nature portfolio

Peer Review File

Arctic Sea Route access reshapes global shipping carbon emissions

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Dear Authors!
The manuscript examines the impact of the opening of the Arctic Shipping Route (ASR) on carbon emissions from international shipping. The introduction of the paper demonstrates the relevance of the study, as global warming is contributing to increased shipping opportunities in the Arctic by shortening transportation routes and reducing fuel costs. However, the authors note that such changes have serious environmental consequences.
The strength of the introduction is the clear statement of the problem - on the one hand, the Arctic route can help reduce CO_2 emissions through shorter routes, but on the other hand, increased shipping in this region creates new environmental risks.
However, the introduction has several limitations:
1) There is no clear definition of the research question: what specific aspects of shipping emissions are being investigated? Is the focus on absolute emissions growth or on the redistribution of emissions between different routes?
2) It is not clear how the study differs from previous work. The text mentions other studies on the topic of shipping emissions, but does not explain what scientific niche this work occupies.
3) Endogeneity of the model: the authors assume that increased trade automatically leads to increased emissions. However, technological changes in shipping, such as switching to alternative fuels, are not taken into account.
4) Hypotheticality of long-term projections: the projection to 2100 has a significant degree of uncertainty. There is no assessment of probabilistic scenarios that would take into account possible changes in emission regulation.
5) The influence of ice coverage and seasonality is not analyzed: shipping in the Arctic will depend on climatic conditions, but these factors are not represented in the model.
6) There is no assessment of the impact of redistribution of emissions. The work shows that emissions move from some areas to others, but does not assess which ecosystems will be most affected.
7) There is no analysis of the impact on regional economies. Reduced shipping through the Suez Canal could economically impact the countries in the region, but these impacts are not considered.
8) There is no discussion of alternative routes. For example, is it possible to increase the share of land transport (railroads)?
The manuscript is a strong study but requires substantial revision in the area of data interpretation.

Reviewer #2

(Remarks to the Author)
This is an interesting and solid piece of work. The effects of Arctic shipping is not a new topic but definitely calls for more insightful investigation for bettter operations and management of Arctic shipping for environmental as well as ecobomic purposes.

The effects of CO2 emissions from Arctic shipping is a good question but not a local issue. In this case, what we are interested in is how much CO2 emissions as well as energy consumption have been reduced globally due to Arctic shipping while more and more cargo transport is shifting from the tradditional shipping routes to those passing through the Arctic.

More importantly, as stated in this manuscript, is "sensitive Arctic seas" regarding the environment, including living creatures in the region. So, we care about external effects of heat, waste, and harmful emissions from Arctic shipping on the Arctic region. Unfortunately, this is not investigated in this work whereas what is invesitgated in this work does not really have direct effects on the Arctic environment.

Reviewer #3

(Remarks to the Author)
This paper investigates the effects of Arctic passage opening on global shipping networks and shipping carbon emissions based on a TISEP framework. The topic is very interesting. However, my major concern is that the TISEP framework still has significant uncertainty in terms of ice and weather conditions in the Arctic, as well as policies, international relations, trade volume, shipping network, etc. The prediction is extremely complex and involves many factors. Any of these factors could significantly impact the results. I suggest the authors pay more attention and address the following questions and comments.
1. Line 8-9, what about the global shipping carbon emissions, as well as the carbon emissions along the ASRs and the TSRs?
2. Line 10-11, please specify the fossil-fueled development pathway and middle-of-the-road pathway.
3. Line 11-13, compared with the southern part, the opening of Arctic shipping routes will attract more marine time transportation in the northern part. Why are emissions stronger in the north and weaker in the south?
4. Line 14, are the sea areas between the ASRs and the TSRs, or among them, respectively?
5. Does the Arctic passage refer only to the Northeast Passage in this paper? Please specify.
6. Line 23-28, can the high efficiency and low carbon emissions be maintained when taking into account other factors, such as ice resistance and adverse weather conditions in the Arctic?
7. Line 28-29, it is environmentally friendly on a global scale, but it may have adverse effects on the local Arctic region, especially for the accumulation of particulate matter such as black carbon.
8. Line 54-59, what is the impact of uncertainties related to sea ice, adverse weather conditions, and low temperatures in the Arctic?
9. How were the values in Lines 86-87 derived from Fig. 1c? The container ships dominate global maritime CO2 emissions, but it seems that the density is one order of magnitude lower than others. What does this mean?
10. What are the total annual carbon emissions of each type of vessel?
11. Fig. 2, will the Northwest Passage and Transpolar Sea Route not open by the end of this century? And will the shipping flow on the Arctic passage be the largest at that time?
12. Why does Asia, rather than North America, become the center of shipping in 2100? Is there any background information in the design of the predictive model? How about the mid-century?
13. Line 124 and Fig. 2, why does the proportion of containers decline rapidly and the gas carriers remain the biggest category over the century?
14. Please clarify the differences in various SSPs.
15. Line 147, compared with the situation at the end of this century, the situation in the mid-century may be more relevant and practical.
16. Line 152, “The trends of total shipping flow show that there will be a general rise in the total shipping flows for all vessel types”, and “There will be high activity for the sea routes running along the East-Asian coast and through the Indian Ocean, with values for the flow of between 200,000 and 600,000”. Why do emissions decrease in traditional shipping routes despite the increase in shipping flow?
17. Fig. 3b, why does the emission peak in 2080 and then continue to decrease till 2100?
18. How about the emissions under different SSPs in the mid-century?
19. Line 164-165, the shift of traffic toward ASRs is logical. However, it implies a change in relative proportions. The total shipping flow is increasing.
20. Why does this study primarily focus on the SSP2 scenario?
21. Fig. 4, attention should be given to the situations in the Suez Canal, the Cape of Good Hope, the Panama Canal, and Arctic seas.
22. In the conclusion section, it is suggested to incorporate policy recommendations and future research directions to enhance the practicality.
23. Line 293-294, is the carbon emission per vessel a constant value per unit grid? How is it calculated?
24. Line 304, is ARIMAX a nonlinearity method?
25. Line 313, the variables (GDP, population data, common official language, common border, common colonial history, and regional trade agreement data) should be filtered before model construction.
26. Line 387-389, the Northeast Passage will not be fully navigable year-round in the coming decades either.
27. Equation (12), it might be applicable to global estimations, but it is not suitable for Arctic estimates due to sea ice and other unique environmental factors.

Reviewer #4

(Remarks to the Author)
The authors target to forecast future shipping carbon emissions and assess the potential of ASR in reducing shipping carbon emissions on the global shipping network. The work is interesting and the authors have done an abundant work on global trade forecast and shipping emissions forecast, while I have concerns on the forecasts model and the final results of the emissions. Maybe a reject and resubmission is suggested. The detailed suggestions are listed below:
1. The authors target to investigate the potential of ASR in absorbing future trade and shipping activities, but the literature review lacks reviewing some latest literature of Arctic shipping in recent 5 years. Some references are relatively too old, e.g. 3, 4.
2. The proposed model of trade-integrated shipping emission projection (TISEP) framework is relatively novel, however, it lacks a deep understanding of shipping industry itself. E.g. the authors emphasized the importance of IMO’s regulations on

shipping activities, but for some key assumptions they did not show the shipping or IMO considerations, such as emission measurement criterion: well to wake emission or well to tank emission? This is a key focus of recent IMO regulations. As the author forecast till 2100, this must be considered. Besides, the bunker fuels used by ships in the future is also critical, due to IMO's and EU's latest regulations, current heavy fuels might not be used globally, new fuels (methanol, green methanol, ammonia, etc.) may have totally different fuel consumptions and GHG emissions. The authors solely calculate the future carbon emissions based on historical data and simple assumptions as in formula (12), I do not think this is enough.
3. Another key element is that ASR is not suitable for all kinds of trade or shipping. E.g. container shipping may not be economically viable via ASR as no large ports or economic hinterlands exist in the Arctic area, no matter Russia or Canada. ASR is good for bulk shipping and oil/LNG shipping. This could affect the trade forecast and trade assignment.
4. One more concern is that for the global trade forecast, the authors applied the ARIMAX model. I think the logic is OK, while they considered the variables of GDP, population, etc. and value chain (value added) and transport costs. The later 2 are new in the model. However, according to the recent situation, political factor is also critical in determining future trade volumes. Thus, I suggest the authors also include political factor in the forecast model.
5. At last, for the emission projection part, I suggest the authors clarify the emission measurement criterion, more fuel types need to be considered under future IMO regulations. The authors need to have a deep look at the latest IMO and EU's regulations on shipping and shipping fuels.
6. Based on above comments, a reject is suggested.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Dear Authors!
You have done a great job. Almost all comments have been taken into account. Before accepting your manuscript, it is necessary to proofread the text once more.

Reviewer #2

(Remarks to the Author)
No further comments.

The manuscript is good enough for publication.

Reviewer #4

(Remarks to the Author)
the authors have revised the paper accordingly, the quality of it has been significantly improved. therefore, I recommend an accept.

Response to Reviewer Comments
Clarifications and Appeals

Manuscript ID: NCOMMS-25-01783-T

Revised Title: *Arctic Sea Route access reshapes global shipping carbon emissions*

Previous Title: *The effects of opening the Arctic passage on shipping carbon emissions*

This study presents a comprehensive, quantitative, and spatially explicit assessment of how climate-driven Arctic Sea Route (ASR) access is reshaping the global structure of maritime carbon emissions. We develop a trade-integrated shipping emissions projection (TISEP) model that integrates future trade growth, route reconfiguration, and climate policy pathways to simulate global shipping emissions trajectories through the end of the 21st century. By capturing both the scale and spatial redistribution of shipping emissions under ASR access, our analysis uncovers emerging environmental inequities and highlights critical gaps in current decarbonization strategies. This work provides essential foresight for policymakers and contributes a systems-level understanding of how Arctic climate change reverberates through global emissions governance and environmental justice.

We are encouraged that all of the reviewers acknowledged the significance and academic contribution of our work. As Reviewer #2 noted, “This is an interesting and solid piece of work.” We are grateful for this recognition. At the same time, we sincerely thank the reviewers for their insightful and constructive feedback, which has been instrumental in improving the clarity, rigor, and overall quality of the manuscript. The review process has deepened our understanding of the modeling challenges and guided major improvements to the analytical framework.

In particular, we recognize concerns regarding the technical reliability of the TISEP model, especially with respect to scenario design and uncertainty treatment. In response, we have undertaken substantial revisions to enhance the model’s robustness, transparency, and explanatory power. Specifically, we implemented the following four major improvements.

1. **Reconstruction of the international trade module**. We introduce two distinct trade trajectories—an optimistic trade scenario (OTS) and a pessimistic trade scenario (PTS)—to more realistically reflect future global trade dynamics and their implications for shipping emissions.

2. **Enhancement of the maritime transport module**. We reforecast the spatial distribution of shipping volumes and routes, incorporating seasonal and interannual variability in Arctic sea ice and navigability conditions.

3. **Redesign of the decarbonization pathways**. We recalibrate the IMO 2023 and Green Corridor scenarios within the TISEP framework. The model outputs reveal that these existing strategies are insufficient to fully decarbonize Arctic shipping. Accordingly, we propose a new **Net-Zero strategy** characterized by stricter fuel criteria and regionally prioritized implementation in the Arctic.

4. **Discovery of key new findings**. Our updated simulations show that ASR access could increase global shipping emissions by 8.2% by 2100 while the Arctic's share of emissions may rise from 0.22% to 2.72%. These shifts highlight emergent global environmental justice issues. We have added in-depth interpretation of these findings, and the Results section has been substantially revised accordingly.

In addition to these technical revisions, we have also addressed several conceptual and structural concerns raised during peer review.

1. **Clarification of the central research question**. We now explicitly ask, *How will the opening of the Arctic Sea Route reshape the scale and spatial distribution of global shipping carbon emissions under alternative trade and policy scenarios?* This framing directly addresses concerns about ambiguity in the scope and focus of the study.

2. **Articulation of novelty**. While earlier studies focused on Arctic shipping feasibility or voyage-scale carbon intensity, our work is, to our knowledge, the first to quantify **global**, **long-term**, and **spatially disaggregated** shipping emissions under integrated trade and policy scenarios using the TISEP model.

3. **Deepened fuel transition analysis**. We have expanded our treatment of future fuel transitions and technology adoption by adopting a *tank-to-wake* emissions accounting

boundary to prioritize combustion-stage emissions, with emphasis on ecologically sensitive regions such as the Arctic. We have systematically evaluated a broad set of decarbonization scenarios under various trade and technological assumptions to support forward-looking climate policy design.

We believe that the revised manuscript now fully addresses the key concerns raised by the reviewers and makes a distinct and timely contribution to the understanding of global maritime emissions in the context of a warming Arctic. Below, we provide a detailed, point-by-point response to each comment and suggestion from the reviewers and editors.

REVIEWER COMMENTS

We have improved our paper by responding ti each of the comments one-by-one. The reviewers' remarks are shown in *red*, and quoted excerpts from the revised manuscript are presented in *blue*.

Reviewer #1

The manuscript examines the impact of the opening of the Arctic Shipping Route (ASR) on carbon emissions from international shipping. The introduction of the paper demonstrates the relevance of the study, as global warming is contributing to increased shipping opportunities in the Arctic by shortening transportation routes and reducing fuel costs. However, the authors note that such changes have serious environmental consequences.

The strength of the introduction is the clear statement of the problem - on the one hand, the Arctic route can help reduce CO_2 emissions through shorter routes, but on the other hand, increased shipping in this region creates new environmental risks.

However, the introduction has several limitations:

Comment 1*:* *There is no clear definition of the research question: what specific aspects of shipping emissions are being investigated? Is the focus on absolute emissions growth or on the redistribution of emissions between different routes?*

Response 1: We thank the reviewer for raising this foundational question. We have now revised both the **Abstract** and **Introduction** to more explicitly define our research objective and clarify the dual focus of our investigation. Specifically, our study seeks to answer:

"**How will increasing accessibility of the Arctic Sea Route (ASR) reshape the scale and spatial distribution of global shipping carbon emissions under future trade growth and climate policy scenarios?**"

To address this question, we focus on two interrelated dimensions.

1. Absolute emissions impact

We quantify the increase in global maritime CO_2eq emissions attributable to ASR access by 2100 under both the optimistic and pessimistic trade trajectories. The emissions increase is analyzed across four distinct climate policy pathways:

(1) **A Business-as-Usual (BAU) baseline**

(2) Three decarbonization strategies: **IMO 2023, the Green Corridor strategy, and the Net-Zero strategy** designed around zero-emission fuel deployment.

Our results reveal that ASR access will lead to an 8.2% increase in global shipping emissions by 2100, with the Arctic's share rising markedly, from 0.22% to 2.72%.

2. Spatial redistribution of emissions

We assess the geographical reallocation of global emissions as shipping routes adjust to ASR accessibility. In particular, we identify emissions intensification in:

(1) **Arctic waters**, which are ecologically sensitive and previously low-impact zones

(2) Major commercial corridors surrounding **Northeast Asia, Northern Europe,** and the **North American** East Coast, owing to rerouting dynamics

These spatial shifts have implications for both regional environmental burdens and international carbon accountability frameworks and raise questions about environmental equity that are not addressed in traditional global emissions studies.

This dual-focus framework—on both global emissions scale and regional redistribution—is a key innovation of our study and has been clearly articulated in the following locations of the revised manuscript.

Abstract

Here, we quantify the long-term carbon consequences of ASR access using a trade-integrated shipping emissions projection (TISEP) model that integrates trade scenarios, *vessel routing, and climate policy pathways. The results of our analysis show that ASR access will increase global shipping emissions by 8.2% by 2100, with the share of emissions in the Arctic increasing from 0.22% to 2.72%. At the same time, environmental disparities in emissions exposure will increase since Northeast Asia, Northern Europe, and North America will experience particularly large increases in emissions because of the changes in the flow of ships.*

Main Text (Introduction, paragraph 4):

The model quantifies the overall increase in global shipping carbon emissions attributable to ASR access while also capturing the spatial redistribution of emissions—particularly the emergence of new hotspots in ecologically vulnerable Arctic waters and along major global shipping corridors.

And, TISEP enables a spatially resolved, policy-relevant assessment of how ASR access reshapes the scale and distribution of maritime carbon emissions that highlights not only the implications for overall decarbonization but also the emerging equity risks embedded in the evolving structure of global shipping networks.

We hope that this revised framing clarifies the core research question and the methodological novelty of our approach.

Comment 2*:* *It is not clear how the study differs from previous work. The text mentions other studies on the topic of shipping emissions, but does not explain what scientific niche this work occupies.*

Response 2: We thank the reviewer for this important comment. We acknowledge that the original submission did not sufficiently emphasize the distinct contributions of our study relative to existing literature. In the revised Introduction (**paragraph 3**), we have clarified the **scientific niche** our work addresses.

Previous studies of ASR access and shipping emissions have primarily focused on either (i) **localized environmental impacts in the Arctic region**, such as sea ice feedback, black carbon deposition, and short-term emissions near the Northern Sea Route, or (ii) **routing and economic efficiency gains**, without linking them to long-term global carbon consequences. Other research explores future emissions scenarios but typically uses **route-agnostic models** that overlook how new corridors such as the ASR may restructure global shipping flows and emissions geography.

By contrast, our study fills a critical gap by offering an **integrated, global-scale analysis** of how ASR access:

1. alters both the **magnitude** (net increase) and **spatial distribution** of maritime CO_2 emissions,

2. interacts with long-term **trade dynamics** (the OTS and PTS) and the **climate policy strategies** (i.e., IMO 2023, Green Corridor, Net-Zero), and

3. reveals previously unexamined **regional disparities** in emissions exposure, highlighting the equity dimensions of global maritime decarbonization.

Methodologically, we contribute a novel modeling framework—i.e., the **TISEP** model—that unifies global trade forecasts, vessel routing simulation, sea ice constraints, and spatially explicit emission estimation. This approach enables us to simulate real-world shifts in maritime geography and assess policy effectiveness under contrasting futures.

To our knowledge, this is the **first study** to quantify both the **net global carbon impact** and the **geographic carbon redistribution effects** of the opening of the ASR across a range of policy pathways. This comprehensive and spatially resolved perspective offers new insights into climate governance, particularly in evaluating the **resilience and equity** of current maritime decarbonization strategies.

Comment 3: *Endogeneity of the model: the authors assume that increased trade automatically leads to increased emissions. However, technological changes in shipping, such as switching to alternative fuels, are not taken into account.*

Response 3: We thank the reviewer for pointing out this important concern. In the original version of the manuscript, our carbon emissions projections were indeed based primarily on proportional scaling of trade volumes, which limited the ability to account for technological progress in fuel and vessel systems.

In the revised manuscript, we address this issue by incorporating one baseline scenario and three decarbonization policy scenarios, each reflecting varying degrees of technological advancement and fuel transition (see Methods).

1. Baseline scenario – BAU (Business as Usual)

This scenario assumes no additional decarbonization efforts. Emissions scale directly with projected trade growth and shipping activity, and fuel use patterns continue their historical trajectories.

2. Decarbonization scenario 1 – IMO 2023 Strategy

This scenario incorporates the International Maritime Organization's revised GHG reduction targets, along with fuel mix projections and technology adoption pathways from the *DNV Maritime Forecast to 2050* (DNV, 2024). It takes into account alternative fuels (e.g., LNG, methanol, ammonia, hydrogen, biofuels, electricity, and nuclear) as well as fuel costs, energy efficiency measures, infrastructure constraints, and onboard carbon capture.

3. Decarbonization scenario 2 – The Green Corridor strategy

This scenario introduces spatially differentiated fuel standards—requiring zero-emission fuels (Ismail et al., 2024; Silk Alliance, 2022) along selected international routes, particularly in ecologically sensitive regions such as the Arctic.

4. Decarbonization scenario 3 –The Net-Zero Strategy.

The Net-Zero strategy models a transformative decarbonization pathway where technology, regulation, and regional prioritization work together to **decouple trade growth from emissions increases** (Wang et al., 2023; Zhou & Tao, 2025). This scenario features a **tank-to-wake emissions boundary**, mandates truly zero-emission energy carriers, and initiates a **regionally phased rollout** starting with the Arctic by 2040 (Results, p. 12; Discussion, p. 14).

These pathways explicitly incorporate the impacts of **alternative fuels, regulatory stringency, and adoption timelines**, thereby allowing the model to evaluate not only emissions growth under rising trade but also the **efficacy of mitigation strategies** under realistic technological conditions.

We hope that, in this way, we have made clear the centrality of technological change to our modeling framework and that the revised study no longer assumes a fixed or automatic link between trade volume and emissions.

References

1. DNV. (2024). *Maritime Forecast to 2050: A deep dive into shipping's decarbonization journey*. *Energy transition outlook 2024*.
2. Ismail, A. M. et al. (2024). Integrating ports into green shipping corridors: Drivers, challenges, and pathways to implementation. *Marine Pollution Bulletin*, *209*, 117201.
3. Silk Alliance. (2022). *The silk alliance: Fleet decarbonisation strategy for green corridor implementation*. LR Maritime Decarbonisation Hub.
4. Zhou, Z., & Tao, J. (2025). Hydrogen-powered vessels in green maritime decarbonization: policy drivers, technological frontiers and challenges. *Frontiers in Marine Science*, *12*, 1601617 (2025).
5. Wang, Q., Zhang, H., & Zhu, P. (2023). Using nuclear energy for maritime decarbonization and related environmental challenges: Existing regulatory shortcomings and improvements. *International Journal of Environmental Research and Public Health*, *20*, 2993.

Below is the detailed explanation of each scenario as presented in the ***Methods*** section of the manuscript.

Future Strategies Setting

To explore long-term decarbonization pathways in maritime shipping, we construct one baseline and three policy scenarios, each defined by distinct policy frameworks specifying emission targets, fuel mandates, and geographic coverage. These scenarios reflect a spectrum of ambition levels from inertial growth to full systemic decarbonization and are implemented within the TISEP model to quantify their respective impacts on global *shipping emissions. The scenario-specific inputs include fuel mixes, policy timelines, and spatial applicability, all calibrated using historical AIS data, techno-economic fuel forecasts, and institutional targets. The scenarios are detailed as follows.*

(1) BAU*. This baseline assumes that the global shipping sector maintains its exact 2025 fuel mix through 2100 with no further policy intervention, technological innovation, or behavioral shift. The fuel composition is held constant over time, consisting primarily of low-sulfur fuel oil and marine gas oil (LSFO/MGO, 67.6%), HFO with scrubbers (17.7%), and LNG (12.5%), along with marginal shares of LPG (0.4%), fossil methanol (0.4%), and bio-MGO (1.4%) (Supplementary Table 7). All zero-carbon fuels (e.g., bio-LNG, e-fuels, and ammonia) and carbon capture technologies are assumed to remain unused throughout the simulation period. Shipping demand continues to grow in line with projected trade flows, but the proportional composition of fuel use remains fixed at 2025 levels. As such, this scenario represents an inertial emissions trajectory under current operational and regulatory conditions and serves as the counterfactual baseline for evaluating the mitigation potential of alternative pathways.*

(2) IMO 2023 strategy*. This scenario assumes full compliance with the International Maritime Organization's Revised GHG Strategy, which targets a 20% reduction in emissions by 2030, 70% by 2040, and net-zero by 2050 relative to 2008 levels[12]. The scenario also envisions a progressive transition from fossil-based fuels to low- and zero-carbon alternatives, including methanol, ammonia, hydrogen, and e-fuels. The projected fuel mix is based on DNV's predictive modeling, which incorporates fuel cost trajectories, technology readiness levels, and improvements in vessel energy efficiency. Specifically, the shares of HFO scrubbers and LSFO/MGO will decline from 17.7% and 67.6% in 2025 to 0% and 2.1% by 2050, respectively, while zero- and low-carbon fuels such as e-ammonia (27.6%), e-MGO (27.8%), and bio-methanol (2.9%) will become dominant (Supplementary Table 7). Carbon capture technologies will be progressively deployed from 2030 onward, accounting for a combined 40.8% of the fuel mix by 2050. This scenario reflects a policy-driven transformation of fuel structures aligned with mid-century decarbonization targets.*

It is important to note that the IMO's definition of "net-zero by or around 2050" refers to well-to-wake emissions, encompassing the entire fuel lifecycle, from production and transport to onboard combustion. This accounting framework allows fuels with upstream carbon mitigation (e.g., biofuels, e-ammonia with renewable electricity, or carbon capture at production sites) to qualify as zero-emission even though combustion at sea still generates substantial tailpipe emissions. This distinction is particularly relevant for trans-Arctic shipping, during which vessels release residual CO_2 and black carbon directly into highly sensitive ecosystems. By contrast, the Net-Zero strategy defined in this study involves the adoption of a stricter operational boundary, targeting zero emissions at the point of use (tank-to-wake) through the use of fully non-emitting propulsion technologies such as battery-electric systems, nuclear propulsion, and hydrogen fuel cells. This divergence highlights both the limitations of current international frameworks and the importance of spatially differentiated mitigation strategies for ecologically vulnerable regions.

(3) The Green Corridor strategy. *This strategy builds on the IMO pathway by introducing route-specific acceleration in green fuel adoption, consistent with the Global Maritime Forum's strategy for green shipping corridors. Eight major corridors are designated as green corridors based on their ecological vulnerability and strategic significance (Extended Data Figure 10). Within these corridors, the share of preferred green fuels such as LNG, methanol, and MDO will increase linearly from 2025 to 2050 to reach full substitution. For routes supporting multiple fuel options, the shares are evenly allocated. This scenario reflects both climate ambition and the operational challenges of low-carbon navigation in ice-prone and environmentally sensitive regions (Supplementary Table 8).*

Fuel selection varies by corridor depending on infrastructure readiness, trade function, and ecological risk. For example, e-ammonia is prioritized on iron ore routes such as South Africa-Europe and Western Australia-North Asia while bio-methanol and hydrogen are preferred along shorter, high-traffic corridors such as US-UK and Oslo-Rotterdam. The Green Corridor strategy is supported by the IMO and promoted through initiatives such as the Silk Alliance Green Corridor cluster. These efforts are grounded in *the Clydebank Declaration launched at COP26 and are implemented through multi-stakeholder collaborations involving port authorities, shipowners, financial institutions, and fuel providers.*

Notably, the ASR is incorporated as a green corridor in this study because of its projected strategic importance and environmental sensitivity. Although it is not featured in current policy frameworks, its inclusion highlights the need to extend decarbonization efforts to emerging high-latitude routes. Given the ecological fragility of the Arctic, high-risk fuels such as ammonia are excluded, and lower-impact options, including CCS-equipped low-sulfur fuel oil (LSFO), CCS LNG, and methanol, are designated to minimize environmental harm.

(4) The Net-Zero strategy. *This scenario represents a high-ambition pathway toward deep decarbonization of the maritime sector, surpassing existing strategies such as those laid out by the IMO and Green Corridor initiatives. The scenario assumes the phased adoption of zero-carbon energy carriers—namely electricity, hydrogen, and nuclear—beginning regionally in the Arctic in 2040 and expanding globally from 2050 onward. The earlier regional deployment reflects the Arctic's heightened environmental sensitivity and the amplified climate feedback driven by black carbon and CO_2 emissions. The urgent need to mitigate accelerated warming in this region, exacerbated by growing trans-Arctic shipping activity, justifies its prioritization for zero-emission transitions. Under this scenario, zero-carbon fuels will remain negligible prior to 2045, when their initial deployment begins exclusively within the Arctic. By 2050, global-scale adoption will commence, supported by anticipated infrastructure development, carbon pricing mechanisms, and regulatory enforcement. Between 2045 and 2100, the share of Super_Energy in total maritime energy use will increase exponentially, from 0.14% in 2045 to 39.6% in 2055, and 86.6% in 2070, reaching 100% by 2100. This trajectory captures the expected curve of technology diffusion, regulatory maturation, and system-wide substitution of fossil-based marine fuels (Supplementary Figure 15). Real-world initiatives such as Green Shipping Corridors are assumed to serve as early pilots for zero-emission deployment, particularly in technologically advanced ports. The Net-Zero strategy thus defines the upper bound of maritime decarbonization potential and assumes* *the complete and irreversible transition to non-emitting propulsion technologies across all vessel classes and regions by the end of the century.*

Comment 4: *Hypotheticality of long-term projections: the projection to 2100 has a significant degree of uncertainty. There is no assessment of probabilistic scenarios that would take into account possible changes in emission regulation.*

Response 4: We appreciate the reviewer's valuable comment regarding the uncertainty associated with long-term projections. Indeed, forecasting trade volumes and carbon emissions to 2100 involves substantial uncertainty, especially considering the dynamic nature of global regulations, technological innovation, and geopolitical shifts.

To address this concern, we have substantially revised the manuscript to incorporate a **scenario-based modeling framework** that does not rely on a single deterministic outcome. This framework enables us to explore a wide range of plausible futures by systematically varying trade conditions, routing responses, emission factors, and policy regimes. Specifically, we have implemented **four major improvements** in the revised study.

1. Revised Trade Modeling with Dual Scenario Design

We updated our trade projection module by adopting a five-pathway framework based on the Shared Socioeconomic Pathways (SSP1–SSP5), which reflect a range of global development, energy, and cooperation assumptions. These projections are validated against historical trade data and detailed in the Supplementary Information. Furthermore, we explicitly introduce two contrasting trade scenarios in the main analysis:

(1) the OTS, assuming continued global integration and maritime expansion, and

(2) the PTS, reflecting rising protectionism and geopolitical fragmentation.

This dual-scenario approach captures macro-level uncertainty in trade trajectories through 2100.

2. Improved Shipping Network Forecasting with ASR Access

We have enhanced our routing module to simulate how the opening of the ASR reshapes global shipping patterns under various navigational, seasonal, and regulatory constraints. The model accounts for ice-class vessel requirements, seasonal navigability windows, and infrastructure readiness and enables a more realistic representation of ASR-induced rerouting, chokepoint shifts, and voyage redistribution across regions and vessel classes.

3. Refined Emissions Modeling Framework

We have upgraded our emissions module by applying fuel-specific emission factors and considering vessel efficiency improvements over time. Emissions are computed using a tank-to-wake accounting boundary aligned with IMO standards. For projections beyond 2050, we extrapolate using the IMO’s Energy Efficiency Operational Indicator (EEOI) framework, incorporating expected advances in ship design and energy management.

4. Expanded Climate Policy Scenarios

We have developed four emissions scenarios that reflect uncertainty in global climate governance and fuel transitions:

(1) the BAU scenario involving no major decarbonization effort,

(2) the IMO 2023 Strategy involving the gradual uptake of low-carbon fuels per the IMO’s revised GHG targets and DNV Maritime Forecast to 2050,

(3) the Green Corridor Strategy involving route-specific zero-emission mandates in ecologically sensitive and developed regions, and

(4) the Net-Zero Strategy involving complete fuel substitution, a tank-to-wake emissions boundary, and phased geographic rollout beginning with the Arctic.

These scenarios allow us to explore the effectiveness and spatial consequences of decarbonization under various regulatory futures. We also integrate Arctic-specific rules such as the IMO’s heavy fuel oil (HFO) ban into the policy logic.

Together, these enhancements enable us to account for the structural, behavioral, and regulatory uncertainties embedded in long-range emissions forecasting. The scenario framework is explained in the Methods and further elaborated in the Discussion and Supplementary Information, with relevant citations provided. We hope that we have clarified how the revised manuscript directly addresses the uncertainty concerns and provides a robust basis for exploring the future carbon impacts of Arctic maritime transformations.

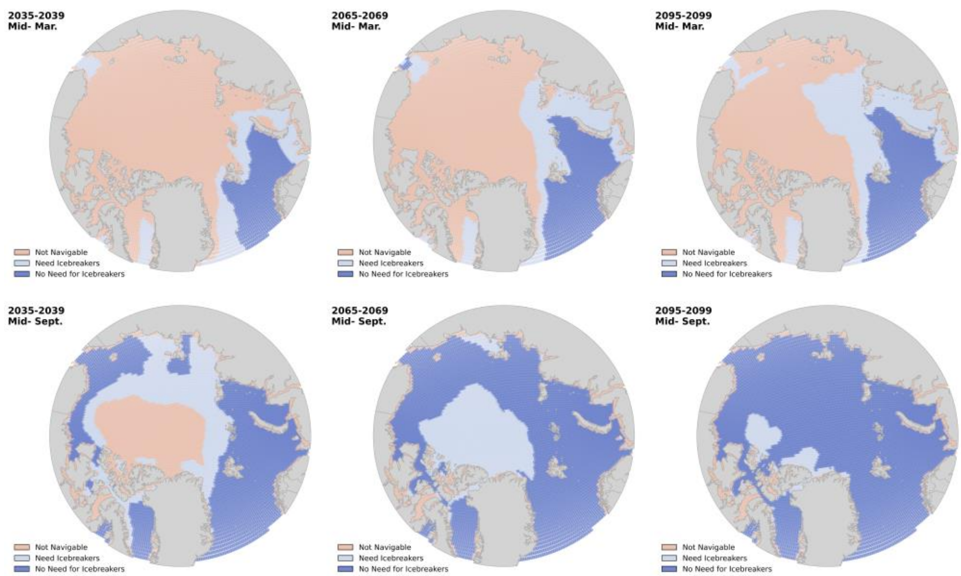
Comment 5: *The influence of ice coverage and seasonality is not analyzed: shipping in the Arctic will depend on climatic conditions, but these factors are not represented in the model.*

Response 5: We appreciate the reviewer's insightful comments regarding the influence of ice coverage and seasonality on Arctic shipping. We fully agree that climatic conditions, particularly the dynamic nature of sea ice, play a crucial role in determining navigability in the Arctic. These variations not only affect navigation windows but also influence vessel speed, fuel consumption rates, operational expenditures, and icebreaking tariffs—factors that collectively shape the generalized cost of Arctic shipping (Theocharis et al., 2018). We acknowledge that our initial manuscript did not sufficiently address these critical aspects.

Accordingly, we have substantially updated the Arctic trade forecasting model to comprehensively account for both the direct and indirect impacts of dynamic ice conditions. First, based on authoritative data (Table 2, Zhao et al., 2024), we projected sea ice thickness (SIT), sea ice concentration (SIC), and sea ice motion under the SSP2 scenario for the period 2023–2100. Given the strong seasonal variability of Arctic ice conditions, these projections are provided at 10-day intervals.

Next, we determined the navigable areas for open-water vessels from 2023 to 2100 based on the methodology developed in our previous study (Zhao et al., 2024) under two conditions, namely, with and without the assistance of icebreakers. On this basis, we updated both the route search algorithm and the generalized cost model. This enhancement captures not only the temporal dynamics of sea ice (at 10-day intervals) but also the spatial and operational challenges, such as icebreaking tariffs along the Northern Sea Route and difficult navigation conditions in the Northwest Passage. The resulting spatiotemporal navigability patterns are visualized in Supplementary Fig. 11, which shows projected Arctic accessibility by season, time period, and navigational requirement (i.e., ice-free, icebreaker-assisted, or inaccessible conditions).

Furthermore, in our simulation of global vessel flows, the routing optimization integrates these climate-induced accessibility windows and imposes constraints on navigability and safety. We also assume that only ice-class vessels or those with icebreaker support can access the ASR, depending on the severity of the ice. These constraints affect not only route choice but also emissions and regional impacts. The enhanced treatment of sea ice dynamics is now clearly described in the Methods section and the Supplementary Materials.



Supplementary Fig. 11 | Projected Arctic Sea Route navigability under SSP2. Spatial distribution of vessel accessibility conditions (not navigable, requires icebreaker, or open water) across the ASR during future periods derived from high-resolution simulations of SIT, SIC, and ice motion.

Table 2 | Datasets used for Arctic ice conditions and navigability modeling

Data Type	Source	Resolution & Period
Sea Ice Thickness (SIT)	CS2SMOS (Ricker et al., 2017)	25 km, weekly, 2015–2023
Sea Ice Concentration (SIC)	NSIDC (NSIDC-0051.002)	25 km, daily, 2015–2023
Sea Ice Motion	NSIDC (NSIDC-0116.004)	25 km, daily, 2015–2023
Sea Ice Concentration	CMIP6 EC-Earth3-Veg (AIMS CMIP6 Data)	~100 km, daily/monthly, 2015–2100
Sea Ice Thickness	CMIP6 MIROC6	~100 km, daily/monthly, 2015–2100
Sea Ice Motion	CMIP6 CESM2-WACCM	~100 km, daily/monthly, 2015–2100
Bathymetry (Water Depth)	CMIP6 CESM2-WACCM	~100 km, static

References

1. Zhao, P., Li, Y., & Zhang, Y. (2024). Ships are projected to navigate whole year-round along the North Sea route by 2100. *Communications Earth & Environment*, *5*, 1–9.
2. Theocharis, D., Pettit, S., Rodrigues, V. S., & Haider, J. (2018). Arctic shipping: A systematic literature review of comparative studies. *Journal of Transport Geography*, *69*, 112–128.

Comment 6: *There is no assessment of the impact of redistribution of emissions. The work shows that emissions move from some areas to others, but does not assess which ecosystems will be most affected.*

Response 6: We thank the reviewer for highlighting this important point. We fully agree that understanding the **ecological consequences of emissions redistribution** is critical, particularly for regions such as the Arctic where fragile ecosystems may be disproportionately exposed to increased shipping activity and related environmental stressors.

Our study focuses primarily on the **quantification of CO_{2eq} emissions and their spatial redistribution** under various trade and climate policy scenarios. While we do not directly model ecosystem impacts, we explicitly acknowledge the ecological implications of spatial emissions shifts in the **final paragraph of the Discussion**, where we state:

Even under a Net-Zero scenario that eliminates carbon emissions, the non-carbon externalities of intensified Arctic traffic remain unaddressed. These externalities include heightened risks of underwater noise, ballast-mediated species invasions, oil spills, and ship strikes, all of which jeopardize the ecological integrity of polar marine systems.

Furthermore, we emphasize that

Governance of the ASR must, therefore, move beyond decarbonization to embrace a comprehensive environmental protection agenda by integrating climate mitigation with biodiversity safeguards and local community resilience.

Although our study does not directly evaluate ecosystem-specific exposure, the spatially explicit emissions projections that we provide, such as those shown in Figure 4, provide an important foundation for future interdisciplinary studies that may overlay emission intensity maps with ecological vulnerability indices or species distribution data.

We have clarified this point in the revised Discussion to emphasize that our findings are intended to support, rather than substitute for, ecosystem impact assessments, and we appreciate the reviewer's encouragement of this important research direction.

Comment 7*: There is no analysis of the impact on regional economies. Reduced shipping through the Suez Canal could economically impact in the region, but these impacts are not considered.*

Response 7: We thank the reviewer for this thoughtful comment. While our study focuses on the spatial redistribution of shipping-related carbon emissions, we agree that ASR access has important implications for regional economic geographies, especially in relation to traditional chokepoints such as the Suez Canal.

Although we did not conduct a formal economic impact analysis (e.g., GDP, port revenues), our model does capture route-level shifts in vessel flows, which serve as a structural indicator of evolving maritime connectivity. As shown in Figure 2d, ASR access leads to declining traffic density through traditional equatorial chokepoints—notably the Suez and Panama Canals—while increasing flows through high-latitude corridors. This pattern is particularly pronounced for oil, gas, and chemical tankers (Fig. 2a), which are redirected toward Arctic passages under both optimistic and pessimistic trade scenarios.

We address this issue explicitly in the Discussion (p. 15), where we state:

Nations positioned to benefit from trans-Arctic shipping, such as Vietnam, South Korea, and Russia, may experience accelerated trade growth while other nations face marginalization as traditional routes lose strategic relevance. For example, the Suez Canal is currently a major source of foreign exchange for Egypt, contributing around 5% of the country's GDP and generating over $5 billion annually in toll fees, but it is economically exposed to traffic declines, with reduced flow directly diminishing canal revenues (Kenawy, 2016).

In this passage, we recognize the geoeconomic redistribution of maritime opportunity arising from ASR-induced rerouting. While not modeled quantitatively, our flow redistribution results can serve as a foundation for future work examining the socioeconomic consequences for chokepoint-dependent regions and port economies, including the Suez corridor. We have clarified this point in the revised manuscript and agree that integrating emission, trade, and economic impact modeling would be a valuable next step for interdisciplinary assessments.

Reference

1. Kenawy, E. (2016). The economic impacts of the new Suez Canal. *IEMed Mediterranean. Yearbook*, 282–288.

Comment 8*: There is no discussion of alternative routes. For example, is it possible to increase the share of land transport (railroads)? The manuscript is a strong study but requires substantial revision in the area of data interpretation.*

Response 8: We appreciate the reviewer's insightful comment regarding alternative transport routes, particularly the potential role of land-based modes such as rail. While the central focus of our study is on the maritime domain—specifically, the implications of ASR access on global shipping emissions—we agree that land transport options such as the China–Europe Express Railway could play an increasingly important role in reshaping international freight dynamics, especially in light of decarbonization targets, infrastructure investment, and shifting geopolitical conditions.

In the revised manuscript, we have added a sentence to the Discussion section explicitly acknowledging the potential relevance of rail-based transport:

While trade forecasts may overstate the reliance on the ASR by neglecting intermodal alternatives such as trans-Eurasian rail, such unquantified local feedback as soot-induced sea ice loss suggest that our projections may underestimate the long-term regional impacts.

This addition clarifies that, although intermodal shifts may partially mitigate ASR traffic in the future, their current potential remains constrained. Specifically, while rail transport generally offers lower carbon intensity per tonne-kilometer for certain cargo types and corridors, its scalability, infrastructure interoperability, and political risks—especially along transcontinental routes—currently limit its capacity to fully substitute for maritime flows.

We agree that the role of rail and other land-based alternatives is an important topic for further investigation. In fact, we are actively pursuing this direction in a follow-up study of the comparative carbon and cost trade-offs between Arctic maritime routes and transcontinental rail corridors under alternative development and climate policy scenarios.

We thank the reviewer again for this valuable suggestion, which has allowed us to more fully contextualize our findings and highlight future research needs.

Reviewer #2

Comment 1*:* *This is an interesting and solid piece of work. The effects of Arctic shipping is not a new topic but definitely calls for more insightful investigation for bettter operations and management of Arctic shipping for environmental as well as ecobomic purposes.*

Response 1: We thank the reviewer for the positive assessment of our work. We fully agree that, while Arctic shipping has been studied previously, there remains a pressing need for deeper and more integrated analyses, particularly given the accelerating navigability of Arctic routes and their implications for both environmental integrity and global maritime logistics.

Our study builds on this foundation by providing a scenario-resolved, spatially explicit assessment of how ASR access may reshape the patterns of global shipping emissions. By combining long-term trade projections, vessel routing simulations, and an evaluation of decarbonization policy, we offer new insights that are both scientifically grounded and operationally relevant for the sustainable development of Arctic shipping. We greatly appreciate the reviewer's encouragement and believe that the insights presented in this study can contribute to improved understanding and management of the evolving Arctic maritime landscape.

Comment 2*:* *The effects of CO_2 emissions from Arctic shipping is a good question but not a local issue. In this case, what we are interested in is how much CO2 emissions as well as energy consumption have been reduced globally due to Arctic shipping while more and more cargo transport is shifting from the tradditional shipping routes to those passing through the Arctic.*

Response 2: We thank the reviewer for raising this critical and common question. It is indeed a common assumption that ASR access, by shortening shipping distances, will reduce global CO_2 emissions and energy use. Our study is explicitly designed to evaluate this assumption through a global, scenario-based, and spatially resolved modeling framework. In the Introduction, we acknowledge this prevailing view while immediately qualifying its limitations:

Although ASR access may reduce emissions per voyage through shorter routes, the overall climate benefit would be offset by the projected increases in total traffic, especially from carbon-intensive vessel classes such as oil, gas, and chemical tankers.

This statement establishes the central motivation for our work: to quantify whether ASR access yields net global climate benefits, rather than merely localized or per-voyage efficiencies.

To answer this question, we constructed simulations with and without the ASR conditions. This design enables a direct estimation of the net global emissions impact attributable solely to Arctic accessibility. In the Results section, we present this comparison clearly:

Compared with a counterfactual without ASR access, global emissions will increase by 384.29 Mt CO_{2eq} under the OTS by 2100 (Fig. 2c), an 8.2% rise (+143.67 Mt; +9.5% under the PTS) (Fig. 2c).

This finding demonstrates that ASR access increases, rather than decreases, total global shipping emissions. This counterintuitive result emerges from two key drivers discussed in the same section: overall traffic growth, especially after 2050, as ASR offers new cost-competitive routes and induces higher cargo throughput, and shifts in vessel composition, as high-emission ship types—particularly oil, gas, and chemical tankers—are disproportionately rerouted through the Arctic. These mechanisms are also illustrated in Fig. 2a (projected Arctic emissions by vessel type), in which oil, gas, and chemical tankers dominate ASR-related emissions growth.

In the Discussion and Conclusion, we reflect on the broader implications of these results:

Although ASR access reduces voyage distances, these efficiency gains will be overwhelmed by the scale of induced traffic growth. These findings reinforce the role of the Arctic as a rapidly emerging emissions frontier in global shipping.

And further, *Our evaluation of decarbonization strategies also indicates that current international efforts fall short of mitigating ASR-induced emissions…*.

These interpretations make it clear that shortening routes alone is insufficient to deliver climate benefits unless paired with systemic fuel transitions and policy mechanisms. This finding reinforces the global significance of ASR impacts beyond localized Arctic concerns and supports the need for globally coordinated emissions mitigation.

In summary, our study directly addresses the reviewer's question by providing quantitative, system-level evidence that ASR access would not reduce global CO_2 emissions but, rather, would lead to a substantial net increase driven by demand growth and the routing of high-emission vessels. This conclusion is a core contribution of the manuscript and is supported by multiple results figures (particularly Fig. 2a and c).

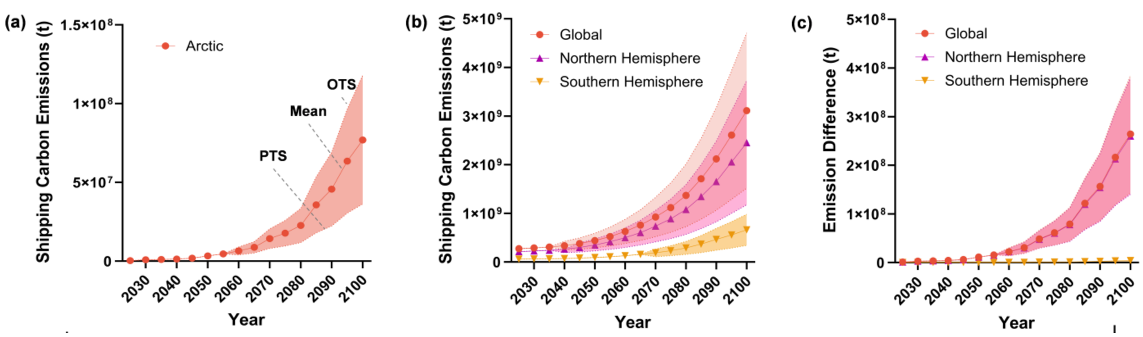


Fig. 2 | Evolution and spatial redistribution of global shipping carbon emissions resulting from ASR access from 2025 to 2100 under the BAU trade scenario. (a) Projected Arctic shipping emissions under ASR access, disaggregated by vessel type (bulk, container, oil, chemical, and gas carriers); **(b)** global and hemispheric trajectories of shipping carbon emissions under ASR access over time; **(c)** net increases in global and hemispheric shipping emissions attributable to ASR access by 2100 relative to a no-ASR counterfactual.

Comment 3*: More importantly, as stated in this manuscript, is "sensitive Arctic seas" regarding the environment, including living creatures in the region. So, we care about external effects of heat, waste, and harmful emissions from Arctic shipping on the Arctic region. Unfortunately, this is not investigated in this work whereas what is invesitgated in this work does not really have direct effects on the Arctic environment.*

Response 3: We thank the reviewer for highlighting this critical point. We fully agree that the Arctic's ecological sensitivity—including vulnerability to thermal stress, noise, and other harmful by-products of intensified shipping—deserves close attention. Our study focuses primarily on CO_2-equivalent emissions redistribution as a proxy for understanding structural changes in global shipping patterns with ASR access. While this approach captures the spatial and policy dimensions of carbon emissions, it does not extend to modeling non-carbon externalities such as underwater noise, oil spills, waste discharge, or direct ecosystem disruptions.

That said, we explicitly recognize these issues in the Discussion section (p. 16) of the revised manuscript:

Even under a Net-Zero scenario that eliminates carbon emissions, the non-carbon externalities of intensified Arctic traffic remain unaddressed. These externalities include heightened risks of underwater noise, ballast-mediated species invasions, oil spills, and ship strikes, all of which jeopardize the ecological integrity of polar marine systems.

In this passage, we acknowledge the environmental threats beyond CO_2 emissions and underscore the need for Arctic governance frameworks to expand beyond climate mitigation to comprehensive marine protection. We further emphasize that future research could build on our spatial emissions maps by overlaying them with ecological sensitivity indices and biodiversity data to assess risks to specific marine ecosystems.

We appreciate the reviewer's concern, and this comment has helped us clarify the scope and limitations of our current study as well as identify valuable directions for future interdisciplinary integration.

Reviewer #3

This paper investigates the effects of Arctic passage opening on global shipping networks and shipping carbon emissions based on a TISEP framework. The topic is very interesting. However, my major concern is that the TISEP framework still has significant uncertainty in terms of ice and weather conditions in the Arctic, as well as policies, international relations, trade volume, shipping network, etc. The prediction is extremely complex and involves many factors. Any of these factors could significantly impact the results. I suggest the authors pay more attention and address the following questions and comments.

Response:

We thank the reviewer for this thoughtful and comprehensive comment. We fully agree that modeling the long-term effects of ASR access involves **substantial structural uncertainties** regarding not only sea ice dynamics and climate conditions but also trade development trajectories, geopolitical shifts, regulatory evolution, and maritime technology adoption. Accordingly, we have taken several important steps to better reflect and communicate these uncertainties in the revised manuscript:

1. **Trade Uncertainty**

We hage updated the trade forecasting component by incorporating five SSP-based global trade pathways and constructing two distinct Arctic routing scenarios—the **OTS** and **PTS**—to represent divergent macroeconomic and geopolitical outcomes.

2. **Routing and Navigability Uncertainty**

We have revised the Arctic shipping network model using **high-resolution sea ice datasets** (10-day interval) for sea ice thickness, concentration, and drift speed to determine **navigability windows** and icebreaker needs dynamically from 2023 to 2100, accounting for both seasonal and spatial variability (Zhao et al., 2024). This revision enhances the realism of route accessibility projections.

3. **Emissions and Policy Uncertainty**

We have introduced **four emissions policy scenarios**—the BAU, IMO 2023, Green Corridor, and Net-Zero—each incorporating distinct assumptions about fuel type transitions, technology diffusion, and regulatory enforcement. These scenarios enable us to explore a range of decarbonization trajectories and transcend the simplistic trade-emission correlation.

4. **Scenario-Based Analysis Framework**

Rather than offering a single deterministic forecast, our study adopts a **scenario-based approach** to transparently reflect how the results vary across alternative futures. We emphasize this methodological choice in both the Methods and Discussion sections as a key strength for informing policymaking under uncertainty.

We acknowledge that the future of Arctic shipping is inherently complex and unpredictable. Our goal is not to eliminate this complexity but, rather, to **structure it analytically** to help identify which dimensions—climate, trade, or policy—have the greatest impact on future outcomes. We thank the reviewer again for underscoring this important point, which we now better articulate throughout the manuscript (in the revised Abstract, Methods, and Discussion).

Comment 1*: Line 8-9, what about the global shipping carbon emissions, as well as the carbon emissions along the ASRs and the TSRs?*

Response 1: We thank the reviewer for this insightful comment. While the primary focus of this study is on assessing the impact of the opening of the ASR on global maritime emissions, we report both **global and regional shipping carbon emissions** using the global total as a reference baseline to evaluate the contribution of the ASR.

Specifically, we compare emissions along the ASRs with those along traditional shipping routes (TSRs) to capture the spatial redistribution and varying intensities of emissions under different trade and policy scenarios. As shown in **Figure 2**, ASR access will lead to a net increase in global shipping CO_2-equivalent emissions of **8.2% by 2100**, with the Arctic's share rising from **0.22% to 2.72%**, reflecting substantial rerouting and regional concentration effects.

This dual-scale framing is now more clearly reflected in the **revised Abstract**: *The results of our analysis show that ASR access will increase global shipping emissions by 8.2% by 2100, with the share of emissions in the Arctic increasing from 0.22% to 2.72%. At the same time, environmental disparities in emissions exposure will increase since Northeast Asia, Northern Europe, and North America will experience particularly large increases in emissions because of the changes in the flow of ships.*

We have also added clarifications in the **Results section (paragraph describing Fig. 2d)** and in **Extended Data Figs. 5, 6**, which disaggregate Arctic shipping emissions across major northern corridors. These additions make the spatial scope and regional contrasts in emissions trends more explicit.

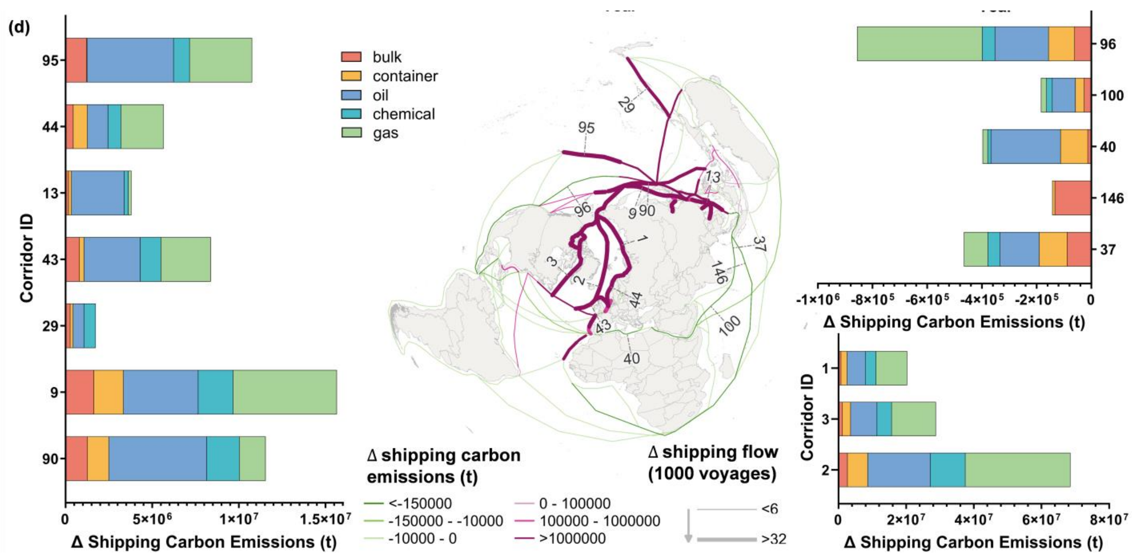
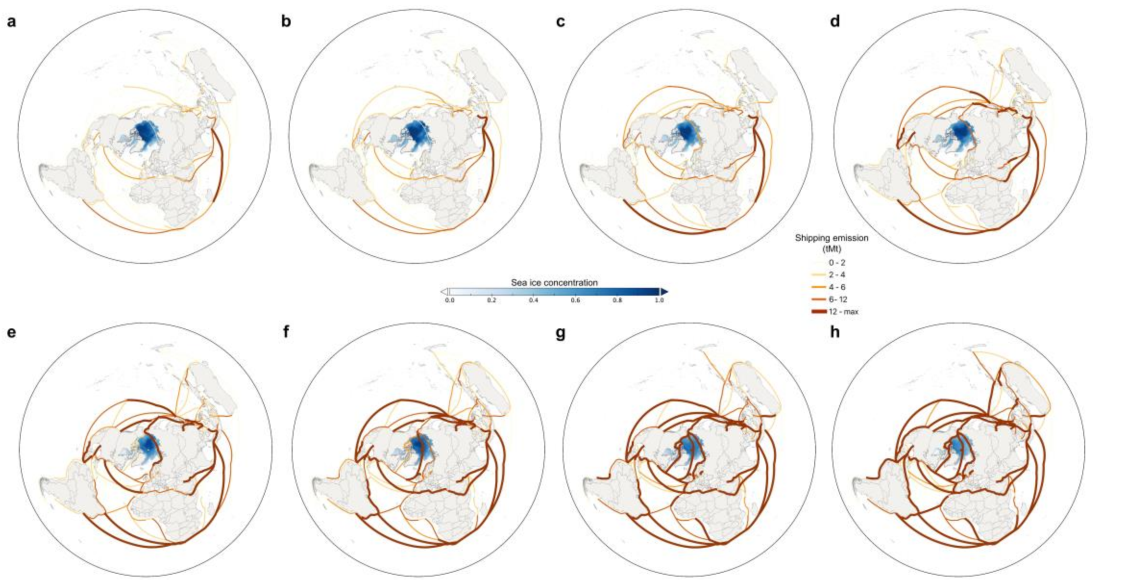
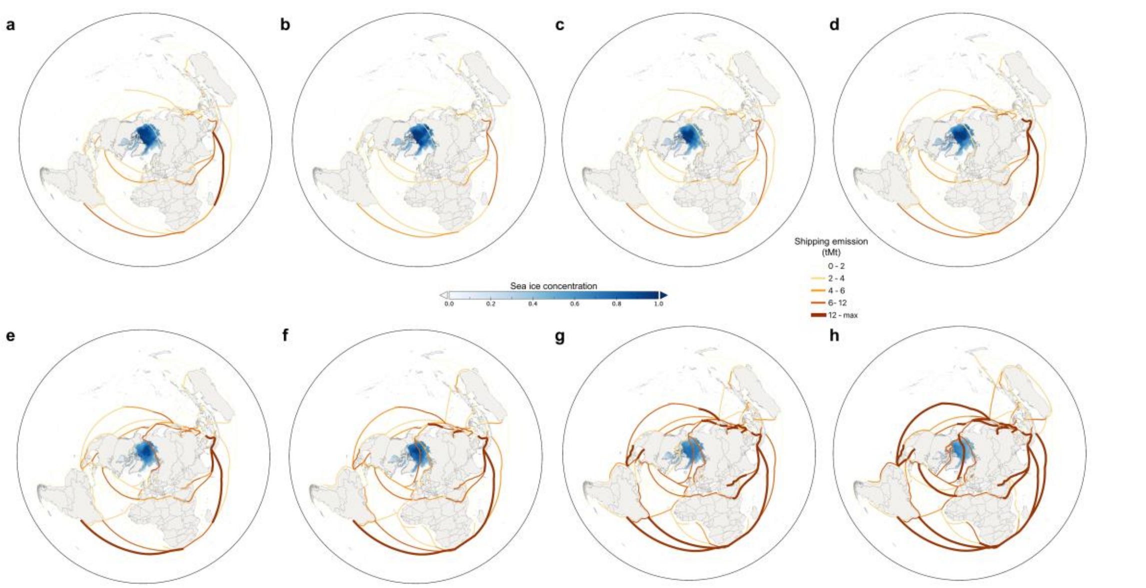


Fig. 2 | Evolution and spatial redistribution of global shipping carbon emissions resulting from ASR access from 2025 to 2100 under the BAU trade scenario. (d) spatial distribution of net increases in shipping carbon emissions across major global shipping routes by 2100 attributable to ASR access relative to a no-ASR counterfactual. The key routes and chokepoints include the Arctic Northeast Passage (1), the Central Arctic Route (2), the Arctic Northwest Passage (3) the Tsugaru Strait, (9) the Taiwan Strait, (13) the Luzon Strait, the Coral Sea (northeastern Australia) (90), Malacca Strait (37), the Suez Canal (40), the US-UK corridor (43), the Oslo-Rotterdam corridor (44), the North Pacific Transoceanic corridor (95), the North Pacific corridor (96), the South Arabian Sea corridor (100), and the Indian Ocean Transoceanic corridor (146).



Extended Data Figure 5 | Projected CO_{2eq} emissions along major global shipping routes for five vessel types under the BAU scenario with OTS. The blue shading indicates annual mean sea ice concentration, which varies across the panels according to the projected climate conditions. Emission intensities are shown in shades of yellow, with darker tones indicating higher emissions (in million tons).



Extended Data Figure 6 | Projected CO_{2eq} emissions along major global shipping routes for five vessel types under the BAU scenario with PTS. The blue shading indicates annual mean sea ice concentration, which varies across the panels according to the projected climate conditions. Emission intensities are shown in shades of yellow, with darker tones indicating higher emissions (in million tons).

Comment 2*: Line 10-11, please specify the fossil-fueled development pathway and middle-of-the-road pathway.*

Response 2: We thank the reviewer for the suggestion. To clarify, the "fossil-fueled development pathway" refers to SSP5, which is characterized by rapid economic growth driven by intensive fossil fuel use and high energy demand. The "middle-of-the-road pathway" refers to SSP2, which assumes a continuation of historical trends with moderate socioeconomic development and energy transitions.

However, in the revised version, in the case of carbon emissions, the scenarios differ in terms of fuel usage rather than SSPs (see the Methods section and the responses to Comments 16 and 18). Thus, we have revised the corresponding part of the abstract.

The TISEP modeling results show that two ongoing strategies, IMO 2023 and the Green Corridor, are not strong enough to achieve emission targets in Arctic, but a novel net-zero strategy featuring stricter fuel standards and regionally phased rollout could fully eliminate ASR-related emissions.

Comment 3*: Line 11-13, compared with the southern part, the opening of Arctic shipping routes will attract more marine time transportation in the northern part. Why are emissions stronger in the north and weaker in the south?*

Response 3: Thank you for the thoughtful comment. The sentence refers to the redistribution of carbon emissions along traditional shipping routes (TSRs) following the opening of Arctic shipping routes. Specifically, the northern parts of TSRs, which are geographically close to the newly accessible Arctic passages (e.g., Northern Sea Route), are expected to receive rerouted traffic because of the shorter distances and reduced transit times. As a result, emissions will increase in the north.

Conversely, the southern segments of traditional routes (e.g., through the Suez Canal or the Indian Ocean) will experience a relative decline in traffic volume, leading to a decrease in emissions. The "stronger in the north and weaker in the south" pattern reflects this geographical shift in traffic flow and associated emissions resulting from the substitution of routes rather than the inherent emission characteristics of the regions. A more detailed explanation of the difference in patterns is provided in the response to Comment 12. Below is the revised sentence in the Abstract.

At the same time, environmental disparities in emissions exposure will increase since Northeast Asia, Northern Europe, and North America will experience particularly large increases in emissions because of the changes in the flow of ships.

Comment 4: *Line 14, are the sea areas between the ASRs and the TSRs, or among them, respectively?*

Response 4: We thank the reviewer for pointing this out. To clarify, the sentence serves to highlight the spatial heterogeneity in carbon emissions within the sea areas of the TSR and the ASR. That is, we are referring to the differences among sea areas within these routes rather than between them. We did not mention the sea area difference in the abstract, but in the Results.

Spatially, under the IMO 2023 strategy (Fig. 4a), emissions would intensify most sharply in the Arctic, especially those from gas and oil carriers, rising from <0.05 Mt/km² in 2025 to >0.87 Mt/km² by 2100, and traditional chokepoints such as the Singapore Strait and North Pacific Ocean would experience reductions of more than 50%. The Green Corridor strategy (Fig. 4b) would reduce emissions in most targeted regions (e.g., those of container ships in the Singapore Strait from 6.65 to 0.24 Mt/km²) but would fail to control growth in the Arctic, where mitigation gaps would persist. Under the Net-Zero strategy (Fig. 4c), all ship types would converge to near-zero emissions across all regions, including the Arctic, despite traffic growth—an outcome that demonstrates the robustness of full-fleet decarbonization. These findings likewise reflect the emergence of the Arctic as the primary residual emissions hotspot under partial mitigation strategies.

Comment 5: *Does the Arctic passage refer only to the Northeast Passage in this paper? Please specify.*

Response 5: We appreciate the reviewer's request for clarification. In this study, the term **"Arctic passage"** (or Arctic Sea Route, ASR) refers broadly to **multiple navigable routes**

across the Arctic Ocean, not just the Northeast Passage. Specifically, we consider three main corridors:

1. **Northeast Passage** following the Russian Arctic coastline
2. **Central Arctic Route** across the central Arctic Ocean under reduced ice conditions
3. **Northwest Passage** through the Canadian Arctic Archipelago

In our simulations, we include all three routes in the routing optimization module of the TISEP model. However, because of their differing navigability and infrastructure readiness, the **Northeast Passage dominates the projected traffic** in most scenarios, particularly during the mid-21st century. The **Central Arctic Route** becomes more viable only in the latter half of the century under high warming scenarios, while the **Northwest Passage** remains limited by complex geography and shallow depths. We mention this in the Introduction:

As this transformation continues, previously inaccessible Arctic passages—including the Northeast Passage, the Central Arctic Route, and the Northwest Passage—are becoming viable for commercial navigation.

Comment 6: *Line 23-28, can the high efficiency and low carbon emissions be maintained when taking into account other factors, such as ice resistance and adverse weather conditions in the Arctic?*

Response 6: We thank the reviewer for raising this important point regarding the operational complexities of Arctic navigation. While the ASR offers shorter distances than traditional shipping routes, its theoretical advantages in fuel efficiency and carbon reduction are partially offset by real-world navigational challenges. In our revised model, we incorporate several critical Arctic-specific factors that directly affect energy use and emissions, including:

- Sea ice thickness (SIT), concentration (SIC), and motion, updated at 10-day intervals from 2023 to 2100 based on CMIP6 projections and Zhao et al. (2024)
- Seasonal accessibility of the ASR, distinguishing among open water, icebreaker-supported, and non-navigable periods

- Operational penalties, such as reduced vessel speed in ice-covered waters, elevated fuel consumption rates because of ice resistance, and additional costs associated with icebreaking escort services
- Route-specific emissions factors reflecting various vessel classes, ice-strengthened hull designs, and engine performance under Arctic conditions

Our results show that, while the ASR shortens transit distances, these physical and operational constraints will significantly dampen the emissions savings, especially before mid-century. In fact, under most scenarios, net global emissions will increase, largely because of rising traffic volumes and the continued use of high-emission fuel types.

Thus, the high efficiency and low carbon narrative does not universally hold once Arctic operational constraints are fully integrated. We now explicitly discuss this trade-off in both the Results (section on Fig. 2c) and the Discussion, arguing that shortening routes alone cannot guarantee climate benefits unless paired with full-sector decarbonization.

Comment 7: *Line 28-29, it is environmentally friendly on a global scale, but it may have adverse effects on the local Arctic region, especially for the accumulation of particulate matter such as black carbon.*

Response 7: We thank the reviewer for this insightful comment regarding the potential environmental consequences of Arctic shipping, particularly concerning particulate matter such as black carbon (BC). We fully agree that, while our study evaluates the global and spatial redistribution of CO_{2eq} emissions, the local ecological effects, especially in sensitive Arctic seas, deserve critical attention.

In our modeling, we estimate tank-to-wake CO_{2eq} emissions, which include short-lived climate pollutants such as BC, recognizing their disproportionate warming potential in the Arctic because of reduced albedo from ice surface deposition. To mitigate this effect, our future scenario design explicitly integrates regulatory developments such as the IMO Arctic HFO ban, thereby excluding high-BC fuels from Arctic routes and prioritizing low-BC alternatives (e.g., LNG, ammonia, and hydrogen). However, we acknowledge that actual BC emissions depend on combustion conditions and engine type, factors that introduce uncertainty not fully captured in this version of the model.

We emphasize in the Discussion and Conclusion that Arctic shipping expansion may bring global carbon efficiency but imposes localized risks, such as particulate matter deposition, thermal stress, invasive species, and vulnerability to oil spills, particularly in ecologically sensitive zones such as the Barents Sea, Kara Sea, Lincoln Sea, and Baffin Bay. These areas, previously near-zero emission zones, now emerge as emissions hotspots under ASR access.

As we state in the manuscript:

Even under a Net-Zero scenario that eliminates carbon emissions, the non-carbon externalities of intensified Arctic traffic remain unaddressed. These externalities include heightened risks of underwater noise, ballast-mediated species invasions, oil spills, and ship strikes, all of which jeopardize the ecological integrity of polar marine systems.

Furthermore, our spatial results indicate that, while the South China Sea, North Atlantic, and North Pacific may see net emission declines, Arctic marine ecosystems face increasing burdens that reinforce regional environmental injustice. We cite relevant literature (e.g., Huntington et al., 2023; Schmid et al., 2006) to underscore the ecological vulnerability and governance challenges, and we reference Liu et al. (2024) regarding the need for decarbonization pathways tailored to Arctic conditions, including stricter BC control and ballast water management. Lastly, while the impacts of BC are not explicitly quantified in this study, we agree that they are critical and should be the focus of future work. We now explicitly flag this issue in the Discussion as a key direction for further interdisciplinary integration between climate science, marine ecology, and shipping regulation.

We are grateful to the reviewer for highlighting this critical point, which has strengthened our framing of environmental equity and regional sensitivity in Arctic maritime governance.

References

1. Schmid, M. K. et al. (2006). Trophic pathways and carbon flux patterns in the Laptev Sea. *Polar Biology, 29,* 509–519.

2. Huntington, H. P. et al. (2023). Effects of Arctic commercial shipping on environments and communities: context, governance, priorities. *Transportation Research Part D: Transportation and Environment*, *118*, 103731
3. Liu, H., Mao, Z., & Zhang, Z. (2024). From melting ice to green shipping: Navigating emission reduction challenges in Arctic shipping in the context of climate change. *Frontiers of Environmental Science*, *12*, 1462623

Comment 8: *Line 54-59, what is the impact of uncertainties related to sea ice, adverse weather conditions, and low temperatures in the Arctic?*

Response 8: We appreciate the question regarding environmental uncertainties in Arctic navigation. As noted in our response to Comment 6, we have incorporated dynamic sea ice conditions into our Arctic shipping predictions, which serve as the basis for route accessibility and emission estimates. Furthermore, we account for Arctic-specific challenges such as low temperatures and weather variability in our assumptions regarding fuel choice and the operation of vessels (see Supplementary Table 8). Considering the ecological vulnerability of Arctic routes and the specific challenges of navigating in frozen areas, we have designated these routes green corridors and designed specialized fuel substitution pathways, such as LNG, methanol, and MDO (Foretich et al., 2021; Palmén et al., 2023), to address the environmental challenges and navigation needs of these specific regions.

Supplementary Table 8 | Fuel Preferences of Green Corridors

Green Corridors	Fuel
Chile Piscocultura Corridor	bio-methanol, hydrogen，
Oslo-Rotterdam Corridor	hydrogen
Republic of Korea-United States Corridor	bio-methanol
Rotterdam-Singapore Corridor	e-NH3, hydrogen, bio-methanol
South Africa-Europe Iron Ore Corridor	e-NH3
Western Australia-North Asia Iron Ore Corridor	e-NH3
European Green Corridors Network Corridor Network	bio-methanol
US-UK Corridor	Hydrogen, e-NH3, bio-methanol
Arctic shipping routes	CCS LSFO MGO, CCS LNG， methanol

Note: The table lists the preferred alternative fuels for selected green shipping corridors. For Arctic shipping routes, environmental sensitivity is prioritized. Fuels with high ecological risk—such as ammonia because of its toxicity and potential for leakage—are excluded. Instead, lower-impact options such as CCS-equipped low-sulfur fuel oil (LSFO), marine gas oil (MGO), CCS LNG, and methanol are designated to minimize risks to the fragile Arctic ecosystem.

Additionally, to address predictive uncertainty, our previous work included a DISO (distance between indices of simulation and observation) analysis of various SSP scenarios. This analysis showed that SSP2 offers the best alignment with observed Arctic sea ice trends and, therefore, forms the basis for our main scenario.

References

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2. Foretich, A., Zaimes, G. G., Hawkins, T. R., & Newes, E. (2021). Challenges and opportunities for alternative fuels in the maritime sector. *Maritime Transport Research*, *2*, 100033.

Comment 9: *How were the values in Lines 86-87 derived from Fig. 1c? The container ships dominate global maritime CO_2 emissions, but it seems that the density is one order of magnitude lower than others. What does this mean?*

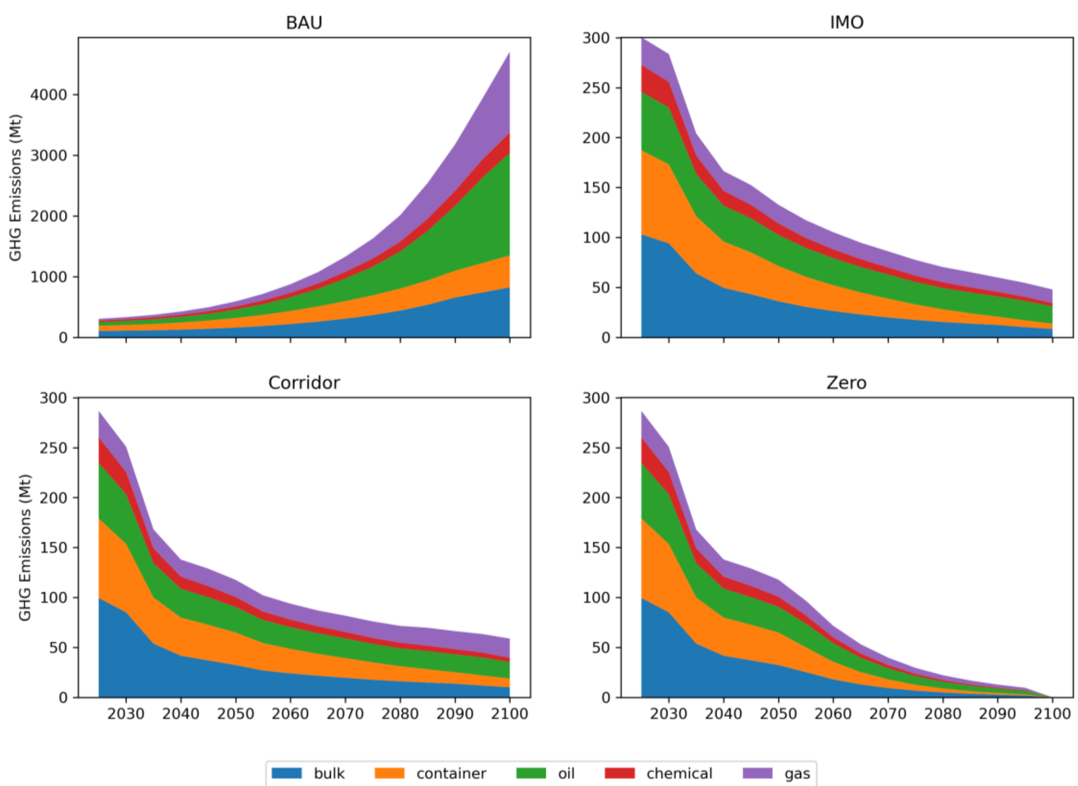
Response 9: We appreciate the reviewer's observation. The interpretation in Lines 86‑87 refers to the overall contribution of container ships to global maritime CO_2 emissions in absolute terms, rather than to their localized emission intensity within specific sea grid cells. The original Fig. 1 has been moved to the Supplementary Information as Supplementary Fig. 14. As shown in this figure, although the grid-level CO_2 emission density for container ships appears lower than that of oil or bulk carriers, this lower per-grid intensity reflects the widespread and dispersed global routing of container vessels rather than indicating lower total emissions. Container ships operate frequently across extensive trade corridors, and this widespread activity results in lower emissions per grid cell but a larger aggregate emission volume on a global scale.

This distinction between per-grid intensity and total emission is key: the right-skewed distribution curve in **Supplementary Fig. 14**c for container ships illustrates the lower emission values per grid cell, but, when integrated across all global grids, the cumulative emission volume surpasses that of other vessel types. This finding is further supported by the emission intensities in **Supplementary Fig. 14a** and the route-based aggregation in **Supplementary Fig. 14b**, which together capture the high operational intensity and trade volume of container fleets. Therefore, the values in Lines 86–87 are not contradictory but, rather, reflect the macro-scale emission dominance of container shipping, which may not be directly inferred from per-grid density alone.

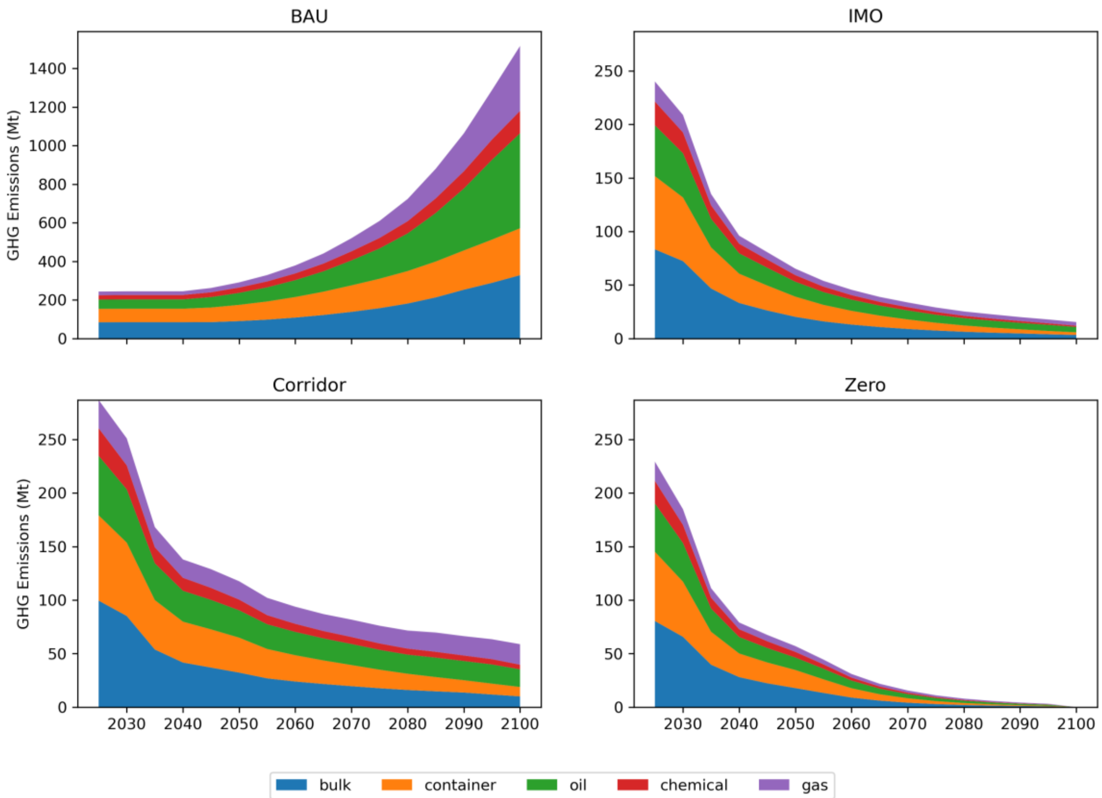
Comment 10: *What are the total annual carbon emissions of each type of vessel?*

Response 10: The total annual carbon emissions of each type of vessel can be seen in Extended Data Figures 8 and 9. These figures provide a detailed breakdown of emissions by vessel category throughout the study period under the four emission scenarios.

Under the BAU scenario, emissions rise steeply over the projected period, reflecting continued reliance on conventional fuels and minimal intervention. Bulk carriers contribute the largest share, followed by oil and container ships. The fact that total emissions would nearly triple by 2100 suggests a substantial environmental burden if no mitigation is implemented. By contrast, the IMO scenario shows a gradual decline in emissions over time, reflecting policy-driven decarbonization measures. Despite this reduction, bulk and oil vessels still dominate emissions, though their absolute values decrease markedly. The impact of regulation is evident, for total emissions would fall to a fraction of BAU levels by the century's end. The corridor scenario is the most aggressive mitigation pathway in terms of achieving the lowest emissions among the three scenarios. This outcome reflects a future in which green corridors and alternative fuels are widely adopted. Emissions from all ship types would diminish significantly, with gas and chemical ships becoming relatively more prominent because of lower emissions from the bulk and oil segments.



Extended Data Figure 8 | Projected shipping CO_2 emissions by vessel type under four policy scenarios (BAU, IMO 2023, Green Corridor, Net-Zero) with ASR open in the Optimistic Trade Scenario (OTS).



Extended Data Figure 9 | Projected shipping CO_2 emissions by vessel type under four policy scenarios (BAU, IMO 2023, Green Corridor, Net-Zero) with ASR open in the Pessimistic Trade Scenario (PTS).

Comment 11: *Fig. 2, will the Northwest Passage and Transpolar Sea Route not open by the end of this century? And will the shipping flow on the Arctic passage be the largest at that time?*

Response 11: While Arctic shipping routes—including the Northeast Passage (NEP), Central Arctic Route (CAR), and Northwest Passage (NWP)—will experience substantial growth throughout the 21st century, the ASR as a whole is projected to become the eighth largest global corridor by 2100 under the SSP2 scenario, with a total flow share of approximately 2.25%.

Our results indicates that the ASR will not surpass traditional high-volume trade corridors, such as those in the North Pacific, Indian Ocean, or around Southeast Asia. Instead, it will act as a strategic supplement to existing routes, particularly for flows between Northeast Asia and Northern Europe (see Figure 3 below).

Moreover, not all shipping routes will experience rerouting toward the Arctic. Rather, the redirection is geographically selective, primarily affecting corridors closely associated with the Northern Hemisphere and ASR. By contrast, trade between Southern Hemisphere nodes or intra-regional flows within the Global South will remain largely unaffected. This spatial selectivity is detailed in Table S4, which provides a corridor-level breakdown of shipping flows under the OTS and PTS.

Thus, while the ASR gains in importance, it does not displace global shipping centers, particularly those in Northeast Asia, which remain dominant because of their established port infrastructure, manufacturing capacity, and network centrality.

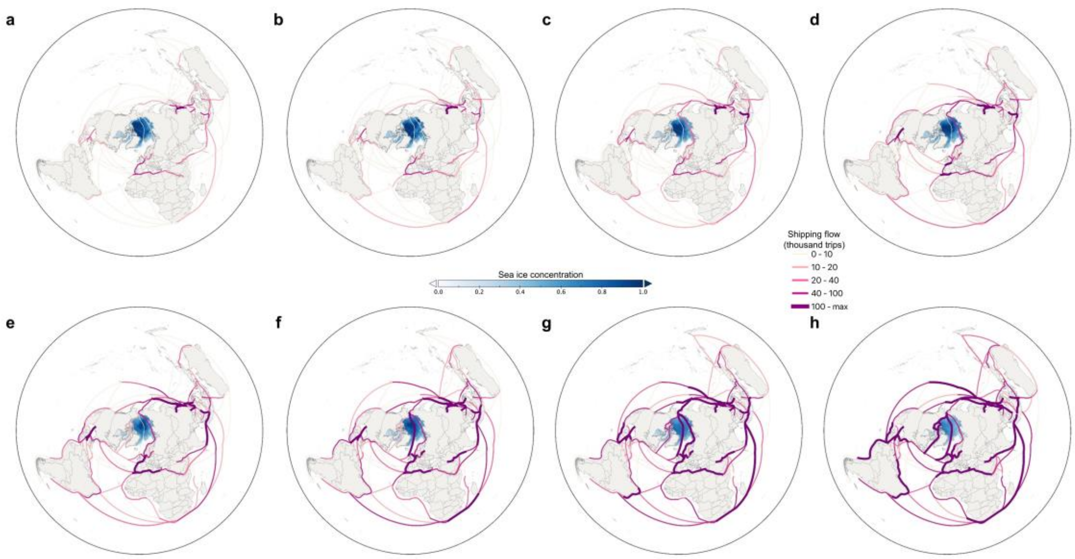


Figure 3 | Projected shipping flow with ASR open in the Optimistic Trade Scenario (OTS).

Comment 12: *Why does Asia, rather than North America, become the center of shipping in 2100? Is there any background information in the design of the predictive model? How about the mid-century?*

Response 12: We thank the reviewer for this thoughtful question regarding Asia's central role in global shipping by 2100. This outcome in our model is not solely the result of the accessibility of the ASR but also reflects persistent macroeconomic and geostrategic realities that are already evident in the base year.

In our model, **Asia is already the center of global shipping activity in the base year (2022)**, primarily because of

1. the dominant export role of **China and other East Asian economies** in global manufacturing,
2. the critical function of the **Strait of Malacca** as a key chokepoint linking the Indian Ocean and the Pacific, and
3. the high volume of intra-Asian trade, which continues to outpace intercontinental shipping volumes.

As shown in **Figure 4** below, Asia already accounts for most global maritime flows in 2022. The **opening of the ASR reinforces its centrality** by

1. **shortening transit times between Asia and Europe**, making Asian ports even more competitive in Eurasian trade,
2. **diverting shipping flows** that originally passed through traditional chokepoints such as the Suez Canal and Panama Canal toward the northern corridors adjacent to Asia, and
3. **attracting cargo flows** from the southern hemisphere toward **Northern Hemisphere trade hubs**, particularly in East Asia.

Thus, rather than reducing Asia's shipping activity, **access to the ASR amplifies it**, for many rerouted voyages would now traverse Arctic passages that begin or end in Northeast Asia. These results are supported by our trade projections under the SSP2 scenario, which show a significant concentration of ASR-linked shipping flow near East Asian ports by 2100.

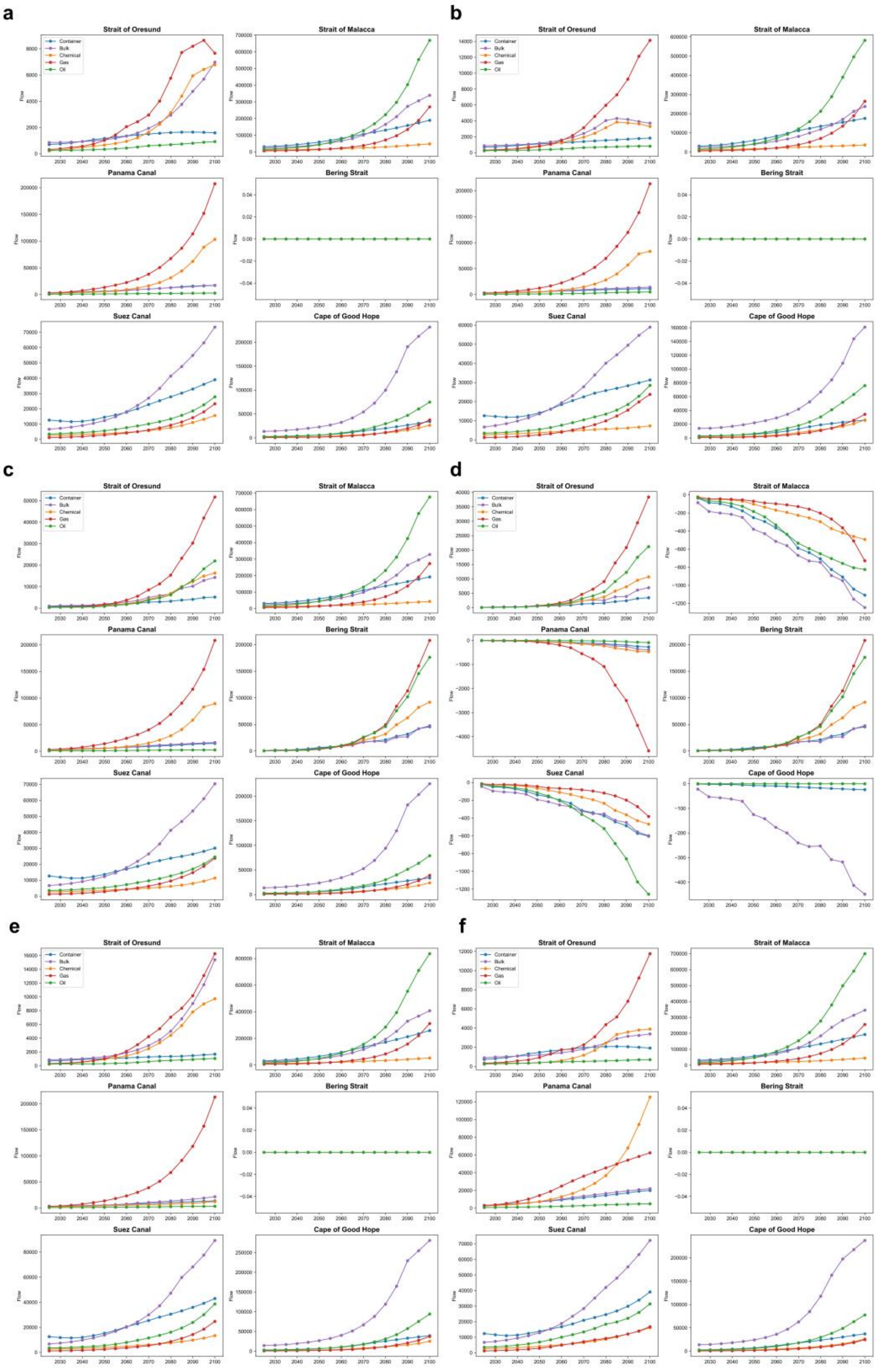


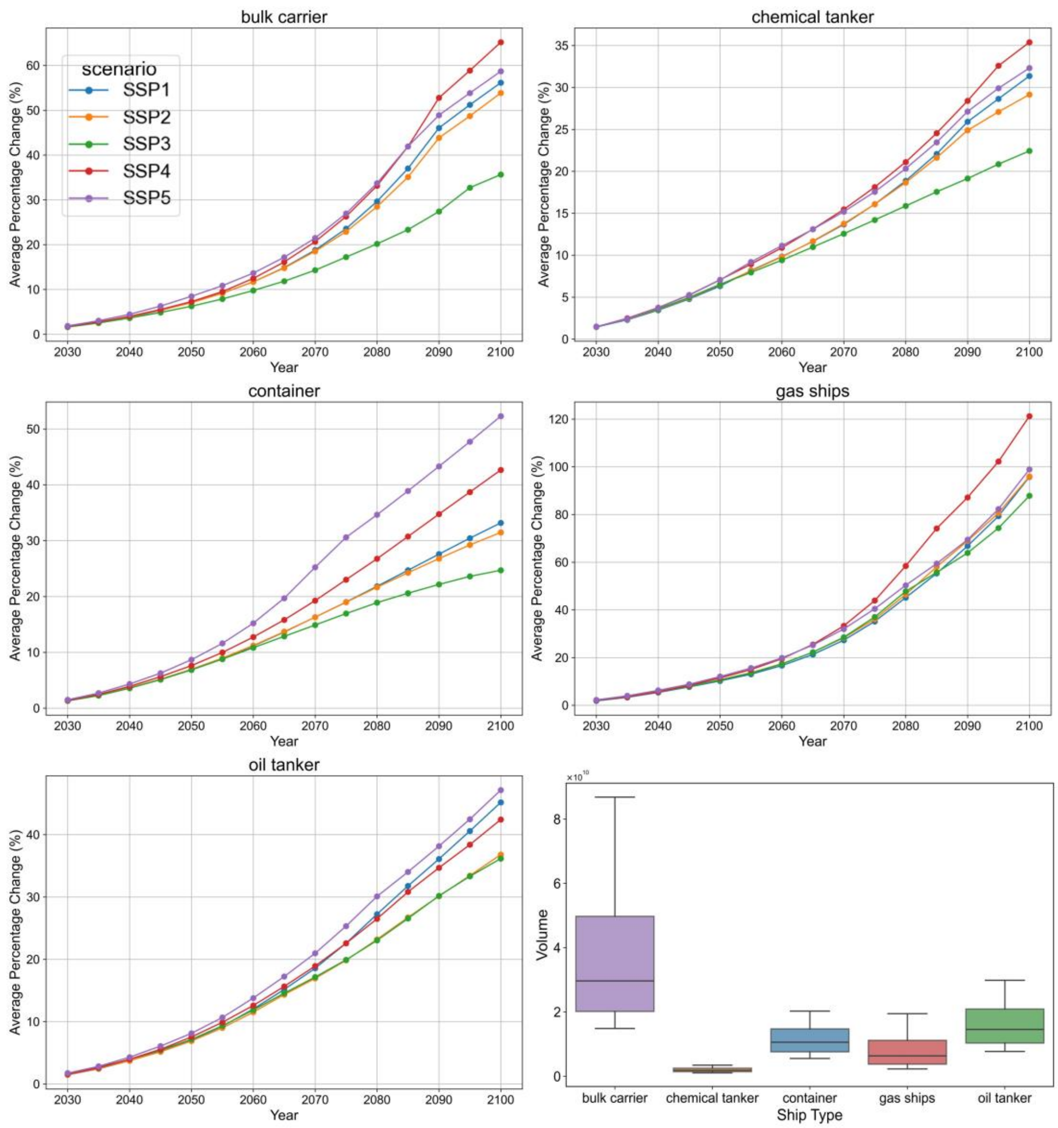
Figure 4 | Change in shipping flow among SSPs of main chokepoints. (a) SSP1. (b) SSP2. (c) Difference in shipping flow between with and without ASR opening of SSP2. (d) SSP3. (e) SSP4. (f) SSP5.

Comment 13: *Line 124 and Fig. 2, why does the proportion of containers decline rapidly and the gas carriers remain the biggest category over the century?*

Response 13: We thank the reviewer for this insightful question. In the revised manuscript, the main text focuses on the net increase in shipping flow by vessel type while the temporal variation in their relative proportions is presented in Supplementary Fig. 6. This supplementary figure illustrates the projected changes in global trade volume by vessel category, which is the basis for shipping flow modeling.

Our results show that gas carriers experience the most significant increase in relative share, while the growth of container vessels is more moderate. This trend is driven by long-term structural shifts in global trade and energy systems, which we now clarify in the revised text. Specifically, the rise of gas carriers over the 21st century (2025–2100) is largely attributable to the global energy transition. As countries pursue decarbonization targets, the demand for liquefied natural gas (LNG) as a transitional fuel is expected to remain strong in the medium term. Over time, this demand shifts toward low- or zero-carbon alternatives such as hydrogen and ammonia, both of which also rely on specialized gas tankers for bulk maritime transport. These fuels are central to net-zero strategies and are projected to dominate cross-regional energy logistics by mid-to-late century, thus cementing the role of gas carriers as the leading vessel type in global flows.

Conversely, the decline in container ship share is linked to a plateau in globalized manufacturing trade. Factors such as nearshoring and regionalization of production, automation and digital supply chains, and the growth of the circular economy (Ellen MacArthur Foundation, 2022) are expected to reduce the volume and distance of containerized freight. Additionally, carbon pricing mechanisms and regulatory burdens such as fuel-specific emission limits tend to impose higher compliance costs on container ships, thereby further constraining their competitiveness relative to gas tankers, which are more adaptable to fuel substitution.



Supplementary Fig. 6 | The average percentage change and the trade volume (metric tons) distribution by vessel type of SSP2.

Comment 14: *Please clarify the differences in various SSPs.*

Response 14: We thank the reviewer for pointing this issue out. We have now added a clear explanation of the differences among the Shared Socioeconomic Pathways (SSPs) in the revised Supplementary Method 1. Briefly, the SSPs represent five distinct global development scenarios that combine varying degrees of societal, technological, and policy challenges to mitigation and adaptation. These narratives guide our assumptions for trade volume, energy use, and policy environments in various future pathways, thereby influencing our emissions projections. We hope this clarification strengthens the understanding of the scenario-based uncertainties in our study.

Comment 15: *Line 147, compared with the situation at the end of this century, the situation in the mid-century may be more relevant and practical.*

Response 15: We appreciate the reviewer's thoughtful observation. Indeed, while end-of-century projections (e.g., for the year 2100) offer important insights into long-term structural trends, we fully agree that conditions around 2050 are often more relevant and actionable for current policy, infrastructure planning, and technological development. To account for the practical importance of these mid-century conditions, our modeling framework includes full temporal trajectories from 2025 to 2100, enabling granular analysis at intermediate time points. In particular, we highlight mid-century (2045-2055) transitions in our results.

1. changes in global and Arctic shipping emissions under different decarbonization scenarios (see Fig. 3),
2. shifts in vessel-type composition across the Arctic Sea Route (see Extended Data Table 1), and
3. the impacts of regional chokepoints and emissions redistribution across sea basins (see Fig. 4).

Our fuel transition assumptions are benchmarked to 2050 based on empirical projections from the DNV Maritime Forecast to 2050 (2024) for the near- and mid-term decarbonization pathways. Beyond 2050, our extrapolations adopt the IMO's EEOI-based framework, with conservative assumptions about efficiency gains and fuel availability. We explicitly note that policy implications and infrastructure investments such as port retrofitting, fleet modernization, and route governance must be grounded in mid-century planning horizons, especially given the uncertainties associated with late-century technological and geopolitical developments. Thus, while our model extends to 2100 to illustrate full scenario envelopes, we have taken care to emphasize mid-century insights in both the Results and Discussion sections. We thank the reviewer again for pointing out the practical importance of this temporal focus.

Comment 16: *Line 152, "The trends of total shipping flow show that there will be a general rise in the total shipping flows for all vessel types", and "There will be high activity for the sea routes running along the East-Asian coast and through the Indian Ocean, with values for the flow of between 200,000 and 600,000". Why do emissions decrease in traditional shipping routes despite the increase in shipping flow?*

Response 16: We thank the reviewer for this insightful question. In the revised manuscript, we have updated both the shipping flow redistribution model and the carbon emissions estimation method to better reflect the influence of decarbonization policies and vessel-level fuel transitions. While total shipping flow increases globally across all vessel types, particularly along key corridors such as the East Asian coast and the Indian Ocean, the relationship between shipping activity and emissions becomes non-linear under the policy scenarios because decarbonization strategies directly alter the carbon intensity per unit of transport, thus decoupling emissions from flow. Specifically,

1. Under the **BAU** scenario, emissions will grow proportionally with shipping volume, and traditional routes will continue to carry significant cargo, and the lack of fuel reform leads to higher emissions.

2. Under the **IMO 2023** and **Green Corridor** strategies, cleaner fuels such as LNG, methanol, and biofuels would be introduced along major trade lanes. As a result, **emissions would decrease along traditional shipping routes despite increasing shipping flow**. For example, emissions along the Suez Canal and Indian Ocean would decline significantly under the Green Corridor scenario, where these regions are prioritized for zero-carbon fuel deployment.

3. This trend is most pronounced under the **Net-Zero strategy**, which imposes tank-to-wake fuel neutrality and stricter fuel standards globally. The results would be **near-linear reductions in emissions** even as trade and vessel activity continue to grow (Fig. 3; Extended Data Figures 8 and 9).

As we state in the manuscript:

Under the BAU baseline, Arctic emissions would rise steeply, as noted. The IMO strategy (Fig. 3a) would moderate but not reverse this trend, with emissions peaking at ~1.32 Mt CO_{2eq} *by 2070. The Green Corridor strategy would perform better, with emissions peaking at ~0.63 Mt long-term mitigation effectiveness, in 2030, before declining. Only the Net-Zero strategy delivers near-linear reductions, reaching zero emissions by 2100 with >90% cumulative abatement relative to IMO 2023*.

In sum, **emissions would decrease along traditional shipping routes in scenarios with strong decarbonization commitments**, even as trade flows increase. This outcome highlights the critical role of **fuel transition and policy ambition**, rather than traffic volume alone, in shaping spatial emission outcomes.

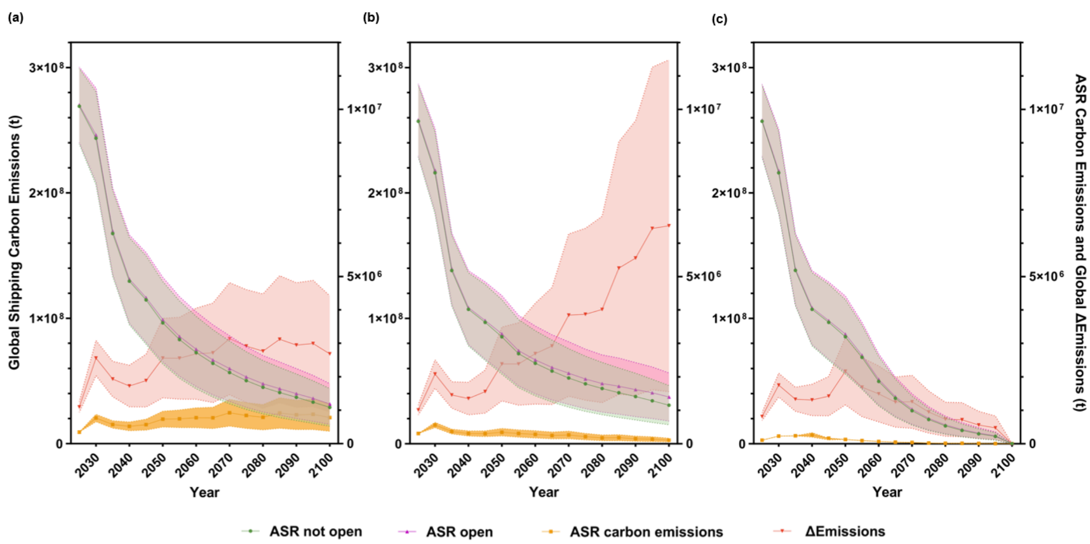


Fig. 3 | Temporal impacts of the opening of the ASR on global shipping CO_2 emissions under three decarbonization strategies from 2025 to 2100. Each panel displays projected global shipping carbon emissions and associated Arctic-induced emission changes under three policy strategies. (a) the IMO 2023 Strategy, (b) the Green Corridor Strategy, and (c) the Net-Zero Strategy. For each strategy, the solid green line represents global emissions without ASR access while the solid pink line shows emissions with ASR access. The orange line reflects emissions occurring specifically along ASR corridors. The red line indicates the net increase in global emission attributable to ASR access (ΔEmissions = ASR open − ASR not open). The upper and lower bounds of each shaded band represent emissions under the OTS and PTS, respectively.

Comment 17： *Fig. 3b, why does the emission peak in 2080 and then continue to decrease till 2100?*

Response 17: As we revised the methods in carbon emission prediction, the temporal variation also changed, as shown in Fig. 3; we also address this issue in the response to Comment 16. The trend of the carbon emission under the BAU scenario goes along with the change in the trade volume (Fig. 2).

The Arctic is emerging as a critical frontier for maritime carbon emissions under the business-as-usual (BAU) scenario. With fuel structures unchanged and trade volumes rising, the opening of the ASR is projected to drive a substantial increase in shipping carbon emissions across the North Polar Region (Fig. 2a; Extended Data Figs. 5 and 6). According to the TISEP model, emissions are expected to rise from a minimal baseline of 1.01 Mt CO_{2eq} in 2022 to 117.61 Mt under the OTS and 36.25 Mt under the PTS by 2100, with the Central Arctic Route contributing 58.28%, the Northeast Passage 17.25%, and the Northwest Passage 24.47%. Consequently, the ASR is poised to become one of the five most carbon-intensive shipping corridors globally, with its share of global maritime emissions rising from 0.22% to 2.72% under the OTS or 1.01% under the PTS. This escalation—largely occurring after 2050—will be driven primarily by increasing traffic from gas, oil, and chemical tankers, which together account for 87.37% of ASR emissions under the OTS or 81.05% under the PTS. Although ASR access shortens voyages and reduces per-trip emissions, these gains will be offset by a sharp increase in overall traffic across all vessel classes, including bulk, container, oil, chemical, and gas carriers.

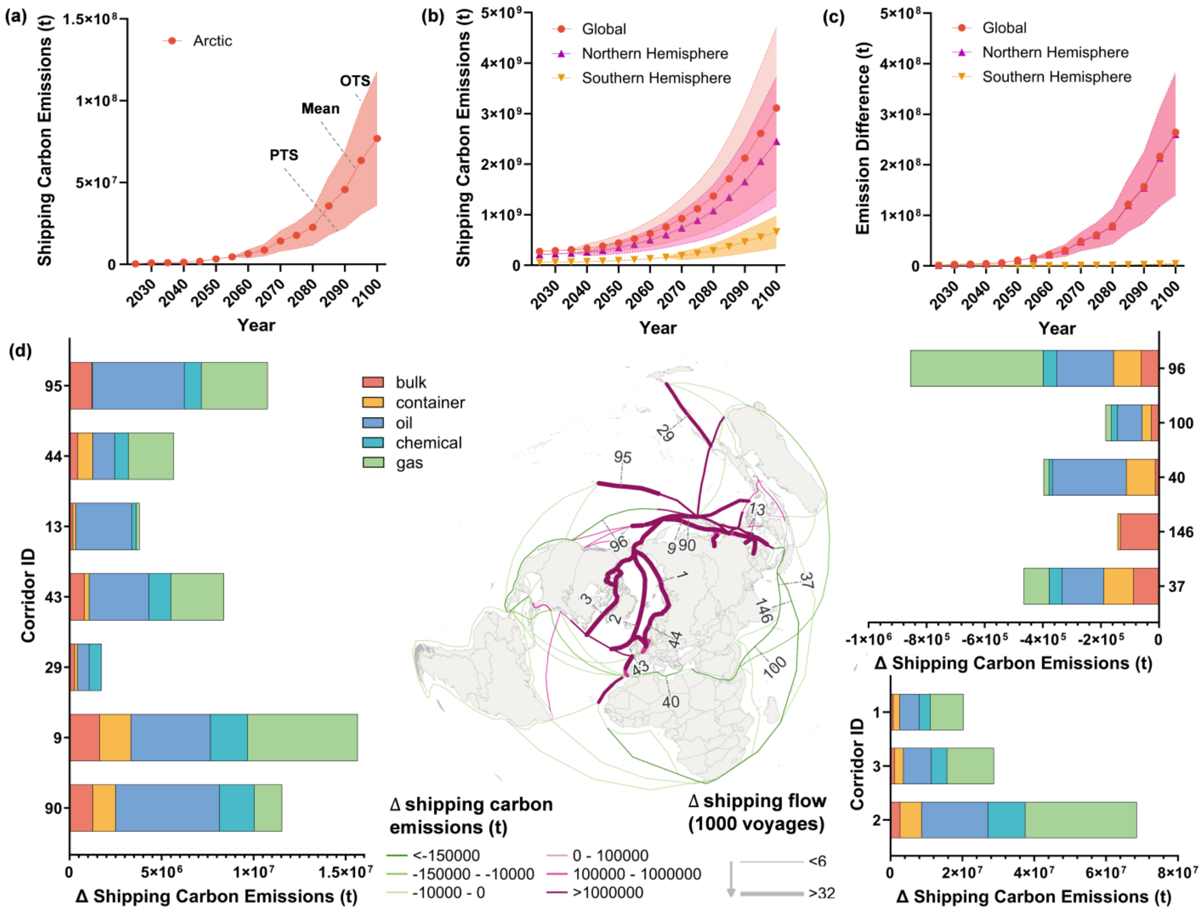


Fig. 2 | Evolution and spatial redistribution of global shipping carbon emissions resulting from ASR access from 2025 to 2100 under the BAU trade scenario. (a) Projected Arctic shipping emissions under ASR access, disaggregated by vessel type (bulk, container, oil, chemical, and gas carriers); **(b)** global and hemispheric trajectories of shipping carbon emissions under ASR access over time; **(c)** net increases in global and hemispheric shipping emissions attributable to ASR access by 2100 relative to a no-ASR counterfactual; **(d)** spatial distribution of net increases in shipping carbon emissions across major global shipping routes by 2100 attributable to ASR access relative to a no-ASR counterfactual. The key routes and chokepoints include the Arctic Northeast Passage (1), the Central Arctic Route (2), the Arctic Northwest Passage (3), the Tsugaru Strait (9), the Taiwan Strait (13), the Luzon Strait (90), the Coral Sea (northeastern Australia) (29), the Malacca Strait (37), the Suez Canal (40), the US-UK corridor (43), the Oslo-Rotterdam corridor (44), the North Pacific Transoceanic corridor (95), the North Pacific corridor (96), the South Arabian Sea corridor (100), and the Indian Ocean Transoceanic corridor (146).

Comment 18: *How about the emissions under different SSPs in the mid-century?*

Response 18: In the revised manuscript, we have added the analysis of carbon emissions under the four emission scenarios and excluded the variation in the SSP scenario. We demonstrate the spatial pattern of carbon emissions in mid-century in Extended Data Figures 5 and 6.

Comment 19: *Line 164-165, the shift of traffic toward ASRs is logical. However, it implies a change in relative proportions. The total shipping flow is increasing.*

Response 19: While the total volume of global shipping would increase throughout the 21st century across all scenarios, the relative share of traffic routed through the ASR would also increase over time. This trend reflects the growing navigability and commercial attractiveness of Arctic routes as sea ice retreats, especially under high-emission and high-trade scenarios.

For example, under the SSP2–BAU scenario, the proportion of ASR traffic would increase from less than 0.3% in the base year to 2.25% by 2100, with the Central Arctic Route and Northwest Passage contributing more significantly after 2070. This increase reflects not only absolute increases in Arctic traffic but also a shift in the global shipping geography, particularly for trade routes linking Northeast Asia and Northern Europe. This growing proportion underscores the importance of including Arctic-specific emissions and policy considerations in long-term global shipping strategies.

Comment 20: *Why does this study primarily focus on the SSP2 scenario?*

Response 20: In this study, we adopt SSP2 ("middle of the road") as the core scenario for our main analysis. This pathway assumes that global socioeconomic trends—including population growth, economic development, and technological progress—follow historical trajectories without major deviations toward radical sustainability or extreme regional fragmentation. As such, SSP2 provides a balanced and widely accepted baseline for long-term projections.

Importantly, SSP2 ensures consistency with major climate-economy assessments, including those conducted by the IPCC, and facilitates comparability with other modeling studies. From a maritime perspective, because this scenario reflects moderate assumptions about global trade intensity, fuel transition progress, and international policy coordination, it is well-suited to capture the plausible evolution of global shipping networks.

Furthermore, in our previous work focusing on Arctic sea ice projections (Zhao et al., 2024), SSP2 demonstrated the lowest DISO (distance between indices of simulation and observation) when compared to observed historical sea ice data. This finding indicates that SSP2 exhibits the best simulation fidelity for Arctic conditions and, thereby, improves the reliability of future accessibility estimates for the Northeast Passage, Central Arctic Route, and Northwest Passage.

For these reasons, we use SSP2 as the default development pathway in our analysis while also providing comparisons across multiple trade and policy scenarios to reflect uncertainty in future global conditions.

Comment 21: *Fig. 4, attention should be given to the situations in the Suez Canal, the Cape of Good Hope, the Panama Canal, and Arctic seas.*

Response 21: We thank the reviewer for this insightful comment. In the revised manuscript, we have updated **both Fig. 1 and Fig. 4** and expanded the **Results** section to address the influence of access to the ASR on several key global chokepoints and sensitive maritime regions explicitly.

Fig. 1 presents a comprehensive analysis of shipping flow changes through major maritime chokepoints including the **Bering Strait, the Suez Canal, the Panama Canal, the Strait of Malacca, and the Cape of Good Hope**. Our findings show that, by 2100, the Arctic is projected to support year-round navigation for all major vessel types, with the ASR accommodating 2.25% (569,214 voyages) of global traffic under the OTS and 2.07% (180,608 voyages) under the PTS, surpassing Suez Canal traffic (OTS: 163,339 voyages) and approaching that of the Panama Canal (OTS: 331,435 voyages) (Fig. 1c,d).

Further, compared with a counterfactual scenario without ASR access (Fig. 1e,f), cargo flows through the Bering Strait would increase by 94.2–99.8% while traffic through the Suez and Panama Canals would decrease by up to 5.1% and 3.6%, respectively (Fig. 1g). These patterns reflect cost-driven rerouting and the growing role of the Arctic as a global transit corridor.

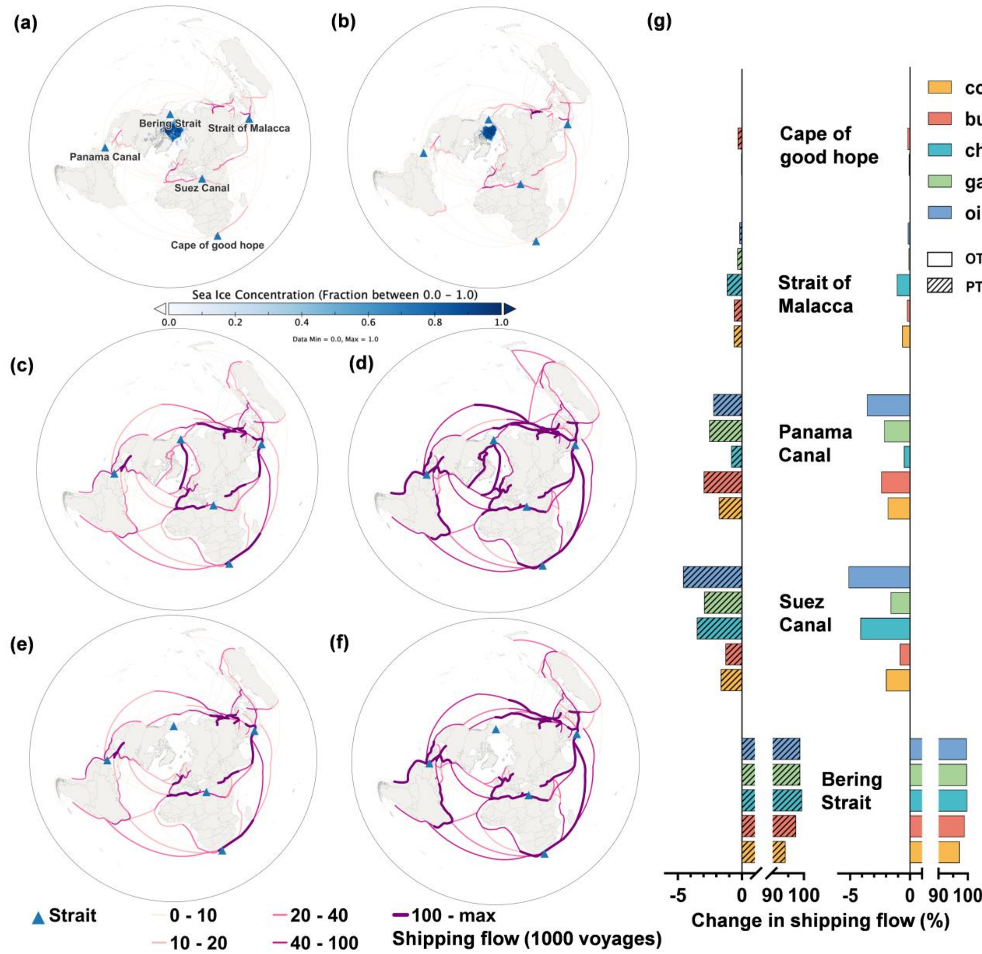


Fig. 1 | Global shipping flows with and without ASR access, 2022-2100, under the OTS and PTS. (a) Global shipping flows in 2022 overlaid with Arctic sea ice concentration; **(b)** projected shipping flows in 2050 under the OTS, with partial Arctic sea ice retreat; **(c)** projected shipping flows in 2100 under PTS; **(d)** projected shipping flows in 2100 under the OTS; **(e)** counterfactual scenario: shipping flows in 2100 under the PTS assuming no ASR access; **(f)** Counterfactual scenario: shipping flows in 2100 under the OTS assuming no ASR access; **(g)** impact of ASR access on shipping flows in 2100 (% change) at key global chokepoints (the Bering Strait, the Suez Canal, the Panama Canal, the Strait of Malacca, and the Cape of Good Hope).

Fig. 4 further illustrates the **spatial redistribution of shipping-related CO_2 emissions** under the three decarbonization scenarios. We highlight the following findings.

1. Suez Canal, Cape of Good Hope, and Panama Canal: These traditional routes show noticeable emission reductions because of the diversion of traffic toward Arctic routes under the ASR-accessible futures, particularly under the BAU and IMO scenarios.

2. Arctic Seas: Previously low-emission waters such as the Kara Sea, Lincoln Sea, and Baffin Bay emerge as carbon concentration hotspots because of increased ASR traffic.
3. The Strait of Malacca, while maintaining high throughput, also reflects the shift in flow patterns under regional trade reconfigurations.

We have updated the figure legends and incorporated this analysis into the revised Results section. These revisions help clarify how ASR access is reshaping **both the magnitude and spatial distribution of global shipping emissions**, with consequences for **regional economies**, **environmental exposure**, and **governance needs** in both polar and equatorial chokepoints.

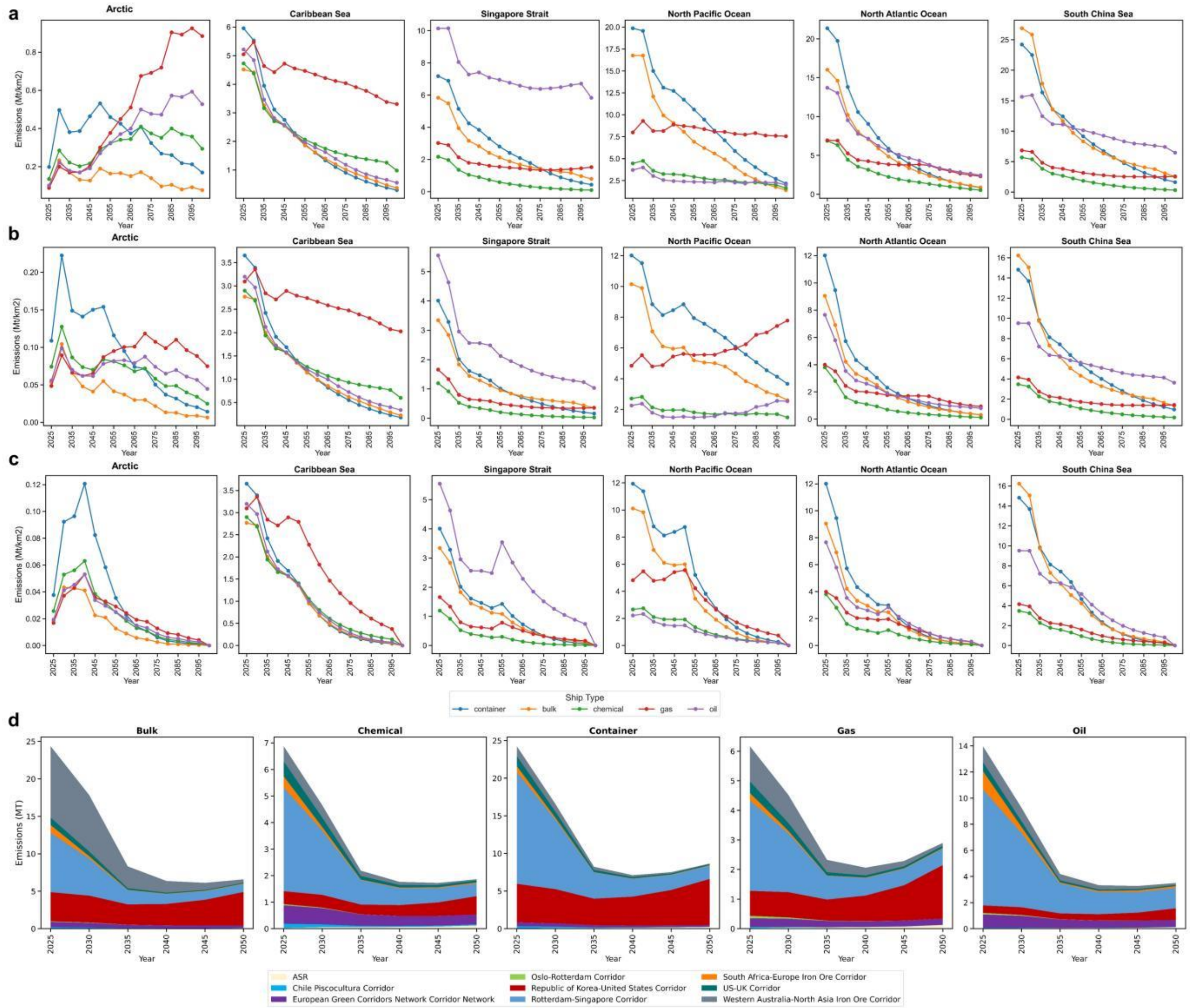


Fig. 4 | Projected regional shipping carbon emissions by ship type under three decarbonization strategies. Spatial projections of emission intensity (Mt CO_2/km^2) from 2025 to 2100 under **(a)** the IMO 2023 Strategy, **(b)** the Green Corridor Strategy, and **(c)** the Net-Zero Strategy across six major sea regions, namely, the Arctic, the Caribbean Sea, the Singapore Strait, the North Pacific Ocean, the North Atlantic Ocean, and the South China Sea. Each subplot shows emissions disaggregated by ship type: container, bulk, chemical, gas, and oil. **(d)** Sectoral distribution of projected carbon emissions along key green shipping corridors from 2025 to 2050.

Comment 22: *In the conclusion section, it is suggested to incorporate policy recommendations and future research directions to enhance the practicality.*

Response 22: We thank the reviewer for this helpful recommendation. In the revised **Conclusion** section, we have included specific **policy implications** and proposed **future research directions** based on the limitations and findings of our study. This addition increases the generalizability of our results by taking into account environmental justice, the vulnerability of the Arctic ecosystem, and more comprehensive Arctic governance.

Thus, the final paragraph in the Conclusion reads as follows:

As Arctic accessibility intensifies under continued climate change, the resulting shifts in maritime geography are poised to restructure global trade networks by redistributing economic opportunities and environmental burdens in profoundly unequal ways. Nations positioned to benefit from trans-Arctic shipping, such as Vietnam, South Korea, and Russia, may experience accelerated trade growth while other nations face marginalization as traditional routes lose strategic relevance. For example, the Suez Canal is currently a major source of foreign exchange for Egypt, contributing around 5% of the country's GDP and generating over $5 billion annually in toll fees, but it is economically exposed to traffic declines, with reduced flow directly diminishing canal revenues. While trade forecasts may overstate the reliance on the ASR by neglecting intermodal alternatives such as trans-Eurasian rail, such unquantified local feedback as soot-induced sea ice loss suggests that our projections may underestimate the long-term regional impacts. Even under a Net-Zero scenario that eliminates carbon emissions, the non-carbon externalities of intensified Arctic traffic remain unaddressed. These externalities include increased underwater noise and the risk of ballast-mediated species invasions, oil spills, and ship strikes, all of which jeopardize the ecological integrity of polar marine systems. Governance of the ASR must, therefore, move beyond decarbonization to embrace a comprehensive environmental protection agenda by integrating biodiversity safeguards and local community resilience into climate mitigation efforts. Absent such coordinated oversight, the gains of a decarbonized maritime future may come at the cost of irreversible harm to one of the planet's most climate-sensitive regions.

Comment 23: *Line 293-294, is the carbon emission per vessel a constant value per unit grid? How is it calculated?*

Response 23: We thank the reviewer for raising this question. The base-year carbon emissions per vessel are not constant across the grids. Moreover, our carbon emission projections are not based on individual grid cells or vessel track points but, rather, on aggregated emissions per shipping route, as described in the carbon emission prediction section of the **Methods**. Emissions are calculated using route-specific shipping flows, vessel types, fuel characteristics, and emission factors.

Based on the 2022 AIS data (including vessel speed, position, and time) and vessel archive data (such as maximum rated power and design speed), we employ a bottom-up approach (Johansson, et al., 2017; Wang et al, 2021) to calculate carbon dioxide emissions at the trajectory scale (Comer, 2021). The calculation formula is

$$\begin{aligned} E &= E_m + E_a + E_b \\ E_m &= P_m \times (V_{act}/V_{max})^3 \times T_v \times EF_m \\ E_a &= P_{a,i} \times T_v \times EF_a \\ E_b &= P_{b,i} \times T_v \times EF_b \end{aligned} \tag{14}$$

where E represents a vessel's total emissions; E_m, E_a, *and* E_b *represent emissions from the main engine (ME), auxiliary engine (AE), and boiler (BO), respectively;* P_m, P_a, *and* P_b *denote the rated power of the ME, AE, and BO, respectively;* V_{act} *indicates the vessel's actual speed;* V_{max} *indicates the vessel's design speed;* T_v *represents the time that the vessel operates at speed* V_{act}*; the vessel's operational modes i (such as "at berth," "anchoring," "maneuvering," and "cruising") are defined by* V_{act}*; and* EF_m, EF_a, *and* EF_b *are the emission factors for the ME, AE, and BO, respectively. The results are presented in Supplementary Fig. 14.*

To explore long-term decarbonization pathways in maritime shipping, we construct one baseline and three policy scenarios, each defined by distinct policy frameworks specifying emission targets, fuel mandates, and geographic coverage. These scenarios reflect a spectrum of ambition levels from inertial growth to full systemic decarbonization and are implemented within the TISEP model to quantify their respective impacts on global shipping emissions. The scenario-specific inputs include fuel mixes, policy timelines, and spatial applicability, all calibrated using historical AIS data, techno-economic fuel forecasts, and institutional targets.

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2. Wang, X.-T. et al. (2021). Trade-linked shipping CO2 emissions. *Nature Climate Change*, *11*, 945–951.

3. Comer, B., & Osipova, L. (2021). *Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies*. International Council on Clean Transportation.

Comment 24: *Line 304, is ARIMAX a nonlinearity method?*

Response 24: We appreciate the opportunity to clarify this point. The ARIMAX model is an extension of the ARIMA framework that incorporates exogenous variables, but it remains a linear time-series model. That is, the model assumes linear relationships between the dependent variable and both its own values and the external explanatory variables (Peter & Silvia, 2012; Ray & Bhattacharyya, 2020). While it is not inherently designed to capture nonlinear dynamics, it provides statistically grounded forecasts for time-dependent processes influenced by external drivers.

"The linear autoregressive integrated moving average with exogenous variable (ARIMAX) model was proposed, as this method achieved almost perfect forecasting performance for data previously difficult to predict, in most cases, with smaller values of root mean square error (RMSE) and mean absolute percentage error (MAPE) than time-series models and economic structural models." (Shen et al., 2021)

References

1. Peter, Ď., & Silvia, P. (2012). ARIMA vs. ARIMAX–which approach is better to analyze and forecast macroeconomic time series. In *Proceedings of 30th International Conference Mathematical Methods in Economics*, Vol. 2 (pp. 136–140).
2. Ray, S., & Bhattacharyya, B. (2020). Statistical modeling and forecasting of ARIMA and ARIMAX models for food grains production and net availability of India. *Journal of Experimental Biology and Agricultural Sciences*, *8*(3), 296–309.

3. Shen, M. L. et al. (2021). Effective multinational trade forecasting using LSTM recurrent neural network. *Expert Systems with Applications*, *182*, 115199.

Comment 25: *Line 313, the variables (GDP, population data, common official language, common border, common colonial history, and regional trade agreement data) should be filtered before model construction.*

Response 25: We thank the reviewer for the constructive comment. We agree that careful preprocessing of the explanatory variables is essential to improve the interpretability and robustness of the model. Accordingly, we have refined our treatment of the key variables used in the trade flow and emissions projection components of the TISEP model as follows.

Filtering for multicollinearity: Before constructing the model, we conducted a variance inflation factor (VIF) analysis and pairwise correlation checks among socioeconomic variables, including GDP, population, common language, colonial history, border adjacency, and trade agreements. Highly collinear variables (e.g., GDP vs. population in some regions) were assessed and adjusted to avoid distortion of coefficients.

Variable standardization: Continuous variables such as GDP and population were normalized (log-transformed and scaled) to ensure comparability and numerical stability during estimation.

Binary variable validation: Categorical indicators (e.g., common official language, colonial history, common border) were re-verified using consistent datasets from CEPII and the WTO RTA database to ensure up-to-date and globally comparable inputs.

Relevance filtering: To reduce noise, we excluded variables that showed consistently low explanatory power in preliminary regressions and conducted stepwise selection to retain only the most significant predictors in the final gravity model.

These steps are now described in the revised **Methods** section and further detailed in the **Supplementary Materials** to ensure that our modeling approach is transparent and replicable. For the ARIMAX model, we removed countries without maritime trade links and retained over 98% of the world's major economies (see Supplementary Fig. 1). Additionally, we processed the missing values and calculated the VIF among the exogenous variables to minimize multicollinearity and ensure the robustness of the estimation of the model. All of the variables selected in this model are shown in Supplementary Table 2, and their low VIFs (< 5) indicate the relative independence of our trade forecast model and ensure its stability and interpretability.

Comment 26: *Line 387-389, the Northeast Passage will not be fully navigable year-round in the coming decades either.*

Response 26: We thank the reviewer for this important clarification. We fully agree that the Northeast Passage is unlikely to be fully navigable year-round in the coming decades. In the revised manuscript, we have carefully revised the corresponding sentence to avoid any implication of continuous year-round accessibility.

Based on our previous work (Zhao et al., 2024), the Northeast Passage is projected to experience extended seasonal accessibility under mid- and late-century climate scenarios, particularly under SSP2. However, ice-related constraints during winter months will remain, limiting full-year navigability. We also emphasize that the Northwest Passage remains even more constrained because of narrow channels, multi-year ice, and complex topography, which render it less viable for commercial transit compared to the Northeast Passage or Central Arctic Route.

Importantly, in this study, we do not assume full navigability for any Arctic passage at any time. Instead, we use a high-resolution, 10-day interval sea ice dataset to dynamically assess navigability across the three major Arctic routes:

the Arctic Northeast Passage (along the Russian coast),

the Central Arctic Route (through the Transpolar Sea), and

the Northwest Passage (across the Canadian Arctic Archipelago).

We used these dynamic sea ice conditions to constrain both the Arctic shipping redistribution modeling and the spatial visualization of projected flows. This approach ensures that our results are consistent with the latest scientific understanding of variability in Arctic sea ice and do not overstate future accessibility.

Reference

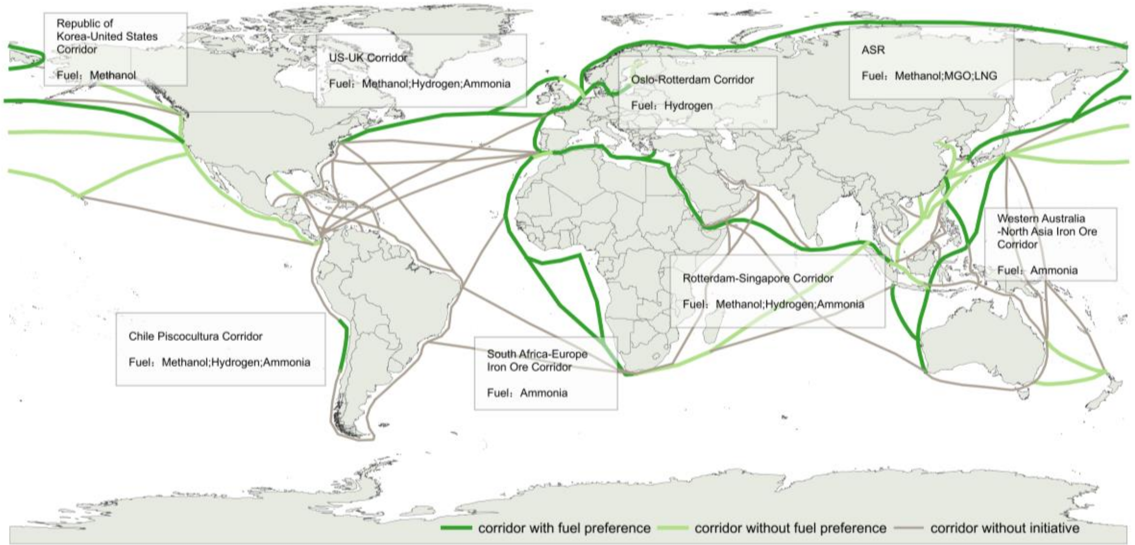
1. Zhao, P., Li, Y., & Zhang, Y. (2024). Ships are projected to navigate year-round along the North Sea Route by 2100. *Communications Earth & Environment*, *5*, 407

Comment 27： *Equation (12), it might be applicable to global estimations, but it is not suitable for Arctic estimates due to sea ice and other unique environmental factors.*

Response 27: We appreciate the reviewer’s important observation. In the revised manuscript, we have refined our carbon emission estimation methodology, particularly for Arctic-specific contexts (in the Methods section). Specifically, we have integrated the influence of dynamic sea ice conditions into the Arctic shipping prediction that is the basis for Arctic carbon emission estimates. Furthermore, our emission projections account for Arctic-specific considerations in fuel selection, including the operational challenges posed by low temperatures and the environmental sensitivity of the region (detailed in the Supplementary Information). These refinements ensure that our approach better reflects the unique environmental constraints of Arctic navigation.

We project Arctic sea ice conditions, including sea ice thickness (SIT), sea ice concentration (SIC), and drift, from 2022 to 2100 under the SSP2 scenario. The methodology integrates the CMIP6 climate projections with vessel-specific operability thresholds to determine navigable windows. Given the strong intra-annual variability of ice conditions, we generate forecasts at 10-day intervals (hereafter referred to as “periods”). Based on these projections, we delineate seasonally navigable corridors with and without the assistance of icebreakers across the 2022–2100 horizon (see Supplementary Fig. 11 for visual reference). The methodological details are available in our previous work (Zhao et al., 2024).

Additionally, considering the ecological vulnerability of Arctic routes and the specific challenges of navigating in frozen areas, we have designated these routes as green corridors and designed specialized fuel substitution pathways, such as LNG, methanol, and MDO, to address the environmental challenges and navigation needs of these specific regions. The fuel preferences for each green corridor are shown in Extended Data Figure 10.



Extended Data Figure 10 | The spatial distribution of the green shipping corridor; the main corridors are shown with the fuel preference.

Reviewer #4

The authors target to forecast future shipping carbon emissions and assess the potential of ASR in reducing shipping carbon emissions on the global shipping network. The work is interesting and the authors have done an abundant work on global trade forecast and shipping emissions forecast, while I have concerns on the forecasts model and the final results of the emissions. Maybe a reject and resubmission is suggested. The detailed suggestions are listed below:

Comment 1: *The authors target to investigate the potential of ASR in absorbing future trade and shipping activities, but the literature review lacks reviewing some latest literature of Arctic shipping in recent 5 years. Some references are relatively too old, e.g. 3, 4.*

Response 1: We thank the reviewer for pointing this out. We agree that incorporating recent research is essential for grounding our work in the current scientific discourse. In the revised manuscript, we have updated the literature review section to include several studies published within the past five years addressing Arctic navigability, environmental risks, and international shipping emissions.

The literature reviewed in this study is contained in documents numbered 1–26. Of these 26 documents, most (18) were published between 2020 and 2025, while only a few (8) were published earlier, between 2015 and 2019. These are classic works on the opening of the ASR and the calculation of shipping carbon emissions.

1. Arctic navigability (in the first paragraph of Main)

As this transformation continues, previously inaccessible Arctic passages—including the Northeast Passage, the Central Arctic Route, and the Northwest Passage—are becoming viable for commercial navigation[3,4]. Collectively referred to here as the Arctic Sea Route (ASR), this emerging corridor can reduce the distance of voyages between Europe and Northeast Asia by as much as 40% and shorten transit times by as much as 30%[5,6]. By 2030, access to the ASR is projected to increase trade volumes between these regions by 5% to 10%[7,8] because of lower per-voyage fuel costs and improved network efficiency. These developments point to a gradual but *significant shift in global maritime connectivity, with Arctic routes becoming increasingly integrated into the evolving network of international shipping.*

2. Environmental risks (in the second paragraph of Main)

However, the environmental implications of expanded Arctic shipping remain a significant concern, particularly regarding long-term emissions trajectories and the spatial redistribution of carbon burdens[9-12]. International shipping already accounts for nearly 3% of global anthropogenic CO_2 emissions [13,14]. Although ASR access may reduce the amount of emissions per voyage through shorter routes, the overall climate benefit would be offset by the projected increases in total traffic, especially from carbon-intensive vessel classes such as oil, gas, and chemical tankers [15-17].

3. International shipping emissions (in the second paragraph of Main)

[This situation poses] significant risks to ecologically vulnerable Arctic regions [18-20]. The increases in total traffic will also create challenges to achieving the decarbonization targets set by the International Maritime Organization (IMO) to reduce total annual GHG emissions by at least 20% relative to 2008 levels by 2030, at least 70% by 2040, and reach net-zero emissions by around 2050[12,21]. For the Arctic especially, the IMO has been promoting low-environment-impact initiatives, including the Polar Code[22] and a scheduled ban on the use and carriage of heavy fuel oil (HFO) in Arctic waters[23]. However, the effectiveness of these measures depends on enforcement, monitoring, and broad international compliance[21,24].

4. The research gaps regarding the above three aspects are summarized in the third paragraph.

While some earlier studies have examined the effects of access to the ASR on shipping emissions[15,16,25,26], significant gaps in the research remain. First, most of the existing literature focuses on the local environmental impacts of access to the ASR in the Arctic region[18,19,23] while the impacts on global shipping emissions have received little attention. In particular, the geographic redistribution of carbon burdens and the resulting environmental inequalities in exposure to emissions across regions have not been sufficiently addressed[16,27]. Second, a practical prospective scenario for achieving zero emissions in the Arctic is lacking[21,28]. Third, there is a shortage of comprehensive *prediction models that integrate global trade forecasts, shipping route decisions, and alternative fuel scenarios, for most current models focus either on routing efficiency*[21,26,29] *or global trade projections*[27,30] *in isolation. There is, therefore, a pressing need for an integrated, forward-looking framework that links trade intensity, routing dynamics, and international climate goals.*

These additions ensure that our work is better contextualized in the evolving body of literature and help clarify our approach, particularly through the TISEP framework and scenario-based analysis. We appreciate the suggestion and have, accordingly, strengthened our literature review.

Comment 2: *The proposed model of trade-integrated shipping emission projection (TISEP) framework is relatively novel, however, it lacks a deep understanding of shipping industry itself. E.g. the authors emphasized the importance of IMO's regulations on shipping activities, but for some key assumptions they did not show the shipping or IMO considerations, such as emission measurement criterion: well to wake emission or well to tank emission? This is a key focus of recent IMO regulations. As the author forecast till 2100, this must be considered. Besides, the bunker fuels used by ships in the future is also critical, due to IMO's and EU's latest regulations, current heavy fuels might not be used globally, new fuels (methanol, green methanol, ammonia, etc.) may have totally different fuel consumptions and GHG emissions. The authors solely calculate the future carbon emissions based on historical data and simple assumptions as in formula (12), I do not think this is enough.*

Response 2: We sincerely appreciate the reviewer's insightful comments regarding the assumptions embedded in our TISEP framework. We agree that forecasting maritime carbon emissions through 2100 requires a deep integration of maritime regulatory frameworks, particularly those of the IMO, and a deep understanding of future fuel transitions and emission calculation methods. In response, we have revised and expanded both the Methods and Supplementary Information sections to clarify these points and better align our modeling assumptions with current industry and regulatory developments.

1. Emission Measurement Criteria: Tank-to-Wake (TtW)

We have updated the manuscript to clarify that our emission estimates are based on tank-to-wake (TtW) emissions rather than well-to-wake. TtW accounting encompasses the emissions of combustion onboard. This methodology is consistent with the latest IMO and EU regulatory discussions, which emphasize full lifecycle emissions in fuel standard comparisons (EU FuelEU Maritime, 2023; IMO, 2023).

The final paragraph of the Main and the scenario setting for the IMO 2023 strategy in the Methods section emphasize that the emissions measurement criteria in this study is tank-to-wake.

Leveraging over 6.49 billion AIS signals and long-term trade projections, the TISEP model simulates global shipping flows and associated CO_{2eq} emissions under varying trade intensities and decarbonization policy strategies.

Notably, the IMO's definition of "net-zero by or around 2050" refers to well-to-wake emissions, encompassing the entire fuel lifecycle, from production and transport to onboard combustion. This accounting framework allows fuels with upstream carbon mitigation (e.g., biofuels, e-ammonia with renewable electricity, or carbon capture at production sites) to qualify as zero-emission though combustion at sea still generates substantial tailpipe emissions. This distinction is particularly relevant for trans-Arctic shipping, during which vessels release residual CO_2 and black carbon directly into highly sensitive ecosystems. By contrast, the Net-Zero strategy introduced in this study involves the adoption of a stricter operational boundary, targeting zero emissions at the point of use (tank-to-wake) through the deployment of fully non-emitting technologies such as battery-electric systems, nuclear propulsion, and hydrogen fuel cells. This divergence highlights both the limitations of current international frameworks and the importance of spatially differentiated mitigation strategies for ecologically vulnerable regions.

2. Future Fuel Structure and IMO GHG Strategy Integration

To address concerns about fuel transitions, we have significantly expanded the assumptions related to alternative fuels and carbon capture technologies based on recent IMO strategies and forecasts from maritime research institutes, particularly the 2023 IMO

GHG Strategy and the DNV Maritime Energy Transition Outlook (2024). Accordingly, we set four scenarios according to the 2023 IMO GHG Strategy, the Green Shipping Corridor Initiative, and the potential for disruptive change in decarbonized fuels/technologies.

A brief introduction about these decarbonizing scenarios can be found in the last paragraph of Main:

Leveraging this framework, we examine how three decarbonization strategies shape future emissions trajectories and spatial outcomes under various trade and routing scenarios. Two of these strategies, the IMO 2023 strategy[12] and the Green Corridor strategy[31,32], are supported by international efforts involving the IMO. The IMO 2023 strategy reflects the organization's revised GHG reduction targets and assumes a sector-wide shift toward low- and zero-carbon fuels through gradual compliance mechanisms. The Green Corridor strategy builds on this approach by accelerating green fuel deployment along maritime routes selected for their geopolitical or ecological significance. The third strategy, Net-Zero, is new. It introduces a structurally distinct decarbonization pathway anchored in two core features: stricter fuel standards and a regionally phased rollout. The first feature centers on a tank-to-wake emissions boundary, requiring zero emissions at the point of combustion, and marks a fundamental departure from the well-to-wake accounting in the IMO 2023 and Green Corridor strategies[32,33], which credit upstream mitigation but allow significant emissions at sea. To meet this stricter criterion, the Net-Zero strategy prioritizes the deployment of truly zero-emission energy carriers—specifically, electricity, hydrogen, and nuclear propulsion[34-36]. The second feature involves spatially staged implementation, beginning in the Arctic, where ecological sensitivity is greatest, by 2040 and extending globally after 2050. This phased rollout enables the sector to reach full operational decarbonization by 2100. The projections of the TISEP model show that neither the IMO 2023 nor the Green Corridor strategy would fully eliminate Arctic emissions by the end of the century. By contrast, the Net-Zero strategy, through a combination of fuel strictness and geographic prioritization, would not only achieve zero emissions in the Arctic but also help mitigate global environmental inequalities in shipping-related pollution exposure.

More specific information on each scenario can be found in the "Carbon emission prediction" section in Methods and Tables 7–10 in the Supplementary Information.

Comment 3: *Another key element is that ASR is not suitable for all kinds of trade or shipping. E.g. container shipping may not be economically viable via ASR as no large ports or economic hinterlands exist in the Arctic area, no matter Russia or Canada. ASR is good for bulk shipping and oil/LNG shipping. This could affect the trade forecast and trade assignment.*

Response 3: We thank the reviewer for this insightful comment. We fully agree with this view. In our previous manuscript, we indeed overlooked the economic differences of Arctic navigation across vessel types. As the reviewer rightly points out, the current absence of major ports and developed economic hinterlands along the Russian and Canadian Arctic coasts represents a fundamental constraint for container shipping (liner services), which relies heavily on such infrastructure for the efficient collection and distribution of cargo. This limitation indeed constitutes a key disadvantage for the utilization of the ASR by container vessels.

We address this limitation and the inherent economic differences across ship types in the following ways.

1. **Incorporating Cargo Utilization (Load Factor):** Building on insights from existing studies (Furuichi & Otsuka, 2015; Lasserre, 2014, 2015; Verny & Grigentin, 2009), which highlight the impact of limited commercial opportunities along the ASR on vessel profitability, we have explicitly integrated the load factor (LF) into our revised generalized cost model. The core logic is that the scarcity of developed ports/hinterlands will limit cargo utilization on ASR voyages, thereby increasing the generalized cost per unit of cargo for segments such as container shipping.

2. **Differentiating Ship-Type Parameters:** Based on our comprehensive review of the existing research on the economic feasibility of Arctic navigation for various vessel types, we have our updated generalized cost model. It now incorporates distinct parameter sets (including speed, fuel consumption rates, and operational costs) tailored specifically

for container ships, bulk carriers, and tankers (including LNG carriers). This differentiation captures the varying operational realities and cost structures across these segments in the Arctic context.

3. **Calibrating Trade Forecasts:** Crucially, these ship-type-specific economic assessments, particularly the higher generalized costs for container shipping due to the LF constraint, directly inform our trade flow predictions and allocations. We calibrate our projections for future ASR trade volumes and their distribution among ship types by referencing empirical trade patterns and explicitly modeling the economic competitiveness revealed by the updated cost model. This approach ensures that our forecasts more realistically reflect the anticipated dominance of bulk and energy cargoes over containerized goods on the ASR.

At the same time, we have fully considered important dynamic factors beyond the reviewers' opinions. Thus, our predictive model also implicitly incorporates the possibility of long-term development in the Arctic region. Existing research and industry reports indicate that major liner shipping companies have a strong interest in developing Arctic shipping routes, which they view as potential future strategic options (e.g., Wu et al., 2024). More importantly, Arctic coastal nations (particularly Russia and Canada) are engaged in significant strategic planning, actively competing for control and usage rights of the ASR, and continuously investing in the development of Arctic ports and infrastructure (e.g., the expansion of Russia's Sabetta Port and Canada's related planning). These national-level strategic actions and this potential port/hinterland development could gradually enhance the economic appeal of the ASR for container shipping in the future (especially during the mid-to-late stages of the forecast period for the model). While our revised model is based on current constraints and emphasizes the dominance of bulk and energy cargoes in its forecast results, we recognize that large-scale infrastructure investments could alter the competitive landscape for various vessel types, potentially creating opportunities for container ships to utilize the ASR in the future.

These significant revisions to our methodology (detailed in the revised Methods section and Supplementary Materials) provide a more nuanced and realistic assessment of the potential impact of the ASR and addressing the reviewer's specific concern about the differential suitability of the route for various shipping segments and its implications for trade forecasts and allocations.

References

1. Furuichi, M., & Otsuka, N. (2015). Proposing a common platform of shipping cost analysis of the Northern Sea Route and the Suez Canal Route. *Maritime Economics and Logistics*, *17*, 9–31.
2. Lasserre, F. (2014). Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector. *Transportation Research Part A*, *66*, 144–161.
3. Lasserre, F. (2015), Simulations of shipping along Arctic routes: Comparison, analysis and economic perspectives. *Polar Record*, *51*, 239–259.
4. Verny, J., & Grigentin, C. (2009). Container shipping on the Northern Sea Route. *International Journal of Production Economics*, *122*, 107–117.
5. Wu, A., Che, T., Xu, Q., Wang, J., Chen, J., & Zhu, X. (2024). Assessing the economic viability of the Arctic Northeast Passage from 2021 to 2065. *International Journal of Digital Earth*, *7*(1), 2323182.

Comment 4: *One more concern is that for the global trade forecast, the authors applied the ARIMAX model. I think the logic is OK, while they considered the variables of GDP, population, etc. and value chain (value added) and transport costs. The later 2 are new in the model. However, according to the recent situation, political factor is also critical in determining future trade volumes. Thus, I suggest the authors also include political factor in the forecast model.*

Response 4: We thank the reviewer for raising this important point regarding the influence of political factors on future trade volumes. We fully agree that geopolitical dynamics—including diplomatic tensions, sanctions, and political alignment—play a critical role in shaping global trade patterns.

In our modeling framework, we have incorporated political variables into the ARIMAX trade forecast model through both structural and relational proxies. Specifically, we include:

1. bilateral political affinity, proxied by sentiment in joint news coverage,
2. interaction frequency, based on co-mentions in international media,
3. diplomatic tension index (diplo_disagreement), and
4. legal/institutional alignment, captured by bilateral and multilateral trade agreements (e.g., fta_wto, legal_newo, legal_newd).

These variables reflect the evolving geopolitical landscape and help us capture both formal trade institutions and informal political relations. All of them are detailed in Supplementary Table 2 and integrated as time-varying covariates in the ARIMAX specification (see Eq. 1 in the Methods section).

To further capture exogenous geopolitical shocks, we construct the aforementioned pessimistic trade scenario (PTS) alongside the baseline optimistic trade scenario (OTS). The PTS explicitly simulates the effect of a global trade downturn—such as one driven by trade wars or sanctions—by imposing a shock in 2025 and modeling its decay over time using an exponentially adjusted growth path (see Eq. 2 and Supplementary Method 1). This hybrid structure allows us to realistically account for both structural political influences and short-term disruptions.

We appreciate the reviewer's suggestion, which has helped us to better emphasize how political considerations are embedded in our trade forecasting approach.

Comment 5: *At last, for the emission projection part, I suggest the authors clarify the emission measurement criterion, more fuel types need to be considered under future IMO regulations. The authors need to have a deep look at the latest IMO and EU's regulations on shipping and shipping fuels.*

Response 5: In the revised study, we consider various fuel types, including heavy fuel oil (HFO), marine gas oil (MGO), liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol, ammonia, hydrogen, biofuels (2nd/3rd gen), electricity, and nuclear, augmented with carbon capture and storage (CCS) technology.

In detail, shipping emission measurement criteria are set to be regulated by a combination of the IMO and the European Union, with a focus on TtW and greenhouse gas (GHG) emissions. The IMO's (2023) revised 2023 GHG strategy aims for net-zero emissions by around 2050 and includes ambitious reduction targets—a 20% reduction by 2030 and a 70% reduction by 2040 relative to 2008 levels.

We examine how three decarbonization strategies shape future emissions trajectories and spatial outcomes under various trade and routing scenarios. Two of these strategies, the IMO 2023 strategy[12] *and the Green Corridor strategy*[31,32]*, are supported by international efforts involving the IMO. The IMO 2023 strategy reflects the organization's revised GHG reduction targets and assumes a sector-wide shift toward low- and zero-carbon fuels through gradual compliance mechanisms. The Green Corridor strategy builds on this approach by accelerating green fuel deployment along maritime routes selected for their geopolitical or ecological significance. The third strategy, Net-Zero, is new. It introduces a structurally distinct decarbonization pathway anchored in two core features: stricter fuel standards and a regionally phased rollout. The first feature centers on a tank-to-wake emissions boundary, requiring zero emissions at the point of combustion, and marks a fundamental departure from the well-to-wake accounting in the IMO 2023 and Green Corridor strategies*[32,33]*, which credit upstream mitigation but allow significant emissions at sea. To meet this stricter criterion, the Net-Zero strategy prioritizes the deployment of truly zero-emission energy carriers—specifically, electricity, hydrogen, and nuclear propulsion*[34-36]*. The second feature involves spatially staged implementation, beginning in the Arctic, where ecological sensitivity is greatest, by 2040 and extending globally after 2050. This phased rollout enables the sector to reach full operational decarbonization by 2100. The projections of the TISEP model show that neither the IMO 2023 nor the Green Corridor strategy would fully eliminate Arctic emissions by the end of the century. By contrast, the Net-Zero strategy, through a combination of fuel strictness and geographic prioritization, would not only achieve zero emissions in the Arctic but also help mitigate global environmental inequalities in shipping-related pollution exposure*.

The EU's (2023) FuelEU Maritime Regulation, effective from 2025, mandates well-to-wake GHG intensity requirements. These standards will progressively tighten, with the required GHG intensity decreasing from 89.3 gCO_2e/MJ in 2025 to 18.2 gCO_2e/MJ by 2050. In addition to mandating the use of qualified low-GHG fuels, FuelEU Maritime also introduces the option for compliance pooling across multiple ships, thereby providing flexibility in meeting the standards.

Well-to-wake emissions account for the full lifecycle emissions of a fuel, from production to consumption, including both well-to-tank and tank-to-wake emissions. The focus of the IMO and EU on these comprehensive measures is intended to prevent the shifting of emissions to other sectors, such as fuel production. Accordingly, the IMO (2024) is developing guidelines for calculating the lifecycle of GHG emissions for marine fuels and adopted the 2024 guidelines on life cycle GHG intensity of marine fuels in June 2024, which will incorporate sustainability criteria and fuel certification.

Future regulations may also consider onboard carbon capture and storage technologies and fuels produced from renewable sources or with carbon capture to ensure that shipping emissions are addressed comprehensively without inadvertently increasing emissions in other sectors.

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1. International Marine Organization. (2023). *2023 IMO strategy on reduction of GHG emissions from ships*. Resolution MEPC.377(80). https://www.imo.org/en/MediaCentre/HotTopics/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx
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