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

Jinlei Chen[1], Shichang Kang[1, 2], Wentao Du[1], Junming Guo[1], Min Xu[1], Yulan Zhang[1], Xinyue Zhong[3], Wei Zhang[1], Jizu Chen[1]

[1]State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China

[2]CAS Centre for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China

[3]Key Laboratory of Remote Sensing of Gansu Province, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China

Correspondence: Shichang Kang (shichang.kang@lzb.ac.cn)

Abstract The ~~retreating~~retreat of sea ice ~~wasis~~has been found to be very significant in the Arctic under ~~the~~ global warming. It is projected to continue and ~~has~~ will have great impacts on ~~the~~ navigation. Perspectives ~~to~~on the changes ~~of~~in sea ice and navigability are crucial to the ~~future and~~ circulation pattern and future of the Arctic ~~future and pattern~~. In this investigation, the decadal changes ~~of~~in sea ice parameters were evaluated by the ~~multi-model~~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 s~~S~~ea ice extent ~~would~~ shows a high possibility of decreasing ~~decrease~~ along ~~the~~ SSP5-8.5 ~~with high possibility~~ under current ~~emission~~emissions and climate change. The decadal ~~decreasing~~ rate of decreasing sea ice will ~~increasing~~increase in March~~,~~ but ~~decreasing~~decrease in September until 2060, when the oldest ice ~~would completely disappeardisappears~~will have completely disappeared and

the sea ice ~~would reaches~~ will reach an irreversible tipping point. Sea ice thickness ~~will~~ is expected to decrease and transit in certain parts,~~,~~ ~~and totally decline~~ declining ~~with~~by –0.22 m per decade after September 2060. Both the sea ice concentration and volume will thoroughly decline ~~with~~ at decreasing decadal rates, ~~while and the decreasing~~with a greater –decrease in volume ~~is higher~~ in March than in September~~ for the volume~~. Open water ships ~~are would~~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 ~~is would be advanced~~ will shift to October–December during the period from 2021–2030, ~~while the~~with a maximum navigable area ~~would showsoccurs~~ in October. In addition, the Central Passage~~ also~~ ~~would~~ will be open for PC6 ships ~~during~~ between September~~–~~ and October during 2021–2030.

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

1. Introduction

The Arctic has ~~under gone~~ experienced significant warming ~~after~~since 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, ~~losing~~loss of the Greenland ice sheet, ~~decreasing~~decrease ~~of~~ in snow coverage, and thawing of permafrost (Biskaborn et al., 2019; Box et al., 2019; Brown et al., 2017; Loomis et al., 2019).~~ Sea~~ The sea ice extent has declined at a rate of approximately 3.8% per decade. In comparison, perennial ice had~~s~~ a higher proportion of loss of approximately 11.5% per decade during the period from1979−2012 (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~~in sea ice ~~were~~ 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 ~~though~~ with some significant differences in timing ~~difference~~ (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~~ the retreatment of sea ice, thermohaline circulation has changed (Jourdain et al., 2017), and global warming has intensified (Abe et al., 2016). However, climate change ~~the shrinkageing and thinning of sea ice lead~~ 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~~Passage~~ (~~NEP~~NSR) 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~~approximately 15%−50% relative to the southern routes through the ~~Panama Canal and~~ Suez Canal (Buixadé Farré et al., 2014). It is navigable for ~~about~~approximately ~~a 1.5~~3 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~~to 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 ~~American~~America and ~~across~~crosses 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 ~~free showed~~ was ~~shown~~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. 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 ~~condition~~conditions and Arctic Passages are ~~more~~ increasingly important, in which ~~the~~ climatic changes should be ~~taken into account~~considered (Gascard et al., 2017). ~~Climate models are effective and reliable to producefor producing 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 represent~~underrepresentative concentration ~~pathway~~pathways (RCP) 4.5 and RCP 8.5~~,~~ and found that OW ships and Polar Class 6 (PC6) ships (Table 1)~~are~~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 ~~rising~~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 ~~European~~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~~has shown 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 (~~SSP~~SSPs) 2–4.5 (Chen et al., 2020). However, ~~it is deficient to evaluate~~evaluating sea ice ~~condition~~conditions and ~~the~~ Arctic navigability by ~~the~~a single climate model, even one with a higher resolution, is insufficient.

This prospective study was designed to ~~get~~obtain further insight into the future changes ~~of~~in sea ice in the Arctic and the navigability of the Arctic during this century with ~~an~~ 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 ~~liner~~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~~in 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

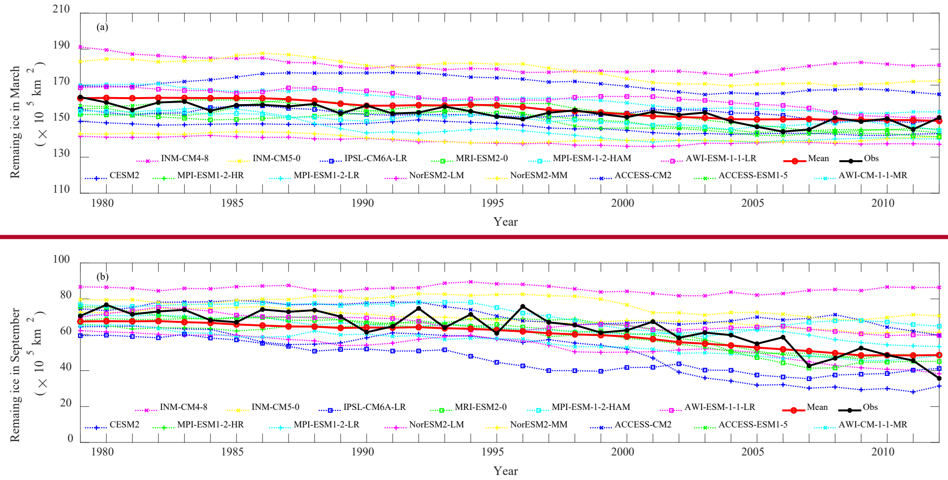
2.1. Data and Model Selection

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~~multi-model ensemble mean provides a more realistic estimate ~~to~~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 observation~~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-LM, NorESM2-MM, ACCESS-ESM1-5, AWI-CM-1-1-MR, and AWI-ESM-1-1-LR in September~~,~~ and CESM2, MPI-ESM1-2-LR, ACCESS-ESM1-5, AWI-CM-1-1-MR, INM-CM5-0, MPI-ESM-1-2-HAM, and AWI-ESM-1-1-LR in March. The mean of the ~~excellent~~ selected models corresponds well with the ~~observation~~observations, 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 ~~in~~from analyzing the navigability of the Arctic ~~for~~in the absence of sea ice concentration. The spatial resolution of monthly sea ice concentration and thickness ~~were~~ was normalized to 1°×1° by bilinear interpolation. Variables in figures and tables were from the ensemble means of selected models.



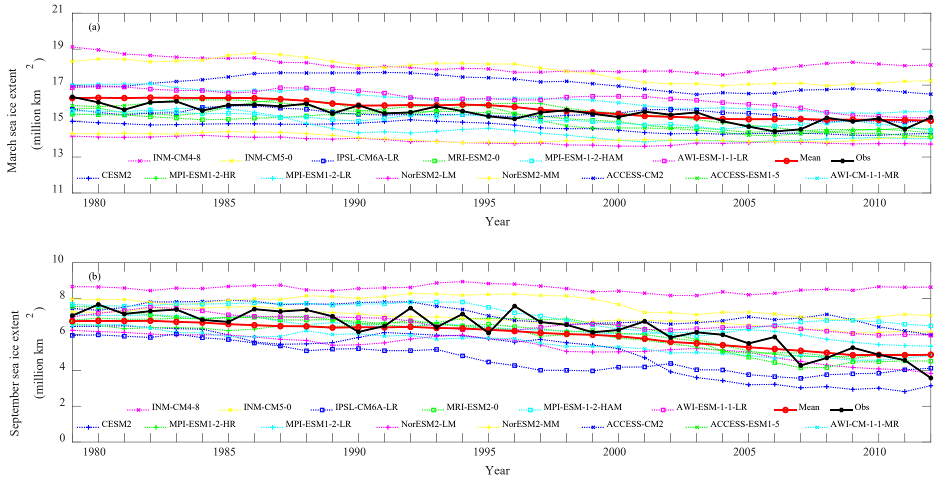


Figure. 1. The observations and ~~F~~five-point moving averages of sea ice extent in March and September during 1979–2012.

2.2. Accessibility Evaluation

Safety and pollution are two of the opposite factors ~~which~~that ~~were~~ considered in

~~making~~ developing regulatory transport ~~standard~~standards. AIRSS was designed to minimize the risk of pollution in the Arctic due to damage ~~of~~to vessels by ice (Transport Canada, 1998). ATAM, developed by AIRSS, ~~was~~is commonly used to quantify the temporal and spatial accessibilities in the Arctic, in which ~~Ice Number~~ the ice number (IN) represents the ability of a ship to enter ice-covered water:

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

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~~ Positive IM and IN represent less risk to the vessel and safe region for navigation, respectively. Vessel ~~Class is a character of ship reflecting its~~ class reflects the 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 ~~this~~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:

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

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

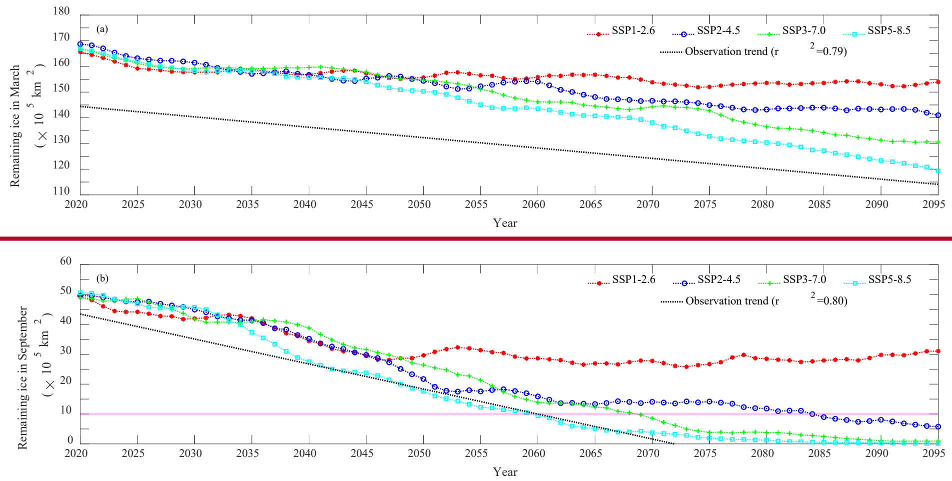
Table 1 Vessel classes versus operating ice thickness

Vessel class	Maximum allowable ice type	Ice thickness (cm)
Polar class 3	Second year	No limit
Polar class 6	Medium first-year	0–120
Ordinary merchant	Open water/Grey	0–15

3. Results

3.1. Future Changes ~~of~~ in 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, SSP4-34, and SSP4-6.0 were not discussed in ~~multi-sceenarios~~the multi-scenario evaluation for the less released models. According to ~~the~~ historical development and scenarios, sea ice will ~~retreating~~retreat in the future with a more significant decreasing trend in September. The difference between SSPs and observation ~~trend~~trends 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. ~~It~~This suggests that ~~the~~ Arctic sea ice might ~~turns out for~~ be the worst scenario in the future under the current emission and climate change trends. ~~Actually, the~~ The Arctic is regarded as ~~“Ice~~“ice -free” when the sea ice area ~~little~~ is less than ~~one~~ 1 million km^2 ~~square kilometers~~ (Lenton et al., 2019). ~~It~~ This will ~~occurs~~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.



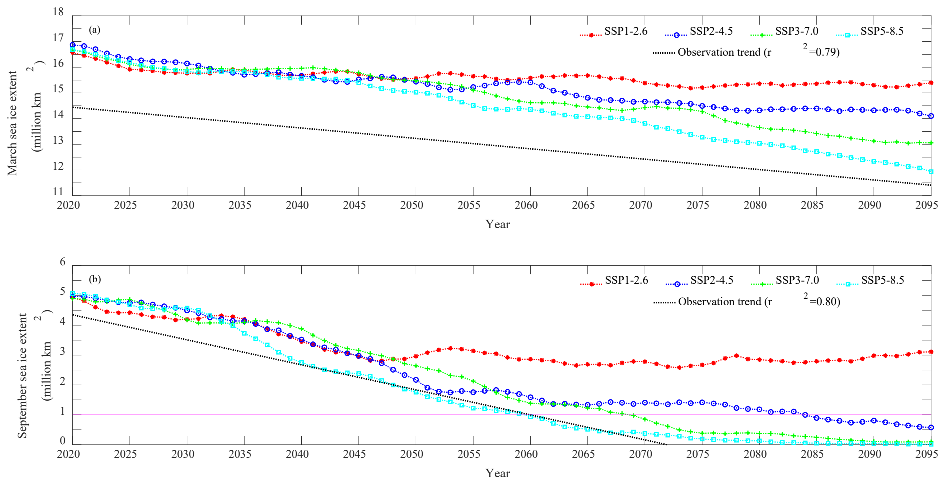


Figure. 2. ~~Remaining s~~Sea ice extent under ~~multi-~~multiple scenarios and observation ~~trend~~trends in ~~the future~~March and September

“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 ~~of~~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 ~~of~~in sea ice and the difference in models. Sea ice linear trends are less than zero in both ~~in~~ 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~~“ice free” in September. The dispersion of SSPs will increase in March over time, as ~~well as~~will the absolute decadal trends of SSP3-7.0 and SSP5-8.5. However, it is aggregated in September, and the decadal variability ~~of~~in SSPs, especially SSP2-4.5 and SSP5-8.5, has a decreasing trend. ~~Multi-model~~Multi-model simulations ~~are~~ mainly range from -0.8 to 0 million km^2 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 km^2 per decade during 2021–2040, 2041–2060, and 2061–2100, respectively. ~~Relatively~~A relatively even distribution is shown in September before the mid-century, while it is concentrated in [-0.4, 0) in the late century. ~~It~~This indicates that the difference among models is still great in September before 2060, while the results are reliable in 2061–2100.

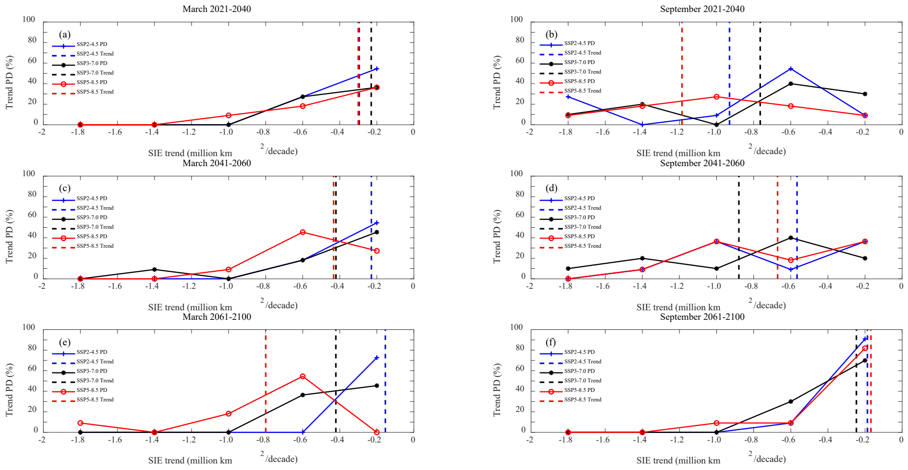
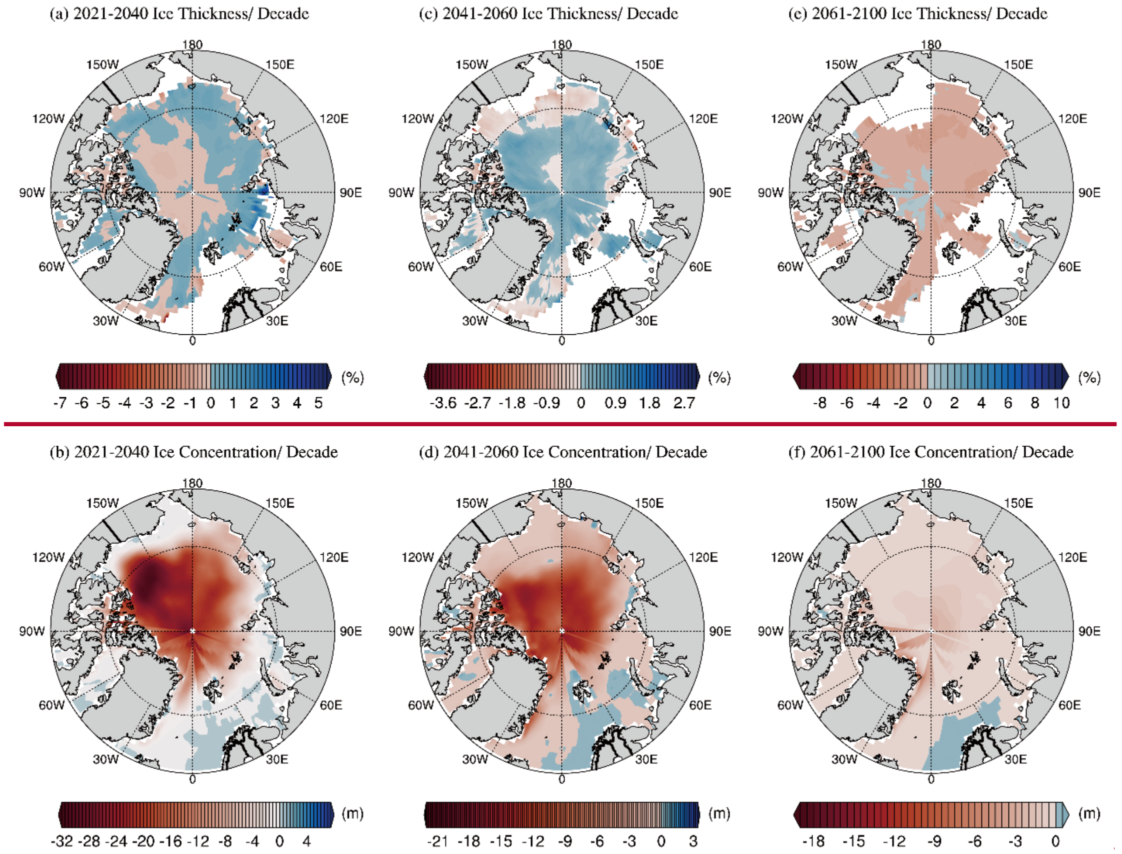


Figure. 3. ~~Future l~~Linear trends and ~~its~~ probability distributions (PD) of ~~the~~ Arctic sea ice extent (SIE) in March and September

3.2. Future Changes ~~of~~ in Other Sea Ice Parameters

In addition to the extent and area, thickness, concentration, volume, and age are ~~also~~ important indicators ~~for the~~ of changes ~~of~~in sea ice in the future. ~~Figure~~Figures 4 and 5 ~~are~~show the linear trends of ice thickness and concentration~~,~~ and the changes ~~of~~in 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. ~~It~~ The trend is reversed in the Arctic Ocean, and the decreasing area ~~which~~ near the shore will extend~~s~~ to the north in 2041–2060, after ~~when~~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 ~~in~~ 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 ~~shrinking~~shrink, and the decadal linear rate will ~~decreasing~~decrease until the second half of the century, when the ~~decreasing rates~~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~~ in the three stages. Sea ice volume will ~~decreasing~~decrease in both ~~in~~ March and September 2021–2100. The ~~decreasing ra~~rate of ~~te~~ decrease is higher in March, ~~while~~ and 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 ~~makes u~~comprises just a small fraction in March ~~now~~, and it might eventually disappear ~~around~~ at approximately the mid-century. With the degeneration of older ice, the extent of the younger ice will ~~increasing~~increase ~~in~~ over a period ~~of time~~, such as 3- to –4-year-~~s-~~old ice in the next 10 years, 2- to –3--year-~~s-~~old ice before 2035, and 1- to –2-year-~~s-~~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 ~~when~~which it starts to decrease ~~for~~ due to the lack of ~~supplement~~supplementation from degraded older ice.



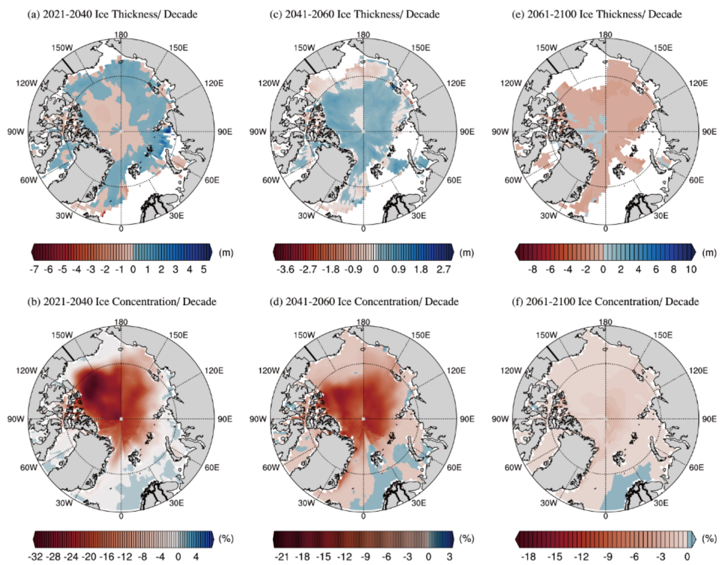


Figure. 4. Linear trends of sea ice thickness and concentration under SSP5-85 in September

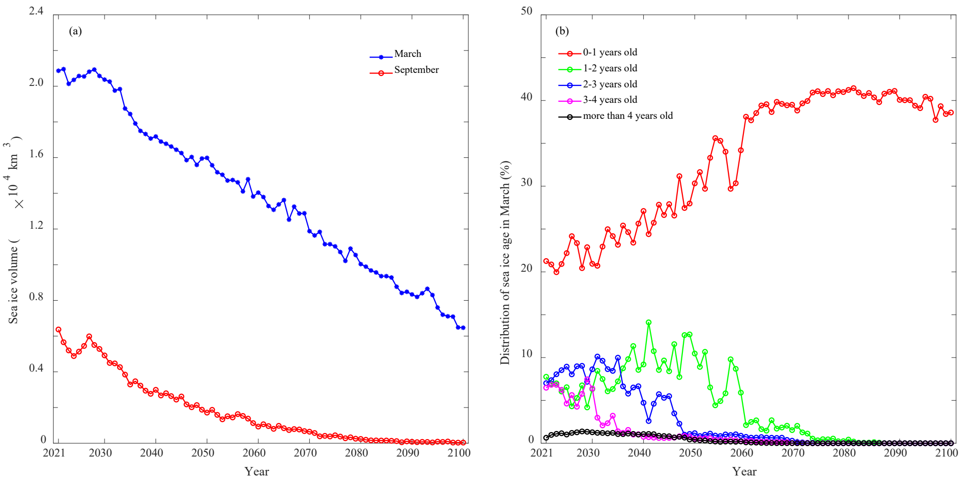
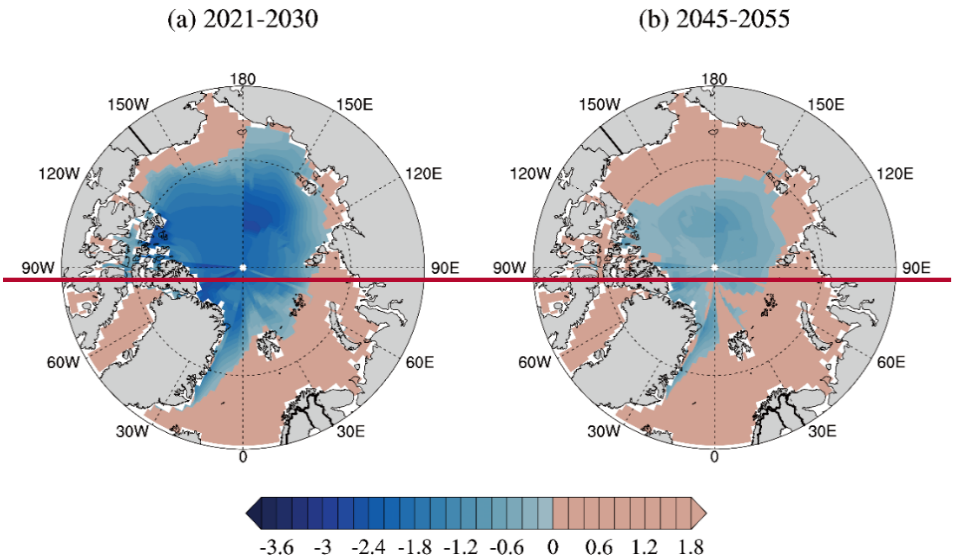


Figure. 5. The changes ~~of~~ in sea ice volume and age under SSP5-85

3.3. Future Changes ~~of~~ in ~~the~~ Arctic Navigability

With ~~retreating~~the retreatment of sea ice, the possibility for navigation is rising in the Arctic. ~~The number of vessels passing through the Arctic was increasinghas increased year by year, but OW ships usually need the guidance of icebreakers, which increaseincreases the transportation cost.~~ The opening of passages ~~for OW ships It is~~will be profitable for ocean shipping companies (Chang et al., 2015)~~ with the openopening of passages for OW ships~~. The most likely navigable window is in September. Figure 6 ~~showed~~shows Arctic accessibility for the OW ships under SSP5-8.5 in September. The probability ~~for~~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 ~~draft~~drafts. ~~Fortunately, f~~Four crucial straits, the Vilkitskty 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'-Clure 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 ~~the~~ OW ships. In the mid-century, both ~~NEP~~ NSR and NWP will open for OW ships under SSP5-8.5 in September.



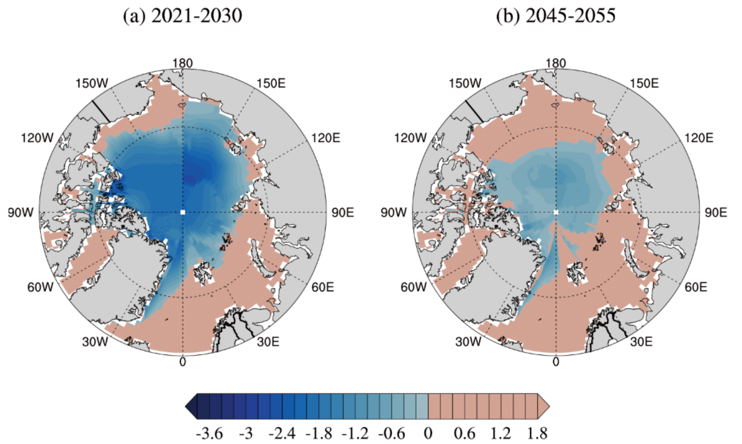


Figure. 6. ~~Arctic navigability~~INs for OW ships under SSP5-8.5 in September

The ~~open~~opening of the Arctic Passages ~~is~~ mainly ~~depend~~depends on the connectivity among grids, during which the potential of individual ~~unit~~units, which might ~~connects~~connect with other units ~~around~~ in the next period, ~~was~~is usually ignored. The overall navigable potential in a region can be measured by the percentage of accessible grids with total grids. Figure 7 ~~displayed~~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~~ of~~ 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~~in ~~both 2021–2030 and~~ 2045–2055. The navigable area within every 5 latitude degrees from 65°N to 90°N ~~was~~is plotted in Figure 8 for ~~the~~ further study. ~~It~~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 ~~concentrates in~~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 ~~distribute~~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.

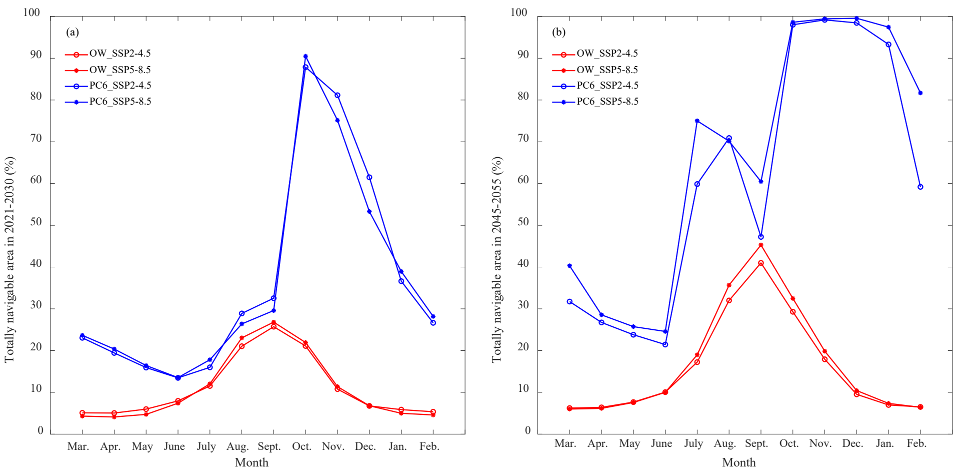


Figure. 7. Totally navigable areas for OW ships and PC6 ships under SSP2-4.5 and SSP5-8.5

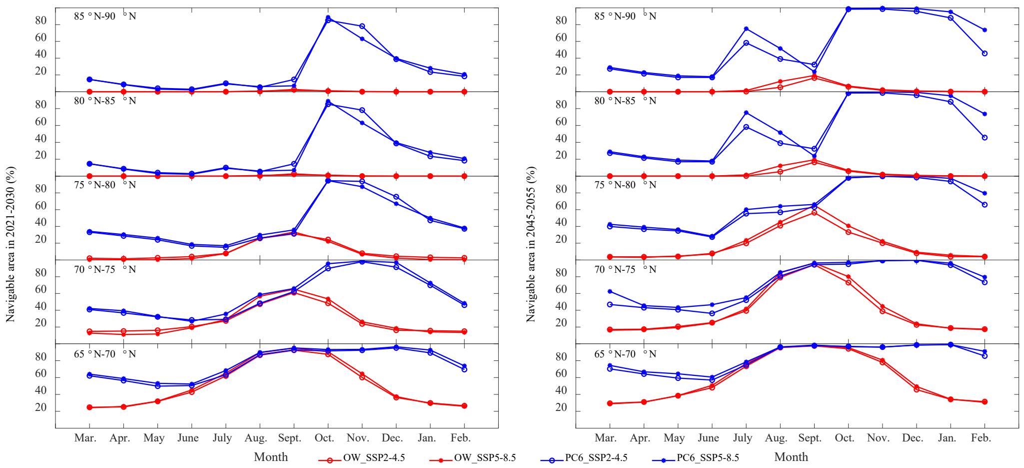


Figure. 8. Navigable areas for OW ships and PC6 ships under SSP2-4.5 and SSP5-8.5 ~~at~~ winthin different ~~latitude~~latitudes

4. Discussion and concluding remarks~~Conclusions~~

The Arctic warming rate is more than double the global average, and it has ~~made~~had great impacts ~~to~~on the Arctic and globe (Cohen et al., 2020). This paper investigated the future changes ~~of~~in sea ice and navigability of ~~Passages~~passages in the Arctic under two kinds of shared socioeconomic pathways. It provides a vision of the earth's future and has great ~~significant to the~~significance for navigation planning. The following results were found.

(1) The changes ~~of~~in sea ice would occur along ~~the~~ SSP5-8.5 with a higher possibility

under the current trend. “Ice free” might ~~shows~~appear in September 2060, and sea ice would completely disappear by the end of the century.

(2) The retreat~~ing~~ of sea ice is more significant in September before 2060, after ~~when~~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 of~~decrease 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 ~~decreasing~~decrease ~~with~~ at 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 ~~when~~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 ~~area~~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~~in ~~sea ice and the navigability in the Arctic.~~ However, the uncertainty of the models might have affected the results and ~~its~~their reliability in this research. ~~It~~ 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 un-real~~unreal ~~parameters in the model.~~ ~~The differences~~ Differences still ~~exist~~existed even when the models were filtered by comparing the historical simulations with the ~~observation~~observations of sea ice extent. The abnormal decrease ~~of~~in navigable area ~~in~~at high ~~latitude~~latitudes (80°N–90°N) in September might be an example. ~~It~~ This is against conventional wisdom, but it could ~~also~~ be true. The uncertainty of the models is ~~increasing~~ expected to ~~in~~decrease in ~~the~~ future ~~perspective~~prospective research. Different ice types do make a big difference to ship navigability. For example, for the same ice thickness * ice concentration (e.g. SIT * SIC = 0.3), 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.

Acknowledgements Thanks for the data from CMIP6 and NSIDC. Our cordial gratitude should be extended to anonymous reviewers and the Editors for their professional and pertinent comments on this manuscript.

Financial support. This work was financially supported by the National Natural Science Foundation of China (~~42005075 and~~ 41721091), the Frontier Science Key Project of CAS (QYZDY-SSW-DQC021, and QYZDJ-SSW-DQC039), the State Key Laboratory of Cryospheric Science (SKLCS-ZZ-2021), the China National Key Research and Development Program (2020YFA0608500, and 2020YFA0608503), and

Foundation for Excellent Youth Scholars of “Northwest Institute of Eco-Environment and Resources”, CAS (FEYS2019020).

References

Abe, M., Nozawa, T., Ogura, T., & Takata, K.: Effect of retreating sea ice on Arctic cloud cover in simulated recent global warming, Atmos. Chem. Phys., 16, 14343–14356, https://doi.org/10.5194/acp-16-14343-2016, 2016.

AMSA: Arctic marine shipping assessment 2009 report. Arctic Council, 2009.

Barnhart, K. R., Miller, C. R., Overeem, I., and Kay, J. E.: Mapping the future expansion of Arctic open water, Nat. Clim. Change, 6, 280–285, https://doi.org/10.1038/nclimate2848, 2015.

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A.: Permafrost is warming at a global scale, Nat. Commun., 10, https://doi.org/10.1038/s41467-018-08240-4, 2019.

Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F.-J. W.: Key indicators of Arctic climate change: 1971–2017, Environ. Res. Lett., 14, 045010, https://doi.org/10.1088/1748-9326/aafc1b, 2019.

Brown, R., Vikhamar Schuler, D., Bulygina, O., Derksen, C., Luojus, K., Mudryk, L.: Arctic terrestrial snow cover. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017, Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 25–64, 2017.

Buixadé Farré, A., Stephenson, S. R., Chen, L., Czub, M., Dai, Y., Demchev, D.: Commercial Arctic shipping through the Northeast Passage: routes, resources, governance, technology, and infrastructure, Polar Geography, 37, 298–324. https://doi.org/10.1080/1088937x.2014.965769, 2014.

Chang, K. Y., He, S. S., Chou, C. C., Kao, S. L., Chiou, A. S.: Route planning and cost analysis for travelling through the Arctic Northeast Passage us ing public 3D GIS. Int. J. Geogr. Inf. Sci., 29, 7–8, 1375–1393, https://doi.org/10.1080/13658816.2015.1030672, 2015.

Chen, J. L., Kang, S. C., Chen, C. S., You, Q. L., Du, W. T., Xu, M.: Changes in sea ice and future accessibility along the Arctic Northeast Passage, Global Planet. Change, 195, 103319, https://doi.org/10.1016/j.gloplacha.2020.103319, 2020.

Chen, S. Y., Cao, Y. F., Hui, F. M., and Cheng, X.: Observed spatial-temporal changes in the autumn navigability of the Arctic Northeast Route from 2010 to 2017 (in Chinese), Chinese Sci. Bull., 64, 1515–1525, https://doi.org/10.1360/N972018-01083, 2019.

Cohen, J., Zhang, X., Francis, J. A., Jung, T., Kwok, R., Overland, J.: Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather, Nat. Clim. Change, 10, 20–29, http://doi.org/10.1038/s41558-019-0662-y, 2020.

Comiso, J. C.: Large decadal decline of the Arctic multiyear ice cover, J. Climate, 25, 1176–1193, https://doi.org/10.1175/JCLI-D-11-00113.1, 2012.

Comiso, J. C., and Hall, D. K.: Climate trends in the Arctic as observed from space, Wires. Clim. Change, 5, 389–409, https://doi.org/10.1002/wcc.277, 2014.

Cressey, D.: Arctic melt opens Northwest Passage, Nature, 449, 267–267. https://doi.org/10.1038/449267b, 2007.

Gascard, J.-C., Riemann-Campe, K., Gerdes, R., Schyberg, H., Randriamampianina, R., Karcher, M.: Future sea ice conditions and weather forecasts in the Arctic: Implications for Arctic shipping, Ambio, 46, 355–367, https://doi.org/10.1007/s13280-017-0951-5, 2017.

Howell, S. E. L., and Yackel, J. J.: A vessel transit assessment of sea ice variability in the Western Arctic, 1969–2002: implications for ship navigation, Can. J. Remote Sens., 30, 205–215, https://doi.org/10.5589/m03-062, 2004.

Huang, L. F., Li, M. H., Romu, T., Dolatshah, A., Thomas, G.: Simulation of a ship operating in an open-water ice channel. Ships Offshore Struc., https://doi.org/10.1080/17445302.2020.1729595, 2020.

Huang, L. F., Tuhkuri, J., Igrec, B., et al.: Ship resistance when operating in floating ice floes: a combined CFD&DEM approach. Mar. Struct., 74, 102817, 2020.

IMO: Guidelines for ships operating in Arctic ice-covered waters, In: MSC/Circ.1056 and MEPC/Circ.399, 2002.

Jourdain, N. C., Mathiot, P., Merino, N., Durand, G., Le Sommer, J., Spence, P.: Ocean circulation and sea-ice thinning induced by melting ice shelves in the Amundsen Sea, J. Geophys. Res-Oceans, 122, 2550–2573, https://doi.org/10.1002/2016jc012509, 2017.

~~Khon, V. C., Mokhov, I. I., Latif, M., Semenov, V. A., and Park, W.: Perspectives of Northern Sea Route and Northwest Passage in the twenty-first century, Climatic Change, 100, 757–768, https://doi.org/10.1007/s10584-009-9683-2, 2009.~~

Kwok, R.: Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018), Environ. Res. Lett., 13, 105005, https://doi.org/10.1088/1748-9326/aae3ec, 2018.

Lenton, T., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W.: Climate tipping points-too risky to bet against, Nature, 575, 592–595, https://doi.org/10.1038/d41586-019-03595-0, 2019.

Liu, X., Ma, L., Wang, J., Wang, Y., and Wang, L.: Navigable windows of the Northwest Passage, Polar Sci., 13, 91–99, https://doi.org/10.1016/j.polar.2017.02.001, 2017.

Loomis, B. D., Rachlin, K. E., and Luthcke, S. B. Improved Earth oblateness rate reveals increased ice sheet losses and mass‐driven sea level rise. Geophys. Res. Lett., 46, 6910–6917, https://doi.org/10.1029/2019gl082929, 2019.

Melia, N., Haines, K., Hawkins, E., and Day, J. J.: Towards seasonal Arctic sh ipping route predictions. Environ. Res. Lett., 12, 084005, https://doi.org/10.1088/1748-9326/aa7a60, 2017.

Meredith, M. P., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A. A., Hollowed, A.: Chapter 3: Polar Regions. IPCC special report on the ocean and cryosphere in a changing climate, In press. https://report.ipcc.ch/srocc/pdf/SROCC_FinalDraft_FullReport.pdf, 2019.

Notz, D.: Sea-ice extent and its trend provide limited metrics of model performance, Cryosphere, 8, 229–243, https://doi.org/10.5194/tc-8-229-2014, 2014.

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. R., Hallegatte, S., Carter, T. R.: A new scenario framework for climate change research: the concept of shared socioeconomic pathways, Climatic Change, 122, 387–400. https://doi.org/10.1007/s10584-013-0905-2, 2014.

~~Parkinson, C. L., Vinnikov, K. Y., and Cavalieri, D. J.: Evaluation of the simulation of the annual cycle of Arctic and Antarctic sea ice coverages by 11 major global climate models, J. Geophys. Res., 111, https://doi.org/10.1029/2005jc003408, 2006.~~

Richter-Menge, J., Druckenmiller, M. L., and Jeffries, M.: Arctic Report Card 2019, https://www.arctic.noaa.gov/Report-Card, 2019.

Ryan, C., Thomas, G., and Stagonas, D.: Arctic Shipping Trends 2050, https://doi.org/10.13140/RG.2.2.34680.67840, 2020.

Screen, J. A., and Simmonds, I.: Increasing fall-winter energy loss from the Arctic Ocean and its role in Arctic temperature amplification, Geophys. Res. Lett., 37, https://doi.org/10.1029/2010gl044136, 2010.

Serova, N. A., and Serova, V. A.: Critical tendencies of the transport infrastructure development in the Russian Arctic. Arctic and North, 36, 42–56, https://doi.org/10.17238/issn2221-2698.2019.36.42, 2019.

Shu, Q., Wang, Q., Song, Z. Y., Qiao, F. L., Zhao, J. C., Chun, M.: Assessment of sea ice extent in CMIP6 with comparison to observations and CMIP5. Geophys. Res. Lett., 47, e2020GL087965, https://doi.org/10.1029/2020GL087965, 2020.

SIMIP Community: Arctic sea ice in CMIP6, Geophys. Res. Lett., 47, e2019GL086749, https://doi.org/10.1029/2019GL086749, 2020.

Smith, L. C., and Stephenson, S. R.: New Trans-Arctic shipping routes navigable by midcentury, P. Nati. Acad. Sci. USA, 110, E1191–E1195, https://doi.org/10.1073/pnas.1214212110, 2013.

Stephenson, S. R., Smith, L. C., Brigham, L. W., and Agnew, J. A.: Projected 21st-century changes to Arctic marine access, Climatic Change, 118, 885–899, https://doi.org/10.1007/s10584-012-0685-0, 2013.

Streng, W., Eger, K. M., Flistad, B., Jgensen-Dahl, A., Lothe, L., Mejlnder-Larsen, M., Wergeland, T.: Shipping in Arctic waters: a comparison of the northeast, northwest and trans polar passages, https://doi.org/10.1007/978-3-642-16790-4, 2013.

Tillman, H., Yang, J., and Nielsson, E. T.: The Polar Silk Road: China's New Frontier of International Cooperation. China Quarterly of International Strategic Studies, 04(03), 345–362, https://doi.org/10.1142/S2377740018500215, 2019.

Transport Canada: Arctic Ice Regime Shipping System (AIRSS) Standards (Ottawa), Transport Canada, Ottawa, https://tc.canada.ca/en/marine-transportation/arcticshipping/arctic-ice-regime-shipping-system-airss, 1998.

Yu, M., Lu, P., Li, Z. Y., Li, Z. J., Wang, Q. K., Cao, X. W., Chen, X. D..: Sea ice conditions and navigability through the Northeast Passage in the past 40 years based on remote-sensing data. Int. J. Digit. Earth, 1–20, https://doi.org/10.1080/17538947.2020.1860144, 2020.