



Vessel Operations in the Arctic, 2015–2017

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The Arctic is among the most rapidly-changing regions on Earth. Diminishing levels of sea-ice has increased opportunities for maritime activities in historically inaccessible areas such as the Northern Sea Route and Northwest Passage. Degradation of Arctic marine ecosystems may accompany expanding vessel operations through introduced underwater noise, potential for large oil spills, among other things; and may compound stressors already effecting biological populations due to climate change. Assessments are needed to track changes in vessel traffic patterns and associated environmental impacts. We analyzed Arctic-wide vessel Automatic Identification System data 1 January 2015 to 31 December 2017 to quantify the amount and spatial distribution of vessel operations, assess possible changes in these operations, and establish a baseline for future monitoring. Nearly 400,000 vessel transits were analyzed. Number of trips, hours of operation, and amount of sea surface exposed to vessel traffic were used to compare operations between 14 delineated waterways. Operations were extensive and diverse: an average of 132,828 trips were made annually by over 5,000 different vessels. Transits were made in all areas studied and all months of the year. Maritime activities were intensive in some areas, but ice-limited in others. Amount of sea surface exposed to vessel traffic exceeded 70% in all but three areas. Bulk carriers, cargo ships, passenger/cruise ships, research survey ships, and vessels supporting oil/gas-related activities were represented. However, fishing vessels, primarily in the Barents, Bering, and Norwegian Seas, surpassed operations of all other vessel types and comprised about one-half of all voyages each year. We observed no overt increasing or decreasing trends in vessel traffic volume in our limited study period. Instead, inter-year variation was evident. While the number of unique vessels and transits increased year-to-year, hours of operation declined in the same period. Abundance/distribution of fisheries resources, economic feasibility of Arctic marine travel as weighed against inherent risks, and other factors likely accounted for inter-year variation in regional activity levels. Measures have been established to protect Arctic marine ecosystems but may need strengthening to address potential ecosystem threats from existing and growing commercial and industrial activities in the region.

Keywords: Arctic, shipping operations, Northern Sea Route, Northwest Passage, Arctic routes, Arctic fishing, Arctic marine ecosystems, climate change

INTRODUCTION

The Arctic is one of the globe's most rapidly-changing regions (Intergovernmental Panel on Climate Change [IPCC], 2018). Annual average Arctic sea ice extent has declined steadily at least since the early 1980s, and Northern Hemisphere snow and ice extent in 2016 was the lowest on record (U.S. Global Change Research Program [USGCRP], 2017). Diminishing annual and seasonal Arctic sea ice cover is expected to continue or accelerate in the foreseeable future (Overland et al., 2018). Predicted timing for seasonal ice-free waters in certain locations has ranged from within a few decades (Overland and Wang, 2013), to mid-century, (Smith and Stephenson, 2013), to as late as 2100 (Boé et al., 2009; Melia et al., 2016).

Expansion of the duration and spatial extent of seasonal ice-free water will bring changes in accessibility, and therefore the quantity and character, of maritime activities in the region (e.g., Arctic Council, 2009). Extended navigation periods resulting from decreasing ice cover are expected to encourage intercontinental transportation along routes with historically limited access (Khon et al., 2010; Smith and Stephenson, 2013; Zheng et al., 2016). Among these, the Northwest Passage (Guy, 2006; Buixadé Farré et al., 2014) and Russia's Northern Sea Route (Liu and Kronbak, 2010; Stephenson et al., 2014) are increasingly viewed as economically-viable alternatives to Suez or Panama Canal routes (Stroeve et al., 2012; Melia et al., 2016). Changing conditions also favor high-latitude tourism (Hamilton et al., 2005), new opportunities for exploitation of vast sub-seafloor oil and gas reserves (Arctic Monitoring and Assessment Programme [AMAP], 2008; Petrick et al., 2017; Wilkinson et al., 2017), and expansion of other commercial and industrial activities (e.g., Christiansen et al., 2014; Congressional Research Service [CRS], 2018).

As Arctic maritime activities increase, so are expected impacts to Arctic marine ecosystems (Arctic Council, 2009; Congressional Research Service [CRS], 2018). Expanding vessel activities will increase air-borne emissions levels (Corbett et al., 2010; Johansson et al., 2017) and contribute to the likelihood of maritime casualties (United States Coast Guard [USCG], 2010). Environmental degradation associated with increased vessel traffic will also include the effects from increased underwater noise levels on marine organisms (Moore et al., 2012; Halliday et al., 2017), introduction of non-native species (Miller and Ruiz, 2014; Nong et al., 2018), and ship strikes of marine mammals (Huntington et al., 2015; Cooke and Clapham, 2018). These, in turn heighten exposure of Arctic species already susceptible to the effects of climate change (Ragen et al., 2008; Silber et al., 2017) and negatively influence indigenous people reliant on the region's resources (Huntington et al., 2015).

Among the greatest potential threats to Arctic biological processes are large-scale oil and chemical spills (Arctic Council, 2009; Congressional Research Service [CRS], 2018; Walker et al., 2018). Substantial oil and gas reserves are being tapped in Arctic shelf waters (e.g., Congressional Research Service [CRS], 2018) increasing the likelihood of spills from well blowouts, tanker spills, or vessel accidents (Arctic Monitoring and Assessment Programme [AMAP], 2008; U.S. Committee on the Marine

Transportation System [CMTS], 2013). Effects from spills are particularly acute given the region is remote, insufficiently charted, and inadequately supported by spill response infrastructure (Ivanova, 2011; National Research Council of the National Academies of Science [NRC], 2014). Long-term entrainment of oil in cold-water biological communities (Vergeynst et al., 2018) make Arctic ecosystems particularly vulnerable to spills.

Threats from increasing vessel activity on the integrity of Arctic marine ecosystems are real. However, there have been only limited efforts to quantify the amount and spatial features of Arctic-wide maritime operations (Eguíluz et al., 2016; Adams and Silber, 2017; Ocean Conservancy, 2017), and to our knowledge there are no studies of yearly changes in these operations. The magnitude of potential risks will not be fully known until the extent of maritime activities is known. Previously, we analyzed Automatic Identification System (AIS) data to quantify Arctic-wide vessel activities for calendar year 2015 and to establish a baseline of marine traffic in the region (Adams and Silber, 2017). Here, we quantify vessel operations in 2016 and 2017. Incorporating the 2015 data, and using the same metrics used in the 2015 study, we provide a 3 year, pan-Arctic characterization of current maritime activities.

MATERIALS AND METHODS

Data synthesis and analytical methods were the same as those used in Adams and Silber (2017)¹. Descriptions of analytical approaches detailed in that report are summarized here.

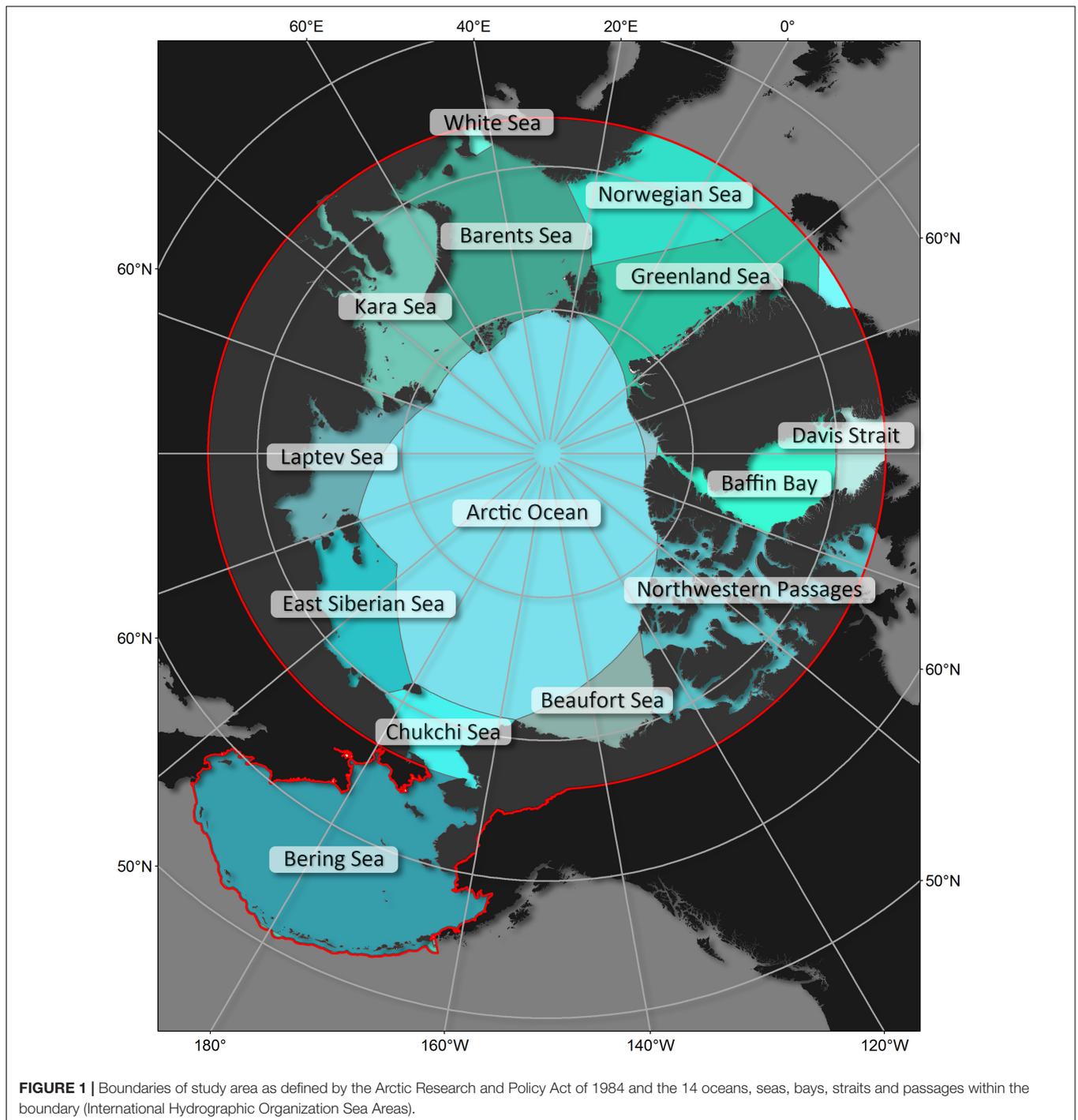
Global satellite AIS data were obtained from exactEarth® for 2015 and from ORBCOMM™ for 2016 and 2017. The Transview (TV32) software application, developed by the Department of Transportation's VOLPE National Transportation Systems Center², was used to decode raw, global AIS data into monthly comma separated value (CSV) files. The decoded monthly data was imported into a spatially-enabled PostgreSQL/PostGIS database and linked to an enhanced vessel database (IHS Markit, 2017) to obtain verified vessel type, gross tonnage, and country of origin (flag country) information.

AIS data were then overlaid on the Arctic as defined by the Arctic Research and Policy Act of 1984 (ARPA) and data located within the ARPA-delineated boundary were analyzed. Within this area, 14 bodies of water were identified using spatial boundaries defined in the International Hydrographic Organization's Sea Areas³ data set, namely: the Arctic Ocean, Baffin Bay, Barents Sea, Beaufort Sea, Bering Sea, Chukchi Sea, Davis Strait, East Siberian Sea, Greenland Sea, Laptev Sea, Kara Sea, Northwest Passages, Norwegian Sea, and the White Sea (**Figure 1**). These spatial designations were used to parse and characterize vessel activity in each body of water.

¹<https://www.fisheries.noaa.gov/resource/document/technical-memorandum-2015-vessel-activity-arctic>

²<https://www.volpe.dot.gov/>

³<https://www.arcgis.com/home/item.html?id=44e04407fbaf4d93afcb63018fbc9e2>



Each AIS record contains a speed, position, and timestamp. We used this information to assess the spatial and temporal integrity of a given record using temporally adjacent AIS records by the same vessel. Records for an individual vessel were sorted using timestamps and then aggregated into transits (i.e., individual trips made by vessels) according to time elapsed between successive records. If elapsed time between successive records for a given vessel was <4 h, they were

aggregated into the same transit; if ≥ 4 h, a new transit was initiated for the vessel. Distance-based computational checks were also made for two temporally adjacent records to ensure the integrity of the derived transit. To segment trips by area, we intersected transits with clipped body of water polygons. Transits that straddled the end and the beginning of a month were split between consecutive months using interpolation.

Spatial density analyses produce gridded surfaces containing cell values representing the concentration of certain features. Linear vessel transit features were used in calculating areas of relative traffic density. A Line Density tool in ArcGIS for Desktop was used with a search radius of 10km and an output cell size of 5km for all transits and specific vessel classes to determine linear distances. Color ramps were used to depict relative densities throughout the study area. We also computed the percent of the total water surface area exposed to vessel traffic by summing the area associated with grid cells containing non-zero density values. An area represented by a grid cell was considered exposed to vessel traffic when the associated vessel traffic density value was greater than zero.

Data from over 360 million individual AIS transmissions logged within the Arctic spatial boundary during the study period were analyzed. These data were first screened to remove any transmissions that contained suspect position, speed or timestamp data. Transmissions by vessels that were not actively engaged in travel were also removed. The remaining AIS transmissions were aggregated into transits. Transits that contained less than 5 AIS transmissions or represented less than 5 nm of travel were removed. The remaining transits were linked to a third-party vessel database (IHS Markit, 2017) to obtain more detailed and accurate information on vessel size and type. Transits by vessels that could not link to the above-described (IHS) database were dropped from the analysis. The remaining transits were then segmented based on sea area, year and month. It should be noted that vessels engaged in nationally-sensitive operations, involving for example military, sovereign, or other government vessels, may not routinely transmit AIS signals and these are data potentially unavailable to this study.

A set of metrics were used to characterize vessel activity: number of trips, hours of operation, and trip distance. Each of these metrics were used to compare operations between areas, between years, and IHS vessel type class. Gross vessel class designations (using AIS “Level 3” data) were used to characterize broad-scale (e.g., Arctic-wide) seasonal and inter-year variation

in vessel activities, whereas finer scale (“Level 5” AIS data) vessel class information was used in describing results for all other metrics. The 14 delineated bodies of water differ a great deal in size; as a result, absolute counts of number of trips and values for distances traveled may be of limited value in inter-area comparisons. Therefore, in an effort to provide a measure of relative amount of vessel traffic volume in each of the 14 areas studied, we also determined transit densities (trip distance per unit of water surface area, or km/km²) and extent of sea surface exposed to vessel trips (percent of total water surface area with non-zero density values).

RESULTS

Arctic vessel operations were substantial and spatially varied. During the study period, an average of 132,828 trips were made each year by over 5,000 different vessels (Table 1). These vessels represented more than 60 different IHS Level 5 vessel types. Annually, vessels operated an average of over 3.2M hours (yearly range 2.8M–3.7M hours). Transits were made in all areas studied (Figures 2A–C) and all months of the year in Figure 3. While the number of individual vessels and the number of transits increased steadily during our study period, the number of hours of operation and total distances traveled declined (Table 1). Thus, on the whole Arctic-wide, vessels engaged in an increasing number of trips, but these trips tended to be relatively shorter in duration.

TABLE 1 | Annual Arctic-wide vessel traffic metrics, 2015–2017.

Vessel traffic metric	2015	2016	2017	Average
Number of unique vessels	5,437	5,475	5,606	5,506
Transit counts	116,317	140,105	142,062	132,828
Operational hours	3,752,055	3,053,909	2,820,561	3,208,842
Transit distance (nm)	24,536,244	19,865,667	18,299,701	20,900,537

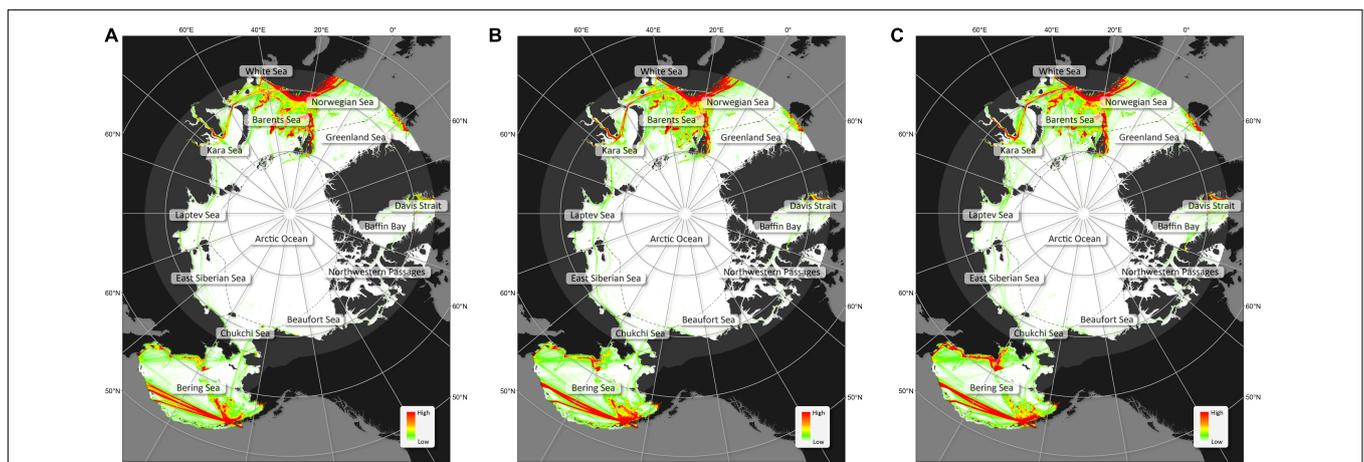


FIGURE 2 | Relative track densities of all vessel types in (A) 2015, (B) 2016, and (C) 2017. Areas with no color indicate no vessel traffic or low traffic volumes relative to other locations.

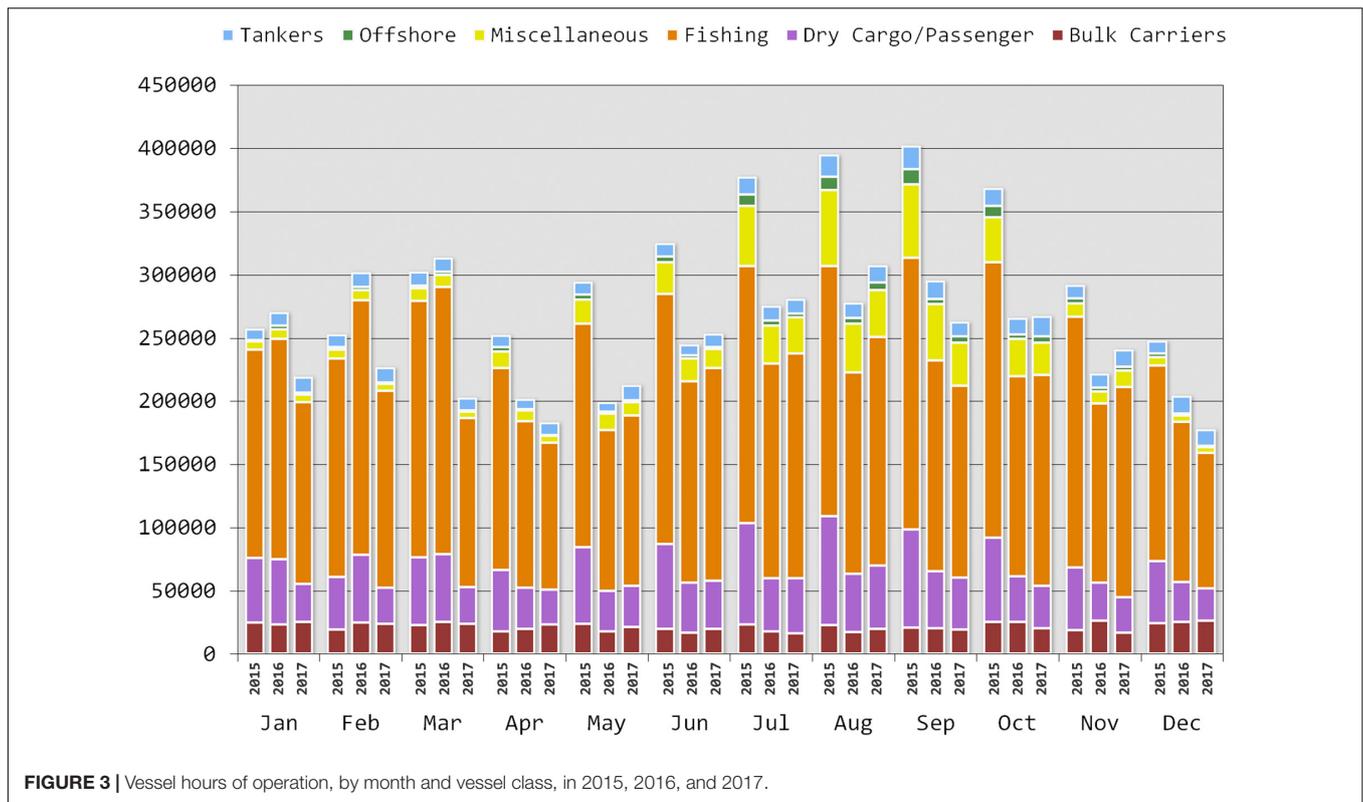


TABLE 2 | Nations with > 100 flagged vessels operating in Arctic waters and number of registered ships, 2015–2017.

Country	2015	2016	2017
Panama	754	826	767
Russia	734	763	800
Norway	639	702	727
United States	412	419	410
China, Hong Kong	319	336	334
Liberia	290	288	332
Marshall Islands	267	268	338
Malta	212	216	263
Singapore	210	206	236
Bahamas	189	174	180
Denmark	*	127	126
Iceland	121	111	115
Netherlands	113	105	*
Cyprus	103	119	113

*66 Denmark-registered ships in 2015; 90 Netherlands-registered ships in 2017.

Country of origin for vessels utilizing Arctic waters was diverse, with most being registered to Panama, Russia, Norway and the United States (Table 2). Norwegian-flagged vessels made the most trips (mean = 42,365; range 37,429 in 2017 to 49,394 in 2015) followed by vessels flagged by Russia (mean = 36,422; range 21,008 in 2015 to 48,092 in 2017) and the United States (mean = 17,536; range 16,583 in 2017 to 18,580 in 2016).

The distribution and number of nations under which vessels were registered (also referred to as its “flag state”) reflect at least two types of activities in the region. One, ships from Arctic countries (Norway, Russia, the United States, etc.) were engaged in extensive commercial fishing industries, local/regional shipping activities, or resource extraction operations. A second group was comprised of commercial vessels registered in countries (e.g., Panama, Marshall Islands) that may have little or no direct interest in Arctic operation. Instead, “flags of convenience” are nations who offer attractive tax and employment regulations that confer cost benefits to owners, and our findings mirror, in part, a worldwide registry of vessels. The number of vessels registered in nations distant from Arctic waters (e.g., China, Liberia) also illustrate the importance of Arctic routes to inter-continental shipping activities.

Overall, fishing vessels, primarily <1000 gross tons (gt), logged the greatest number of trips and hours of operation (Table 3). In all 3 years combined, these vessels made 52.2% of all trips in the entire study area, and constituted 43.9, 54.2, and 57.0% of all Arctic vessel trips in 2015, 2016, 2017, respectively. Of the 14 waterways studied, fishing vessel activity was highest in the Bering, Barents, and Norwegian Seas, representing 66.3, 62.1, and 41.4% of all trips in those areas, respectively. Fishing vessel activities (including Stern Trawlers) in those three seas also represented 42.4–46.7% of the hours of operation of all vessel types combined (Table 3). Fishing vessels (primarily < 1,000gt) also accounted for more trips than any other vessel type in the Greenland Sea, Davis Strait, and Baffin Bay.

TABLE 3 | Hours of operation by fishing vessels in waterways in which commercial fisheries operations were the predominant vessel activity (as measured by hours of operation).

Location	Vessel type	2015			2016			2017		
		Hours	% Sea	% Arctic	Hours	% Sea	% Arctic	Hours	% Sea	% Arctic
Barents Sea	Fishing vessels	217,792	19.3	5.8	154,825	17.8	5.1	303,480	39.6	10.8
	Stern trawlers	599,641	43.5	13.1	487,353	43.4	12.4	259,398	26.5	7.2
Bering Sea	Fishing vessels	376,295	35.7	10.0	365,515	33.0	12.0	467,779	40.0	16.6
	Stern trawlers	228,441	11.4	3.2	275,790	9.7	3.5	249,656	10.6	4.4
Norwegian Sea	Fishing vessels	152,385	14.5	4.1	113,532	17.5	3.7	115,555	25.2	4.1
	Stern trawlers	329,685	22.6	6.3	249,436	28.4	6.0	149,036	22.8	3.7
Greenland Sea	Fishing vessels	30,194	17.2	0.8	22,084	15.7	0.7	64,262	43.5	2.3
	Stern trawlers	92,788	40.6	1.9	79,443	45.3	2.1	43,600	22.1	1.2
Davis Strait	Fishing vessels	1,310	2.8	0.0	9,485	19.2	0.3	27,842	46.8	1.0
	Stern trawlers	31,815	47.3	0.6	30,781	45.2	0.7	18,143	21.6	0.5
Baffin Bay	Fishing vessels	980	3.5	0.0	3,494	14.1	0.1	16,763	52.3	0.6
	Stern trawler	13,449	30.7	0.2	13,062	30.0	0.2	2,088	6.3	0.1

Stern Trawlers here include Factory Stern Trawlers and Stern Trawler AIS Level 5 (see text for explanation) vessel categories. Percent (%) Sea indicates the proportion of hours of operation by the indicated vessel class relative to all other vessel classes in the specified body of water. Percent (%) Arctic values are the same proportion relative to all vessel classes operating in the entire study area.

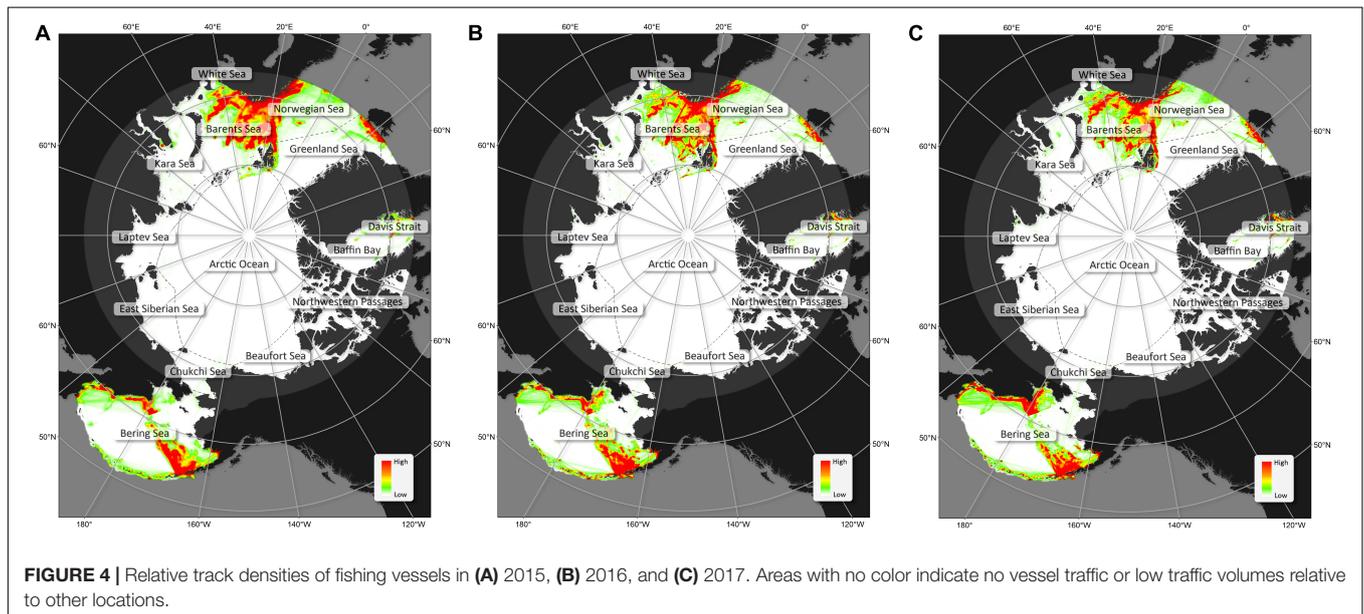


FIGURE 4 | Relative track densities of fishing vessels in (A) 2015, (B) 2016, and (C) 2017. Areas with no color indicate no vessel traffic or low traffic volumes relative to other locations.

In 2017, fishing vessels in the Bering Sea alone accounted for 16.6% of all operational hours for all vessel types in the entire study area combined, the highest such value in our dataset. However, total hours logged (as well as proportions of hours of operation within a given body of water) by fishing vessels varied inter-annually both within those seas and across the Arctic (Table 3). Tracks of fishing vessel routes were numerous and spatially diffuse (Figures 4A–C), indicative of the magnitude of this industry and the importance of fisheries resources in these areas. The spatial distribution of these trips also underwent inter-annual changes (Figures 4A–C).

Excluding all vessels engaged in fishing operations, the greatest number of transits occurred in the Norwegian, Barents, and Bering Seas (Table 4). (Note, we excluded fishing vessel

activities in this table and in other representations to better highlight/discuss activities and metrics involving other vessel classes). Well over 100,000 trips were made in 3 years in the Norwegian and Barents Seas alone. The number of trips in these three Seas exceeded those in the Greenland Sea (the location with the fourth highest number of trips) by fourfold or more. In comparison to other locations, trips in these areas exceeded the number of trips made in the Northwest Passage, the Beaufort and East Siberian Seas and other locations by nearly two orders of magnitude.

Average sea surface area exposed to vessel traffic exceeded 96% in the Norwegian, Barents, and Bering Seas and over 90% of the sea surface was exposed to vessel transits in the Davis Strait and Chukchi Sea (Table 4). The Arctic Ocean had the

TABLE 4 | Total number of transits and percent surface area exposed to vessel traffic, excluding all fishing vessel operations, for each body of water in the study area.

Waterway	Total transits (3 years)	Water surface exposed (%; avg/year)
Norwegian Sea	149,271	99.1
Barents Sea	109,441	96.4
Bering Sea	98,526	98.3
Greenland Sea	25,559	77.5
Kara Sea	17,279	85.3
Davis Strait	9,447	91.8
Baffin Bay	5,350	80.1
White Sea	4,682	88.9
Chukchi Sea	3,999	90.2
Arctic Ocean	3,528	18.6
Laptev Sea	2,969	76.2
East Siberian Sea	2,015	75.4
Northwest Passage	1,847	36.5
Beaufort Sea	1,433	48.0

greatest overall surface area but was also at least 50% ice-bound for 12 months and 75% ice-covered for 11 months of the year. It ranked last in both density and percent sea surface covered by vessel transits. The Beaufort Sea and the Northwest Passage also exhibited low sea surface exposure and also hosted the fewest trips.

Vessel Types

Excluding Fishing Vessels, General Cargo Ships were among the vessel types making the most trips in nine of the 14 bodies of water studied (Table 5). Research/survey vessels, supporting primarily academic oceanographic and geophysical seismic research, were also among the most common vessel types, totaling an average of over 79,000 h of operation in each year of study period. Most of this work was conducted, in rank order, in the Barents, Kara, Norwegian, and Greenland Seas totaling between 21,000 and 93,000 h of operation during 2015–2017. In addition, vessels engaged in fisheries research logged an annual average of over 6,500 h; the majority occurring in the Greenland, Norwegian, Bering, and Barents Seas, in that order.

Vessel operations associated with the oil and gas industry were also strongly represented in our records, both numerically and spatially. Level 5 vessels types associated with the production and transport of oil and gas included, but were not limited to, Platform Supply Ships, Anchor Handling Tugs, Standby Safety Vessels, Drilling Ships, and Tankers. The Norwegian, Barents, and Kara Seas exhibited the greatest extent of oil/gas exploration- and extraction-related activities. Collectively, oil industry ships (excluding tankers) accounted for a total (for all 3 years) of 4,633, 2,821, and 671 transits in the Norwegian, Barents, and Kara Seas, respectively. Tankers moving hydrocarbon products [crude oil, Liquefied Natural Gas (LNG), and Liquid and Petroleum Gas (LPG)] made 2,089, 1,930, and 596 transits in these three seas in 2015, 2016, and 2017, respectively.

Ships in the Passenger/Cruise vessel class made the greatest number of trips in the Greenland Sea (3 year total = 3,740 trips; mean = 1,246.7/yr), followed by the Barents (mean 630.0/yr) and Norwegian Seas (mean 484.0/yr) and the Arctic Ocean (mean 263.3/yr) (Table 5). Passenger/Cruise vessels comprised 22.4 and 20.8% of all vessel trips in the Arctic Ocean and Northwest Passage, respectively. Tugs made more trips than all other vessel classes in the Chukchi and Beaufort Seas (1,464 and 570 transits, respectively) and ranked among the top three vessel types in trips made in the Barents, Bering, and Kara Seas (Table 5). Transits by Icebreakers were most common in the Arctic Ocean and Northwest Passages, but trips by this vessel class were relatively few elsewhere.

Vessel Activities by Location

The Norwegian Sea exhibited the highest overall number of transits in 2015 ($n = 56,952$ trips) and 2016 ($n = 47,103$); whereas the greatest number of trips occurred in the Barents Sea in 2017 ($n = 45,578$ transits). Highest overall number of vessel operating hours occurred in the Bering Sea in 2015, 2016, and 2017, followed by the number of hours logged in the Barents Sea in those same years.

Most transits in the Bering Sea were logged by fishing vessels (exceeding 11,000 trips in each of the 3 years; mean = 13,520; range 11,089–15,082). These were generally short in duration (3 year mean = 30 h/trip) and distance (3 year mean = 143 nm). In addition, stern trawlers and factory stern trawlers collectively logged over 20,000 trips in the 3 year study period (mean = 3,464/yr; range = 2,146–4,559), a mean of 38 h/trip. Bulk Carriers in the Bering Sea logged more hours of operation than all other (non-fishing) vessel types in all locations, exceeding the second-highest, Cellular Container Ships in the Bering Sea, by over 280,000 h (Table 5). Transits by these vessels involved considerable distances (Bulk Carriers: mean = 712 nm/trip; Cellular Container Ships: mean = 669 nm/trip) many having been engaged in lengthy intercontinental voyages between western North America and Asia using the North Pacific Great Circle Route (Figures 2A–C).

In the East Siberian, Kara, and Laptev Seas (along with portions of the Chukchi, Beaufort, and Barents Seas), collectively considered as segments of the Northern Sea Route, General Cargo Ships made the greatest number of trips (Table 5). Research Survey Vessels and Products Tankers were also among ship classes making the greatest number of trips along this shipping route. Relative to other locations in the study area, comparatively small portions (75.4–85.3%) of these waterways were exposed to vessel traffic.

Most transits through the Canadian archipelago including the Northwest Passage, Baffin Bay and Davis Strait were made by General Cargo Ships (1,375 total, in these three areas in all 3 years) and Passenger/Cruise ships (1,048 in 3 years). Container Ships, Refrigerated Cargo Ships, Bulk Carriers, Chemical/Products Tankers, and Icebreakers were also among vessel types making the greatest number of trips in these waterways (Table 5). In the Northwest Passage, alone, total number of trips increased from 443 in 2015 to 644 in 2016 to 760 in 2017. In this location, the total number of hours under

TABLE 5 | Two most common (as measured by number of trips) vessel classes in each Arctic waterway studied.

Location	Vessel type	Trips	% of total	Mean	SD	Operation hours
Norwegian Sea	Passenger/Ro-Ro ship (vehicles)	20,452	14	6,817	±3,498	177,261
	General cargo ship	19,305	13	6,435	±825	244,188
Barents Sea	General cargo ship	7,939	7	2,646	±345	126,207
	Research survey vessel	3,148	3	1,049	±417	93,215
Bering Sea	Bulk carrier	8,628	9	2,876	±241	554,950
	Container ship (fully cellular)	6,731	7	2,244	±121	274,134
Greenland Sea	Passenger/Cruise	3,740	15	1,247	±121	34,914
	Research survey vessel	1,156	5	385	±38	21,030
Kara Sea	General cargo ship	3,748	22	1,249	±318	75,009
	Tug	1,676	10	559	±71	27,733
Davis Strait	General cargo ship	778	8	259	±91	5,141
	Container ship (fully cellular)	670	7	223	±10	5,896
Baffin Bay	General cargo ship	597	11	199	±40	126,207
	Refrigerated cargo ship	502	9	167	±13	3,759
White Sea	General cargo ship	2,318	50	773	±210	18,942
	Products tanker	372	8	124	±21	2,532
Chukchi Sea	Tug	1,464	37	488	±122	26,944
	General cargo ship	430	11	143	±26	6,833
Arctic Ocean	Passenger/Cruise	790	22	263	±65	7,191
	Research survey vessel	551	16	184	±32	12,673
Laptev Sea	General cargo ship	1,284	43	428	±99	17,481
	Research survey vessel	400	13	133	±62	8,329
East Siberian Sea	General Cargo Ship	876	43	292	±82	15,835
	Research survey vessel	253	13	84	±49	5,474
Northwest Passage	Passenger/Cruise	384	21	128	±8	4,282
	Bulk carrier	341	18	114	±53	2,767
Beaufort Sea	Tug	570	40	190	±81	6,600
	Pusher tug	204	14	68	±12	2,482

Values here include all vessel types, except fishing vessels. Total number of transits, 3 year mean (\pm standard deviation) number of transits by vessel class, and percent of total trips by all vessel types in specified body of water are indicated.

operation progressed from 8,669 h in 2015 to 6,766 in 2016 to 10,158 in 2017.

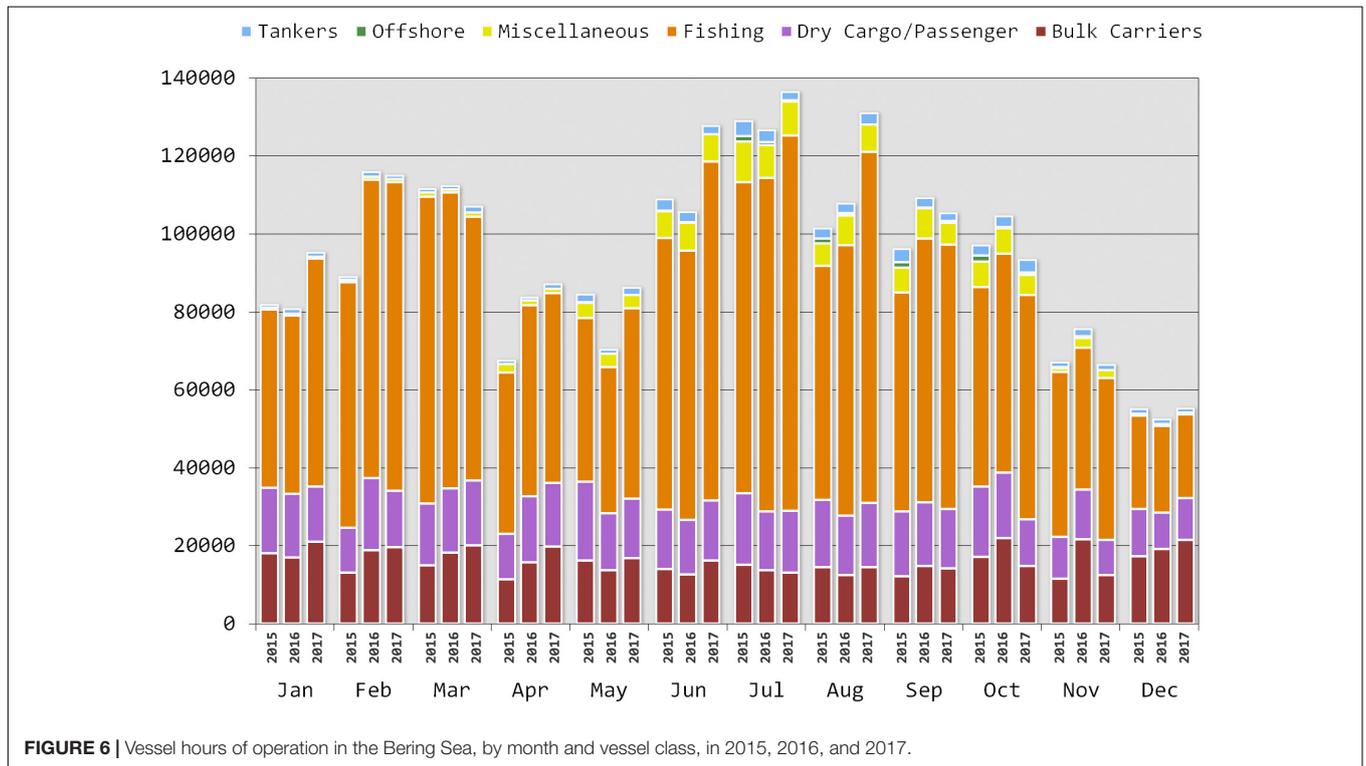
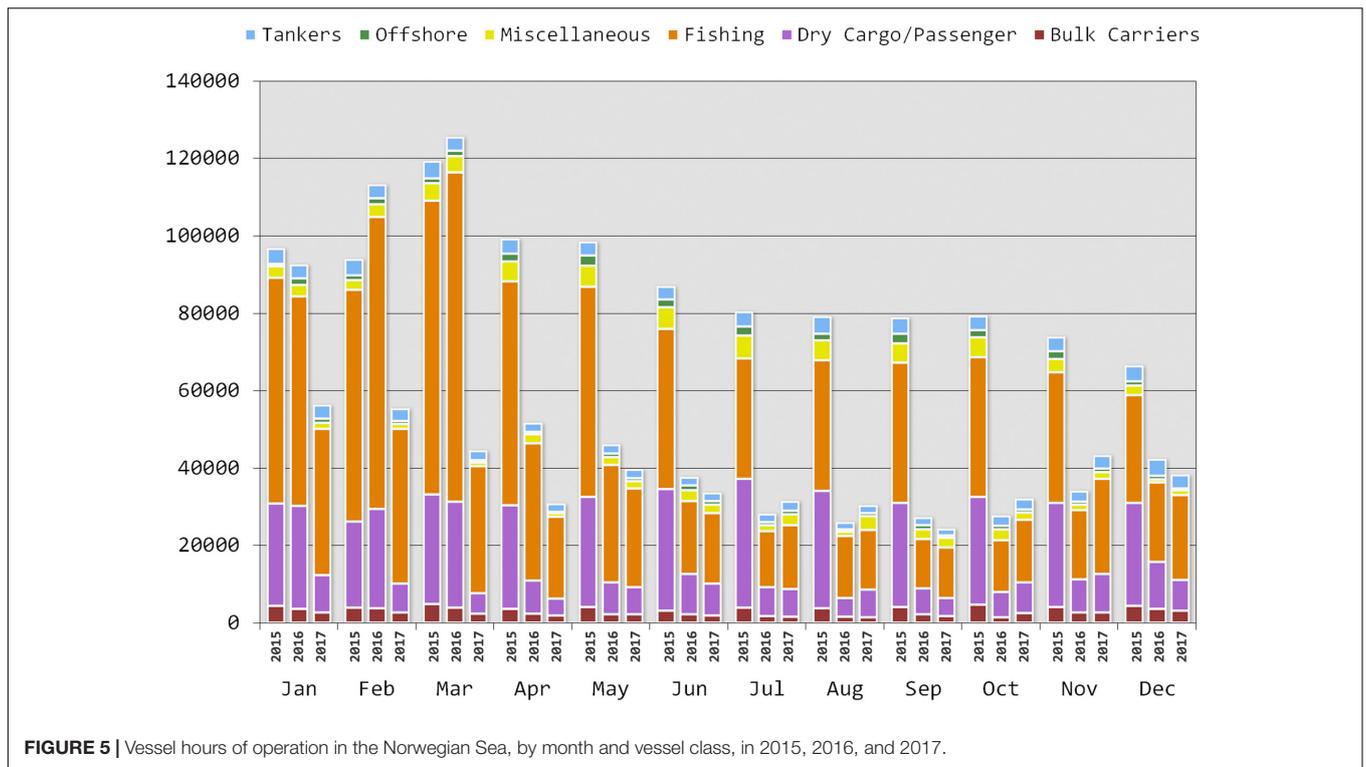
Inter-Year Comparisons

We observed modest inter-year changes in the number of individual vessels (by vessel type) operating in Arctic waters. Dry Cargo/Passenger vessels comprised the highest overall number of individual vessels operating in 2015 (1,771 vessels) and 2016 (1,699 vessels); while most ships operating in 2017 were in the Bulk Carrier class (1,779 vessels).

The overall number of trips increased in each year of the study period over the previous year while hours of operation and distances traveled declined (Table 1). At least some observed inter-annual variability can be attributed to large-scale changes in fishing vessel operations. For example, vessels engaged in fishing operations in aggregate logged a total of 51,093, 75,892, and 80,958 trips in 2015, 2016, and 2017, respectively (constituting more trips than all other vessel types in each year). Fishing vessels also represented 39.6% of all vessel operating hours in the Barents Sea in 2017 (and 10.8% of all vessels in the entire study area), but only 17.8% in 2016; in the Bering Sea fishing vessels logged over 100,000 more hours in 2017 than in 2016 (Table 3).

Other regional inter-annual fluctuations in vessel operations occurred. The number of trips and hours of operation by Bulk Carriers and Cellular Container Ships in the Bering Sea exhibited increases of 3–15% in 2016 relative to 2015, and the number of trips either declined (by 7%) for Cellular Container Ships or increased (by 7%) Bulk Carriers in 2017 relative to 2016. Hours logged by Chemical Tankers, Chemical/Products Tankers, Crude/Oil Products Tankers, and Products Tankers in the East Siberian Sea (a 3 years collective total of 5,958 h) increased 4.6% in 2016 over 2015 but declined 5.3% the following year. Total operating hours by these same four vessel classes in the Kara Sea went from 10,579 h in 2015 to 18,241 h in 2016 and 12,427 in 2017.

Trips by Passenger/Cruise vessels in the Greenland Sea increased by 2% in 2016 over 2015 and increased 20% in 2017 relative to 2016. In contrast, voyages by passenger/cruise ships in the Barents Sea was greatest in 2015 and dipped by about 5% in each of the subsequent 2 years. Trips by this vessel class in the Norwegian Sea were most numerous in 2015, subsequently declined 21% in 2016 and then increased 13% the following year. In one perplexing example an abrupt and precipitous drop occurred in vessel hours of operation in the Norwegian Sea



in mid-2016 that continued at similar levels throughout 2017 (Figure 5) – a pattern that did not occur in monthly hours of operation in the Bering Sea (Figure 6). In this Norwegian Sea case, the number of trips by Passenger/Roll-On, Roll-Off vehicle

transport (or “Ro-Ro”) vessels alone dropped from 11,656 trips in 2015 to 5,291 in 2016, and 3,505 in 2017 (Figure 5); while the number of transits by General Cargo Ships was 7,468, 6,389, and 5,448 in 2015, 2016, and 2017, respectively. In contrast, General

Cargo Ships and Bulk Carriers operating in the Barents Sea added an average of 363 and 264 trips, respectively, in each subsequent year of the study while operating hours of these two vessel classes declined between 6.1 and 35.6% each year in the same period.

DISCUSSION

Tens of thousands of voyages were undertaken in Arctic waters in each year of our study. And, yet, high latitude vessel activity is projected to grow as conditions evolve. This in turn is expected to heighten negative consequences for Arctic marine ecosystems (Arctic Council, 2009; Roach, 2018). While vessel traffic levels were extensive in some locations, they remained limited in others. It is the latter areas that may undergo the greatest amount of growth in changing ice conditions.

Characteristics of Maritime Activities in Various Waterways

Based on the volume, nature, and spatial characteristics of vessel traffic, Arctic waterways can be organized into three groups. These are the Barents, Bering, and Norwegian Seas; the Northern Sea Route and Northwest Passage and associated complexes of bays and straits; and the Arctic Ocean. In the first of these, the Barents, Bering, and Norwegian Seas include relatively low-latitude areas with extensive seasonal ice-free zones. Access to the Barents and Norwegian Seas is facilitated by warm northward-bearing North Atlantic surface waters creating vast ice-free areas during much or all of the year. Consequently, operations in these three seas were conducted by a diverse set of vessel types and represented an overwhelming majority of all vessel activity in the entire study area. Fishing activities predominated and were a major contributor to observed levels of surface area exposure to vessel activity (over 95%), a function of both the number of trips and broad spatial footprint of this industry. However, the importance of these bodies of water to both long- and short-distance transport of goods was also evidenced by the presence of large vessels such as General Cargo Ships, Bulk Carriers, Container Ships, and Passenger/Ro-Ro (vehicle) transport vessels, among others (Table 5).

In the Bering Sea, for example, long-distance, inter-continental trade was indicated by Bulk Carriers having logged the highest number of hours of operation of all (non-fishing) vessel classes, surpassing by nearly twofold the next-highest vessel class, Container Ships. These values are due, in part, to the expanse of this body of water, i.e., temporally and spatially lengthy trips were needed to traverse it. A significant inter-continental trade route exists in a portion of the Bering Sea connecting Asian and North American ports along a Great Circle Route atop the North Pacific Ocean (Burns and Poe, 2014) (a portion of this route is evident in Figures 2A–C). While most of the substantial ship traffic along this route passes south of the Aleutian Islands, much of it utilizes the Unimak Pass through the Aleutians and passes into waters north of the archipelago (Schwehr and McGillivray, 2007).

A second group of waterways – the East Siberian, Laptev, Kara and White Seas (or, the Northern Sea Route), and in the Northwest Passage, Baffin Bay, Davis Strait and the Beaufort and

Chukchi Seas – generally exhibited ice cover that exceeded 50% (up to 9/10 in some locations) in winter and relatively little (e.g., <10%) ice cover in summer/fall (Adams and Silber, 2017). Some trips were regional in nature delivering supplies and goods to ports within the Northern Sea Route (Humpert, 2014; Zhang et al., 2016) or Northwest Passage (Haas and Howell, 2015).

A comparatively small number of unique, primarily large vessels (e.g., bulk and container ships, tankers) (Table 5) undertook lengthy trips in the Northern Sea Route, a finding consistent with previous studies (Zhang et al., 2016). Some of these ships were on trans-Arctic voyages delivering supplies and materials, transporting oil and gas products, or otherwise connecting distant ports (Humpert, 2014; Dalaklis and Baxevani, 2017). Arctic waterways as tourism destinations was evidenced by numerous passenger cruise ship transits in waters comprising the Northwest Passage and Northern Sea Route, although these vessels made far fewer trips than containerized ships and tankers. The number of vessels engaged in transport of energy products along the Northern Sea Route reflected the presence of a mature oil/gas industry on the Siberian coast.

Varying amounts (36.5–88.9%) of sea surface exposure to vessel traffic along the Northern Sea Route and in the Northwest Passage (including the Greenland and Beaufort Seas here) (Table 4) appear related to prescribed, non-diffuse routes and restricted access due to ice cover for at least part of each year. Total water surface extent available for transits was also a factor. In the Davis Strait, for example, a comparatively small body of water, a relatively modest number of trips resulted in over 90% its surface area being exposed to trips. In contrast, in the Greenland Sea, a spatially vast area, numerous trips (fourth highest of all areas studied) exposed only 77% of its surface area to vessel activities, suggesting these trips (many by passenger cruise and research survey vessels) were localized or bounded by certain routes.

Research survey vessels logged a substantial number of hours in the Greenland, Kara, Laptev, and East Siberian Seas (Table 5). Much of this, notably in locations such as the Kara (Smith, 2016) and Laptev Seas (Soldatkin, 2017), can be attributed to seismic surveys for sub-seafloor oil reserves evidenced as grid pattern ship tracklines in our sample. Separately, research survey cruises in locations such as the Barents Sea (and Arctic Ocean) were tied to scientific studies of the oceanography, glaciology and marine ecosystems of the region (e.g., Hopkins, 2018), and fisheries stocks research cruises (e.g., Ingvaldsen et al., 2017; Vedenin et al., 2018). Bathymetric surveys in support of Arctic nation's recent claims to Exclusive Economic Zones under the United Nations Convention on the Law of the Sea were also undertaken during our study (e.g., Shimeld and Boggild, 2017). Because they can involve visits to remote sampling locations and may include extended data-collection periods, research and scientific cruises can be long in duration, thereby inflating hours of operation values.

Studies indicate the Northern Sea Route maintains regional and potential international importance (Pierre and Olivier, 2015). However, its economic relevance, especially regarding global trade implications, may remain somewhat limited in the near term due to market conditions (Raspotnik and Stephen, 2013; Lee and Kim, 2015; Zhang et al., 2016) and lingering

concerns regarding navigational hazards (Stephenson et al., 2014). Voyages may be similarly limited in the Northwest Passage at present, particularly as significant ice hazards still exist (Haas and Howell, 2015).

Nonetheless, commercial and logistical boundaries along these two major shipping routes are currently being tested with real trials. In July 2016, the *Yong Sheng*, an ice class ship owned by Chinese shipping giant COSCO, made its third trip (its first two voyages having taken place in 2013 and 2015) delivering wind turbine equipment from China to the United Kingdom through the Northern Sea Route, and then returned via this route (Humpert, 2016). The company sent several additional general cargo vessels along this same passage that same year. In addition, in fall 2018, the *Venta Maersk* became the first container ship to travel (albeit while still being aided by an icebreaker for a portion of the trip) from Vladivostok along the Northern Sea Route, via portions of the Bering, Chukchi, East Siberian, and Barents Seas, to the German port of Bremerhaven (Reuters News, 2018). In the same period, two LNG-powered bulk carriers owned by Finnish shipping company ESL bore general cargo loads from Japan, westbound along the Northern Sea Route, to the Swedish port of Oxelösund (also icebreaker-aided) (Corkhill, 2018). In August 2016 a cruise ship made a journey from Seward, AK to New York, NY, the first of its class to traverse the Northwest Passage (Dennis and Mooney, 2016). Tens of cruise ships capable of long Arctic voyages now exist, with several more being added each year (Nilson, 2018).

Cases involving these “firsts” notwithstanding, overall, we observed relatively small increases in trips in these key Arctic passageways. However, as changes in environmental conditions evolve toward greater accessibility, sea-borne industries now enter a critical phase of testing increased use of these areas. It is precisely these areas that may be experiencing the most growth in the coming years and may be most ecologically vulnerable as maritime activities expand.

Last, the truly polar Arctic Ocean consisted of the greatest overall surface area in our study and was characterized by comparatively low (but, not zero) ship traffic volume (<1,500 trips annually). Being ice-bound much of the year travel is limited in the Arctic Ocean and limited amounts (<25%) of the water surface was exposed to vessel traffic each year. Here, passenger cruise ships, research survey vessels, and ice-breakers, in that order, made most trips in the 3 years study period. These voyages were also highly-seasonal, most having occurred primarily June to October.

Sea Ice Cover

Amounts of ice on the sea surface and in the water column are important determinants in the location and extent of Arctic vessel traffic. Globally, the highest recorded annual global temperature occurred in 2016 (U.S. Global Change Research Program [USGCRP], 2017), exceeding a 139-year annual average by 0.95°C (NOAA, 2019b). The Earth's historical annual average temperature was surpassed in 2017 by 0.85°C. Related, in 2016 Northern Hemisphere snow and ice extent was the lowest recorded in the period 1979 to present (NOAA, 2019a), a substantial decline from 2015 coverage. Snow/ice cover was 2% greater in 2017 relative to 2016, but these 2 years represented

the lowest levels in the last 39 years (U.S. Global Change Research Program [USGCRP], 2017). Likewise, in our study area sea ice coverage changed minimally (ca. <2% between years) in the course of our study (National Snow and Ice Data Center [NSIDC], 2018). Thus, relative amounts of Arctic-wide ice coverage may have been only one factor influencing observed inter-annual changes in volume and distribution of vessel traffic patterns.

Three-Year Trends

Numerous sources have indicated declining ice cover will prompt increased maritime activities in historically ice-limited areas. Sea ice extent almost certainly had a role in the observed number of trips observed in some locations (e.g., the Northern Sea Route) and by some vessel classes. However, we observed no overt increasing or decreasing trends in vessel traffic volume in our limited study period. For example, as noted, although the overall number of voyages steadily increased during our study, distances traveled and time underway decreased. Instead, a more apparent pattern involved considerable regional inter-annual variability in operations. This variation confounds conclusions about region-wide activities and defy simple, single-factor explanations regarding trends and their causes.

A suite of variables, nearly all of which are beyond the scope of this study, likely had roles in Arctic maritime activity levels. These might include, for example, abundance, availability, and locations of fisheries resources (e.g., Watson and Haynie, 2018); market forces (e.g., oil/gas demand and prices); global economic factors effecting intercontinental trade (e.g., Eurasia Group, 2014; International Energy Agency [IEA], 2019); and economic feasibility relative to navigational safety of high Arctic marine travel (e.g., Zheng et al., 2016). As one example, in late-2015 Royal Dutch Shell abandoned pursuit of further exploratory drilling in the U.S. Chukchi Sea. This decision resulted from assessments of expected risks and high project costs relative to potential return (i.e., comparatively low oil prices at the time) after finding insufficient indications of crude in the region (Schaps, 2015).

Potential Impacts

The release of air-borne emissions from shipping activities has become a growing concern for high-latitude marine transportation (Dalsøren et al., 2007; Johansson et al., 2017). Amounts of aerosols and gaseous emissions, including carbon dioxide, are expected to increase with increased shipping activities thereby accelerating the melting of ice and snow (Corbett et al., 2010). Air-borne pollutants and greenhouse gases are also emitted as by-products of ongoing oil and gas extraction activities (Peters et al., 2011). In addition, scores of non-indigenous species have been detected in Arctic ballast water exchange operations (Miller and Ruiz, 2014).

The U.S. Coast Guard has indicated an increased likelihood of maritime accidents is expected to accompany expanded Arctic vessel operations (United States Coast Guard [USCG], 2010). Fatal vessel strikes (Huntington et al., 2015; Cooke and Clapham, 2018) and fishing gear entanglement of Arctic marine mammal species (George et al., 2017) are reported conservation concerns. Adverse impacts to fish and marine mammal populations are expected as industrial activities increase

(Reeves et al., 2012) in turn impacting indigenous people reliant on the region's resources (Huntington et al., 2015). These impacts may compound the vulnerability of Arctic species as they undergo shifts in distribution and habitats change as a result of rapidly changing Arctic ecosystems (Silber et al., 2017).

Our findings indicate waters exposed to at least some vessel traffic exceeded 75% in nearly all areas studied and exposure levels exceed 90% in 5 of the 14 areas (Table 4). Associated vessel-related impacts, such as those related to introduced noise, may follow. Anthropogenic underwater noise sources may alter marine mammal intra-species acoustic signaling behavior (Moore et al., 2012; Fournet et al., 2018) or disrupt normal behavior (Gordon et al., 2003). These noise sources and other stimuli may compound stressors already impinging on Arctic marine mammal populations as a result of climate change itself (Ragen et al., 2008; Kovacs et al., 2011).

The possibility of an uncontained, large-scale oil spill may be the single greatest threat to Arctic ecosystems (Afenyo et al., 2017; Congressional Research Service [CRS], 2018). Effects from a spill on biological communities could be severe and long-lasting. And, while local effects may linger, high winds and moving ice fields may transport surface oil to locations other than a spill site. Among other potential impacts, Arctic seabird and mammal species (e.g., polar bears, Aleutian sea otters) are highly vulnerable to oiling whereby thermoregulation and buoyancy are effected (e.g., Renner and Kuletz, 2015). Yet, spill response infrastructures and contingency planning are generally regarded as inadequate in many poorly supported locations where severe and unpredictable weather conditions can prevail (e.g., National Research Council of the National Academies of Science [NRC], 2014; Wilkinson et al., 2017). The plausibility of a substantial spill appears high given the levels of activity devoted to oil/gas industries in our findings.

To be sure, the severity of some potential impacts identified here has not been fully quantified in all cases, particularly at the population level. However, given projections for growth of vessel operations, it is reasonable to assume that potential threats may become realities.

Fishing Vessels and Effort

Multi-billion-dollar commercial fisheries exist in the Norwegian, Bering, and Barents Seas for various species of cod, halibut, capelin, pollock, salmon, herring, and crustaceans, among others. Norwegian and Barents Sea fisheries resources destined for markets throughout Europe, Russia and Asia are supported by a vast network of fishing vessels, trawlers, and vessels engaged in processing and transporting fish products (Food and Agriculture Organization of the United Nations [FAO], 2011). Crustacean and groundfish fisheries for Walleye Pollock (*Gadus chalcogrammus*), Pacific Cod (*Gadus macrocephalus*), Atka Mackerel (*Pleurogrammus monopterygius*) among other species render the Bering Sea one of the most productive fishing regions in the world.

As measured by number of trips, unique vessels, and hours of operation, fishing vessel operations, collectively, dwarfed activity levels by all other vessel classes. Our metrics also attest to the magnitude and breadth of these fleets. For example, in the Bering

Sea, alone, fishing vessels accounted for 10–17% of all vessel operating hours Arctic-wide (Table 3).

But industry activities were not static. Availability of fisheries resources in Arctic waters can be variable (e.g., Haug et al., 2017; Troell et al., 2017). Therefore, the extent and locations of vessel operations associated with these resources will likewise vary. Observed inter-year changes in spatial distribution may have reflected shifts in targeted species locations (Figures 3A–C) in turn having been driven by changing prey distribution and other factors. Evidence indicates that commercially important fish species are undergoing northward distributional shifts in response to warming water temperatures (e.g., Fossheim et al., 2015; Misund et al., 2016) and fishing practices are adjusting to these ecosystem-level changes (Watson and Haynie, 2018). The industry also responds to changing markets, seeking to maximize profits depending on fish products sought or proximity of processing centers (Watson and Haynie, 2018). Diminishing sea ice levels may also contribute to the emergence of, and increased access to, previously inaccessible fishing locations. In short, a malleable industry was apparent in our sample.

An abrupt decline in hours of operation logged in the Norwegian and Barents Seas noted here may be at least in part related to a substantial reduction in availability of capelin (*Mallotus villosus*), an integral part of this ecosystem (ICES, 2017). Landings for this species declined from 11,500 landed tones in 2015 to zero in 2016 and 2017 (but subsequently increased in 2018) (ICES, 2017). Some inter-year variability in fishing trips may also be attributed to changes in catch limits for Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and other species established each year for Norwegian and Barents Sea by Norwegian-Russian bilateral agreements and the International Council for the Exploration of the Sea (ICES) (Seaman, 2017).

Impacts From Fisheries

The size of the fleet and number of vessels supporting the vast industry suggest impacts from the industry may be significant. While typically smaller in size than large container, tanker, or bulk carrying ships, fishing vessels nonetheless contribute a proportional share to air-borne emissions (Dalsøren et al., 2007; Roiger et al., 2015), radiated underwater noise (Hovem et al., 2015; Peng et al., 2017), or small fuel spills during routine operations or accidents (International Maritime Organization [IMO], 1988; Richardson et al., 2016). Active and “lost” gear may entangle Arctic-dwelling marine mammals and other marine vertebrates (Reeves et al., 2014; George et al., 2017); and like all ships, fishing vessels are capable of fatally striking marine mammals (Jensen and Silber, 2003).

Factoring in incidental bycatch (e.g., Ianelli and Stram, 2014; Breivik et al., 2017) and the effects of trawling (represented by Stern Trawlers and Factory Stern Trawlers in this study; Table 3) on demersal communities (Puig et al., 2012; Christiansen et al., 2014), impacts on ecosystem integrity from this industry are indeed consequential. Effects on targeted species assemblages themselves and related ecosystem impacts compound negative influences on these biological communities (Zeller et al., 2011; ICES, 2018; Popov and Zeller, 2018). Therefore, considering the

volume of fishing operations, as characterized by numbers of trips in our sample, this source may dwarf ecosystem impacts typically ascribed to larger vessels.

Oil and Gas

Intensive vessel activity found in some locations reflected a dynamic Arctic energy industry. Terrestrial and undersea oil deposits in the region are expansive (US Geological Survey [USGS], 2009; Gautier et al., 2011) and they have been accessed in waters of the Norwegian/Barents Seas and off Russian coasts. Year-round ice-free conditions and relatively shallow shelf waters enhance the economic viability of drilling in the Norwegian and Barents Seas. Over 30 exploratory wells were drilled on the Norwegian Shelf in each of 3 years, 2016–2018 and 11 new discoveries were made in 2017 (Norwegian Petroleum Directorate, 2018). In the Barents Sea, alone, 15 new exploratory oil wells were drilled in 2017 north of Hammerfest, Norway (Norwegian Petroleum Directorate, 2017).

Vessel operations related to oil/gas activities were strongly represented in our sample. For example, plots of ship tracks indicated hubs of oil and gas vessel activities in Russia's Kara Sea (**Figures 2A–C**) in support of the Prirazlomnoye oil field, south of Novaya Zemlya. Production from the field began in December 2013. By the end of 2017, over 41 million barrels of oil had been extracted from the site (Gazprom Neft, 2018). In addition, construction was completed at the Russian seaport of Sabetta in mid-2016, one of the most complex LNG projects ever undertaken (Dalaklis et al., 2018), to handle LNG and gas condensate from the Yamal Peninsula. Shipments of LNG from the facility began in late 2017, and by August 2018 over 4 million tons had been removed (World Maritime News, 2017). Transport of gas from these facilities, across the Barents Sea to Murmansk, Russia (**Figures 2A–C**) via ice breaking shuttle tankers occurs year-round (Offshore Technology Focus, 2018).

Seismic survey vessels, shallow and deep-water ice islands, and ice-strengthened drillships were in use in the Alaskan and Canadian Beaufort Sea throughout the 1970s and 1980s (Timco and Frederking, 2009). By 2000, hundreds of exploratory or producing wells had been opened in the region. While at present only the Beaufort Sea has producing wells in U.S. federal waters (Bureau of Ocean Energy Management [BOEM], 2018), the region is expected to remain of interest to oil companies. For example, in December 2017 the Italian oil producer Eni began drilling a new well from an existing man-made island in the U.S. Beaufort Sea, becoming the first company to do so since 2015 (Congressional Research Service [CRS], 2018). Whereas energy production may one day ramp up again in the Beaufort Sea, we found some of the lowest levels of vessel transits and hours underway in this location.

Impacts From Oil/Gas Industries

Our findings indicate energy products are on the move on large scales and traversing great distances in some Arctic waters, thereby contributing to the vulnerability of marine environments. Potential for large spills from oil- and gas-bearing vessels are a serious concern (Arctic Council, 2009; National Research Council of the National Academies of Science [NRC], 2014). Indications

are insufficient infrastructure and resources exist to respond to, contain, or clean spills in remote and hazardous locations (National Research Council of the National Academies of Science [NRC], 2014; Nevalainen et al., 2017; Wilkinson et al., 2017). In addition, long residency times of spilled oil (Hazen et al., 2016) especially in cold-water ecosystems (Engelhardt, 1985; Vergeynst et al., 2018), and long-term entrainment in marine biological processes (Hicken et al., 2011; National Research Council of the National Academies of Science [NRC], 2014; Yüewen and Adzibli, 2018) contribute to the potential severity of impacts from a large spill.

Seismic survey exploration of sub-seafloor oil reserves introduces loud sounds into the water column. Pulsed seismic signals are among the most powerful man-made sound sources (Hildebrand, 2009). Exposure to these sounds have consequences for marine mammal populations and other organisms (Nowacek et al., 2015; Kyhn et al., 2019) by disrupting normal behavior (Richardson et al., 1995), eliciting startle responses (Heide-Jørgensen et al., 2013), and resulting in temporary and permanent hearing loss (National Marine Fisheries Service [NMFS], 2018).

Global reliance on fossil fuels assures energy production will remain a feature in Arctic waters for the foreseeable future. However, in the past, market forces have influenced the levels of Arctic oil industry activities (Harsem et al., 2015). For example, a 2007/2008 global decline in oil demand and prices slowed oil/gas production in the Arctic (Petrick et al., 2017). Economic conditions akin to the 2007/2008 downturn, or other factors, may once again slow production in the future (Lindholt and Glomsrød, 2012). Inherent hazards associated with existing long supply lines through inhospitable natural environments are areas of legitimate concern. Severe ecosystem degradation may follow.

Conservation Measures

The Polar Code

In January 2017, the International Maritime Organization's (IMO) Polar Code went into effect. Intended to protect unique environments and ecosystems of polar regions, the Code provided new requirements for vessel navigational safety and pollution prevention by addressing new ship design; operations and mariner training; and search and rescue capabilities. Years in the making, the Code applies to passenger and cargo ships >500 gt engaged in international voyages in polar regions (but does not apply to fishing vessels, pleasure yachts, or military vessels) (International Maritime Organization [IMO], 2014). At the time of this writing, the IMO's Sub-Committee on Ship Design and Construction is considering amendments to the Code to include recommended safety measures for fishing vessels ≥ 24 m in length operating in polar waters and pleasure yachts >300 gt (not engaged in trade)⁴.

The Polar Code was a landmark set of regulations and guidelines for limiting impacts from shipping. However, some maintain it might have established far more stringent protection

⁴<http://www.imo.org/en/MediaCentre/MeetingSummaries/MSC/Pages/MSC-100th-session.aspx>

measures (Friends of the Earth [FOE], 2016; Ocean Conservancy, 2017; Roach, 2018). Nonetheless, as an already IMO-adopted instrument, strengthening the Code's existing framework and its measures in response to more fully understood adverse effects would be commendable.

Routing Measures

Potential increases in north-south flowing vessel traffic through the Bering Strait prompted the IMO to adopt routing measures in the region to increase navigational safety. Jointly submitted to the IMO by the Russian Federation and United States and adopted by the IMO's Maritime Safety Committee in late-2017, the measure (International Maritime Organization [IMO], 2017) established six "two-way routes" and six precautionary areas (for all ships >400 gt, excluding fishing vessels) in the Bering Strait and Bering Sea between the Chukotskiy Peninsula and Alaskan coast. The adopted measure also includes Areas to be Avoided around St. Lawrence Island, King Island, and Nunivak Island (Hobson, 2018).

In its analysis of the routing measures, the U.S. Coast Guard indicated "increased cargo traffic, passenger ship traffic, adventure tourism traffic, oil and gas exploration, and research and scientific activities" would increase the likelihood of maritime casualties and threaten environments inhabited by endangered marine species and remote indigenous communities that rely on traditional subsistence activities (United States Coast Guard [USCG], 2014). Therefore, anticipated benefits of this action include helping ships avoid numerous hazardous shoals, reefs and islands; reducing "...risk of pollution or other damage to the marine environment, including national and international recognized habitat and species; and avoiding the key areas of fishing activities and areas of subsistence activities by local indigenous communities..." It is generally accepted that these measures will also contribute to the reduction of vessel strikes of large cetaceans such as bowhead (*Balaena mysticetus*), gray (*Eschrichtius robustus*), and North Pacific right (*Eubalaena japonica*) whales (Allen, 2014; Huntington et al., 2015).

However, extensive use of the international Unimak Pass and Bering Sea route by large vessels (Figures 2A–C), along with activities of the spatially diffuse commercial fishing industries (Figures 4A–C), may have significant consequences for biological communities occurring in this region. Numerous endangered mammal species occur in this area including bowhead and the highly depleted North Pacific right whales and other whale species. Critical habitat for right whales (National Oceanic and Atmospheric Administration [NOAA], 2008) and conservation zones for the endangered Steller sea lion (*Eumatopis jubatus*) has been established in this area (National Oceanic and Atmospheric Administration [NOAA], 1993). Therefore, east-west vessel traffic near the Aleutian Islands likely rivals or exceeds the threat of ship strikes of endangered marine mammals from the relatively smaller amount of traffic on north-south trips through the Bering Strait and Bering Sea. As such, inter-continental vessel routes near the Aleutian Islands should also be candidates for imposing conservation measures to minimize

impacts to marine mammals and sensitive ecosystems near the archipelago.

Oil Spill Contingency Planning

At this time, planning and preparation for a major oil/chemical spill in Arctic waters is inadequate. Cognizant of the deficiencies, several Arctic nations have met jointly or attempted independently to increase response and remediation readiness. Fortified and double-hulled tankers are routinely in use by oil companies and subsidiaries as a safeguard against spills. However, existing contingencies for such an event are almost certainly insufficient. International bodies such as the Arctic Council (Arctic Monitoring and Assessment Programme [AMAP], 2008; Arctic Council, 2009) and the IMO have highlighted and attempted to address these shortcomings. These efforts are commended, should be continued or accelerated, and where feasible, resources provided to prepare for the occurrence of a spill of significant magnitude.

CONCLUSION

Vessel operations were extensive in volume and diverse in the types (e.g., long-range shipping, fishing) and location of activity. The observed already substantial maritime activity is projected to increase. Our study period was too brief to demonstrate significant growth in maritime activities; instead, inter-annual variation prevailed. While receding ice coverages have created new opportunities for increased use of these waters, expansion of Arctic maritime traffic may not be tied solely to receding amounts of ice-covered waters. Decisions regarding utilization of new or expanded routes are likely to be a function of logistical and economic factors.

Vessel traffic volume is somewhat limited in some areas. However, maritime transport operations will likely experience the greatest growth in locations undergoing the most rapid increases in seasonally ice-free zones, which includes water bodies along the Northern Sea Route and the Northwest Passages. Increased use of these locations will be driven by assessments of economic feasibility weighed against inherent risks to hazardous high-latitude travel. These boundaries are currently being tested with real trials (both with and without ice breaker assistance) in locations with historically limited access. Cost/benefit ratios will shift with global demand for certain goods and resources (e.g., oil), and logistical costs may diminish as needs for ice-breaker assistance is diminished. A modest growth of the tourist cruise industry occurred during our study and will likely undergo additional growth as certain destinations become increasingly accessible. Commercial fisheries operations, including those engaged in stern trawler fisheries, are largely year-round in many locations and spatially vast primarily in the lower latitudes. By volume alone, these industries may have the greatest overall impact (e.g., bycatch, disruption of benthic communities) to Arctic marine biological processes. Therefore, considerations regarding ecosystem protection should include direct and indirect impacts from fishing activities.

Exact threats to Arctic marine ecosystems are not known with certainty especially as related to population levels impacts. However, increased use of this region by trans-Arctic shipment of goods, oil/gas exploration and other commercial enterprises is accompanied by concurrent risks to Arctic ecosystems. Limited supporting infrastructures and constraints of response capabilities in the case of a large oil spill suggest existing protective measures are probably inadequate and should be strengthened. AIS data have been used to support maritime security, vessel traffic monitoring, and regulatory functions. Coupled with baseline descriptions of the volume and spatial distribution of Arctic-wide commercial activities, the AIS can aid in characterizing trends in Arctic vessel operations and assessing potential threats to Arctic marine ecosystems. Only through monitoring of trends in vessel activities, particularly those areas where growth is most likely to occur, will assessments of impacts be possible. As understanding of maritime activity levels and concurrent environmental impacts improves, so should a strengthening of ecosystem protection measures.

DATA AVAILABILITY

All datasets generated for this study are included in the manuscript and/or the supplementary files.

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AUTHOR CONTRIBUTIONS

GS and JA helped to build the NOAA Fisheries AIS program, jointly conceived this analytical project, and worked collaboratively to complete it. JA conducted most of the data analysis. GS prepared most of the text.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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