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Full Length Article

Comparative and critical analysis of data sources used for ship traffic spatial pattern analysis in Canada and across the global Arctic

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ABSTRACT

This study presents a comprehensive comparative analysis of three primary datasets commonly employed to evaluate shipping patterns in Arctic waters: 1) Northern Canada Vessel Traffic Zone (NORDREG), 2) satellite-based Automatic Identification System (S-AIS) from a private provider, and 3) the Arctic Ship Traffic Database (ASTD). Covering the years 2011 to 2022, the analysis assesses spatial and temporal metrics for each dataset while employing robust data cleaning techniques to address signal manipulation and detection gaps. Findings reveal that S-AIS and NORDREG excel in detecting vessel traffic in Canadian waters, including the Northwest Passage (NWP), while ASTD demonstrates strong performance in regions with dense terrestrial AIS coverage, such as Norway and Iceland. However, ASTD is less effective along critical shipping routes, including the NWP and the Northern Sea Route (NSR), where S-AIS provides broader coverage. Both datasets indicate an upward trend in AIS-based traffic throughout the Arctic. The results underscore the value of fusing S-AIS and ASTD datasets to provide a more complete and accurate understanding of Arctic shipping patterns. This research offers critical insights for policymakers and researchers selecting ship traffic data for regional and global Arctic analyses, maritime safety, and environmental decision-making.

1. Introduction

Maritime shipping is the foundation of global economic trade. The value of trade by sea surpasses 14 trillion US dollars annually and supports almost 90 % of the movement of all goods globally (ICS, 2024). In addition to trade-based vessel activity, both domestic and international, global seas support other multi-trillion-dollar industries such as fisheries, natural resources, tourism, and local transportation (i.e., ferries), in addition to supporting national security, research, and government operations. Considering the scale of the shipping sector, the importance and need to have reliable and robust data and understanding of shipping traffic trends that can then be used to answer a wide range of scientific, strategic, and political questions has exponentially increased in importance over time. Originally used to aid in collision avoidance, the use of shore-based, and more recently satellite-based, digital position data transmitted

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from vessels termed 'Automated Identification System' (AIS) has rapidly evolved over the past decades. AIS data is now used regularly for operational scale decision-making and to understand multi-scale movement patterns.

In the Arctic, warming is occurring 3–4 times faster than the global average (Timmermans et al., 2018). This region also faces disputes over sovereignty claims in the Northwest Passage (Geddert, 2019). Coupled with ongoing instability in Russia, the largest Arctic nation, the need for accurate spatial and temporal shipping data is increasingly important. Reliable ship traffic data can support various initiatives, including marine protected area development (Thoya et al., 2021). It can also be used to model underwater noise impacts on marine mammals, which are essential for ecosystem sustainability and regional food security (Martin et al., 2023; Hague et al., 2024). Additionally, this data helps evaluate potential economic and development opportunities (Peng et al., 2022) and assess navigation risks associated with climate change (Roa et al., 2021). Furthermore, ship traffic data is crucial for understanding ship-to-ship and ship-to-object interactions (Zhou et al., 2023), as well as for traffic management and waterway design (Nowy et al., 2021). This data also supports database development (Spadon et al., 2024) and aids in mitigating risks related to shipping accidents, spills, and both local and regional security threats (Marty et al., 2016; Nicoll et al., 2024).

Studies that have utilized ship traffic data in the global Arctic have reported overall increases in ship traffic for the entire region (Eguíluz et al., 2016; Berkman et al., 2022; Müller et al., 2023). This includes Trans-Arctic shipping routes, such as the Northwest Passage and Northern Sea Route, which are becoming more viable for transportation due to sea ice change (Mudryk et al., 2021; Li et al., 2023). There are also reported increases in ship traffic observed within certain areas of northern Canada (Dawson et al., 2022), Russia (Gunnarson, 2021), and Norway (Stocker et al., 2020). The increased activity has been specifically linked in these regions to several economic trends, including growing demand for adventure and expedition tourism experiences (Dawson et al., 2009; Hansen-Magnusson et al., 2023), commercial and non-commercial fishing opportunities (Fauchald et al., 2021; Galappaththi et al., 2022), exploration and operation of natural resource mines (i.e., oil, gas, precious metals) (Shapovalova et al., 2020; Wang et al., 2024), community re-supply needs and demographic trends (Huntington et al., 2023), and a global desire for Arctic trade (Bayırhan et al., 2021).

This study focuses on the Canadian Arctic specifically and the global Arctic more generally to critically evaluate the most commonly used data sources for understanding spatial shipping patterns. Among these, the Northern Canada Vessel Traffic Zone (NORDREG) and satellite-based Automatic Identification System (S-AIS) data from private providers are pivotal for quantifying historical shipping activities in the Canadian Arctic. On a broader scale, across the global Arctic, S-AIS data from private providers and the Arctic Ship Traffic Database (ASTD) from the Protection of the Arctic Marine Environment (PAME) are predominant datasets for quantitative shipping analyses. Despite the widespread use of these datasets, anecdotal evidence suggests discrepancies in their coverage, accuracy, and temporal resolution. However, no comprehensive analysis has been conducted to evaluate the spatial and temporal utility of these datasets in the Arctic context. Addressing this gap is crucial for identifying the most reliable data sources to assess shipping patterns, particularly given the rapidly changing environmental and geopolitical conditions in the region.

Data sources supporting Arctic shipping analyses include AIS, Long-Range Identification and Tracking (LRIT), Vessel Monitoring Systems (VMS), and derived products from private providers like MarineTraffic (Kpler), Lloyds, and IHS-Markit (S&P Global). These services aggregate data from various sources, including terrestrial and satellite AIS, tailoring outputs for operational needs. Government-led systems like NORDREG and administrative databases such as the Northern Sea Route (NSR) administration contribute

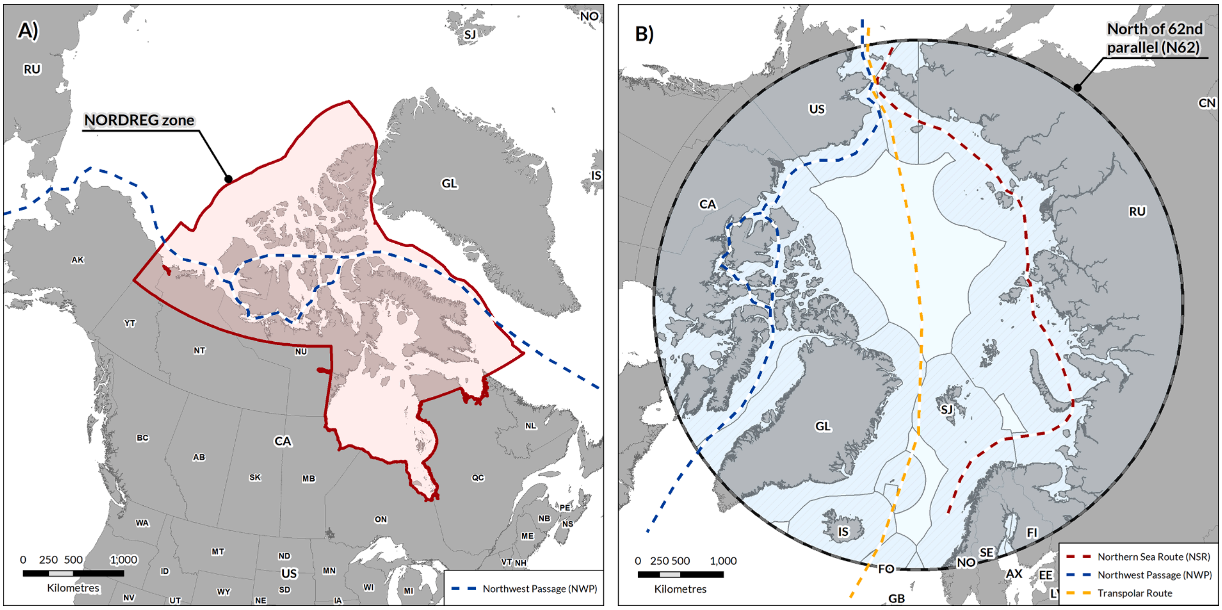

Fig. 1. The two study areas used in this analysis: a) Canadian Arctic outlined by the NORDREG zone. b) global Arctic, North of the 62nd parallel (N62). Dotted lines indicate major shipping routes.

region-specific records. While manual evaluation of permit records and ship logs is possible, these methods are time-intensive and lack the spatial and temporal resolution provided by AIS-based datasets.

Some of these data sources are already integrated into larger datasets. For example, ASTD incorporates S-AIS and terrestrial-based AIS (T-AIS) data from over 50 land-based stations and satellites, with regional contributions from government agencies in Norway and the United States. Similarly, NSR administrative data, while useful for sub-regional analyses, overlaps with AIS sources already included in ASTD and S-AIS, making it less applicable for Arctic-wide studies. Private providers like MarineTraffic (Kpler) and VesselFinder primarily rely on terrestrial AIS networks and often source satellite AIS data from primary operators like exactEarth (Spire) or Orbcomm, limiting their uniqueness for pan-Arctic analyses.

In this study, we leverage three complementary and widely used datasets: ASTD Level 1 (L1), S-AIS from exactEarth (Spire), and NORDREG. Together, these datasets balance spatial coverage, temporal resolution, and accessibility in the Arctic. This research aims to determine the strengths and weaknesses of these key datasets and identify the most accurate sources for analyzing historical, current, and future ship traffic trends. We hypothesize that fusing these datasets offers the most comprehensive understanding of Arctic shipping patterns by improving accuracy and temporal resolution. Ultimately, this research contributes to informed decision-making for Arctic marine policy, environmental protection, and strategic planning.

2. Data and methods

Multiple sources of ship traffic data can be used to understand traffic patterns in the Canadian Arctic and global Arctic, In this study, we compare the three datasets within the Canadian Arctic as outlined by the NORDREG zone (Fig. 1a) from 2011 to 2022, and compare the S-AIS and ASTD data for overlapping areas in the global Arctic North of the 62nd (N62) parallel (Fig. 1b) from 2013 to 2022.

2.1. NORDREG data

The NORDREG zone is managed by the CCGs Marine Communications and Traffic Services (MCTS) Centre in Iqaluit, Nunavut. The NORDEG zone encompasses all marine waters within the Canadian Arctic, including Hudson Bay. Vessels that must report to NORDREG are: (1) vessels of 300 Gross Tonnes (GT); (2) vessels engaged in towing or pushing another vessel if the combined gross tonnage of the vessel and the vessel being towed or pushed is 500 GT or more; and (3) vessels that are carrying as cargo a pollutant or dangerous goods, or that are engaged in towing or pushing a vessel that is carrying as cargo a pollutant or dangerous good. Vessels which are required to report must provide a daily position to the MCTS Centre, which is then captured within the NORDREG database. The NORDREG data used in this study is comprised of daily vessel positions containing information on ship particulars (e.g., IMO number, MMSI number, and or ship name), location (latitude and longitude), and the date. Data from 2011 to 2020 covering only the NORDREG zone (Fig. 1a) was used in the study.

2.2. S-AIS data

Automatic Identification System (AIS) is an automated tracking system fitted onboard certain vessels, based on automated returns from a transponder mounted on the ship. AIS broadcasts information relating to the movement of the vessel and the vessel itself while operating in the Very High Frequency (VHF) maritime radio band, generally using Self-Organizing Time Division Multiple Access (SOTDMA) and Carrier-Sense Time division Multiple Access (CSTDMA) technologies to broadcast frequently (typically every few seconds to minutes).

AIS was originally intended as a navigation safety tool (collision avoidance) for ship-to-ship communication. The broadcasted messages sent out by an AIS transponder can generally be collected by terrestrial and satellite receivers, often referred to as T-AIS and S-AIS, respectively. 27 AIS message types can be exchanged through the AIS system, with messages generally providing dynamic (e.g., GPS position, speed, course) and static information (e.g., vessel name, vessel size, destination) about a vessel. The transponders send out dynamic information much more frequently than static information.

Internationally, (1) all vessels that are greater than 300 GT and engaged in an international voyage, or (2) cargo vessels with GT of greater than 500 GT not engaged in an international voyage, or (3) all passenger vessels, regardless of size, are required to carry a Class A AIS transponder on board, per regulation 19 of the International Convention for the Safety of Life at Sea (SOLAS) Chapter V, as of December 31, 2004. Class B transponders are voluntary and are generally equipped aboard smaller vessels (e.g., pleasure vessels, small fishing vessels). Class A transponders can emit dynamic information every 2 to 10 s while underway, whereas Class B transponders can emit dynamic information every 30 to 180 s.

One of the main differences between the two transponders is that Class A transponders, in comparison to Class B transponders, broadcast messages at a more frequent rate along with a stronger signal power (12.5 W compared to 1–2 W), making it easier for satellite and terrestrial receivers to pick-up Class A messages than Class B messages. Although Class B transponders are voluntary, they are becoming more common to be fitted onboard vessels (i.e., they have become more affordable). This is especially true in the Arctic, where it has been reported that there has been an increase from approximately 100 recorded vessels in 2010 using Class B transponders, to approximately 500 recorded vessels in 2014 (Eriksen et al., 2018).

There are some limitations with AIS messages in general; for example, it is optional for vessels <300 GT vessels to carry AIS on them, meaning that many smaller vessels (i.e., small recreational or fishing vessels) might not be captured. There are also many threats relating to the security of AIS messages; there have been reported cases and potential for spoofing (e.g., ship positions, aids to navigation, ship-collision, search & rescue, and weather forecasting), hijacking and availability disruption (Androjna et al., 2023). There have been reports of fishing vessels practicing spoofing their positions to fish illegally and ensure their locations are not detected (Natale et al., 2015; Brown et al., 2024).

The S-AIS data used in this study were provided by exactEarth (Spire[1]) via a data license from MEOPAR. This study specifically used positional AIS messages (message types 1–3, 18, 27), which contain information on the location (latitude and longitude) and other relevant information for the analysis including the MMSI (Maritime Mobile Service Identity), datetime, COG (course over ground), and SOG (speed over ground). Data from 2011 to 2022 covering both the NORDREG zone and the entire area N62 was used in this study.

2.3. ASTD data

The Arctic Ship Traffic Database (ASTD) contains similar information to what S-AIS provides, as the positions within the database are derived from AIS collected by satellites and land-based stations from Norway and the United States of America. This means that the ASTD incorporates both S-AIS and T-AIS positional messages. Additionally, the AIS data in the ASTD is supplemented with other information from data providers IHS Fairplay and DNV-GL, including detailed ship particulars and fuel consumption metrics, which are not relevant for this study.

It is important to note the differences between S-AIS and T-AIS, as both have distinct advantages and limitations. T-AIS spatial coverage is generally limited to a range of approximately 40–60 nautical miles (Veinot et al., 2023) from a terrestrial receiver, depending on factors such as weather and atmospheric conditions. In contrast, S-AIS achieves global coverage through a constellation of Low Earth Orbit (LEO) satellites, capable of receiving AIS messages worldwide. Temporal resolution also varies between these systems: terrestrial AIS typically provides continuous, high-frequency detection, often receiving messages as frequently as every 2 s. However, its limitations are primarily spatial, particularly in remote regions without terrestrial infrastructure. On the other hand, S-AIS may experience latency and revisit time variability depending on satellite positioning, revisit frequency, and the number of satellites in the constellation (Carson-Jackson, 2012). This variability is especially pronounced in the Arctic, where longer revisit times can lead to inconsistent message rates (Winther et al., 2014). Receiver strength also differentiates these datasets; terrestrial receivers are more effective at capturing lower-power Class B messages due to their proximity, whereas satellites often underreport Class B messages.

The ASTD data used in this study was provided by PAME under a data license supporting the Horizon 2020 Arctic Passions project. Specifically, ASTD Level 1 (L1) data was utilized, which is the most granular level available. L1 data includes AIS-derived attributes such as MMSI, latitude, longitude, and datetime, but it does not include speed over ground (SOG) or course over ground (COG). These were computed separately for this study, as detailed below.

It is worth noting that ASTD Level 3 (L3) is more widely accessible than L1 but comes with significant limitations for detailed analyses. L3 data aggregates positional information to coarser temporal intervals (6 min or more), lacks certain vessel-specific attributes, and encrypts vessel IDs monthly, making it unsuitable for long-term vessel-specific studies. While L3 data is valuable for broader analyses, such as emissions modeling (Figenschau et al., 2024) or general traffic trends (Müller et al., 2023), it lacks the granularity necessary for comparing spatial and temporal patterns across datasets as done in this study. These constraints underscore the importance of using L1 data, which aligns with the study's goals of analyzing detailed shipping patterns in the Arctic.

For this study, ASTD L1 data was used to compare against NORDREG and S-AIS data from 2013 to 2022, covering both the NORDREG zone and the entire area north of the 62nd parallel (N62). To ensure comparability with the S-AIS dataset, intermediate SOG and COG variables were calculated using the Haversine formula and bearing formula, respectively, for the ASTD L1 data. The intermediate SOG variable was calculated based on the distance and time between consecutive positions using the Haversine formula (Eq. (1)):

$$\begin{aligned} a &= sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos\varphi^1 \cdot \cos\varphi^2 \cdot \ sin^2\left(\frac{\Delta\lambda}{2}\right) \\ c &= 2 \cdot atan2\left(\sqrt{a},\ \sqrt{1-a}\right) \\ d &= R\ \cdot c \end{aligned} \tag{1}$$

Where φ_1 is the latitude of the first point; φ_2 is the latitude of the second point; $\Delta\varphi$ is the difference in latitude between the two points; $\Delta\lambda$ is the difference in longitude between the two points; a is the square of half the chord length between the points; c is the angular distance in radians; and R is the Earth's radius.

The COG variable was calculated using the bearing formula (Eq. (2)) between consecutive positions:

$$bearing = atan2(\sin(\Delta\lambda) \cdot \cos(\varphi 2),\ \cos(\varphi 2) \cdot \sin(\varphi 2) - \sin(\varphi 1) \cdot \cos(\varphi 2) \cdot \cos(\Delta\lambda)). \tag{2}$$

Where φ_1 is the latitude of the first position; φ_2 latitude of the second position; $\Delta\lambda$ is the difference in longitude between the two positions. These calculations ensured that the derived SOG and COG values were comparable to those provided in the S-AIS dataset.

[1] Spire Maritime is set to be acquired by Kpler during the first quarter of 2025.

2.4. Data cleaning

Prior to running any analysis on the S-AIS or ASTD L1 positional datasets, we applied a comprehensive series of cleaning techniques to remove erroneous data and identify potential spoofing vessels (i.e., when a vessel emits incorrect positions on purpose) on over one billion positions. Initially, we filtered the datasets to retain only positions with valid country identities, defined by MMSIs between 201,000,000 and 775,999,999. Additionally, we included only positions with speeds (SOG) between 0.5 and 60 knots, eliminating stationary positions and those with unrealistic speeds. Vessels with reported COG values of 361 were also removed to address potential spoofing or erroneous data.

Following this initial filtering, we constructed ‘tracklines’ to represent vessel movements using linear interpolation. This involved creating GIS polylines from consecutive positions, ordered by time for each vessel. Tracklines were segmented if they exceeded a predefined threshold of 300 min and/or 50 miles. For each trackline, we computed the average speed in two ways: (a) the average SOG from the positions that formed the trackline, and (b) the average speed based on the elapsed time (e.g., hours) and the distance of the trackline (e.g., kilometres).

To ensure the consistency of the data, we compared the average speeds calculated by these two methods. Tracklines exhibiting differences of ±30 km/h were flagged and removed from the dataset. Finally, we used the cleaned tracklines to re-query the positions, ensuring that all subsequent analyses were based on accurately filtered data.

The ASTD L1 dataset, designed to be a cleaned (L1) dataset, exhibited minimal instances of spoofing, thus our analysis here primarily highlights the S-AIS data for its prevalent spoofing activities. In 2020, spoofing was notably most prevalent in the S-AIS data within the global Arctic. The cleaned S-AIS tracklines accounted for 67.1 million kilometres sailed in this region (Fig. 2a). In contrast, the spoofing S-AIS tracklines contributed 1.9 million kilometres sailed in this region. Had these erroneous tracklines not been removed, the analysis would have suffered from an error of approximately 2.8 % in the 2020 S-AIS tracklines. Notably, the spoofing patterns near the Kara Sea in Russia displayed star-like formations. However, most spoofing patterns that evolved into tracklines exhibited straight-line trajectories originating near the Arctic Circle, passing through Greenland, and extending to Norway (Fig. 2b).

2.5. Canadian Arctic (NORDREG zone) comparison

To compare the temporal and spatial resolution of the datasets within the Canadian Arctic, we computed two main metrics. First, the re-detection rate per time interval (RRpTI), for only the S-AIS and ASTD L1 data (since NORDREG data are daily positions RRpTI was not computed). Secondly, we computed the unique daily vessels (UDV) for all three of the NORDREG, S-AIS, and ASTD L1 datasets.

The RRpTI metric measures the frequency of vessel re-detections within specified time intervals, providing insights into the temporal resolution of the datasets. Higher RRpTI values indicate more frequent re-detections, suggesting better temporal resolution. To compute the RRpTI for the S-AIS and ASTD datasets, we first filtered the data to include only positions within the Canadian Arctic. For each yearly dataset, we grouped the data by various time intervals (10, 15, 30, 60, 90, 120, 180, 240, 300, 360, 720, and 1440 min) and identified unique MMSIs within each group. The re-detection rate was calculated by comparing the MMSIs detected in consecutive intervals. The RRpTI was expressed as the percentage of MMSIs re-detected in each time interval relative to the previous interval.

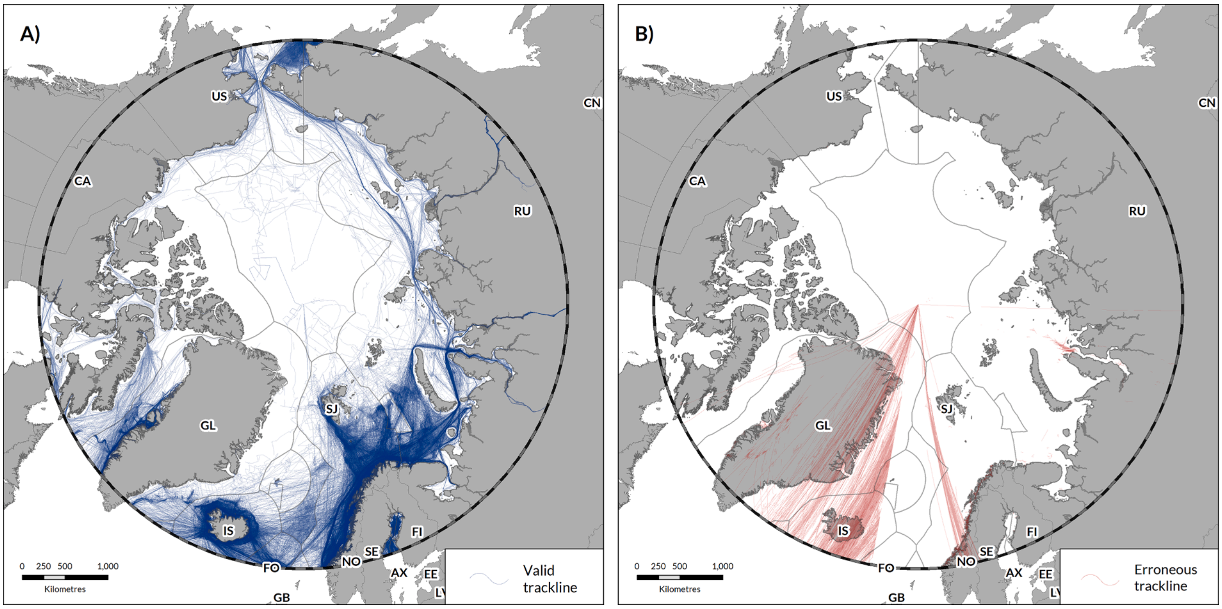

Fig. 2. a) cleaned S-AIS tracklines in N62 for the year 2020 as an example. b) S-AIS tracklines identified as spoofing vessels, which were subsequently removed from the cleaned trackline data for 2020.

For the next metric, we calculated the unique daily vessels (UDV) for all three datasets: NORDREG, S-AIS, and ASTD L1. This metric provides a straightforward measure of the number of distinct vessels detected each day by each data source. For each dataset, we grouped the data by MMSI, year, month, and day. We then counted the number of unique MMSIs per day, providing a daily snapshot of vessel activity within the Canadian Arctic. The daily vessel counts for the NORDREG, S-AIS, and ASTD L1 datasets were compared to assess differences in detection capabilities and coverage between them. Additionally, the unique daily vessels were 'fused' to obtain a maximum count of unique daily vessels covered by all sources combined. The fusion occurred by merging all daily vessel counts, and dropping duplicates based on the MMSI, day, month, and year.

2.6. Global Arctic (North of 62nd parallel) comparison

For the global Arctic, we extended our analysis to evaluate the temporal and spatial resolution of the S-AIS and ASTD L1 datasets. This involved computing the RRpTI and UDV metrics, as described in Section 2.5, but focused exclusively on the S-AIS and ASTD L1 datasets for the larger global Artic area. Additionally, we compared two other metrics, including the kilometres travelled based on the tracklines created from these datasets, as well as conducting a spatial comparison of UDV within 0.5 × 0.5-degree grid cells from 2013 to 2022.

The RRpTI and UDV were computed as described in Section 2.5, but for the global Arctic, to understand the broader re-detection rates and vessel counts. To compare the distances travelled as captured by the S-AIS and ASTD L1 datasets, we analyzed the tracklines constructed during the data cleaning process. For each trackline, we computed the total distance travelled by summing the distances between consecutive positions. The kilometres travelled were then compared between the two datasets to identify any discrepancies or differences in spatial coverage and data quality.

To assess the spatial differences in dataset coverage, we performed a spatial comparison of UDV within 0.5 × 0.5-degree grid cells. This involved creating a grid of 0.5 × 0.5-degree cells covering the N62 region (global Arctic), calculating the average yearly UDV for both S-AIS and ASTD L1 datasets within each grid cell, and comparing the results to identify areas with better coverage by either dataset. The results were visualized to highlight spatial differences in detection capabilities and coverage.

By combining these analyses, we obtained a comprehensive evaluation of the temporal and spatial resolution of the S-AIS and ASTD L1 datasets within the global Arctic. These insights are crucial for understanding the strengths and limitations of each dataset, guiding their use in scientific and decision-making contexts.

3. Results

3.1. Canadian Arctic (NORDREG zone)

From 2013 to 2022, the RRpTI results indicate that the S-AIS dataset consistently shows higher re-detection rates across all time intervals compared to ASTD L1 (Table 1). This suggests that S-AIS has a better temporal resolution, with more frequent re-detections of vessels over shorter time intervals (10-to-90-minute RRpTIs). Conversely, the lower re-detection rates for ASTD L1 suggest it might miss some re-detections or have longer intervals between detections in this area.

The analysis of the UDV reveals that the NORDREG dataset typically shows the highest count of UDV, very closely followed by S-AIS and then by the ASTD L1 data. This indicates that NORDREG provides the most comprehensive vessel coverage, likely due to its mandatory reporting requirements for vessels >300 GT, while S-AIS is close, the ASTD L1 captures fewer vessels in this zone. Both S-AIS and NORDREG exhibit an increasing trend in UDVs over the years, reflecting growing vessel activity in the Canadian Arctic (Table 2).

The percentage of UDV captured by S-AIS, NORDREG, and ASTD L1 compared to the fused data demonstrates varying detection

Table 1
Average Redetection Rate per Time Interval for S-AIS and ASTD L1 within the NORDREG zone from 2013 to 2022.

Time interval	*Average RRpTI % 2013 to 2022*	
	S-AIS	ASTD L1
10 mins	65.9 %	16.4 %
15 mins	69.1 %	20.1 %
30 mins	77.5 %	29.3 %
60 mins	88.8 %	54.1 %
90 mins	93.7 %	73.9 %
120 min (2 hrs)	94.0 %	78.2 %
180 mins (3 hrs)	94.0 %	82.2 %
240 mins (4 hrs)	93.3 %	83.6 %
300 mins (5 hrs)	92.7 %	84.3 %
360 mins (6 hrs)	92.0 %	84.1 %
720 mins (12 hrs)	88.6 %	80.1 %
1440 mins (24 hrs)	84.2 %	71.8 %

Table 2
Unique daily vessels per year recorded by each source within the NORDREG zone from 2011 to 2022.

Year	S-AIS	NORDREG	ASTD L1	Fused Data
2011	2489	3800	N/A	4560
2012	3145	3919	N/A	4911
2013	3727	4285	580	5348
2014	3661	4101	2148	5196
2015	3827	4000	1697	5247
2016	4014	4439	1646	5682
2017	4894	5007	2811	6965
2018	5160	5060	3162	7121
2019	5923	5739	4794	7987
2020	4227	4350	3774	5782
2021	6764	N/A	4183	6779
2022	6982	N/A	4191	6996

capabilities (Fig. 3a). The NORDREG dataset shows a consistently high percentage of vessel detection, reaching up to 83.3 % in 2011 and maintaining around 70–80 % in subsequent years until 2020. In contrast, S-AIS shows a steady increase in vessel detection percentage, starting from 54.6 % in 2011 and reaching up to 99.8 % in 2021 and 2022, when no NORDREG data was available to use at the outset of the study. ASTD L1 starts with a very low detection percentage in 2013 at 10.8 %, but improves, reaching 65.3 % in 2020, but this is still much lower overall in comparison to NORDREG and S-AIS for the Canadian Arctic.

S-AIS records a substantial increase in positional messages over the years, peaking at over 5 million in 2018, which could be indicative of an increase in satellites in the S-AIS constellation (Soldi et al., 2021). NORDREG shows a stable number of positional messages from 2011 to 2020, reflecting its daily reporting (Fig. 3b). The relatively low number of positional messages in the NORDREG dataset is due to its collection of daily positions only, whereas S-AIS and ASTD L1 collect multiple positional messages per day via AIS transponders. ASTD L1, while starting with fewer positional messages, shows an increase over time in this area, particularly in 2019 with 173,091 messages.

These results highlight the large variance in the capabilities and coverage of the datasets in this area. NORDREG's consistently high percentage of UDVs underscores its comprehensive coverage due to close to mandatory reporting, but also reveals its lower temporal resolution due to the limited number of positional messages. S-AIS demonstrates increases in both unique daily vessels and positional messages, indicating its improving detection capabilities over time. ASTD L1, while initially capturing fewer vessels and messages, shows improvement in later years, but is lacking in RRpTI at a high temporal resolution and detection in general, compared to S-AIS in this region.

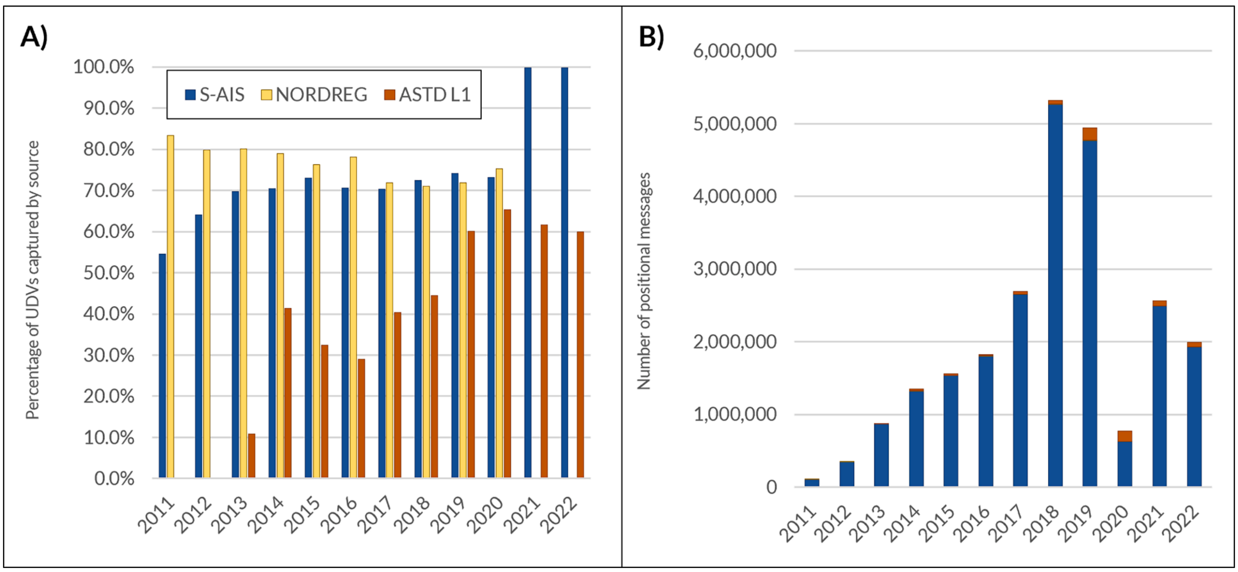

Fig. 3. a) percentage (%) of unique daily vessels (UDVs) captured by S-AIS and ASTD L1 North of the 62nd parallel from 2011 to 2022. The percentages are calculated relative to the total number of UDVs captured by the fused dataset (not shown). b) number of positional messages recorded by S-AIS and ASTD L1 North of the 62nd parallel from 2011 to 2022.

3.2. Global Arctic (North of 62nd parallel)

At the global Arctic scale, from 2013 to 2022, the RRpTI results indicate that the S-AIS and ASTD L1 datasets show varying re-detection rates across different time intervals. The ASTD L1 dataset consistently shows higher re-detection rates for shorter time intervals (10-to-90-minute RRpTIs), suggesting better temporal resolution over these periods. For example, at the 10-minute interval, ASTD L1 achieves an average re-detection rate of 88.3 %, compared to 56.8 % for S-AIS. However, as the time interval increases, the re-detection rates for both datasets converge, with S-AIS showing slightly higher rates for intervals of 12 h or more (Table 3). This indicates that while ASTD L1 may provide more frequent updates over shorter periods, S-AIS offers more consistent coverage over longer intervals. We see a slight dip after 2–3 h, and a larger dip after 24 h, likely due to vessels leaving the region.

The analysis of the UDV for the global Arctic reveals an increasing trend in vessel activity from 2013 to 2022. The S-AIS and ASTD L1 datasets both show significant growth in UDVs, with the fused data indicating even higher numbers, suggesting that combining these datasets provides a more comprehensive view of vessel activity (Table 4). For instance, in 2013, S-AIS detected 239,313 UDV, while ASTD L1 detected 276,797 UDV. By 2022, these numbers increased to 324,002 for S-AIS and 510,910 for ASTD L1, with the fused data showing 573,539 UDV.

The percentage of UDV captured by S-AIS and ASTD L1 compared to the fused data (Fig. 4a) highlights the general strengths and limitations of each dataset. ASTD L1 shows higher percentages, reaching up to 94.6 % in 2019, while S-AIS percentages range from 56.5 % to 77.6 %. This suggests that ASTD L1 provides more comprehensive coverage in certain regions, particularly those with terrestrial AIS receivers.

S-AIS records a substantial increase in positional messages over the years, peaking at over 114.1 million in 2019 (Fig. 4b). In comparison, ASTD L1 shows a more gradual increase, with a peak of 58.8 million messages in 2016. The large volume of positional messages from S-AIS reflects its capability to provide detailed tracking information, while ASTD L1′s coverage improves significantly over time. The large increase in positional messages after 2017 for S-AIS could be indicative that the increase in satellites within the S-AIS constellation (Soldi et al., 2021) had a large impact in terms of AIS message detection.

The total kilometres travelled by vessels, as recorded by S-AIS and ASTD L1, show significant increases over the years (Fig. 5). In 2013, S-AIS recorded 39.9 million kilometres traveled, while ASTD L1 recorded 48.5 million kilometres. By 2022, these numbers increased to 52.3 million kilometres for S-AIS and 81.7 million kilometres for ASTD L1, increases of 31.1 % and 68.5 %, respectively. Overall, these metrics indicate that there has been a substantial growth in maritime activity in the global Arctic over the past decade.

Spatial comparisons of the UDV within 0.5 × 0.5-degree grid cells reveal substantial regional differences in coverage between the datasets (Fig. 6a-d). Higher UDV values are clustered close to land around Norway, Iceland, the Faroe Islands, and the Gulf of Bothnia in the ASTD L1 dataset, likely due to the presence of terrestrial AIS receivers in these regions used to collect the ASTD L1 data. This suggests that ASTD L1′s metrics might be skewed towards areas with better terrestrial coverage, potentially lacking in more remote regions. In contrast, S-AIS shows better coverage across most of the Arctic, particularly in Canadian waters, along the East Coast of Greenland, along the Northern Sea Route in Russia, and especially in the Barents Sea (Fig. 6a).

4. Discussion

4.1. Regional performance differences

The temporal and spatial resolution of the ASTD L1 and S-AIS datasets reveal significant insights into the coverage and detection capabilities of the sources at the global Arctic scale (N62). While the ASTD L1 dataset shows high re-detection rates, indicating potentially higher temporal resolution, this is primarily due to the clustering of terrestrial AIS receivers around regions such as Norway, the Faroe Islands, and Iceland that feed into the ASTD L1 data. However, in other regions outside of these areas, such as major

Table 3
Average Redetection Rate per Time Interval for S-AIS and ASTD L1 North of the 62nd parallel from 2013 to 2022.

Time interval	*Average RRpTI % 2013 to 2022*	
	S-AIS	ASTD L1
10 mins	56.8 %	88.3 %
15 mins	61.2 %	87.7 %
30 mins	70.7 %	85.3 %
60 mins	82.1 %	85.5 %
90 mins	87.4 %	86.9 %
120 min (2 hrs)	88.5 %	87.4 %
180 mins (3 hrs)	89.0 %	86.6 %
240 mins (4 hrs)	88.4 %	85.3 %
300 mins (5 hrs)	87.4 %	84.5 %
360 mins (6 hrs)	86.4 %	84.1 %
720 mins (12 hrs)	83.9 %	83.6 %
1440 mins (24 hrs)	79.0 %	79.3 %

Table 4
Unique daily vessels per year recorded by S-AIS and ASTD L1 North of the 62nd parallel from 2011 to 2022.

Year	S-AIS	ASTD L1	Fused Data
2011	93,810	N/A	N/A
2012	157,285	N/A	N/A
2013	239,313	276,797	372,517
2014	277,835	331,592	406,259
2015	290,240	397,358	444,338
2016	289,381	413,214	466,553
2017	296,551	433,786	482,778
2018	298,707	449,799	493,657
2019	337,575	490,794	519,068
2020	482,064	490,594	620,891
2021	342,971	503,436	566,526
2022	324,002	510,910	573,539

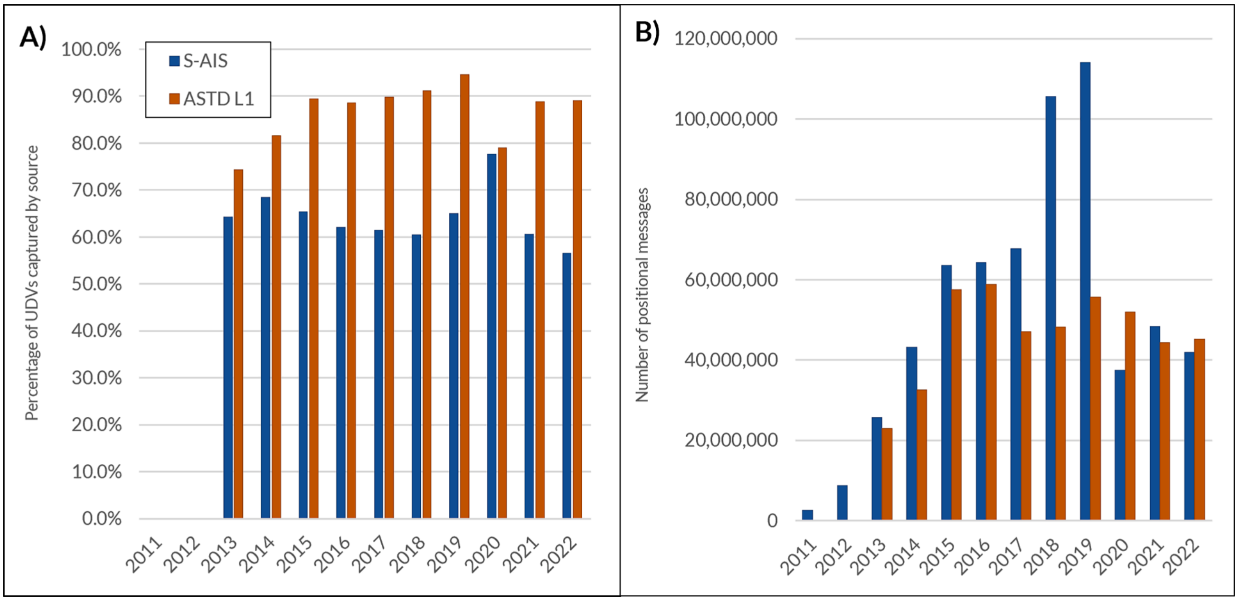

Fig. 4. a) percentage (%) of unique daily vessels (UDVs) captured by S-AIS and ASTD L1 North of the 62nd parallel from 2011 to 2022. The percentages are calculated relative to the total number of UDVs captured by the fused dataset (not shown). b) number of positional messages recorded by S-AIS and ASTD L1 North of the 62nd parallel from 2011 to 2022.

Arctic shipping routes like the NWP and NSR (Fig. 1b), where terrestrial AIS coverage is non-existent in the ASTD L1 data, the re-detection rates and unique ship counts for ASTD L1 are much lower.

For the Canadian Arctic NORDREG zone, the NORDREG dataset shows the best coverage due to its mandatory reporting system for ships over 300 GT (and high compliance rate among smaller vessels) (Pizzolato et al., 2014), the S-AIS data is very close in terms of vessel detection and exhibits a much higher temporal resolution. This suggests that S-AIS can serve as a reliable alternative or complement to NORDREG data for spatio-temporal analyses in this area. In contrast, the ASTD L1 data does not perform well in the NORDREG zone (i.e., Canadian Arctic), highlighting its limitations in regions without dense terrestrial AIS coverage.

4.2. Technological advancements

The observed increase in unique daily vessels (UDV) in both the ASTD L1 and S-AIS datasets over the study period aligns with findings in prior studies for the global Arctic (e.g., Eguíluz et al., 2016; Berkman et al., 2022; Müller et al., 2023). However, this increase also reflects other significant factors. For example, the growing affordability and adoption of AIS transponders among smaller vessels under 300 GT (Serra-Sogas et al., 2021) is likely contributing to this trend. Smaller vessels, which were historically undetected due to the lack of transponders, are increasingly visible in AIS datasets, even though international regulations do not mandate AIS carriage for these vessels.

Another key factor is the expansion of satellite constellations. Following 2017, both public and private constellations experienced significant growth, improving spatial and temporal detection capabilities (Eriksen et al., 2020; Soldi et al., 2021). For ASTD, the addition of NorSat-1 and NorSat-2 enhanced coverage and detection rates in the Arctic (Eriksen et al., 2020). These technological

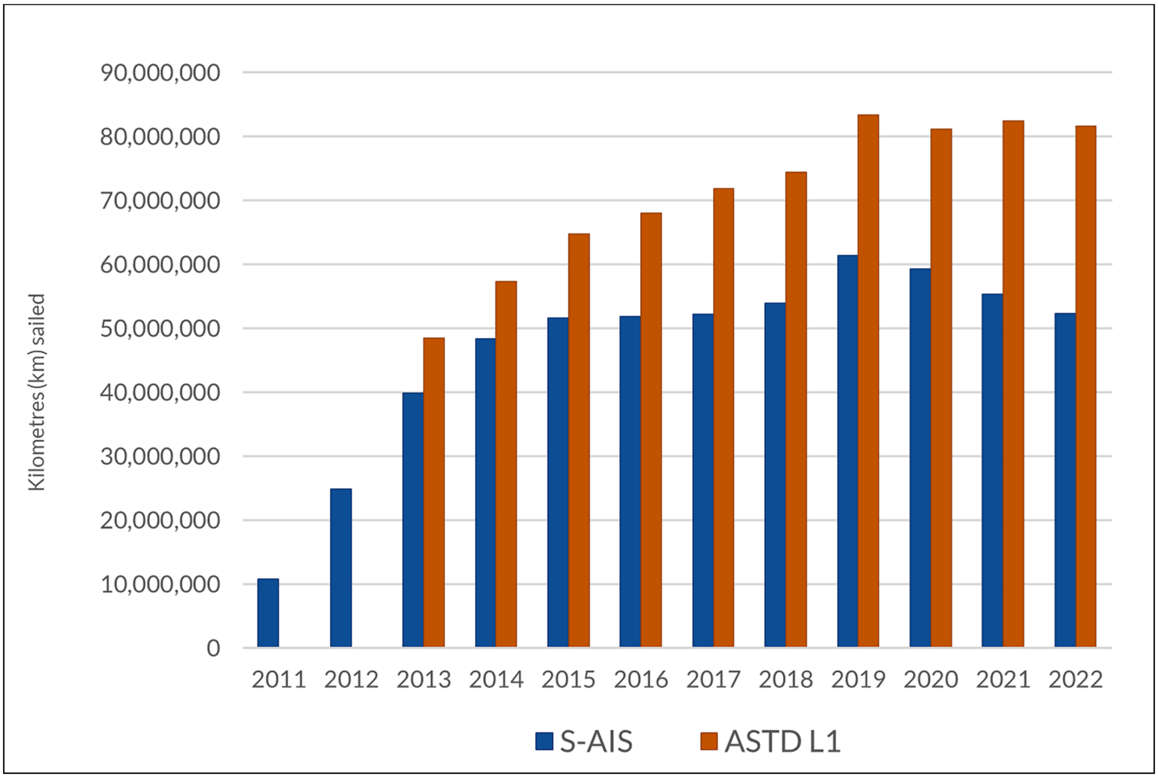

Fig. 5. Derived kilometres (km) sailed by S-AIS and ASTD L1 based on the tracklines created for each of the sources North of the 62nd parallel from 2011 to 2022.

advancements highlight the importance of considering both regulatory changes and improvements in data collection infrastructure when interpreting long-term trends in maritime activity.

Our study highlights the need for comprehensive AIS analysis to assess vessel activity. However, future research could focus on distinguishing patterns between smaller (<300 GT) and larger vessels to better understand their respective contributions to overall traffic trends. Such investigations could clarify the relative impacts of regulatory changes and satellite advancements on the increasing visibility of Arctic vessel traffic.

4.3. Data fusion leveraging strengths

The complementary nature of the ASTD L1 and S-AIS datasets presents a compelling case for a granular level data fusion, at the positional message level. S-AIS provides extensive coverage in remote areas such as the Canadian Arctic, along the East Coast of Greenland, and the Northern Sea Route through Russia. In contrast, ASTD L1 excels in regions with dense terrestrial AIS infrastructure feeding into the AIS dataset. Using the underlying AIS information within the ASTD L1 data and fusing it with the S-AIS positional data, used in this study, can leverage their respective strengths, providing a more comprehensive and accurate picture of Arctic maritime traffic. This integrated approach can mitigate the limitations of individual datasets and enhance the reliability of ship traffic analyses in the Arctic.

4.4. Challenges and limitations

In addition to the datasets analyzed in this study, a comprehensive understanding of Arctic maritime traffic requires incorporating additional satellite, land-based, and other AIS sources. Even the S-AIS in this study might be missing some information from key areas like the NWP and NSR, especially smaller vessels that might not be as well detected by satellite receivers or during periods when satellites are not positioned for detection (Fournier et al., 2018). A multi-source fusion approach can address the spatial and temporal gaps identified in the individual datasets.

Shipping density maps generated in this study clearly illustrate that relying solely on ASTD L1 could bias analyses toward regions with dense terrestrial AIS coverage, such as Norway and Iceland, while missing critical information in major shipping lanes such as the NWP and NSR. Conversely, S-AIS, while providing better coverage in these critical lanes, may lack detailed information in regions well-covered by terrestrial AIS. Future research should explore the integration of other AIS data providers to further improve coverage and accuracy. Moreover, continuous monitoring and updates to AIS infrastructure in key regions can help maintain high data quality and

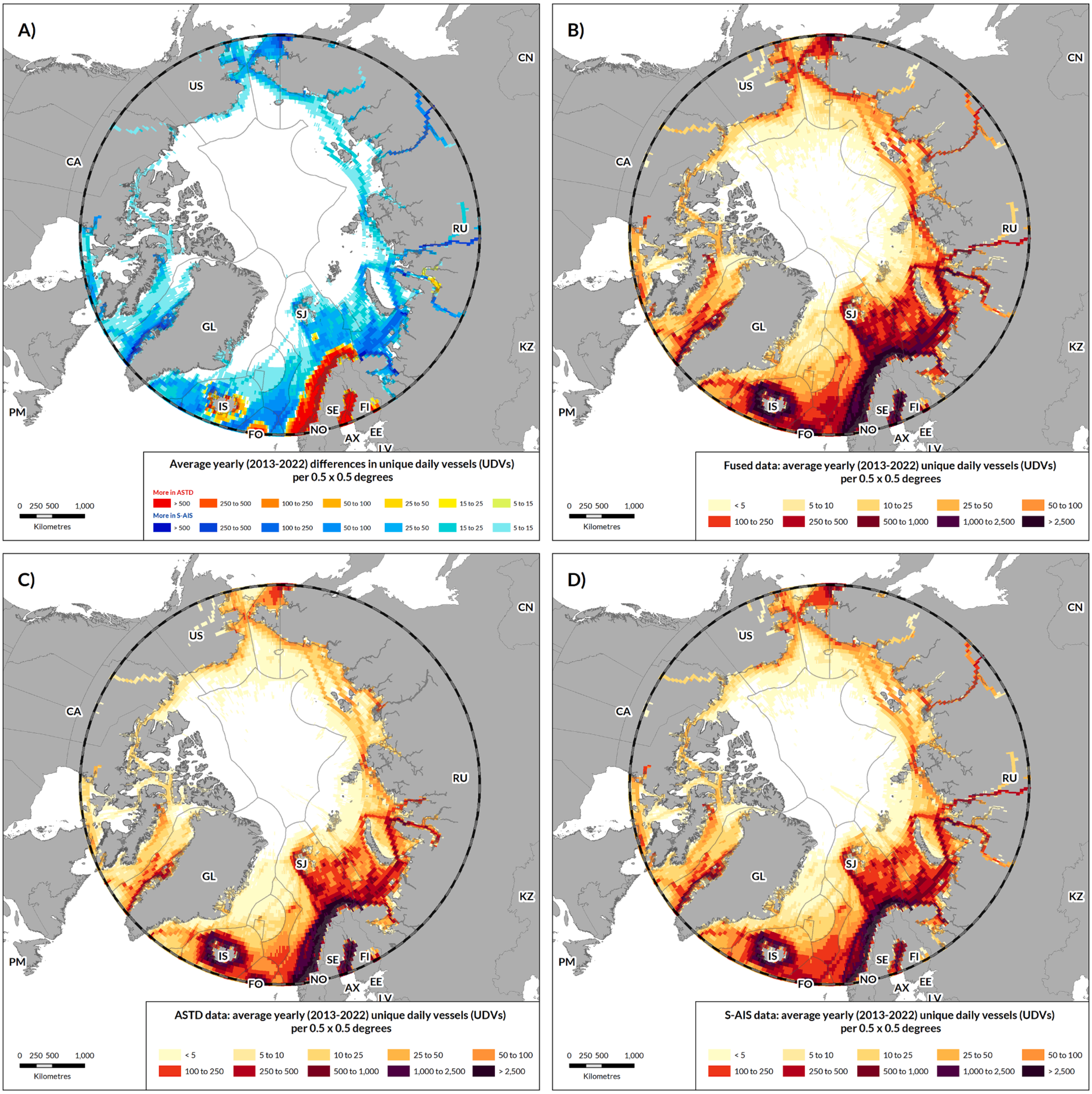

Fig. 6. a) yearly average (2013–2022) difference in unique daily vessels (UDV) between ASTD L1 and S-AIS datasets per 0.5 × 0.5-degrees; grid cells in red represent more UDV detected in the ASTD L1 data, while grid cells in blue represent more UDV detected in the S-AIS data. b) yearly average UDV from the fused ASTD L1 and S-AIS data. c) yearly average UDV from the ASTD L1 data. d) yearly average UDV from the S-AIS data.

reliability.

Signal manipulation and interference remain significant challenges when working with AIS data. While instances of signal spoofing and anomalies in AIS data have been documented in the literature (Natale et al., 2015), additional concerns have been raised about potential disruptions, such as interference from vessels operating in confined areas or geopolitical activities like GPS jamming during military exercises (Boulègue, 2019). These concerns highlight the necessity for ongoing vigilance and the implementation of robust cleaning protocols.

It is essential to acknowledge that AIS data can be inherently messy due to the nature of GPS signals, spoofing, and other anomalies (Androjna et al., 2023; Brown et al., 2024). Implementing robust data cleaning techniques (He et al., 2021; Spadon et al., 2024) is crucial to ensure the accuracy and reliability of the data prior to analysis. This study underscores the importance of preprocessing steps to mitigate the effects of such distortions, ensuring a more accurate representation of maritime traffic patterns.

By addressing these limitations and incorporating additional data sources where feasible, future research can further refine the insights into Arctic maritime activity, particularly in light of the rapid environmental and geopolitical changes impacting the region.

4.5. Policy implications and future research

The results underscore the complementary nature of S-AIS and ASTD L1 datasets and make a compelling case for their fusion at the positional level. This fusion can be achieved by combining datasets based on common features such as MMSI, latitude, longitude, speed, course, and datetime, with the positional data aligned to the lowest common denominator (e.g., resolution up to six decimal places for latitude and longitude). Duplicates can be dropped by MMSI, latitude, longitude, and datetime to create a single, fused dataset. From this fused positional dataset, analyses such as unique daily vessels (UDV), redetection rate per time interval (RRpTI), and kilometres sailed—metrics that form the foundation of many studies using ship traffic data—can be conducted with higher accuracy and reliability. Without such fusion, studies relying on a single data source may inadvertently misrepresent trends due to inherent biases or gaps in coverage.

The fusion of datasets would provide a more accurate and complete picture of Arctic shipping traffic, which is crucial for policymakers. Enhanced data accuracy can inform better decision-making regarding shipping regulations, including vessel traffic monitoring, the establishment of marine protected areas, and navigation safety. For instance, policymakers can use more accurate vessel tracking data to enforce regulations on vessel routing, speed restrictions, and emissions controls in sensitive Arctic regions. Moreover, the insights gained from voluntary vs. mandatory reporting could guide the development of policies that incentivize smaller vessels to adopt AIS transponders, improving overall maritime safety and environmental protection. Given that Arctic governance involves multiple nations with overlapping claims and interests, improved shipping data can also facilitate international cooperation. More accurate, harmonized datasets can provide a shared understanding of maritime activity, supporting joint decision-making on environmental protection and navigation safety across borders (Albrechtsen et al., 2021; Kirchner et al., 2022). This would be particularly useful for international agreements on safe shipping corridors, emissions regulations, and coordinated responses to maritime emergencies in Arctic waters (Mileski et al., 2018).

Further regional differences across the Arctic, at the country level, could be explored using this fusion approach, providing a more detailed understanding of shipping patterns. Importantly, this methodology is not confined to the Arctic; it can be applied in other global contexts. For example, high-density shipping regions like Eastern Asia, the Mediterranean, and the North Sea often encounter detection challenges due to packet collisions in satellite-based AIS data (Clazzer et al., 2014), where multiple AIS messages are transmitted simultaneously, leading to errors, or missed detections. By integrating satellite and terrestrial AIS data, these limitations can be mitigated, offering a completer and more accurate picture of vessel activity. This fusion approach is particularly critical for studies that rely on a single AIS source, which may miss significant portions of vessel traffic. For instance, terrestrial AIS alone may underperform in remote or offshore areas, while satellite AIS struggles in high-density regions.

Incorporating newer AIS technologies, such as data from ship-based receivers designed for high-density areas, could further refine this approach. These advancements, currently being developed under various initiatives (e.g., Dynamic AIS, roaming AIS, tier-based AIS), aim to address existing gaps in coverage and enhance global applications. By extending the lessons learned from Arctic shipping analyses to other regions, future research can build on this study's findings to address both regional and global shipping challenges.

Moreover, a compelling avenue for future research would involve examining voluntary (<300 GT) versus mandatory (>300 GT) vessel reporting. The ASTD dataset, which includes terrestrial AIS, likely captures voluntary vessels (such as those operating class B AIS transponders) more effectively, particularly around Norway, where there is a high density of terrestrial receivers. Since terrestrial AIS systems are better at picking up class B messages from smaller vessels, the fusion of datasets could offer insights into how voluntary versus mandatory vessels are detected across various regions and datasets. Additionally, exploring the differences in ship type density using fused datasets could provide a more nuanced view of traffic patterns. While the voluntary versus mandatory analysis would give an overview, focusing on specific ship types could reveal further regional and operational differences in shipping traffic, providing valuable information for policymakers and researchers.

Overall, fusing datasets at the positional level presents a valuable opportunity to enhance the accuracy of shipping traffic analyses, and its potential extends beyond the Arctic. By improving data quality and understanding regional differences, this approach can guide policy development, maritime safety, and environmental protection efforts globally.

5. Conclusion

This study compares three primary datasets—NORDREG, S-AIS, and ASTD L1—used for analyzing Arctic shipping patterns. Each dataset has unique strengths and limitations: NORDREG and S-AIS provide the best vessel coverage in Canadian waters, S-AIS offers high temporal resolution and broad coverage around the NWP and NSR, and ASTD L1 excels in regions with dense terrestrial AIS infrastructure around Norway, Iceland, and the Faroe Islands but underperforms in the NWP and NSR.

The complementary nature of S-AIS and ASTD L1 highlights the importance of data fusion to obtain a comprehensive picture of Arctic maritime traffic. Fusing these datasets can mitigate individual limitations and enhance traffic analysis reliability. The observed increase in unique daily vessels over the study period reflects growing maritime activity, likely driven by the greater adoption of AIS transponders among smaller vessels and technological advancements, such as the expansion of satellite constellations. Future research should integrate all available data sources to avoid regional biases and gaps, ensuring comprehensive coverage. Combining terrestrial and satellite-based AIS data will be crucial for capturing both voluntary and mandatory vessels, especially in remote regions. Robust data cleaning is essential to address AIS data anomalies and provide accurate traffic representations.

Overall, this study underscores the value of a multi-source approach to Arctic maritime traffic analysis. Beyond supporting environmental monitoring and maritime safety, the insights gained from data fusion have important implications for strategic planning and international cooperation in the Arctic, where accurate and comprehensive data is essential for managing a rapidly changing environment.

Glossary

AIS: Automatic Identification System
ASTD: Arctic Ship Traffic Database
ASTD L1: ASTD Level 1
COG: Course over ground (degrees)
GIS: Geographic Information System
GT: Gross Tonnes
MMSI: Maritime Mobile Service Identity
N62: North of the 62nd parallel
NORDREG: Northern Canada Vessel Traffic Zone
NSR: Northern Sea Route
NWP: Northwest Passage
PAME: Protection of the Arctic Marine Environment
RRpTI: Redetection rate per time interval
S-AIS: Satellite-based AIS
SOG: Speed over ground (knots)
T-AIS: Terrestrial-based AIS
UDV: Unique daily vessel

CRediT authorship contribution statement

Adrian Nicoll: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jackie Dawson:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **Jérôme Marty:** Writing – review & editing, Supervision. **Michael Sawada:** Writing – review & editing, Supervision. **Luke Copland:** Writing – review & editing, Validation, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See Appendix Table A1 and Table A2

Table A1
The total number of all S-AIS positions compared to the number of cleaned S-AIS positions used in the N62 analysis of this study from 2011 to 2022.

Year	All S-AIS positions	Cleaned S-AIS positions
2011	4,634,865	2,570,256
2012	13,903,885	8,710,839
2013	37,857,493	25,687,636
2014	65,743,032	43,202,901
2015	94,310,227	63,525,807
2016	94,222,249	64,314,316
2017	101,058,677	67,764,916
2018	160,711,894	105,584,784
2019	171,510,524	114,120,138
2020	167,381,675	37,444,915

(*continued on next page*)

Table A1 (*continued*)

Year	All S-AIS positions	Cleaned S-AIS positions
2021	76,866,597	48,386,445
2022	67,697,194	41,835,789

Table A2
The total number of all ASTD L1 positions compared to the number of cleaned ASTD L1 positions used in the N62 analysis of this study from 2013 to 2022.

Year	All ASTD L1 positions	Cleaned ASTD L1 positions
2011	N/A	N/A
2012	N/A	N/A
2013	69,037,288	22,916,892
2014	95,007,219	32,533,987
2015	186,699,280	57,554,164
2016	196,510,438	58,798,344
2017	174,763,122	47,127,520
2018	176,288,146	48,213,303
2019	190,732,558	55,689,545
2020	187,270,786	51,887,991
2021	169,278,392	44,334,185
2022	178,155,916	45,268,441

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