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Variation of sea ice and perspectives of the Northwest Passage in the Arctic Ocean

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Abstract

The continued warming of the Arctic atmosphere and ocean has led to a record retreat of sea ice in the last decades. This retreat has increased the probability of the opening of the Arctic Passages in the near future. The Northwest Passage (NWP) is the most direct shipping route between the Atlantic and Pacific Oceans, producing notable economic benefits. Decadal variations of sea ice and its influencing factors from a high-resolution unstructured-grid finite-volume community ocean model were investigated along the NWP in 1988−2016, and the accessibility of the NWP was assessed under shared socioeconomic pathways (SSP245 and 585) and two vessel classes with the Arctic transportation accessibility model in 2021−2050. Sea ice thickness has decreased with increasing seawater temperature and salinity, especially within the Canadian Arctic Archipelago (CAA) in 1988−2016, which has facilitated the opening of the NWP. Complete ship navigation is projected to be possible for polar class 6 ships in August−December in 2021−2025, after when it may extends to July under SSP585 in 2026−2030, while open water ships will not be able to pass through the NWP until September in mid-21st century. The navigability of the NWP is mainly affected by the ice within the CAA. For the accessibility of the Parry Channel, the west part is worse than that of the eastern part, especially in the Viscount-Melville Sound.

Keywords: Arctic; Sea ice; Northwest passage; Canadian arctic archipelago; Strait

1. Introduction

The Arctic is known as one of the most sensitive regions to climate change, with warming rate more than double the global average surface air temperature (Cohen et al., 2020; Wu et al., 2020). The potential of Arctic shipping passages has been improved with the rapid melting of sea ice in recent decades (Khon et al., 2010; Chen et al., 2020a; Wang et al., 2020a), in which the Northwest Passage (NWP) is the shortest connection between markets in the Atlantic and Pacific regions (Zou and Yi, 2012). Borgerson (2008) pointed out that the NWP is important for world shipping because it decreases the distance up to 9000 km compared with the traditional routes via the Panama Canal, the Suez Canal, and the Horn of Africa (Liu et al., 2017).

The navigability of passages and the choice of routes are affected by many factors, such as meteorological and hydrological conditions, extreme events, facilities, water depth, draft restrictions, and local laws and regulations (Smith and Stephenson, 2013). Besides, sea ice is widely regarded as a critical factor restricting the opening of Arctic shipping routes (Liu et al., 2017). Sea ice extent and multiyear ice extent within the Canadian Arctic Archipelago (CAA) exhibited statistically significant decreases of −8.7% per decade and −6.4% per

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decade during 1979−2008, respectively, with longer melt seasons (Howell et al., 2009). The number of ships sailing through the CAA nearly tripled during 1900−2015 (Dawson et al., 2018). A plenty of evidence provided by Eguíluz et al. (2016) showed that the extent of Arctic shipping was significantly increase in 2011−2014 and that was predominantly accessed via the Northeast Passage and NWP. Liu et al. (2017) investigated the open windows of the NWP with sea ice concentration and found that Route 4, as given in the Arctic Marine Shipping Assessment 2009 Report, had the best navigable expectation in 2005−2015. Ice thickness was measured by airborne electromagnetic surveys, which indicated that ice condition must still be regarded as a critical factor for safe shipping (Haas and Howell, 2015). The accessibility of the NWP was projected with representative concentration pathways (Stephenson et al., 2013; Meng et al., 2017; Ng et al., 2018), which showed that both polar class 6 (PC6) ships and open water (OW) ships would be navigable in expanded September by the mid-21st-century. The frequency of navigable periods would double for OW ships, with routes across the central Arctic becoming available (Melia et al., 2016). The alternative sea routes from the North Atlantic to Asia will considerably increase during the 21st century, and the model predict prolongation of the season with a free passage from 2 to 4 months for the NWP by the end of the 21st century (Khon et al., 2010).

Sea ice along the Passages is influenced by the coast with boundary currents and eddies at scales of a few kilometers or less (Aksenov et al., 2017). The function of coast can be captured by the high-resolution unstructured-grid finite-volume community ocean model (FVCOM) in this investigation. In addition, further study is essential as the Coupled Model Intercomparison Project (CMIP) is updated. This study aims to provide comprehensive analysis on decadal changes in oceanographic elements and future accessibility along the NWP. The variations in sea ice thickness and influencing factors were analyzed with FVCOMin recent decades (1978−2016). The accessibility of the NWP was evaluated with the Arctic Transportation Accessibility Model (ATAM) under two vessel types (open water ships and polar class 6 ships) and two climate-forcing scenarios (SSP 245 and 585 in CMIP6) in the next 30 years (2021−2050). In addition, the navigability of crucial straits, such as M'Clure Strait (MCS), Viscount-Melville Sound (VMS), Barrow Strait, and Lancaster Strait, were evaluated at the monthly scale.

2. Methodology

2.1. Study area and data

The NWP is an umbrella term for a variety of marine routes spanning the CAA and connecting the Atlantic Ocean and the North Pacific Ocean (Howell et al., 2008) (Fig. 1). Arctic Council (2009) displayed five feasible routes of the NWP (Fig. 1), in which Route 1 and Route 2 are optimal schemes with deeper water, while the others are restricted to vessels with a draft less than 10 m due to shallow shoals and rocks (Liu et al., 2017). Route 3A is an alternative when there are lighter ice conditions (Wang et al., 2020b). The ice condition and future accessibility in these three routes, shown as red lines in Fig. 1, were investigated. Specific attention was paid to the crucial straits, MCS, VMS, Barrow Strait, and Lancaster Strait, in the Parry Channel.

Sea ice thickness, seawater temperatures and salinities at 45 sigma layers in the study period (1978−2016) were obtained from FVCOM. FVCOM is a prognostic, unstructured-grid, three-dimensional primitive equations model of Marine Ecosystem Dynamics Modeling Laboratory, University of Massachusetts−Dartmouth, which is fully coupled ice-ocean-waves-sediment-ecosystems and combines the best of finite-element methods for geometric flexibility and finite-difference methods for simple discrete structures and computational efficiency (Chen et al., 2013). It considers the influence of coast and has higher spatial resolution when approaching the edges of mainland and islands. The changes of mass and energy, especially for quantization, are different with commonly used structured-grid model, and these information is crucial for evaluating the accessibility of routes, especially within straits. The model was evaluated and shown in Chen et al. (2016). This dataset had a daily temporal resolution and a spatial resolution of up to ~8−10 km (Chen et al., 2003). Future accessibility of the NWP was investigated with monthly sea ice thickness and concentrations under SSP245 and SSP585 (representing medium and high anthropogenic radiation forcing increases, respectively) from Geophysical Fluid Dynamics Laboratory Climate Model 4, with a nominal spatial resolution of 0.25° (1440 × 1080).

2.2. Methods

Sea ice thickness and anomalies were analyzed in each decade in 1988−2016, as were the average and relative changes in seawater temperature and salinity in the 45 layers. The ATAM provided by the Arctic Ice Regime Shipping System was used to quantify the temporal and spatial accessibility of the NWP during 2021−2050, and it is a function of the structural properties of ships and ice conditions (Transport Canada, 1998).

Open water (OW) and polar class 6 (PC6) ships are vessels without ice strengthening (IMO, 2002) and with moderate ice strengthening (Stephenson et al., 2013), respectively. The calculation for ice number (IN) of the OW and PC6 ships is shown in Chen et al. (2020b). A positive IN represents a safe region for navigation. The accessibility of the NWP for OW and PC6 ships was investigated under SSP245 and SSP585. Passable state and rate in a month are number of accessible years and probability of navigation, respectively. The ice type is related to the ice age and can be approximated by SIT.

3. Results

3.1. Changes in sea ice thickness and influencing factors

Sea ice thickness is one of the physical factors that directly impacts the accessibility of the NWP and the selection of ships

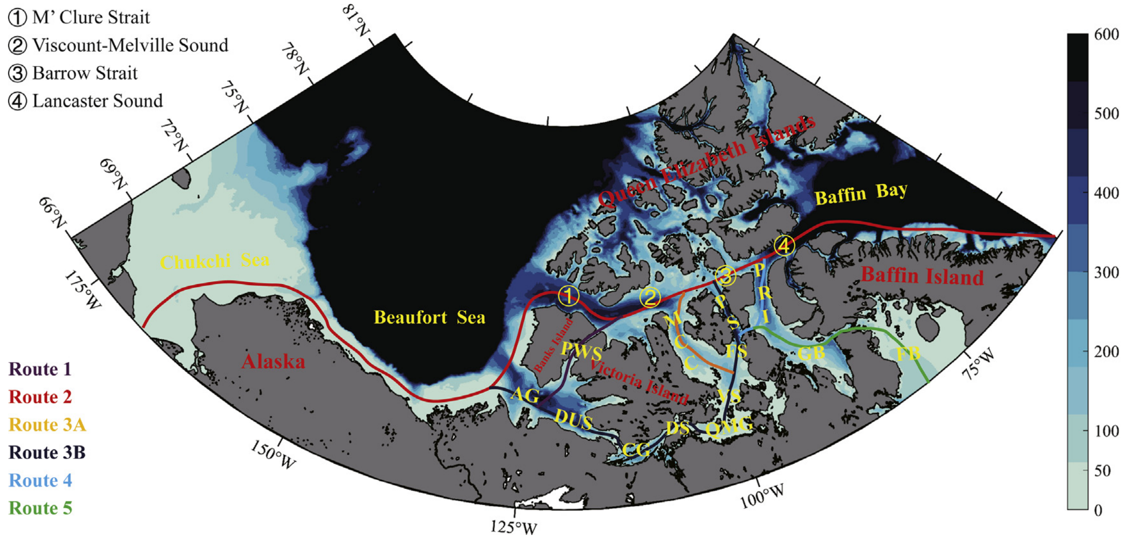

Fig. 1. Northwest Passage and surrounding water depth in the Arctic (Route 1: Amundsen Gulf (AG)−Prince of Wales Strait (PWS)−VMS−Barrow Strait (BS)−Lancaster Strait (LS); Route 2: MCS−VMS−BS−LS (Parry Channel); Route 3A: AG−Dolphin and Union Strait (DUS)−Coronation Gulf (CG)−Dease Strait (DS)−Queen Maud Gulf (QMG)−Victoria Strait (VS)−Larsen Sound−Franklin Strait (FS)−Peel Sound (PS)−BS−LS; Route 3B: AG−DUS−CG−DS−QMG−Simpson Strait−Rae Strait−James Ross Strait−FS−PS−BS−LS; Route 4: AG−DUS−DS−QMG−VS−FS−Bellot Strait (BTS)−Prince Regent Inlet (PRI)−LS; Route 5: AG−DUS−DS−QMG−VS−FS−BTS−Gulf of Boothia (GB)−Fury Hecla Strait−Foxe Basin (FB)).

in different ice classes. It changes with increasing seawater temperature and salinity feedbacks. The variations in sea ice thickness and its anomalies in September from 1988 to 2016 are shown in Fig. 2, in which sea ice thickness was mainly concentrated at 0−2 m along the NWP, and the high values displayed in the north of the Beaufort Sea and the Arctic Basin west of the CAA were positive anomalies detected in 1988−1997. Meanwhile, a decrease occurred within the CAA, indicating a negative anomaly, as well as in the north of the Beaufort Sea and west of Bank Island in 1998−2007. This condition is favorable for promoting the navigability of Route 2. The study area was dominated by negative anomalies with the large-scale recession of ice in the recent decade. Ice conditions and trends were beneficial to all of the routes mentioned in Fig. 1 for the thinning ice thicknesses under 1 m and even near 0 m in coastal areas.

The genesis and destruction of sea ice are influenced by seawater temperature and the seawater salinity feedbacks. It is harder to freeze when the freezing point of seawater decreases with increasing salinity. The variations in seawater

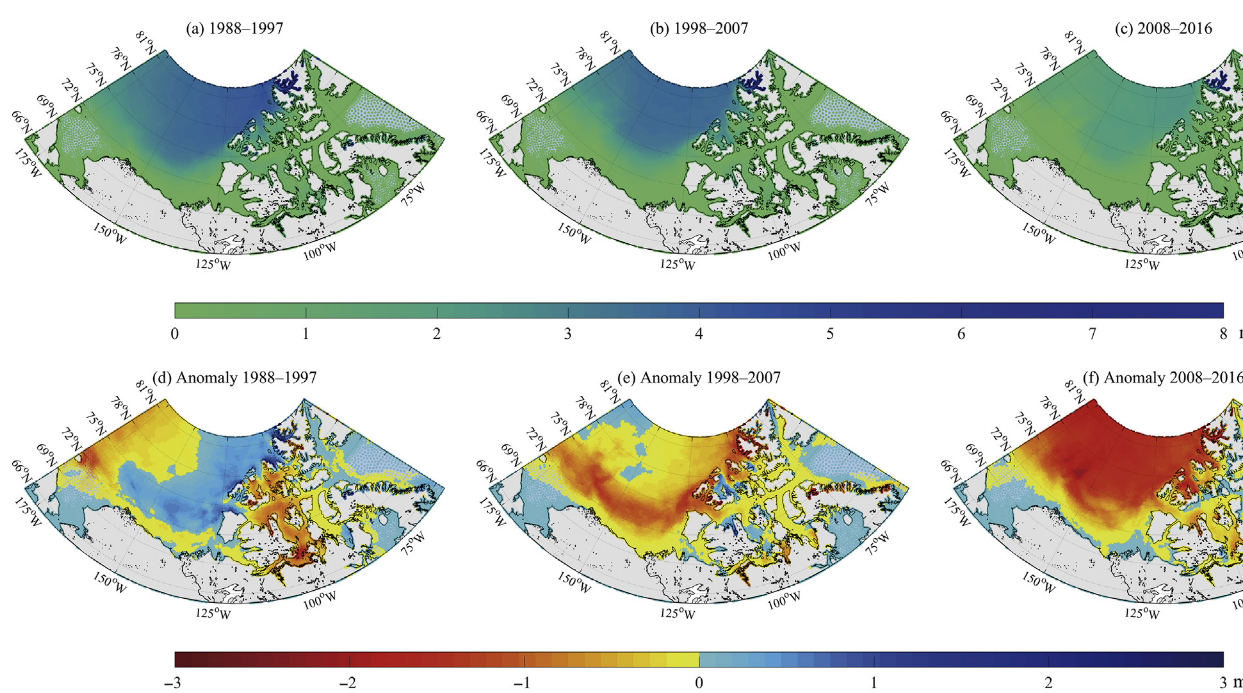

Fig. 2. Variations in sea ice thickness and its anomalies relative to that in the previous decade in September during 1988−2016.

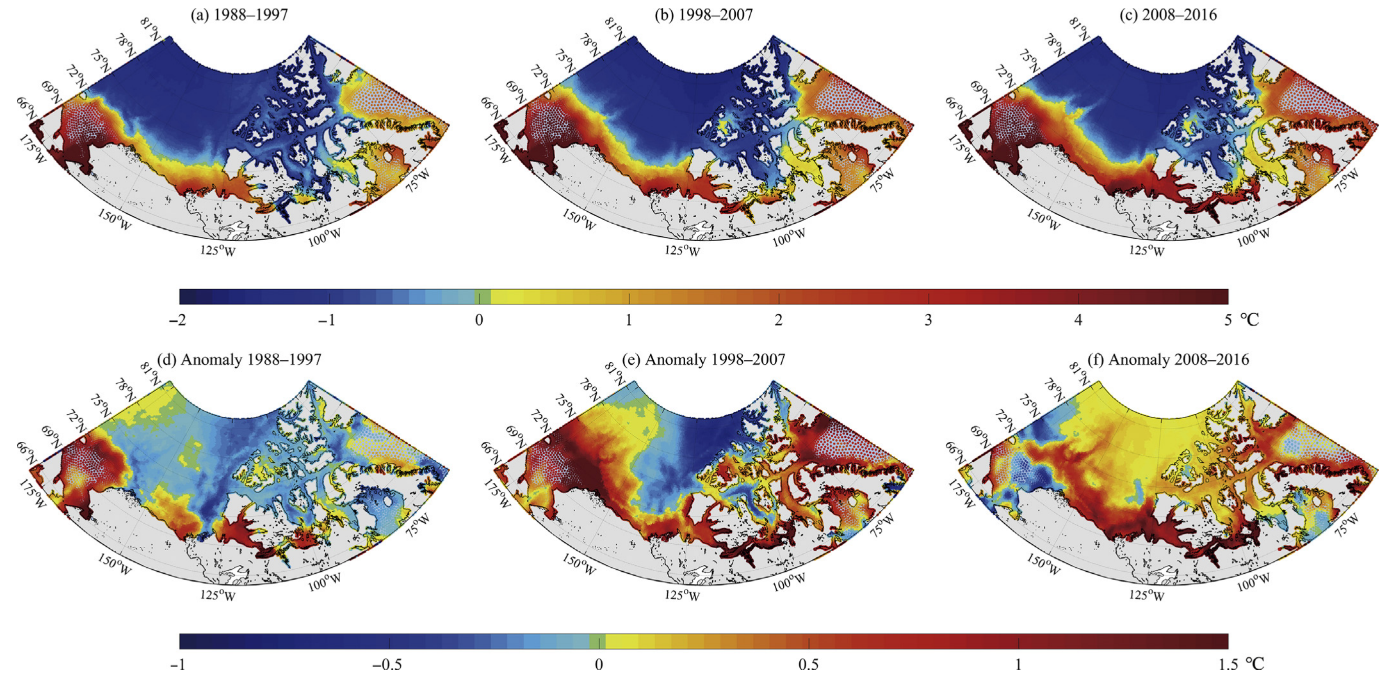

Fig. 3. Variations in the average seawater temperature and its anomalies relative to that in the previous decade in September during 1988−2016.

temperature, salinity, and anomalies in September from 1988 to 2016 are shown in Figs. 3 and 4. The average seawater temperature of 45 sigma layers ranged from −2 °C to 5 °C in the last three decades. It started to increase in the coastal water of the Chukchi Sea, Beaufort Sea, Amundsen Gulf, Dolphin and Union Strait, and Coronation Gulf in northern Alaska and Canada in 1988−1997, after which the positive intensity was significantly increased, and the extent was extended especially in the CAA, except for the VMS and MCS in 1998−2007 (Fig. 3). The southern parts of Routes 1 and 3A had sound navigation conditions for increase in temperature with the overall warming that has occurred in the recent decade. Persistent overheating was also shown in the Parry Channel in 2008−2016, and the negative temperature still controlled most parts. Seawater salinity ranged from 24‰ to 34‰, with slight changes of −2‰–2‰ during 1988−2007 (Fig. 4). It increased in the Chukchi Sea and Queen Elizabeth Island and extended to the Parry Channel and Baffin Bay in 1998−2007, after

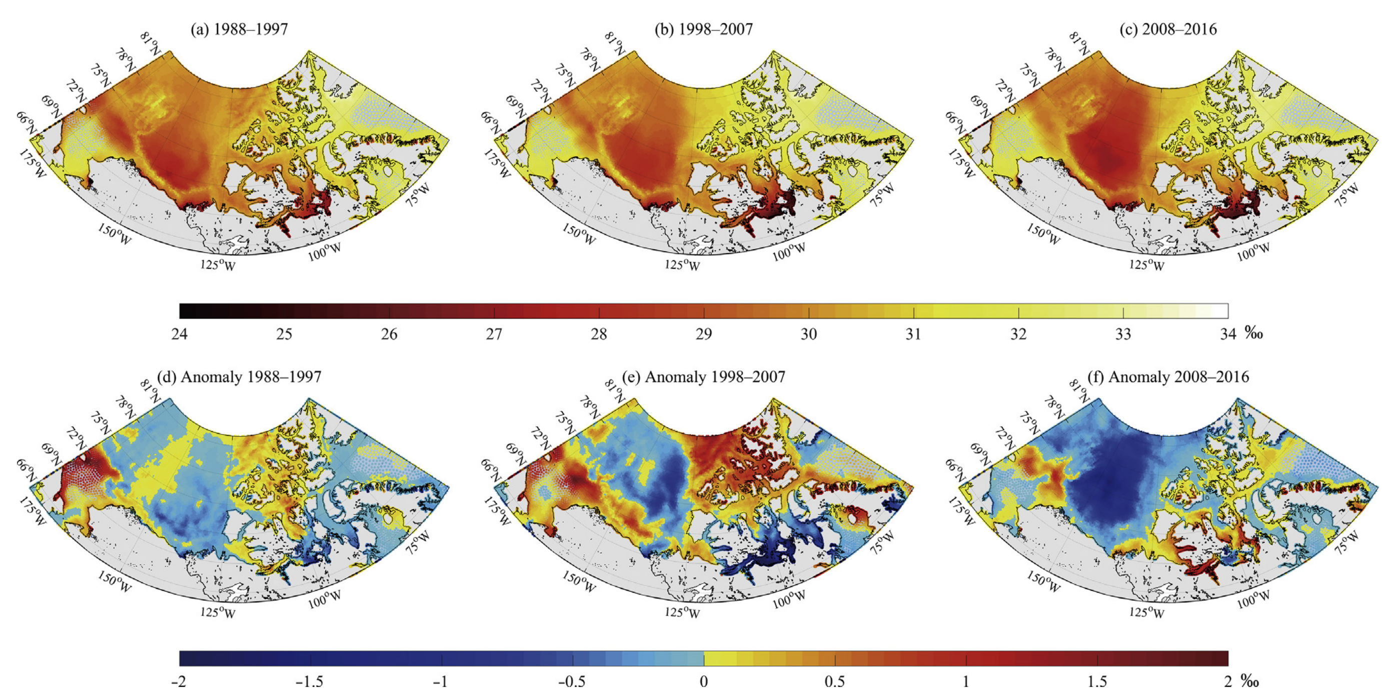

Fig. 4. Variations in average seawater salinity and its anomalies relative to that in the previous decade in September during 1988−2016.

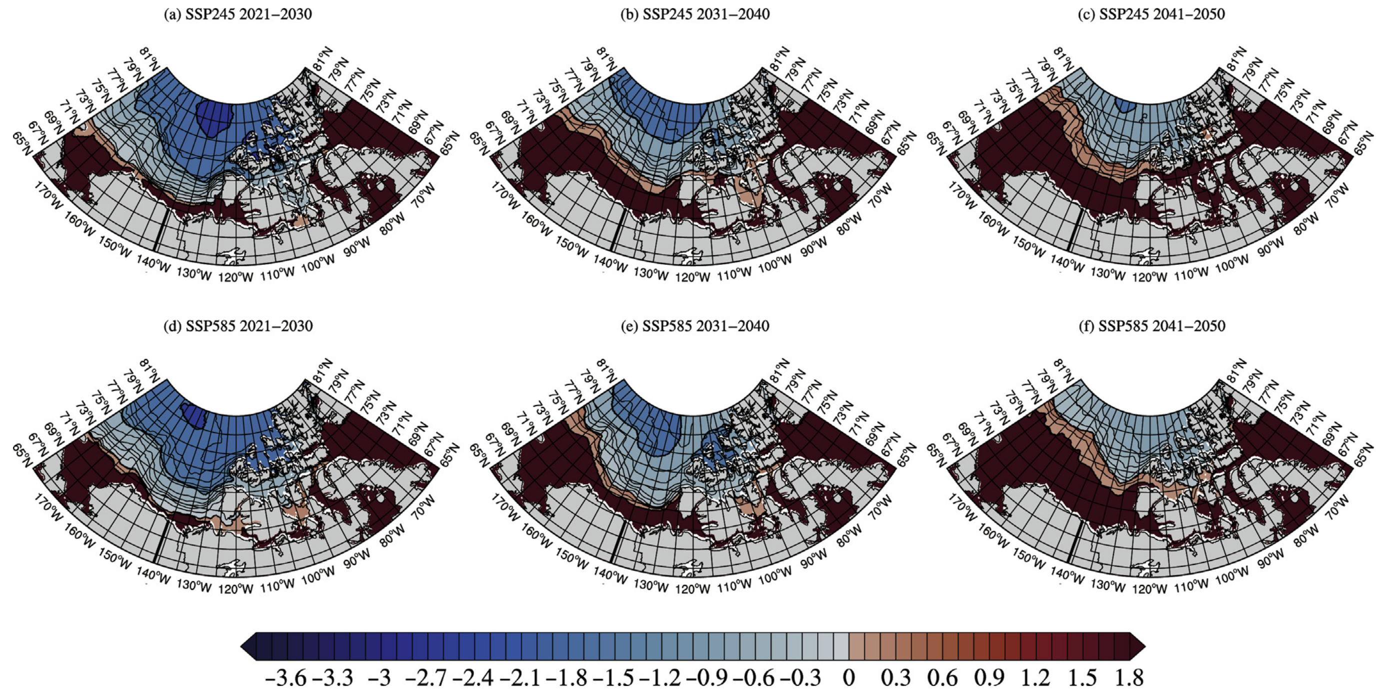

Fig. 5. Accessibility of the Northwest Passage for Open Water ships under SSP245 and SSP585 in September 2021−2050.

which the positive anomaly was mainly concentrated in the CAA, which limited the growth of ice and was helpful to the opening of routes within the CAA, especially Route 2.

3.2. Accessibility of the NWP

The navigation of Passages has been facilitated with the increase in seawater temperature and salinity, as well as sea ice shrank in extent, thickness, and concentration. However, the accessibility is still indistinct along the NWP due to the complex ice and meteorological conditions in the CAA. Accessibility was investigated for the OW and PC6 ships under SSP245 and SSP585, as shown in Figs. 5 and 6, respectively. Accessibility for OW ships maybe only occur in September during 2021−2050, in which Amundsen Gulf, Dolphin and Union Strait, and the water north of Alaska and

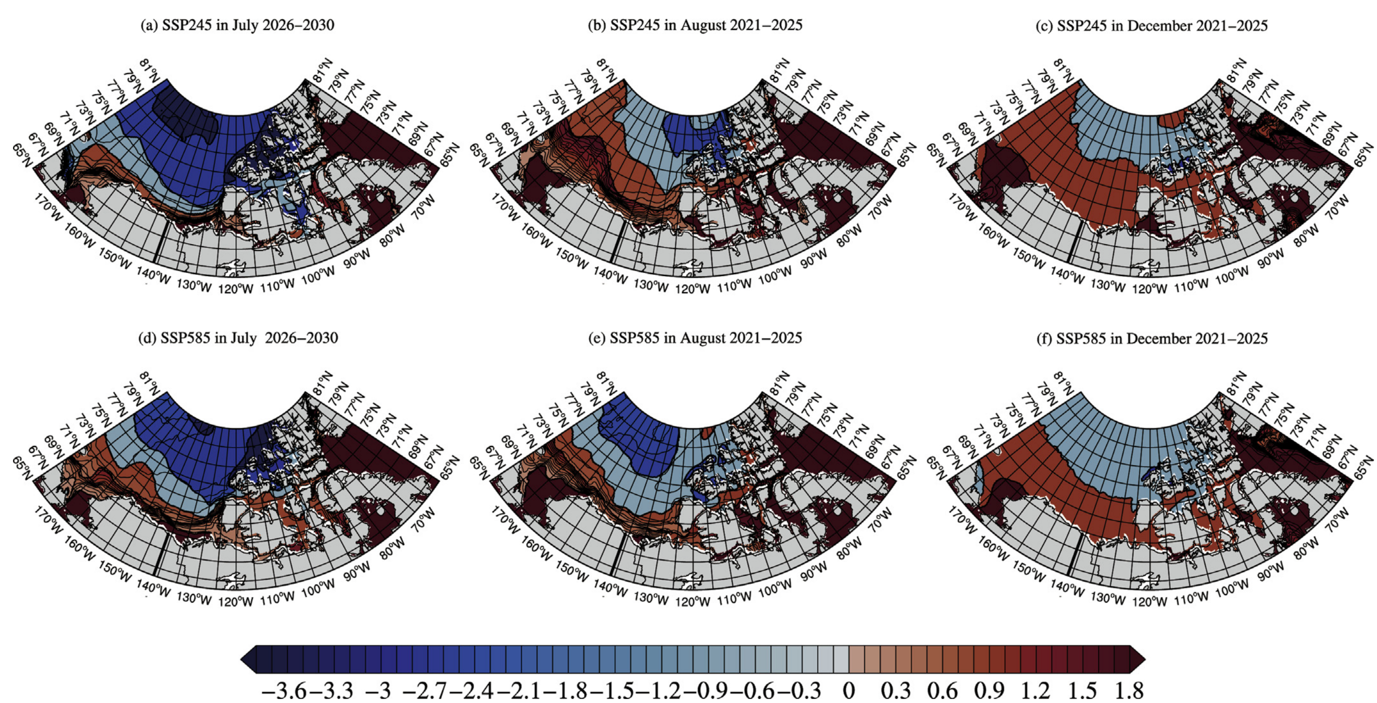

Fig. 6. Accessibility of the Northwest Passage for Open Water ships under SSP245 and SSP585.

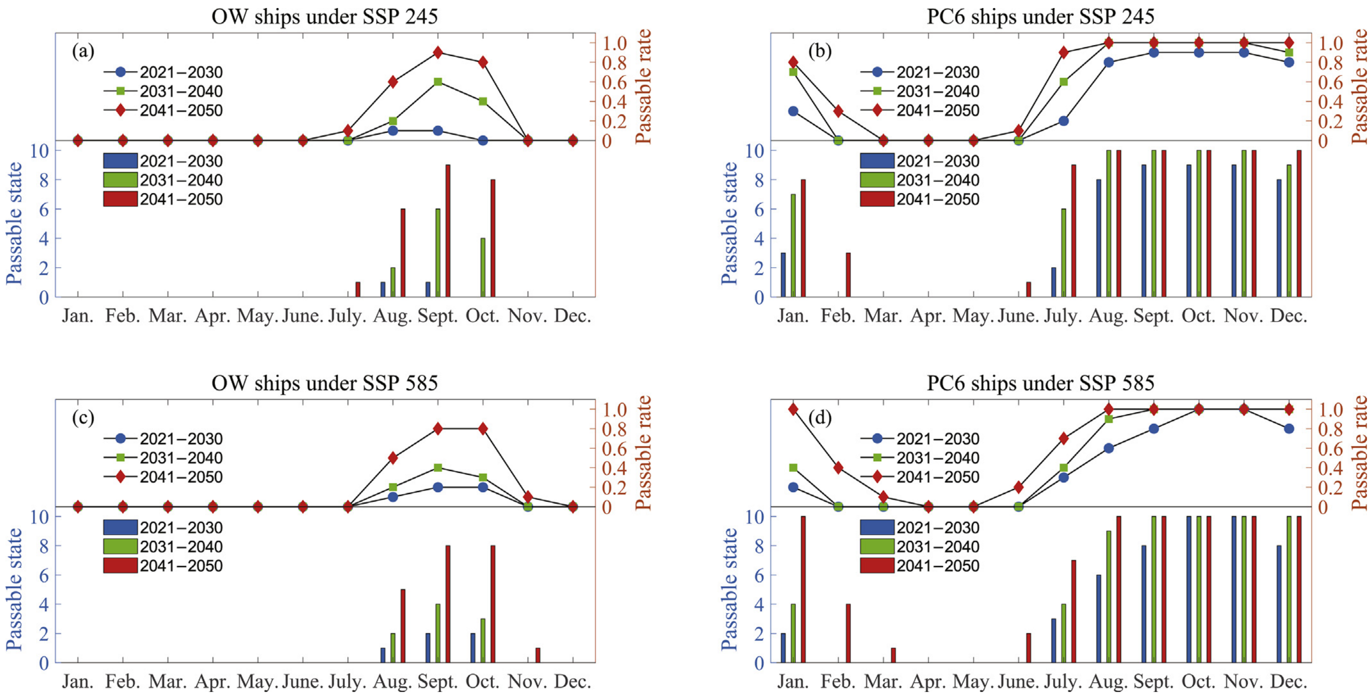

Fig. 7. Accessibility of the M′Clure Strait for OW and PC6 ships under SSP245 and SSP585 during 2021−2050.

around Baffin Island are open under both of SSP245 and SSP585 scenarios. However, accessibility is very complicated in the CAA. OW ships are incapable of passing west of the Parry Channel, which is impacted by multiyear ice flowing from the Arctic Ocean (Howell et al., 2008). It is accessible in the eastern part of the Parry Channel, in which the Lancaster Strait has a trend of being ice-free due to the North Atlantic Current and less ice in the north of the Barrow Strait due to the surface current from east to west (Prinsenberg and Hamilton, 2005). The accessibility improves in 2031−2040 when most of the straits are navigable under SSP245 in the CAA. The navigation of the NWP is controlled by the water between the VMS and Barrow Strait, which will be discussed in the next section. The NWP is thoroughly open to OW ships with a high

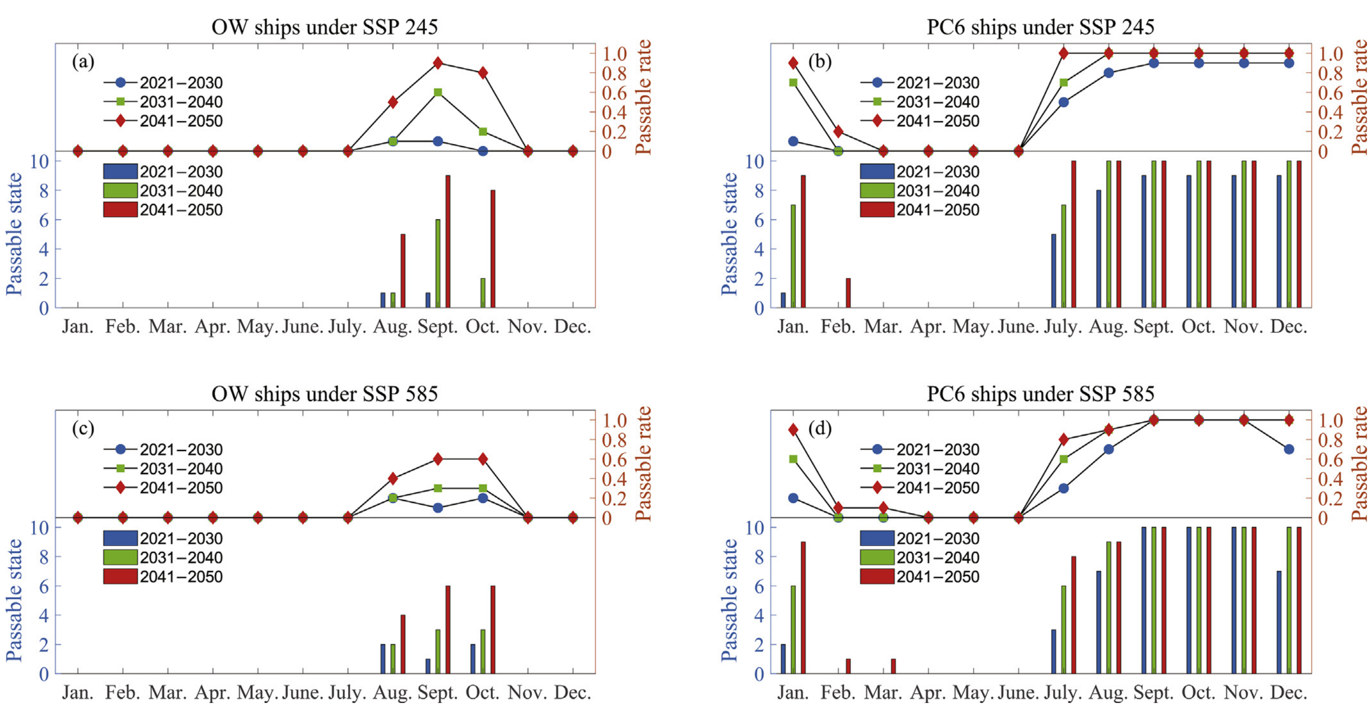

Fig. 8. Accessibility of the Viscount-Melville Sound for OW and PC6 ships under SSP245 and SSP585 during 2021−2050.

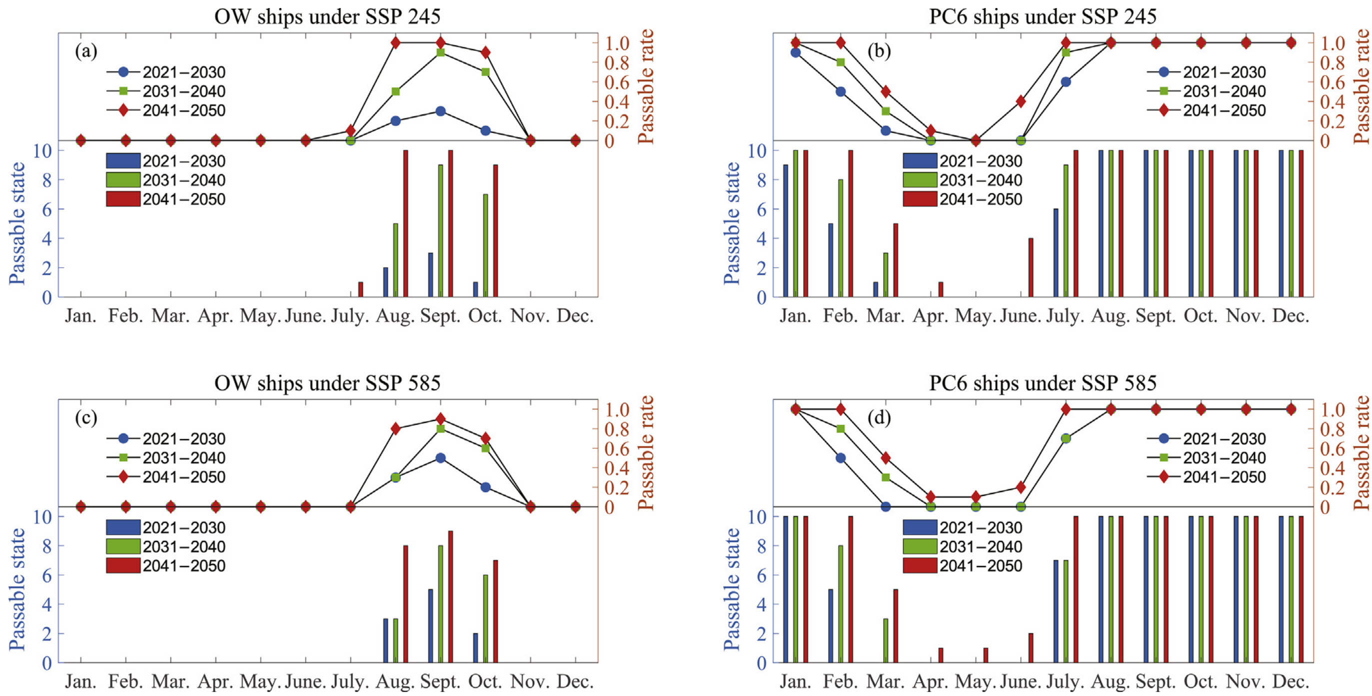

Fig. 9. Accessibility of the Barrow Strait and Lancaster Strait for OW and PC6 ships under SSP245 and SSP585 during 2021–2050.

IN under both SSP245 and SSP585 in the mid-century. Compared with OW ships, PC6 ships have a longer open window and a more robust ability to break the ice. Under SSP245, the NWP is accessible for PC6 ships during August–December during 2021–2025, while close attention still should be paid to the west part of the Parry Channel and the water between the VMS and Barrow Strait. The open window may extend to July under SSP585 in 2026–2030.

3.3. Accessibility of the Parry Channel

The Parry Channel is an ideal choice, with wide and straight waters, for the NWP, but the ice condition inside is complex and impacted by the multiyear ice that invades from the Arctic Ocean (Tivy et al., 2011; Howell et al., 2013). As shown in Fig. 7–9, the potential of the M'Clure Strait, Viscount-Melville Sound, Barrow Strait, and Lancaster Strait in the Parry Channel were assessed for OW and PC6 ships under both climate-forcing scenarios. The accessibility of the Parry Channel is very poor in the western part, which is unnavigable for OW ships in the next ten years, regardless of SSP245 and SSP585. Under the SSP245, only September may offer accessibility during 2031–2040, and the real opening of the MCS occurs in September and October during 2041–2050, with high passable rates equal to or greater than 0.8. PC6 ships have a longer open window. They are capable of crossing the MCS in September–December during 2021–2050, and the window may extend to August and January during 2041–2050. The accessibility has also improved in February, March, June, and July. The Viscount-Melville Sound navigability is worse than that of the MCS for OW ships, especially during 2031–2050, when the passable rates are lower in most corresponding months, such as August and October under SSP245 in 2031–2040 and from August to November under SSP585 during 2041–2050. One possible reason is the multiyear ice flowing through the Byam Martin Channel (Howell et al., 2013). However, the influence is slight for PC6 ships. They are capable of crossing the VMS from August to December under SSP245 in 2021–2030. The passable rates are still high in August and December under SSP585. The open window may extend to July and January during 2031–2040, and the passable rates increase and exceed 0.8 during 2041–2050.

The Barrow Strait and Lancaster Strait belong to the eastern part of the Parry Channel, and these waterways are included in most routes of the NWP. The ice condition is better than that of the western part of the Parry Channel due to the warm current from the North Atlantic Ocean, but research has shown that the sea ice is still heavy on the south side of the Barrow Strait and Lancaster Strait (Prinsenberg and Hamilton, 2005). In general, the accessibility of the east Parry Channel is superior to that of the western part for both OW and PC6 ships under SSP245 and SSP585, as shown in Fig. 9. However, OW ships are still incapable of passing these two straits in 2021–2030, and the passable rates are less than 0.5. The accessibility improves in 2031–2040, especially in September and October, and full navigability will appear in September. The open window may extend to August–October in 2041–2050. For PC6 ships, the possible opening of the east Parry Channel would initially be from August to January in 2021–2030, and the window may extend to July–February after 2031.

4. Conclusions and discussion

In this study, past changes in sea ice and its influencing factors along the NWP were analyzed, and the future accessibility of the NWP and Parry Channel was investigated under SSP245 and SSP585. The following results were found.

(1) Sea ice thickness decreased along the NWP, especially within the CAA. The entire recession occurred, with thin ice thickness near 0 m in the coastal areas.
(2) The average seawater temperature and salinity both increased in 1988−2016 and limited the growth of sea ice.
(3) The ice condition within the CAA mainly controls the accessibility of the NWP. OW ships cannot pass the NWP until September in the mid-21st century, while PC6 ships would be capable of passing through the NWP during August−December in 2021−2025.
(4) The ice condition is worse in the VMS in the western part of the Parry Channel. It is unnavigable for OW ships until September and October during 2041−2050. The passable rates for PC6 ships are high in August−December after 2021, and the open window may expand during 2041−2050.
(5) The eastern part of the Parry Channel is accessible to OW ships during September 2031−2040, and accessibility extends to August−October in the mid-21st-century. The navigable period for PC6 ships would be August−January during 2021−2030, and the window may extend to July−February after 2031.

As a potential shipping lane connecting the Atlantic and Pacific markets, the future accessibility of the NWP was investigated. It serves as a reference for future changes in sea ice and navigability in the Arctic. However, it might be deficient to evaluate sea ice conditions and Arctic navigability by a single climate model, and the uncertainty of the model might has affected the results and their reliability in this research. It is generally assumed that more models offer ensemble result and reduce the uncertainly, but it is at the expense of spatial resolution. In fact, more models may also bring errors to the result if some models are far from the truth. For the research of the NWP, especially the accessibility within straits, higher spatial resolution is preference. GFDL4 has highest spatial resolution SSP data, and this dataset has been used in the study of the Northeast Passage.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgments

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