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From melting ice to green shipping: navigating emission reduction challenges in Arctic shipping in the context of climate change

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The effects of global climate change have accelerated the melting of glaciers and the decline of sea ice coverage in the Arctic. In tandem with advancements in icebreaker and other shipping technologies, the navigability of Arctic shipping routes has dramatically improved. Given the geographical advantages of the Arctic region in terms of shipping routes and resource potential, various countries have implemented initiatives to secure a foothold in the Arctic shipping industry. However, the current shipping industry has not yet achieved the ideal state of net-zero emissions, and the rapid increase in Arctic shipping has brought serious and even irreversible negative impacts on the Arctic environment. The study employs document and policy analyses to conduct an in-depth examination of legal and policy documents related to Arctic shipping, especially those from the past 5 years, systematically outlining the relevant legal and policy frameworks, as well as their historical context. At the same time, interdisciplinary research methods are utilized to comprehensively assess the new challenges. It is concluded that against the backdrop of the Arctic region's unique and fragile environment, the International Maritime Organization (IMO) and the Arctic Council are introducing increasingly stringent regulations for Arctic shipping, posing a complex array of challenges for the industry. Not only must it navigate the mounting pressure of emission reduction policies and intensifying public scrutiny but it must also overcome a multitude of complex technical and operational hurdles. Consequently, the joint efforts of the international community are essential to promote the sustainable development and emission reduction goals of the Arctic shipping industry.

KEYWORDS

climate change, Arctic shipping, greenhouse gas reduction, black carbon, decarbonization of shipping

1 Introduction and methodology

Global climate change and the accelerated melting of polar ice have already rendered the Arctic a seasonally navigable maritime region. Propelled by the converging forces of climate change, technological innovation, and steadily enhancing safety measures, the Arctic is poised to support routine and large-scale navigation in the future (Li, 2023). Compared to traditional routes via the Suez Canal and Panama Canal, maritime transport across the Arctic Ocean can substantially reduce sailing distances between Asia and Europe, as well as between Asia and North America, resulting in lower shipping costs (Liu and Kronbak, 2009; Faury et al., 2020). Research estimates that by 2030, the share of world trade that is re-routed through the Northern Sea Route to capitalize on the shorter distances will be about 4.7% (Bekkers et al., 2018). Moreover, Russia is actively developing year-round navigation along the Northern Sea Route, seeking to engage target countries in joint endeavors. The Arctic's strategic location and abundant mineral resources have also contributed to a rapid surge in shipping volumes in recent years.

This study employed three key words, namely, "Arctic shipping," "the Northern Sea Route," and "the Northwest Passage," to search for relevant information on China's largest polar and ocean-themed website, "The Polar and Ocean Portal," as well as official websites of related international organizations and countries. The study aims to provide an overview of the current status and future development of Arctic shipping, indicating that shipping volumes through both the Northern Sea Route and the Northwest Passage are expected to exhibit a growing trend in the future. Nevertheless, the shipping industry still lags behind in achieving net-zero emissions, and the surge in shipping activities has exacerbated the harm inflicted on the Arctic's fragile and complex ecosystem. This study employs document analysis to conduct an in-depth examination of legal and policy documents related to Arctic shipping, particularly those from the past 5 years. It systematically outlines the relevant legal and policy frameworks and their historical context, including amendments to Annex I of the International Convention for the Prevention of Pollution from Ships (MARPOL) and the Initial IMO Strategy on the Reduction of GHG Emissions from Ships (Initial Strategy). Additionally, it examines the Enhanced Black Carbon and Methane Emissions Reductions: An Arctic Council Framework for Action of the Arctic Council; the set of recommendations aimed at protecting the Arctic environment and promoting sustainable development of the Clean Arctic Alliance. The study also utilizes policy analysis to examine typical policies of countries with the significant presence in the Arctic, including Canada's Qanittaq Clean Arctic Shipping Initiative, Russia's Northern Sea Route development plan until 2035, and Norway's IMO-Norway GreenVoyage 2050 project. Furthermore, it looks at examples of support for Arctic shipping industry development from non-Arctic countries, such as China and South Korea. Simultaneously, interdisciplinary research methods are employed to comprehensively assess the interactive effects between Arctic shipping and climate change. This includes the feedback loop of increased maritime activity and accelerated warming, as well as the negative impacts of climate change on Arctic shipping.

It is concluded that the mounting pressure of intensifying public scrutiny on emission reduction is driving the enforcement of increasingly stringent emission standards for Arctic shipping, which, in turn, poses new challenges for the development and improvement of existing emission reduction technologies. In response to mounting international pressure to mitigate Arctic shipping emissions and acknowledging the limitations imposed by technological challenges and other objective factors, the study seeks to propose comprehensive strategies that leverage governance frameworks, technological innovations, and green financing solutions to effectively address these pressing issues.

Based on the above analysis, the theoretical framework and methodology flowchart of this paper are shown in Figure 1.

2 Current status and development trends in Arctic shipping

Arctic sea routes refer to the maritime passages through the Arctic Ocean that connect the Atlantic and Pacific oceans. These primarily include the Northern Sea Route and the Northwest Passage (Arctic Council, 2009). Due to global warming, September sea ice extent declined by 43% from 1971 to 2019, and sea ice thickness has decreased by 2 m toward the end of the melt season from the submarine period (1958–1976) to the CryoSat-2 period (2011–2018) (Kwok, 2018). The melting of sea ice has greatly expanded the navigable waters and lengthened the shipping seasons of Arctic routes, particularly the Northern Sea Route, which is on track to become the world's first ice-free Arctic shipping lane.

2.1 The Northern Sea Route

The Northern Sea Route extends from the Kara Strait to Providence Bay, with a total length of approximately 5,600 km. Most of its course lies in the offshore waters of the Arctic Ocean along Russia's northern coast. The Northern Sea Route connects Asia and Europe with an up to 40% reduction in sailing distance compared to the traditional Asia–Europe Suez Canal Route (Furuichi and Otsuka, 2013). The development of the Northern Sea Route is a pivotal element of Russia's Arctic strategy, offering substantial economic opportunities for the country.

Russia has been consistently bolstering cargo transportation along the Northern Sea Route, with the ambitious goal of transforming it into a primary trade artery connecting Europe and Asia. According to the press service of Rosatom Corporation, Russia's State Atomic Energy Corporation, the total transportation volume on the Northern Sea Route reached 36.254 million tons in 2023, surpassing its initial target by over 250 thousand tons (Arctic Today, 2023). Vladimir Panov, a Special Representative for Arctic Development at Rosatom Corporation, announced that, according to agreements signed with all major shippers to date, the projected transportation volume is set to reach 193 million tons by 2030 and 270 million tons by 2035 (High North News, 2023a). To further tap the economic potential of the Northern Sea Route, the Russian government announced plans at the Far Eastern Urban Development Conference on 11 September 2023, to establish a dedicated maritime transport corridor. The proposed corridor aims to facilitate cargo transportation between the seaports of the Northwestern and Far Eastern Federal Districts and accommodate transit shipments along the Northern Sea Route.

Meanwhile, Russia is actively seeking dependable partners to co-develop the Northern Sea Route, with the goal of bolstering its international influence and strategic significance. A recent report by the Center for High North Logistics in Norway reveals a sharp decline in international transit traffic along the Northern Sea Route, with Russian-flagged vessels now accounting for nearly 90% of all ships using the route. In a bid to reverse this trend, Russia is taking a two-pronged approach to increase the accessibility of the Northern

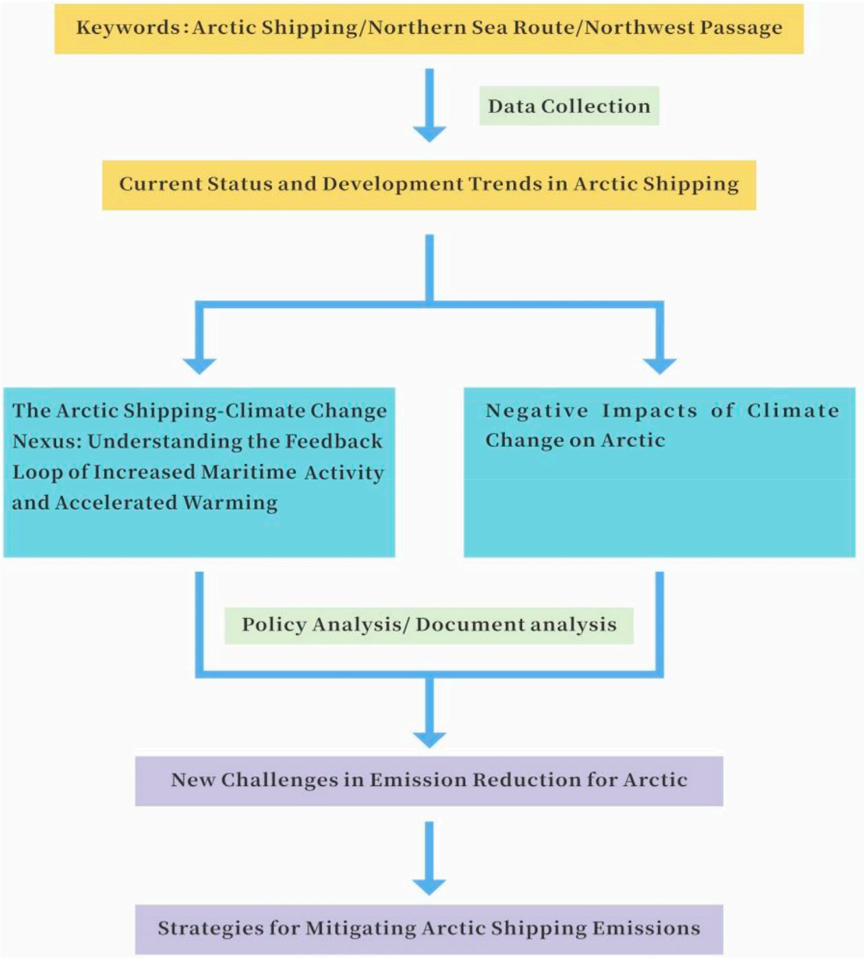

FIGURE 1
Theoretical framework and methodology flowchart.

Sea Route. On one hand, it has announced plans to open the port of Tiksi, located on the Northern Sea Route in the Laptev Sea, to foreign vessels, with the aim of transforming it into a major international transshipment hub. Moreover, a Kremlin aide has urged the Russian government to enact legislation permitting foreign-flagged vessels to navigate the Northern Sea Route, with the ambitious goal of turning it into a new Suez Canal equivalent (Arctic Business journal, 2023). On the other hand, Russia is proactively pursuing opportunities to expand Arctic route cooperation with key partners, including China and India. During a 2023 visit to India, a deputy minister from the Russian Ministry for the Development of the Far East and Arctic highlighted the importance of Russia–India cooperation in the Far East and Arctic regions, emphasizing India's role as a vital strategic partner. Furthermore, he noted that Russia is launching satellites to ensure safe navigation along the Northern Sea Route, with projections indicating that the route will handle 220 million tons of cargo by 2035. The Russian government and economic sectors are committed to transforming this critical artery into a truly global transport corridor (AK&M, 2024). With regard to China, it is a major importer of Russian oil and gas resources and one of the key nations leveraging the Northern Sea Route. In 2022, Russia overtook Saudi Arabia as China's largest oil supplier. China's total oil imports from Russia reached 58 billion USD in 2022, a figure that is likely to grow in subsequent years. Furthermore, China purchased 8 billion USD worth of liquefied natural gas (LNG) from Russia, predominantly from Novatek's Yamal LNG plant in the Arctic (High North News, 2023b). During his attendance at the opening ceremony of the Belt and Road Forum in China, Russian President Putin extended an invitation to interested countries to collaborate on the development of the Northern Sea Route. In response to a question about China's interest in collaborating with Russia on the development of the Northern Sea Route, Chinese Foreign Ministry spokesperson stated that China is willing to cooperate with Russia in various fields, including the Arctic, on the basis of mutual respect, equality, and reciprocal benefit (The Arctic, 2023).

The Northern Sea Route, connecting the Eurasian continent via the shortest maritime route, offers significant reductions in transportation costs for shipping nations while bolstering Russia's status and influence in the Arctic. In the wake of the Ukrainian crisis, the United States, Europe, and other Western countries have intensified sanctions against Russia. Against this backdrop, Russia's foreign economic and trade activities have undergone a notable shift, with the Arctic shipping routes playing an increasingly vital role. As Russia actively develops the Northern Sea Route, it is poised to experience unprecedented growth and internationalization, with far-reaching implications for global transportation and trade patterns.

2.2 The Northwest Passage

The Northwest Passage denotes the maritime route that spans from the Pacific Ocean, through the Bering Strait, and into the Arctic Ocean, navigating along the northern coast of Alaska, through the Canadian Arctic Archipelago, past Greenland, and ultimately into the North Atlantic Ocean. Despite its potential, the development of the Northwest Passage as a viable shipping route has lagged significantly behind that of the Northern Sea Route, mainly due to geographical constraints and unpredictable ice patterns. Notably, the Northwest Passage, as the shortest route bridging the Atlantic and Pacific Oceans, affords a substantial reduction in approximately 20% in voyage length compared to the conventional route linking Northeast Asia and the North American East Coast via the Panama Canal. In recent years, as Arctic temperatures have risen and sea ice has declined, the navigable period for the Northwest Passage has been steadily lengthening. As a result, the Northwest Passage continues to hold considerable allure for cargo vessels and container shipping, offering a potentially game-changing alternative to traditional routes. Furthermore, the Northwest Passage, renowned for its treacherous conditions and breathtaking landscapes, has long been a magnet for adventurers and tourists. Following the pioneering voyage of Crystal Serenity in 2016, several companies have launched similar high-end cruise routes, capitalizing on the passage's allure. Although the COVID-19 pandemic forced a 2-year hiatus in cruise and tour boat operations in the Northwest Passage, activity has gradually resumed. According to 2023 itineraries, over 15 cruise lines have introduced Northwest Passage voyages, featuring an array of high-end vessels, including Ponant's Le Commandant Charcot, Quark Expeditions' Ultramarine, Aurora Expeditions' Sylvia Earle, and Lindblad's National Geographic Resolution.

Technological strides have revolutionized polar equipment, yielding cutting-edge icebreakers (Zhang et al., 2017) and sophisticated Arctic maritime safety assurance systems that are transforming the navigational landscape and increasing the allure of the Northwest Passage. Currently, Canada is intensifying its investment in the design and construction of state-of-the-art icebreakers, with the Parliamentary Budget Officer estimating that the government's plan to build two new heavy icebreakers could come with a price tag of up to USD 7.25 billion. Furthermore, a project supporting sustainable Arctic shipping has received a substantial research grant of 91 million USD from the Canadian government in 2023. The project goals include the following:

- Build a knowledge base to address Inuit shipping priorities, promote the safety of ships operating in the Arctic, and protect Arctic environments.
- Create the tools and solutions needed for responsible ship design and improve the affordability, sustainability, and efficiency of the Arctic fleet.
- Deliver evidence to effect national and international policy changes for ships operating in the Arctic.
- Enhance the quality of life for Inuit and reduce regional food insecurity (Nunatsiaq News, 2024).

Although the Northwest Passage still lags behind the Northern Sea Route in terms of trans-Arctic transportation capabilities (Cook et al., 2024; Howell et al., 2023), its navigability is significantly increasing due to the impacts of climate change (Wang et al., 2023; Wang et al., 2022). The Northwest Passage is now presenting itself as a viable and attractive option for international shipping, offering a shorter and more economical route than traditional alternatives. For North American countries, this emerging trade route provides a critical alternative for mitigating risk and ensuring timely cargo delivery to destinations (Lin and Wu, 2024; Dong and Hu, 2021).

3 The interactive effects between Arctic shipping and climate change

As the effects of global climate change intensify, the Arctic region is becoming increasingly navigable, offering international shipping companies a highly competitive alternative to traditional routes. The economic advantages of Arctic shipping, including reduced canal fees and lower fuel costs, are significant. However, the growing presence of shipping vessels in the Arctic is also taking a toll on the region's fragile ecosystem, highlighting the urgent need for sustainable and environmentally responsible shipping practices. Arctic shipping heavily relies on fossil fuels, more specifically, on heavy fuel oil, the combustion of which is highly polluting and thereby results in high emissions of sulfur oxides, heavy metals, volatile organic compounds, and black carbon particles (Zhang et al., 2019), all of which accelerate Arctic climate warming. Consequently, the question of whether the thawing Arctic routes represent a boon or a bane for humanity has sparked extensive debate (Maheshwar, 2022).

3.1 The Arctic shipping–climate change nexus: understanding the feedback loop of increased maritime activity and accelerated warming

The escalating levels of greenhouse gas emissions, primarily carbon dioxide, have been unequivocally identified as a major driver of global climate change (UN, 2024). The Intergovernmental Panel on Climate Change (IPCC) has conducted comprehensive research on the far-reaching consequences of greenhouse gas emissions on the atmosphere and global warming. From 1984 to 2021, the concentration of carbon dioxide in the Arctic atmosphere exhibited a steady and consistent upward trend, with the annual average concentration being slightly higher than the global average (Figure 2). According to the IPCC's projections, the planet is likely to experience a 1.8°C–4°C increase in global temperatures by 2100, which could lead to a 22%–33% decline in Arctic sea ice coverage (IPCC, 2022). This dramatic warming trend is expected to have multifaceted impacts on the planet, underscoring the urgent need for mitigative measures to curb emissions and mitigate the effects of climate change.

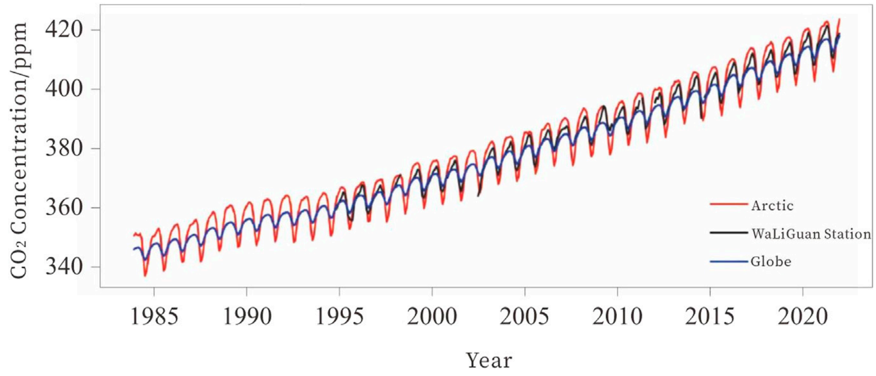

FIGURE 2
Changes in Arctic and global CO_2 concentrations from 1984 to 2021. Source from the Annual Report of Polar Climate Change (2022) (Ding, 2023).

International shipping accounts for 80%–90% of global trade volume, serving as the primary mode of international trade and a crucial link in global economic connectivity (Mao et al., 2024). However, the increasing shipping activities are having negative impacts on the global climate. According to IMO statistics, the greenhouse gas emissions of total shipping (international, domestic, and fishing) have increased from 977 million tons in 2012 to 1,076 million tons in 2018 (9.6% increase). In 2012, 962 million tons were CO_2 emissions, while in 2018, this amount grew 9.3% to 1,056 million tons of CO_2 emissions. The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018 (IMO, 2020). The near-surface annual average temperature in the Arctic has exhibited a striking upward trend between 1979 and 2022, with a pronounced warming rate of 0.67°C per decade. Notably, this rate is 3.7 times higher than the global average, underscoring the Arctic's exceptional vulnerability to the impacts of global warming (China Meteorological Administration, 2023). The increase in Arctic shipping activities is expected to significantly intensify climate warming in the Arctic region. Results indicate that under the BAU scenario, the overall shipping CO_2 emission on the Northern Sea Route by 2050 will be over 5.5 million tons, which is 1.76 times of the emission level in 2020. This might form a reinforcement feedback that a continuous melting Arctic would attract more ships with a better navigability that might generate more shipping-caused GHG emissions. This reinforcement feedback system would harm the Arctic regional ecosystem severely (Jing et al., 2021).

Furthermore, the extreme cold weather conditions in the Arctic region exacerbate the incomplete combustion of fuel, particularly heavy fuel oil, during ship navigation, leading to the deposition of black carbon particles on ice and snow. As the second most significant contributor to global warming after CO_2, black carbon plays a crucial role in accelerating climate change. When black carbon particles settle on snow and ice, they trigger a cascade of effects, including the acceleration of melting on illuminated surfaces and a reduction in albedo. This, in turn, leads to the increased absorption of solar radiation, causing heat to penetrate deeper into the ocean and soil and ultimately amplifying the warming trend in the Arctic region (Liu, 2022). According to research conducted by the International Council on Clean Transportation (ICCT), 1% of black carbon is emitted at 60°N latitude and above. Although black carbon emitted at all latitudes has a climate warming effect, black carbon emitted in the Arctic has a nearly five times greater Arctic surface warming effect than black carbon emitted in mid latitudes. However, 11% of black carbon is emitted from ships in the Arctic Front (40°N latitude and above), an area where black carbon emissions may have a direct impact on the Arctic through atmospheric transport (International Council on Clean Transportation, 2017). Currently, the shipping industry generates approximately 42 million tons of carbon dioxide and 4 million tons of black carbon annually. The effects of the comparatively small amount of black carbon can add considerably to those of carbon dioxide from ships in the Arctic region. One ton of black carbon emitted in the Arctic region produces a warming effect equivalent to 4,000–7,000 tons of carbon dioxide over a short-term period of approximately 20 years (Maheshwar, 2022).

Although Arctic shipping routes offer the benefit of shorter distances compared to traditional routes, the growing number of vessels navigating these routes is having a profound impact on the Arctic climate. The region's unique environmental vulnerability and the potent snow albedo effect of black carbon emissions from shipping activities are likely to offset the global climate change benefits gained from reduced emissions resulting from shorter voyages.

3.2 Negative impacts of climate change on Arctic shipping

The melting of Arctic sea ice has opened up new trans-Arctic shipping routes by expanding areas of navigable water. Nevertheless, climate warming does not uniformly benefit Arctic shipping in terms of navigability and safety as the region's climate conditions remain extreme and unpredictable. In fact, as open water areas in the Arctic continue to increase, the impact of adverse meteorological factors such as strong winds, high waves, and sea fog on vessel navigation is intensifying.

First, climate warming is expected to increase the instability of Arctic meteorological conditions, thereby posing significant challenges for sea state monitoring, a critical factor in ensuring safe shipping operations. Climate warming may alter the energy

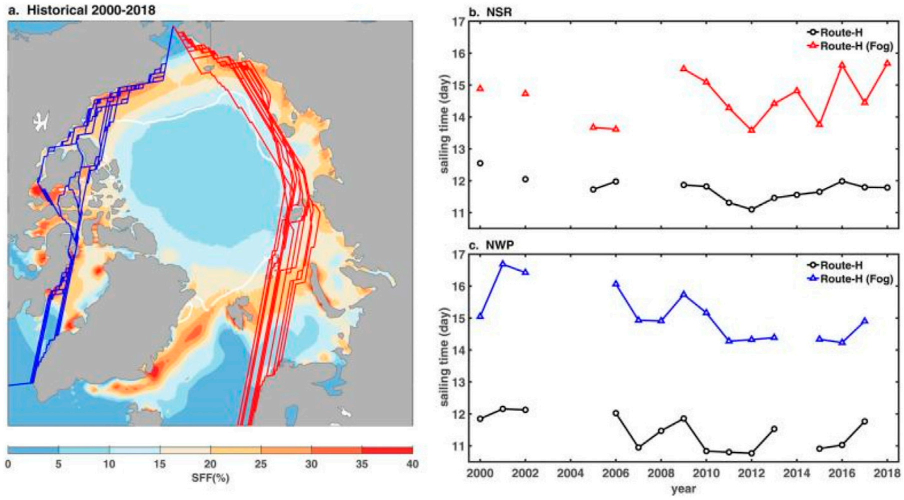

FIGURE 3
Navigation routes for hypothetical ships to cross the Arctic Ocean along the Northern Sea Route (NSR) and NorthWest Passage (NWP) during 2000–2018. **(A)** Red and blue lines represent the Route-H of NSR and NWP every year, respectively. The white line indicates the isopleth of 45% sea ice concentration. Simulated sea fog frequencies are shaded. **(B)** and **(C)** are total sailing time along NSR and NWP, respectively. The line with circle markers indicates the Route-H only based on sea ice conditions. The line with triangle markers indicates the Route-H, considering the deceleration of sea fog. The gap means that no route is available due to the sea ice cover (Song et al., 2023).

balance and atmospheric circulation patterns in the Arctic (Liang et al., 2022), leading to a higher likelihood of sudden and unpredictable meteorological changes. This, in turn, would exacerbate the difficulties in monitoring and assessing sea conditions, thereby impacting the safety and efficiency of Arctic shipping. Second, earlier estimates of cost savings from shortened trans-Arctic routes may have been overly optimistic as they overlooked the impact of increased sea fog frequency in areas of sea ice retreat. An increase in the frequency of sea fog occurrences will result in longer overall voyage times for ships (Figure 3). The escalating sea ice melt leads to more extensive and prolonged advection fog, resulting in sea fog that adversely affects Arctic climate, visibility, and hydrological cycles. This phenomenon is particularly pronounced in the open waters of the East Siberian and Chukchi seas, where foggy days occur 15–20 days per month during summer. Notably, the Russian northern coast experiences an average of over 80 foggy days annually, with some sea areas exceeding 100 days, and the Severnaya Zemlya archipelago reporting over 150 foggy days per year. Research suggests that fog-induced delays can range from 1 to 4 days, and sea fog increases the shipping time by approximately 23%–27% along the Northwest Passage and 4%–11% along the Northern Sea Route than previous estimations (Song et al., 2023). Third, the rising frequency of extreme weather conditions substantially compromises the safety of Arctic shipping. For example, fog absorbs and scatters sound, light, and electromagnetic waves, thereby diminishing the visibility range and flash duration of light beacons. It also impairs the effective transmission distance of sound signals, undermining the accuracy of sound source localization based on acoustic judgments. In some water areas of the Arctic shipping routes (especially the Northwest Passage), the topography of the route is complicated, the width is narrow, and the water depth is shallow due to the interference of sea ice, and ships need to turn or adjust speed several times to prevent collision or ice trapping. In addition, navigating in the ice-covered area sometimes requires frequent rudder operation, so the crew has to analyze various hydrometeorological information in time and look for the passage between the ice, which causes a great labor intensity and pressure (Lin et al., 2023).

The relationship between Arctic shipping and climate change is intricately intertwined. As vessel capacity continues to increase and shipping activities intensify in the Arctic region, they significantly impact ocean temperatures, contributing to the rise in Arctic air temperatures. Ship emissions and the disturbance of sea ice lead to a steady decline in sea ice volume, resulting in the release of stored heat from the upper ocean layers into the atmosphere, which, in turn, accelerates atmospheric warming. Although navigating through the Arctic reduces shipping times and energy consumption, it also has deleterious effects on the Arctic marine environment, climate conditions, air quality, and biodiversity. The worsening of Arctic environmental issues ultimately hinders the further development of Arctic shipping, creating a self-perpetuating vicious cycle. Therefore, strengthening Arctic green governance and achieving emission reduction and sustainable development in Arctic shipping have become both a pressing and formidable task.

4 New challenges in emission reduction for Arctic shipping

In February 2022, the IPCC released the second part of its Sixth Assessment Report, which examines the vulnerabilities, capacities, and limitations of natural ecosystems and human societies in adapting to climate change, emphasizing the urgency of implementing rapid climate action to achieve societal development goals (IPCC, 2022a). In April, the IPCC released the third part of its Sixth Assessment Report, providing the most recent global assessment of progress and commitments toward mitigating climate change and reviewing the sources of global emissions. Specifically, Chapter Ten evaluates the transport sector, highlighting that a transformative reduction in emissions is necessary for the transport industry to achieve climate action goals (IPCC, 2022b). As climate change continues to impact the Arctic region and the exploitation of oil, gas, and mineral resources persists, Arctic shipping trade volumes are on the rise. The trend toward increased shipping activity and larger vessel tonnage has become an irreversible reality. However, growing public pressure for green governance in Arctic shipping, increasingly stringent emission reduction policies, and the prospects for emission reduction technology development all suggest that Arctic shipping will face significant challenges in reducing its emissions.

4.1 Growing international call for emission reduction in Arctic shipping

4.1.1 IMO

IMO, a specialized agency of the UN, is responsible for ensuring the safety and security of shipping and preventing marine and atmospheric pollution from vessels. In accordance with the Kyoto Protocol, which entrusted the IMO as the primary authority for reducing shipping emissions, the organization has prioritized efforts to mitigate greenhouse gas emissions from ships. To this end, the Marine Environment Protection Committee (MEPC) has been tasked with investigating measures to reduce shipping emissions, with a focus on evaluating reduction technologies and methodologies.

In June 2021, the 76th session of the MEPC adopted amendments to Annex I of the MARPOL, implementing a ban on heavy fuel oil in the Arctic. As of 1 July 2024, the use and carriage of heavy fuel oil as fuel will be prohibited, with exceptions for vessels engaged in ensuring ship safety, search and rescue operations, and oil spill response and reaction. Moreover, according to IMO's Initial Strategy, the IMO is ambitiously accelerating its original goal of eliminating shipping greenhouse gas emissions by the end of this century, now targeting a completion date of 2050. To achieve this, the IMO proposed technical candidate measures for CO_2 emission reduction in the Initial Strategy, categorizing them into short-term, medium-term, and long-term candidates. The short-term goal is to reduce the carbon intensity of international shipping by an average of 40% by 2030, compared to 2008 levels. In support of this goal, the Initial Strategy continually develops and refines efficiency measures, including the Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP), Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Indicator (CII). These efforts consistently promote the adoption and implementation of energy-efficient technologies and devices onboard ships (Liu et al., 2023). The implementation phase of the heavy fuel oil ban has commenced, and it is anticipated that this prohibition will significantly contribute to the reduction in black carbon emissions in the Arctic (Sun, 2019; Dalaklis et al., 2023). However, the ban also poses new challenges, including increased economic costs for Arctic shipping and the need for accelerated research and development of alternative fuel technologies.

4.1.2 Arctic Council

Although the IMO has a broad regulatory scope that encompasses safety, security, and environmental protection issues across the entire international shipping industry, including Arctic shipping, the Arctic Council plays a unique and crucial role in governing Arctic affairs. As the premier regional intergovernmental forum for Arctic issues, the Arctic Council has an indispensable function in promoting environmental protection and sustainable development in the Arctic region (Olav, 2013).

Since 2015, the Arctic Council has prioritized the mitigation of black carbon emissions through the adoption of the "Enhanced Black Carbon and Methane Emissions Reductions: An Arctic Council Framework for Action." In tandem, the Council established an Expert Group on Black Carbon and Methane to facilitate the implementation of the framework's commitments and provide recommendations for collective black carbon reduction targets. In 2017, informed by the Expert Group's research, the Arctic Council formulated and adopted a pan-Arctic collective goal to reduce black carbon emissions by approximately 25%–33% by 2025, relative to 2013 levels (Arctic Council, 2017). On 11 May 2023, Norway formally assumed the rotating chairmanship of the Arctic Council, with the overarching goal of promoting stability and constructive cooperation during its tenure. The Norwegian Chairship will focus on four key priority areas: the oceans, climate and environment, sustainable economic development, and the wellbeing of people in the North. Notably, Arctic shipping is highlighted as a critical issue across multiple themes within these priority areas (Arctic Council, 2023):

- The oceans: Norway will strengthen Arctic cooperation on sustainable shipping and risk reduction measures in response to the growing volume of shipping in the Arctic.
- Climate and environment: Norway will support existing initiatives to reduce the environmental footprint of Arctic shipping and explore opportunities to establish green shipping corridors in the Arctic as a pilot project.
- Sustainable economic development: The green transition, the blue economy, sustainable shipping, and Arctic food systems will be special thematic priorities for the Norwegian Chairship.

The Arctic Council plays a pivotal role in shaping Arctic marine pollution governance through its expertise in knowledge construction, agenda-setting, and framing effects. By fostering a scientific community that extends beyond mere data provision, the Council facilitates the formation of authoritative scientific consensus on shipping pollution issues (Zhang, 2020). Under Norway's chairmanship, reducing emissions and promoting sustainable development in Arctic shipping are likely to become key focal areas of the Council's Arctic environmental governance efforts.

4.1.3 Clean Arctic Alliance

The Clean Arctic Alliance (CAA) is a coalition of environmental non-profit organizations dedicated to protecting the Arctic ecosystem. The CAA advocates for a phase-out of fossil fuels to mitigate climate change in this sensitive region. It prioritizes key objectives that include ending the use and transportation of heavy fuel oil in the Arctic, eliminating black carbon emissions and reducing other pollutants from the shipping industry (Xue, 2020). In May 2023, the CAA released a set of recommendations aimed at protecting the Arctic environment and promoting sustainable development, with a special focus on measures to mitigate the impact of Arctic shipping. Through persistent advocacy and monitoring, CAA exerts significant influence on Arctic shipping and related international organizations and countries, providing authoritative research reports and actively lobbying governments to take action. By shaping public opinion and demonstrating its expertise, CAA has a profound impact on Arctic shipping in multiple areas, including the promotion of international green shipping standards, the fostering of technological innovation, and the facilitation of international cooperation.

4.1.4 Arctic and non-Arctic countries

Through the advocacy efforts of the aforementioned organizations, numerous Arctic and non-Arctic countries have acknowledged the growing environmental impact of Arctic shipping activities and have joined forces to mitigate emissions from this sector.

On 28 April 2023, the Canadian Minister of Innovation, Science and Industry announced a significant investment of 91 million USD in support of the Qanittaq Clean Arctic Shipping Initiative. This initiative seeks to address the environmental consequences of increased Arctic shipping on local communities while also meeting the Inuit communities' need for safe and cost-effective resupply. Its key objectives include the following:

- Build a knowledge base to address Inuit shipping priorities, promote the safety of ships operating in the Arctic, and protect Arctic environments;
- Create the tools and solutions needed for responsible ship design and to improve the affordability, sustainability and efficiency of the Arctic fleet;
- Deliver evidence to effect national and international policy change for ships operating in the Arctic;
- Enhance the quality of life for Inuit and reduce regional food insecurity.

During Russia's chairmanship of the Arctic Council (2021–2023), sustainable shipping development was identified as a key goal, and efforts were made to accelerate the development of Arctic shipping resources. In August 2022, Russia approved the "Northern Sea Route Development Plan until 2035," allocating a total of nearly 1.8 trillion rubles in funding. A primary goal of the plan is to bring Northern Sea Route infrastructure projects and environmental shipping regulations into alignment with international standards. The plan's main components include the following:

- Mandatory application of existing best technologies to reduce pollution in Arctic waters;
- Comprehensive monitoring of the lithosphere, cryosphere, hydrosphere, and atmosphere in the Russian Federation's Arctic regions and Northern Sea Route waters;
- Updating regulations for preventing ship pollution in accordance with the requirements of MARPOL and the Polar Code (NSR Public Council, 2022).

The three Nordic countries have also made shipping pollution governance a key aspect of their Arctic strategy. Norway's climate department provided 64.5 million Norwegian kroner for the implementation of the first phase of IMO's GreenVoyage 2050 project until 2023. In 2023, the Norwegian government confirmed funding of 210 million Norwegian kroner for the second phase of the GreenVoyage 2050 project to continue its work on reducing shipping emissions until 2050. The overall objective of the GreenVoyage 2050 project is to support IMO's Initial Strategy, particularly in supporting developing countries' efforts to reduce greenhouse gas emissions from ships. GreenVoyage 2050 aims to achieve this by supporting partnering countries to

- Undertake an assessment of maritime emissions in the national context;
- Develop policy frameworks and National Action Plans (NAPs) to address GHG emissions from ships;
- Draft legislation to implement MARPOL Annex VI into national law;
- Assess emissions and develop port-specific emission reduction strategies;
- Identify opportunities and deliver pilot projects through the establishment of public–private sector partnerships and mobilization of financial resources;
- Access funding and investments into energy efficient technologies; and
- Establish partnerships with the industry to develop new and innovative solutions to support low carbon shipping (IMO, 2019).

Furthermore, several non-Arctic nations, including the United Kingdom, China, and South Korea, benefit significantly from Arctic shipping routes. Recognizing the pivotal importance of emission reduction in achieving sustainable Arctic shipping, these countries are redoubling their efforts in this relatively less politicized domain. In 2023, the UK House of Lords' International Relations and Defense Committee released a new report examining Britain's Arctic policy, highlighting that climate change is opening up and internationalizing the region. Commenting on the report, Lord Ashton noted that as the Arctic's nearest neighbor, the UK has a great interest in protecting fragile ecosystems and ensuring that all economic activities are conducted sustainably. The expected expansion of Arctic shipping will especially increase the risk of accidents and pollution.

In recent years, China has been actively promoting the development and utilization of Arctic shipping routes as part of its efforts to jointly build the "Polar Silk Road" with various partners. Given the vulnerability of the Strait of Malacca, which could be susceptible to disruptions in the event of future conflicts, China seeks to contribute to the establishment of a more secure international waterway, and the Arctic shipping routes could serve as a promising alternative. At the 33rd Assembly of the IMO, China was re-elected as a Category A Council member, underscoring its commitment to adhering to the Polar Code and supporting the IMO's active role in formulating Arctic shipping regulations. In line with its commitments under the Paris Agreement, China has proposed its "dual carbon" goals and is vigorously promoting energy conservation, emission reduction, and green low-carbon development in Arctic shipping. Through these efforts, China is actively advancing global processes and cooperation to address climate change.

South Korea holds a world-leading position in the construction of polar shipping vessels, particularly in the LNG vessel building sector, where it commands over 90% of the global LNG vessel market share. Given LNG's multifaceted advantages, including energy availability, emission reduction, economic efficiency, technological maturity, and regulatory completeness, it is poised for strong development prospects in ship emission reduction applications. Leveraging its leading edge in LNG, South Korea is well-positioned to actively promote the transition of Arctic shipping vessels to clean energy.

4.2 Technical challenges in Arctic shipping emission reduction

With the stringent enforcement of Arctic shipping emission reduction policies, a combination of restrictive regulations and incentive-driven guidelines is driving the Arctic shipping industry to allocate more resources toward technological innovation, striving to progressively attain zero-carbon emission targets. In this latest wave of shipping emission reduction technological advancements, significant progress has been made in emission reduction technologies; however, achieving breakthroughs in net-zero emission technologies remains a persistent challenge.

First, as the ship's propulsion system is the primary source of emissions, the transition to a clean and low-carbon power system is a key research focus for reducing Arctic shipping emissions (Ali et al., 2022). The crucial step in decarbonizing the propulsion system lies in the green transformation of ship fuels. Research on clean alternative fuels for shipping primarily focuses on low-carbon or zero-carbon options such as LNG, methanol, ammonia, and hydrogen. Given LNG's comprehensive advantages in terms of energy availability, emission reduction potential, economic efficiency, technological maturity, and regulatory completeness, it is expected to have a promising development outlook until 2035. However, the inherent carbon content of LNG limits its contribution to emission reduction (Liu et al., 2023). From a medium to long-term perspective, green methanol, hydrogen, and ammonia are key development directions for achieving future ship emission reductions. Nevertheless, most of these clean energy sources exhibit characteristics such as high flammability and explosiveness, biological toxicity, and specific material compatibility requirements (Li, 2021). The cost and availability of alternative fuels are pivotal factors in determining their deployment in the shipping industry. Although some new energy sources and alternative fuels, such as hydrogen, methanol, and lithium-ion batteries, have been successfully applied in land-based transportation, their direct transfer to ships is hindered by differences in operating environments, system complexity, and power requirements (Gan, 2023). The use of alternative fuels also raises compatibility concerns with specialized marine engines and storage technologies, leaving many alternative fuels in the shipping industry still in the research and development stage. Furthermore, the lack of comprehensive application regulations and technical requirement standards for alternative fuels poses an additional barrier to the development of application technologies.

Second, in addition to seeking solutions from the source of marine fuels, carbon capture, utilization, and storage (CCUS) is also an important aspect of achieving effective emission reduction in shipping. CCUS technologies remove existing carbon dioxide emissions, store them safely and effectively, and provide opportunities to utilize them for future projects. These innovative technologies play a significant role in achieving the energy industry's emission reduction goals and turning carbon waste into high-value products. For onboard CCUS technology powered by traditional energy systems, chemical absorption methods are typically employed to capture carbon from exhaust gases. This process utilizes temperature fluctuations in the absorption liquid to facilitate CO_2 absorption and release, thereby separating and capturing CO_2 from the exhaust gas. The system comprises four primary stages: CO_2 capture, separation, compression and liquefaction, and finally, storage and offloading (CCS, 2023a). Each stage of onboard CCUS involves distinct technical, operational, and safety requirements, and many countries have already issued relevant application guidelines. For example, in December 2023, the China Classification Society released the "Guidelines for the Application of Carbon Capture Systems on Ships." The main contents include the design and arrangement of onboard carbon capture systems, carbon dioxide absorption and desorption, decarbonizing agent supply systems, carbon dioxide compression and liquefaction, carbon dioxide storage and unloading, and monitoring and safety systems (CCS, 2023b). However, it is worth noting that onboard CCUS technology is not yet mature, with low carbon capture rates, and its application cost is significantly higher than the price of carbon trading (Zhou and Leng, 2021).

Third, ensuring the accuracy and reliability of carbon emission data in Arctic shipping is crucial for determining the direction of emission reduction policies and technologies. The EU introduced Regulation (EU) 2015/757, also known as the THETIS MRV, in 2015 to monitor, report, and verify (MRV) carbon emissions from international shipping. To support more efficient and accurate ship carbon emission MRV work, relevant organizations and countries have also conducted research on the methodology of shipping carbon emission MRV. However, the environmental complexity of the Arctic region poses significant challenges to monitoring Arctic shipping, resulting in an increased uncertainty in the data.

5 Strategies for mitigating Arctic shipping emissions

The rapid increase in Arctic shipping activities poses a significant threat to the Arctic's fragile ecosystem and contributes to global climate change. Studies have shown that over the past few decades, the Arctic warming rate has been 0.67°C/10a, which is 3.7 times the global warming rate (Figure 4), a phenomenon known as Arctic amplification (Screenm and Simmonds, 2010; Serreze and Barry, 2011; Mokhov, 2022; Li et al., 2023).

In response to mounting international pressure to mitigate Arctic shipping emissions and acknowledging the limitations imposed by technological challenges and other objective factors, this section seeks to propose comprehensive strategies that leverage governance frameworks, technological innovations, and green financing solutions to effectively address these pressing issues.

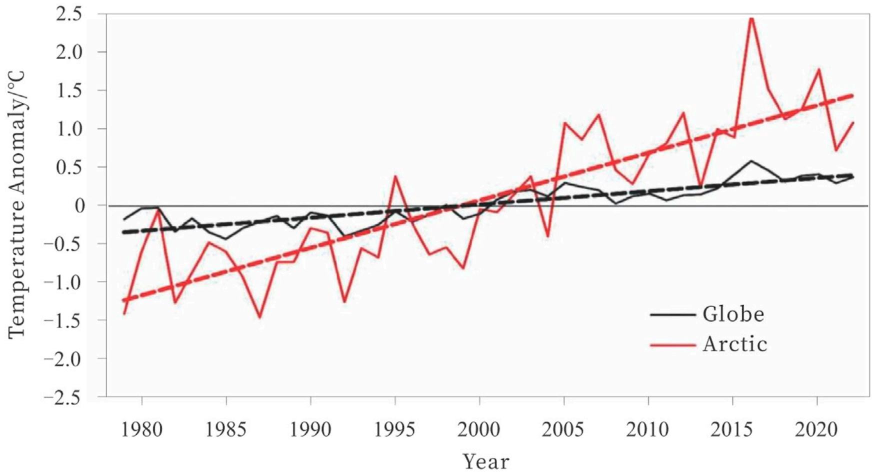

FIGURE 4
Near-surface annual mean temperature anomalies (relative to 1991–2020) for the Arctic and the globe from 1979 to 2022. The dashed lines represent the trends in annual mean temperature anomalies. Source from the Annual Report of Polar Climate Change (2022) (Ding, 2023).

5.1 Enhance the governance framework for emission reductions in Arctic shipping

The intricate nature of Arctic environmental challenges, coupled with the conflicting dynamics among multilevel governance mechanisms for reducing Arctic shipping emissions, as well as the complex geopolitical landscape, hinders the effective governance of Arctic shipping emission reduction. A substantial body of evidence suggests that existing frameworks have proven inadequate in mitigating the environmental impacts of Arctic shipping activities, with many Arctic shipping companies still lacking effective and feasible management programs and measures to address these concerns (Qi et al., 2024). There is a pressing need to refine and strengthen the governance framework for reducing Arctic shipping emissions.

First, it is essential to align with the goal of achieving net-zero emissions by 2050, as proposed by the IMO. Currently, the governance rules for Arctic shipping are inadequate, resulting in issues such as "inadequate regulatory coverage for polar vessels, leaving certain types of vessels unregulated," "the ban on heavy oil has yet to be formally enforced," "lack of regulations on black carbon emissions," and "the shipbuilding industry lacks clear and unified standards." The governance rules for Arctic shipping are far behind the needs of addressing climate change and environmental protection (Dong and Wei, 2024). Therefore, it is necessary to conduct regular reviews and adjustments to MARPOL and the Polar Code to ensure they can respond in a timely and effective manner to the ever-changing climate conditions in the Arctic region. Meanwhile, countries within and outside the Arctic region should establish relevant domestic laws and policies to effectively align with international regulations, following the example of the IMO in building a multidimensional policy system that covers planning guidance, mandatory constraints, and support guarantees, and strictly fulfill their obligations (Zhang and Guan, 2022).

Second, it is necessary to establish effective cooperation and coordination mechanisms to enhance the coherence and synergy between different levels of governance frameworks. As an open and inclusive organization, the Arctic Council can facilitate connections with all relevant stakeholders in the shipping industry, fostering a collaborative approach to address the challenges of Arctic shipping (Li, 2022). As patchwork approaches, regional actions can sometimes even be superior to long-pending global policies. Many Arctic issues generally have local and regional characteristics; therefore, regional actions should be more heavily emphasized (Wan et al., 2018). By fostering extensive collaborative networks and establishing specialized task forces focused on shipping emission reduction, the Arctic Council can more effectively monitor and orchestrate various initiatives aimed at mitigating Arctic shipping emissions. Serving as a crucial platform for multilateral negotiations, the Arctic Council can facilitate policy harmonization and concerted action among nations, thereby minimizing discrepancies between regulatory frameworks and implementation standards. Moreover, regional actions should remain consistent with globally cooperative actions or global policies and foster cooperation that links scientists, policymakers, ship owners, shipyards, and marine equipment suppliers (Zhang et al., 2019).

5.2 Expedite the research and development of technologies for energy efficiency and emission reduction in shipping

Accelerating the research and development of energy-saving and emission reduction technologies for shipping is a fundamental strategy for achieving the goal of net-zero emissions in the shipping industry. To this end, it is urgently necessary to establish a comprehensive evaluation system for the carbon emissions of alternative fuels for ships throughout their entire lifecycle, compare them from multiple aspects such as technological maturity, safety, and emission reduction effectiveness, in order to select the optimal alternative fuel and reduce greenhouse gas emissions from the source. Meanwhile, the medium- and long-term plans are released for the development of low- or zero-carbon emission fuels for ships, clearly defining the timeline and roadmap for pilot demonstration applications of these fuels on ships (Peng, 2022). In addition, while alternative fuels are a strong candidate for decarbonization of this sector in the long run, deploying these to the required scale will take significant time, considering technical modifications onboard the vessels, as well as the changes in fuel production and infrastructure for distribution (Sadi et al., 2024). Furthermore, various technological and operational enhancements, including optimized hull design, waste heat recovery and utilization, and wind-assisted propulsion, can also contribute to the reductions in shipping-related greenhouse gas emissions.

The development of alternative fuels and the optimization of technological and management measures rely heavily on international cooperation. By fostering global partnerships, the scientific community can expand its exchange networks, facilitate the sharing and updating of information and data, eliminate redundant research efforts, reduce development costs, and enhance the research efficiency. Furthermore, achieving net-zero emissions across the shipping industry necessitates a concerted effort to facilitate technology transfer and knowledge dissemination. This includes addressing intellectual property concerns and establishing international cooperation platforms to promote the widespread adoption of technologies and sharing of expertise, ultimately ensuring the effective attainment of global technological advancements and emission reduction objectives.

5.3 Investigate green financing options and incentivization mechanisms for sustainable shipping

The shipping industry's transition to a more sustainable and environmentally friendly model necessitates significant technological investments and substantial capital expenditures (Jiang, 2022). To facilitate this transformation, it is essential to develop and explore green financing options and incentive mechanisms that can provide the necessary funding support for the industry's technological upgrades and environmental protection initiatives.

First, green bonds and green loans can serve as crucial instruments for green financing, providing shipping companies with the necessary capital for energy-efficient and emission-reducing projects. Green bonds are designed to fund initiatives that yield substantial environmental benefits and contribute to climate change mitigation, attracting investors interested in sustainable shipping to support eco-friendly projects. Green loans, on the other hand, offer low-interest rates and preferential terms, helping companies cope with the high costs generated by technological transformation and green transition. Second, government fiscal subsidies and tax incentives are also crucial tools in supporting the shipping industry's green transition. Governments can offer targeted subsidies to alleviate the financial burden on companies investing in the research and development of energy-efficient and emission-reducing technologies. Additionally, tax incentives can be provided for the adoption of low-carbon and zero-carbon technologies, encouraging companies to invest in sustainable solutions. By developing a comprehensive tax policy framework that promotes low-carbon and zero-carbon development, governments can provide economic support for companies' green transformation, mitigate the financial burden associated with emission reduction investments, and enhance the market competitiveness of shipping companies. These green financing and incentive mechanisms not only address the economic shortcomings of green transition policies but also amplify their implementation effectiveness (Liu and Wu, 2024). By doing so, they effectively foster the sustainable development of the shipping industry, ultimately yielding a mutually beneficial outcome for both environmental protection and economic growth.

6 Conclusion

Although climate change presents unparalleled opportunities for Arctic shipping, it also poses substantial challenges that necessitate careful consideration. The melting of glaciers and sea ice has significantly increased the navigable period of Arctic routes, thereby enhancing navigability and reducing shipping distances. This development holds the potential to transform global maritime trade patterns. However, the growing navigation activities in the region are exerting additional ecological pressure on the already fragile Arctic environment. The harsh and unpredictable weather conditions, as well as the complex sea states characteristic of the Arctic environment, remain a major concern for ships traversing these routes. The consequences are far-reaching, impacting not only the monitoring and assessment of Arctic shipping data but also resulting in increased voyage delays and, more critically, compromising the safety and emergency response capabilities of Arctic maritime operations.

In the face of climate change, Arctic shipping faces not only the imperative of reducing emissions to meet international policy frameworks and public expectations but also a range of complex technical constraints. To address these challenges and capitalize on the opportunities presented by Arctic shipping, a collective effort from the international community is necessary. This can be achieved through a multifaceted approach that incorporates several key strategies, including strengthening the governance framework for emission reductions in Arctic shipping, accelerating research and development of relevant technologies, and exploring green financing options and incentivization mechanisms for sustainable shipping. By fostering effective cooperation and collaboration among all stakeholders, we can ensure that Arctic shipping contributes to the wellbeing of both the global economy and the Arctic environment.

Author contributions

HL: writing–original draft. ZM: conceptualization, formal analysis, and writing–original draft. ZZ: data curation, methodology, and writing–review and editing.

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