

Article

The Spatiotemporal Pattern Evolution Characteristics of Ship Traffic on the Arctic Northeast Passage Based on AIS Data

Changrong Li , Zhenfu Li and Chunrui Song

College of Transportation Engineering, Dalian Maritime University, Dalian 110626, China;
lizhenfu@dlnu.edu.cn (Z.L.); ln_scr@163.com (C.S.)

* Correspondence: lcr891230@163.com

Abstract: Warming weather has led to melting sea ice, and increasingly complex global geopolitics has drawn more countries' attention to the Arctic. The Arctic Northeast Passage, as an emerging route connecting Eurasia, has seen a sharp increase in vessel activity. The period from 2015 to 2020, being a stable and undisturbed data period, is of significant theoretical importance for exploring the natural development of the Arctic Northeast Passage. The study found that the research period can be divided into three stages: from 2015 to 2017, the number of vessels grew slowly. In 2018 and 2019, the number of vessels and vessel activities saw significant growth, but an unexpected reverse growth occurred in 2020. Different types of vessels have unique activity characteristics and evolutionary patterns, influenced by the Arctic's unique geographical environment, abundant natural resources, deepening Sino-Russian cooperation, and increasing global trade supply and demand. The results of this study aim to provide policymakers with analysis based on the initial development stage of the route, offering data support for future policy formulation, route planning, and research on the navigation safety of vessels on the Arctic Northeast Passage.

Keywords: Arctic Northeast Passage; spatiotemporal patterns; AIS Data



Citation: Li, C.; Li, Z.; Song, C. The Spatiotemporal Pattern Evolution Characteristics of Ship Traffic on the Arctic Northeast Passage Based on AIS Data. *J. Mar. Sci. Eng.* **2024**, *12*, 1508. <https://doi.org/10.3390/jmse12091508>

Academic Editor: Eugen Rusu

Received: 11 July 2024

Revised: 23 August 2024

Accepted: 30 August 2024

Published: 1 September 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

As global warming leads to the melting of Arctic sea ice, seasonal Arctic sailing becomes possible [1,2]. Maritime traffic is a complex, dynamic, and multi-layered system. By analyzing the characteristics of the maritime system and the factors affecting its evolution, we can optimize maritime traffic and reduce the probability of maritime traffic accidents. This helps ensure maritime traffic safety, reduce marine environmental pollution, and improve the overall efficiency of maritime vessels. In 2018, the Chinese government issued the white paper “China’s Arctic Policy”, proposing to rely on the development and utilization of Arctic routes to jointly build the “Polar Silk Road” with all parties. Studying the evolution of Arctic maritime traffic patterns can support the formulation of China’s Arctic shipping plans, reducing dependence on traditional Suez Canal routes.

The Arctic Northeast Passage (NEP) has garnered widespread attention due to its potential to connect the two continents of Eurasia within a shorter route. Global climate change has accelerated the melting of Arctic ice, making this route gradually navigable in summer [3]. As the route opens up, vessel traffic activity has increased, bringing not only commercial opportunities but also challenges in environmental protection and route management [4]. Therefore, it is particularly important to use Automatic Identification System (AIS) data to analyze the spatiotemporal evolution of vessel activities on the NEP. The Arctic Northeast Passage is a sea route that traverses the northern seas of Russia, connecting Asia and Europe via the Arctic. Early research concentrated on assessing the economic viability and navigability of the NEP. Smith and Stephenson explored the commercial potential of the NEP by comparing the time cost-effectiveness of traditional routes and the NEP [3]. Wu et al.’s research indicates that the NEP offers potential for maritime

transport between Europe and Asia due to longer sailing seasons from global warming, but despite lower CO₂ emissions and costs for larger vessels, it remains less economically viable than the Suez Canal Route, especially for year-round operations before 2065 [5]. Zhang et al. proposed a risk assessment-based method to evaluate the economic benefits of the NEP and emphasized the importance of risk management in route planning [6]. Petrov and Tulaeva analyzed the potential impact of Arctic route development on local community economies [7]. Ol'khovik et al. analyzed the shipping development trends of the NEP, noting that while the number of ships remains stable, the seasonal variation in ship navigation has significant impacts on the safety and efficiency of NEP shipping [8]. Koyama et al. utilized AIS and TOPAZ4 data to propose a non-heuristic optimal route search method, demonstrating the potential of data-driven approaches in Arctic route planning [9]. Research on the environmental impact of vessel activities on the NEP usually focuses on the disruption of the Arctic ecosystem by shipping activities. Kim and Choi studied the impact of Northern Sea Route (NSR) activities on noise pollution in Arctic waters and proposed strategies to reduce shipping noise [10]. Silber and Adams quantified the impact of vessels on Arctic waters using AIS data [11]. However, methodologies and data acquisition for environmental impact assessment still face challenges, especially in extreme and remote areas [12]. Research on route safety mainly focuses on the operational safety of vessels under extreme climatic conditions. Studies like those by Eguíluz et al. analyzed the risks of the global shipping network using AIS data, but existing research on the safety management of the NEP has yet to fully cover all potential safety risks [13], such as narrow straits [14], complex geopolitical [15] and natural environments, etc. Lee and Kim dynamically simulated the ice conditions of the NEP and assessed the safety risks under different climate change scenarios [16]. Vanhatalo et al. used Bayesian analysis to assess the probability of ships getting trapped in ice conditions, providing a scientific basis for route safety management [17]. Yang et al. systematically reviewed the research literature on Arctic navigation safety, summarized the shortcomings of existing studies, and provided future prospects [18]. In studies on the impact of Arctic international laws and policies on Arctic routes, there is often a lack of in-depth analysis of the differences between the legal systems of different countries and the issues of actual enforcement [13]. Lynch et al. discussed the application and challenges of international law in managing Arctic routes [19]. Chen and Huang analyzed the policy differences of various countries regarding the right to use Arctic routes and proposed recommendations for enhancing international cooperation [20]. International cooperation plays a crucial role in coordinating the interests of Arctic countries and standardizing shipping operations, but it still needs to be strengthened [21]. Existing studies rarely address the spatiotemporal patterns of vessel traffic on the NEP; this study aims to propose strategies for improving navigation management and route safety by deeply analyzing AIS data, with a particular focus on the safety, economic benefits, and environmental impacts of the route.

Since 2010, vessel activity along the NEP has begun to increase significantly. The main reason is the melting of Arctic ice, which has made the route more navigable for most of the year. The development of icebreaker technology and the growing international interest in Arctic resources have further influenced the increase in maritime activities. Especially since 2015, with Russia's initiatives to promote the route as a viable commercial shipping pathway, vessel activity through the NEP has significantly increased. The period from 2015 to 2020 serves as an important baseline for understanding long-term trends in Arctic navigation. This timeframe captures the early stages of significant increases in shipping through the NEP, influenced by the melting of Arctic ice and global shipping dynamics. By analyzing this period, researchers can provide a deeper historical context for the changes observed in navigation patterns later on. With the impact of the COVID-19 pandemic in 2020, the pandemic widely disrupted global shipping and trade routes. Studying the period before the COVID-19 pandemic provides insights into the natural progression and growth of vessel activity on the NEP, free from the external disruptions caused by the pandemic, thereby offering a clearer understanding of the potential trends and influencing factors of

vessel activity on the NEP. From 2015 to 2020, significant developments occurred in the infrastructure and regulatory policies affecting the NEP. For example, China and Russia deepened their cooperation on Arctic development projects. Analyzing this period helps us understand the policy framework that supported the subsequent increase in shipping activities. During this period, there were advancements in navigation technology and icebreakers, as well as modifications of vessels for ice-bound waters. Research during this period helps understand how technological and operational advancements impacted vessel activities on the NEP, laying a foundation for future studies. Finally, from an economic and strategic perspective, significant geopolitical changes occurred from 2015 to 2020, including the expansion of the Belt and Road Initiative to the Arctic Maritime Silk Road. Studying vessel activities during this period provides insights into the economic strategies of key stakeholders like China and Russia and their long-term impact on global Arctic trade. The outbreak of the Russia-Ukraine war in 2022 significantly affected Russian maritime trade, and the ongoing conflict has introduced non-natural factors influencing Arctic vessel activities. In summary, from the current perspective, the NEP from 2015 to 2020 provides a more stable and undisturbed dataset, allowing for the analysis of growth, challenges, and strategic developments related to the NEP without the abnormal impacts of political changes due to the COVID-19 pandemic and the subsequent Russia-Ukraine war after 2020. This makes the period from 2015 to 2020 a more valuable timeframe for understanding the potential and sustainability of Arctic maritime routes. Against this backdrop, studying the evolution patterns and influencing factors of vessel activities on the NEP from 2015 to 2020 holds significant practical relevance. This paper constructs an Arctic vessel AIS database from 2015 to 2020, utilizing quantitative models and ArcGIS spatial analysis techniques to analyze the temporal and spatial characteristics of Arctic vessel distribution, speed, size, and density, revealing the patterns of Arctic vessel activities and providing support for the planning, safety assurance, and management of Arctic vessel routes.

Although maritime traffic and maritime transport both involve vessel activities on water, they have essential differences, mainly in terms of purpose, scope, and management: (1) Purpose and Scope: Maritime traffic is defined as the movement and flow of vessels in the ocean or other waters, similar to traffic systems on land. This includes all types of vessel movements on water, regardless of their purpose. Maritime transport is a subset of maritime traffic, specifically referring to the activities of transporting goods or people by ships on the ocean. It is one of the most important modes of transport in international trade, crucial to the global economy. (2) Management and Regulations: Maritime traffic mainly focuses on the safety and efficiency of vessel navigation, involving a wide range of rules, such as those by the International Maritime Organization (IMO), Vessel Traffic Services (VTS), and the Automatic Identification System (AIS). Maritime transport, on the other hand, emphasizes the management of commercial logistics and transport services, including cargo handling, route planning, vessel maintenance, and economic efficiency. The NEP is still in its early development stages; studying maritime traffic is more practical than studying maritime transport. This is mainly because it is crucial to comprehensively understand and assess the potential impacts, safety, feasibility, and environmental factors of the route. Research on maritime traffic can provide comprehensive information on route safety, risk factors, route selection, and management. This is crucial for ensuring the safe operation of routes, especially in extreme and sensitive environments like the Arctic. Research on maritime traffic can also lay a solid foundation for understanding the impact of Arctic vessels on the fragile Arctic ecosystem, providing data support for the formulation of sustainable development policies. Maritime traffic also involves route operational efficiency, identifying optimal routes and potential bottlenecks through traffic flow analysis. For an emerging route, the formulation of regulations and policies is also crucial; research on maritime traffic helps understand and construct the legal and policy framework in this area, ensuring the legal and efficient operation of the route. In summary, this paper focuses on studying the evolutionary characteristics of maritime traffic on the NEP, identifying four types of vessels as the research subjects through preliminary data

analysis: cargo ships, tankers, fishing vessels, and passenger ships. Other vessel types are currently relatively few in number; as the route develops, they will become targets for future research. For an emerging route like the NEP, comprehensive research on maritime traffic will provide a solid foundation, offering critical support for the development and operation of the route. As the route matures and commercializes, specific research on maritime transport will become more important to optimize operational efficiency and enhance commercial benefits.

2. Materials and Methods

2.1. Research Area

Typically, the Arctic region is divided into three routes: the NEP, the Northwest Passage (NWP), and the Transpolar Sea Route (TSR). Parts of the NEP have lighter ice conditions in the summer, making it more navigable and with a higher number of vessels compared to the NWP and the TSR. The NEP connects East Asia and Europe, and its geographical location holds significant strategic importance for the future development of international shipping. Therefore, this study focuses on all vessels within the scope of the NEP. The geographical coordinates of the study area are 65° N to 90° N, 15° W to 175° E. It includes the Bering Sea, East Siberian Sea, Laptev Sea, Kara Sea, Barents Sea, and Norwegian Sea, as shown in Figure 1. Different sea areas have distinct characteristics and different navigation requirements, making it necessary to study the activity patterns and evolution of vessels within the NEP region.

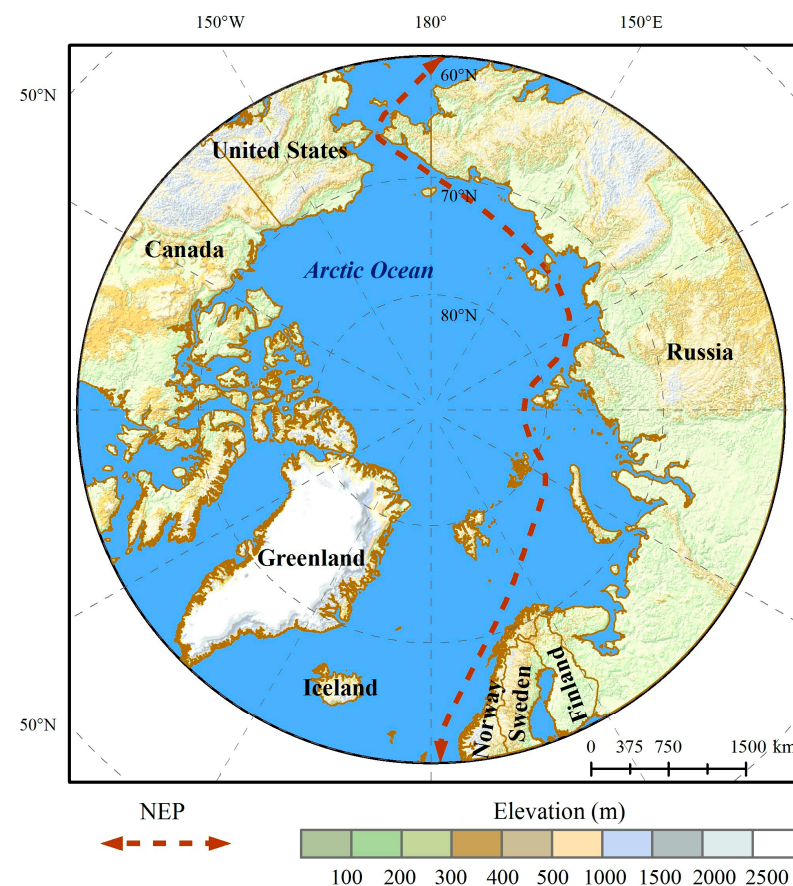


Figure 1. Schematic diagram of the Arctic NEP.

2.2. Data Source and Processing

The AIS vessel data used in this study were purchased by the research group. AIS data include Maritime Mobile Service Identity (MMSI), vessel dimensions, speed, course over ground, and latitude and longitude. This study selected AIS data from 1 January 2015 to 31

December 2020; data storage capacity is about 87.9 G. During data processing, the raw AIS vessel data were first cleaned by deleting vessel data corresponding to erroneous MMSI, and by removing duplicate, missing, or unreasonable data records. For vessel records where the speed is consistently 0 or excessively high (>23 knots) and latitude and longitude change, the erroneous speed is replaced by calculating the average speed between two consecutive pieces of information for the same vessel. AIS vessel data in the Arctic region, this study adopts a uniform sampling method. Starting from 1 January 2015, data were sampled every three days and for the same vessel every 15 min each day, selecting 122 days of data per year, finally, 13.32 G AIS data were obtained. The vessel types categorized include fishing vessels, passenger ships, tankers, and cargo ships, while other vessel types are temporarily excluded. To further analyze the spatial distribution characteristics of vessels in the Arctic region, this study divides the study area into grids with a scale of 50 km by 50 km, resulting in 15,049 grids.

A comparison of the number of vessel voyages on the NEP from 2015 to 2020 to preliminarily delineate the evolution stages of vessel activities during this period is shown in Figure 2.

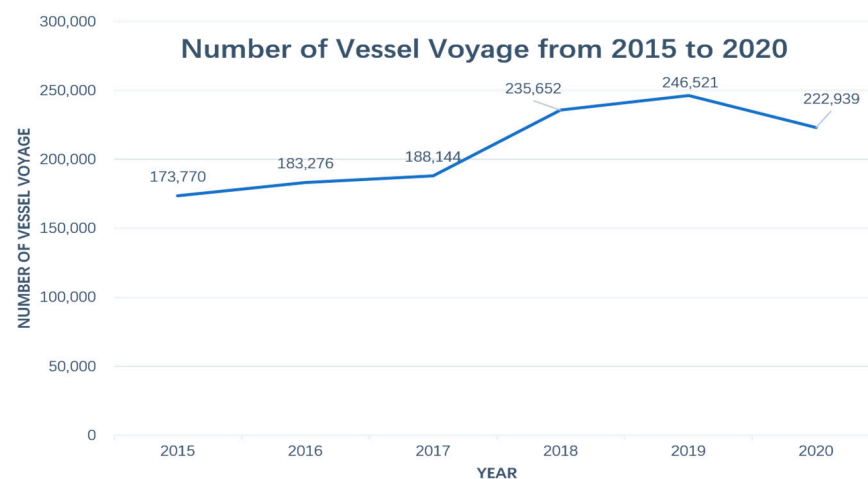


Figure 2. Number of Vessel Voyages.

As shown in Figure 2, from 2015 to 2017, the number of vessel voyages increased slowly, with the number of vessel voyages between 17,000 and 19,000 each year, which can be categorized as the first stage. From 2018 to 2019, the growth rate of vessel voyages increased significantly, with the number of vessel voyages around 23,000 to 25,000, which can be classified as the second stage. In 2020, the number of vessel voyages dropped to 222,939, showing reverse growth, which can be classified as the third stage. This paper selects data from the first year of each of the three stages to analyze the characteristics and influencing factors of the evolution of vessel activities on the NEP.

2.3. Methods

Based on the NEP AIS data, the temporal characteristics of vessel traffic flow and taking monthly and seasonal time series as the time series by calculating the vessel density, supplemented by vessel speed and vessel size, and screening and classifying the vessel tracks to extract the centerline of the vessel's main track, a research indicator is identified to analyze the spatial characteristics of the vessel traffic flow in the NEP [22].

Vessel Flow Calculation Method

Vessel flow refers to the number of vessels passing through a certain location in a certain water area per unit of time. Its value can reflect the traffic flow and busyness of the water area. The larger the vessel flow, the more complex the vessel traffic flow. Therefore,

vessel flow is an important indicator to characterize maritime navigation safety and vessel scheduling. The statistical model is as follows:

$$\bar{Q} = \sum_{i=1}^n Q_i / n \quad (1)$$

$\bar{Q}$ is the average traffic volume of vessels during a certain period of time; Q_i is the traffic volume at a certain moment i ; n is time.

3. Results

3.1. Spatiotemporal Distribution Characteristics of Vessel Numbers

3.1.1. Monthly Change in Number of Vessels

The monthly distribution of traffic flow density for four typical types of vessels—fishing vessels, cargo ships, passenger ships, and tankers—on the NEP is shown in Figure 3. Traffic flow density reflects the number of vessels on the NEP to a certain extent. It can be observed that the number of these four types of vessels on the NEP has been increasing annually, with their numbers in the summer far exceeding those in other seasons, especially for fishing vessels and cargo ships. Among the Arctic maritime vessel numbers, fishing vessels outnumber the combined total of cargo ships, passenger ships, and tankers (as shown in Table 1). Further analysis reveals that all four types of vessels exhibit strong temporal variation patterns. The monthly variation patterns of the four types of Arctic maritime vessels are generally consistent. In 2015, the numbers of all four types of vessels were relatively low, but after 2018, their numbers increased significantly. January to June is the low peak period for the numbers of the four types of vessels, reaching the annual lowest point in June. From July, the numbers of the four types of vessels increase significantly, reaching the annual peak in September. From October to December, the numbers slowly decrease but remain much higher than in January to June.

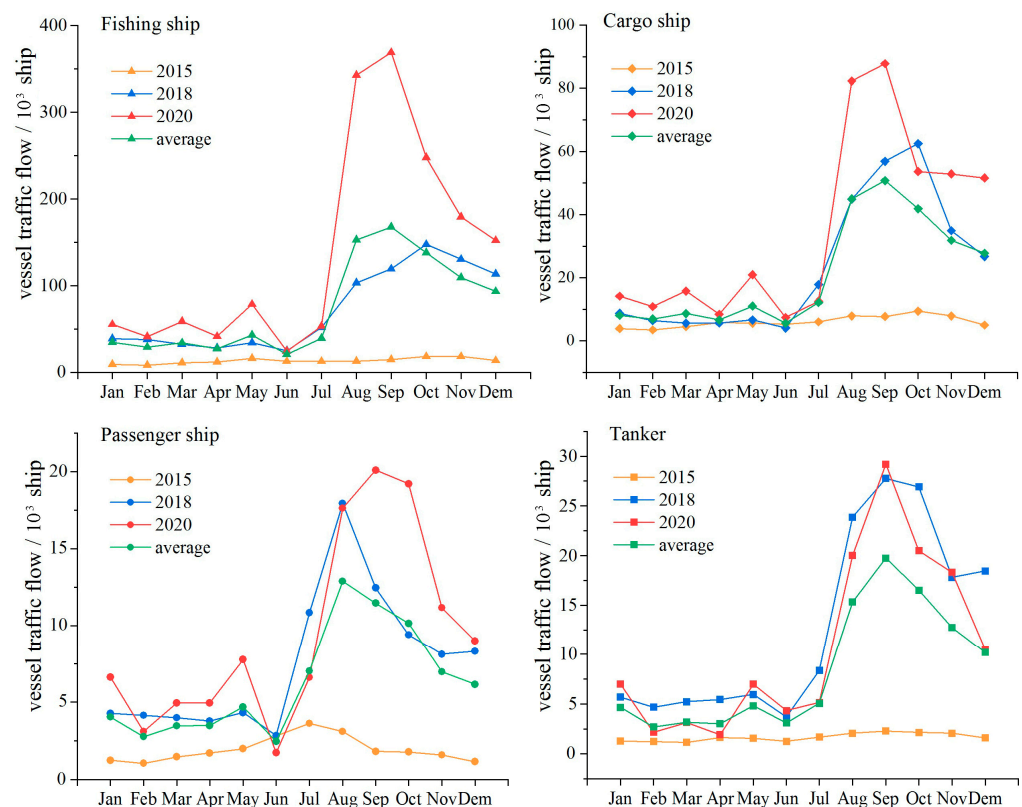


Figure 3. Monthly distribution of traffic flow density on the Arctic Northeast Passage.

Table 1. Quarterly vessel numbers by type.

Year	Season	Cargo Ship		Tanker		Fishing Ship		Passenger Ship	
		Numbers of Ship	Voyage Number	Numbers of Ship	Voyage Number	Numbers of Ship	Voyage Number	Numbers of Ship	Voyage Number
2015	Winter (December–February)	228	7598	65	2853	425	22,954	33	1947
	Spring (March–May)	197	8119	65	2815	434	27,162	40	2419
	Summer (June–August)	252	10,248	87	3430	349	26,053	60	5327
	Autumn (September–November)	277	13,702	82	4139	364	32,385	39	2619
	Total	474	39,667	141	13,237	538	108,554	68	12,312
2018	Winter (December–February)	350	8676	159	5076	942	35,009	113	5137
	Spring (March–May)	98	5725	35	4316	418	29,330	38	4533
	Summer (June–August)	408	13,896	210	7161	705	35,113	145	8155
	Autumn (September–November)	606	19,506	239	7427	1028	40,325	137	7267
	Total	822	46,803	377	23,980	1327	139,777	215	25,092
2020	Winter (December–February)	302	2870	87	739	922	14,603	59	1241
	Spring (March–May)	154	1788	44	458	501	10,599	40	1176
	Summer (June–August)	428	3989	107	1259	1563	19,711	120	5729
	Autumn (September–November)	587	13,136	144	3077	1953	79,783	91	1781
	Total	860	22,783	221	5533	2343	124,696	148	9927

3.1.2. Quarterly Change in the Number of Vessels

Table 1 presents the seasonal variation statistics for the number of different types of vessels on the Arctic Northeast Passage. “Unique vessel” indicates each vessel (MMSI number) counted only once, while “voyage” indicates a single trip counted as one voyage. From the table, it can be seen that the number of unique cargo ships nearly doubled from the first stage in 2015 to the second stage in 2018. However, the number of voyages did not increase as much as the number of unique vessels. Some cargo ships joined the Arctic Northeast Passage due to climate and policy reasons but did not have many voyages. From 2018 to the third stage in 2020, the number of unique cargo ships remained relatively stable, but the number of voyages decreased, likely due to the global economic downturn caused by the pandemic in 2020. The trends for tankers and passenger ships across the three stages are generally similar to those of cargo ships, except that the number of voyages from the first to the second stage increased almost as much as the number of unique vessels. Unlike the other three types of vessels, the number of unique fishing vessels showed a continuous doubling trend from the first stage in 2015 to the third stage in 2020. A large number of fishing vessels have entered the Arctic Northeast Passage, closely related to the warming climate and melting sea ice, with the pandemic having very little impact on seafood. From a seasonal perspective, except for passenger ships, which are most numerous in summer, the other three types of vessels reach their highest numbers in autumn. September is the peak month for vessel activities on the Arctic Northeast Passage, leading to a significantly higher number of vessels in autumn compared to other seasons. The high demand for summer tourism makes the higher number of passenger ships in this season reasonable. In Table 1, the overall trend from the first stage to the second stage shows significant growth, but this trend halted from the second stage to the third stage, indicating that the pandemic’s impact on the global economy also affected the Arctic Northeast Passage region.

3.1.3. Spatial Distribution of Vessels

As shown in Figure 4, over time, the distribution range of various types of vessels on the NEP has gradually expanded. Initially, tankers operated in small numbers in the Norwegian Sea and Barents Sea, but later, their activity extended widely throughout the entire NEP, reaching as far east as the East Siberian Sea. Influenced by ocean currents, most fishing vessels operate in the Norwegian Sea and Barents Sea. Due to the development of tourism, most passenger ships operate between the Svalbard archipelago and Norway. The

activity range of cargo ships has gradually moved to the Laptev Sea and East Siberian Sea, thanks to Russia's construction and policy support for its eastern ports.

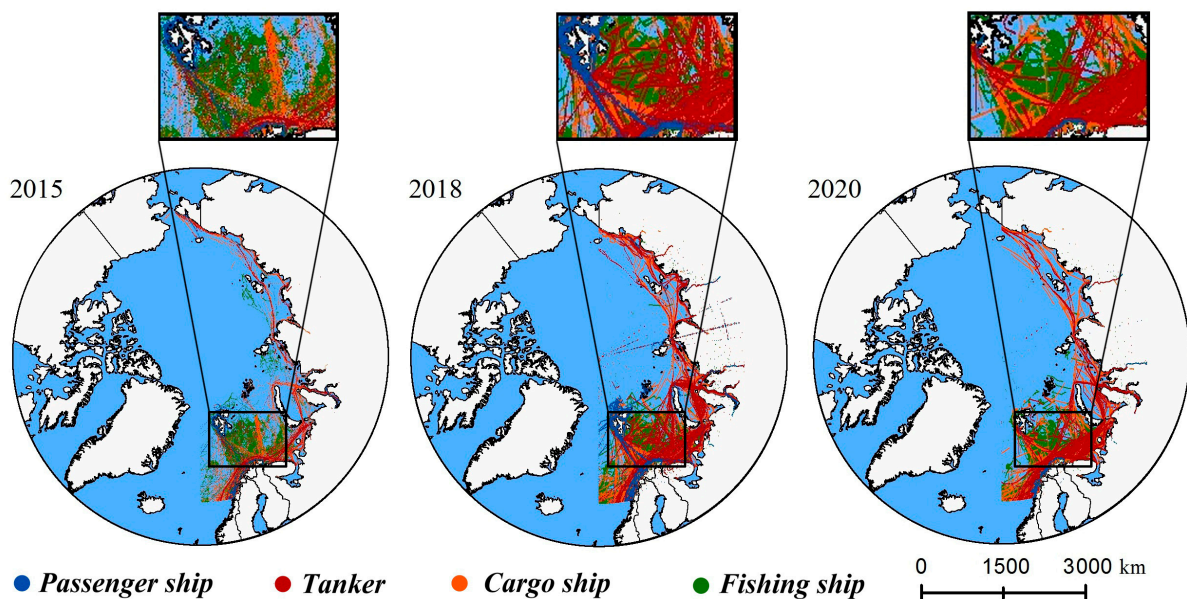


Figure 4. Annual distribution of ship types on the Arctic Northeast Route.

3.1.4. Spatial Distribution of Traffic Flow Density

As shown in Figure 5, the spatial distribution of traffic flow density can show the areas where ships tend to gather on the Arctic Northeast Passage, which plays a vital role in analyzing navigation safety. Regarding vessel density in the Arctic, the entire NEP had a similar overall density in 2015 due to the low number of vessels. By 2018, vessel density increased significantly in the Norwegian, Finnish, and Swedish waters, with denser areas gradually approaching the Arctic center. Some areas in the Kara Sea also reached a density of over five vessels per hour, and the high-density area gradually extends eastward. In 2020, the area with a density greater than five vessels per hour further expanded, showing a significant change compared to 2015.

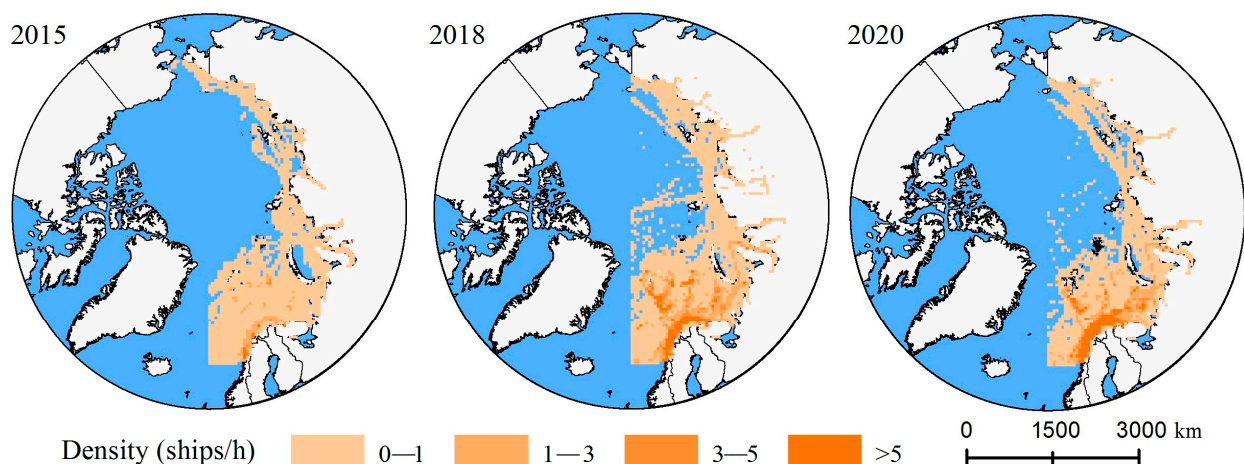


Figure 5. Annual density of ships on the Arctic Northeast Route.

3.2. Spatiotemporal Distribution Characteristics of Vessel Speed

3.2.1. Temporal Distribution Characteristics of Vessel Speed

A statistical analysis of vessel speeds in the Arctic region was conducted using ArcGIS 10.7 spatial analysis tools. As shown in Table 2, the results indicate that fishing vessels

primarily operate at medium to low speeds, with the proportion of low-speed fishing vessels gradually increasing over time. Cargo ships primarily operate at medium to high speeds; however, the proportion of low-speed cargo ships is increasing year by year. Tankers primarily operate at medium to high speeds, and the proportion of high-speed tankers has increased annually. Before 2020, passenger ships mainly operated at high speeds; nevertheless, the proportion of low-speed fishing vessels has increased significantly in 2020.

Table 2. Proportion of average speeds of various vessel types in the Arctic Northeast.

Vessel Type	2015				2018				2020			
	Low Speed (0–4 kn)	Medium Speed (4–8 kn)	Mid-High Speed (8–12 kn)	High Speed (12–23 kn)	Low Speed (0–4 kn)	Medium Speed (4–8 kn)	Mid-high Speed (8–12 kn)	High Speed (12–23 kn)	Low Speed (0–4 kn)	Medium Speed (4–8 kn)	Mid-High Speed (8–12 kn)	High Speed (12–23 kn)
Fishing ship (%)	52.307	24.302	21.444	1.947	60.951	20.624	16.271	2.154	74.404	14.714	9.668	1.213
Cargo ship (%)	14.810	16.111	57.268	11.811	26.743	15.297	45.245	12.716	44.275	12.080	34.317	9.328
Tanker (%)	20.966	16.532	42.622	19.879	27.572	14.548	35.421	22.459	24.972	12.580	35.050	27.399
Passenger ship (%)	11.871	8.922	31.787	47.420	18.500	8.360	31.327	41.813	51.616	8.744	21.694	17.946

3.2.2. Spatial Distribution Characteristics of Vessel Speed

As shown in Figure 6, The NEP spans many sea areas, and vessel speeds vary significantly across these regions. In the Norwegian Sea, vessel speeds are mostly between 8–12 knots, while in the Barents Sea, they are mostly below 8 knots. In the Kara Sea, Laptev Sea, East Siberian Sea, and Chukchi Sea, vessel speeds near the coast are slower, likely due to the extensive distribution of coastal ice and numerous shoals, and they predominantly have medium speeds, with a few high-speed vessels. The central sea areas have many straits and complex navigation environments, which may be why vessel speeds cannot be too fast. In the northern sea areas, there are more high-speed vessels. During the ice-free period in summer, the navigation environment is better, and vessel speeds are relatively faster.

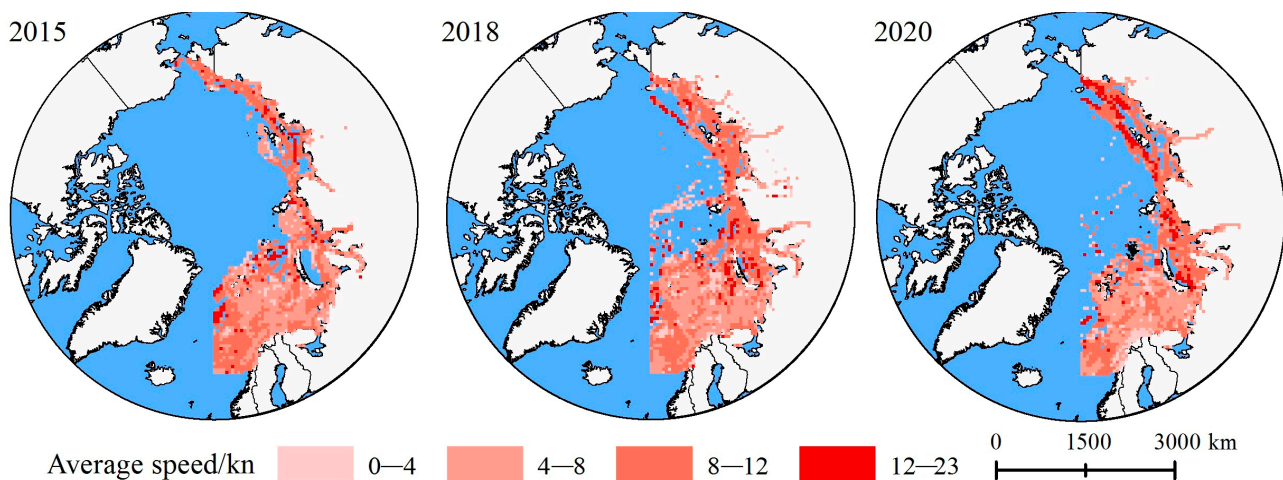


Figure 6. Annual distribution of ship speeds on the Arctic Northeast route.

3.3. Spatiotemporal Distribution Characteristics of Vessel Size

3.3.1. Temporal Distribution Characteristics of Vessel Size

The classification of various vessel types in the NEP region was conducted based on the “International Ship Classification”. From Table 3, before 2020, fishing vessels were mainly medium to large-sized ships with lengths between 20–80 m, accounting for about 75%. Over time, the proportion of small vessels under 20 m gradually increased, reaching

54.4% by 2020, while the number of mega fishing vessels remained low, consistently in the single digits. It can be seen that fishing vessels show a trend of decreasing in size, while cargo ships and tankers show a trend of increasing in size. The size of passenger ships remains relatively stable, with most being medium to large-sized.

Table 3. Classification statistics of vessel sizes by type on the Arctic Northeast Passage.

Vessel Type		2015				2018				2020			
		Small	Medium	Large	Mega	Small	Medium	Large	Mega	Small	Medium	Large	Mega
Fishing ship	Length (m)	0–20	20–50	50–80	>80	0–20	20–50	50–80	>80	0–20	20–50	50–80	>80
	Proportion (%)	17.261	32.864	47.641	2.234	19.701	27.432	46.332	6.535	54.559	20.864	22.115	2.461
Cargo ship	Load (10 ⁴ t)	0–0.5	0.5–2	2–5	>5	0–0.5	0.5–2	2–5	>5	0–0.5	0.5–2	2–5	>5
	Proportion (%)	54.665	29.025	9.232	7.078	40.458	42.709	9.921	6.912	49.404	35.068	7.525	8.002
Passenger ship	Length (m)	0–50	50–100	100–150	>150	0–50	50–100	100–150	>150	0–50	50–100	100–150	>150
	Proportion (%)	16.314	52.213	26.679	4.794	22.991	40.479	33.151	3.380	39.992	42.471	17.280	0.257
Tanker	Load (10 ⁴ t)	0–1	1–5	5–10	>10	0–1	1–5	5–10	>10	0–1	1–5	5–10	>10
	Proportion (%)	42.506	26.764	15.128	15.601	31.475	22.015	24.223	22.287	28.933	14.403	22.762	33.902

3.3.2. Spatial Distribution Characteristics of Vessel Size

As shown in Figure 7, initially, in 2015, small fishing vessels were mostly distributed in the coastal waters of Norway, Sweden, and Finland, regardless of the season, but the scope of activities is limited. In 2018 and 2020, the activity locations of small fishing vessels remained relatively stable, and their activity range gradually moved away from the coast. Most medium-sized fishing vessels were distributed in the waters between Norway, Sweden, Finland, and the Svalbard archipelago. In the winter of 2020, a small portion of medium-sized fishing vessels appeared in the coastal waters of the Kara Sea. Large fishing vessels were mainly distributed in the offshore waters around the Svalbard archipelago and Franz Josef Land archipelago. In summer and autumn, large fishing vessels appeared in the Kara Sea and Laptev Sea. Mega fishing vessels were sparsely distributed in the central offshore areas, with almost none in the winter of 2015 and small numbers present throughout the year in 2018 and 2020.

As shown in Figure 8, in 2015, small tankers were mainly primarily distributed in the coastal waters of Norway, Sweden, and Finland. In summer and autumn, medium to large tankers with a deadweight tonnage of 50,000 to 100,000 tons were spread across the entire NEP. Mega tankers were only active in the Norwegian Sea and Barents Sea. In the spring and winter of 2018, small tankers were mainly concentrated in the coastal waters of Norway, Sweden, and Finland, while medium to mega tankers were mainly in the Norwegian Sea, Barents Sea, and Kara Sea. In summer and autumn, small tankers appeared not only in their spring and winter locations but also in the coastal areas along the entire NEP. Medium to mega tankers were spread across the entire NEP. Nevertheless, the distribution of small to large tankers narrowed in 2020, while mega tankers further expanded their range of activities.

Overall, the size of fishing vessels has gradually decreased over time, and by 2020, small fishing vessels had become the most prevalent type in the NEP region. Cargo ships show a slow increasing trend in size. While they have mainly been less than 50,000 tons, the number of cargo ships in the 50,000 to 200,000 tons range significantly increased in 2018 and 2020. The size of tankers has significantly increased, and over time, the number of mega tankers over 100,000 tons has noticeably grown throughout the Arctic region. The size of passenger ships has remained relatively stable, with medium-sized passenger ships (50–100 m) being the most common. Only in 2020 did the number of small passenger ships significantly increase, primarily concentrated in the coastal waters of Norway, Sweden, and Finland.

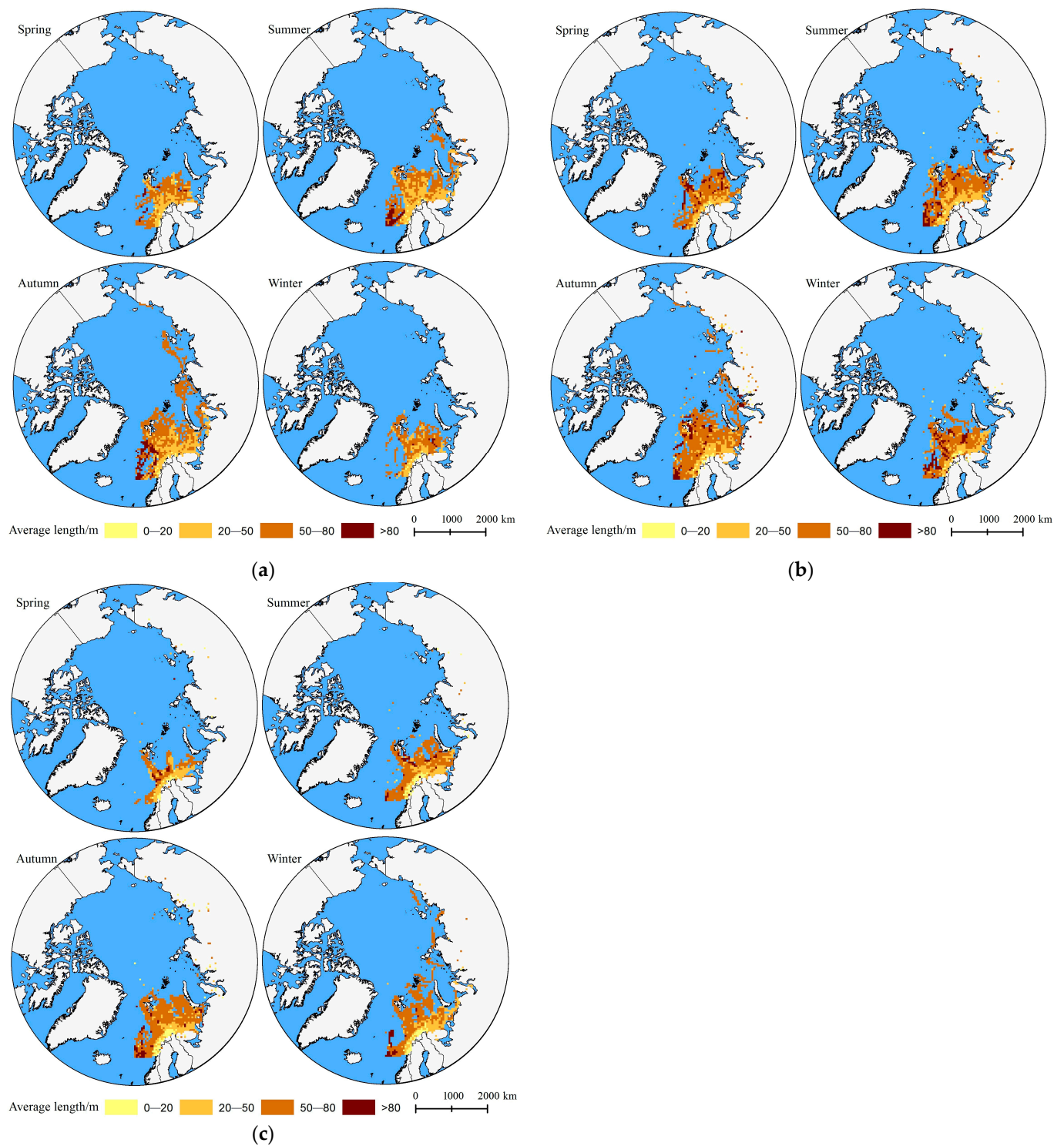


Figure 7. Seasonal distribution of fishing vessel length: (a) represents 2015; (b) represents 2018; (c) represents 2020.

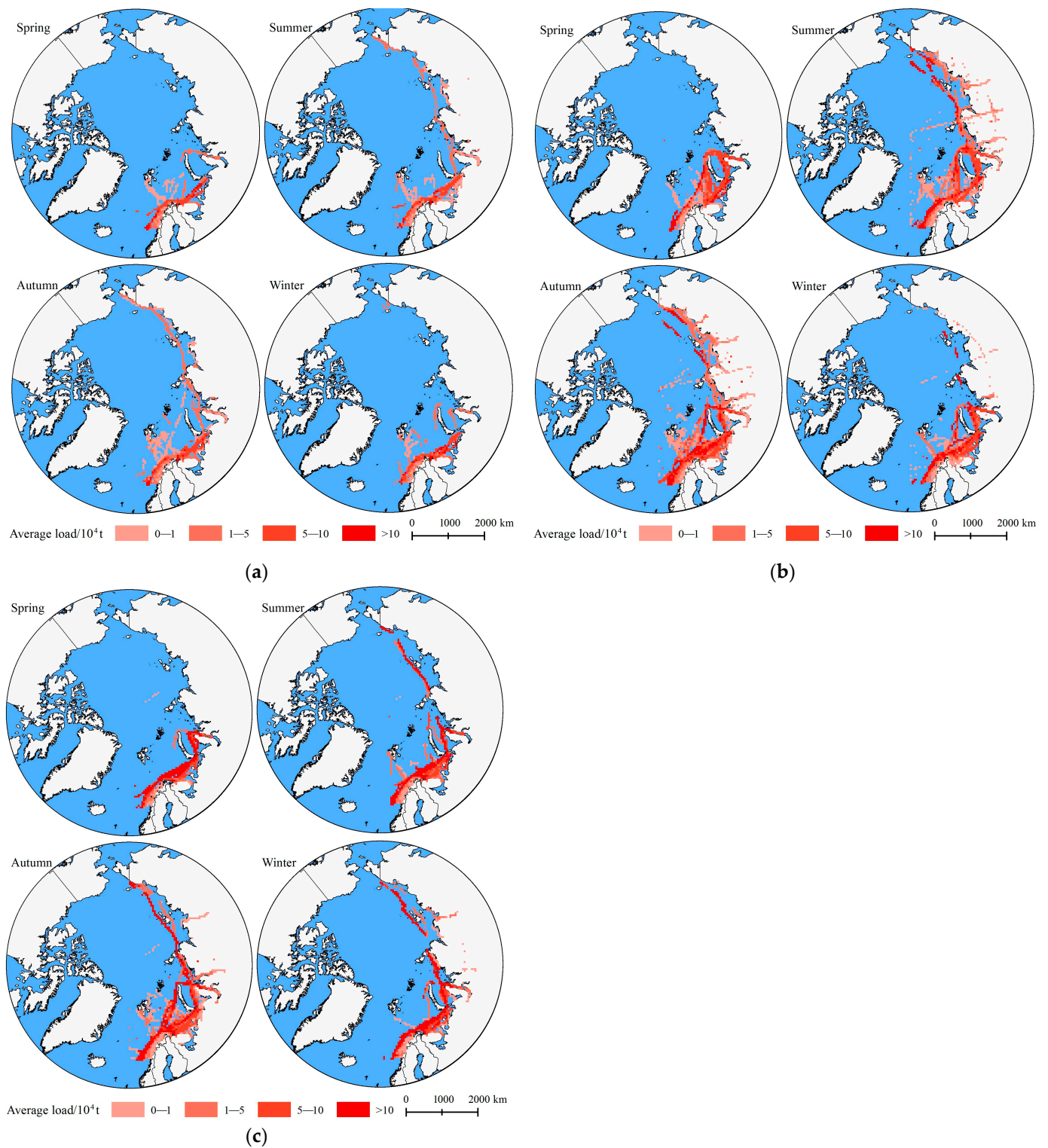


Figure 8. Seasonal distribution of oil wheel load capacity: (a) represents 2015; (b) represents 2018; (c) represents 2020.

3.4. Spatiotemporal Distribution Characteristics of Vessel Trajectories

From Figure 9, it can be seen that in 2015, vessel trajectories on the NEP were mainly concentrated in the Barents Sea and Norwegian Sea during spring and winter, primarily involving passenger ships and fishing vessels. In the summer and autumn of 2015, vessel trajectories extended to the Kara Sea, Laptev Sea, and East Siberian Sea, with denser trajec-

tories in autumn compared to summer. In 2018, vessel trajectories increased significantly compared to 2015, with a broader sea area coverage. In spring, vessel trajectories appeared only in the Norwegian Sea, Barents Sea, and Kara Sea. In summer, autumn, and winter, vessel trajectories were present across the East Siberian Sea, Laptev Sea, Kara Sea, and Barents Sea along the entire NEP. Summer and autumn trajectories approached the center of the Arctic Ocean, while winter trajectories were relatively sparse compared to summer and autumn. In 2020, the global COVID-19 pandemic affected vessel numbers and activities to some extent. However, the track density in the Norwegian Sea, Barents Sea, and Kara Sea increased.

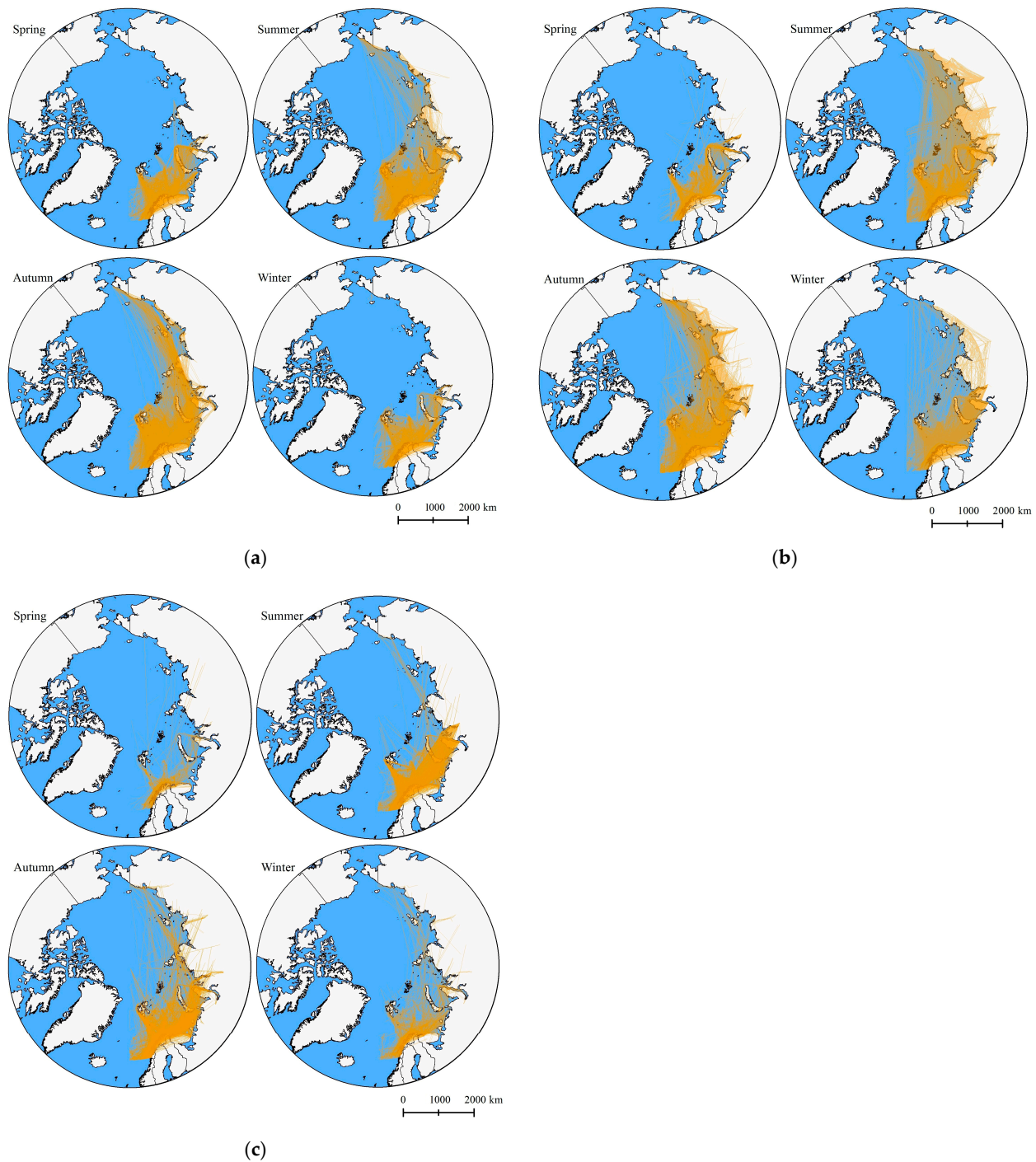


Figure 9. Seasonal distribution of ship trajectories on the Arctic Northeast route: (a) represents 2015; (b) represents 2018; (c) represents 2020.

3.5. Analysis and Summary

Based on the AIS data of vessels on the NEP from 2015, 2018, and 2020, and using ArcGIS 10.7 spatial analysis tools, the spatiotemporal distribution characteristics of fishing vessels, cargo ships, tankers, and passenger ships were explored, and the factors affecting their evolution were analyzed. The results show the following:

In 2015, the number of various types of vessels was relatively low. As the climate warmed and navigable time increased, along with the introduction of national policies, the number of all types of vessels has been steadily rising. Overall, various types of vessels are greatly influenced by seasonal and climate changes. Every year, after the ice starts to melt in June, the number of vessels begins to rise, peaking in August and September. After October, as some areas start to freeze, the number of vessels gradually decreases. Cargo ships, tankers, and passenger ships experienced a significant acceleration in growth starting in the second stage (2018) against the backdrop of deepening Arctic cooperation between China and Russia. Due to the global pandemic, the international economy weakened with the exception of seafood, and the number and activity frequency of other vessel types declined compared to the second stage. Especially the number of tankers, which was lower than in the first stage (2015 to 2017). One reason was the decreased demand for crude oil due to the COVID-19 pandemic, and another was the oil price collapse caused by disputes between Russia and Saudi Arabia over production cuts, which reduced global oil supply and significantly impacted crude oil transportation. Additionally, the International Maritime Organization (IMO) implemented stricter ship emission regulations in 2020 (IMO decided to enforce a global 0.5% sulfur cap starting in 2020). These factors combined led to a reverse growth in the number of cargo ships, tankers, and passenger ships in 2020.

Fishing vessels on the NEP are mainly medium to small-sized, primarily distributed in the Norwegian Sea and Barents Sea. The proportion of small fishing vessels is increasing yearly, with most operating near Norway, Sweden, Finland, and Murmansk ports and at relatively slow speeds. Medium to large fishing vessels mostly operate in the waters around the Svalbard archipelago at relatively higher speeds. Most cargo ships are medium to small-sized vessels under 20,000 tons. The proportion of medium-sized cargo ships (5000–20,000 tons) is increasing yearly, mostly operating in nearshore channels and usually traveling at speeds of 8–12 knots. The size of tankers is gradually increasing, with the proportion of small tankers decreasing and that of large and mega tankers increasing. Tankers typically travel at speeds of 8–12 knots, but when navigating the East Siberian Sea, speeds can reach 12–23 knots. The East Siberian Sea offers more open waters and a reduced sea ice threat compared to other seas like the Chukchi Sea, where icebergs and narrower channels restrict vessel speed. Most passenger ships are medium to large vessels (50–150 m), primarily operating in the Norwegian Sea and around the Svalbard archipelago. Passenger ships in the Norwegian Sea travel at relatively slower speeds, while those around the Svalbard archipelago travel faster. The peak season for Arctic tourism is in summer, resulting in higher numbers of passenger ships during this season compared to others, with tourism interest continuously growing.

From the spatiotemporal trajectories of vessels on the NEP, it is observed that vessel trajectories in the Norwegian Sea and Barents Sea are dense year-round. This is due to the influx of the Atlantic Current and North Cape Current, providing rich fishery resources in these sea areas. The Barents Sea also has abundant oil and gas resources. Additionally, Norway's Arctic tourism is well-developed, with ice-free areas suitable for navigation throughout the year. Consequently, these areas see a high year-round activity of fishing vessels, tankers, and passenger ships. The Kara Sea, Laptev Sea, and East Siberian Sea primarily see activity from large tankers and cargo ships. Seasonally, the activity periods for tankers and cargo ships are increasing yearly, extending the navigation season. From the trajectory positions, it is evident that the paths of cargo ships and tankers are gradually approaching the Arctic center over time. All these observations indicate that under the influence of Arctic policies from various countries and global warming, year-round navigation in the Arctic is within reach.

4. Discussion

In this chapter, we will discuss the influencing factors of the spatiotemporal evolution of maritime traffic on the Northeast Arctic route based on the results of the previous section. The NEP was navigable for 86 days in 2015 [23], which was the longest navigable period between 2015 and 2020. However, the number of vessel voyages in 2015 was the lowest in these years. This shows that the temporal and spatial evolution of ship navigation on the NEP is not only caused by the increase in the number of navigable days due to climate warming. Next, we will analyze the factors affecting the temporal and spatial evolution of vessel navigation on the NEP from the aspects of geographical conditions, climate conditions, natural resource distribution, Sino–Russian cooperation and infrastructure construction along the Route and demand and supply factors.

4.1. Geographic Conditions, Climate Conditions, and Natural Resource Distribution

The Arctic and its unique geographical location greatly influence the spatiotemporal distribution characteristics of vessel activities on the NEP. Although the NEP cannot yet achieve year-round navigation, vessel activity frequency has already increased significantly during the limited navigable time in summer.

The natural conditions of different sea areas on the NEP vary greatly, which plays a key role in whether vessels can sail normally, as shown in Table 4.

Table 4. Geographical conditions and vessel activity characteristics in different sea areas.

Sea Area	Natural Conditions	Characteristics of Vessel Activities
Barents Sea	Warm pool of the ice sea; the sea temperature is relatively high; abundant oil and gas resources; inflow of the Atlantic Current.	Frequent activities of various types of vessels all year round; more tanker and fishing vessel activity.
Kara Sea	Many islands; areas less than 50 m deep account for 40% of the sea; sea ice never melts in some areas all year round.	more suitable for summer navigation
Laptev Sea	Polar night lasting 3–5 months; ice-free only in summer;	In addition to being navigable in summer, allowing for navigation with the assistance of icebreakers in autumn.
East Siberian Sea	influenced by low pressure, resulting in a short winter.	From May to October is suitable for navigation.

There are many straits on the NEP. The passability of the straits is the key to the navigation of ships on the Northeast Passage. Table 5 shows the natural conditions and navigation conditions of key straits on the NEP.

The Arctic is rich in natural resources, including energy, minerals, and biological resources, and is known as the “Middle East at the end of the Earth”. For example, the Siberian Basin and Barents Sea regions have abundant oil and gas resources. The extraction and processing of petroleum resources and the construction of dedicated port terminals influence the spatiotemporal patterns of tanker activities, resulting in dense tanker traffic in the Barents Sea and Norwegian Sea regions. Additionally, the increasing oil demand from countries such as China and Japan, as well as the shift in Russia’s oil export direction, have led to increased tanker activities in the Barents Sea—Kara Sea—Laptev Sea—East Siberian Sea. The inflow of the Atlantic Current and North Cape Current results in abundant plankton in the Norwegian Sea and Barents Sea, rich in fishery resources. The surrounding areas have developed fishing industries and the warm currents extend the navigable period, leading to a high concentration of fishing vessels year-round (as shown in Table 4) [11].

Table 5. Natural and navigation conditions in key straits.

Strait	Natural Conditions	Navigation Conditions
Yugorsky Shar Strait	relatively well-developed navigation aids; strong currents; heavy fog	navigation difficult for small to medium-sized vessels
Kara Strait	a short ice period; floating ice year-round	suitable for navigation during the ice-free summer
Matochkin Shar Strait	narrow and shallow;	unsuitable for mega vessels
Vilkitsky Strait	wide; well-developed navigation aids	suitable for medium to mega vessels in summer as the ice melts
Shokal'sky Strait	the central part is narrow; ice conditions are complex	unsuitable for medium to mega vessels; suitable for navigation only in summer
Red Army Strait	narrow channels; severe ice conditions; many small islands	no vessels navigate
Yana Bay Strait	narrow channels; severe ice conditions; many small islands	no vessels navigate
Dmitry Laptev Strait	a shallow area of only 8 m; with floating ice present even in summer	unsuitable for mega vessels; navigation difficult
Sannikov Strait	scattered shallow areas;	unsuitable for medium to mega vessels; only suitable for navigation in September

4.2. Sino–Russian Cooperation and Infrastructure Construction along the Route

In 2015, China and Russia first proposed “strengthening cooperation on the development and utilization of the Northern Sea Route and conducting Arctic shipping research”. By 2017, Putin explicitly stated that he hoped China could use the Arctic Route to connect the Arctic Route with the Belt and Road Initiative. Additionally, China’s “Vision for Maritime Cooperation under the Belt and Road Initiative” identified the “Arctic Route” as one of the three main maritime corridors of the Belt and Road Initiative. In 2018, the Chinese government issued the white paper “China’s Arctic Policy”, proposing that China is willing to rely on the development and utilization of the Arctic Route to jointly build the “Polar Silk Road” with all parties [24]. In addition to Sino–Russian cooperation, China’s cooperation with Nordic countries is also strengthening. These collaborations are driving the rapid growth of modern shipping and port logistics industries, making Arctic maritime traffic increasingly complex. These policies led to a significant increase in the number of vessels in the Arctic starting from the second stage in 2018, with activities becoming more frequent than before. Port, logistics, and shipping infrastructure construction are among the key factors influencing vessel activities in the Arctic. For instance, Murmansk Port in northern Russia is the largest Arctic port in Russia. It boasts a well-developed infrastructure and a high level of automation. With channel depths of 17.1 to 18.2 m, it can safely accommodate large vessels. The port is a hub for oil and gas trade and fishing trade, attracting large tankers, cargo ships, and fishing vessels. Tromsø Port in northern Norway is one of the important Arctic ports. The main industries of Tromsø Port are fishing and tourism, with fishing vessels and passenger ships gathering at the port year-round. The Svalbard archipelago in Norway is a famous tourist destination, home to the deep-water port of Svalbard. Every summer, numerous passenger ships travel between Tromsø and Svalbard, with many gathering near Svalbard port. Russia has signed agreements with other coastal countries and international organizations, clarifying the responsibilities and obligations of all parties in the use, development, and protection of the Northern Sea Route, indirectly promoting the development of the NEP. Moreover, Russia’s open policy on the Northern Sea Route has attracted more shipping companies to join, and the opening of ports and infrastructure along the route to international shipping companies provides vessels with more convenient docking and replenishment opportunities. To ensure the safety of vessel navigation, Russia shares information on navigation conditions, weather forecasts, and ice reports with other countries, which also promotes the increase in the

number of vessels and navigation time on the NEP. In terms of infrastructure construction: (1) Russia has built multipurpose ports along the route to accommodate different types of vessels (such as the port of Sabetta); (2) in terms of ship service facilities, Russia installs and maintains navigation buoys, lighthouses, radar systems, and other aids to navigation to ensure vessel safety; (3) establishing emergency rescue facilities: Russia and Norway have set up corresponding rescue centers, such as Russia's Murmansk Rescue Center and Novosibirsk Rescue Center, and the Murmansk Search and Rescue Cooperation Center established by Norway and other Arctic countries. These measures strengthen the infrastructure level and service quality of the NEP, providing a safer and more efficient navigation environment for more vessels. This has led to an increase in the number of vessels, extended navigation times, and expanded navigation ranges on the NEP [25].

4.3. Demand and Supply Factors

The Arctic region has a vast amount of untapped natural resources. As Russia's geopolitical environment worsens, Russia has decided to vigorously develop oil, gas, and mineral resources to alleviate its heavy dependence on imports. This has caused the number of cargo ships and tankers on the NEP to increase more than 10-fold within five years [26]. Additionally, the distribution of cargo ships and tankers has become more widespread. The port of Pevek in the Chukchi Sea has seen a significant increase in the number of cargo ships and tankers within five years, with the size and tonnage of vessels also increasing as the strategic importance of the NEP grows. Sabetta Port in the Kara Sea is an important Russian port for natural gas and oil projects. Spatiotemporal distribution shows a significant increase in the number of cargo ships and tankers near the port within five years, with vessels present year-round. With the increase in global trade, Russia's natural gas exports are also increasing. Siberia in Russia has natural oil and gas fields, and the demand for transporting these resources is expanding, as evidenced by the significant growth in the number of nearby vessels. Modern icebreakers and ice-class vessel designs make it possible to navigate under certain ice conditions. Innovations such as reinforced hulls and specially designed propellers have enhanced the safety of navigating through ice-covered areas. The seasonal distribution of vessels shows that while the number of vessels increases rapidly in summer and autumn, there is also a significant increase (about sevenfold) in vessel numbers even under ice-covered conditions in winter, especially in the harsh navigation environments of the Kara Sea, Laptev Sea, and East Siberian Sea. The Kara Sea near the NEP is rich in cod and flounder, while the East Siberian Sea and Chukchi Sea are abundant in polar cod, salmon, and other species. However, the winter navigation conditions in these sea areas are unfavorable for fishing, so the spatiotemporal distribution shows that fishing vessels mainly appear in summer and autumn. As navigable time increases, the density of fishing vessels in summer and autumn also grows. The Barents Sea and Norwegian Sea, influenced by Atlantic currents, have relatively higher water temperatures compared to other sea areas of the NEP and are two of the world's most important fishing grounds. As these waters continue to open up, they attract a large number of fishing vessels, with the number of fishing vessels increasing most significantly within five years. However, countries like Norway place more emphasis on fishery management. To maintain the sustainable development of fishery resources, they typically implement seasonal fishing bans and establish fishing quotas [15]. This is well reflected in the spatiotemporal changes of fishing vessels, where the number of fishing vessels drops sharply every June and July. Over five years, the proportion of small fishing vessels has consistently increased because fishery management often focuses more on large fishing vessels due to their greater fishing capacity and wider fishing range, which have a larger impact on fishery resources. Notably, in 2020, the number of fishing vessels increased, unlike other types of vessels. Climate change in the Arctic is accelerating the melting of sea ice, providing more fishing waters and new fishing seasons for fishing vessels. This is particularly attractive to fishing companies seeking new fishing grounds. Even though global trade was generally affected by the pandemic, the activity and number of fishing vessels still increased. The global pandemic

in 2020 prompted many Arctic countries to reconsider and restructure their supply chains, particularly in terms of food security and self-sufficiency. The development of Arctic fisheries may be seen as a strategic project to increase domestic food supply, ensuring the stability and safety of seafood supply during the pandemic. Arctic tourism is becoming an increasingly popular market, attracting tourists worldwide who are interested in adventure travel and natural landscapes [27]. Due to harsh environmental conditions, the Kara Sea, Laptev Sea, East Siberian Sea, and Chukchi Sea currently do not have large-scale tourism projects. Only a few projects operate in these areas during the ice-free summer period. The Norwegian Sea, Barents Sea, and Svalbard archipelago are important tourist destinations on the NEP, featuring stunning natural landscapes, unique wildlife, and rich historical culture. As the demand for tourism continues to expand, the number of passenger ships has tripled over five years. Although summer and autumn are more suitable for tourism in these three areas, they also offer unique winter attractions, such as polar expeditions in the Svalbard archipelago.

5. Conclusions

Global climate warming accelerates the melting of Arctic sea ice, and vessels traversing the Arctic to connect Asia, Europe, and America can significantly reduce navigation time [6]. The Arctic sea areas are extremely complex; in winter, most areas are covered by ice and snow. Even in summer, dense fog, strong winds, and floating ice significantly affect the safety of vessel navigation. Even though there are many straits in the Arctic sea areas, most are narrow and have widely distributed shoals, making them unsuitable for large vessels. Due to the influence of ocean currents, the various sea areas in the Arctic have distinctly different navigation conditions. The emphasis placed by Russia and China on the NEP, along with the introduction of multiple policies [28], has significantly increased vessel activity on the route. In the future, to further promote the development of the NEP, the following suggestions are proposed:

- (1) Strengthen multilateral cooperation and international agreements. The increase in vessel numbers and activity patterns observed in the second stage (starting in 2018) clearly shows that Sino–Russian cooperation in developing the NEP has revitalized the route. In the future, coastal and interested countries should be encouraged to enhance international cooperation by sharing technology, information, and resources to improve the overall efficiency and safety of the route;
- (2) Improve infrastructure quality and safety technology for the route. Increase infrastructure construction along the NEP, including port upgrades, enhanced icebreaking services, and improved safety facilities to attract more shipping companies and national vessels. Develop and deploy advanced navigation technologies and monitoring systems to enhance navigation safety in complex sea conditions and low visibility environments;
- (3) Optimize economic strategies for the route. Provide tax incentives, financial subsidies, and other incentives to attract investment from shipping companies and international investors, especially in energy, fisheries, and tourism. Encourage diversified use of the route, not limited to cargo transport but also include tourism, scientific research, and other developments to increase the economic value and attractiveness of the route;
- (4) Strengthen hull structures. For the NEP, which mainly consists of medium to small-sized vessels, enhance the ice-class standards for these vessels to ensure sufficient ice resistance, significantly improving the safety of vessels on the route.

This paper studies the spatiotemporal distribution characteristics of vessel activities on the NEP to explore maritime traffic flow patterns. It analyzes the spatiotemporal evolution of vessel size, speed, and density at different hotspot locations on the NEP, providing data support for the safety of Arctic navigation. The next step will be to study the relationship between vessel activity characteristics on the NEP and Arctic vessel safety assurance. This will involve combining the evolutionary patterns of vessel activities with the unique

navigation environment of the Arctic to assess the navigation risks in various sea areas of the NEP.

Author Contributions: Conceptualization, C.L. and Z.L.; methodology, C.L.; software, C.L.; validation, C.L. and Z.L.; formal analysis, C.L.; investigation, C.L.; resources, C.L.; data curation, C.L.; writing—original draft preparation, C.L.; writing—review and editing, C.L.; visualization, C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Mudryk, L.R.; Dawson, J.; Howell, S.E.; Derksen, C.; Zagon, T.A.; Brady, M. Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. *Nat. Clim. Chang.* **2021**, *11*, 673–679. [\[CrossRef\]](#)
2. Stephenson, S.R.; Wang, W.; Zender, C.S.; Wang, H.; Davis, S.J.; Rasch, P.J. Climatic responses to future trans-Arctic shipping. *Geophys. Res. Lett.* **2018**, *45*, 9898–9908. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Smith, L.C.; Stephenson, S.R. New Trans-Arctic shipping routes navigable by midcentury. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, E1191–E1195. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Lasserre, F. Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the shipping industry. *Polar Sci.* **2014**, *8*, 404–413.
5. Wu, A.; Che, T.; Xu, Q.; Wang, J.; Zhu, X. Assessing the economic viability of the Arctic Northeast Passage from 2021 to 2065. *Int. J. Digit. Earth* **2024**, *17*, 2323182. [\[CrossRef\]](#)
6. Zhang, Z.; Huisinigh, D.; Song, M. Exploitation of trans-Arctic maritime transportation. *J. Clean. Prod.* **2019**, *208*, 1227–1236. [\[CrossRef\]](#)
7. Petrov, A.N.; Tulaeva, S. Socio-economic impacts of Arctic transportation routes: The case of the Northern Sea Route. *Local Econ.* **2020**, *35*, 597–615.
8. Ol'khovik, E.; Tezikov, A. Shipping development trends in the Eastern sector of the Northern Sea Route. In Proceedings of the 26th International Conference on Port and Ocean Engineering under Arctic Conditions, Moscow, Russia, 14–18 June 2021.
9. Koyama, T.; Nakanowatari, T.; Inoue, J. Information retrieval for Northern Sea Route (NSR) navigation: A statistical approach using the AIS and TOPAZ4 data. *Polar Sci.* **2021**, *27*, 100626. [\[CrossRef\]](#)
10. Kim, D.; Choi, K. Noise pollution in Arctic waters: Sources and mitigation strategies. *Environ. Sci. Technol.* **2022**, *56*, 2103–2112.
11. Silber, G.K.; Adams, J.D. Vessel operations in the Arctic, 2015–2017. *Front. Mar. Sci.* **2019**, *6*, 573. [\[CrossRef\]](#)
12. Chen, Q.; Lau, Y.; Ge, Y.E.; Ng, A.K.Y. Implications of Arctic shipping emissions for marine environment. *Marit. Policy Manag.* **2022**, *49*, 155–180. [\[CrossRef\]](#)
13. Eguíluz, V.M.; Fernández-Gracia, J.; Irigoien, X.; Duarte, C.M. A quantitative assessment of Arctic shipping in 2010–2014. *Sci. Rep.* **2016**, *6*, 30682. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Li, X.; Lynch, A.H. New insights into projected Arctic sea road: Operational risks, economic values, and policy implications. *Clim. Chang.* **2023**, *176*, 30. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Schach, M.; Madlener, R. Impacts of an ice-free Northeast Passage on LNG markets and geopolitics. *Energy Policy* **2018**, *122*, 438–448. [\[CrossRef\]](#)
16. Lee, J.; Kim, Y.H. Ice hazards on the Northern Sea Route: A simulation study. *Polar Sci.* **2020**, *25*, 100534.
17. Vanhatalo, J.; Huuhtanen, J.; Bergström, M.; Helle, I. Probability of a ship becoming beset in ice along the Northern Sea Route—A Bayesian analysis of real-life data. *Cold Reg. Sci. Technol.* **2021**, *184*, 103238. [\[CrossRef\]](#)
18. Yang, X.; Lin, Z.Y.; Zhang, W.J.; Xu, S.; Zhang, M.Y.; Wu, Z.D.; Han, B. Review of risk assessment for navigational safety and supported decisions in arctic waters. *Ocean Coast. Manag.* **2024**, *247*, 106931. [\[CrossRef\]](#)
19. Lynch, A.H.; Norchi, C.H.; Li, X. The interaction of ice and law in Arctic marine accessibility. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2202720119. [\[CrossRef\]](#)
20. Chen, G.; Huang, L. National policies on the Northern Sea Route and implications for international collaboration. *Mar. Policy* **2019**, *108*, 103662.
21. Bennett, M.M.; Stephenson, S.R.; Yang, K.; Bravo, M.T. The opening of the Transpolar Sea Route: Logistical, geopolitical, environmental, and socioeconomic impacts. *Mar. Policy* **2020**, *121*, 104178. [\[CrossRef\]](#)
22. Kim, J.K. Semi-Continuous Spatial Statistical Analysis Using AIS Data for Vessel Traffic Flow Characteristics in Fairway. *J. Mar. Sci. Eng.* **2021**, *9*, 378. [\[CrossRef\]](#)

23. Ji, M.; Liu, G.; He, Y.; Li, Y.; Li, T. Analysis of Sea Ice Timing and Navigability along the Arctic Northeast Passage from 2000 to 2019. *J. Mar. Sci. Eng.* **2021**, *9*, 728. [[CrossRef](#)]
24. MA, X.M. China's Arctic policy on the basis of international law: Identification, goals, principles and positions. *Mar. Policy* **2019**, *100*, 265–276. [[CrossRef](#)]
25. Christodoulou, A.; Dalaklis, D.; Raneri, P.; Sheehan, R. An overview of the legal search and rescue framework and related infrastructure along the Arctic Northeast Passage. *Mar. Policy* **2022**, *138*, 104985. [[CrossRef](#)]
26. Galappaththi, E.K.; Falardeau, M.; Harris, L.N.; Rocha, J.C.; Moore, J.S.; Berkes, F. Resilience-based steps for adaptive co-management of Arctic small-scale fisheries. *Environ. Res. Lett.* **2022**, *17*, 083004. [[CrossRef](#)]
27. Varnajot, A.; Saarinen, J. 'After glaciers?' Towards post-Arctic tourism. *Ann. Tour. Res.* **2021**, *91*, 103205. [[CrossRef](#)]
28. Liu, C.; Fan, H.; Dang, X.; Zhang, X. The arctic policy and port development along the Northern Sea route: Evidence from Russia's arctic strategy. *Ocean Coast. Manag.* **2021**, *201*, 105422. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.