

Bathymetry- and Sea-Ice-Constrained Feasibility Screening for Trans-Arctic Navigation

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ABSTRACT: Arctic route planning requires an initial assessment of whether candidate corridors are physically navigable before detailed voyage optimisation, vessel-performance modelling, or operational risk assessment is attempted. This paper presents a reproducible feasibility-screening workflow for trans-Arctic navigation under bathymetry and sea-ice concentration constraints. A regular pan-Arctic routing grid is constructed over 40–85°N and 20°W–180°E for a Rotterdam–Yokohama case study. GEBCO 2024 bathymetry is used to exclude land and shallow-water cells, while CMEMS Arctic sea-ice concentration fields are used to exclude cells above selected ice-screening thresholds. The remaining feasible cells are represented as a graph, and A-star search with geodesic edge costs is used to compute shortest feasible routes. The contribution lies in the transparent integration of bathymetry and sea-ice screening into a reproducible navigation-feasibility workflow, rather than in proposing a new shortest-path algorithm. The case study evaluates a bathymetry-only baseline, date-dependent sea-ice feasibility maps, seasonal route-distance behaviour, and sensitivity to sea-ice concentration thresholds. The results show how route availability and route-distance ratio vary with the selected environmental screening assumptions. The workflow provides a practical pre-routing layer for Arctic navigation studies and can support later integration with vessel-performance, risk, and voyage-planning models.

1 INTRODUCTION

Seasonal reduction in Arctic sea ice has increased interest in shorter Europe–Asia shipping corridors through the Arctic. However, shorter geometric distance alone does not imply navigability. Candidate corridors must first satisfy physical constraints such as land exclusion, sufficient water depth, and acceptable sea-ice concentration. These constraints are especially important in early-stage route screening, where the aim is to determine whether a continuous feasible corridor exists before applying vessel-specific performance models, fuel-consumption calculations, or operational risk assessment.

This paper addresses that first screening step. It presents a reproducible graph-based workflow that converts bathymetry and sea-ice concentration data into feasibility masks and then evaluates route continuity and route distance for a Rotterdam–Yokohama trans-Arctic case study. The workflow is intended as a navigation-feasibility layer: it identifies candidate corridors and sensitivity to screening assumptions, while leaving detailed operational routing, ice-risk modelling, and vessel-performance assessment to later analysis.

The methodological contribution is the transparent integration of bathymetry and SIC constraints into a reproducible graph-based feasibility workflow. The paper does not claim that A-star search is new. Instead,

it shows how standard graph-search methods can be embedded in a clearly specified environmental-screening procedure for Arctic navigation studies. This is useful because many Arctic routing studies focus directly on optimisation, weather routing, fuel consumption, or operational decision support, whereas a route must first be topologically feasible under basic environmental constraints.

This paper addresses four practical research questions:

- RQ1. Does a continuous trans-Arctic route between Rotterdam and Yokohama exist on the selected 0.5° pan-Arctic grid when bathymetry constraints are applied?
- RQ2. How does adding a SIC constraint change route continuity and corridor selection relative to the bathymetry-only baseline?
- RQ3. How do selected SIC thresholds and late-summer dates affect route distance ratio and route availability in the Rotterdam–Yokohama Arctic case study?
- RQ4. What assumptions and limitations follow from using this workflow as a strategic route-feasibility layer rather than as complete operational navigation guidance?

The paper is structured as follows. Section 2 positions the study relative to existing Arctic route-planning work. Section 3 describes the routing domain, bathymetry data, sea-ice data, and grid construction. Section 4 defines the feasibility masks, graph construction, edge costs, A-star search, and sensitivity setup. Section 5 presents the route-feasibility and sensitivity outputs. Section 6 discusses interpretation, limitations, and use in future navigation and digital-twin studies. Section 7 summarises the findings.

2 RELATED WORK AND STUDY POSITIONING

Arctic route planning has been studied from several perspectives, including route feasibility, ice-aware routing, vessel-performance modelling, weather routing, risk assessment, and decision support. Recent review work emphasises that Arctic weather routing depends on both ship-performance models and ice-routing algorithms, and that the field still requires transparent modelling choices and clearer treatment of ice conditions (Liu et al., 2023). Route-View demonstrates how big Earth data can be used in an interactive Arctic route-planning system (Wu et al., 2022). Other studies have addressed Arctic route design using multi-objective formulations that combine safety, economic, and environmental criteria (Chen et al., 2023). Work on icebreaker-assisted routing also shows that operational Arctic routing can require additional constraints beyond simple distance minimisation (Topaj et al., 2019). Economic and operational studies of the Northern Sea Route further show that distance reduction alone is insufficient for assessing practical route attractiveness (Theocharis et al., 2019).

2.1 Arctic route planning under environmental constraints

Sea-ice concentration is commonly used as a first indicator of ice accessibility. In operational navigation, however, SIC alone is insufficient because vessel capability, ice thickness, ridging, drift, visibility, weather, icebreaker support, and regulatory constraints also matter. The IMO Polar Code and the POLARIS guidance link polar navigation to vessel capability and ice-risk assessment rather than to sea-ice concentration alone (IMO, 2016; PAME, 2024). Bathymetry is similarly important but incomplete: a minimum-depth screen is not a full under-keel-clearance assessment and does not replace nautical charts. In this paper, bathymetry and SIC are therefore used as strategic screening constraints, not as complete safety criteria.

2.2 Graph-based routing and shortest-path methods

Graph-based routing represents a navigable area as nodes and edges. Once infeasible cells are removed, shortest feasible paths can be computed by standard graph-search algorithms. A-star search is appropriate when a lower-bound heuristic is available. Here, the heuristic is the geodesic distance from a node to the destination. Since any feasible path through the graph cannot be shorter than the direct geodesic distance to the destination, the heuristic does not overestimate the remaining distance. A-star is therefore used as an efficient shortest-path implementation rather than as a claimed methodological novelty.

2.3 Study positioning

Compared with full weather-routing, vessel-performance, or ice-risk models, the present study deliberately focuses on the pre-routing feasibility layer. Weather-routing models use wind, waves, currents, and sometimes ice to generate time-, fuel-, or safety-oriented routes. Ice-routing models may use SIC, ice thickness, ice charts, and vessel ice capability to generate ice-aware or risk-aware routes. Vessel-performance routing uses ship particulars, propulsion, ice resistance, and metocean state to estimate speed loss, fuel consumption, emissions, or estimated time of arrival. Operational decision-support systems use forecasts, traffic, operational rules, and vessel constraints to support route advice.

The present workflow does not replace these approaches. Its purpose is earlier in the analysis chain: it tests whether a continuous candidate corridor exists under specified bathymetry and SIC assumptions. Its value is that the screening choices are explicit: routing domain, grid resolution, bathymetry threshold, SIC threshold, graph topology, edge costs, route metrics, and sensitivity design.

3 DATA AND ROUTING DOMAIN

3.1 Routing domain and endpoints

The routing domain covers 40–85°N and 20°W–180°E. This domain captures the northern Europe–Asia routing region and the main Arctic corridor space

considered in the study. The route endpoints are Rotterdam and Yokohama. Rotterdam is represented by an approximate port coordinate near 51.95°N, 4.14°E, and Yokohama by an approximate port coordinate near 35.45°N, 139.65°E. Each endpoint is mapped to the nearest feasible routing-grid node. The endpoint pair is held constant across the bathymetry-only and ice-constrained scenarios so that route differences reflect the environmental constraints rather than different origin–destination definitions.

3.2 Bathymetry data

Bathymetry is taken from the GEBCO 2024 global grid (GEBCO Bathymetric Compilation Group, 2024). The bathymetry layer is used to classify cells as feasible or infeasible according to a minimum-depth screen. The reference bathymetric feasibility case uses a 50 m minimum-depth threshold. This threshold is a strategic screening value and not a navigation-grade under-keel-clearance calculation.

3.3 Sea-ice concentration data

SIC fields are taken from the CMEMS Arctic Ocean Sea Ice Reanalysis (Copernicus Marine Environment Monitoring Service, 2023). For a selected threshold SIC_{max}, cells with SIC above the threshold are excluded from the graph. The sensitivity figures evaluate SIC thresholds of 5%, 10%, 15%, 30%, and 50%. The date-threshold analysis uses selected hindcast dates between 15 June and 30 September 2018. These cases are interpreted as feasibility screening examples, not as climatological trend estimates.

3.4 Grid construction

The routing graph is constructed on a regular 0.5° latitude–longitude grid. Each grid-cell centre is treated as a candidate node. SIC and bathymetry values are assigned to the routing grid according to the gridded data extraction procedure used in the routing scripts. A node is retained only if it satisfies the active sea, bathymetry, and SIC constraints. Edges connect neighbouring retained nodes, and the cost of each edge is the geodesic distance between the two node centres. The same grid definition is used for the bathymetry-only baseline and the ice-constrained cases.

4 METHODOLOGY

4.1 Workflow overview

The workflow converts gridded environmental data into a constrained routing graph and then computes route existence and shortest feasible distance. The process has eight steps:

1. Load GEBCO 2024 bathymetry and CMEMS SIC fields.
2. Define the routing domain over 40–85°N and 20°W–180°E.
3. Construct the regular 0.5° routing grid.
4. Apply the land–sea and 50 m bathymetry screens.
5. Apply the selected SIC threshold or date-threshold feasibility mask.

6. Build the feasible routing graph from retained grid nodes.
7. Run A-star path search with geodesic edge costs.
8. Report route existence, route distance, corridor geometry, and sensitivity outputs.

The workflow is designed to make each screening step traceable from input data to route output.

4.2 Feasibility masks

A grid cell is treated as feasible if it satisfies all active constraints. The bathymetry constraint is

$$d_i \geq d_{\min} \quad (1)$$

where d_i is the water depth at cell i , and $d_{\min} = 50$ m in the reference bathymetry screen. The SIC constraint is

$$SIC_i(t) \leq SIC_{\max} \quad (2)$$

where $SIC_i(t)$ is the SIC at cell i on date t , and $SIC_{\max}$ is the selected ice-screening threshold. A node is included in the ice-constrained graph only if both constraints are satisfied.

4.3 Graph construction and edge costs

Let $G = (V, E)$ denote the feasible routing graph. The node set V contains retained grid-cell centres, and the edge set E connects neighbouring feasible nodes. An edge is created only when both endpoint nodes are feasible. The graph uses neighbouring grid cells as candidate connections; diagonal connections are included where both adjacent nodes are feasible. The edge cost is the geodesic distance between node centres:

$$c_{i,j} = \text{dist}_{\text{geo}}(i, j) \quad (3)$$

The route distance is the sum of all edge costs along the selected path:

$$D(P) = \sum_{(i,j) \in P} c_{i,j} \quad (4)$$

where P is the ordered set of route edges. Route distances are reported in nautical miles.

4.4 A-star route search and validity argument

A-star search is used to find the shortest feasible route on the constrained graph. The evaluation function is

$$f(n) = g(n) + h(n) \quad (5)$$

where $g(n)$ is accumulated distance from the origin to node n , and $h(n)$ is the geodesic distance from node n to the destination. Because direct geodesic distance is a lower bound on the distance of any feasible graph path to the destination, this heuristic is admissible for distance-minimising search. Under non-negative geodesic edge costs, A-star is equivalent to Dijkstra search with an admissible heuristic for the purpose of distance-optimal routing on the constructed graph.

4.5 Scenario and sensitivity design

The scenario design contains five groups. First, the bathymetry-only baseline tests whether a continuous sea route exists when land and shallow-water cells are excluded. Second, the seasonal SIC analysis tests how the ice-safe sea area changes across selected 2018 dates. Third, the route-distance analysis evaluates how the feasible route distance changes under selected late-summer SIC fields. Fourth, the threshold-sensitivity analysis varies the SIC upper bound across 5%, 10%, 15%, 30%, and 50%. Fifth, the date-threshold heatmap combines selected dates and SIC thresholds to show how route-distance ratio responds to both assumptions.

The sensitivity analysis is parameter-based rather than probabilistic. It varies SIC thresholds and selected late-summer dates to test whether route availability and route-distance ratio are robust to screening choices. It does not quantify uncertainty in the underlying SIC reanalysis, bathymetry data, or vessel response.

4.6 Route metrics

The workflow reports route existence, route distance, route-distance ratio, and route position. Route existence indicates whether a continuous feasible path connects Rotterdam and Yokohama. Route distance is the total geodesic path length along the graph. The relative distance change is computed as

$$\Delta_{rel} = \frac{D(P) - D_{GC}}{D_{GC}} \times 100\% \quad (6)$$

where $D(P)$ is the feasible route distance and D_{GC} is the direct great-circle distance between the endpoints.

5 RESULTS

The results show three main effects. First, the bathymetry-only route provides a continuous sea-route baseline between Rotterdam and Yokohama on the selected 0.5° grid. Second, adding SIC screening changes route availability and route-distance ratio depending on date and threshold. Third, the date-threshold heatmap shows that late-summer route feasibility is not controlled by a single SIC threshold alone; it also depends on the timing of the selected hindcast field. In the feasible late-summer cases, the ice-constrained route remains approximately 1.21–1.25 times the great-circle distance, indicating that environmental feasibility imposes a non-negligible detour even when a continuous Arctic corridor exists. These outputs are interpreted as sensitivity-based feasibility screens rather than deterministic operational routes.

5.1 Bathymetry domain and sea-only feasibility

The bathymetry domain mask is shown in Figure 1. This figure defines the land–sea and bathymetric structure used to construct the feasible routing graph. The bathymetry-only case removes land and shallow-water cells while ignoring SIC. This scenario provides

a sea-route baseline and identifies where shallow shelves affect route geometry.

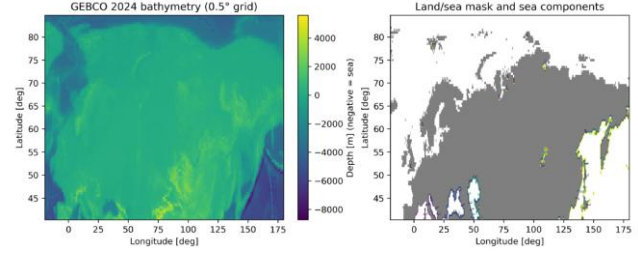


Figure 1. Bathymetry domain mask used for the pan-Arctic feasibility-screening workflow. The left panel shows GEBCO 2024 bathymetry on the routing grid, and the right panel shows the land–sea mask and connected sea components used to define the graph domain.

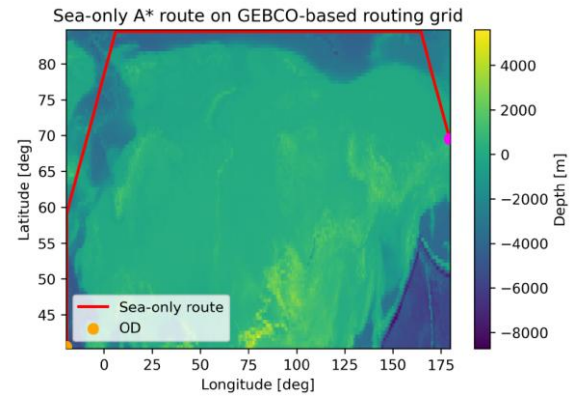


Figure 2. Bathymetry-only sea route between Rotterdam and Yokohama on the reference 0.5° grid. This route is used as the physical sea-route baseline before applying SIC constraints.

The bathymetry-only route remains continuous across the selected domain. It is longer than the direct great-circle reference because the graph must follow feasible sea cells and avoid land and shallow-water regions. This baseline is important because later ice-constrained routes should be interpreted relative to an already constrained sea route, not relative only to an idealised great-circle line.

5.2 Bathymetric connectivity

Figure 3 shows how the bathymetric screen affects domain connectivity. The figure indicates that increasing the minimum-depth threshold reduces the fraction of sea cells classified as depth-safe and changes the number of connected components. This supports the use of bathymetry as a first feasibility screen: even before sea ice is considered, the selected depth threshold influences which corridors remain connected on the routing graph.

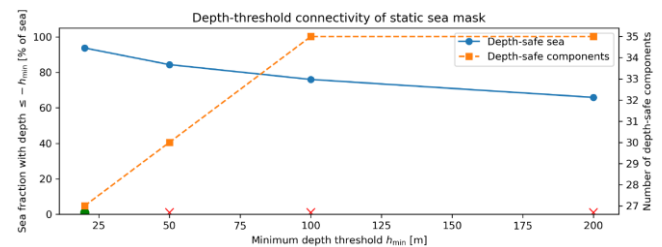


Figure 3. Connectivity response of the bathymetry-screened routing graph. The figure shows how the fraction of depth-safe sea cells and the number of depth-safe components change with the selected minimum-depth threshold.

5.3 Seasonal sea-ice feasibility

The seasonal ice-area output is shown in Figure 4. For the selected SIC threshold, the ice-safe sea area increases from early summer towards late summer, while the number of ice-safe components decreases. This indicates that the ice-safe domain becomes more connected as the summer season progresses.

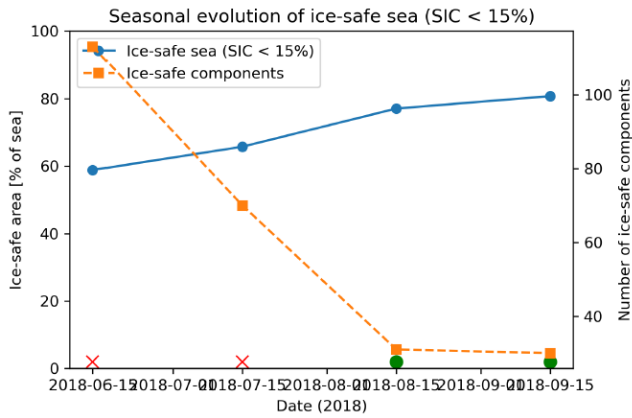


Figure 4. Seasonal variation in ice-safe sea area and ice-safe graph components for the selected routing domain and SIC threshold. The result shows how the accessible sea area and graph connectivity evolve during the 2018 summer season.

The seasonal route-distance output is shown in Figure 5. The figure shows that continuous ice-safe routes are obtained only for selected late-summer dates in the available output. The plotted route distances remain longer than the great-circle reference, showing that even when an ice-safe route exists, the environmental masks impose a distance penalty relative to an idealised direct route.

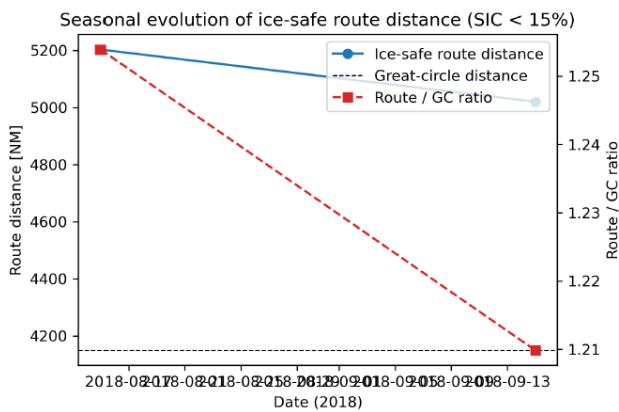


Figure 5. Seasonal route-distance response under the selected SIC screening setup. The figure compares ice-safe route distance, great-circle distance, and the route-to-great-circle distance ratio for feasible late-summer cases.

5.4 Sensitivity to SIC threshold and date

The threshold-sensitivity output is shown in Figure 6. This figure reports the response of ice-safe sea area and graph connectivity to selected SIC thresholds on 15 September 2018. Lower thresholds represent more conservative screening assumptions. Higher thresholds allow more ice-affected cells to remain in the graph and can change the number of connected ice-safe components.

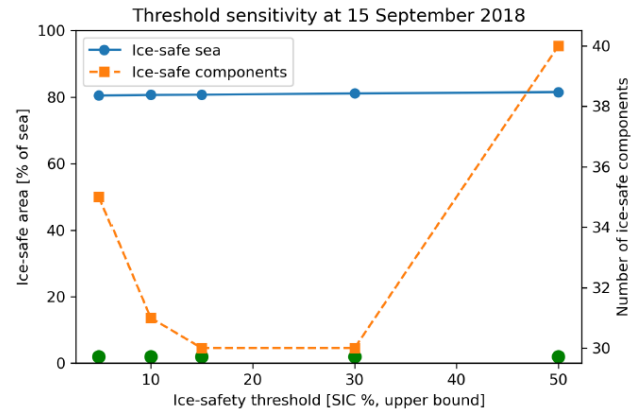


Figure 6. Sensitivity of ice-safe sea area and ice-safe graph connectivity to selected SIC thresholds on 15 September 2018. Lower thresholds represent more conservative ice-screening assumptions.

Figure 7 shows the combined effect of selected date and SIC threshold on the route-to-great-circle distance ratio. The heatmap indicates that the distance ratio varies with both the date of the SIC field and the threshold used to define ice-safe cells. The strongest variation appears across dates rather than across all thresholds, which suggests that seasonal timing is a dominant factor in this case-study output.

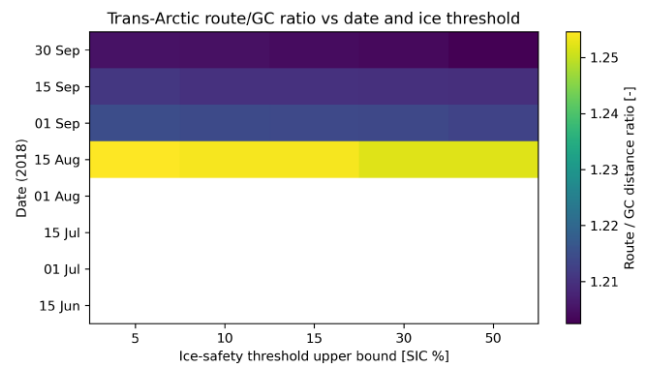


Figure 7. Date-threshold sensitivity output showing the combined effect of selected date and SIC threshold on the route-to-great-circle distance ratio. Blank cells indicate cases where a continuous feasible route was not obtained in the available output.

6 DISCUSSION

6.1 Interpretation of feasibility-screening results

A feasible route in this workflow means that a continuous graph path exists through cells satisfying the selected bathymetry and SIC thresholds. It does not mean that the route is safe for all vessels, operationally optimal, commercially attractive, or compliant with all polar-navigation requirements. Conversely, an infeasible route under a conservative threshold does not imply that no vessel could navigate the region. It means only that the selected screening assumptions do not produce a continuous path on the selected grid.

The results also show why great-circle distance alone is not a sufficient indicator of Arctic route feasibility. Even the bathymetry-only route differs from the direct geometric reference because land, shallow water, and graph connectivity constrain the feasible path. When SIC is added, route availability and

distance depend further on seasonal timing and threshold choice.

6.2 Use in navigation and maritime-safety applications

For navigation and planning applications, the main value of the workflow is early exclusion. A route planner or researcher can first test whether a corridor remains topologically connected under selected depth and ice constraints. Only corridors that pass this screening step need to be evaluated with more detailed models for vessel speed loss, fuel consumption, ice risk, weather exposure, regulatory restrictions, or operational cost. In this sense, the workflow acts as a pre-routing filter rather than a complete route-advice system.

The workflow can also support comparative studies. Because the same endpoint pair, grid, graph construction, and route metric are held fixed, changes in route distance can be attributed to changes in the environmental screening assumptions. This makes the approach useful for testing how sensitive Arctic route feasibility is to selected bathymetry and SIC thresholds.

6.3 Limitations and assumptions

The main limitations are:

1. The SIC constraint uses concentration only. It does not include ice thickness, ridging, floe size, ice drift, compression, or ice-class-specific performance.
2. The 50 m bathymetry screen is a strategic threshold, not a nautical-chart or under-keel-clearance calculation.
3. The 0.5° grid is suitable for research screening but not for operational navigation.
4. The ice analysis uses selected hindcast dates and thresholds and should not be interpreted as a full multi-year climatological route-availability estimate.
5. The route is static at the routing-step level. It does not yet sample evolving SIC along the route as a function of vessel speed and arrival time.
6. Weather, waves, currents, traffic separation schemes, icebreaker support, legal restrictions, fuel consumption, emissions, and risk-cost tradeoffs are not included in this feasibility layer.
7. A-star is justified by its admissible geodesic heuristic, but the present implementation does not include a separate empirical comparison against Dijkstra search in the reported results.

6.4 Future work

Future work should extend the workflow in four directions. First, time-dependent routing should sample SIC fields according to the estimated arrival time at each route segment. Second, uncertainty analysis should vary SIC thresholds, bathymetric thresholds, departure dates, and grid resolution systematically. Third, the graph layer should be coupled with vessel-performance, fuel-consumption, emissions, and ice-risk models. Fourth, the feasibility-screening layer should be integrated into a voyage-planning digital-twin framework that separates environmental feasibility, route choice, performance prediction, and operational risk.

7 CONCLUSION

This paper presented a reproducible feasibility-screening workflow for trans-Arctic navigation under bathymetry and SIC constraints. The workflow uses GEBCO 2024 bathymetry, CMEMS Arctic sea-ice concentration, a 0.5° pan-Arctic grid, a 50 m bathymetric screen, and A-star pathfinding with geodesic edge costs. The case study considers a Rotterdam–Yokohama route within 40–85°N and 20°W–180°E, including a bathymetry-only baseline, ice-feasibility outputs, seasonal route-distance outputs, and sea-ice-threshold sensitivity figures.

The paper treats the workflow as a transparent environmental-constraint layer rather than as a new routing algorithm or operational navigation tool. This positioning is useful for navigation studies because the value of the workflow lies in explicit assumptions, reproducible feasibility masks, route-continuity screening, and sensitivity to ice-threshold choice. The workflow can support future dynamic voyage planning, maritime-safety analysis, and Arctic routing digital-twin development once time dependence, uncertainty, vessel performance, and risk models are added.

ACKNOWLEDGEMENTS

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DATA AND CODE AVAILABILITY

Bathymetry data are taken from the GEBCO 2024 global grid (GEBCO Bathymetric Compilation Group, 2024). Sea-ice concentration fields are taken from the CMEMS Arctic Ocean Sea Ice Reanalysis (Copernicus Marine Environment Monitoring Service, 2023). The scripts and configuration files used to construct feasibility masks and perform route searches are available from the corresponding author upon reasonable request and will be deposited in an open repository after manuscript acceptance.

APPENDIX A. SUPPLEMENTARY ROUTE MAPS AND SENSITIVITY RESULTS

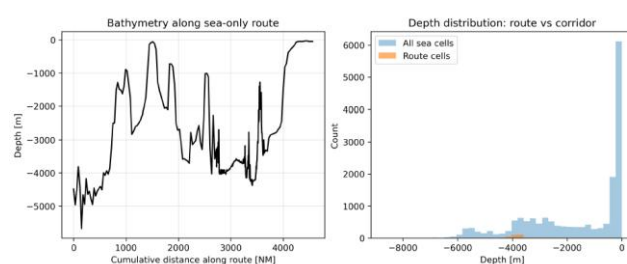


Figure A.8. Depth profile along the reference sea-only route and distribution of depths in route cells compared with all sea cells.

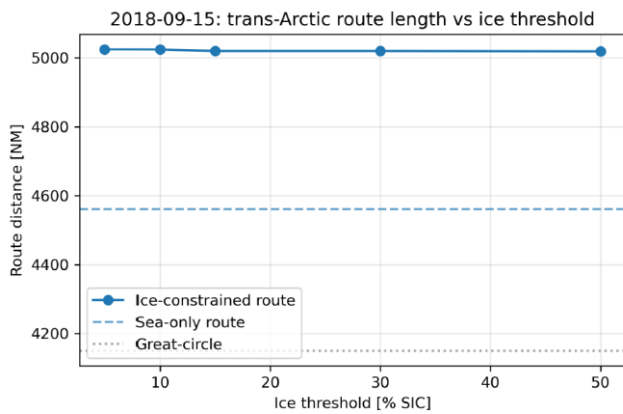


Figure A.9. Supplementary route-distance sensitivity to the selected SIC threshold for the late-summer case. Solid line: ice-constrained route; dashed line: bathymetry-only sea route; dotted line: great-circle distance.

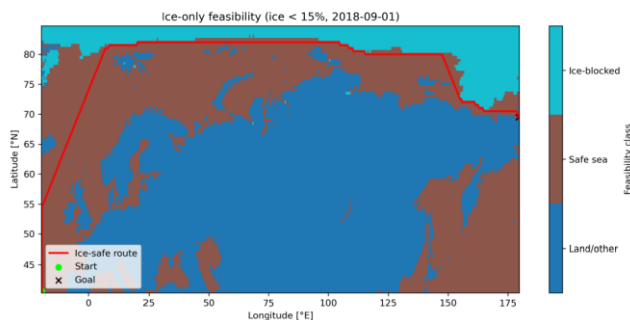


Figure A.10: Supplementary ice-feasibility route map for 1 September 2018 under the selected screening setup. The figure illustrates the corridor obtained after classifying grid cells by SIC threshold.

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