Estimating the risk of outbreaks of COVID-19 associated with shore leave by merchant ship crews: simulation studies for New Zealand

Nick Wilson, Tony Blakely, Michael G Baker, Martin Eichner

ABSTRACT

AIM: We aimed to estimate the risk of COVID-19 outbreaks in a COVID-19-free destination country (New Zealand) associated with shore leave by merchant ship crews who were infected prior to their departure or on their ship.

METHODS: We used a stochastic version of the SEIR model CovidSIM v1.1 designed specifically for COVID-19. It was populated with parameters for SARS-CoV-2 transmission, shipping characteristics and plausible control measures.

RESULTS: When no control interventions were in place, we estimated that an outbreak of COVID-19 in New Zealand would occur after a median time of 23 days (assuming a global average for source country incidence of 2.66 new infections per 1,000 population per week, crews of 20 with a voyage length of 10 days and 1 day of shore leave per crew member both in New Zealand and abroad, and 108 port visits by international merchant ships per week). For this example, the uncertainty around when outbreaks occur is wide (an outbreak occurs with 95% probability between 1 and 124 days). The combination of PCR testing on arrival, self-reporting of symptoms with contact tracing and mask use during shore leave increased this median time to 1.0 year (14 days to 5.4 years, or a 49% probability within a year). Scenario analyses found that onboard infection chains could persist for well over 4 weeks, even with crews of only 5 members.

CONCLUSION: This modelling work suggests that the introduction of SARS-CoV-2 through shore leave from international shipping crews is likely, even after long voyages. But the risk can be substantially mitigated by control measures such as PCR testing and mask use.

Historically, shipping has been involved in the global spread of pandemics, and maritime quarantine has been used as a successful control measure (eg, in the 1918 influenza pandemic). Maritime quarantine was even used successfully to prevent the arrival of the 2009 influenza pandemic in some island jurisdictions, such as Tokelau.

The COVID-19 pandemic has also had an impact on maritime vessels during 2020, as well as spread to people on shore. On the Diamond Princess, 19% of the passengers and crew became positive with the pandemic virus (SARS-CoV-2) and there was spread to Japanese responders on shore. Similarly, on the Grand Princess, 17% of those tested had positive results. On a much smaller cruise ship with 217 passengers and crew onboard, 59% were reported to be test-positive. On a fishing vessel, 85%
(104/122) of the crew were infected.\(^5\) In terms of merchant vessels, an outbreak on a container ship was reported as infecting 23\% (5/22) of the crew.\(^6\) Other such outbreaks have been detailed in media reporting (referred to in a review\(^7\)).

In response to the COVID-19 pandemic, border controls have been widely used to limit pandemic spread. Such border controls are particularly relevant for two types of strategy for controlling pandemics: (1) the exclusion strategy, as successfully practiced by some Pacific Island nations (eg, Tonga and the Cook Islands),\(^8\) and (2) the elimination strategy, as used by New Zealand\(^9\) and other jurisdictions (eg, Mainland China, Taiwan, and Australia).

Some of these jurisdictions have completely prohibited maritime vessels arriving at their seaports from countries that are not COVID-19-free (eg, the Marshall Islands have prohibited such incoming ships\(^8\)). But time periods are also used to lower risk. For example, a minimum of 14 days at sea before being allowed to enter the Marshall Islands,\(^9\) or 14 days plus a negative PCR test to enter New Zealand.\(^10\) There is also the standard international requirement for pratique whereby any ‘illness during the voyage’ must be notified to health authorities at the destination port.\(^11\) Collectively, these control measures seem to be working fairly well, although in October 2020 New Zealand reported that a ship maintenance worker became infected with SARS-CoV-2 after spending time working on a ship that had recently arrived in the country.\(^12\) This worker then infected other workers and a household contact onshore (but with no further known subsequent spread). Genome sequencing has indicated that the source of infection was shipping crew flying into New Zealand to join their ship.\(^13\) Also in October 2020, another island nation (Australia) faced outbreaks on two cargo ships in a port in Western Australia, where (in one case) two onboard workers left a ship before the outbreak was detected.\(^14\)

Given this background, we aimed to expand on previous modelling work for air transport spread of COVID-19,\(^15\) to determine the risk of merchant ships being the source of COVID-19 outbreaks in an otherwise COVID-19-free country: New Zealand.

**Methods**

**Model design and parameters for SARS-CoV-2 and COVID-19**

We used a stochastic SEIR type model with key compartments for susceptible [S], exposed [E], infected [I] and recovered/removed [R]. The model is a stochastic version of CovidSIM, which was developed specifically for COVID-19 (http://covidsim.eu; version 1.1). Work has been produced from previous versions of this model,\(^15-17\) and in two places we detail the relevant equations and their stochastic treatment.\(^18,19\) The model was built in Pascal, and the computer code is available on request from the authors.

We ran 100 million simulations for each set of parameter values. Such a large number of simulations was necessary due to the very high probability of zero infected crew members boarding a departing merchant ship, given the low assumed incidence of infection (see Table 1). The overall framework for the processes modelled is shown in Figure 1. The parameters were based on available publications and best estimates used in the published modelling work on COVID-19 (as known to us on 27 August 2020). We assumed that 71\% of infected COVID-19 cases develop clearly detectable symptoms (Table 1). Another assumption was the contagiousness in terms of the effective reproduction number (\(R_{eff}\)), which was 3.0 among crew members on board the ship and 2.5 in the destination country (Table 1).

**Shore leave in the destination country**

We selected New Zealand as a case study destination country, as it has previously achieved elimination of community transmission of SARS-CoV-2\(^9\) and appears to have successfully controlled subsequent cross-border incursions of the pandemic virus. Upon arrival of ships in New Zealand, we used a period of shore leave by all the crews of one day (the median time ships are in port, based on Ports of Auckland data, the port in New Zealand’s largest city).

**Potential control measures**

Potential control measures are detailed in Table 2 and Figure 1 and include a PCR test on all the crews on arrival and mask use by the crews during shore leave. If any
crew member tested positive, then the shore leave for that particular crew was assumed to be prohibited and therefore no risk of any community outbreak from shore leave was assumed. If a crew member on shore leave developed and self-reported symptoms and then tested positive, this case would be isolated, and this could also trigger contact tracing, which was assumed to identify 80% of the infected contacts within 48 hours. Identified contacts would be isolated after a delay of one or two days.

Ongoing infection transmission in the destination country

Untraced secondary cases who were infected by crew members in the destination country, and tertiary cases who were infected by traced secondary cases before they were isolated, were assumed to roam freely for the full length of their infectious period and to potentially trigger outbreaks in the community.

Control measures assumptions

The full details on the considered control measures are given in Table 2.

Results

The results suggest that, if no pandemic-related maritime controls were in place, the COVID-19-free destination country (New Zealand) would quickly experience an outbreak because of the arrival of ships with infected crew members taking shore leave. That is an outbreak after a median duration of 0.064 years (23 days), which is equivalent to a total of 355 port visits and 7,100 total days of shore leave (for international vessels with 20 crew members and one day of shore leave per person per port; Table 3). However, there is high uncertainty, with 95% of outbreaks likely to occur between 1 to 124 days (ie, 0.0023 to 0.34 years; Table 3).

The median time to an outbreak would increase markedly by obligatory PCR testing of crew members before shore leave is permitted (ie, up to 168 days (0.46 years), or after a total of 2,592 port visits). An even further reduction of risk would occur when requiring face mask use during shore leave (increased median time to 1.00 years). But, relatively little extra gain in risk reduction

Figure 1: Flow diagram of the assumed movements of merchant ship crews in the model including interventions (simplified and not showing all control measures (eg, the seeking of medical attention when symptomatic in the destination country and the associated isolation of identified cases and contact tracing as detailed in Table 2)).
Table 1: Input parameters used for modelling the potential spread of SARS-CoV-2 infections via merchant shipping with the stochastic version of CovidSIM (v1.1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(s) used</th>
<th>Further details for parameter inputs into the modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incidence of SARS-CoV-2 infection (using the global average)</td>
<td>Daily incidence = 0.00038 (ie, 2.66 infections per 1000 population per week)</td>
<td>We estimated the incidence of new infections globally for 15 August 2020 using the following data and assumptions:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For the initial estimate of the numerator, we used the global reporting to WHO of new laboratory-confirmed cases of SARS-CoV-2 infection on 15 August 2020 (n=294,237 new cases).&lt;sup&gt;20&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For the denominator, we used the UN global population estimate for 2020 (7,794,799,000).&lt;sup&gt;21&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>To adjust for under-estimating of actual infections (compared to reporting of cases), we used the estimate of a 10-fold difference between reported cases and infections based on sero-surveys by Havers et al for the US (with this 10-fold factor still probably being an under-estimate).&lt;sup&gt;22&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>We assumed that, prior to the ship leaving for the destination country, the crew members have 1 day of shore leave during which they can pick up the infection at the given probability.</td>
</tr>
<tr>
<td>Percentage of infections that are asymptomatic</td>
<td>29% (50% in scenario analysis)</td>
<td>We used the estimate from a very large Spanish survey of 61,075 participants.&lt;sup&gt;23&lt;/sup&gt; It found the proportion of individuals with a positive test who were asymptomatic was 32.7% (30.2–35.4) for the point-of-care test and 28.5% (25.6–31.6) for the immunoassay. Given the immunoassay is likely to be more accurate than the point-of-care test, we used the 28.5% result. This estimate is similar to that for a working-age adult population of healthcare workers in the UK, in whom 27% of all infections were asymptomatic.&lt;sup&gt;24&lt;/sup&gt;</td>
</tr>
<tr>
<td>Latency period</td>
<td>5 days</td>
<td>We used the best estimate from CDC in May 2020 of a mean of 6 days until symptoms (ie, the latency period plus the prodromal period).&lt;sup&gt;21&lt;/sup&gt; We used a standard deviation (SD) of 25% (1.25 days) (calculated using 16 stages; Erlang distribution).</td>
</tr>
<tr>
<td>Prodromal period</td>
<td>1 day</td>
<td>There was (at the time of writing) insufficient information on this prodromal period for COVID-19, so we used an assumed value for influenza (SD=25%; 0.25 days, Erlang distribution).</td>
</tr>
<tr>
<td>Symptomatic period</td>
<td>10 days (split into 2 periods of 5 days each)</td>
<td>The WHO-China Joint Mission report stated that “the median time from onset to clinical recovery for mild cases is approximately 2 weeks and is 3-6 weeks for patients with severe or critical disease.”&lt;sup&gt;26&lt;/sup&gt; But, given that mild cases may have been missed in this particular assessment, we used a slightly shorter total time period of 10 days (SD=25%; 2.5 days, Erlang distribution).</td>
</tr>
</tbody>
</table>

would result from any sick crew on shore leave self-reporting symptoms and the associated contact tracing (Table 3). Using the base case value of $R_{eff} = 2.5$ in New Zealand, a single untraced infection in the community leads to an outbreak in 88.2% of cases (78.5% for $R_{eff} = 2.0$). When we considered super-spreading events in the community in a scenario analysis, the outbreak probability per person was actually reduced to 57.4%. This is because allowing for super-spreading events means that a smaller proportion of infected crew members transmit infection, even though those that do will typically infect more people (assuming the same overall value of $R_{eff}$).

In scenario analyses, a smaller crew size reduced the outbreak risk (eg, the median time to an outbreak would be 3.8 years for ships with a crew size of five; Table 4). The risk of outbreaks was also lower when making assumptions around lower contagiousness in the destination country (ie, $R_{eff}$ lowered to 2.0). The risk remained basically unchanged when contagiousness on the ship was assumed to be higher (ie, $R_{eff}$ increased to 4.0). Increasing the shore leave to either two or three days increased the risk of an outbreak (ie, it reduced the median time to this event). When super-spreading events were considered in the destination country, this led to the same average number of untraced infections caused by crew members in New Zealand, but as each one of them had a lower risk of leading to an outbreak, the overall outbreak risk was lower than in the baseline study.
Table 1: Input parameters used for modelling the potential spread of SARS-CoV-2 infections via merchant shipping with the stochastic version of CovidSIM (v1.1) (continued).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(s) used</th>
<th>Further details for parameter inputs into the modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contagiousness</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative contagiousness in the prodromal period</td>
<td>100%</td>
<td>We used the best estimate from CDC in May 2020 of infectiousness of asymptomatic individuals relative to symptomatic individuals of 100%.(^{21})</td>
</tr>
<tr>
<td>Contagiousness after the prodromal period</td>
<td>100% and 50%</td>
<td>In the first five days of symptoms, cases were considered to be fully contagious. In the second five-day period, this was assumed to be at 50%. The latter figure is still uncertain, but it is broadly consistent with one study on changing viral load.(^{22})</td>
</tr>
<tr>
<td>Effective reproduction number ((R_{eff})) on board the ship</td>
<td>3.0 (4.0 in a scenario analysis)</td>
<td>The enclosed nature of the ship environment (and shared sleeping quarters in smaller vessels of under 3,000 gross tonnage) would favour spread of infection, and so we used a higher value than for the community (see in the next row). Noting the fishing boat outbreak (detailed in the Introduction) where 85% of the crew became infected,(^2) we also used a higher value ((R_{eff}=4.0)) in a scenario analysis. We assumed no routine mask use on the ship or specific additional physical distancing behaviours by the crew.</td>
</tr>
<tr>
<td>(R_{eff}) in the destination country (New Zealand)</td>
<td>2.5 (2.0 in a scenario analysis)</td>
<td>We used the best estimate from the CDC of 2.5 for community transmission.(^{29}) We assumed for New Zealand that the social behaviour in the elimination period (since May 2020) was fairly similar to the pre-COVID-19 state (ie, relatively little additional physical distancing, normal occurrence of large social events and no routine mask use by the great majority of the population). Nevertheless, we also considered a value of 2.0 in a scenario analysis. We assumed a population with no specific immunity to SARS-CoV-2.</td>
</tr>
<tr>
<td>Super-spreading in the destination country (New Zealand)</td>
<td>Just in a scenario analysis</td>
<td>Given some evidence for super-spreading phenomena with this pandemic virus,(^{29–31}) we also considered a scenario where in New Zealand just 10% of the cases generated 10 times as many secondary cases as the other cases.</td>
</tr>
<tr>
<td><strong>Shipping-related parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Merchant ship visits to the destination country (New Zealand)</td>
<td>108 per week</td>
<td>In the last three quarters of 2019 and the first quarter of 2020, there were 5,600 merchant ship port visits in New Zealand by vessels originating in overseas ports (counting each port visit separately where multiple ports were visited).(^{22}) This is 108 port visits per week for such vessels. These vessels include bulk carriers, container ships, reefers, tankers, vehicle carriers and a range of other types of cargo vessels.</td>
</tr>
<tr>
<td>Voyage length</td>
<td>10 days (scenario analyses ranging from 1 to 30 days)</td>
<td>We calculated merchant ship travel times using a specific website for travel times between seaports (<a href="http://ports.com/">http://ports.com/</a>) and using a typical travel speed of 24 knots (44km per hour). This gave the shortest trip to New Zealand (Sydney to Auckland) at 1,330 nautical miles (nm) (2,463 km) taking 2.3 days at sea. It gave the longest possible trip to New Zealand (Montreal to Auckland) at 17,100nm taking 29.7 days at sea. Also, it gave the trip from the world’s busiest container port (Singapore) to Auckland of 5,828nm taking 10.1 days at sea. It gave the trip from the busiest European container port (Rotterdam) to Auckland of 14,569nm taking 25.4 days at sea. Given the complexities, we did not consider port calls and shore leave on route between the original departure point and the first New Zealand port of call. Also, we note that slower voyages than these can sometimes arise (eg, from storms at sea, port congestion, etc).</td>
</tr>
<tr>
<td>Crew size</td>
<td>20 (scenario analyses: 5, 10, 30)</td>
<td>This value varies for the type of merchant vessel, but we used a figure of 20, which is mid-range for the crew size of a container ship (range 10 to 30 crew).(^{33}) A wider range of values was used in scenario analyses.</td>
</tr>
<tr>
<td>Duration of shore leave</td>
<td>1 day (scenario analyses: 2, 3)</td>
<td>We analysed Port of Auckland data (the port in New Zealand’s largest city) for the 140 merchant ship visits detailed on their website for 20 August 2020. This indicated a median stay in this port of 1 day (range 0.3 days to 6 days).(^{34}) However, 31% of these international merchant ships had most recently come from another New Zealand port prior to the Port of Auckland.</td>
</tr>
</tbody>
</table>
Table 2: Control measures and their estimated efficacy.

<table>
<thead>
<tr>
<th>Control measure</th>
<th>Key value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pratique</td>
<td>Not considered as PCR testing more accurate</td>
<td>Although some cases of SARS-CoV-2 infection will be asymptomatic (see above) and others fairly mild, it is likely that some proportion of onboard outbreaks of COVID-19 would come to the awareness of the ship’s captain. A small proportion of cases would also become seriously ill requiring immediate treatment and potentially the diversion of the ship to a nearby port (or removal of a case by helicopter). The captain would be then legally required to alert health authorities in the destination port as part of pratique. On the other hand, if a captain knows that the crew are in particular need of shore leave, then such information about onboard outbreaks might not always be divulged. The captain may also discount any cases of respiratory illness as being due to other causes (eg, respiratory infections such as the common cold) and any such cases may have been resolved at the time of arrival. Hence we assumed that port authorities should place little reliance on pratique as a control process and should require PCR testing of all crew wanting shore leave (as outlined in the next row).</td>
</tr>
<tr>
<td>Compulsory PCR test on arrival of all crew</td>
<td>Variable sensitivity based on time since infection</td>
<td>As per our previous modelling work, we used the results of a study that fitted a Bayesian hierarchical logistic regression model for test sensitivity. This meant, for example, that at day 4 after infection, 67% of test results were false negatives (95%CI: 27% to 94%). This decreased to 20% (95%CI: 12% to 30%) on day 8 and then increased after this (eg, up to 66% (95%CI: 54% to 77%) on day 21). For cases who already recovered before their PCR test, we use the final value reported by Kucirka et al (ie, 34% sensitivity). We assumed all crew would request shore leave and that port health authorities would prioritise the PCR testing of seafarers immediately on arrival to allow for a day of shore leave (eg, we note that, as per some airports, PCR test results can be obtained within a few hours). We also note imminent access to faster testing (eg, FDA approval of a 15-minute test, which may have different sensitivity and specificity from the PCR test).</td>
</tr>
<tr>
<td>Mandatory mask use by the crews during shore leave</td>
<td>85% efficacy but only two-thirds (66.7%) adherence (and one-third adherence in scenario analysis)</td>
<td>We used the efficacy value of 85% from a systematic review and meta-analysis (n=2647; adjusted odds ratio=0.15, 95%CI: 0.07 to 0.34). Adherence to mask use in social settings in New Zealand (where local citizens are not typically using masks, except on public transport where it was mandated in August 2020) was considered likely to be suboptimal at two-thirds. In a scenario analysis, we set adherence to mask use at one-third (33.3%).</td>
</tr>
<tr>
<td>Self-reporting of crew members whose sicknesses start shortly before or during shore leave (ie, they are among the 71% of infected individuals who become symptomatic)</td>
<td>50% (self-reporting, occurring on average 1 day after symptom onset)</td>
<td>We used the same estimated value as in our previous Australia to New Zealand air travel study. Such reporting can trigger contact tracing among the public in the destination country and therefore lower the risk of an outbreak (see the next row, Table 1). But due to the complexities, we do not consider backward contact tracing among the crew. Of note is that 39.5% of people in New Zealand with ‘fever and cough’ symptoms routinely seek medical attention, as reported by the New Zealand Flutracking surveillance system. This value is very similar to other estimates of people in high-income countries with influenza who seek medical attention (eg, at 40% as used in other modelling).</td>
</tr>
<tr>
<td>Contact tracing if crew members develop symptoms in New Zealand, seek medical attention and are confirmed by PCR (see above)</td>
<td>80% of infected contacts are traced and isolated within 48 hours</td>
<td>We used performance data for the cluster of cases in Auckland in August 2020 where the official estimate was 80% of contacts contacted within 48 hours (as reported by the Prime Minister). We divided this into 60% within the first 24 hours and 20% in the next 24 hours. Of note is that variable performance for contact tracing has been reported for New Zealand at other times in August 2020, with 86% of contacts traced in 48 hours at one point.</td>
</tr>
</tbody>
</table>
Figure 2 shows that voyage duration is a key determinant of outbreak risk in the destination country, and this risk is especially high once voyages are longer than five or so days (ie, once the latent period is typically over and crews have become infectious). Onboard spread can maintain this risk over subsequent weeks, leading to more infected individuals on board; but this also increases the detection probability by testing on arrival in New Zealand. It can take a long time for the onboard epidemic to come close to ‘burning out’. Indeed, the outbreak risk in the destination country when there are no controls only starts to decline after a voyage time of three weeks, and even then it declines quite slowly (Figure 2). For larger crew sizes of 10 to 20 people, the risk of community outbreaks is still increasing slightly after three to four weeks of voyaging when no controls are used (Figure 3 and Figure 4). Interestingly, if PCR tests are implemented, the effect of longer travel durations generates results that are the inverse: the more the infection can spread on board, the more likely it will be detected. As none of the crew members were assumed to be allowed to go to shore if any one of them tested positive, the probability that infected people being allowed to enter New Zealand decreases as the number of infected people on board the ship increases. Adding additional interventions like wearing masks, self-reporting symptoms and contact tracing further improves the results; but the main effect is obtained by PCR testing prior to shore leave being permitted. With the full set of interventions, the median time to an outbreak increased, but this time varied widely by length of voyage and size of the crew (Figure 3 and Figure 4).

Discussion

Main findings

In this modelling work, we found that it might only be a matter of a few weeks before crew from international trading maritime vessels would trigger COVID-19 pandemic outbreaks in the destination country, if no control measures were in place. Of particular note is that even small five-person crews appear to contribute a risk after voyages of several weeks, and this risk only declines slowly thereafter. Fortunately, however, the risk of such outbreaks can be substantially reduced with the available interventions. In particular, PCR testing before leaving the vessel appears to be a valuable intervention, though this benefit still comes with high uncertainty as indicated by the wide range for 95% of the simulation results (shown in Table 3).

The results for our case study country (New Zealand) are likely generalisable to most countries that have seaports and maritime trade. Nevertheless, the risk could be somewhat less for some nations on a per population or per gross domestic product (GDP) basis because New Zealand’s economy is particularly trade orientated and especially dependent on sea trade. That is, it has no international trade by land routes and only a small proportion of trade volume is by air cargo. With a population of five million, New Zealand has 1,120 port visits from vessels with an international origin per million population per year.

Table 3: Results of the simulations without interventions and with multi-layered interventions (with these being for a base case of 10 days at sea and 108 merchant ship visits per week, 20 crew per ship, one day of shore leave each per port visit in New Zealand, and with 100 million stochastic simulations being run for each set of parameters).

<table>
<thead>
<tr>
<th>PCR test upon entry</th>
<th>Wearing face masks when on shore leave (by the crew)</th>
<th>Self-reporting of symptoms (when in New Zealand)</th>
<th>Contact tracing for self-reported cases</th>
<th>Median duration until outbreak in New Zealand (years)</th>
<th>95% of outbreaks are likely to occur in this time interval (years)</th>
<th>Probability that outbreak occurs within 1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>0.06</td>
<td>0.002–0.34</td>
<td>100.0%</td>
</tr>
<tr>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>0.46</td>
<td>0.017–2.47</td>
<td>77.5%</td>
</tr>
<tr>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>1.00</td>
<td>0.037–5.53</td>
<td>49.9%</td>
</tr>
<tr>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>1.02</td>
<td>0.037–5.41</td>
<td>49.4%</td>
</tr>
<tr>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>1.02</td>
<td>0.037–5.43</td>
<td>49.3%</td>
</tr>
</tbody>
</table>
Study strengths and limitations

This is the first study (to our knowledge) to explore the risk of COVID-19 outbreaks arising from shore leave of maritime ship crews. Another strength is that the work builds on an established model that has been used to also study air transport and other aspects of SARS-CoV-2 transmission (see Methods).

But, as with all modelling, there are important limitations. Some of these relate to parameters. A particularly critical one is the daily incidence of SARS-CoV-2 infection in the source country that the ship leaves from. We used a global average for this incidence to account for the diverse maritime trading patterns that New Zealand has and also because the crews are internationally diverse (often flying in from another country just prior to the ship's departure, which may expose them to higher risks via air terminals and on aircraft). Yet there are likely to be highly variable risks of infection between different source countries that the ship leaves from and countries that the crew come from, and these will change with the evolving global pandemic of COVID-19.

Other examples of parameter limitations are the $R_{eff}$ onboard such vessels and the $R_{eff}$ for shore leave by crew. The former is likely to vary by different designs of merchant vessels (container ships vs tankers vs bulk carriers etc) and also by size (eg, it is likely that, in vessels of under 3,000 gross tonnage, the crew are in shared sleeping rooms). However, we did not have sufficient data to model such heterogeneity. We also didn't account for prior immunity among crew members from past exposure to the SARS-CoV-2 virus, which is likely to increase over time with global progression of the pandemic. Given the data limitations, we did not consider port calls and shore leave on route between the original departure point and the first New Zealand port of call. Such port calls may either increase the risk for New Zealand (if the visited port city on route has a higher incidence of infection than the origin country), or they may decrease the risk (by extending the time length of the voyage, if the origin country had a higher incidence of infection than the visited city). We also did not model risk of transmission to port workers who might go onto arriving ships (eg, pilots and health workers conducting PCR tests on board vessels), given the assumption that they would take appropriate precautions with physical distancing and use of personal protective

Table 4: Results of the scenario analyses for 108 merchant ship visits per week and the full set of interventions taking place (see last line of Table 3) with 100 million stochastic simulations run for each set of parameters. (For further information, see text and Table 2.)

<table>
<thead>
<tr>
<th>Scenario (compared to base case)</th>
<th>Median duration until outbreak in New Zealand (years)</th>
<th>95% of outbreaks are likely to occur in this time interval (years)</th>
<th>Probability that outbreak occurs within 1 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case with all interventions (for comparison purposes)</td>
<td>1.02</td>
<td>0.037–5.43</td>
<td>100.0%</td>
</tr>
<tr>
<td>5 crew members instead of 20</td>
<td>3.81</td>
<td>0.139–20.27</td>
<td>16.6%</td>
</tr>
<tr>
<td>10 crew members instead of 20</td>
<td>2.02</td>
<td>0.074–10.74</td>
<td>29.1%</td>
</tr>
<tr>
<td>30 crew members instead of 20</td>
<td>0.68</td>
<td>0.025–3.63</td>
<td>63.9%</td>
</tr>
<tr>
<td>2 days of shore leave instead of 1</td>
<td>0.28</td>
<td>0.010–1.51</td>
<td>91.3%</td>
</tr>
<tr>
<td>3 days of shore leave instead of 1</td>
<td>0.14</td>
<td>0.005–0.74</td>
<td>99.3%</td>
</tr>
<tr>
<td>$R_{eff}$ in New Zealand is 2.0 instead of 2.5</td>
<td>1.38</td>
<td>0.050–7.34</td>
<td>39.5%</td>
</tr>
<tr>
<td>$R_{eff}$ on board the ship is 4.0 instead of 3.0</td>
<td>1.07</td>
<td>0.039–5.68</td>
<td>47.8%</td>
</tr>
<tr>
<td>Super-spreading events can occur in New Zealand</td>
<td>1.61</td>
<td>0.059–8.54</td>
<td>35.1%</td>
</tr>
<tr>
<td>50% of infections are asymptomatic instead of 29%</td>
<td>1.01</td>
<td>0.037–5.36</td>
<td>49.7%</td>
</tr>
<tr>
<td>Mask use adherence during shore leave is one third (33%) instead of two thirds (67%)</td>
<td>0.64</td>
<td>0.023–3.41</td>
<td>66.1%</td>
</tr>
</tbody>
</table>
Figure 2: For ships with five-member crews, the median duration (log-scale in years) until a COVID-19 outbreak occurs in the destination country because of merchant ship crews taking shore leave. We assumed there were 108 cargo ships arrive each week. In the country of origin, each member can become infected at a rate of 0.00038 per day. Infections spread on board with an effective reproduction number $R_{eff}$ of 3.0 and in New Zealand with $R_{eff}$ of 2.5. Note that a voyage duration of 1 day is not applicable to New Zealand. Full black curves: no interventions are taken; full grey curves: all crew members are prevented from entering the country if one of them is PCR positive upon arrival; dotted grey curves: full set of interventions as outlined in Table 3. For each combination of crew size and voyage duration, 100 million voyages were simulated.

Figure 3: For ships with 10-member crews, the median duration (log-scale in years) until a COVID-19 pandemic outbreak occurs in the destination country because of merchant ship crews taking shore leave (other details as per Figure 2).
equipment. Yet people don’t always follow rules and accidental events may reduce the effectiveness of preventive measures.

Possible implications for future research and policy

Future research is needed to replicate this study (eg, using simulation models with a different structure and for a wider range of destination countries). The routine collection of international shipping transponder data, which is currently underway by other New Zealand-based researchers (funded by the Ministry of Business, Innovation and Employment), may also more precisely identify ship movements, travel times and also unusual events (such as ships exchanging supplies or crew at sea). Research could also explore the acceptability of, and adherence to, mask use by crews on shore leave in different settings.

As detailed above, the results in Table 2 and Table 3 might make some health authorities decide that the risk of allowing shore leave for crew is tolerable with control interventions such as PCR testing and mask use. But for small low-income island states (eg, the nations in the Pacific that were COVID-19-free in November 2020), the risk might still be considered too high, especially if they have limited surveillance and outbreak control capacity. In these states, either all shore leave could be denied (ie, cargo movement is performed without the crew leaving the vessel), or the ships that recently visited countries where COVID-19 transmission is occurring could be completely prohibited (eg, until a vaccine against COVID-19 is in use). Other policy options for risk reduction might include:

- Working with source countries to ensure that departing shipping crew get routinely tested for SARS-CoV-2 just prior to departure, and that any infected crew member is immediately replaced.
- Testing the crew twice with PCR tests in the destination country. Firstly, at the initial port visited in the destination country but with no shore leave permitted at this port. Then a second test at the second port visit in the country, at which point shore leave

Figure 4: For ships with 20-member crews, the median duration (log-scale in years) until a COVID-19 pandemic outbreak occurs in the destination country because of merchant ship crews taking shore leave (other details as per Figure 2).
leave could be permitted if all rounds of test results are negative. Also, once rapid tests are considered reliable enough and cost-effective enough, then crew could potentially be tested daily after their first port contact and until they leave the country.

- Ensuring that any shore leave is highly supervised or otherwise constrained to specific settings. Supervision by port authorities could be used to ensure high adherence with mask use and attendance at only designated settings (eg, specific seafarer clubs). Settings where superspreading events could potentially occur (eg, restaurants, bars and nightclubs) could be prohibited as part of shore leave.

- Limiting shore leave to just a particular port in the country in a town or city where there is particularly intensive routine PCR testing of port workers and in relevant parts of the community (to facilitate early outbreak detection). Such community testing, combined with testing all people hospitalised with respiratory symptoms, can potentially accelerate early outbreak detection.19

- Prioritising the provision of vaccination to shipping crews once vaccines against SARS-CoV-2 infection are available in the relevant countries.

**Conclusions**

Using simulation modelling, we estimated the risk of COVID-19 outbreaks in COVID-19-free settings as a result of merchant ship crews infected at the source of their voyage taking shore leave. Our results can potentially inform policymaker decisions about regulations regarding shore leave for crews and the use of various control measures such as PCR testing and mask use to minimise the risks if shore leave is permitted.

**Competing interests:**
Nil.

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