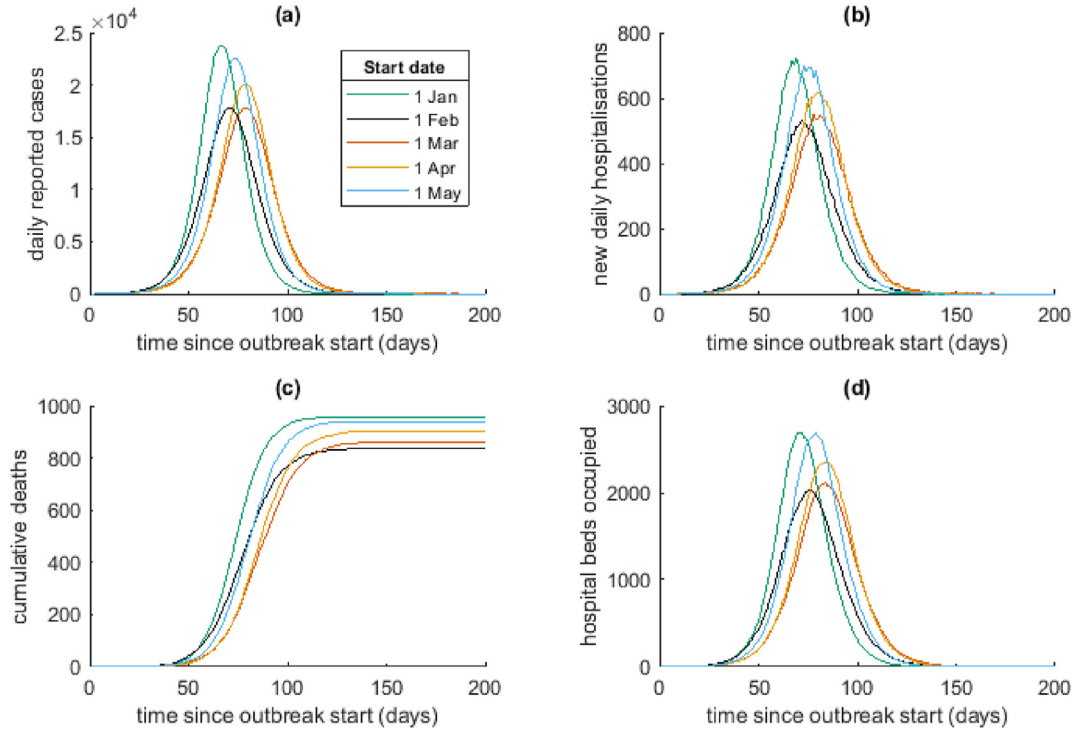

Fig. 2. Results for the baseline scenario for outbreaks seeded on five different dates: (a) daily reported cases; (b) new daily hospital admissions; (c) cumulative deaths; (d) hospital beds occupied. Curves show the median of $n = 100$ independent realisations of the stochastic model. Note different y-axis scales in Figs. 2–4.

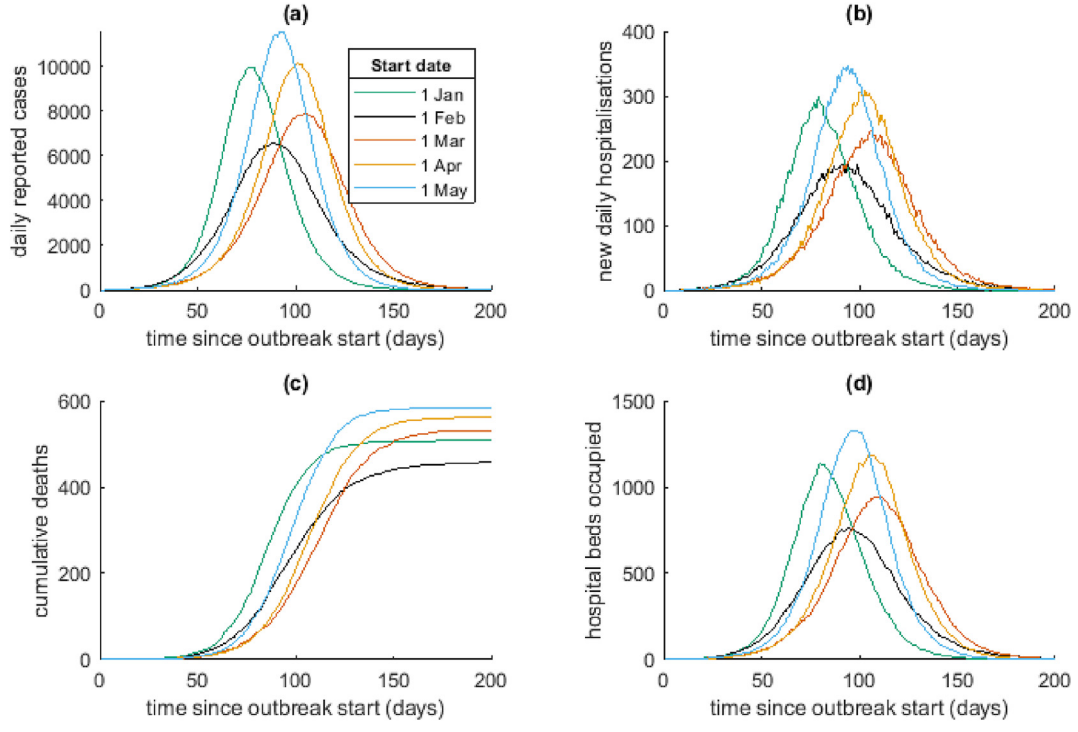

Fig. 3. Results for the low transmission scenario for outbreaks seeded on five different dates: (a) daily reported cases; (b) new daily hospital admissions; (c) cumulative deaths; (d) hospital beds occupied. Curves show the median of $n = 100$ independent realisations of the stochastic model. Note different y-axis scales in Figs. 2–4.

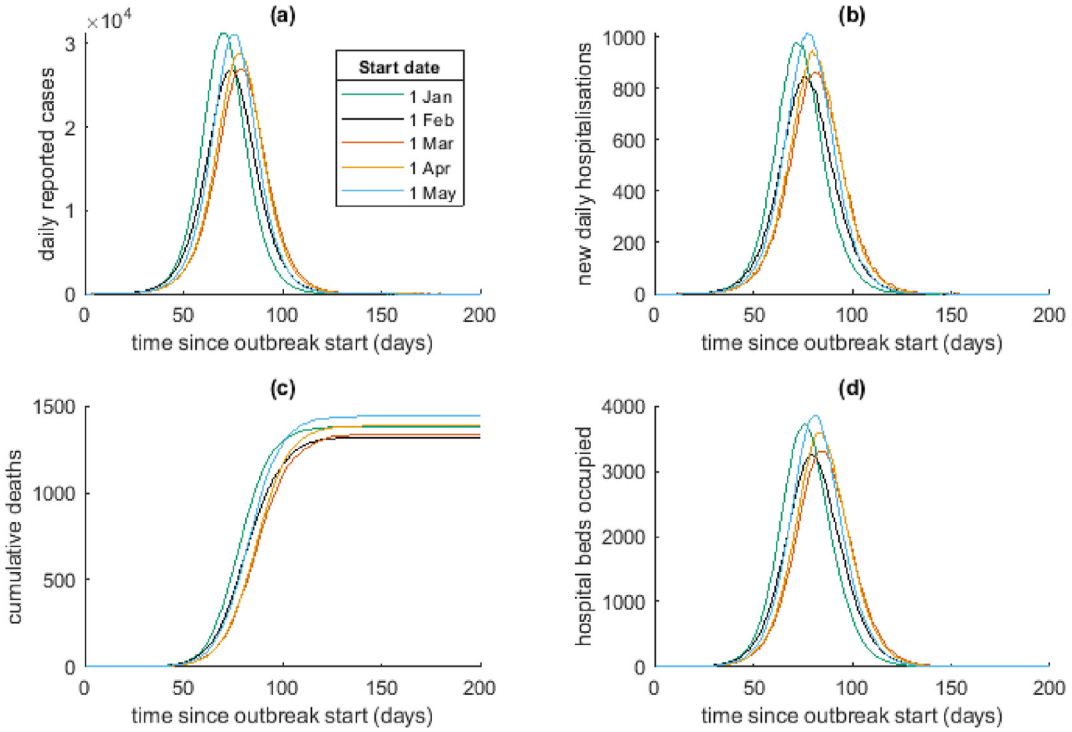

Fig. 4. Results for the high transmission scenario for outbreaks seeded on five different dates: (a) daily reported cases; (b) new daily hospital admissions; (c) cumulative deaths; (d) hospital beds occupied. Curves show the median of $n = 100$ independent realisations of the stochastic model. Note different y-axis scales in Figs. 2–4.

Table 5
Sensitivity analysis comparing model outputs for the baseline scenarios with alternative scenarios: with no booster coverage; using alternative vaccine effectiveness parameters (see Supplementary Table S2); with an adjusted contact matrix modelling increased transmission among younger groups and decreased transmission among older groups relative to the baseline scenario.

Start date	Infections	Cases	Hospitalisations	Deaths	Peak prevalence	Peak daily cases	Peak beds
MEDIUM TRANSMISSION (London) - 90% of eligible get boosted							
1 Jan	2,664,000	683,300	21,450	950	19%	23,540	2,730
1 Feb	2,436,000	625,000	19,300	830	14%	17,600	2,070
1 Mar	2,471,000	637,100	20,130	860	14%	17,600	2,120
1 Apr	2,608,000	673,600	21,590	910	16%	19,800	2,400
1 May	2,731,000	704,500	22,590	950	18%	22,290	2,700
NO BOOSTERS							
1Jan	3,242,000	841,400	31,620	1,430	26%	33,020	4,500
1Feb	3,288,000	852,100	31,370	1,380	28%	34,800	4,630
1Mar	3,229,000	839,300	30,640	1,320	28%	34,550	4,570
1Apr	3,164,000	823,700	30,020	1,290	27%	33,710	4,420
1May	3,194,000	830,700	30,190	1,300	27%	33,930	4,440
LOW VE - 90% of eligible get boosted							
1Jan	3,148,000	780,500	31,300	2,350	28%	32,880	4,780
1Feb	2,736,000	668,600	25,060	1,980	18%	22,000	3,070
1Mar	2,759,000	674,700	25,950	2,090	18%	21,340	3,090
1Apr	2,898,000	712,100	27,900	2,270	20%	23,830	3,490
1May	3,021,000	744,700	29,620	2,410	22%	26,790	3,930
ADJUSTED CONTACT MATRIX - 90% of eligible get boosted							
1Jan	2,015,000	490,400	9,500	300	14%	16,660	1,200
1Feb	1,823,000	443,200	8,300	250	11%	13,710	990
1Mar	1,713,000	418,400	8,000	250	10%	12,080	880
1Apr	1,771,000	433,800	8,400	260	10%	12,190	900
1May	1,908,000	467,300	9,000	280	12%	13,890	1,030

Due to the effects of waning immunity and the ongoing booster and paediatric vaccine rollouts, different groups will have different levels of risk at different times. Groups that are not yet eligible for the booster will be at elevated risk of severe

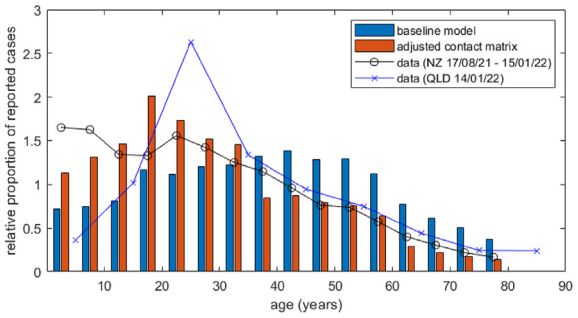

Fig. 5. Age distribution of cases: under the baseline model scenario for an outbreak starting on 1 February 2022 (red bars); the adjusted contact matrix (blue bars); confirmed community cases of COVID-19 in New Zealand for the period of the Delta outbreak from 17 August 2021 to 15 January 2022 ($n = 11,297$, black circles) according to the EpiSurv national database; cases of COVID-19 in Queensland up to 14 January 2022 ($n = 161,871$, blue crosses) from https://www.qld.gov.au/health/conditions/health-alerts/coronavirus-covid-19/current-status/statistics.

illness. This disproportionately includes Māori, who were not adequately prioritised due to an inequitable vaccine roll out (Waitangi Tribunal Wai, 2575), and who have higher risk of severe illness from COVID-19 (McLeod et al., 2020) (Steyn et al., 2021).

In general, lower booster uptake leads to worse outcomes. Slowing an outbreak to allow time for more people to receive their booster dose is a strategy that could reduce the overall health burden. However, waning immunity presents a danger that health outcomes in groups that were earliest to receive their booster become worse after a longer time period. Outbreaks that occur after significant waning of immunity can result in a higher overall health burden compared to outbreaks that occur during peak immunity. Maintaining high immunity levels across all groups will be important for future vaccination strategies.

Given the significant uncertainty about model parameters, we benchmarked model outputs against international data for selected jurisdictions. Each of these jurisdictions had their own particular characteristics including age structure, levels of vaccination and immunity from prior infection, prevalence of comorbidities, testing rates, behavioural change in response to perceived risk, mask use, other non-pharmaceutical interventions, hospital admission practices, and others. Although the situation in some jurisdictions resembled New Zealand's more closely than others, none matched exactly and it was not clear *a priori* which jurisdiction's experience New Zealand would follow most closely. Nevertheless, benchmarking model outputs across a range of international experiences was helpful in partially validating the model and for communicating the different scenarios to government officials and decision makers.

Because of the strong age gradient in severity of COVID-19, the number of hospitalisations and deaths is sensitive to the age distribution of infections. The baseline model scenario uses a contact matrix defining contact rates between different age groups based on pre-pandemic survey data (Prem et al., 2017) and adjusted for the New Zealand population (Steyn et al., 2022). However, people in older, more at-risk age groups might become more cautious and reduce their contacts during an Omicron outbreak. We investigated the possible consequences of this using a modified contact matrix that assumed increased contact rates among younger groups relative to older groups. This resulted in a large decrease in hospitalisations and deaths compared to the baseline scenario. This is due to a shift in the age structure of infections towards younger groups, who have a lower risk of severe illness or death from COVID-19. These results underscore the importance of measures to reduce infection rates in older groups.

4.2. Key limitations and uncertainties

Evidence about vaccine effectiveness and severity for Omicron relative to Delta is still accumulating and estimates of hospitalisation and death rates are subject to uncertainty. We have assumed that the observed prevention of symptomatic COVID-19 is due to infection prevention. However, if overall reduction in transmission is lower than this, our results for the number of cases could be significant underestimates. We assumed that vaccine effectiveness against death is higher than vaccine effectiveness against hospitalisation. This is consistent with observed patterns that vaccines tend to be more effective against more severe health outcomes than against milder outcomes. However, if vaccine effectiveness against death is closer to vaccine effectiveness against hospitalisation, the number of deaths could be up to double our estimates. Deaths are a particularly uncertain model output because, at the time the modelling was undertaken, there was limited direct data on vaccine effectiveness against death and the risk of death for the Omicron variant.

We assumed that vaccine effectiveness is the same in all age groups. There is some evidence that the effectiveness of the Pfizer vaccine against symptomatic disease caused by Omicron wanes faster in over 65-year-olds than in younger groups (United Kingdom Health Security Agency, 2022a, 2022b, 2022c, 2022d). Although vaccine effectiveness against hospitalisation was still high, if waning immunity results in an increasing number of infections in older age groups, our results for the total number of hospitalisation and deaths could be underestimates.

The generation interval of Omicron is a key model parameter that is uncertain at present. We have considered scenarios that range from a relatively high reproduction number and a generation interval that is similar to the ancestral strain of SARS-CoV-2 to a smaller reproduction number and shorter generation interval (Abbott et al., 2022; Kim et al., 2022). However, other combinations of reproduction number and generation time are possible.

Parameters are based primarily on estimates from studies where the BA.1 lineage of the Omicron variant was dominant. The BA.2 lineage is growing faster than BA.1 in several countries and may have a transmissibility advantage, though preliminary estimates are that vaccine effectiveness and severity are similar to BA.1 (United Kingdom Health Security Agency, 2022c, 2022d).

The model investigates how the dynamics of waning immunity and ongoing vaccination interact to affect key outcomes for Omicron outbreaks starting at different times. However, the model ignores other variables that may also affect outcomes, such as higher transmission rates and higher non-COVID-19 demand on the healthcare system during winter months. The model includes waning of vaccine-induced immunity up to around six months after the most recent dose. The model does not include waning of immunity following infection. This means that the model is not suitable for investigating the long-term dynamics of the epidemic and transition to endemicity.

The model does not take into account a stringent policy response such as lockdown, nor any behavioural changes that may arise dynamically as a result of the epidemic. If such measures have a substantial impact on transmission, this would be expected to flatten the curve of cases, hospitalisations and deaths. There could also be a long tail or a second wave following the initial peak if mixing drops and then increases again as normal behaviour resumes. The model assumes a relatively stable proportion of infections are reported as cases and does not take into account the effects of limited testing capacity. If testing capacity is exceeded, reported case numbers may cease to be a useful reflection of the true incidence of COVID-19.

The prevalence of Delta in New Zealand prior to the start of the Omicron wave was very low. However, if the number of Delta cases increases greatly at the same time as an Omicron wave, this could significantly add to the health burden of the epidemic. It would also complicate situational awareness given the large number of anticipated cases, limited genome sequencing capacity, and differential risks of clinical outcomes for the two variants. It is possible that Delta could account for a low proportion of cases but a higher proportion of healthcare demand.

In New Zealand's 2021 Delta outbreak, the proportion of cases hospitalised exceeded model predictions. This could be because the outbreak was concentrated in relatively high-risk groups. If this pattern is repeated in an Omicron outbreak, our results for hospitalisations could be underestimates. The model ignores important sources of heterogeneity in the New Zealand population that could affect rates of transmission, peak number of cases, and clinical outcomes. Model results show the national picture but this is likely to be unevenly distributed across the population. Communities with low vaccination rates, high comorbidity rates, poorly served by healthcare systems, or other risk factors are likely to be disproportionately affected. Māori and Pacific people are at higher risk from an Omicron outbreak: these groups have higher risk of severe illness if infected with previous variants of SARS-CoV-2 (Steyn et al., 2021) and were disproportionately in the 2021 Delta outbreak (Smith et al., 2021).

5. Addendum: qualitative comparison with New Zealand's omicron wave

This section was added during the revision process and provides a qualitative comparison of model results with New Zealand's Omicron wave as at 3 April 2022. Reported cases peaked around 6 March 2022 with a seven-day rolling average of around 20,500 per day, declining to around 12,800 by 2 April. Between 22 January and 3 April 2022, there was a total of around 676,000 reported cases and 298 deaths within 28 days of a positive COVID-19 test. Hospital occupancy peaked at 1,016 on 22 March 2022 and dropped to 678 by 2 April. The timing and size of the peak varied significantly in different regions: cases peaked highest and first in the Northern Region, which includes Auckland (5,830 daily cases per million on 3 March); peaks were lower in other regions and peaked last in the Southern Region (4,100 daily cases per million on 22 March) (Ministry of Health, 2022b). The outbreak was seeded with a mixture of BA.1 and BA.2 lineages and, unlike many other jurisdictions, BA.2 was dominant from relatively early in the wave (>50% of sequenced cases on 26 February and approximately 88% of sequenced cases as of 27 March) (Chen et al., 2021).

The wave is still in progress and the cumulative number of cases, hospitalisations and deaths will increase. In addition, officially reported numbers of hospitalisations and deaths include everyone within 14 days or 28 days of a positive COVID -19 test respectively. As in other jurisdictions, these numbers will include a substantial proportion of incidental admissions and deaths, i.e. those whose primary cause of illness or death is not COVID-19. More detailed data on cause of admission or death is being collated but is not yet available. Therefore, a comparison with model results can only be partial at this stage.

Overall, outcomes have fallen within the broad ranges estimated by the model scenarios. Uptake of boosters was strong in February, accelerated by a reduction in the required interval between the second and third dose from 4 months to 3 months. However, booster uptake slowed in March and is currently closer to the scenario with 70% uptake than to the scenario with 90% uptake. Reported cases have been reasonably consistent with the medium transmission scenario (with an outbreak start date of 1 February) in Table 3, but hospitalisations and deaths have been closer to the low transmission scenario. This is at least partly explained by the fact that the age distribution of cases has been closer to that with the adjusted contract matrix (red bars in Fig. 5) than with the original contact matrix (blue bars in Fig. 5). Comparing with the “adjusted contact matrix” sensitivity analysis in Table 5, the peak in cases was 50% higher than the model estimate and peak hospital occupancy was

2.6% higher. Deaths are already 19% higher than the projected total in this scenario. However, the likely inclusion of some incidental hospitalisations and deaths will affect these comparisons.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.idm.2022.04.002.

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