1   Perspectives on future sea ice and navigability in the Arctic

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10   **Abstract.** The retreat of sea ice is very significant in the Arctic under global warming.

11   It is projected to continue and have great impacts on navigation. In this investigation,

12   decadal changes in sea ice parameters were evaluated by multimodel from the Coupled

13   Model Intercomparison Project Phase 6, and Arctic navigability was assessed under

14   two shared socioeconomic pathways (SSPs) and two vessel classes within the Arctic

15   transportation accessibility model. The sea ice extent is expected to decrease along the

16   SSP5-8.5 scenario with a high possibility under current emissions and climate change.

17   The decadal decreasing rate will increase in March but decrease in September until

18   2060 when the oldest ice completely disappears and sea ice changes reach an

19   irreversible tipping point. The sea ice thickness will decrease and transit in parts of the

20   Arctic and will decline overall by –0.22 m per decade after September 2060. Both the

21   sea ice concentration and volume will thoroughly decline with decreasing decadal rates,

22   while the decrease in volume will be higher in March than in September. Open water

23   ships will be able to cross the Northeast Passage and Northwest Passage in August–

24   October 2045–2055, with a maximum navigable area in September. The opportunistic

25   crossing time for polar class 6 (PC6) ships will advance to October–December in 2021–

26   2030, while the maximum navigable area will be seen in October. In addition, the

27   Central Passage will also open for PC6 ships during September–October in 2021–2030.

28   **1 Introduction**

29   The Arctic has experienced significant warming since the 1970s (Connolly et al.,

30   2017). Along with the increasing surface air temperature, the Arctic communities have

31   experienced unprecedented changes, such as reductions in sea ice extent and thickness,

32   loss of the Greenland ice sheet, a decrease in snow coverage, and thawing of permafrost

33   (Biskaborn et al., 2019; Box et al., 2019; Brown et al., 2017; Loomis et al., 2019). The

34   sea ice extent has declined at a rate of approximately 3.8% per decade. In comparison,

35   perennial ice has a higher proportion of loss, at approximately 11.5% per decade from

36   1979−2012 (Comiso and Hall, 2014). The average ice thickness near the end of the melt

37   season decreased by 2.0 m or 66% between the pre−1990 submarine period (1958–1976)

38   and the CryoSat-2 period (2011–2018) (Kwok, 2018). Continued declines in sea ice are

39   projected by the Coupled Model Intercomparison Project Phase 5 in the Arctic through

40   the end of the century (Meredith et al., 2019), though some significant timing

41   differences have been predicted (Stephenson et al., 2013).

42   Sea ice insulates thermal transport between the ocean and atmosphere by reflecting

43   a high proportion of incoming solar radiation back to space (Screen and Simmonds,

44   2010). With retreating sea ice, thermohaline circulation has changed (Jourdain et al.,

45 2017), and global warming has intensified (Abe et al., 2016). However, the shrinking

46 and thinning of sea ice leads to prolonged open water conditions for the Arctic passages

47 (Barnhart et al., 2015). The Northeast Passage (NEP) extends along the northern coast

48 of Eurasia from Iceland to the Bering Strait and shortens the transit distance from

49 northwest North America and northeast Asia to northern Europe by approximately

50 15%−50% relative to the southern routes through the Panama Canal and Suez Canal

51 (Buixadé Farré et al., 2014). It is navigable for approximately a month and half per year

52 for ice-strengthened ships at the end of summer (Khon et al., 2010). The day at which

53 open water (OW) ships can cross the NEP has reached 297±4 (October 24th) since 2010.

54 However, navigability is still affected by the ice regime around the Severnaya Zemlya

55 Islands, the Novosibirsk Islands, and the East Siberian Sea (Chen et al., 2019). The

56 Northwest Passage (NWP) follows the northern coast of North America and crosses the

57 Canadian Arctic archipelago. Compared to the traditional Panama Canal route from

58 Western Europe to the Far East, the NWP shortens the transit distance by 9000 km

59 (Howell and Yackel, 2004). The shortest navigable period reached 69 days during the

60 period from 2006–2015 (Liu et al., 2017), and the first time the NWP was completely

61 ice free was in September 2007 (Cressey, 2007).

62   For the development of socioeconomics and marine transportation, future

63 projections of ice conditions and Arctic passages are very important, and climatic

64 changes should be taken into account (Gascard et al., 2017). Climate models are

65 effective and reliable for producing present and future spatial and temporal distributions

66 of Arctic sea ice (Parkinson et al., 2006; Stroeve et al., 2014). Smith and Stephenson

67   (2013) investigated the potential of Arctic passages under representative concentration

68   pathways (RCPs) 4.5 and 8.5 and found that OW ships and Polar Class 6 (PC6) ships

69   will be able to cross the NEP and NWP in September by mid-century, respectively. The

70   areas of the Arctic that will be accessible to PC3, PC6, and OW ships are expected to

71   rise to 95%, 78%, and 49%, respectively, of the circumpolar boundary area delineated

72   by the International Maritime Organization guidelines by the late 21st century

73   (Stephenson et al., 2013). Melia et al. (2017) suggested that the Arctic passages from

74   Europe to Asia will be 10 days faster than conventional routes by mid-century and 13

75   days faster by the later part of the century. Recent research has shown that the NEP

76   might become accessible earlier for OW ships in September 2021–2025, and the

77   navigable window may extend to August–October during 2026–2050 under shared

78   socioeconomic pathways (SSPs) 2–4.5 (Chen et al., 2020). However, it is deficient to

79   evaluate sea ice conditions and Arctic navigability by a single climate model, even with

80   a high resolution.

81   This prospective study was designed to obtain further insight into the future

82   changes in sea ice in the Arctic and the navigability of the Arctic during this century

83   with ensemble up-to-date climate models in the Coupled Model Intercomparison

84   Project Phase 6 (CMIP6). The models were filtered by comparing historical simulations

85   and observations of sea ice extent, and the possible shared socioeconomic pathways

86   were investigated with the averages of multiple models. The distributions of the linear

87   trends of sea ice extent, concentration, and thickness were explored in three stages

88   (2021–2040, 2041–2060, and 2061–2100). In addition, the changes in sea ice volume

89   and age were analyzed. The accessibility of the Arctic and the navigable area were

90   evaluated with the Arctic Transportation Accessibility Model (ATAM) developed by

91   the Arctic Ice Regime Shipping System (AIRSS) for OW ships and PC6 ships under

92   SSP2–4.5 and SSP5–8.5 in 2021–2030 and 2045–2055, respectively.

93   **2 Methods**

94   **2.1 Data and Model Selection**

95   The new scenario framework, SSP, in CMIP6 was designed to carry out research

96   on climate change impacts and adaptions by combining pathways of future radiative

97   forcing and climate changes with socioeconomic developments (O'Neill et al., 2014).

98   Compared with CMIP5 models, the CMIP6 multimodel ensemble mean provides a

99   more realistic estimate of the Arctic sea ice extent (SIMIP Community, 2020), but the

100   biases of the models are still large (Shu et al., 2020). This paper selected models by

101   comparing the historical trends of sea ice extent with observations from the National

102   Snow & Ice Data Center during 1979–2012 with a five-point moving average (Figure

103   1). The excellent models are those with a correlation coefficient greater than 0.8 (0.7

104   for March). As shown in Figure 1, 14 historical models were evaluated in both March

105   and September. The models that passed the test were CESM2, MPI-ESM1-2-HR, MPI-

106   ESM1-2-LR, NorESM2-LM, NorESM2-MM, ACCESS-ESM1-5, AWI-CM-1-1-MR,

107   and AWI-ESM-1-1-LR in September and CESM2, MPI-ESM1-2-LR, ACCESS-

108   ESM1-5, AWI-CM-1-1-MR, INM-CM5-0, MPI-ESM-1-2-HAM, and AWI-ESM-1-1-

109   LR in March. The mean of the excellent models corresponds well with the observations,

110   and the correlation coefficients are 0.884 and 0.817 in September and March,

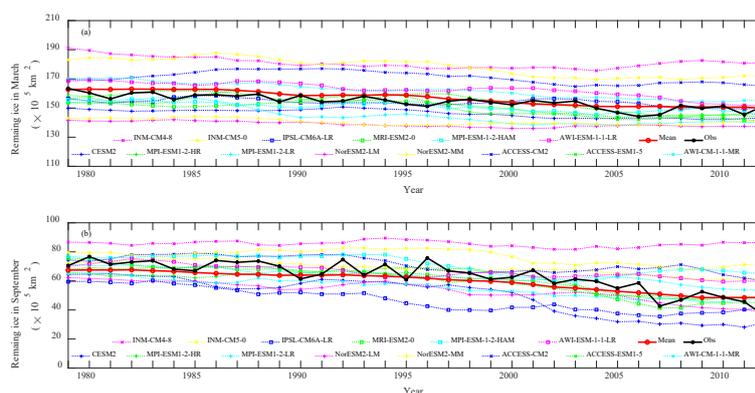
111   respectively. However, sea ice datasets in SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-

112   8.5 after 2020 have not been released for CESM2, MPI-ESM-1-2-HAM, and AWI-

113   ESM-1-1-LR. In addition, AWI-CM-1-1-MR was excluded in the analysis of the

114   navigability of the Arctic due to the absence of sea ice concentration data. The spatial

115   resolutions of the monthly sea ice concentration and thickness data were normalized to

116   1°×1° by bilinear interpolation.

117

118   **Figure. 1.** Five-point moving average of sea ice extents in March and September during

119   1979–2012.

120   **2.2 Accessibility Evaluation**

121   Safety and pollution are two opposing factors that are considered when making

122   regulatory transport standards. The AIRSS was designed to minimize the risk of

123   pollution in the Arctic due to damage to vessels by ice (Transport Canada, 1998). The

124   ATAM, developed by the AIRSS, is commonly used to quantify temporal and spatial

125   accessibilities in the Arctic; in the ATAM, the ability of a ship to enter ice-covered water

126   can be represented by the ice number (IN):

127                $$IN = (C_a * IM_a) + (C_b * IM_b) + \ldots + (C_n * IM_n) \tag{1}$$

128   where IM_a, IM_b, and IM_n are the ice multipliers of ice types a, b, and n,

129   respectively. C_a, C_b, and C_n are the sea ice concentrations. The ice multipliers

130   indicate the severity of each ice type for the given vessel and range from -4 to 2. Positive

131   IM and IN values represent less risk to the given vessel and a safe region for navigation,

132   respectively. The vessel class is a characteristic of a ship that reflects its structural

133   strength, displacement, and power to break ice. PC6 ships and OW ships are vessels

134   that are moderately ice-strengthened and not ice-strengthened, respectively (IMO,

135   2002). In this paper, the navigability of the Arctic for each of these two kinds of ships

136   was investigated under SSP2-4.5 and SSP5-8.5. The IMs for two kinds of ships are as

137   follows:

$$
IM_{OW} = \begin{cases} 2, & if\ SIT = 0\ cm, \\ 1, & if\ 0\ cm < SIT < 15\ cm, \\ -1, & if\ 15\ cm <= SIT < 70\ cm, \\ -2, & if\ 70\ cm <= SIT < 120\ cm, \\ -3, & if\ 120\ cm <= SIT < 151\ cm, \\ -4, & if\ SIT >= 151\ cm \end{cases}
\tag{2}
$$

138

$$
IM_{PC6} = \begin{cases} 2, & if\ 0\ cm <= SIT < 70\ cm, \\ 1, & if\ 70\ cm <= SIT < 120\ cm, \\ -1, & if\ 120\ cm <= SIT < 151\ cm, \\ -3, & if\ 151\ cm <= SIT < 189\ cm, \\ -4, & if\ SIT >= 189\ cm \end{cases}
\tag{3}
$$

139

140

141   **3 Results**

142   **3.1 Future Changes of Sea Ice Area and Extent**

143   The extent and area are the most reliable products of sea ice that can be obtained

144   from satellite retrievals (Comiso, 2012; Notz, 2014). Therefore, the remaining sea ice

145   was taken as an indicator to evaluate the studied models and future scenarios. As shown

146   in Figure 2, the observation trends were obtained with least square regressions of

147   historical ensemble averages from 1979–2019, in which the sea ice might completely

148   disappear in September after 2073. In addition to the classical pathways, such as SSP1-

149   2.6, SSP2-4.5, and SSP5-8.5, CMIP6 provides a variety of new selections. However,

150   SSP1-1.9, SSP4-3.4, and SSP4-6.0 were not discussed in the multiscenario evaluations

151   of the newer models. According to historical development and future scenarios, sea ice

152   will retreat in the future with a more significant decreasing trend in September. The

153   difference between the SSPs and observation trends is greater in March than in

154   September, while both March and September reflect large dispersions among pathways

155   after 2050. Compared with the other scenarios, SSP5-8.5 has the greatest correlation

156   coefficients, at 0.784 and 0.712 in September and March, respectively, with the

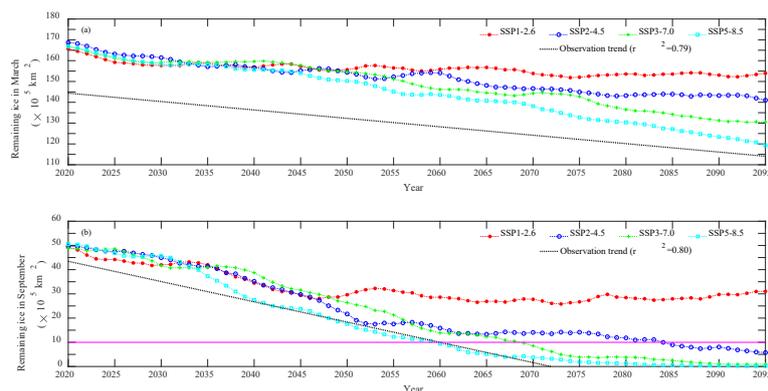
157   observation trend; SSP2-4.5 comes second. This suggests that the worst scenario for

158   Arctic sea ice in the future might occur under the current emission and climate change

159   trends. The Arctic is regarded as "ice-free" when the sea ice area is less than one million

160   square kilometers (Lenton et al., 2019). This is expected to occur in September 2060

161   with a high probability, and ice will almost completely disappear under SSP2-4.5,

162   SSP3-7.0, and SSP5-8.5 by the end of the century.

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164 **Figure. 2.** Remaining sea ice under multiple scenarios and observation trends in the future.

165 "Ice-free" conditions can be considered a tipping point of climate change that has

166 significant irreversible effects (Lenton et al., 2019). Three time periods were extracted

167 and the expected changes in sea ice extent were calculated for each period, as shown in

168 Figure 3. Decadal linear trends and probability distributions with an interval of 0.4 were

169 calculated to evaluate the decline in sea ice and the differences among models. The

170 linear sea ice trends are predicted to be less than zero in both March and September in

171 2021–2100, and the retreat will be more remarkable in September before 2060,

172 especially during 2021–2040, after which the decline is mainly expected in March

173 because the extent might be close to "ice-free" in September. The dispersion of the

174 SSPs will increase in March over time, as will the absolute decadal trends of SSP3-7.0

175 and SSP5-8.5. However, the dispersion is aggregated in September, and the decadal

176 variability in the SSPs, especially in SSP2-4.5 and SSP5-8.5, has a decreasing trend.

177 The multimodel simulations mainly range from -0.8 to 0 million km^2 per decade in

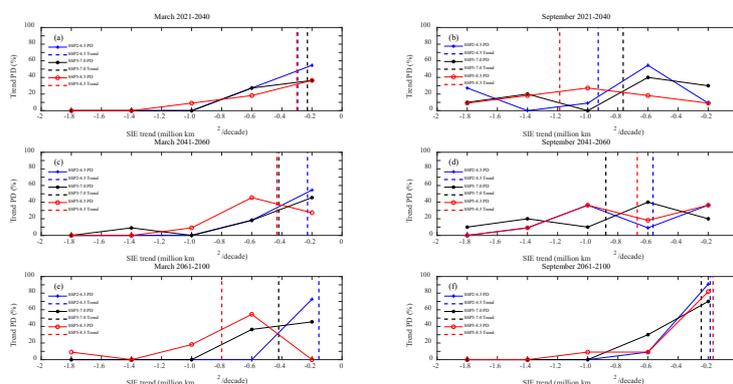
178 March, in which the distributions of SSP5-8.5 are chiefly [-0.4, 0), [-0.8, -0.4), and [-

179 0.8, -0.4) million km^2 per decade during 2021–2040, 2041–2060, and 2061–2100,

180 respectively. A relatively even distribution is shown in September before mid-century,

181 while the distribution is concentrated in the range of [-0.4, 0) in the late century. This

182 indicates that the difference among models is still great in September before 2060,

183 while the results are reliable in 2061–2100.

184

185 **Figure. 3.** Future linear trends and probability distributions (PD) of the Arctic sea ice extent

186 (SIE) in March and September.

3.2. Future Changes of Other Sea Ice Parameters

188 In addition to the extent and area of sea ice, the thickness, concentration, volume,

189 and age are also important indicators of future changes in sea ice. Figures 4 and 5 show

190 the linear trends of sea ice thickness and concentration and changes in sea ice volume

191 and age, respectively, under SSP5-8.5 in 2021–2100. Ice thickness has a negative trend

192 within the Arctic Archipelago, coastal waters, and in the sector to the north of the Arctic

193 Archipelago and Greenland in September, while the other regions will experience slight

194 increases in sea ice thickness in the next 20 years. This trend is reversed in the Arctic

195 Ocean, and the decreasing area near the shore will extend to the north in 2041–2060,

196 after which the thickness of almost all of the sea ice will be reduced with an average

197 trend of –0.22 m per decade in the Arctic. The sea ice concentration will decrease

198 throughout the rest of this century. The area to the north of the Arctic Archipelago and

199 Greenland as well as the Arctic Basin will experience significant changes in September

200 2021–2040. The sea ice extents in these areas will shrink, and the decadal linear rates

201 will decrease until the second half of the century, when the decreasing rates will be

202 even and small in the Arctic. The average decadal change rates of sea ice concentration

203 are predicted to be –12.39%, –6.26%, and –0.81% in the three stages of 2021–2040,

204 2041–2060, and 2061–2100, respectively. The sea ice volume will decrease in both

205 March and September from 2021–2100. The decreasing rate is higher in March, while

206 sea ice might completely disappear in September before 2090. Ice age is also a key

207 descriptor of the state of sea ice cover. Compared to younger ice, older ice tends to be

208 thicker and more resilient to changes in atmospheric and oceanic forcing (Richter-

209 Menge et al., 2019). The oldest ice (>4 years old) makes up just a small fraction of the

210 total sea ice in March currently and might eventually disappear around mid-century.

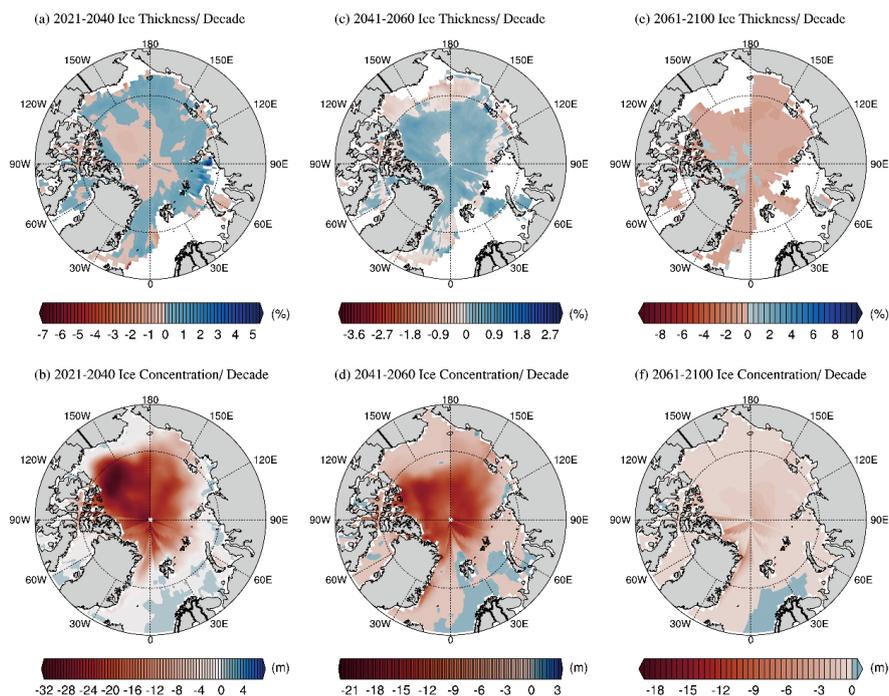
211 With the degeneration of older ice, the extent of younger ice will increase in a given

212 period of time, such as 3–4-year-old ice in the next 10 years, 2–3-year-old ice before

213 2035, and 1–2-year-old ice before 2050, after which multiyear ice will degrade into

214 younger ice. First-year ice dominates the sea ice cover in the both present and future.

215 First-year ice will increase mainly before 2060 and remain stable until 2090, after which

216 it will start to decrease due to the lack of supplementation from degraded older ice.

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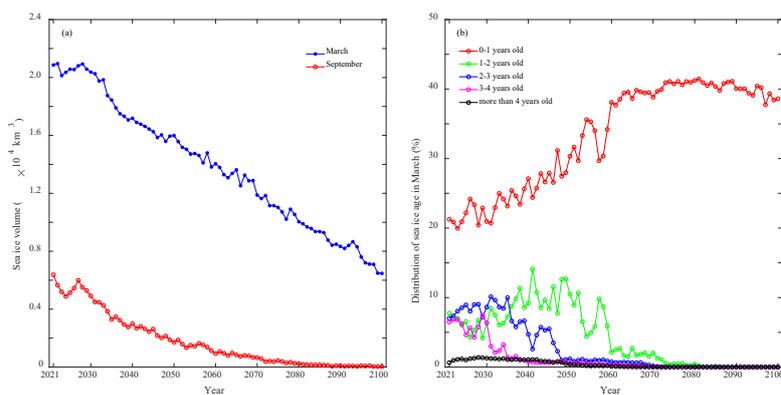
218   **Figure. 4.** Linear trends of ice thickness and concentration under SSP5-8.5 in September.

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220   **Figure. 5.** Changes in sea ice volume and age under SSP5-8.5.

221   **3.3 Future Changes in Arctic Navigability**

222   With retreating sea ice, the possibility of navigation is rising in the Arctic. The

223   number of vessels passing through the Arctic is increasing year by year, but OW ships

224   usually need the guidance of icebreakers, which increases transportation costs. The

225 opening of Arctic passages for OW ships is profitable for ocean shipping companies.

226 The most likely navigable window is in September. Figure 6 shows Arctic accessibility

227 for OW ships under SSP5-8.5 in September. The probability of crossing the NEP and

228 NWP is low in the next 10 years. The impassable areas of the NEP are mainly in the

229 East Siberian Sea and northwestern Laptev Sea, but nearshore waters might be

230 navigable for vessels with shallow drafts. Fortunately, the crucial straits, such as the

231 Shokalskiy Strait, Vilkitskty Strait, Sannikov Strait, and Dmitrii Laptev Strait, will be

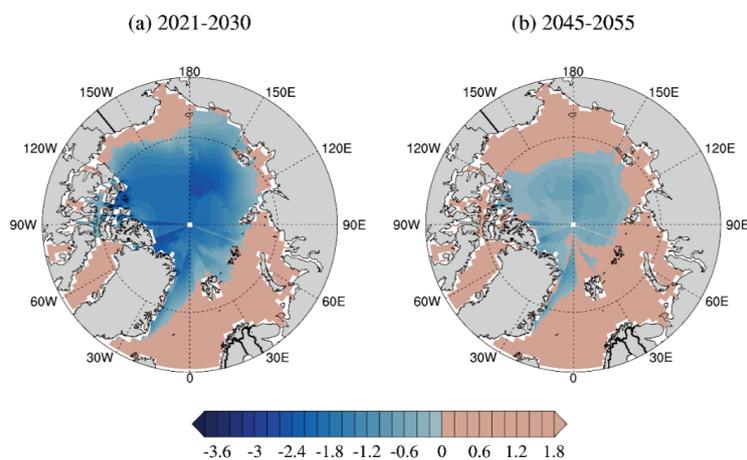
232 accessible for OW ships. The NWP is impassable in the sectors west of Banks Island

233 and Queen Elizabeth Island, as well as the M'Clure Strait, Viscount-Melville Sound,

234 Barrow Strait, and Lancaster Strait within the Parry Channel. All of the routes provided

235 in the Arctic marine shipping assessment report (AMSA, 2009) are under restrictions

236 for OW ships. By mid-century, both the NEP and NWP will open for OW ships under

237 SSP5-8.5 in September.

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

240 The opening of the Arctic passages mainly depends on the connectivity among

241 grids, during which the potential of individual units, which might connect with other

242 units in the next period, is usually ignored. The overall navigable potential in a region

243 can be measured by the percentage of accessible grids relative to the total number of

244 grids. Figure 7 displays the Arctic navigable percentage for two kinds of ships under

245 SSP2-4.5 and SSP5-8.5 in 2021–2030 and 2045–2055. The totally navigable area for

246 OW ships is shown as a unimodal curve in both stages, with a peak in September and a

247 valley in April and March. An irregular curve is observed for PC6 ships, with a

248 minimum value in June. The maximum values are shown in October 2021–2030, while

249 the values range in November and December in the mid-century period. Actually, the

250 Arctic will be navigable for PC6 ships from October to December. It is very strange

251 that an abnormal decrease occurs in September in both the 2021–2030 and 2045–2055

252 periods. The navigable area within every 5 degrees of latitude from 65°N to 90°N is

253 plotted in Figure 8 for further studies. This figure indicates that the abnormal point

254 results from the observed decrease within the region of 85°N–90°N, but the reason for

255 this decrease is hard to explain. The navigable area is mainly concentrated in 65°N–

256 75°N for OW ships in the next 10 years and will extend to 80°N in the mid-century

257 period. The central passage might be accessible for PC6 ships in September and

258 October, and the open window is expected to be from October to January in 2045–2055.

259 The routes of the NEP and NWP are mainly distributed in 70°N–75°N. The possibility

260 of OW ships crossing the two passages is low until August–October 2045–2055, while

261 it is high for PC6 ships during October–December 2021–2030, and the open window is

262 expected to extend to August–January in 2045–2055.

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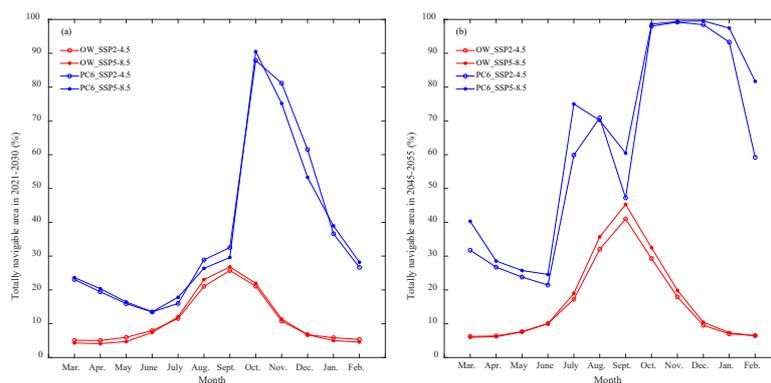
Figure. 7. Total navigable area for OW ships and PC6 ships under SSP2-4.5 and SSP5-8.5.

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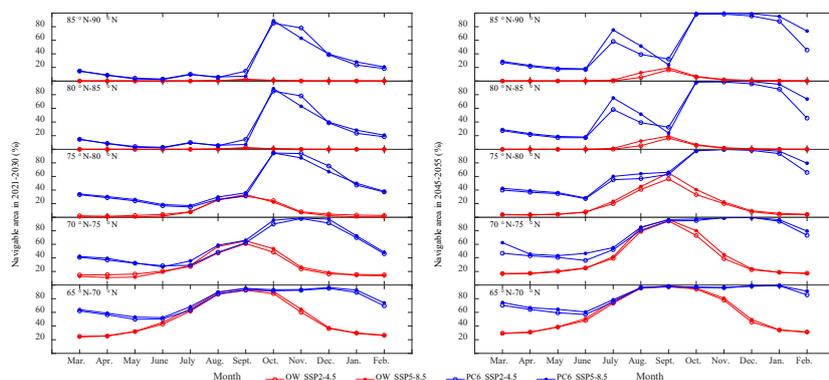
266 **Figure. 8.** Navigable area for OW ships and PC6 ships under SSP2-4.5 and SSP5-8.5 at different

267 latitudes.

4 Conclusions

268

269 The Arctic warming rate is more than double the global average warming rate, and

270 this warming has caused great impacts on the Arctic and globe (Cohen et al., 2020).

271 This paper investigated the future changes in sea ice and the navigability of passages in

272 the Arctic under two kinds of shared socioeconomic pathways. It provides a vision of

273 the Earth's future and has great significance for navigation planning. The following

274 results were found.

275 (1) Changes in sea ice are expected to occur along SSP5-8.5 with a higher possibility

276   under the current trend. "Ice-free" regions might appear in September 2060, and

277   sea ice is expected to completely disappear by the end of the century.

278   (2) Retreating sea ice is more significant in September before 2060, after which the

279   decline is mainly shown in March. The decadal sea ice extent will increase under

280   SSP5-8.5 in March but decrease in September.

281   (3) The decrease in sea ice thickness will transit from the Arctic Ocean north of the

282   Arctic Archipelago and Greenland to the seas along Russia and North America

283   and will totally decline with an average decadal trend of –0.22 m in September

284   after 2060. The sea ice concentration will thoroughly decline with decreasing

285   decadal rates.

286   (4) The sea ice volume will decrease with a higher decadal rate in March than in

287   September. The oldest ice might eventually disappear around the mid-century

288   period. First-year ice will dominate the sea ice cover and will increase mainly

289   before 2060 and remain stable until 2090, after which it will start to decrease.

290   (5) The probability of OW ships crossing the NEP and NWP is low in 2021–2030, while

291   it is high in August–October 2045–2055, with maximum and minimum navigable

292   areas in September and March, respectively.

293   (6) The passages along the coast and crossing the Arctic might open for PC6 ships

294   during October–December and September–October 2021–2030, respectively, with

295   a maximum navigable area in October. The open windows are expected to extend

296   to August–January and October–January in 2045–2055, respectively, and the

297   maximum navigable areas are expected between November and December.

5 Discussions

298

299   The navigable window for OW ships and PC6 ships along the NEP were

300   investigated in our previous work (Chen et al., 2020), but it is deficient to evaluate

301   Arctic navigability by a single climate model, even with a high resolution. This study

302   serves as a reference for future changes in sea ice and navigability in the Arctic,

303   including NEP, NWP, and Central Passage. However, the uncertainty of the models

304   might have affected the results and their reliability in this research. Approximated

305   physical processes and unreal parameters in models are inevitable problems in the

306   geosciences. Differences still exist even though the models were filtered by comparing

307   the historical simulations with observed sea ice extents. The predicted abnormal

308   decrease in navigable area at high latitudes (80°N–90°N) in September might be an

309   example of this uncertainty. This prediction is against conventional wisdom, but it

310   could also be true. The uncertainty of models is increasing in future prospective

311   research.

312

313   *Data Availability.* All the data used in this paper are available online. The simulations

314   to sea ice can get from the CMIP6 (https://esgf-node.llnl.gov/search/cmip6/). The

315   observation of sea ice extent is available from the National Snow & Ice Data Center

316   (https://nsidc.org/data/G02135/versions/3).

317

318   *Author contributions.* JLC and SK developed the concept, and investigated the methods

319   of this paper. JLC and WD analyzed the data and wrote the original draft. JG, MX, XZ,

320   WZ and JZC reviewed and edited the manuscript.

321

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

323

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