Informed Decisionmaking for Sustainability

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Paul Arthur Berkman
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Editors

Governing Arctic Seas: Regional Lessons from the Bering Strait and Barents Sea

Volume 1

Science
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Informed Decisionmaking for Sustainability

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Cover map illustration: Oldest and longest continuous satellite record of ship traffic in the Arctic Ocean from 1 September 2009 through 31 December 2016, produced by the Arctic Options and Pan-Arctic Options projects to facilitate "Holistic Integration for Arctic Coastal-Marine Sustainability" with international, interdisciplinary and inclusive (holistic) collaboration from Canada, China, France, Norway, Russia and the United States. As introduced with the NASA Earth Observatory image of the day on 12 April 2018 (*Shipping Responds to Arctic Ice Decline*), the centroid of ship traffic north of the Arctic Circle has *"moved 300 kilometers north and east—closer to the North Pole—over the 7-year span."* The satellite Automatic Identification System (AIS) data was provided by SpaceQuest Ltd. with big-data analyses and map production by Greg Fiske at the Woods Hole Research Center (for additional details, see *Chapter 11: Next-Generation Arctic Marine Shipping Assessments* in this book).

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Next-Generation Arctic Marine Shipping Assessments

11

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Abstract

The Arctic is prominent in the history of the International Maritime Organization (IMO), following the *RMS Titanic* disaster in 1912 and soon signing in London of the *Convention for the Safety of Life at Sea* in 1914. Eighty years later, the IMO initiated a process to manage shipping in ice-covered oceans. In concert with the *IMO Guidelines for Ships Operating in Arctic Ice-Covered Waters* in 2002 and their 2004 release of the Arctic 2004 Arctic Climate Impact Assessment, the Arctic Council initiated the *Arctic Marine Shipping Assessment* (AMSA), which issued its final report in 2009. The goal of this chapter is to build on AMSA as a case study of informed decisionmaking through the steps of questions to generate data, which are then integrated into evidence to reveal options (without advocacy), informing decisions by relevant institutions to address a 'continuum of urgencies' that involve shipping in the new Arctic Ocean with its transformed sea-ice cap, assessing whether shipping is increasing as sea ice is decreasing ('ship-ice hypothesis'). Primary sources of data for AMSA involved ship tracking from ground-station Automatic Identification System (AIS), shore-based radar systems and details of fishing ves-

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sels as well as other smaller ships provided by the Arctic nations. However, Arctic ship traffic fundamentally changed the year of the AMSA report, when satellite AIS records began providing continuous, synoptic, pan-Arctic coverage of individual ships with data pulsed over seconds to minutes. This chapter reveals the oldest and longest continuous satellite AIS record (from 1 September 2009 through 31 December 2016), applying the 'spacetime cube' (which also was unavailable during AMSA) with more than 120,000,000 satellite AIS messages from SpaceQuest Ltd. to begin addressing synoptic questions with any level of granularity from points to regions to pan-Arctic over time. Future questions can be considered to assess ship attributes (including vessel flag state, size and type) in view of biophysical and socio-economic variables, recognizing that shipping and sea ice are recognized as primary drivers of change in the Arctic Ocean. Contributions to these assessments come from all areas of science (inclusively defined as the study of change), across the natural and social sciences with Indigenous knowledge in an holistic (international, interdisciplinary and inclusive) manner to achieve Arctic sustainability across generations. As a practical outcome in a user-defined manner, this chapter reveals characteristics of next-generation Arctic marine shipping assessments, revealing patterns and trends that can be applied to informed decisionmaking about the governance mechanisms and built infrastructure as well as operations for multilateral stability and sustainable development in the new Arctic Ocean.

11.1 Science Diplomacy and Arctic Shipping

This book is about regional lessons from the Bering Strait and Barents Sea (AMAP 2017a, b; Berkman et al. 2016; Vylegzhanin et al. 2018; Raymond-Yakoubian 2018) in the Arctic Ocean to help address issues, impacts and resources within, across and beyond jurisdictional boundaries generally. As a premise for each region, however defined, there are stakeholder perspectives, geospatial evidence and governance mechanisms that influence all manner of decisions for sustainable development (Preface Figs. 4 and 6). Simply defined as the study of change, the science behind these decisions can be **international, interdisciplinary and inclusive (holistic)**, characterized by patterns, trends and processes with methodologies from the natural sciences and social sciences as well as Indigenous knowledge. At user-defined levels of granularity (across time and space) – **goal of this chapter** is to contribute to informed decisionmaking about a fundamental socio-economic driver of Arctic change, namely ship traffic in the Arctic Ocean.

Human activities in the world ocean operate under the *United Nations Convention on the Law of the Sea* (UNCLOS 1982) and customary international law of the sea more generally, applying to maritime governance and enforcement within, across and beyond national jurisdictions in the Arctic Ocean (Berkman and Young 2009). The International Maritime Organization (IMO 2017a) is the specialized agency of the United Nations in London, established in 1948, with *"global standard-setting authority for the safety, security and environmental performance of international shipping."* The Arctic is prominent in the history of the IMO, following the RMS

Titanic disaster in 1912 and subsequent signing in London of the *Convention for the Safety of Life at Sea* (SOLAS 1914).

With the Arctic Ocean at the center – literally and figuratively – IMO has provided leadership since 1993 to manage shipping in ice-covered oceans (Brigham 2017). Notable steps include adoption of the voluntary or recommendatory *IMO Guidelines for Ships Operating in Arctic Ice-Covered Waters* (IMO 2002) and *Guidelines for Ships Operating in Polar Waters* (IMO 2009), en route to the legally binding *International Code for Ships Operating in Polar Waters (Polar Code)* that came into force on 1 January 2017 (IMO 2017b). The *Polar Code* is implemented by amendments to SOLAS (1974) as well as the *International Convention for the Prevention of Pollution from Ships* (MARPOL 1973) and *International Convention on Standards of Training, Certification and Watchkeeping for Seafarers* (STCW 1978).

During the 2004–2009 period – when the IMO shipping guidelines were expanding to both polar regions – the Arctic Council conducted the *Arctic Marine Shipping Assessment* (AMSA) through its Protection of the Arctic Marine Environment (PAME) working group. With broadly relevant lessons for Arctic sustainability, AMSA (2009a) integrated perspectives from diverse stakeholders into questions, generating data, evidence and options that contributed to informed decisions (Preface Fig. 5). These lessons from AMSA (Brigham 2011; Box 11.1) illustrate practical **applications of science diplomacy as a holistic process,** involving informed decisionmaking to balance national interests and common interests for the lasting benefit of all on Earth across generations (Berkman et al. 2017).

Box 11.1: Arctic Marine Shipping Assessment (AMSA)

On 29 April 2009 the Arctic Council Ministers in Tromsø, Norway approved the Arctic Marine Shipping Assessment (AMSA), involving nearly 200 experts under the Arctic Council's Protection of the Arctic Marine Environment (PAME) working group led by Canada, Finland, and the United States during 2004–2009. AMSA was a broad, interdisciplinary assessment including diverse topics: marine geography and regional climate; governance and law of the sea; Arctic marine transportation history; the human dimension and Indigenous marine use; scenarios or plausible futures of Arctic marine navigation; environmental impacts; marine infrastructure; and a database of vessels in the Arctic marine environment derived from a survey of the Arctic states (prior to era of comprehensive AIS-derived ship information).

A key objective of AMSA was to obtain the official (national) ship data within Arctic regions defined by the individual states. The AMSA team took a holistic approach to Arctic marine use and included nearly all surface vessels over 100 tons (less naval ships), including: tankers; container ships; icebreakers; cruise ships; fishing vessels; offshore support vessels; survey vessels; research ships; coast guard vessels; ferries; salvage vessels; and, tug-barge combinations. The data survey revealed an estimated 6000 individual ships operating in or near the Arctic marine environment during calendar year 2004. The outcome was the first pan-Arctic snapshot of shipping and operations in the Arctic marine environment, within regions defined by each of the

(continued)

Box 11.1: (continued)
Arctic states (who identify themselves collectively as having territories north of the Arctic Circle, which is an objective Earth system boundary). The AMSA effort can be viewed as a:

- *Baseline assessment of Arctic marine activity early in the twenty-first century* using the 2004 database as an historic snapshot of Arctic marine use;
- *Strategic guide* for a host of Arctic and non-Arctic actors and stakeholders; and
- *Policy document of the Arctic Council* since the *AMSA 2009 Report* was negotiated and approval was reached by consensus of the eight, Arctic state Ministers within the Arctic Council.

Ninety-six findings are identified throughout the AMSA (2009a) report and seventeen recommendations are listed under three inter-related themes: (1) Enhancing Arctic Marine Safety; (2) Protecting Arctic People and the Environment; and, (3) Building the Arctic Marine Infrastructure.

A significant challenge for AMSA was to address the future of Arctic marine shipping. Using scenario planning exercises to create plausible futures, AMSA identified nearly 120 factors and forces that could shape the future of Arctic marine operations and shipping. The scenarios effort identified two primary drivers and uncertainties: resources and trade (the level of demand); and governance (the degree of relative stability of rules for use) within the Arctic and globally.

AMSA emphasizes that the vastness and harshness of the Arctic environment make the conduct of marine emergency response more difficult than other marine regions. Missing or lacking marine infrastructure in most Arctic areas include: hydrographic data and marine charts; communications coverage; environmental monitoring (sea ice, weather and icebergs); search and rescue, and environmental response capacities; salvage; aids to navigation; ship monitoring and tracking; icebreaking; ports; and more. The Arctic human dimension is addressed throughout the AMSA report and the final recommendations include the critical need for surveys of Arctic Indigenous marine use to assess local impacts of Arctic marine operations. Moreover, AMSA identified the release of oil from ships through accidental and or illegal discharge as the most significant environmental threat in the Arctic. AMSA further considered potential impacts on Arctic marine ecosystems from lengthening the navigation season, potentially year-round. A major success from AMSA was its contribution to development of the mandatory 'Polar Code' to manage ship operations in the Arctic Ocean into the future.

As fertile ground for informed decisionmaking en route to the *Polar Code* in 2017, AMSA along with other scientific assessments (e.g., ACIA 2004; AMSP 2004; OGA 2007) soon began to bear fruit through the "high level forum" of the Arctic Council with binding legal agreements signed by the Foreign Ministers of the eight

Arctic States regarding search-and-rescue (SAR 2011) as well as marine-oil-pollution prevention, preparedness and response (MOPP 2013). Progress in this arena of informed decisionmaking is further complemented by the Arctic Science Agreement (2017), which "*is a strong signal reaffirming the global relevance of science as a tool of diplomacy, reflecting a common interest to promote scientific cooperation even when diplomatic channels among nations are unstable*" (Berkman et al. 2017).

AMSA provides a benchmark and, as such, it is the organizing feature of this chapter (Box 11.1) to consider characteristics of next generation Arctic marine shipping assessments. The **starting point for informed decisionmaking involves questions (Preface Fig. 5)**, which the Arctic States and Indigenous peoples along with others framed in terms of their common interests about marine shipping to generate the data for the assessments (AMSA 2009b):

- What are the environmental and geographic features that should be assessed (e.g., bathymetry, large marine ecosystems, climate and monthly sea-ice coverage) north of the Arctic Circle and in areas defined by each Arctic state?
- What marine activities based on vessel routes (especially the Northern Sea Route and Northwest Passage) and vessel categories (e.g., general cargo, bulk carriers, tankers, tugs, barges and icebreakers) should be measured and how, but without elaboration of individual ships and with fishing activities treated separately?
- How should origin and destination ports be characterized?

Value of such questions is they initiate holistic integration, contributing to sustainable development in the Arctic Ocean across a **'continuum of urgencies'** from security to sustainability time scales (Preface Fig. 3).

The pan-Arctic context for AMSA (2009a) also includes estimates of Northern Hemisphere sea-ice extent from 1978–2007, building on the Arctic Climate Impact Assessment (ACIA 2004) with its data embedded at different time and space scales to address local-regional-global questions (Preface Table 2). Ancillary data on maritime accidents north of the Arctic Circle, involving vessel damage or failures from 1995–2004, along with adjacent human population demographics were represented in the Geographic Information Systems (GIS) analyses with raster data. There also were derived products from the AMSA data (AMSA 2009b), including the *"the world's first activity-based estimate of Arctic marine shipping emissions."*

Importantly, the AMSA data and analyses demonstrate that nations can balance national interests and common interests through shared methods to answer questions. However, **data to answer questions is different than evidence for decisions**. The evidence is framed by integrating data from the natural and social sciences along with Indigenous knowledge in view of the decisionmaking institutions that produce governance mechanisms and built infrastructure, which require close coupling to achieve sustainability.

As a process, AMSA (2009a, b) took into consideration holistic evidence along with stakeholder perspectives and prevailing governance mechanisms to produce seventeen recommendations across three major themes: *Enhancing Arctic Marine Safety*; *Protecting Arctic People and the Environment*; and *Building the Arctic Marine Infrastructure*. PAME (2017) now is working "*to develop and adopt updated* *shipping priorities and recommendations under the three themes of the 2009 Arctic Marine Shipping Assessment*." Introducing **options (without advocacy), which can be used or ignored explicitly**, this chapter will focus on development of an *Arctic Marine Traffic System* recommended under the AMSA (2009a) theme of *Building the Arctic Marine Infrastructure*:

> comprehensive Arctic marine traffic awareness system to improve monitoring and tracking of marine activity, to enhance data sharing in near real-time, and to augment vessel management service in order to reduce the risk of incidents, facilitate response and provide awareness of potential user conflict. The Arctic states should encourage shipping companies to cooperate in the improvement and development of national monitoring systems.

Recognizing that "*marine use of the Arctic Ocean is expanding in unforeseen ways early in the 21st century*" (AMSA 2009a), this chapter will highlight fundamental contributions of satellite Automatic Identification System (AIS) data and vector-based GIS methodologies that also were unavailable for AMSA to consider.

To operationalize an Arctic Marine Traffic System, it will be necessary to simultaneously assess sea ice and shipping as linked biophysical and socio-economic drivers of human activities in the Arctic Ocean. Informed decisions also will consider an Arctic Marine Traffic System as central for "sustainable infrastructure development" (Berkman 2015) to balance economic prosperity, environmental protection and societal well-being in a pan-Arctic context with global relevance across generations.

11.2 Arctic Shipping Traffic from Satellites

11.2.1 Arctic Satellite AIS Data

Satellite AIS analyses of Arctic ship traffic still are in their infancy (Eucker 2011. Østreng et al. 2013; Eguíluz et al. 2016; Melia et al. 2017; Serkez et al. 2018). The oldest and longest continuous satellite AIS database for the Arctic Ocean is analyzed herein with SpaceQuest (2017) data from its polar-orbiting constellation from 1 September 2009 through 31 December 2016 (Table 11.1).

Table 11.1 Satellite Automatic Identification System (AIS) Data Provided by SpaceQuest Ltd. for *Pan-Arctic Options: Holistic Integration for Arctic Coastal-Marine Sustainability*[a] with Maritime Mobile Service Identity (MMSI) of Unique Ships in the Arctic Ocean (Fig. 11.1) from 1 September 2009 through 31 December 2016

Satellite AIS messages characteristics	Satellite AIS data
	Messages received
Total AIS messages received	122,771,418
Total AIS messages with validated MMSI[b] in the study area (Fig. 11.1)	85,664,811

[a] A Belmont-Forum project (Preface Table 1) with support of national science agencies in Canada, China, France, Norway, Russian Federation and United States (http://panarcticoptions.org/)

[b] MMSI validated by 9-character strings and correct formatting ITU (2019) and USCG (2019)

The satellite AIS data from SpaceQuest (Table 11.1) are from the region north of the Arctic Circle (see Book Cover Figure), focusing on the Barents Sea Region (BaSR) and Bering Strait Region (BeSR), as introduced in Chap. 1. GIS spatial-data files defined by longitude-latitude coordinates were established to enable spatially-consistent comparisons in future assessments of these regions (Fig. 11.1).

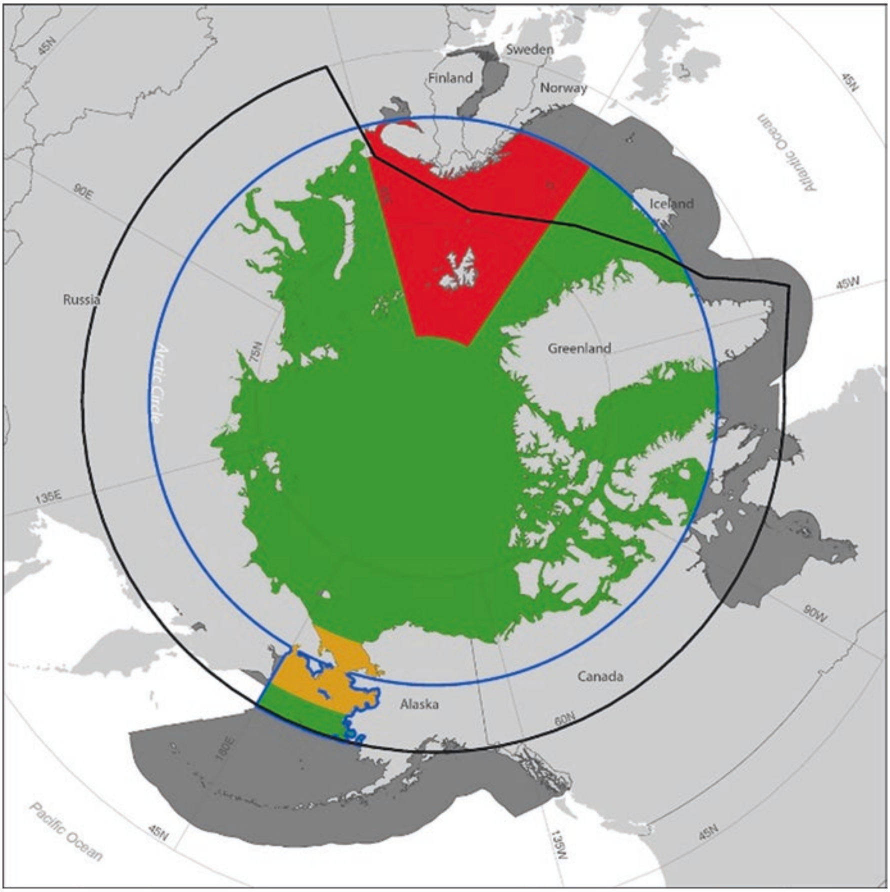

Fig. 11.1 Arctic Ocean regions north of the Arctic Circle (blue), including the Barents Sea Region (BaSR – red) as well as Bering Strait Region extending slightly southward (BeSR – orange), with color coding that is consistent in subsequent figures (green is satellite ship traffic data minus BeSR and BaSR). Rationale for the regional boundaries have been elaborated previously for BeSR (Berkman et al. 2016), BaSR (Vylegzhanin et al. 2018), with the actual data provided for the three colored regions as mapped. Boundaries also are shown for the *Polar Code* north of 60° North latitude (IMO 2017a, b, c) and associated marine boundaries (including dark grey areas) of the *Arctic Science Agreement* (2017), as mapped by Berkman et al. (2017). These boundaries are complemented by additional overlapping boundaries compiled from previous years (Berkman 2015), with the Arctic Circle as a consistent natural system boundary based on the tilt of the Earth's axis. All of these regions can be defined by spatial data for Geographic Information System (GIS) analyses to generate accurate assessments of socio-economic and biophysical patterns, trends and relationships in the Arctic Ocean into the future with synoptic pan-Arctic satellite measurements, available for both shipping (e.g., Table 11.1) and sea-ice (e.g., NSIDC 2017)

Table 11.2 Ship and movement details encoded on Automatic Identification System (AIS) messages from Class A Transponders Versus Class B Transponders with movement details only (see NAVCEN 2017)[a]

Maritime Mobile Service Identify (MMSI) – Unique identification for each transponder;
International Maritime Organization (IMO) number – Unique identification for each ship;
Vessel name;
Type of ship/cargo (e.g., tanker, bulk carrier or enforcement);
Navigation status (at anchor, under way using engines or not under command);
Rate of turn – Right or left, 0 to 720 degrees per minute;
Speed over ground;
Position accuracy;
Longitude and latitude;
Course over ground;
True heading;
Time stamp (UTC, time accurate to nearest second when data was generated);
International radio call sign, assigned to the vessel by its country of registry;
Dimensions of ship;
Type of positioning system (e.g., Global Position System or LORAN-C);
Location of positioning system's antenna on board the vessel;
Draught of ship (0.1–25.5 m);
Destination; and
Estimated time of arrival at destination.

[a] Flag state designation is transmitted as three Maritime Identify Digits (MID) in the MMSI Code ITU (2019) and USCG (2019)

As anticipated in earlier papers, within consistent boundaries, regional governance lessons associated with the Bering Strait (Berkman et al. 2016) and Barents Sea (Vylegzhanin et al. 2018) can be integrated with quantitative assessments from a satellite AIS baseline for the Arctic Ocean. The AIS signals contain information about ship attributes, transmitted on different message channels by Class A transponders linked to the unique IMO number of each ship and by Class B transponders without IMO ship references and details (Table 11.2). The common feature for both classes of AIS transponders is they generate messages with time-position information linked to the Mobile Maritime Service Identify (MMSI) for each ship. In addition to the MMSI data from all of the ships (Table 11.1), SpaceQuest provided the attribute metadata from ships with Class A transponders (Table 11.2). The contributions of Class A and Class B transponder data among the validated MMSI data (Table 11.1) will be evaluated further with the satellite AIS time series extended to 31 December 2018.

11.2.2 Vector-Based AIS Analyses

To assess movements and behavior of individual ships as well as pattern and trends of ship traffic in the Arctic Ocean – the SpaceQuest data have been compiled within an ArcGIS architecture, applying the 'space-time cube' (ESRI 2017). These

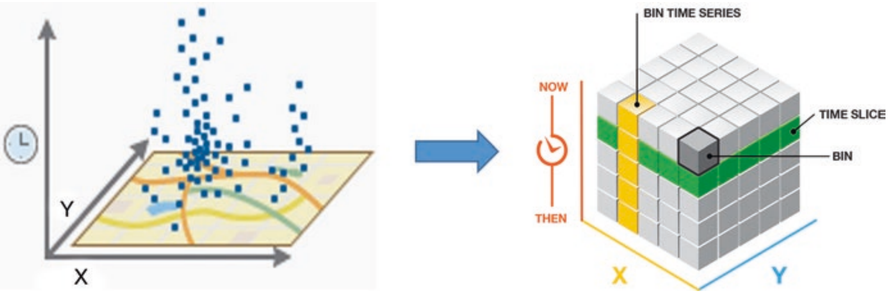

Fig. 11.2 **(Left)** Three-dimensional system to analyze change in issues, impacts or resources that are measured over space (x-y, latitude-longitude) and time (past to future). **(Right)** The 'space-time cube' from ESRI (2017) is a geospatial approach that can be applied to 'big data' questions with vector-based analyses (points, lines and polygons) within and between 'bins'

vector-based analyses (Fig. 11.2) of the satellite AIS data were further enhanced by SQL queries of tables through the Google Compute Engine with BigQuery (Google 2017; Leetaru 2018), enabling questions with user-defined space and time resolution to interrogate the nearly 86 million satellite MMSI data points (Table 11.1) within seconds. Ship latitude and longitude coordinates were mapped with the North Pole Lambert Azimuthal Equal Area (Alaska) projection using the WGS84 ellipsoid (WGS 1984).

Analyses of the SpaceQuest data in this chapter relate to total numbers of unique ships, which are represented by the validated MMSI data (Table 11.1) over time and space. Additionally, the attribute of flag state was included in these initial analyses because it can be extracted directly from the MMSI code of every ship (ITU 2019; USCG 2019). Other **ship attributes** (Table 11.2) **and synoptic biophysical or socio-economic data can be introduced into these vector-based analyses with cloud processing in seconds to reveal trends, patterns and processes that underlie informed decisions, depending on the questions**.

11.2.3 Arctic Ship Traffic and Sea-Ice

Ship traffic in the Arctic Ocean is of increasing interest because the sea-ice is diminishing dramatically in the Arctic Ocean (e.g., NSIDC 2017; PIOMAS 2017). Importantly, these two parameters have the advantage that they can be measured objectively by satellites (Mjelde et al. 2014; Onoda and Young 2018) with high levels of granularity across space (meters to thousands of kilometers) and time (minutes to decades).

At first pass with the satellite AIS data analyses, it appears that Arctic shipping is increasing as sea ice decreasing (Fig. 11.3), which can be treated as a hypothesis (**'ship-ice hypothesis'**) that can be experimentally tested in terms of cause and effect. Recognizing that BaSR is open water throughout the year, unlike the seasonally ice-covered BeSR, provides an experimental control area to test this

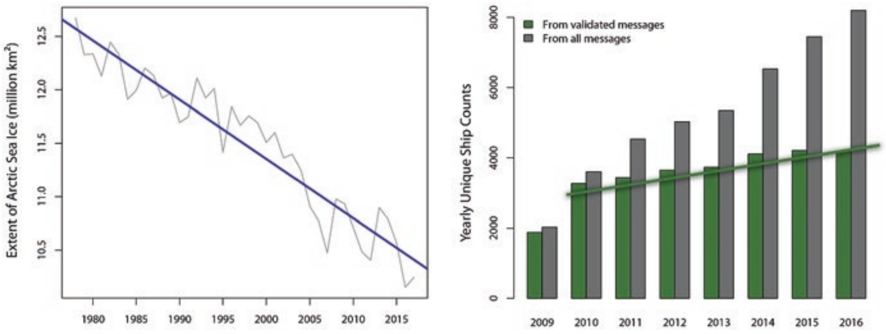

Fig. 11.3 Illustration of the *'Ship-Ice Hypothesis'* that diminishing sea ice is driving the increase in Arctic shipping, which is itself becoming a socio-economic driver in the Arctic Ocean, providing the basis for experimental analyses with available data to test the relationship between these biophysical and socio-economic drivers of change, respectively, recognizing that 'correlation alone does not mean causation.' Based on satellite observations of the Arctic Ocean: **(Left)** Arctic sea-ice extent decreasing 9.7% per decade from 1979–2017 (NSIDC 2017). **(Right)** Arctic ship traffic increasing 6.6% per year, based on unique ship counts (Table 11.1) annually within the study area (Fig. 11.1), during full-observation years of 2010–2016

hypothesis and assess drivers of Arctic ship traffic that may be external to the ice-covered Arctic Ocean (Fig. 11.1), as considered with the AMSA (2009a) scenarios about trade. Such biophysical and socio-economic analyses together have societal importance, particularly with sea ice and shipping as primary drivers of change in the Arctic Ocean, as considered at the *Arctic Options* (2014) workshop at the University of California Santa Barbara (Table 5.1), involving diverse stakeholders:

- Indigenous peoples with subsistence livelihoods in the Arctic;
- National agencies managing Arctic resources, impacts and activities;
- Commercial enterprises utilizing Arctic resources;
- Non-governmental organizations protecting Arctic ecosystems and cultures;
- Natural and social scientists researching Arctic sustainability; and
- International organizations responding to human activities in the Arctic.

Figure 11.3 reveals the number of unique ships operating annually in the Arctic Ocean, involving satellite AIS records from all class of transponders on the ships (NAVCEN 2017). AIS records from Class A and Class B transponders separately require further investigation across regions and time, especially to frame evidence that can be considered for informed decisionmaking about governance mechanisms and built infrastructure in the Arctic Ocean. Additional consideration of **big-data processing strategies** and intercalibration with ground-based as well as satellite receivers is necessary to apply AIS data for operational decisionmaking in the Arctic Ocean.

11.2.4 Historic Arctic Satellite AIS Baseline

The oldest and longest continuous recording of satellite AIS data from the Arctic Ocean (Table 11.1) is shown on a daily basis from 1 September 2009 to 31 December 2016 (Fig. 11.4). The synoptic data in Fig. 11.4 have been integrated with the 'space-time cube' (Fig. 11.2), revealing the relative number of unique ships

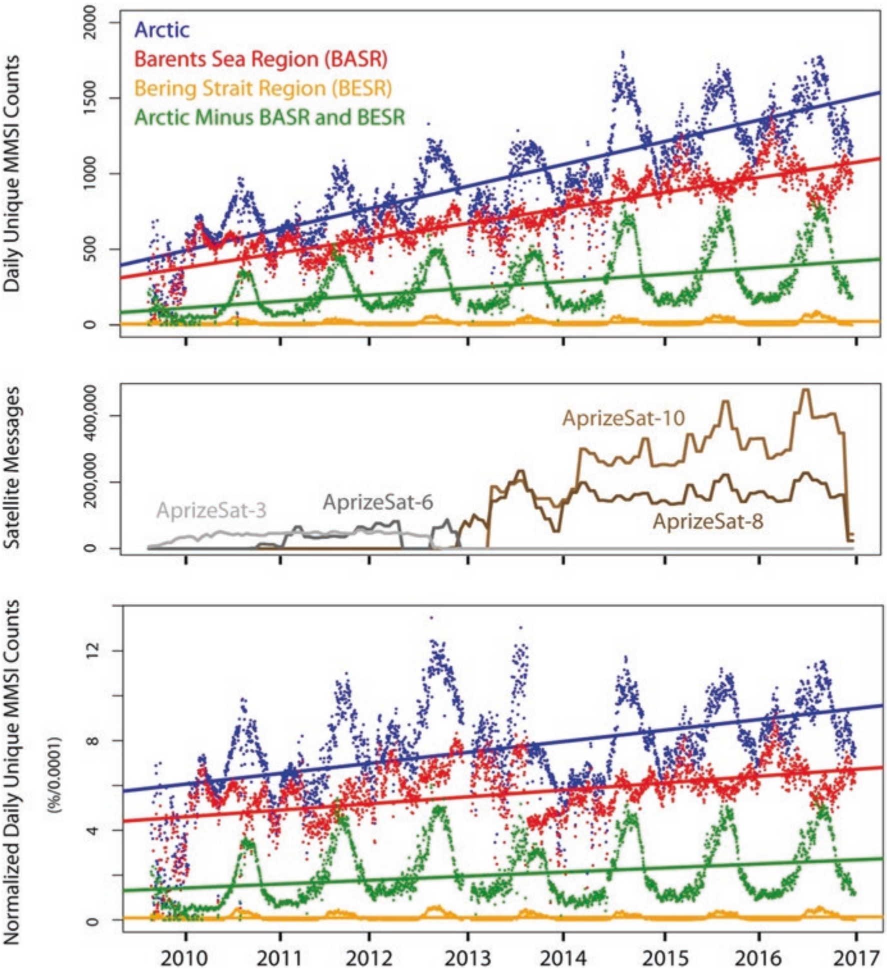

Fig. 11.4 Baseline record of the total validated number of unique ships daily in the Arctic Ocean, derived from satellite automatic Identification System (AIS) data in relation to the Mobile Maritime Service Identity (MMSI) of each ship from 1 September 2009 through 31 December 2016 (Table 11.1). (**Upper**) Number of unique ships each day north of the Arctic Circle, including the Bering Strait Region and Barents Sea Region, as shown in Fig. 11.1 (see legend for regions). (**Middle**) Number of daily MMSI counts from the SpaceQuest satellites during the observation period. (**Bottom**) Number of unique ships each day, normalized in relation to the total number of daily counts collected by the SpaceQuest satellites throughout the observation period

over time within and between BeSR, BaSR and the overall Arctic Ocean region (as represented in the Book Cover Figure). This historic baseline is being updated with 2017–2018 satellite AIS data.

Simply comparing their relative trends (Fig. 11.4), ship traffic is increasing across the entire Arctic Ocean (most of which is ice-covered seasonally) at a faster rate than in BaSR, which is ice-free throughout the year. Moreover, for the entire Arctic Ocean, the rate of ship-traffic increase on an annual basis is similar to the rate of sea-ice decrease on a decadal basis (Fig. 11.3). There also is clear ship traffic seasonality in all regions of the Arctic Ocean, following the growth and decay of the sea ice. All of these conclusions support (i.e., without falsifying) the ship-ice hypothesis that sea ice is the primary driver of increased shipping in the Arctic Ocean.

Interestingly, the seasonality of ship traffic in the Barents Sea is opposite to the trend in ice-covered areas of the Arctic Ocean, as revealed by the ‘diamond’ pattern in their cycles (Fig. 11.4). Analyses based on MMSI numbers just in BaSR (Fig. 11.1) in 2016 indicate that the mean centers of the ship traffic during the winter (November-May) and summer (June-October) moved 400 kilometers northeastward with the seasonal retreat of the sea ice, raising question of year-round traffic (Bourbonnais and Lasserre 2015; Darby 2018). Consequently, while BaSR is largely beyond the defined region of the Polar Code (IMO 2017b), as shown in Fig. 11.1, this **open-water region is coupled closely with summer ship traffic in the seasonally ice-covered Arctic Ocean**. Fortunately, with regard to governance, there is an existing complex of jurisdictions in the Barents Sea to complement implementation of the Polar Code (Vylegzhanin et al. 2018).

In addition, the normalized numbers of unique ships in the Arctic Ocean (Fig. 11.4) indicate the highest ship traffic was in 2012, during the lowest summer ‘sea-ice minimum’ recorded by satellites (NSIDC 2017). Together, these analyses all strengthen the hypothesis that sea-ice changes are a primary driver of Arctic ship traffic over diverse time and space scales (Fig. 11.3), reflecting the importance of their being analyzed together from satellite data for the purposes of maritime operations and real-time decisionmaking to implement all binding agreements that involve ship-borne activities in the Arctic Ocean.

11.2.5 Arctic Ship Traffic Patterns

Ship traffic involves the movements of individual vessels and the flow of all vessels over time and space. Individual vessels have different classifications, dimensions, cargos, crew characteristics, fuels and other features (e.g., Table 11.2) that relate to their *“safe, secure and reliable”* operations in the Arctic Ocean (Deggim 2013). Ultimately, it is the individual vessels that need to be monitored at the time scales of operational decisionmaking. However, it is the aggregations of vessels that need to be characterized for long-term infrastructure investment and development, as is being suggested across the twenty-first century by the ‘belt and road initiative’ (China 2017) with its ‘polar silk road’ (China 2018).

At a macro-level, ship interactions with sea ice can be analyzed to reveal both patterns and trends (such as hypothesized by Smith and Stephenson 2013) that can contribute to informed decisionmaking for sustainable infrastructure development in the Arctic Ocean. Sea-ice coverage can be interpreted from satellites with 4 km^2 grid-spacing on a daily basis across the Arctic Ocean (NSIDC 2017). These sea-ice data were used to model ship-ice interactions during the period of satellite AIS observations (Table 11.1, Figs. 11.3 and 11.4) by: joining the AIS and sea-ice points in the space-time cube (Fig. 11.2); and counting the number of unique ships daily in each 4 km^2 cell with sea ice. Duplicate MMSI points in each 4 km^2 cell with sea ice were deleted. The total number of ship-ice interactions daily then were aggregated on an annual basis in relation to their latitudes (Fig. 11.5).

Figure 11.5 reveals a pattern of Arctic ship-ice interactions with the highest numbers in 2015–2016 in the latitude band from 70°-75° North. Progressively lower numbers surround this zone of highest ship-ice interactions, revealing a **trend of increasing ship-ice interactions annually at higher latitudes**.

Characteristics of the ship traffic across the Arctic Ocean can be further analyzed over time and space, in relation to ship attributes (Table 11.2) at user-defined levels of granularity, to address diverse questions. As an illustration, what nations have the most ships in the Arctic Ocean and where are those ships from 2009–2016? The answer (Fig. 11.6) is derived from the attribute of flag state.

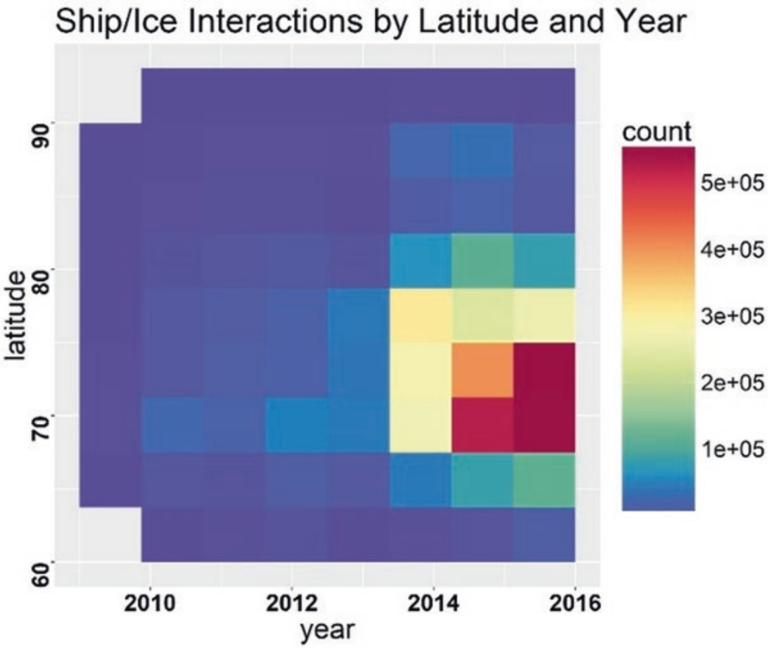

Fig. 11.5 'Heatmap' of ship-ice interactions by joining sea-ice data (NSIDC 2017) and satellite AIS data (Figs. 11.3 and 11.4) across latitudes on an annual basis throughout the observation period (Table 11.1), as described above. There were no ship-ice interactions with latitudes >86° or < 64° degrees in 2009

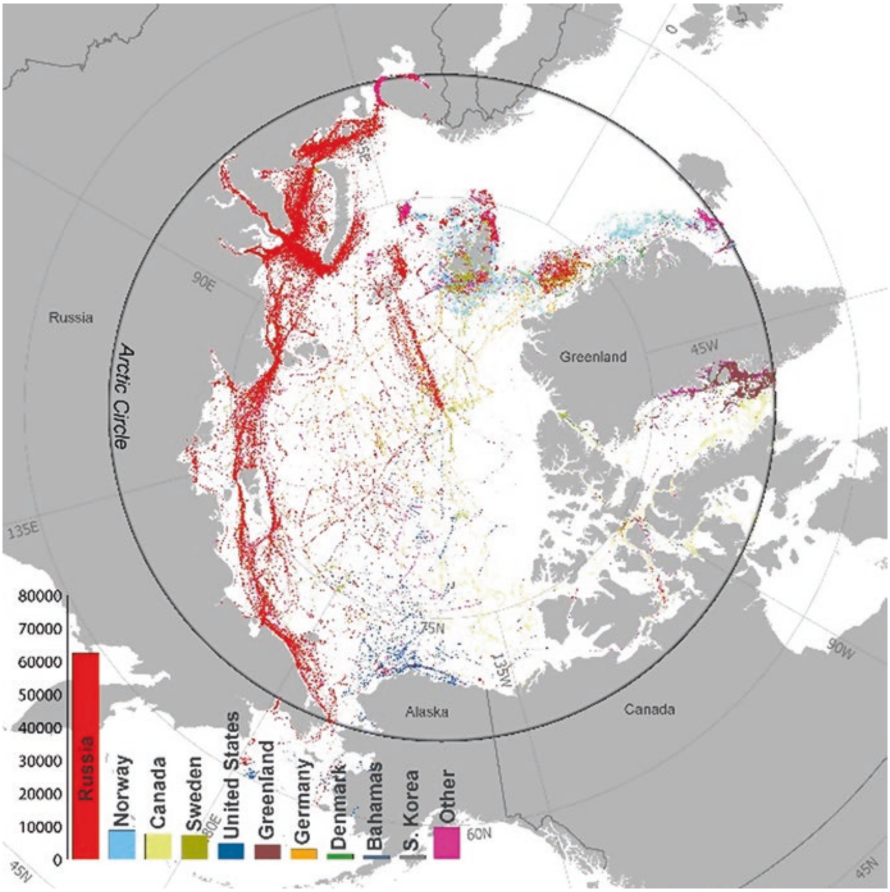

Fig. 11.6 International distribution of ship-ice interactions (see Fig. 11.5) in the Arctic Ocean from 1 September 2009 through 31 December 2016 (Table 11.1), based on the flag state attribute that is encoded on the Mobile Maritime Service Identity (MMSI) message from each unique ship (Table 11.2)

Figure 11.6 shows the **vast majority of ships interacting with sea ice in the Arctic Ocean are Russian, located primarily along the Northern Sea Route**, a well-defined region of the Arctic Ocean (Smith and Stephenson 2013; NGA 2017a) that may be opening to increased international trade (Lakshmi 2018). Norwegian ships are the next most abundant, primarily along East Greenland and throughout the Svalbard archipelago in the Greenland Sea and Barents Sea, respectively, with clusters of diverse nations operating in these regions (reflecting fishing and energy activities). There also is a cluster of diverse nations operating along West Greenland (perhaps reflecting tourism activities). In addition, it is interesting to note the 'straight line' of Russian nuclear icebreakers to the North Pole during August and September each year in the satellite AIS database. At the finest level of granularity, questions can be asked about individual ships over time and space (Fig. 11.7).

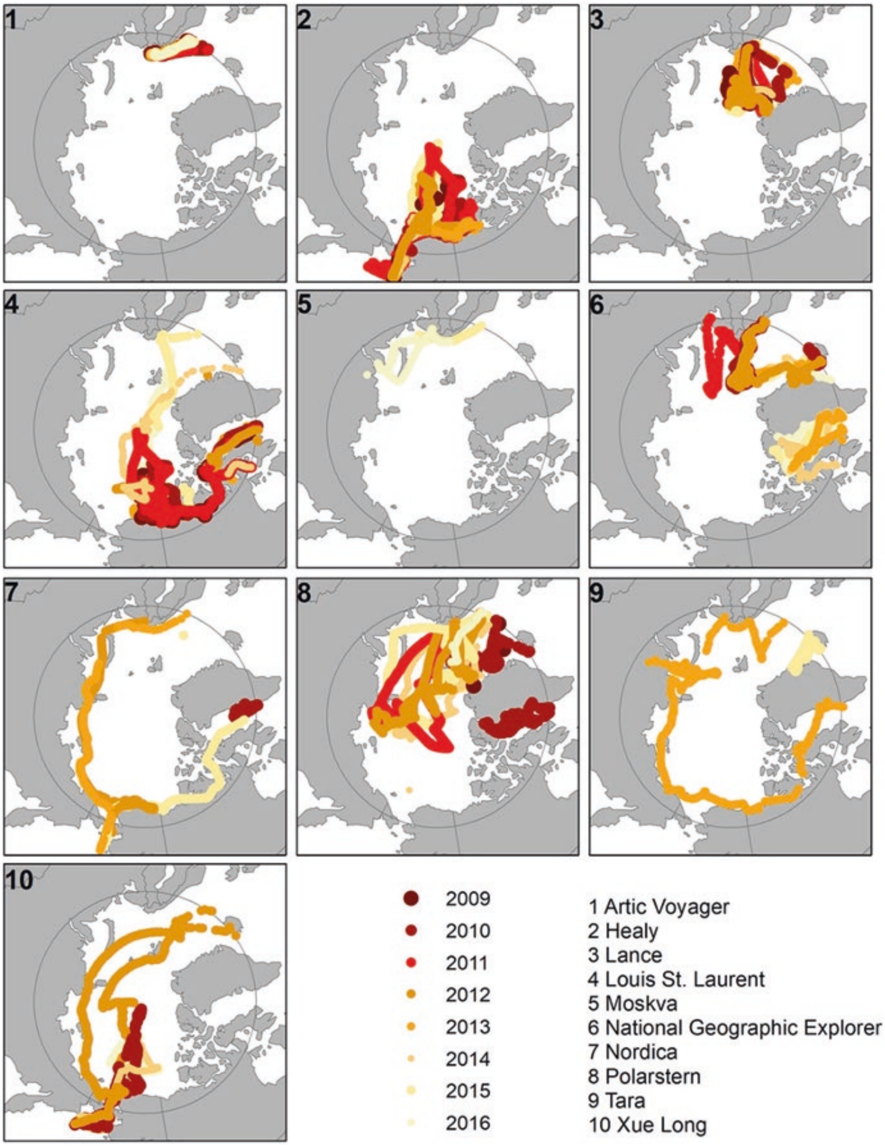

Fig. 11.7 Collage of unique ship tracks (based on their Maritime Mobile Service Identify) throughout the satellite AIS collections period (Table 11.1) associated with international collaboration in the *Pan-Arctic Options* (2017) project: Canada (*Louis St. Laurent*), China (*Xue Long*), France (*Tara*), Norway (*Lance*), Russian Federation (*Moskva*) and United States (*Healy*). Tracks of commercial ships also are shown from the tourism (*Lindblad National Geographic Explorer*), energy (*Arctic Voyager*) and maritime-service (*Arctica*) sectors along with the movements of the *Polar Stern* (Germany), which has logged more than 250 polar research expeditions since 1982

Ship-level questions ultimately will be required for operational decisionmaking about maritime traffic in the Arctic Ocean, analogous to air-traffic control elsewhere (e.g., Flightrader24 2017), regarding the movement and behavior of individual vessels. The ‘space-time’ methodology (Fig. 11.2) can be applied to questions in an open-ended manner across diverse levels of granularity with satellite AIS (along with regional ground-based AIS) and sea-ice and other data, as illustrated by Figs. 11.3, 11.4, 11.5, 11.6, and 11.7, including:

1. GIS spatial-data files (e.g., Fig. 11.1);
2. Definition of the observation periods within the satellite AIS dataset from 2009 onward (Table 11.1), building on the satellite sea-ice dataset that extends from 1979 (Fig. 11.3); and
3. Consideration of the attributes (Table 11.2) that are available to address user-defined questions.

Answers to user-defined questions will have value to diverse communities which are concerned with shipping and sea ice as primary drivers of change in the Arctic (e.g., Table 5.1). In a practical manner, an holistic analytical process also will contribute to informed decisionmaking by ship operators as well marine traffic systems, which exist among all of the surrounding states across the Arctic Ocean (NGA 2017a, b, c, d, e). Ultimately, such crowdsourced analyses will reveal evidence and options for enhancing applications of the Polar Code (IMO 2017b) and other binding international legal agreements (e.g., SAR 2011; MOPP 2013) along with risk-management from the insurance industry (Emerson and Lahn 2012; Stoddard et al. 2016) to ensure safe, secure and reliable shipping in the Arctic Ocean.

11.2.6 Arctic Satellite AIS Intercomparison

SpaceQuest (2017) has been a pioneer with polar-orbiting AIS micro-satellites and there now are other data sources, including from the European Space Agency (ESA 2017) and exactEarth (2017). The Norwegian Coastal Administration (Kystverket 2017) operates HAVBASE (2017), which is the centerpiece of the Arctic Ship Traffic Data (ASTD 2017) project for the Arctic Council, providing an ideal cross-check of the satellite AIS data from SpaceQuest (Table 11.3).

HAVBASE analyzes unique ships in the Arctic Ocean based on their IMO numbers, which are derived from AIS messages generated by Class A transponders (Table 11.2). Observed monthly for BaSR in 2016, numbers of IMO ships from HAVBASE are not significantly different from the numbers of validated ship messages from Space Quest (Fig. 11.3; Table 11.3). While there is rich metadata associated with IMO-registered ships (Table 11.2), analyses only of ships with IMO numbers avoids taking into consideration the segment of Arctic shipping associated with vessels that are utilizing Class B transponders, recognizing that Class A and Class B vessels are two subsets of the total MMSI numbers (Fig. 11.3).

Table 11.3 Monthly Comparison of Ship Traffic Attributes (Table 11.2) from the Barents Sea Region (Fig. 11.1), Based on Independent Satellite Automatic Identification System (AIS) Datasets for the *Pan-Arctic Options* (this chapter) and *Arctic Ship Traffic Data* (ASTD 2017) Projects[a] in 2016

	Pan-Arctic options		Arctic ship traffic database	
Month	MMSI (number)	Validated AIS data (number)	IMO (number)	Travel (nautical miles)
Jan	2435	1315	1153	1,361,442
Feb	2701	1350	1105	1,290,579
Mar	2800	1360	1113	1,392,242
Apr	2557	1310	1112	1,437,113
May	2541	1319	1156	1,629,659
Jun	2532	1442	1378	1,835,211
Jul	2258	1422	1543	2,134,675
Aug	2174	1444	1698	2,597,150
Sep	2402	1406	1640	2,487,115
Oct	2344	1366	1456	2,074,682
Nov	2568	1284	1247	1,701,567
Dec	2428	1187	1106	1,358,833
MEAN	2478 ± 177	1350 ± 74	1308 ± 224	1,775,022 ± 454,464

[a] Acquired from independent polar-orbiting AIS satellites, all validated unique ships from Space Quest (Table 11.1, Fig. 11.3) compared to IMO ships from HAVBASE (2017). These data are not significantly different (T = 0.44, 22 degrees of freedom)

Nonetheless, utilizing Class A messages from IMO-registered ships (Table 11.3), HAVBASE can be used to compare the distribution of different ship types (NAVCEN 2017) in user-defined regions of the Arctic Ocean, as reflected by BaSR, BeSR and north of the Arctic Circle (Figs. 11.1 and 11.8) in 2016. Vessel types represented by "other activities" include enforcement vessels, which will be integral to the cooperative, coordinated and consistent infrastructure for an Arctic Marine Traffic System as envisioned by AMSA (2009a) among all nations around the Arctic Ocean. Moreover, activities among vessels types within operational classes of ships, for example ice classes (e.g., Nyseth and Bertelsen 2014), underscore a suite of user-defined questions that can be addressed with satellite AIS data in a pan-Arctic context.

The HAVBASE system also demonstrates the capacity to model environmental, ecosystem and socio-economic impacts in relation to Arctic marine traffic, bounded in time and space by user-defined questions (e.g., Mjelde 2014; Langdalen 2017). Applying ship attributes from AIS data (Table 11.2), for example, HAVBASE automatically can generate tables to estimate ship emissions, as illustrated for the Barents Sea–Lofoten Management Plan Area (Norway 2015) from August 2016 (Table 11.4), indicating the largest carbon-dioxide emissions were produced by fishing and passenger vessels in the Barents Sea–Lofoten Management Plan Area during August 2016.

Table 11.4 illustrates **the granularity of ship types and size-classes can be incorporated into models to estimate the consequences of ship traffic in the Arctic Ocean**. In the future, such models could be parameterized similarly to

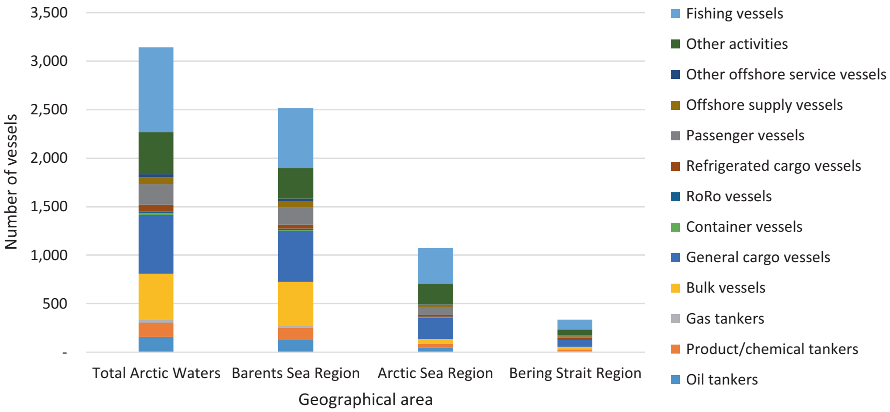

Fig. 11.8 Ship types derived from attributes associated with IMO numbers (Lloyds 2017), from vessels with Class A transponders, in regions of the Arctic Ocean (Fig. 11.1) in 2016, derived from the Arctic Ship Traffic Data (ASTD 2017) project

generate economic value estimates, for example, to address questions about investment patterns, complementing other development forecasts for regions around the Arctic Ocean, especially in the Barents Sea (AMAP 2017a) and across the Bering Strait (AMAP 2017b).

11.3 Informed Decisionmaking About Arctic Marine Shipping

11.3.1 Science-Diplomacy Case Study

The Arctic Marine Shipping Assessment (AMSA 2009a, b) is a successful demonstration of informed decisionmaking, as reflected by the Arctic search-and-rescue agreement (SAR 2011), marine-oil-pollution (MOPP 2013) and the Polar Code (IMO 2017b) as well as many other governance mechanisms (e.g., Preface Fig. 8) that were represented among the seventeen AMSA recommendations (Box 11.1). Value of the AMSA recommendations is further reflected by their being updated by the Protection of the Arctic Marine Environment working group of the Arctic Council (PAME 2017). These invited recommendations within the Arctic Council framework are analogous to options (without advocacy), which can be used or ignored explicitly by the decisionmakers, providing continued utility to build common interests that generate informed decisions (Preface Fig. 5). Moreover, AMSA effectively applied the methodology of science diplomacy, starting with questions about how to achieve safe, secure and reliable shipping in the Arctic Ocean with regulations through the IMO (Deggim 2013; Finland 2014) in the context of "sustainable development and environmental protection," which are the "common Arctic issues" established through the Arctic Council (Ottawa Declaration 1996).

Table 11.4 Carbon Dioxide Emission Estimates Generated by HAVBASE (2017) for Different Ship Size-Classes and Types in the Barents Sea–Lofoten Management Plan Area (Forvaltningsplanområde Barentshavet) During August 2016

		Carbon dioxide (CO_2) emission estimates (tonnes) for different ship-size classes (tonnes)								Future economic value/cost estimates
ID	Skipstype (Ship type in Norwegian)	<1000	1000–4999	5000–9999	10,000–24,999	25,000–49,999	50,000–99,999	>100,000	Total C0^2 emission	
1	Oljetankere	116.78	213.88	138.59	310.06	1292.82	8848.87	0	10,921.0	To Determine
2	Kjemikalie/ produkttankere	87.19	572.50	393.38	5452.90	619,94	0	0	7125.9	To Determine
3	Gasstankere	0	0	0	70.70	355.,58	0	4093.34	4519.6	To Determine
4	Bulkskip	0	685.90	302.37	2897.21	6820.51	1498.58	0	12,204.6	To Determine
5	Stykkgodsskip	510.86	8159.33	1730.88	2899.32	1351.92	0	0	14,652.3	To Determine
6	Konteinerskip	0	0	89.68	0	0	0	0	89.7	To Determine
7	Ro Ro last	16.20	20.78	230.44	0	0	0	0	267.4	To Determine
8	Kjøle/fryseskip	0	2463.54	1102.03	0	0	0	0	3565.6	To Determine
9	Passasjer	2805.16	5132.34	2794,47	13,346.79	1910.99	1678.77	4244.66	31913.2	To Determine
10	Offshore supply skip	24.23	5304.72	5822.47	0	0	0	0	11,151.4	To Determine
11	Andre offshore service skip	199.54	292.50	507.52	0	0	0	0	999.6	To Determine
12	Andre aktiviteter	3029.84	7350.40	3190.81	4559.24	3443.52	0	0	21,573.8	To Determine
13	Fiskefartøy	8088.68	25,105.96	0	0	0	0	0	33,194.6	To Determine
TOTAL		14,878.48	55,301.85	13508.17	29,536.22	14,819.76	12,026.22	8338.00	120,265.5	To Determine

With different nations providing ground-based datasets of ship numbers and characteristics, AMSA identified a functional approach to collect data necessary to answer these questions. Recognizing that data to address specific questions is different than evidence for decisions, AMSA integrated patterns and trends from the natural and social sciences as well as Indigenous knowledge to reveal the need for actions in directions identified by the stakeholders inclusively. Based on their common interests, principally marine safety and environmental protection (Beckman et al. 2017), **the Arctic states fully utilized the resulting AMSA recommendations, contributing to the apex goal of informed decisions** (Preface Figs. 3 and 5) with regard to Arctic marine shipping (PAME 2017).

11.3.2 Next Generation Assessments

Satellite AIS data started the year the Arctic Marine Shipping Assessment was published (AMSA 2009a) as revealed in this chapter with the oldest and longest continuous satellite AIS record from the Arctic Ocean (Table 11.1). Initial analyses herein of this satellite AIS record (Figs. 11.1, 11.2, 11.3, 11.4, 11.5, 11.6, 11.7, and 11.8) explore the open-ended types of questions that can be addressed through the holistic process of science diplomacy (Preface Figs. 3, 5 and 6) for the purpose of informed decisionmaking with regard to Arctic sustainability and marine ship traffic more specifically.

The first requirement is to validate the satellite AIS record, which is an ongoing process. A critical step is to analyze the total number of unique-ship messages received at any point in time, recognizing the capacity of satellite AIS systems have been improving (e.g., Burzigotti et al. 2010). Clearly, the total number of unique-ship messages increased during the 2009–2016 period (Table 11.3), which is attributable in part to the relative number of unique-ship counts received, stored and transmitted by the different satellites. Consequently, for initial interpretations over time, unique-ship counts based on the MMSI data were normalized in relation to the operation of each satellite system (Fig. 11.4), pointing to the largest number of unique-ships in the Arctic Ocean in 2012, during the lowest annual sea-ice minimum on record (Berkman and Vylegzhanin 2013).

The number of validated MMSI messages received independently on a monthly basis by SpaceQuest and Norwegian Coastal Administration satellites, for the same area (i.e., BaSR; see Fig. 11.1), were not significantly different in 2016 (Table 11.3). While this satellite intercomparison provides some validation, it is incomplete without analyzing both Class A and Class B messages, included within the total number of MMSI messages (Figs. 11.3 and 11.4).

Moreover, Fig. 11.3 indicates the total number of validated AIS messages is increasing during the 2009–2016 period of observation, requiring additional data to interpret trends and rates, as are being interpreted with 2017–2018 satellite AIS records. The additional interpretations also are in view of Class A and Class B transponder data, recognizing satellite MMSI records are incompletely characterized if only ships with IMO numbers (i.e., from Class A transponders) are being analyzed. All validated MMSI records are necessary for operational decisionmaking to ensure the safety and security of each ship (Fig. 11.7).

Beyond assessing the movements and increasing numbers of unique ships in the Arctic Ocean (Figs. 11.3 and 11.4), the rich set of attributes associated with IMO-registered vessels (Table 11.2) is important to understand how Arctic marine ship traffic is diversifying over space and time (e.g., Figs. 11.6 and 11.8). Together, the patterns and trends of unique ships along with their attributes will be necessary to address the development of long-term built infrastructure (including fixed and mobile assets for service, emergency and regulatory activities) and associated governance mechanisms (promoting cooperation, coordination and consistency).

This chapter also applies vector-based GIS solutions that were unavailable for AMSA. With the 'space-time cube' (Fig. 11.2), for example, it is now possible to address questions with any level of granularity within user-defined digital boundaries over time and space, involving point to pan-Arctic scales. Questions are the challenge en route to initiate informed decisionmaking (Preface Figs. 3 and 5), considering the distribution of ships with different attributes (Table 11.2; Figs. 11.3, 11.4, 11.5, 11.6, 11.7, and 11.8) in view of any environmental variables.

In this sense, it is important that shipping and sea ice are recognized as primary drivers of change in the Arctic (Table 5.1). Sea-ice coverage has been assessed from satellites much longer than ship traffic in the Arctic Ocean (Fig. 11.3) and the two datasets are herein analyzed together at the scale of 'big data' with more than 100,000,000 satellite AIS messages (Table 11.1). The initial pan-Arctic analyses of ship-ice interactions highlight their international distribution during the period of 2009–2016 period (Fig. 11.6). More importantly, for informed decisionmaking, ship-ice interactions are increasing over time and toward higher latitudes (Fig. 11.5). The 'ship-ice hypothesis' (Fig. 11.3) was used as the theoretical framework to interpret these changes in Arctic marine ship traffic, applying BaSR as experimental control since it is open water throughout the year, unlike BeSR or other regions that are seasonally ice-covered (Fig. 11.1).

AMSA (2009a, b) illustrates the firm foundation for informed decisionmaking, built on questions that only could only be answered at the time with shipping data collected only from the Earth surface and directly from Arctic states individually. There is a threshold change in capacity to address Arctic marine ship traffic from satellite AIS data, fundamentally transforming Arctic marine shipping assessments into the future. Unlike AMSA (2009a, b), which was limited by national dissemination methods with subjective and inconsistent data on a regional basis, **satellite AIS data are synoptic as well as objective and can be accessed from government as well as commercial sources with consistency on a pan-Arctic basis. Moreover, AIS, sea-ice and other data from satellites can be analyzed and integrated with user-defined levels granularity across time (minutes to decades) and space (meters to thousands of kilometers) in relation to diverse attributes and questions in an open-ended manner** (Table 11.5).

Table 11.5 Next generation arctic marine shipping assessments

	Arctic marine shipping assessments	
Attribute	AMSA (2009)	Next generation[a]
Sampling period	2004	2009-present
Data sources	Arctic states individually	Diverse government and commercial automatic identification system (AIS) sources
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 (from seconds to 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 decision-support	Governance mechanisms	Operations, built infrastructure and Governance mechanisms

[a] Involves automatic identification system (AIS) data collected by polar-orbiting satellites

AIS data from ground-stations always will have fundamental importance in dense ship-traffic regions of the Arctic Ocean, especially in the Bering Strait (MXAK 2017) and Barents Sea (VTS 2017), which are the two regions of focus in this chapter (Fig. 11.1). Considering the recommendations from AMSA (2009a; PAME 2017), there is opportunity to unify the analyses of ground-based and satellite-based AIS data as core infrastructure for an operational Arctic Ship Traffic System. Such a system would have the capacity to address the dynamics of Arctic ship traffic in relation to governance mechanisms and built infrastructure, including traffic separation schemes, deep-water ports and emergency response networks. The Arctic Ship Traffic System also would reveal insights about ship interactions with other elements of the Arctic system, such as impacts from heavy fuel oils on the environment or ships strikes on marine mammals. Importantly, the Arctic Ship Traffic System would be a rich source of data to test user-defined questions and hypotheses, such as projections about destinational and transit traffic with various routing strategies and impact considerations (Smith and Stephenson 2013), as through the Central Arctic Ocean (Stevenson et al. 2018) or the Bering Strait (IMO 2017c) as well as across the Arctic Ocean (Eger 2011). Ultimately, next generation Arctic marine shipping assessments will be nimble and flexible enough to ensure safe, secure and reliable shipping in the Arctic Ocean, helping to achieve Arctic sustainability across generations.

With holistic perspective, children borne today will be alive in the twenty-second century, which means that our sights must be at least across the twenty-first century for benefit of the most current generation without being arbitrary (Preface Fig. 1).

The context of '*Next-Generation Arctic Marine Shipping Assessments*' (Table 11.5) underscores the observation that **sustainable strategies involve close coupling between governance mechanisms and built infrastructure** to achieve progress with balance, stability and resilience (Preface Table 1) that underlie progress with sustainable development as a 'common Arctic issue' (Ottawa Declaration 1996).

The integration of different decisionmaking arenas is highlighted by SAR (2011) and MOPP (2013), which are forward-looking agreements that are legally binding, but hollow in the absence of the built infrastructure (requiring technology and capitalization) to implement them (e.g., Struzik 2018). For Arctic sustainability with its diverse 'institutional interplay' (Young 2002), **the option (without advocacy) for built infrastructure is to consider that investment can be phased to achieve Arctic sustainability.** Such phasing across the twenty-first century (Preface Fig. 12) will increasingly involve coastal-marine connections with **coordination, cooperation and consistency among regions on a pan-Arctic scale.**

Ultimately, the foundation for Arctic sustainability is **'multilateral stability'** among diverse stakeholders within and beyond the Arctic (Fig. 11.9). This stability further involves balance among economic, environmental and societal considerations, recognizing there will be an 'economic engine' with diverse facets (Fig. 11.9) that will be both a central source of capacity as well as risk in the Arctic Ocean, where human activities are represented by **shipping as a primary socio-economic**

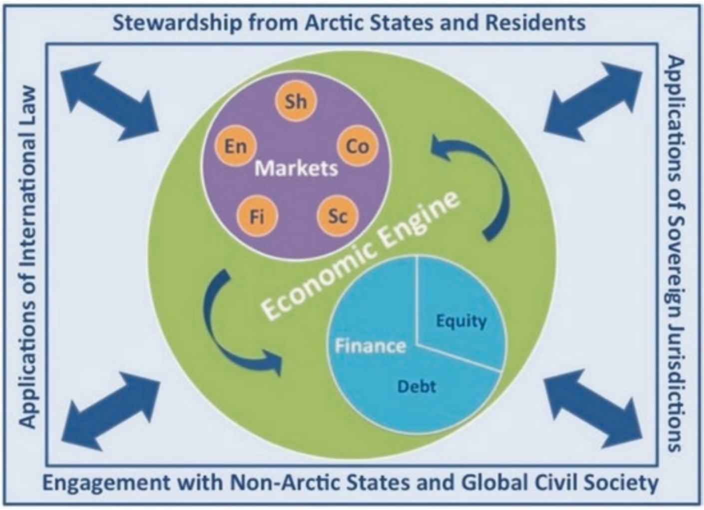

Fig. 11.9 Conceptualization of 'multilateral stability' to insulate the central 'economic engine' that will emerge from diverse markets (e.g., Fisheries, FI; Energy, EN; Shipping, SH; Communications, CO; and Science, SC) in the new Arctic Ocean. In a multilateral context, short-term and long-term perspectives associated with equity and debt financing, respectively, provide a framework to consider resources, issues and impacts across a 'continuum of urgencies' (Preface Figure 3), leading to informed decisionmaking by Arctic and non-Arctic stakeholders (Preface Figure 5) for the benefit of all across generations

measure of change in the Arctic. In this holistic context, insulating the economic engine across a 'continuum of urgencies' (Preface Figure) will involve *Next-Generation Arctic Marine Shipping Assessments* (Table 11.5) as a key for informed decisionmaking to achieve Arctic sustainability with science diplomacy to balance national interests and common interests across generations in the interests of all.

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