Perspectives on future changes in sea ice and navigability in the Arctic

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Abstract The retreating of sea ice was found to be very significant in the Arctic under global warming. It is projected to continue and have great impacts on navigation. Perspectives on the changes of sea ice and navigability are crucial to the future and circulation pattern of the Arctic. In this investigation, the decadal changes of sea ice parameters were evaluated by the multi-model from Coupled Model Inter-comparison Project Phase 6, and the Arctic navigability was assessed under two shared socioeconomic pathways (SSPs) and two vessel classes with the Arctic transportation accessibility model. The sea ice extent would show a high possibility of decreasing along the SSP-8.5 with high possibility under current emissions and climate change. The decadal rate of decreasing sea ice will increase in March, but decrease in September until 2060, when the oldest ice will have completely disappeared and
the sea ice would reach an irreversible tipping point. Sea ice thickness will is expected to decrease and transit in certain parts, and totally decline by

$-0.22 \text{ m per decade after September 2060. Both the sea ice concentration and volume will thoroughly decline with decreasing decadal rates, while the decreasing with a greater decrease in volume is higher in March than in September for the volume.}$

Open water ships are will be able to cross the Northeast–Northern Sea Passage Route and Norwest Passage in between August and October during the period from 2045–2055, with a maximum navigable area in September. The time for polar class 6 (PC6) ships will shift to October–December during the period from 2021–2030, while the maximum navigable area would occur in October. In addition, the Central Passage will be open for PC6 ships during September– and October during 2021–2030.

Keywords: Arctic; Sea ice; Arctic Passages; Navigability; Future Changes

1. Introduction

The Arctic has experienced significant warming after the 1970s (Connolly et al., 2017). Along with the increasing surface air temperature, the Arctic communities have experienced unprecedented changes, such as reduction of sea ice extent and thickness, loss of the Greenland ice sheet, decreasing snow coverage, and thawing of permafrost (Biskaborn et al., 2019; Box et al., 2019; Brown et al., 2017; Loomis et al., 2019). The sea ice extent has declined at a rate of approximately 3.8% per decade. In comparison, perennial ice had a higher proportion of loss of approximately 11.5% per decade during the period...
from 1979–2012 (Comiso and Hall, 2014). The average ice thickness that near the end of the melt season decreased by 2.0 m or some 66% between the pre–1990 submarine period (1958–1976) and the CryoSat-2 period (2011–2018) (Kwok, 2018). Continued declines of sea ice have been projected by the Coupled Model Inter-comparison Project Phase 5 in the Arctic through the end of the century (Meredith et al., 2019), although with some significant differences in timing (Stephenson et al., 2013).

Sea ice reflects a significant fraction of the solar radiation because it has a high albedo. It also reduces the heat transfer between the ocean and the atmosphere as it acts as an insulator. Sea ice insulates thermal transport between the ocean and atmosphere by reflecting a high proportion of incoming solar radiation back to space (Screen and Simmonds, 2010). With retreating sea ice, thermohaline circulation has changed (Jourdain et al., 2017), and global warming has intensified (Abe et al., 2016). However, climate change has led to prolonged open water conditions for the Arctic Passages (Barnhart et al., 2015) and large-scale Arctic shipping that will involve ice channels (Barnhart et al., 2015; Huang et al., 2020). The Northeast Northern Sea Route (NEPSR) extends along the northern coast of Eurasia from Iceland to the Bering Strait, which shortens the transit distance from northwest Northern America and northeast Asia to northern Europe by about 15%–50% relative to the southern routes through the Panama Canal and Suez Canal (Buixadé Farré et al., 2014). It is navigable for about 4–5 months and half per year for ice-strengthened ships at the
end of summer and the beginning of autumn (Yu et al., 2020) (Khon et al., 2010). The end of shipping season for number of days for open water (OW) ships across the NEP vessels has reached 297±4 (October 24th) since 2010. However, the navigability is still affected by the ice regime, such as ice thickness and concentration, around the Severnaya Zemlya Islands, the Novosibirsk Islands, and the East Siberian Sea (Chen et al., 2019). The Northwest Passage (NWP) follows the northern coast of North America and across the Canadian Arctic archipelago. Compared to the traditional Panama Canal route from Western Europe to the Far East, the NWP shortens the transit distance by 9000 km (Howell and Yackel, 2004). The shortest navigable period was up to 69 days during 2006–2015 (Liu et al., 2017), and the first time of being completely free of ice was reported to occur in September 2007 (Cressey, 2007). Geographical and political factors also pose some challenges to the navigability of passages and choice of routes (Ryan et al., 2020). The straits along the NWP are at times narrow and shallow, which are easily clogged by free floating ice. The NSR is greater than NWP in terms of geography, while it still has several choke points where ships must pass through shallow straits between islands and the Russian mainland (Streng et al., 2013). Apart from the geographical factor, the various organizations and groups formed between the surround-Arctic nations, as well as the disputes and agreements, give impetuses for adopting the NSR. Russia has committed several large infrastructure projects to support the NSR, such as Yamal-Nenets railway and emergency rescue centers (Serova, N. A. and Serova, V. A, 2019). China, which is characterized as a near-Arctic state, also outlined the plans to build a Polar Silk Road.
by building infrastructure and conducting trial voyages (Tillman et al., 2019).

For the development of socioeconomics and marine transportation, future projections to the ice conditions and Arctic Passages are increasingly important, in which the climatic changes should be considered (Gascard et al., 2017). Climate models are effective and reliable to produce the present and future spatial and temporal distributions of the Arctic sea ice (Parkinson et al., 2006; Stroeve et al., 2014). Smith and Stephenson (2013) investigated the potential of the Arctic Passages under representative concentration pathways (RCP) 4.5 and RCP 8.5, and found that OW ships and Polar Class 6 (PC6) ships (Table 1) were able to cross NEP-NSR and NWP in September in the mid-century, respectively. The areas of the Arctic accessible to PC3, PC6, and OW ships would rise to 95%, 78%, and 49%, respectively, of the circumpolar International marine Organization Guidelines Boundary area by the late 21st century (Stephenson et al., 2013). Melia et al. (2017) suggested that the Arctic Passages from Europe to Asia would be 10 days faster than conventional routes by the mid-century and 13 days faster by the late in the century. Recent research showed that NEP-NSR might be accessible earlier for OW ships in September 2021–2025, and the navigable window would extend to August–October during 2026–2050 under shared socioeconomic pathways (SSP2–4.5) (Chen et al., 2020). However, it is insufficient to evaluate the Arctic navigability by a single climate model, even with a higher resolution. This prospective study was designed to obtain further insight into the future.
changes of sea ice in the Arctic and the navigability of the Arctic during this century with ensemble-up-to-date climate models in the Coupled Model Inter-comparison Project Phase 6 (CMIP6). To reduce uncertainties of a single high resolution model and multi-model average, the models were filtered by comparing the historical simulations and observation observations of sea ice extent, and the possible shared socioeconomic pathways SSPs were investigated with the average of multi-model multiple models. The distributions of the linear trend of sea ice extent, concentration, and thickness were explored in three stages (2021–2040, 2041–2060, and 2061–2100). In addition, the changes of sea ice volume and age were analyzed. The accessibility of the Arctic and the navigable area were evaluated with the Arctic Transportation Accessibility Model (ATAM) from the Arctic Ice Regime Shipping System (AIRSS) for OW ships and PC6 ships under SSP2–45 and SSP5–85 in 2021–2030 and 2045–2055, respectively.

2. Methods

2.1. Data and Model Selection

The new scenario framework–SSP in CMIP6 was designed to carry out research on climate change impacts and adaption by combining pathways of future radiative forcing and climate changes with socioeconomic development (O’Neill et al., 2014). SSP1 indicates a sustainable development, which proceeds at a reasonably high pace. Technological change is rapid, inequalities are lessened and directed toward environmentally friendly processes. Unmitigated emissions are high in SSP3. It is due to a rapidly growing population, moderate economic growth, and slow technological change in the energy sector. SSP2 is an intermediate case between SSP1 and SSP3.
SSP5 occurs in the absence of climate policies, energy demand is high and most of this
demand is met with carbon-based fuels.

Compared with CMIP5 models, the CMIP6 multi-model ensemble mean provides a more realistic estimate of the Arctic sea ice extent (SIMIP Community, 2020), but the biases of the models are still large (Shu et al., 2020). This study selected models by comparing the historical trend of Arctic sea ice extent in simulation with remote sensing observation during 1979–2012. The observation data comes from Sea Ice Index in the National Snow & Ice Data Center. The selected models are those the correlation coefficient between original simulation and observation greater than 0.8 (0.7 for March). Five-point moving averages of simulations were made in Figure 1. This paper study selected models by comparing the historical trend of sea ice extent with the observations from the National Snow & Ice Data Center during 1979–2012 with a five point moving average (Figure 1). The excellent models are those with a correlation coefficient greater than 0.8 (0.7 for March). As shown in Figure 1, 14 historical models were evaluated in both March and September. The models passing the test are CESM2, MPI-ESM1-2-HR, MPI-ESM1-2-LR, NorESM2-MM, ACCESS-ESM1-5, AWI-CM-1-1-MR, and AWI-ESM-1-1-LR in September, and CEM2, MPI-ESM1-2-LR, ACCESS-ESM1-5, AWI-CM-1-1-MR, INM-CM5-0, MPI-ESM1-2-HAM, and AWI-ESM1-1-LR in March. The mean of the excellent-selected models corresponds well with the observation, and the correlation coefficients are 0.884 and 0.817 in September and March, respectively. However, sea ice datasets in SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 after 2020
are have not been released on CESM2, MPI-ESM-1-2-HAM, and AWI-ESM-1-1-LR up to until now. In addition, AWI-CM-1-1-MR was excluded from analyzing the navigability of the Arctic in the absence of sea ice concentration. The spatial resolution of monthly sea ice concentration and thickness was normalized to $1^\circ \times 1^\circ$ by bilinear interpolation. Variables in figures and tables were from the ensemble means of selected models.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The observations and five-point moving averages of sea ice extent in March and September during 1979–2012.}
\end{figure}

\subsection{Accessibility Evaluation}

Safety and pollution are two of the opposite factors that were considered in
making developing regulatory transport standards. AIRSS was designed to minimize the risk of pollution in the Arctic due to damage to vessels by ice (Transport Canada, 1998). ATAM, developed by AIRSS, was commonly used to quantify the temporal and spatial accessibilities in the Arctic, in which the ice number (IN) represents the ability of a ship to enter ice-covered water:

\[ IN = (C_a \times IM_a) + (C_b \times IM_b) + \ldots + (C_n \times IM_n) \]  

where \( C_a, C_b, \) and \( C_n \) are the sea ice concentrations, \( IM_a, IM_b, \) and \( IM_n \) are the ice multipliers of ice types a, b, and n, respectively. \( a, b, \) and \( n \) are ice within a range of thicknesses corresponding to IMs in equation (2). They indicate the severity of each ice type for the vessel and range from -4 to 2. The positive IM and IN represent less risk to the vessel and safe region for navigation, respectively. Vessel Class is a character of ship reflecting structural strength, displacement, and power—of a ship to break ice. PC6 ships and OW ships are vessels with moderate ice strengthening and without ice strengthening, respectively (IMO, 2002). In this paper, the navigability of the Arctic for these two kinds of ships was investigated under SSP2-45 and SSP5-85. The corresponding IMs for the OW and PC6 ships are as follows:

\[ IM_{ow} = 2, \text{ if } SIT = 0 \text{ cm}, \]
\[ 1, \text{ if } 0 \text{ cm} < SIT < 15 \text{ cm}, \]
\[ -1, \text{ if } 15 \text{ cm} < SIT < 70 \text{ cm}, \]
\[ -2, \text{ if } 70 \text{ cm} < SIT < 120 \text{ cm}, \]
\[ -3, \text{ if } 120 \text{ cm} < SIT < 151 \text{ cm}, \]
\[ -4, \text{ if } SIT \geq 151 \text{ cm} \]  

\[ IM_{pc6} = 1, \text{ if } SIT = 0 \text{ cm}, \]
\[ 1, \text{ if } 0 \text{ cm} < SIT < 15 \text{ cm}, \]
\[ 2, \text{ if } 15 \text{ cm} < SIT < 70 \text{ cm}, \]
\[ 3, \text{ if } 70 \text{ cm} < SIT < 120 \text{ cm}, \]
\[ 4, \text{ if } 120 \text{ cm} < SIT < 151 \text{ cm}, \]
\[ 5, \text{ if } SIT \geq 151 \text{ cm} \]
\[ IM_{PC6} = \begin{cases} 2, & \text{if } 0 \text{ cm} \leq SIT < 70 \text{ cm}, \\ 1, & \text{if } 70 \text{ cm} \leq SIT < 120 \text{ cm}, \\ -1, & \text{if } 120 \text{ cm} \leq SIT < 151 \text{ cm}, \\ -3, & \text{if } 151 \text{ cm} \leq SIT < 189 \text{ cm}, \\ -4, & \text{if } SIT \geq 189 \text{ cm} \end{cases} \] (3)

**Table 1** Vessel classes versus operating ice thickness

<table>
<thead>
<tr>
<th>Vessel class</th>
<th>Maximum allowable ice type</th>
<th>Ice thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar class 3</td>
<td>Second year</td>
<td>No limit</td>
</tr>
<tr>
<td>Polar class 6</td>
<td>Medium first-year</td>
<td>0–120</td>
</tr>
<tr>
<td>Ordinary merchant</td>
<td>Open water/Grey</td>
<td>0–15</td>
</tr>
</tbody>
</table>

**3. Results**

**3.1. Future Changes of Sea Ice Area and Extent**

The extent and area are the most reliable products of sea ice from satellite retrieval (Comiso, 2012; Notz, 2014). Therefore, the remaining sea ice was taken as an indicator to evaluate models and future scenarios. As shown in Figure 2, the observation trends were made with least square regression of historical ensemble averages from 1979 to 2019, in which sea ice might completely disappear in September after 2073. In addition to the classical pathways, such as SSP1-2.6, SSP2-4.5, and SSP5-8.5, CMIP6 provides a variety of new selections. However, SSP1-1.9, SSP4-3.4, and SSP4-6.0 were not discussed in multi-scenarios the multi-scenario evaluation for the less released models. According to the historical development and scenarios, sea ice will retreat in the future with a more significant decreasing trend in September. The difference between SSPs and observation is greater in March than that in September, while both of them have large dispersions among pathways after 2050. Compared with
others, SSP5-8.5 has the greatest correlation coefficients, which are 0.784 and 0.712 in September and March, respectively, with the observation trend; SSP2-4.5 comes second. This suggests that the Arctic sea ice might turn out to be the worst scenario in the future under the current emission and climate change trends. Actually, the Arctic is regarded as “ice-free” when the sea ice area is less than one million km² square kilometers (Lenton et al., 2019). This will occur in September 2060 with high probability, and ice will almost completely disappear under SSP2-4.5, SSP3-7.0, and SSP5-8.5 by the end of the century.

Figure 2. Remaining sea ice extent under multiple scenarios and observation trends in the future March and September.
“Ice free” was taken as one of the tipping points of climate change with significant irreversible effects (Lenton et al., 2019). Three stages were extracted for the changes in sea ice extent in Figure 3. Decadal linear trends and probability distributions with an interval of 0.4 were calculated to evaluate the decline in sea ice and the difference in models. Sea ice linear trends are less than zero in both March and September in 2021–2100, while the retreat will be more remarkable in September before 2060, especially during 2021–2040, after which the decline is mainly shown in March because the extent might be close to “Ice free” in September. The dispersion of SSPs will increase in March over time, as well as the absolute decadal trends of SSP3-7.0 and SSP5-8.5. However, it is aggregated in September, and the decadal variability in SSPs, especially SSP2-4.5 and SSP5-8.5, has a decreasing trend. Multi-model simulations mainly range from -0.8 to 0 million km² per decade in March, in which the distributions of SSP5-8.5 are chiefly in [-0.4, 0), [-0.8, -0.4), and [-0.8, -0.4) million km² per decade during 2021–2040, 2041–2060, and 2061–2100, respectively. Relatively even distribution is shown in September before mid-century, while it is concentrated in [-0.4, 0) in the late century. This indicates that the difference among models is still great in September before 2060, while the results are reliable in 2061–2100.
Figure 3. Linear trends and probability distributions (PD) of the Arctic sea ice extent (SIE) in March and September.

### 3.2. Future Changes of Other Sea Ice Parameters

In addition to the extent and area, thickness, concentration, volume, and age are also important indicators for the changes of sea ice in the future. Figures 4 and 5 show the linear trends of ice thickness and concentration, and the changes of sea ice volume and age, respectively, under SSP5-85 in 2021–2100. Ice thickness has a negative trend within the Arctic Archipelago, in coastal water, and in the sector to the north of the Arctic Archipelago and Greenland in September, while the other parts will slightly increase in the next 20 years. The trend is reversed in the Arctic Ocean, and the decreasing area near the shore will extend to the north in 2041–2060, after which almost all of the sea ice will be reduced with an average trend of −0.22 m per decade in the Arctic. Sea ice concentration will decrease throughout the rest of this century. The significant area is to the north of the Arctic Archipelago and Greenland, and the Arctic Basin in September 2021–2040. The extent will shrink until the second
half of the century, when the decreasing rate of decrease are will be even and small in the Arctic. The average decadal rates of sea ice concentration are $-12.39\%$, $-6.26\%$, and $-0.81\%$ respectively in the three stages. Sea ice volume will decrease in both March and September 2021–2100. The decreasing rate of decrease is higher in March, while sea ice might completely disappear in September before 2090. Ice age is also a key descriptor of the state of sea ice cover. Compared to younger ice, older ice tends to be thicker and more resilient to changes in atmospheric and oceanic forcing (Richter-Menge et al., 2019). The oldest ice (>4 years old) currently comprises just a small fraction in March, and it might eventually disappear around at approximately the mid-century. With the degeneration of older ice, the extent of the younger ice will increase over a period of time, such as 3- to 4-year-old ice in the next 10 years, 2- to 3-year-old ice before 2035, and 1- to 2-year-old ice before 2050, after which it will degrade into next younger ice. First-year ice dominates the sea ice cover in the present and future. It increases mainly before 2060, and remains stable until 2090, after which it starts to decrease due to the lack of supplementation from degraded older ice.
Figure 4. Linear trends of sea ice thickness and concentration under SSP5-85 in September.
3.3. Future Changes of the Arctic Navigability

With the retreatment of sea ice, the possibility for navigation is rising in the Arctic. The number of vessels passing through the Arctic was increasing year by year, but OW ships usually need the guidance of icebreakers, which increases the transportation cost. The opening of passages for OW ships will be profitable for ocean shipping companies (Chang et al., 2015) with the opening of passages for OW ships. The most likely navigable window is in September. Figure 6 shows Arctic accessibility for the OW ships under SSP5-8.5 in September. The probability of crossing the NEP NSR and NWP is low in the next 10 years. The impassable areas for NEP NSR are mainly in the East Siberian Sea and northwestern Laptev Sea, but nearshore waters might be navigable for vessels with shallow drafts. Fortunately, four crucial straits, the Vilkitsky Strait, Shokalskiy Strait, Dmitrii Laptev Strait, and Sannikov Strait, are accessible for the OW ships. NWP is impassable in the sectors west of the Banks Island and Queen Elizabeth Island, as well as the M’Cluer Strait, Viscount-Melville Sound, Barrow Strait, and Lancaster
Strait within the Parry Channel. All of the routes provided in the Arctic marine shipping assessment report (AMSA, 2009) are under restrictions for OW ships. In the mid-century, both NEP NSR and NWP will open for OW ships under SSP5-8.5 in September.

Figure 6. Arctic navigability for OW ships under SSP5-8.5 in September

The opening of the Arctic Passages is mainly dependent on the connectivity among grids, during which the potential of individual units, which might connect with other units around in the next period, was usually ignored. The overall navigable potential in a region can be measured by the percentage of accessible grids with total grids. Figure 7 displays the Arctic navigable percentage area for OW ships and PC6 ships under SSP2-4.5 and SSP5-8.5 in 2021–
2030 and 2045–2055. It is the percentage of grids where INs are greater 0. The totally navigable area for OW ships is shown as a unimodal curve in both stages, with the peak in September, and the valley in April and March, respectively. It is an irregular curve for PC6 ships with the minimum value in June. The maximum values are shown in October 2021–2030, while they range in November and December in the mid-century. Actually, the Arctic would be navigable for PC6 ships from October to December. It is very strange that an abnormal decrease occurs in September no matter under 2021–2030 and 2045–2055. The navigable area within every 5 latitude degrees from 65°N to 90°N was plotted in Figure 8 for the further study. This indicates that the abnormal point is resulted by the decreasing results from the decrease within 85°N–90°N, but the reason is hard to explain. The navigable area is mainly concentrated at 65°N–75°N for OW ships in the next 10 years, and it will extend to 80°N in the mid-century. The central passage might be accessible for PC6 ships in September and October, and the open window would be from October to January in 2045–2055. The routes of the NEP NSR and NWP are mainly distributed in 70°N–75°N. The possibility for OW ships crossing two passages is low until August–October 2045–2055, while it is high for PC6 ships during October–December 2021–2030, and the open window would extend to August–January in 2045–2055.
The Arctic warming rate is more than double the global average, and it has made significant impacts on the Arctic and globe (Cohen et al., 2020). This paper investigated the future changes of sea ice and navigability of passages in the Arctic under two kinds of shared socioeconomic pathways. It provides a vision of the earth’s future and has great significance for navigation planning. The following results were found.

1. The changes of sea ice would occur along the SSP5-8.5 with a higher possibility.
under the current trend. “Ice free” might appear in September 2060, and sea ice would completely disappear by the end of the century.

(2) The retreat of sea ice is more significant in September before 2060, after which the decline is mainly shown in March. The decadal sea ice extent will increase under SSP5-8.5 in March, but decrease in September.

(3) The decreasing in sea ice thickness will transit from the Arctic Ocean north of the Arctic Archipelago and Greenland to the seas along Russia and North America, and will totally decline with an average decadal trend of –0.22 m in September after 2060. Sea ice concentration will thoroughly decline with decreasing decadal rates.

(4) Sea ice volume will decrease with a higher decadal rate in March than that in September. The oldest ice might eventually disappear around at approximately the mid-century. First year ice dominates the sea ice cover. It increases mainly before 2060, and remains stable until 2090, after which it starts to decrease.

(5) The probability for OW ships crossing the NEP NSR and NWP is low in 2021–2030, while it is high in August–October 2045–2055, with maximum and minimum navigable areas in September and March, respectively.

(6) The passages along the coast and crossing the Arctic might open for PC6 ships during October–December and September–October 2021–2030, respectively, with a maximum navigable area in October. The open window would extend to August–January and October–January in 2045–2055, respectively, and the
maximum navigable area ranges in November and December.

5. Discussions

The navigable window for OW ships and PC6 ships along the NSR were investigated in our previous work (Chen et al., 2020), but it is deficient to evaluate Arctic navigability by a single climate model, even with a high resolution. This study serves as a reference for future changes in sea ice and navigability in the Arctic, including NSR, NWP, and Central Passage. The study above serves as a reference for the future changes of sea ice and the navigability in the Arctic. However, the uncertainty of the models might have affected the results and their reliability in this research. Approximated physical processes and unreal parameters in models are inevitable problems in the geosciences. This is an inevitable problem in the geosciences for approximated physical processes and unreal parameters in the model. The differences still existed even when the models were filtered by comparing the historical simulations with the observations of sea ice extent. The abnormal decrease of navigable area in high latitudes (80°N–90°N) in September might be an example. This is against conventional wisdom, but it could also be true. The uncertainty of the models is increasing expected to decrease in the future research. Different ice types do make a big difference to ship navigability. For example, for the same ice thickness, pack ice (say SIT = 0.6 m thick and SIC = 50%) have a high degree of freedom that level ice (say SIT = 0.3 m and SIC = 100%) doesn't have. Thus, ships are easier to navigate in broken ice floes (Huang et al., 2020). ATAM is hard to clearly
distinguish ice types at first, and this might be a future direction.

Data Availability. All the data used in this paper are available online. The simulations to sea ice can get from the CMIP6 (https://esgf-node.llnl.gov/search/cmip6/). The observation of sea ice extent is available from the National Snow & Ice Data Center (https://nsidc.org/data/G02135/versions/3).

Author contributions. JLC and SK developed the concept, and investigated the methods of this paper. JLC and WD analyzed the data and wrote the original draft. JG, MX, XZ, WZ and JZC reviewed and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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