Satellite Record of Pan-Arctic Maritime Ship Traffic

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Highlights

- Satellite-based records from 1 September 2009 through 31 December 2018 reveal increasing maritime ship traffic, with pronounced seasonality, within all Law of the Sea zones north of the Arctic Circle.
- Arctic maritime ship traffic is increasing as sea ice is diminishing, representing the 'ship-ice hypothesis' to test over diverse time and space scales in view of socioeconomic impacts and the dynamics of natural systems.
- Maritime ship traffic into the Central Arctic Ocean High Seas predominates from the Pacific sector through the Bering Strait and Beaufort Sea, as revealed by ship types, sizes, and flag states from 2009-18 with complementary satellite-observed increases in the Bering Sea from 2015 to 2020.

Introduction

A prominent socioeconomic development in recent years has been an increase in maritime ship traffic (characterized in view of ship movements and attributes of type, size, and flag state) in the Arctic Ocean as the sea ice diminishes with climate warming (see essay *Sea Ice*). Increasing maritime ship traffic has diverse implications for Arctic and non-Arctic communities in view of emergent and projected shipping routes (Fig. 1). Shipping activities also impact biogeophysical systems, generating environmental and societal risks—especially for Indigenous Peoples, with system impacts in the:

- **Atmosphere:** Greenhouse gas impacts, including heavy fuel-oil burning that produces black carbon with ice-surface darkness impacts (IMO 2021);
- **Ocean:** Pollution impacts (Sheffield et al. 2021) on marine ecosystems (see essay *Primary Productivity*); overharvesting marine living resources; marine species disturbances, including ship strikes on marine mammals and birds; underwater noise (Stafford 2021); and invasive species introductions that change trophic interactions;
- **Communities:** Port development, socioeconomic impacts, and access changes.

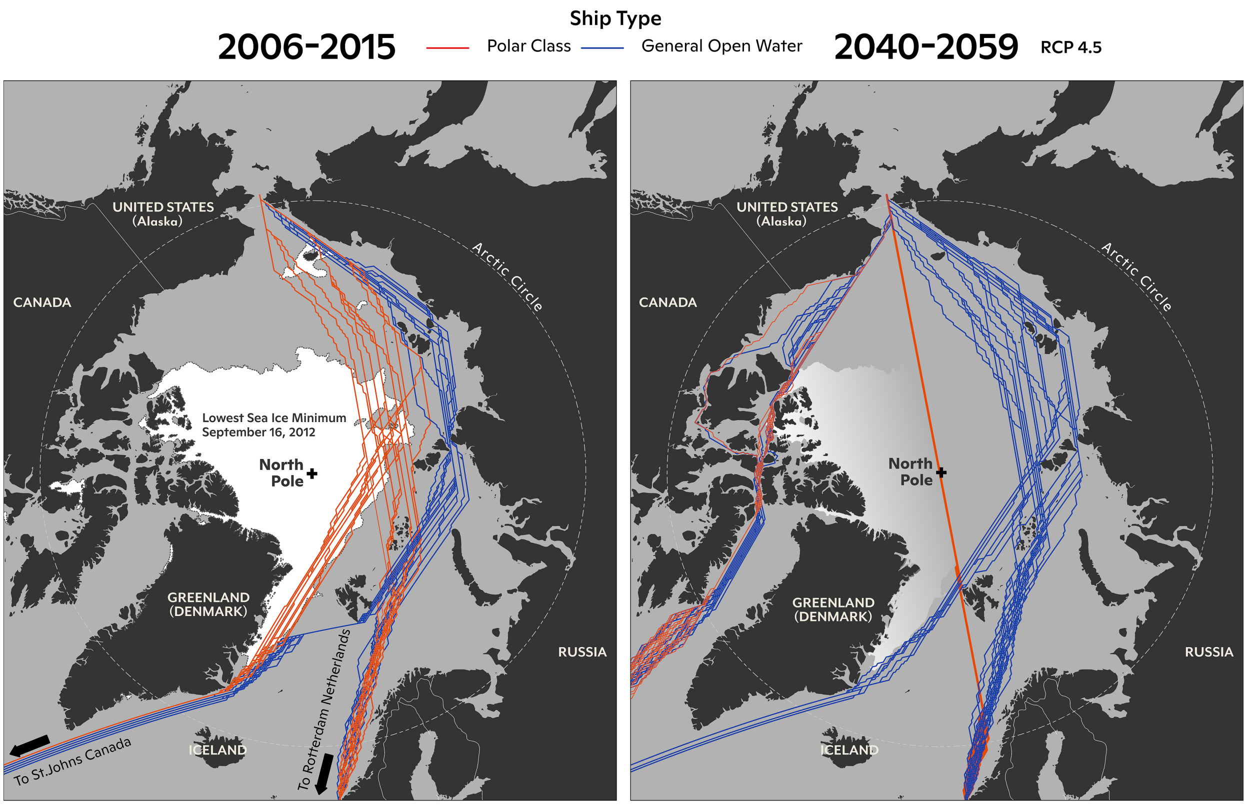

Fig. 1. Model of maritime ship-traffic in the Arctic Ocean (Smith and Stephenson 2013), predicting trade routes that will open as sea ice diminishes through mid-21st century with polar-class ships that are ice-strengthened (orange) according to the International Association of Classification Societies (IACS) and other ship types that are designed for open water (blue).

Indigenous communities are the most vulnerable (Sheffield et al. 2021), respecting they have resided continuously on islands and along the coastlines of Arctic landmasses in a resilient manner in the face of ecosystem changes across millennia. The applications and implications of maritime ship traffic also are cross-cutting with the five binding Arctic agreements that have entered into force during the past decade with Arctic states as well as non-Arctic states (Berkman et al. 2022a).

Maritime ship traffic data across jurisdictions in the Arctic Ocean

Satellite Automatic Identification System (S-AIS) observations north of the Arctic Circle began on 1 September 2009, enabling synoptic coverage of maritime ship traffic in the Arctic Ocean (see Methods and data). The comprehensive pan-Arctic illustration herein (Fig. 2) is based on the framework of the Law of the Sea, to which the eight Arctic states and six Indigenous Peoples' organizations "*remain committed*" (Arctic Council 2013). The Law of the Sea zones are unambiguous in the superjacent waters above the sea floor and objectively defined with the Exclusive Economic Zones (EEZ) beyond and adjacent to the Territorial Sea, extending a maximum of 200 nautical miles from coastal boundaries into the High Seas of the Arctic Ocean (Berkman and Young 2009). This S-AIS baseline from 2009-18 (Berkman et al. 2022b)—which will be brought current with future funding—reveals pronounced seasonality (Fig. 2). The increasing number of ships over time in all national and international maritime jurisdictions north of the Arctic Circle (Tables 1 and 2) raises diverse questions about relative ship-traffic changes and characteristics within as well as between regions seasonally and interannually in view of socioeconomic impacts and the dynamics of natural systems.

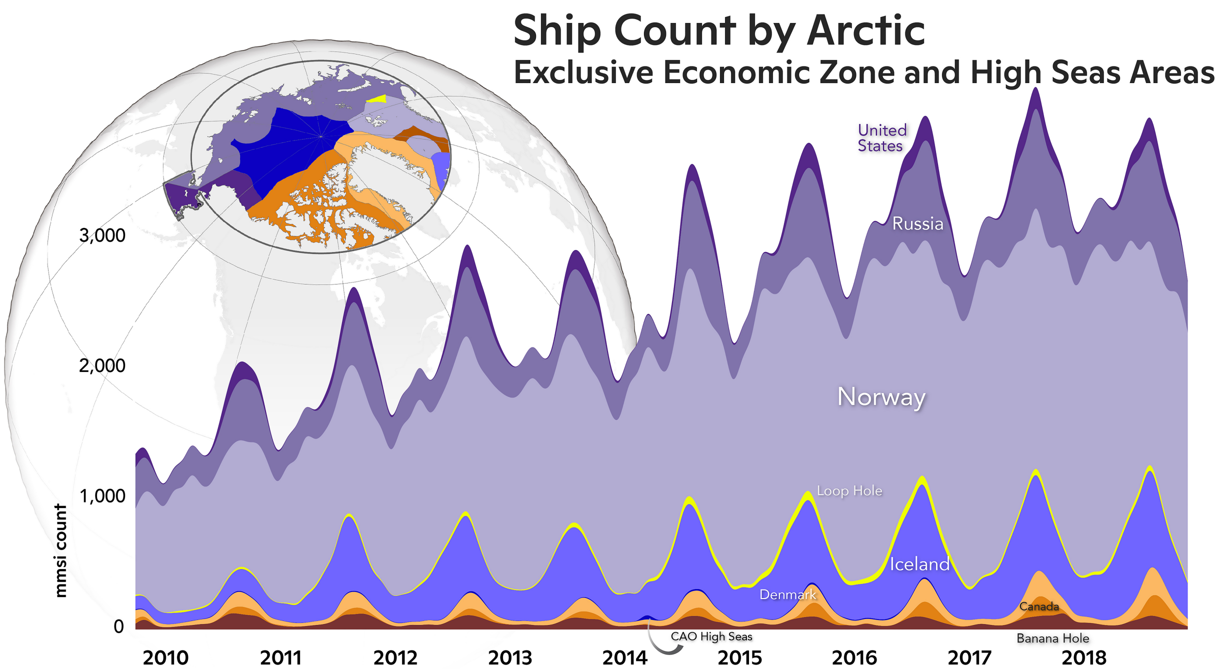

Fig. 2. Oldest continuous S-AIS record of pan-Arctic maritime ship traffic across Law of the Sea zones (United Nations 1982) within and beyond jurisdictions of the six Arctic coastal states north of the Arctic Circle (see Tables 1 and 2), involving more than 173,000,000 S-AIS records from 1 September 2009 to 31 December 2018 (Berkman et al. 2022a,b).

Table 1. Annual and seasonal trends of maritime ship traffic of the Exclusive Economic Zone (EEZ)—areas within national jurisdictions as defined by the international framework of the Law of the Sea for the regions shown in Fig. 2.

Arctic Ocean Area	Total of Monthly Unique Ship Days[1]	Rate of Change[2,3] (2009-18)		
Canada	2,541	Annual: +1.2%	Summer: +2.1%	Winter: -0.1%
Denmark / Greenland	7,563	Annual: +1.7%	**Summer: +2.8%**	**Winter: +0.7%**
Iceland	40,644	**Annual: +10.9%**	**Summer: +15.1%**	**Winter: +5.3%**
Norway	176,048	**Annual: +41.9%**	**Summer: +47.6%**	**Winter: +47.9%**
Russian Federation	43,950	**Annual: +8.8%**	**Summer: +12.5%**	**Winter: +5.0%**
United States	6,836	Annual: +1.0%	**Summer: +1.9%**	Winter: +0.1%

[1]Total number of unique ships derived with S-AIS data in each area north of the Arctic Circle (Fig. 2), summed from 111 monthly totals of ships based on daily observations (Berkman et al. 2022b).
[2]Ship numbers versus time from 2009-18 (statistically significant trends highlighted in bold).
[3]Annual and seasonal trends for summer (June-July-August-September) and winter (December-January-February-March) with shoulder periods unanalyzed.

Table 2. Annual and seasonal trends of maritime ship traffic of the High Seas—areas beyond national jurisdictions (ABNJ) as defined by the international framework of the Law of the Sea for the regions shown in Fig. 2.

Arctic Ocean Area	Total of Monthly Unique Ship Days[1]	Rate of Change[2,3] (2009-18)		
Banana Hole	6,426	Annual: +0.1%	Summer: -0.3%	Winter: +0.5%
Central Arctic Ocean (CAO)	494	Annual: +0.2%	Summer: +0.3%	Winter: +0.3%
Loop Hole	3,275	**Annual: +1.1%**	**Summer: +1.4%**	**Winter: +0.7%**

[1]Total number of unique ships derived with S-AIS data in each area north of the Arctic Circle (Fig. 2), summed from 111 monthly totals of ships based on daily observations (Berkman et al. 2022b).
[2]Ship numbers versus time from 2009-18 (statistically significant trends highlighted in bold).
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The centroid of maritime ship traffic also has shifted hundreds of kilometers to the north and east in the Atlantic sectors (NASA 2018), where maritime ship traffic predominates in the Arctic Ocean (Fig. 2). Complementary analyses of Arctic maritime ship traffic after 2013 are available from the Arctic Ship Traffic Database with redacted S-AIS metadata (Arctic Council 2022) and from other public and private sources (Theocharis et al. 2018).

'Ship-ice hypothesis' testing across the Arctic Ocean

Increasing ship traffic with diminishing sea ice has been framed as the 'ship-ice hypothesis,' (Berkman et al. 2020a) which has been tested comprehensively in a pan-Arctic context with daily satellite observations of ship traffic and sea ice within 4 km^2 grids to reveal 'ship-ice interactions' from 2009-16.

Testing and elaborating this hypothesis leads to useful insights, such as identifying the threshold increase in ship-ice interactions in the Arctic Ocean after 2013 and toward higher latitudes, following the sea-ice minimum observed by satellites in 2012.

The Central Arctic Ocean (CAO) High Seas (Fig. 2, Table 2) offer a unique regional test of the 'ship-ice hypothesis', with diminished sea-ice and open-water seasonally on the Pacific sector adjacent to the 180° EW meridian, in contrast to open water year-round in the Atlantic sectors where the ship traffic predominates (Fig. 2, Table 1). The S-AIS metadata with ship flag state, type, and size attributes (Fig. 3) indicate maritime ship traffic into the CAO High Seas is chiefly originating from the Pacific sector of the Arctic Ocean adjacent to the Bering Strait.

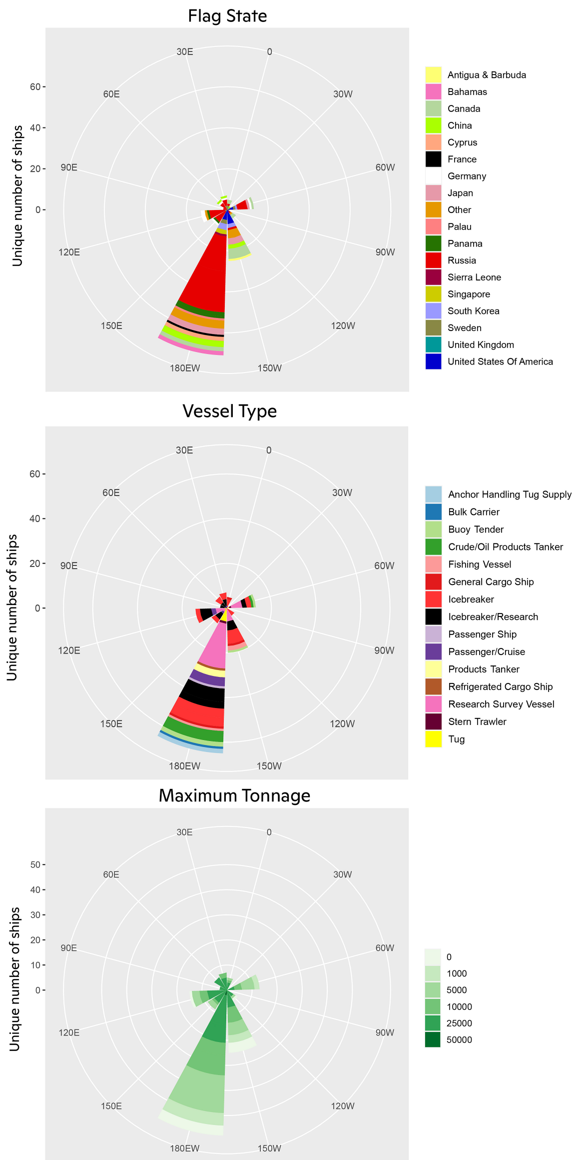

Fig. 3. 'Ship-ice hypothesis' test with the Central Arctic Ocean (CAO) High Seas (Fig. 2), showing predominant directionality of maritime ship traffic from the Pacific sector from the Aleutian Islands northward, in view of: (upper) flag states; (middle) vessel types; and (lower) maximum tonnages, which are recorded in the metadata with S-AIS records of IMO-registered vessels from 2009-18 (Berkman et al. 2022a,b).

Discovery of the primary movement of maritime ship traffic into the CAO High Seas from the Pacific sector (Fig. 3) reveals risks to address among diverse stakeholders, rightsholders, and actors inclusively since the Bering Strait is the narrowest choke point into and out of the Arctic Ocean. This conclusion is reinforced by S-AIS observations of increasing maritime ship traffic in the Bering Sea from 2015-20 (Kapsar et al. 2022), especially considering adjacent Indigenous communities that have inhabited this region for millennia.

Conclusions

From national security interests to continuous considerations among Arctic communities, S-AIS data provide a synoptic pan-Arctic platform (Table 3) to assess patterns, trends, and processes of socioeconomic change with user-defined granularity across the Arctic Ocean. Understanding increasing maritime ship traffic (Figs. 2 and 3, Tables 1 and 2) in relation to the welfare of surrounding coastal communities, dynamics of natural systems with their biogeophysical features, and socioeconomic development of the Arctic as a whole will inform decisions about investments and response capacities across a 'continuum of urgencies' (Berkman et al. 2017) to build resilience in view of Arctic Ocean change.

Methods and data

S-AIS data on a pan-Arctic scale are a technological innovation with distinct advantages, extending the Earth surface observations that had been synthesized from the six Arctic coastal states (Table 1) into the Arctic Marine Shipping Assessment (Arctic Council 2009) and subsequently (Table 3). The baseline S-AIS data herein were collected by AAC SpaceQuest Ltd as part of a public-private partnership supported by the National Science Foundation with Belmont Forum collaborations internationally and deposited in the Arctic Data Center (Berkman et al. 2020b). The key attributes in the S-AIS data are location (latitude and longitude) and timestamp for each unique ship along with metadata about ship characteristics for vessels that are IMO registered.

Table 3. Next-Generation Arctic Marine Shipping Assessments (AMSA)[1]

Attribute	AMSA (Arctic Council 2009)	Next-Generation AMSA[2]
Sampling Period	2004	2009 forward
Data Sources	Arctic States Individually	Diverse Government and Commercial Satellite Automatic Identification System (S-AIS) Receivers
Observation Coverage	Point, Regional	Point, Regional, and Pan-Arctic
Observation Scope	Ground-Based	Ground-Based and Satellite
Observation Frequency	Inconsistent over Space and Time	Synoptic and Continuous (seconds-decades)
Ship-Type Designations	Variable National Designations	Standardized International Designations
Individual Ship Attributes	Inconsistent and Incomplete	Consistent and Comprehensive
Analytical Capacity	Limited Granularity and Questions	Open-Ended Granularity and Questions
Science-Diplomacy Contributions	Scenarios and Negotiated Recommendations	Holistic Evidence and Options (without advocacy)
Informed Decisionmaking	Governance Mechanisms	Operations, Built Infrastructure, and Governance Mechanisms

[1]Modified from Berkman et al. (2020a).
[2]Involves ship transponder data received by polar-orbiting satellites.

Geospatial data were integrated over time with the 'space-time cube' (in the cloud and analyzed with SQL queries of tables through the Google Compute Engine with BigQuery (Berkman et al. 2020a, 2022b). This analytical approach enabled integration with other spatial datasets with time stamps, as demonstrated with sea-ice data on a pan-Arctic scale within 4 km^2 grids to reveal ship-ice interactions. Relational databases in the cloud have a wealth of advantages, including cost-effectiveness, scalability, analytical speed, and n-dimensional dataset integration to 'future-proof' next-generation AMSA with user-defined applications.

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