Influence of sea ice on ship routes and speed along the Arctic Northeast Passage

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Abstract

The accelerated melting of sea ice and the growing influx of ships in the Arctic pose significant challenges to navigational safety and policy formulation. This study aims to explore the influence of sea ice on ship routes and speed by analyzing the spatiotemporal correlation of Sea Ice Concentration (SIC), Sea Ice Thickness (SIT), Sea Ice Volume (SIV), and Automatic Identification System (AIS) data along the Northeast Passage (NEP) in 2022. Our findings indicate that during the navigation window period (July-October), 115 ships traversed the NEP. It was observed that ships preferred navigating at speeds ranging from 6 to 14 knots when the SIC was below 10% and the SIT was less than 0.1 meters. Different ship types exhibited distinct trajectory and speed distribution characteristics. Furthermore, our results suggest that SIV, compared to SIC and SIT, provides a more accurate reflection of the impact of sea ice on ship navigation. These findings hold significant implications for guiding future Arctic shipping activities and serve as a foundation for enhancing existing navigation management policies through validation and refinement.

Keywords: Northeast Passage (NEP); Sea Ice Volume; Ship Routes; Ship Speed; Spatial and Temporal Distribution

1. Introduction

In recent years, global warming and Arctic amplification have led to a declining trend in Arctic sea ice in all seasons, especially in summer (Chen et al., 2019; Kumar et al., 2020). Arctic sea ice shows a trend of thinning thickness and a shift to younger ice (Pörtner et al., 2019). It is expected that Arctic sea ice will continue declining and will lose most of its September sea ice by 2050 for the first time (Notz and Community, 2020), implying the navigation environment of the Northeast Passage (NEP) will be improved (Mahmoud et al., 2024; Pang et al., 2023). Sailing via the NEP not only alleviated the transportation burden on the Suez Canal Route (SCR) (Lee and Wong, 2021), but also substantially reduced cost and time for shipping companies (Tseng et al., 2021). Therefore, the NEP is considered a viable alternative to the SCR and has the potential to reshape global shipping networks (Gogoleva et al., 2023).

However, sea ice was considered as the most important factor affecting ship navigation in the NEP (Ji et al., 2021; Kandel and Baroud, 2024). Recently, many scholars have conducted different studies on ship navigation in NEP based on sea ice conditions. In general, the Sea Ice Concentration (SIC) and Sea Ice Thickness (SIT) were used to evaluate the severity of sea ice conditions (Aksenov et al., 2017; Stroeve et al., 2012). Based on the SIC and SIT, the spatiotemporal changes of sea ice along the NEP were analyzed, and the future trend of sea ice was predicted (Gascard et al., 2017; Lei et al., 2015). Also, the sea ice data were used to calculate the accessibility and navigation window of ships in the NEP, and the optimal annual navigation time distribution for ships of different ice classes was obtained (An et al., 2022). In addition, according to various Arctic ship navigation planning algorithms, the optimal ship routing through NEP under different ice conditions was given (Lee et al., 2021; Shu et al., 2023). For ships navigating in the NEP, many problems also arise. A risk assessment methodology for Arctic ship navigation considered multiple influencing factors and validated the reliability of the methodology by using real ship sailing records (Zhang et al., 2020). Furthermore, an estimation model was established to analyze ships' profitability and pollution emissions with different ice-breaking grades (Chen et al., 2024; Chen et al., 2022; Xu and Yang, 2020). Conventions and regulations for Arctic ships, the legal framework for the search and rescue of ships in distress, and the environmental and social impacts in the Arctic were also studied (Christodoulou et al., 2022; Huntington et al., 2023).

Unlike other shipping routes, the NEP has no predetermined ship routes when considering the special ship navigation environment in the Arctic (Gunnarsson and Moe, 2021; Wang et al., 2021), and ships relied on previous navigational experience in actual sailing (Melia et al., 2016). Eguíluz et al. (2016) quantitatively evaluated the Arctic shipping volume from 2010 to 2014, the results showed that the hotspots of routes were concentrated in the Barents Sea of the NEP. Pastusiak (2020) described ship transportation routes in the Arctic and divided the NEP into transit routes, intermediate routes, and coastal routes. Cao et al. (2022) used the classical least-cost path algorithm to calculate the daily shortest path of the NEP, and the results showed that the actual shortest navigable routes of three ship types (PC4, PC6, and OW) were closer to the North Pole than predicted by the model.

The ship speed in the NEP could also be influenced by sea ice (Kavirathna et al., 2023). The Polar Operational Limit Assessment Risk Indexing System (POLARIS) published by the International Maritime Organization (IMO) only provided simple speed restrictions for ships navigating in ice areas (IMO, 2016). At present, ships still lack speed guidance when encountering different ice conditions. Ol’khovik (2019) studied the speed variations of Arc7 ships in the Kara Sea based on archived information from the Automatic Identification System (AIS). The results indicated minimal variations in ship speed during the summer, contrasting with significant fluctuations observed during the winter months. Zhang et al. (2020) proposed a safe speed identification method based on navigational risk assessment, which could provide safe ship speed suggestions based on different SIC conditions. Chen et al. (2021) used AIS data to analyze the speed distribution of passenger ships in the Arctic region under different navigation states from 2012 to 2017, and it was found that the average speed of passenger ships in the cruising state was between 11kn-13kn.

While previous studies have acknowledged the influence of sea ice on ship routes and speed, quantifying this impact has remained a challenge. The POLARIS offers speed recommendations for ships of varying ice classes in high-risk waters but lacks guidance on optimal routes and speeds in different sea ice conditions. Addressing this gap, our study collected and integrated sea ice and ship data from voyages across the NEP in 2022 to assess and quantify the effects of sea ice on ship routes and speeds.

Initially, Sea Ice Volume (SIV) data were derived from SIC and SIT data, allowing for the analysis of their spatial and temporal distribution alongside ship trajectories along the NEP on a monthly basis. Subsequently, SIC, SIT, and SIV data from ship trajectories were extracted to examine their correlation with ship routes and speed distributions. Furthermore, considering the diversity of ship types, we analyzed how these three sea ice parameters influenced trajectory and speed distributions across various ship types during different periods. The findings of our analysis aim to offer a comprehensive understanding of ship navigation behavior within the ice region of the NEP and provide recommendations for optimal ship routes and speeds in icy conditions.

The structure of the remaining article is as follows: Section 2 describes the research area, data sources, and data preprocessing. In Section 3, we analyze the spatial and temporal distribution characteristics of sea ice and different ship types, along with the impact of sea ice on ship routes and speeds. This is followed by a comprehensive discussion in which policy implications are considered. Finally, Section 5 concludes the study.

2. Methods

2.1. Research area

The research area of the present study is shown in Fig. 1. The NEP covers five seas from west to east, including the Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea, and Chukchi Sea (Hermann et al., 2022; Østreng et al., 2013).

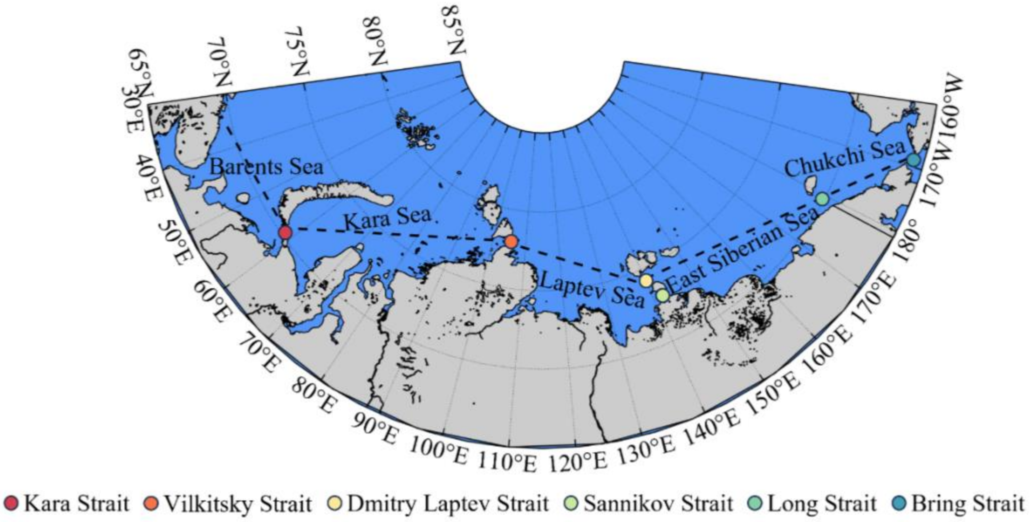

Fig. 1. Map of the research area. (The key seas and straits along the NEP)

2.2. Data processing

The data utilized in this study comprised the SIC, SIT, SIV, and AIS data for the NEP in the Arctic for the year 2022. This section outlines the data processing procedure and methodology employed to investigate the influence of sea ice on ship routes and speed. An overview of the data processing is illustrated in Fig. 2.

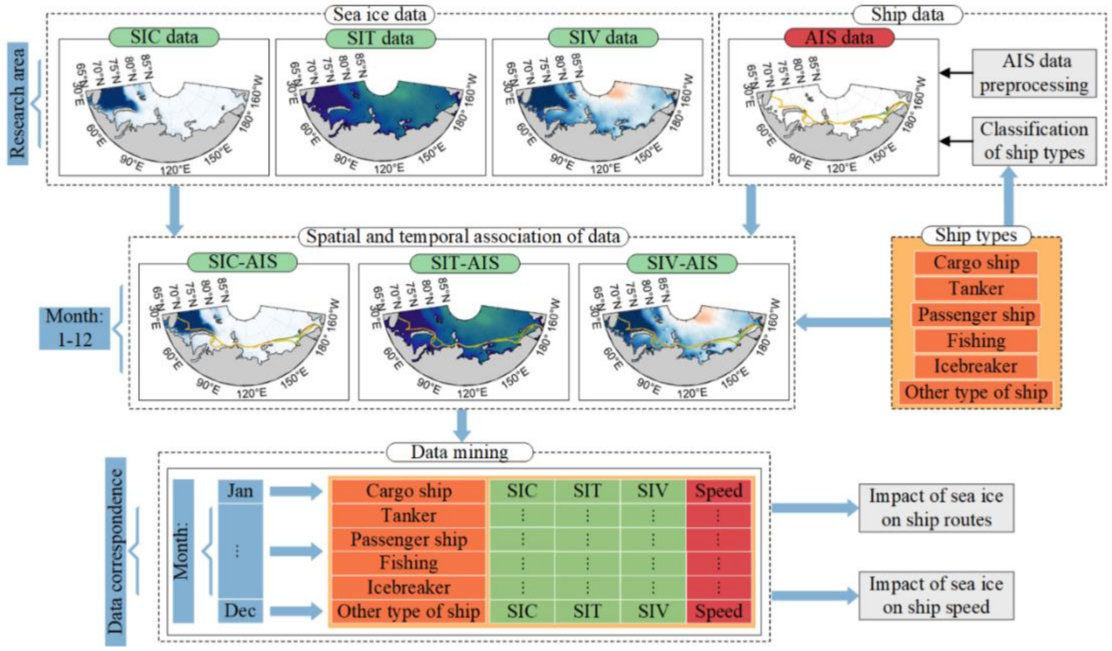

Fig. 2. The framework for sea ice and AIS data processing.

2.2.1. Sea ice concentration, thickness, and volume

The SIC was defined as the percentage of area covered by sea ice within a grid cell (Meier et al., 2014), and could be observed by the satellite (Meier and Stroeve, 2022; Riihelä et al., 2013). The monthly average SIC in 2022 was obtained and stored in the polar stereographic projections at a grid cell size of 25km×25km from the open-source dataset by the National Snow and Ice Data Center (NSIDC) (DiGirolamo et al., 2022; Meier and Stewart, 2020). Based on the SIC data, the navigation state of ships under different SIC was analyzed according to the IMO standards in Table 1 (Shibata et al., 2013).

Table 1. The relationship between SIC, ship navigation state, and sea surface condition.

SIC	Navigation state of ship	Sea surface condition
100%	very severe difficult	Floes are frozen together (no water is visible): compact ice or consolidated ice
90%		Very close ice
70%—80%		Composed of floes mostly in contact: close ice
40%—60%	difficult	Many fractures and floes that are generally not in contact with one another: open ice
10%—30%	easy navigation	More open water than ice: very open ice
10% or less		A large area of freely navigable water: open water

The SIT was defined as the average thickness of sea ice within the grid cell (Li et al., 2022). The lack of long-term and continuous SIT data was attributed to the limitations in satellite observation equipment and technology (Gerland et al., 2019). The combination of satellite observations and numerical modeling was often used to obtain SIT data (Hunke, 2010; Mu et al., 2018). The monthly average SIT in 2022 was synthesized from real satellite observations and numerical model simulations and stored in the polar stereographic projections at a grid cell size of 12.5km×12.5km (Melsom et al., 2012; Sakov et al., 2012). The risk of ship navigation in different SIT conditions was analyzed monthly according to the IMO guideline (IMO, 2016).

Table 2. SIT delineation and corresponding navigational risk for PC6 ice class ships.

Sea ice types	SIT / m	risk value
Ice-free	0.00	3
New ice	0.00-0.10	2
Grey ice	0.10-0.15	2
Grey white ice	0.15-0.30	2
Thin 1st year ice 1st stage	0.30-0.50	2
Thin 1st year ice 2st stage	0.50-0.70	1
Medium 1st year ice 1st stage	0.70-0.95	1
Medium 1st year ice 2st stage	0.95-1.20	0
Thick 1st-year ice	1.20-2.00	-1
Second-year ice	1.20-2.00	-2

The monthly SIV was calculated according to the equation 1 (Notz and Community, 2020):

$$SIV = SIC \times SIT \times grid_{area} \tag{1}$$

where the unit of SIV is m^3, the unit of SIC is %, and the unit of SIT is m. $grid_{area}$ represents the area of the SIT grid cell, with a constant value of $1.5625 \times 10^8 m^2$. The calculated results of the SIV were also saved in the polar stereographic projections at a grid cell size of 12.5km×12.5km. The monthly spatial-temporal distribution of the SIC, SIT, and SIV for the entire NEP in 2022 was presented based on the method above.

2.2.2. Ship routes and speed

In this study, only AIS data from ships navigating the NEP in 2022 were considered. The AIS data comprised both static and dynamic information, including Maritime Mobile Service Identity (MMSI), ship name, type, dimensions, position, timestamps in Coordinated Universal Time (UTC), speed, and heading.

Following the exclusion of errors and duplicates in the raw data, ships were categorized into distinct types such as cargo ships, tankers, passenger ships, fishing vessels, icebreakers, and other ship types based on AIS data. The "other" category encompassed research vessels, search and rescue vessels, drilling ships, and sailing vessels. Monthly quantification of the number and types of ships traversing the NEP was conducted to discern shipping activities over time.

To elucidate variations in ship routes and speed across different months, the spatial and temporal distributions of trajectories and speed for various ship types along the NEP were plotted monthly for the year 2022.

2.2.3. Impact of sea ice on ship routes

The impact of sea ice on ship routes was investigated by spatially and temporally correlating the SIC, SIT, and SIV data with the trajectory data of different ship types. The frequency of ship trajectories in different SIC, SIT, and SIV levels were counted monthly as well to quantify the impact.

2.2.4. Impact of sea ice on ship speed

To reveal the impact of the SIC, SIT, and SIV on shipping speed, the processed sea ice was correlated with the speed of different ship types. Similarly, the frequency of speed sailed under different SIC, SIT, and SIV was counted. Subsequently, the average speed of each ship type under different sea ice conditions was linearly fitted R^2 value was obtained to investigate the correlation between the speed of each ship type with the SIC, SIT, and SIV, respectively.

3. Results

This section presents the spatial and temporal distribution of SIC, SIT, and SIV. Next, the number of various ship types traversing the NEP is quantified, followed by an exhibition of the spatial and temporal distribution of ship trajectories and speed. Subsequently, a detailed analysis of the impact of SIC, SIT, and SIV on ship trajectories and speed is provided.

3.1. Temporal-spatial distribution of sea ice and ships

3.1.1. Temporal-spatial distribution of sea ice

In the NEP, from January to April, the sea surface is mostly covered by ice with over 90% coverage, except the Barents Sea. Coastal waters show decreasing ice thickness. May and June see slower melting, with SIC above 40% in the Kara and Laptev Seas in May, dropping below 30% by June. SIT indicates thicker ice in the East Siberian Sea. SIV, reflecting broken and floating ice, shows severe conditions in the East Siberian Sea. July to September sees faster melting, reflected in the higher credibility of open water in SIV. During freezing (October to December), SIV reflects ice growth better than SIC and SIT, showing less ice extent but similar to SIT.

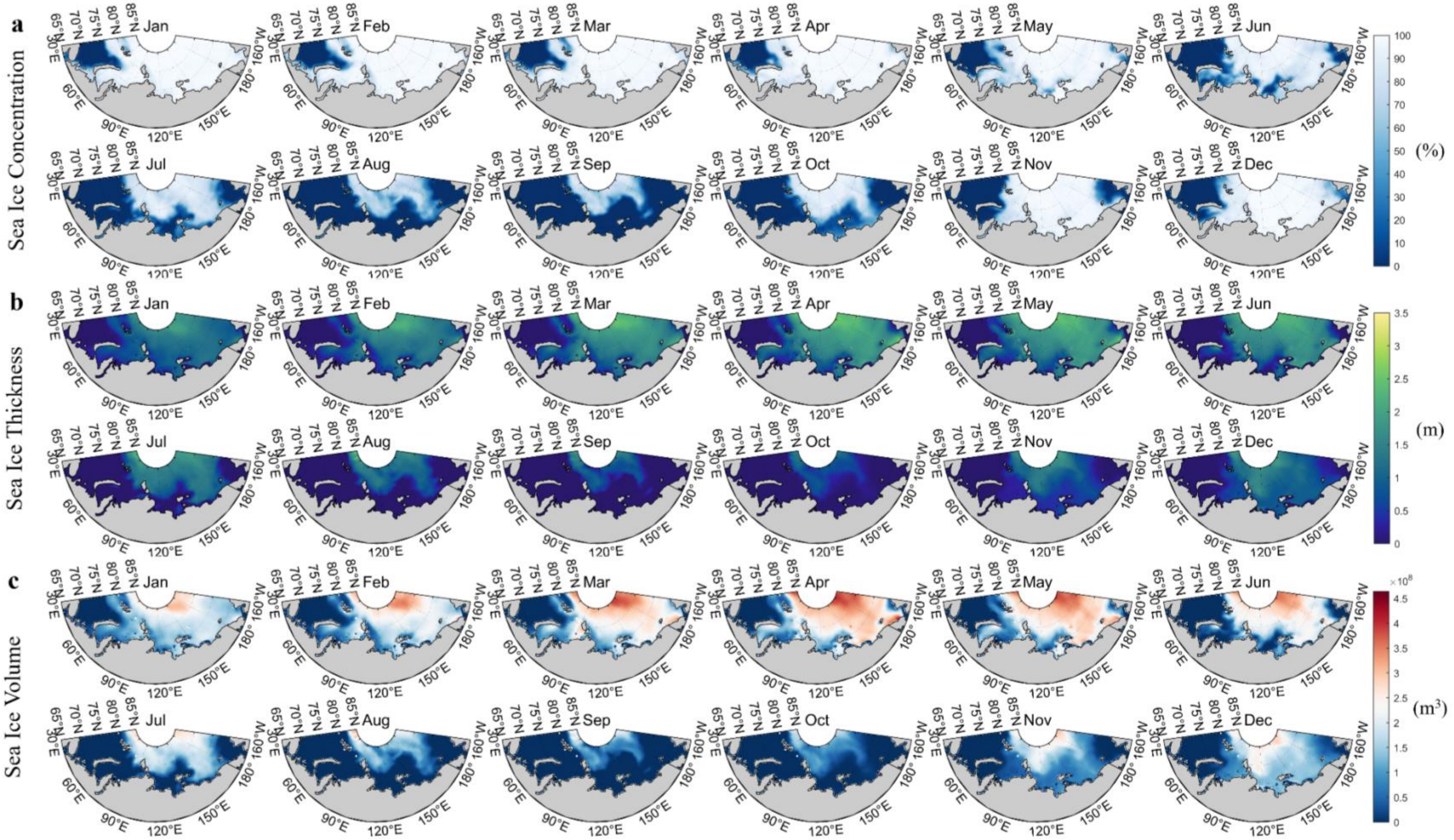

Fig. 3. Spatial and temporal distribution of (a) SIC, (b) SIT, (c) SIV.

3.1.2. Ships traversing the Northeast Passage

In 2022, 121 ships crossed the NEP. Cargo and tankers dominated at 40% and 28%, respectively. Fishing vessels and others made up 12%, with icebreakers at 5%. Passenger ships were minimal at 4%. Few ships sailed in January, February, and March-May. June saw the return, with July to October being peak months. July had 15 cargo ships, 12 tankers, 2 icebreakers, and 2 others. August to October averaged 79 ships. November-December saw a decline due to freezing conditions, with November having 18 ships and December just 4.

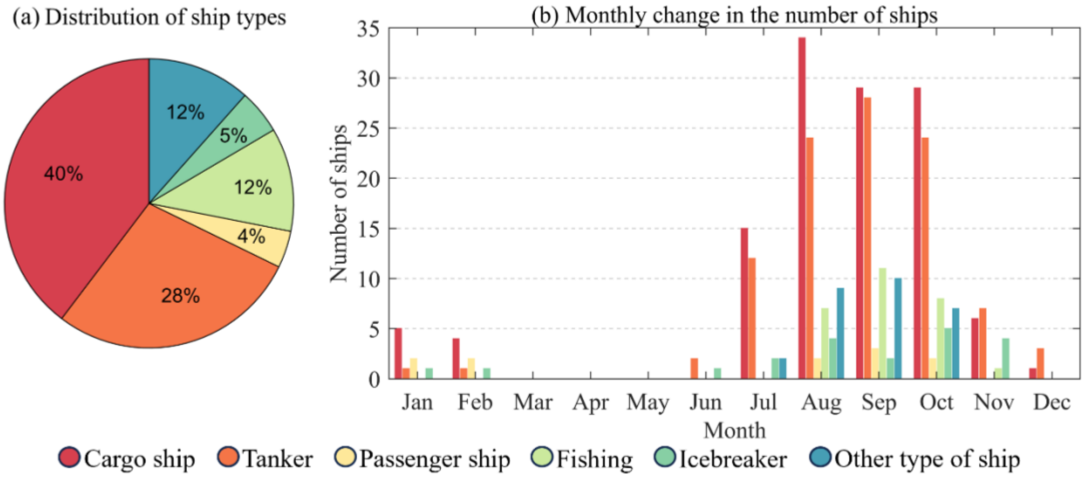

Fig. 4. Distribution of various ship types traversing the NEP.

Fig. 5 illustrates ship trajectories and speeds, revealing distinct patterns based on sea ice conditions. Ships generally avoided areas above 80°N due to ice entrapment risks, favoring lower latitudes during severe ice conditions (Jan, Feb, Jun, Nov, Dec) and moving closer to the coast when ice was lighter (Jul-Oct). Routes typically traversed the Barents Sea, Novaya Zemlya, Kara Sea, and Vilkitsky Strait, with variations in the Laptev and East Siberian Seas depending on ice and port conditions. Speeds dropped significantly in icy areas, with faster speeds along high-latitude routes in milder conditions. Cargo ships and tankers followed similar trajectories, though tankers had higher speeds and broader distributions in the Barents Sea. Passenger ships preferred coastal routes during favorable ice conditions, with slower speeds overall. Fishing vessels maintained uniform speeds in open waters. Icebreakers showed varied trajectories linked to pilotage tasks, with higher speeds in ice-covered areas. Other ship types exhibited diverse patterns, with chaotic trajectories and slower speeds. See Fig. 1 and Fig. 2 in the Supplement for details on passenger ships, fishing, icebreakers, and other ships.

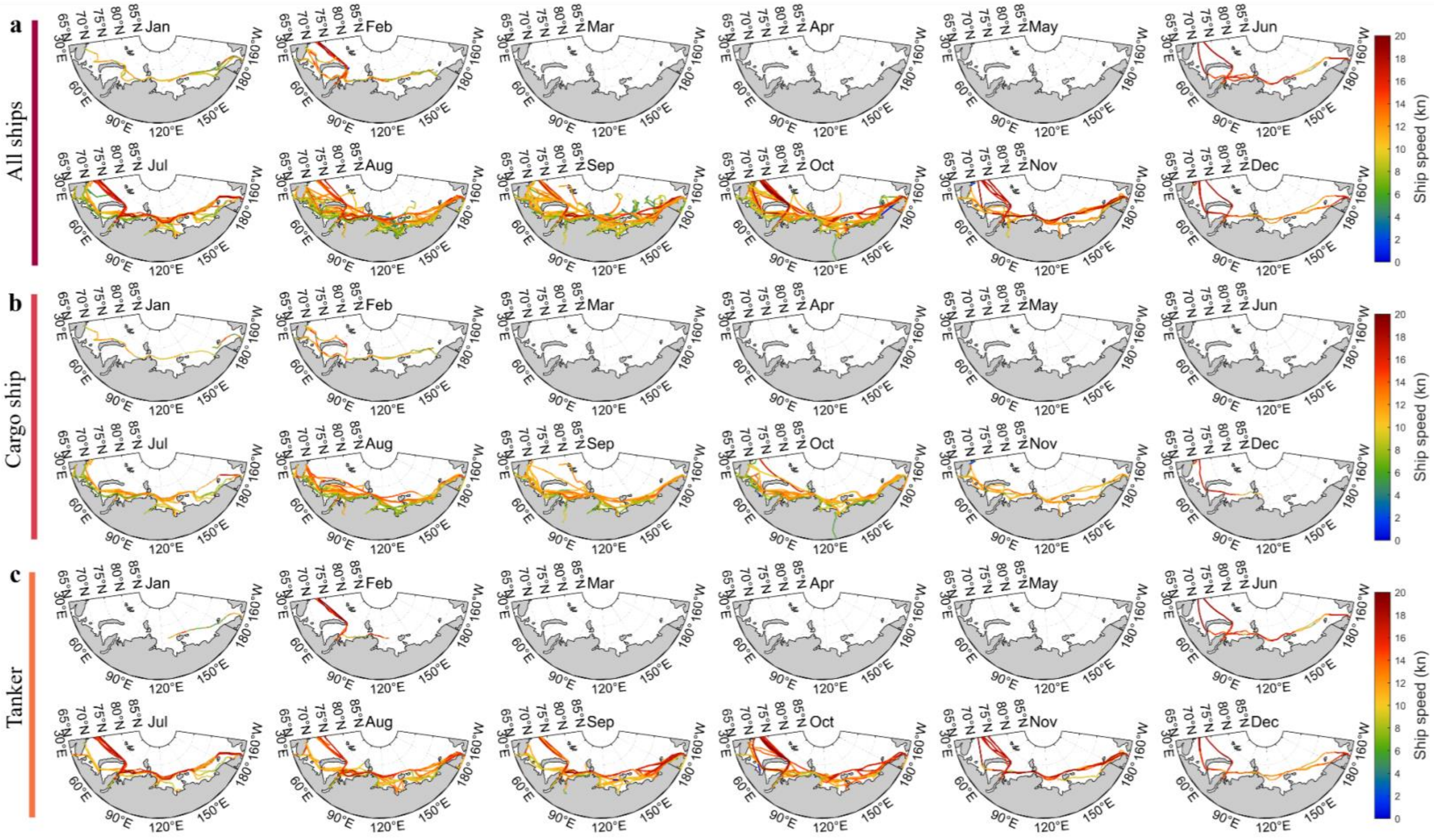

Fig. 5. Distribution of ship trajectories and speed across months: (a) all ship, (b) cargo ship, (c) tanker. Other types of ships are shown in Supplementary Fig. 1&2.

3.2. Impact of sea ice on ship routes

The SIC, SIT, and SIV distribution in ship trajectories are analyzed to study the impact of sea ice on ship routes.

3.2.1. Impact of sea ice concentration on ship routes

This paper analyzed the correlation between SIC and ship trajectories (see Fig. 6 and Fig. 7). In January and February, ships mostly sailed through icy areas, particularly in the Kara Sea, Laptev Sea, and East Siberian Sea. No voyages occurred from March to May. In June, melting ice improved navigation, leading to more uniform SIC distributions. From July to October, ship traffic increased in open waters with SIC levels below 20%. In November and December, high SIC regions shifted back to the Kara Sea, Laptev Sea, and East Siberian Sea. Cargo ships, tankers, passenger ships, and others showed similar trajectories and SIC distribution patterns. Fishing vessels in August encountered higher SIC along ice edges. Outside of the navigation window for ships, icebreakers consistently faced SIC levels exceeding 70% due to their shorter, ice-focused routes. From June to November, icebreaker SIC proportions exceeding 30% surpassed those of all ships, reflecting their specialized operations. July to October emerged as the optimal navigation period in the NEP, with SIC mostly below 10%.

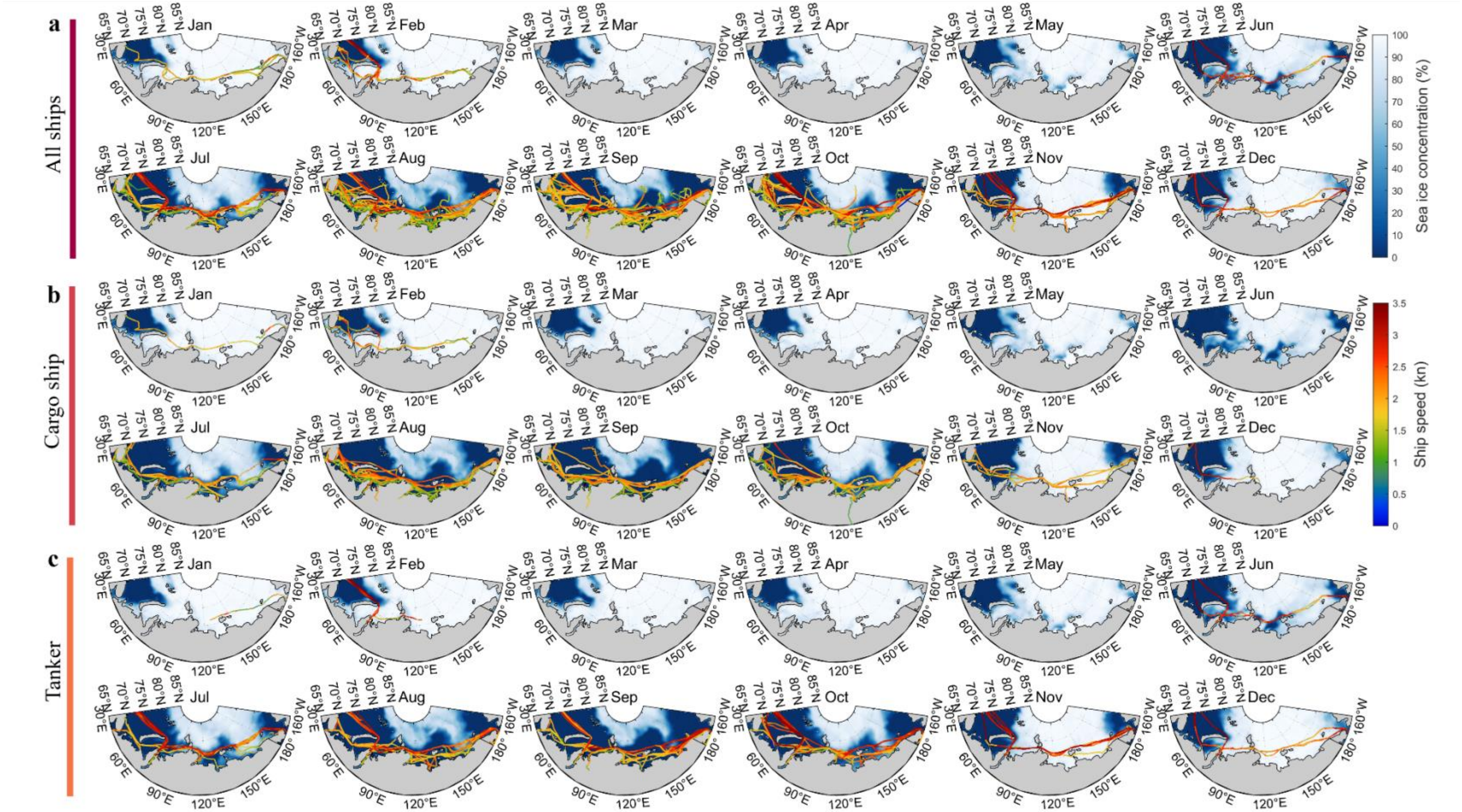

Fig. 6. Distribution of ship trajectories and SIC across months: (a) all ship, (b) cargo ship, (c) tanker. Other types of ships are shown in Supplementary Fig. 3&4.

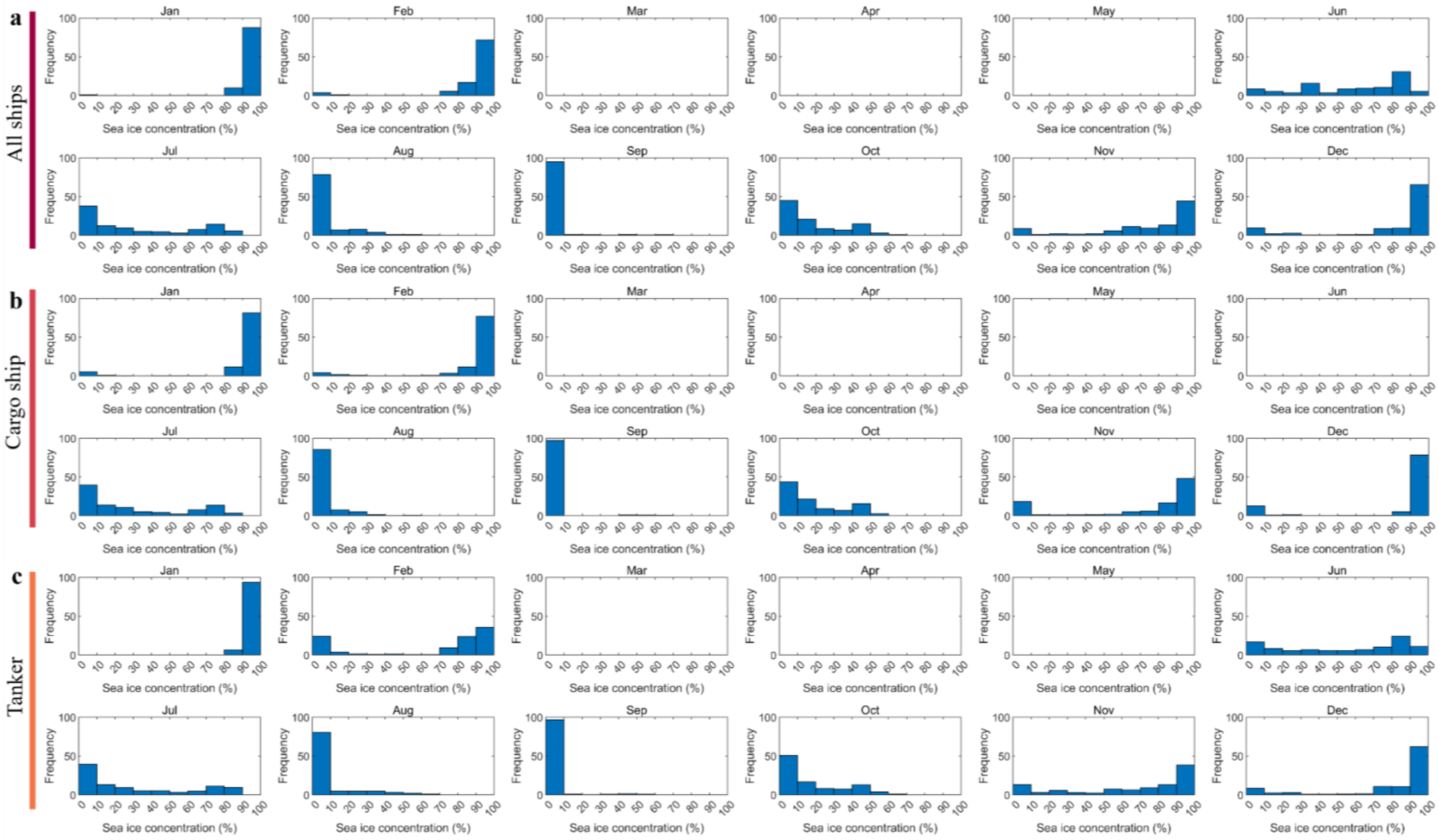

Fig. 7. Distribution of the SIC on ship trajectories: (a) all ship, (b) cargo ship, (c) tanker. Other types of ships are shown in Supplementary Fig. 5&6.

3.2.2. Impact of sea ice thickness on ship routes

This paper analyzed the influence of SIT on ship trajectories (refer to Fig. 8 and Fig. 9). In January, over 50% of ship routes encountered SIT between 0.95m-1.20m, mainly in the Kara, Laptev, East Siberian, and Chukchi Seas. By February, ships faced increased ice thickness, with 32.31% encountering ice exceeding 1.2m. June saw a rise in routes encountering SIT below 0.1m (38.00%) and above 0.9m (46.16%). In July, SIT below 0.15m dominated ship trajectories (50.56%). From August to October, over 90% of ship routes had SIT below 0.15m, suitable for PC6 ice class ships. November and December saw increased SIT above 0.15m, with cargo ships showing distinct patterns in December, mainly in the eastern Kara Sea. Tanker trajectories in January had high SIT due to routes in the East Siberian and Chukchi Seas. Passenger ships and fishing vessels exhibited SIT trends similar to all ships. Before July, icebreaker routes mostly had SIT exceeding 0.15m. Other ship types preferred routes with SIT below 0.15m from July to October. Although January and February had higher ice thickness, only 5.47% of ships sailed during this period, contrasting with 86.50% from July to October preferring thinner ice.

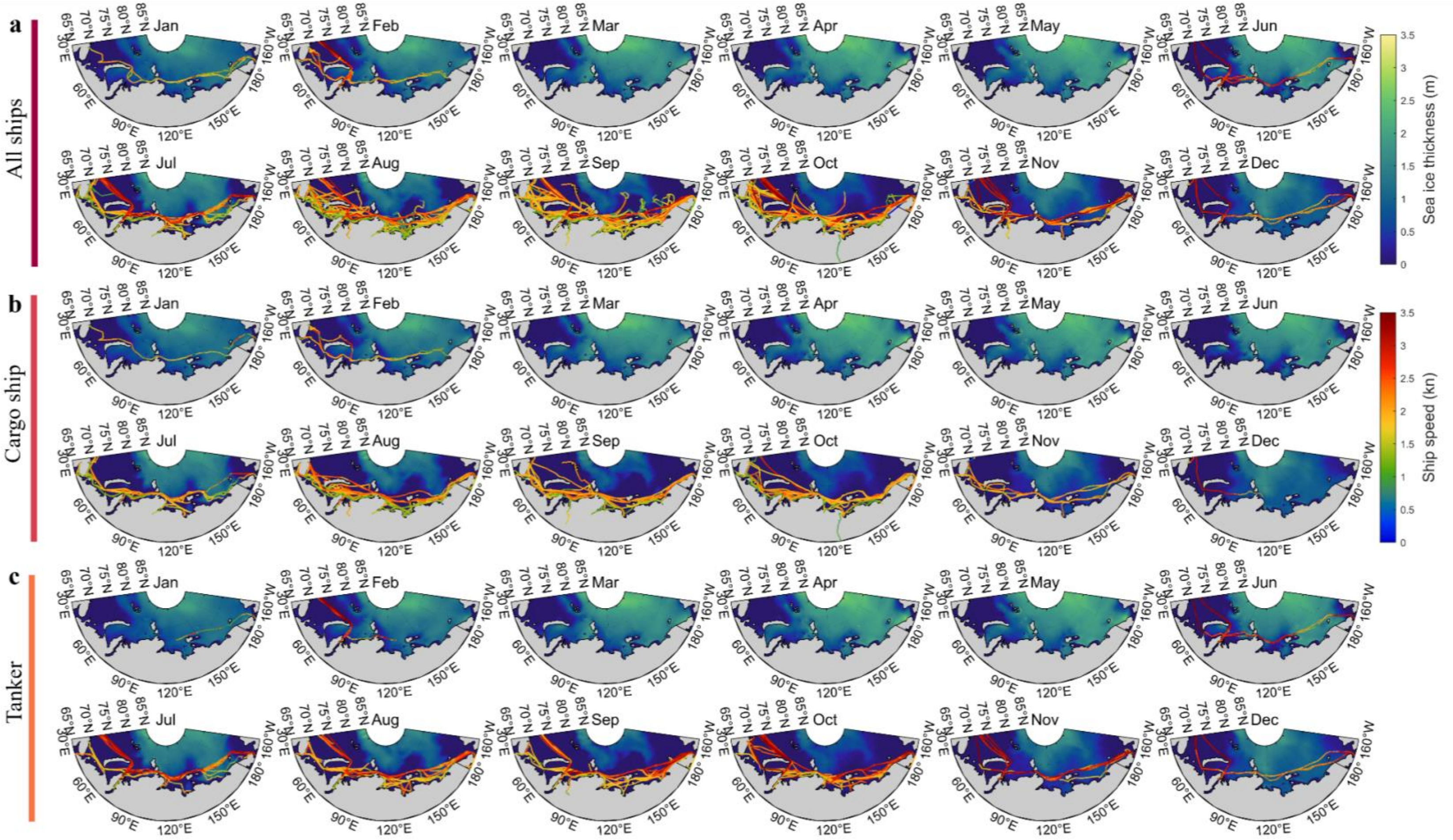

Fig. 8. Distribution of ship trajectories and SIT across months: (a) all ship, (b) cargo ship, (c) tanker. Other types of ships are shown in Supplementary Fig. 7&8.

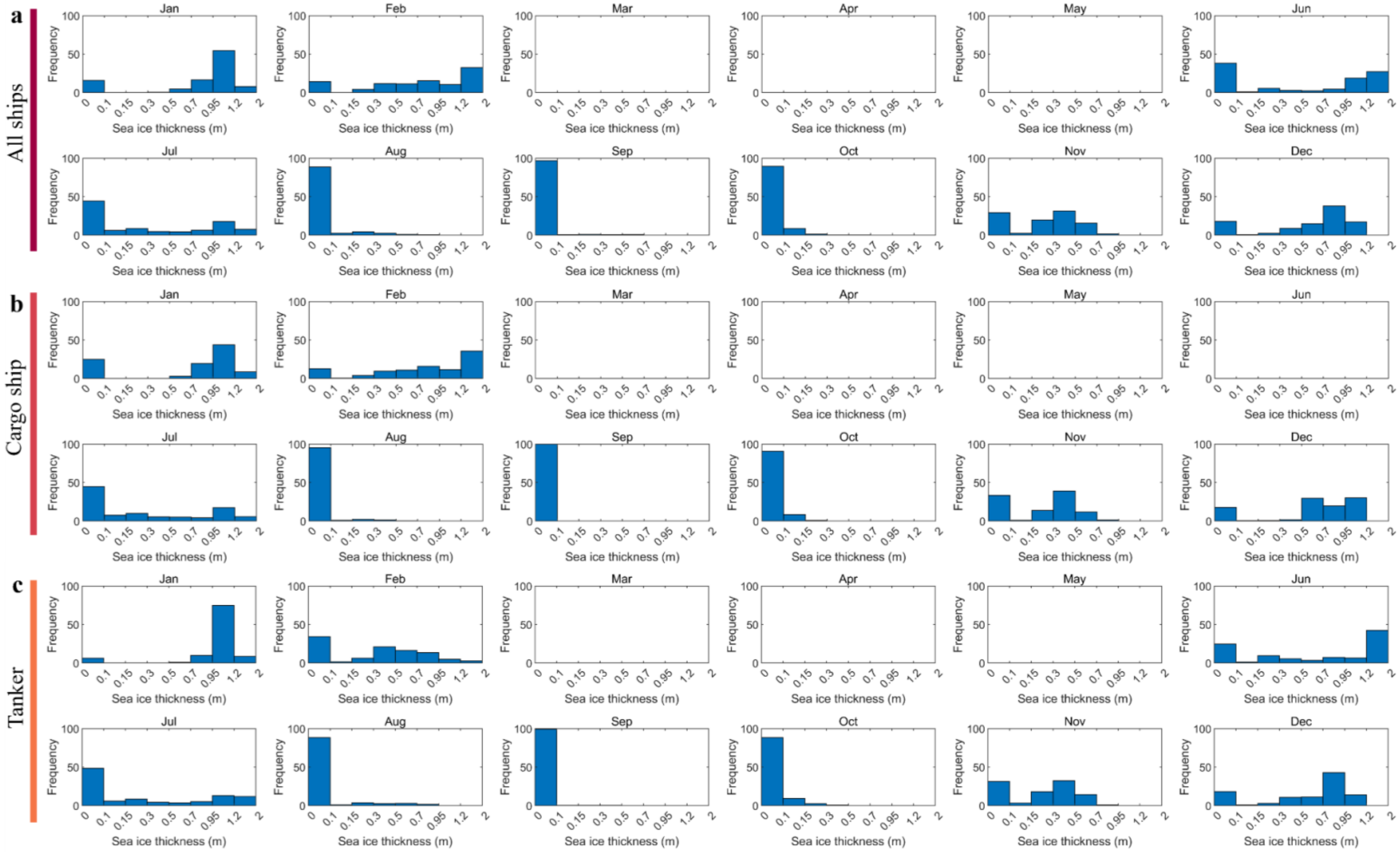

Fig. 9. Distribution of the SIT on ship trajectories: (a) all ship, (b) cargo ship, (c) tanker. Other types of ships are shown in Supplementary Fig. 9&10.

3.2.3. Impact of sea ice volume on ship routes

This paper explores the impact of various sea ice conditions on ship navigation trajectories using SIV parameters derived from SIC and SIT (refer to Fig. 10 and Fig. 11). Unlike SIC and SIT, SIV better represents ice conditions affecting ship routes, revealing that ships tend to navigate in areas with lower ice conditions. Even during severe ice conditions in January, February, and December, as well as lighter ice conditions in August and September, ship trajectories predominantly occur in areas with lighter ice conditions, with SIV below $0.25\times10^8m^3$ accounting for 97.03%, 88.79%, 84.69%, 89.62%, and 97.73% respectively. However, during peak melting (June, July) and freezing (October, November) periods, some trajectories encounter more severe ice conditions, with SIV below $0.25\times10^8m^3$ ranging from 56.09% to 82.99%. Notably, November records instances (35.78%) of trajectories encountering SIV exceeding $1.00\times10^8m^3$, indicating a potential lack of real-time ice condition information. This trend holds across various ship types. Fishing trajectories in August and November experienced increased proportions of SIV exceeding $0.5\times10^8m^3$ due to encounters with thicker ice in the East Siberian Sea. Icebreaker trajectories primarily navigate in SIV below $0.25\times10^8m^3$, except during specific months (July, August, October, and November) when piloting tasks lead them into areas with more severe ice conditions. Overall, ships exhibit a preference for navigating in areas with SIV below $0.25\times10^8m^3$, prioritizing ice-free or lighter ice conditions whenever feasible.

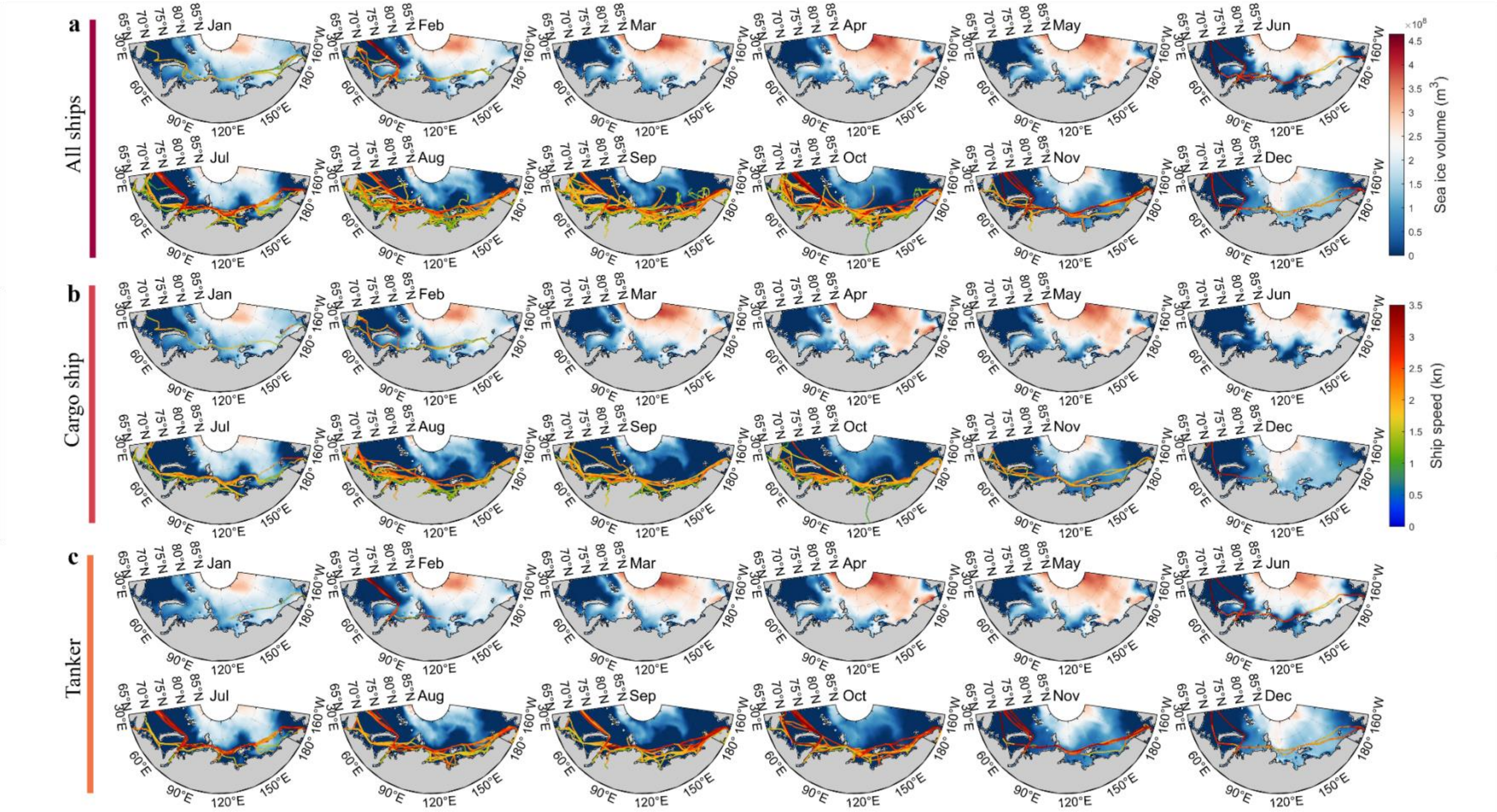

Fig. 10. Distribution of ship trajectories and SIV across months: (a) all ship, (b) cargo ship, (c) tanker. Other types of ships are shown in Supplementary Fig. 11&12.

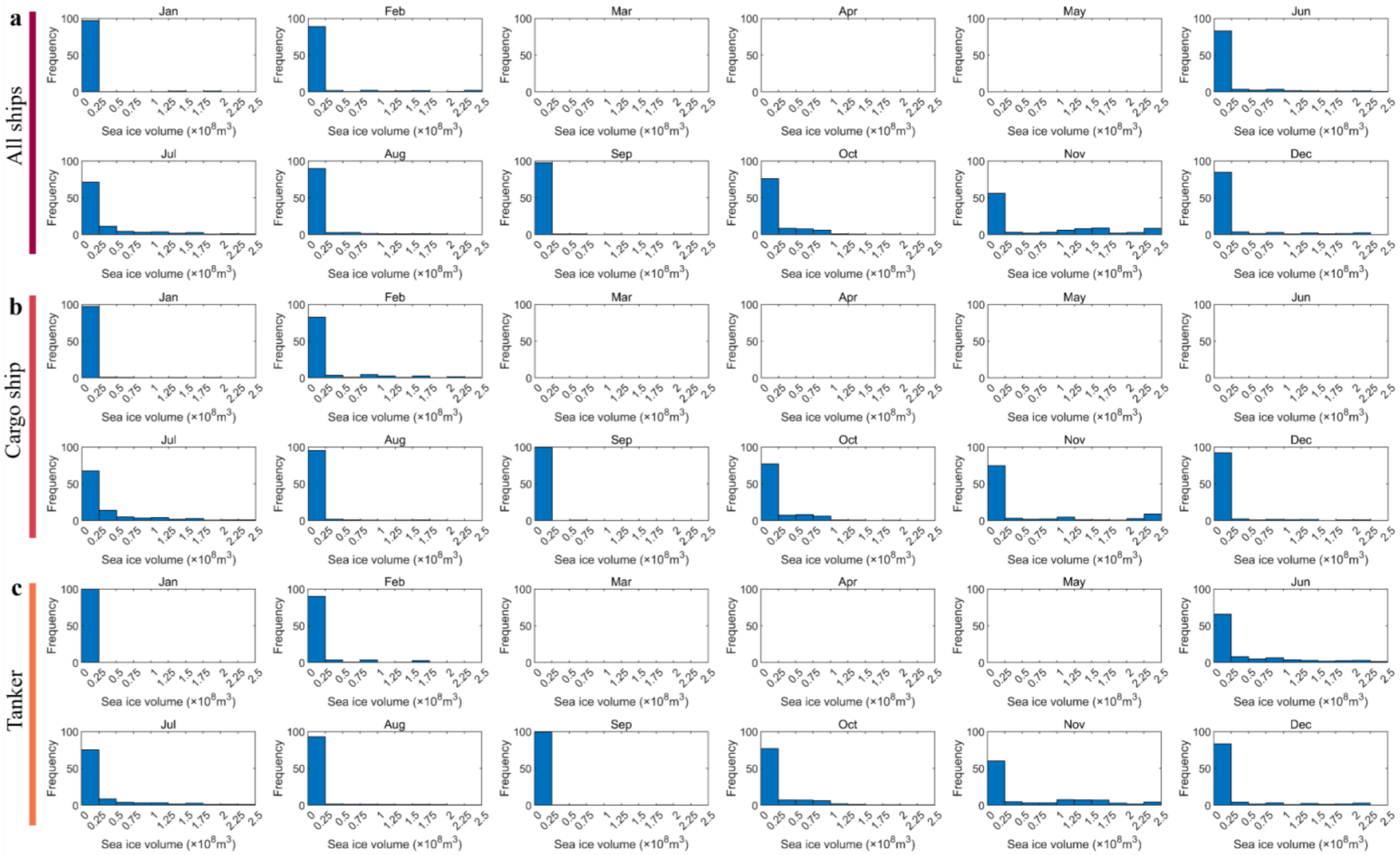

Fig. 11. Distribution of the SIV on ship trajectories: (a) all ship, (b) cargo ship, (c) tanker. Other types of ships are shown in Supplementary Fig. 13&14.

3.3. Impact of sea ice on ship speed

In this section, we examine the distinct impacts of SIC, SIT, and SIV on ship speed by analyzing speed distribution data. We provide statistics for all ships, cargo ships, and tankers, while further details regarding passenger ships, fishing vessels, icebreakers, and other ship types are accessible in the Supplementary Information.

3.3.1. Impact of sea ice concentration on ship speed

The relationship between SIC and ship speed was analyzed, revealing distinct patterns across ship types (see Fig. 12). Overall, ships predominantly sailed in SIC intervals below 20%. Notably, 70.78% of ships sailed in the 0%-30% SIC range, with 62.01% maintaining speeds between 6kn-14kn. Tankers exhibited higher speeds compared to cargo ships, aligning with this distribution pattern. Passenger ships tended to navigate at speeds below 12kn, especially in SIC intervals below 10% and 90%-100%. Fishing vessels avoided high SIC areas, with most speed records below 30% SIC and speeds often below 2kn during fishing operations. Icebreakers displayed more uniform distribution across SIC intervals but were more prevalent in the 90%-100% SIC range. Other ship types, including research vessels and drilling ships, favored SIC intervals below 30%, with speeds often below 6kn.

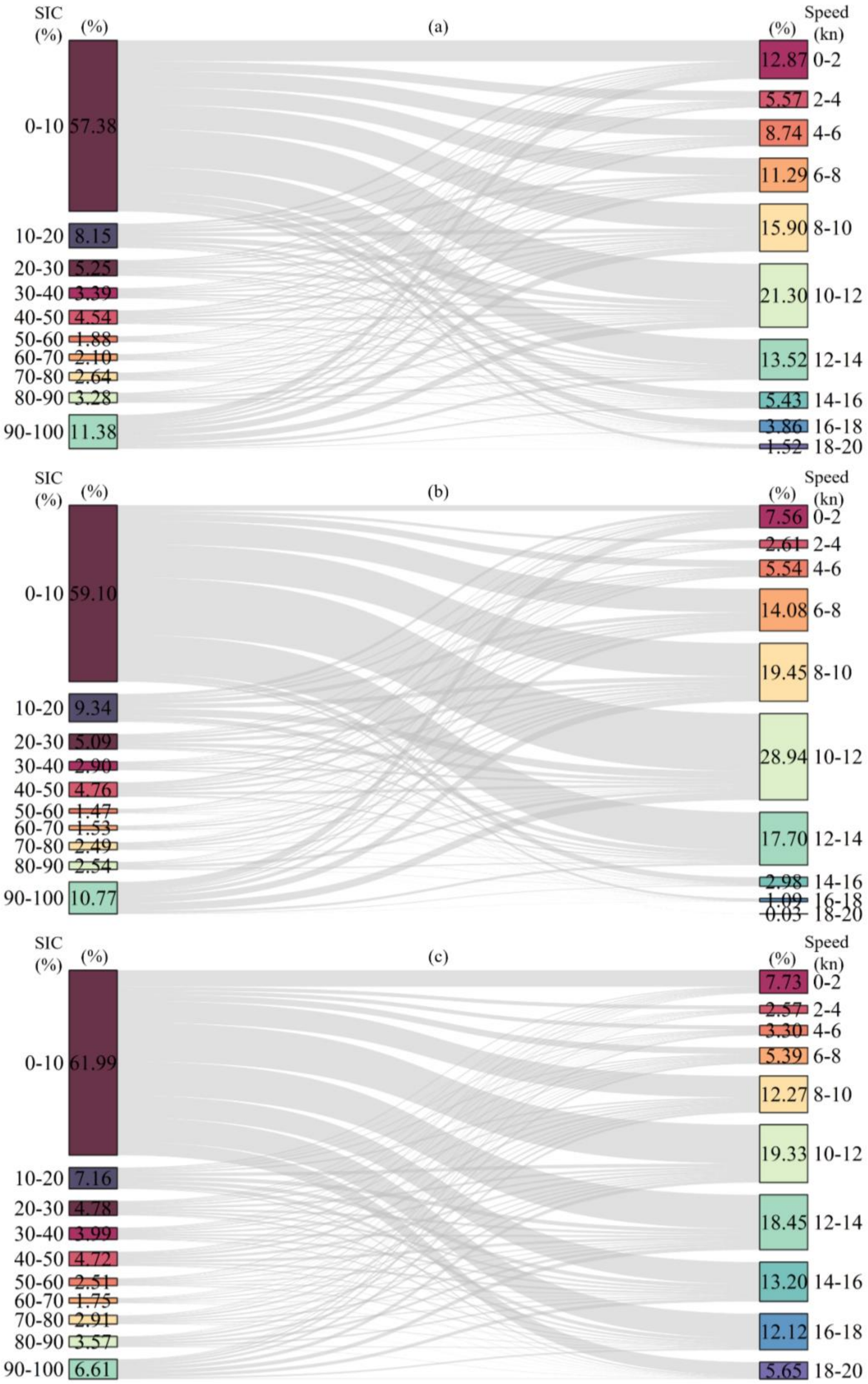

Fig. 12. Distribution of ship speed under various SIC conditions: (a) all ship, (b) cargo ship, (c) tanker. Other types of ships are shown in Supplementary Fig. 15&16.

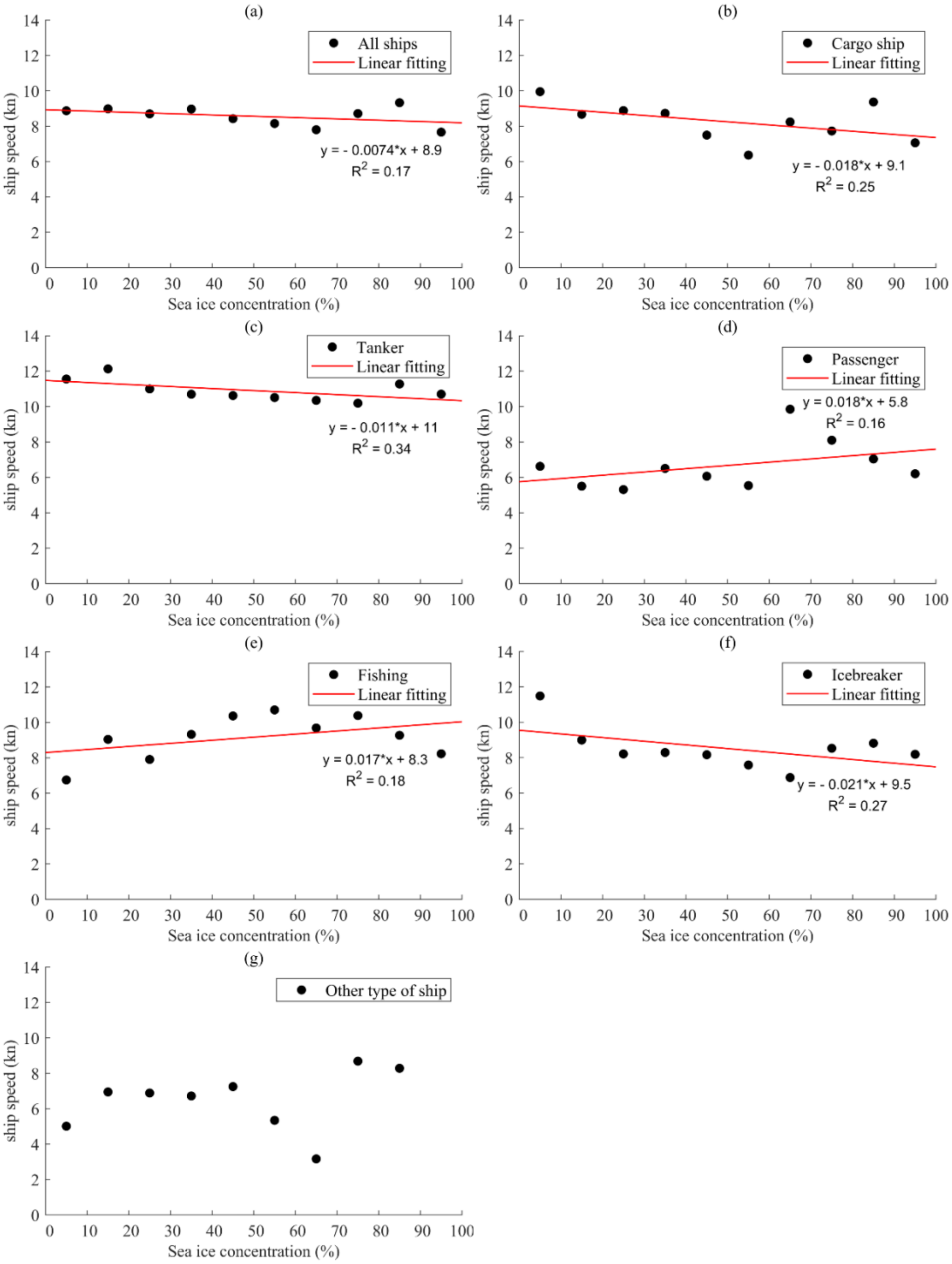

Fig. 13. Correlation between SIC and ship speed: (a) all ship, (b) cargo ship, (c) tanker, (d) passenger ship, (e) fishing, (f) Icebreaker, (g) other type of ship.

The correlation between SIC and ship speed for all ships showed a low R² value of 0.17, indicating no significant trend of decreasing speed with increasing SIC. Overall, ship speed distribution remained relatively uniform across different SIC intervals, with an average speed of 8.56kn. The cargo ships and tankers speed also decreases with the increase of the SIC. Because the regression coefficient for cargo ships and tankers was -0.018 and -0.011, cargo ships were declining faster than tankers. However, the average speed of tankers and cargo ships in each SIC interval was 10.90kn and 8.25kn, with tankers exceeding cargo ships with an average of 2.65kn. The R^2 of the linear fitting of cargo ships and tankers to the SIC were 0.25 and 0.34, which indicated that the correlation between tankers and SIC was higher than cargo ships. The regression coefficient of 0.018 and 0.017 for passenger ships and fishing under the different SIC intervals, the speed distribution showed an increasing trend. The portion of passenger ships with greater than 60% of the SIC was mainly distributed in January and February, and their higher navigation speed may have been due to the pilotage of icebreakers. But the speed distribution of passenger ships in the SIC 60%-100% interval reflected a significant decrease. The reason that fishing speed increased in the higher SIC may have been due to the relatively small percentage of data being counted, which resulted in inaccurate statistics. It was also possible that the average speed was too small because when counting the average speed of the fishing in the 0%-10% interval of the SIC, 37.67% of the fishing speed lower than 3kn was recorded. The average speed value obtained by removing records of fishing speed lower than 3kn in the 0%-10% interval of the SIC was 9.63kn. The linear fitting of the icebreaker's speed to the SIC resulted in the R^2 of 0.27 and the regression coefficient of -0.021, with a better correlation and declining trend of speed compared to all ships. It was worth noting that the average speed of the icebreaker exceeded 8kn at the SIC more than 80%, which could lead to higher speed for the pilotage ships in severe ice condition waters. The other types of ships did not navigate through waters with more than 90% of the SIC. In addition, the mean values of speed distributed in the 70%-90% interval of the SIC were too high probably because the number of counting points was too small resulting in inaccurate results, accounting for 0.02% and 0.03% of the total number of counted speed. The average speed value obtained by removing the records with speed below 3kn in other type of ships in the 0%-10% interval of the SIC was 6.34kn. Overall, the decreasing trend of ship speed with the increase of the SIC was not significant. Among them, tankers had a better correlation with the SIC compared to other ship types.

3.3.2. Impact of sea ice thickness on ship speed

This section explores the relationship between SIT and ship speed, illustrating the quantitative link between the two (see Fig. 14). Across all ships, the majority (72.63%) navigate in SIT intervals between 0m-0.1m, with speeds mainly concentrated between 6kn-14kn. Notably, cargo ships (28.94%) and tankers (50.98%) exhibit distinct speed distributions, with tankers generally sailing at higher speeds, especially in thinner ice. Passenger ships demonstrate a decrease in the proportion of speeds below 12kn compared to all ships, favoring SIT intervals of 0.7m-2m. Fishing vessels typically encounter thinner ice (not exceeding 0.95m) and maintain speeds mainly between 0kn-2kn and 10kn-12kn. Icebreakers show a larger proportion navigating in thicker ice (0.95m-2m), with speeds distributed between 6kn-14kn. Other ship types generally exhibit a decrease in speed with increasing SIT, with speeds predominantly below 10kn.

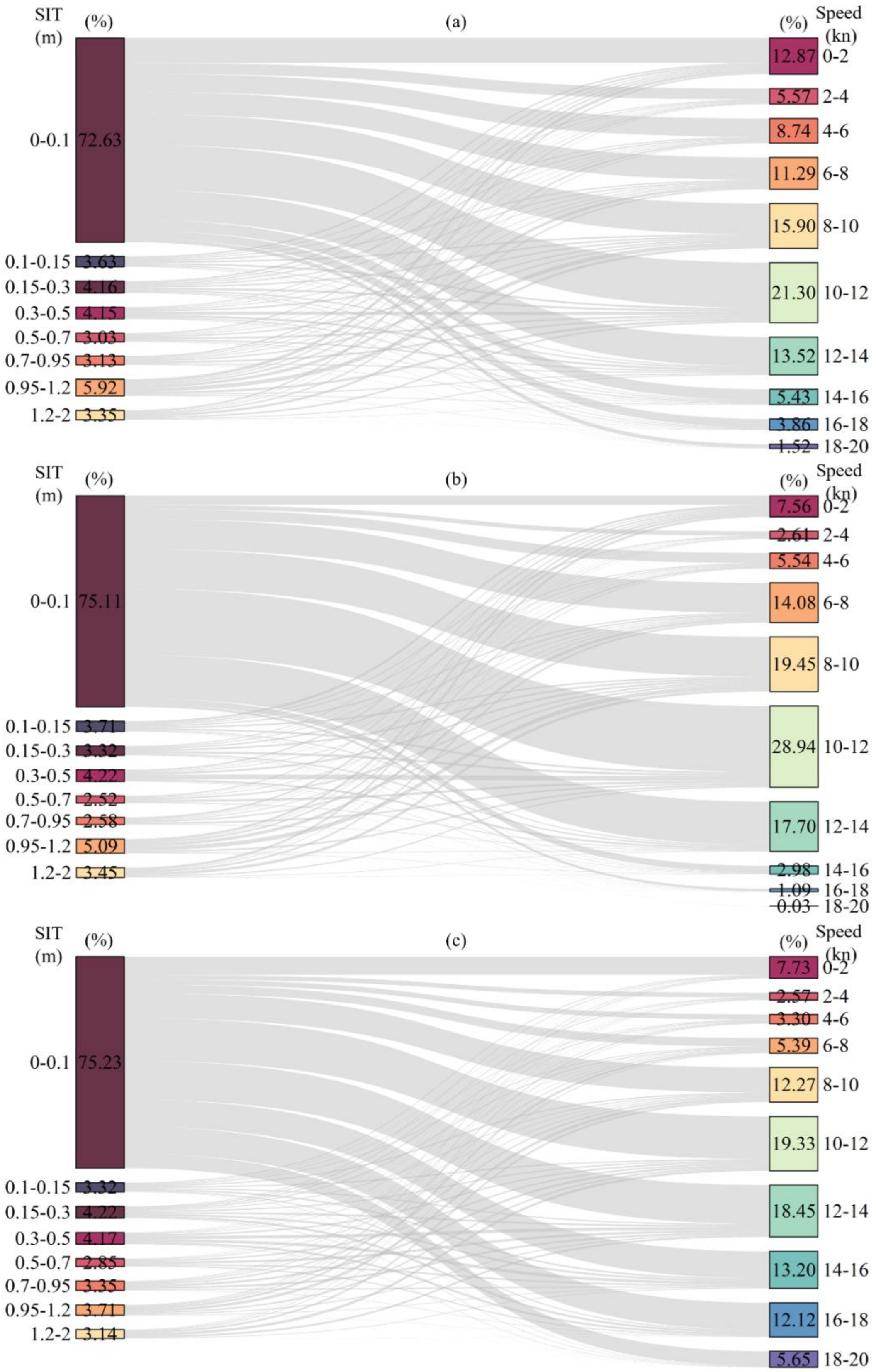

Fig. 14. Distribution of ship speed under various SIT conditions: (a) all ship, (b) cargo ship, (c) tanker. Other types of ships are shown in Supplementary Fig. 17&18.

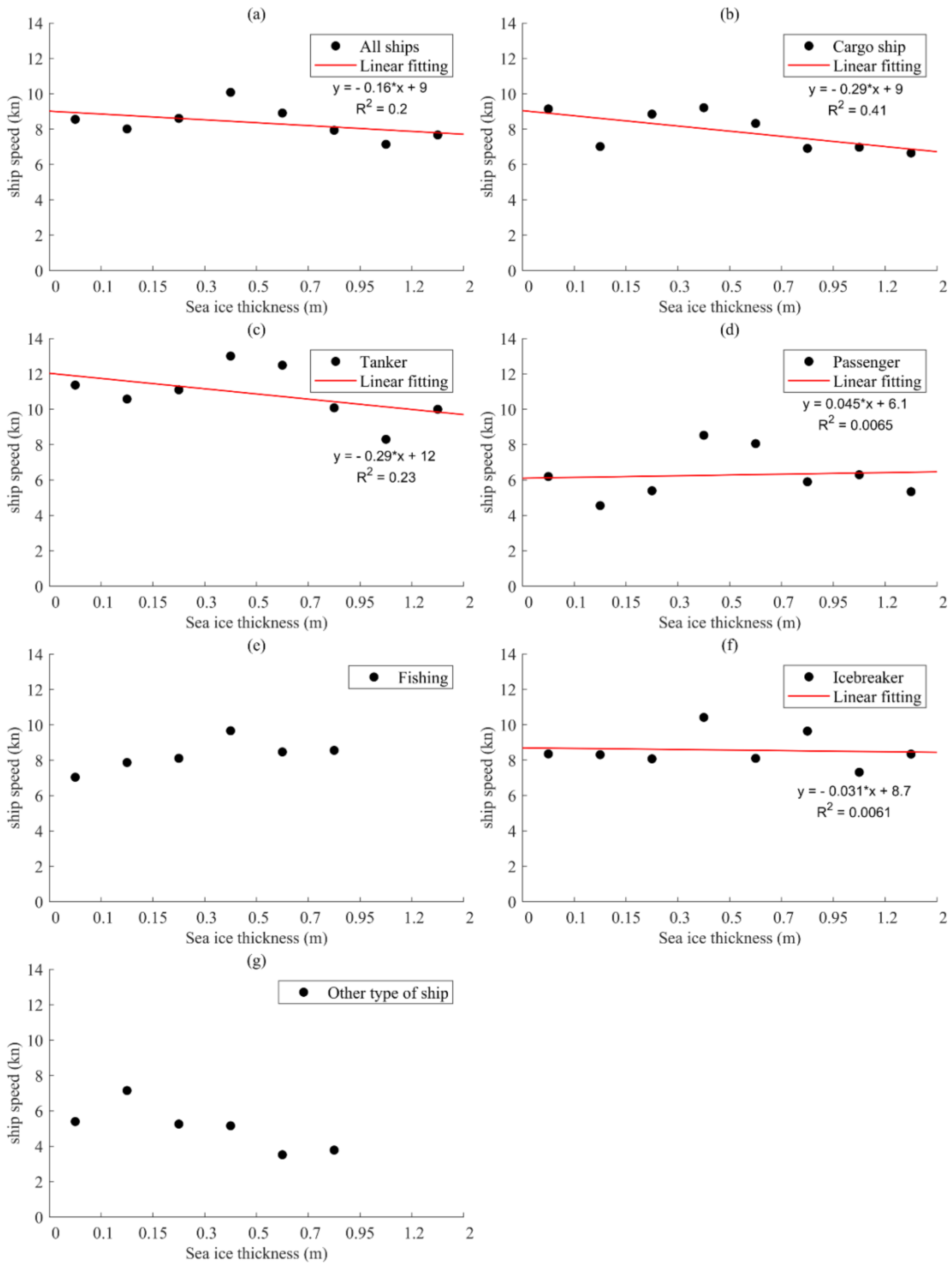

Fig. 15. Correlation between SIT and ship speed: (a) all ship, (b) cargo ship, (c) tanker, (d) passenger ship, (e) fishing, (f) Icebreaker, (g) other type of ship.

Furthermore, the impact of SIT on ship speed is analyzed for each ship type (see Fig. 15). The linear regression coefficient for all ships with SIT is -0.16, indicating a decrease in speed with increasing SIT, albeit less significant compared to SIC. Cargo ships and tankers show higher correlation coefficients with SIT (0.41 and 0.23 respectively), indicating a more pronounced decrease in speed with increasing SIT. Passenger ships and fishing vessels display an increasing trend in speed corresponding with SIT, although the correlation is weaker for passenger ships. Icebreakers show little correlation with SIT, indicating minimal impact on their speed. Conversely, other ship types exhibit a decrease in speed with increasing SIT. Overall, the correlation between ship speed and SIT is stronger than that with SIC.

3.3.3. Impact of sea ice volume on ship speed

In this section, the relationship between SIV and ship speed intervals is examined (see Fig. 16). Unlike the individual analysis of SIC and SIT, SIV provides a more comprehensive reflection of sea ice conditions' impact on ship speed. The majority (81.01%) of all ships operate in SIV intervals below 0.25×108m3, with speeds concentrated between 8kn-14kn. Both cargo ships and tankers exhibit similar distribution patterns, although tankers generally operate at higher speeds. Notably, passenger ships show a higher proportion in SIV intervals of $1.25\times10^8 m^3$-$2\times10^8 m^3$, with speeds mainly below 10kn. Fishing vessels operate primarily in SIV intervals below $0.25\times10^8 m^3$, with slower speeds predominantly in the 0kn-2kn range. Icebreakers, while navigating in thicker ice, display more even speed distributions across various SIV intervals. Conversely, other ship types operate at lower speeds, with essentially all records falling under the SIV of $0.25\times10^8 m^3$.

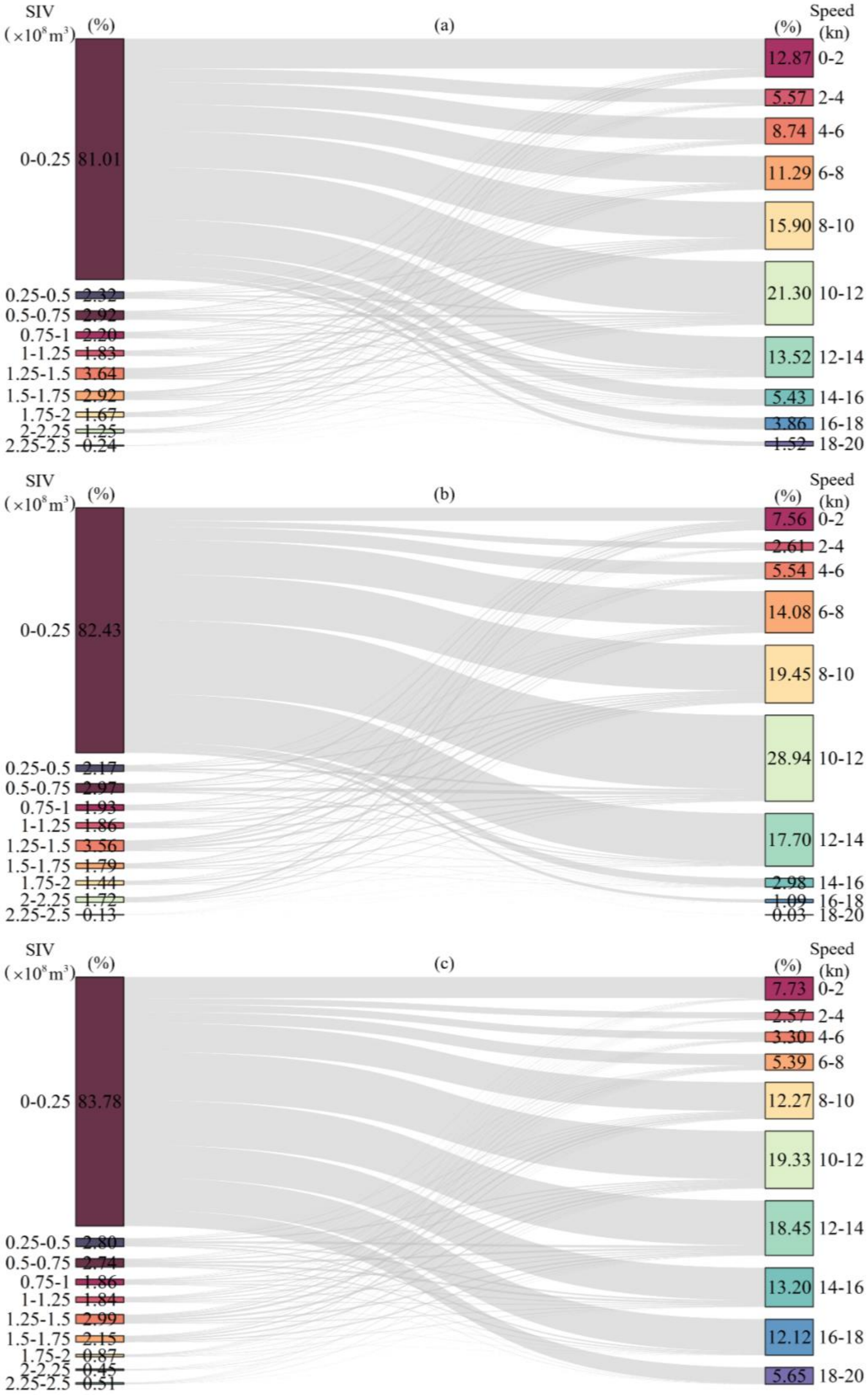

Fig. 16. Distribution of ship speed under various SIV conditions: (a) all ship, (b) cargo ship, (c) tanker. Other types of ships are shown in Supplementary Fig. 19&20.

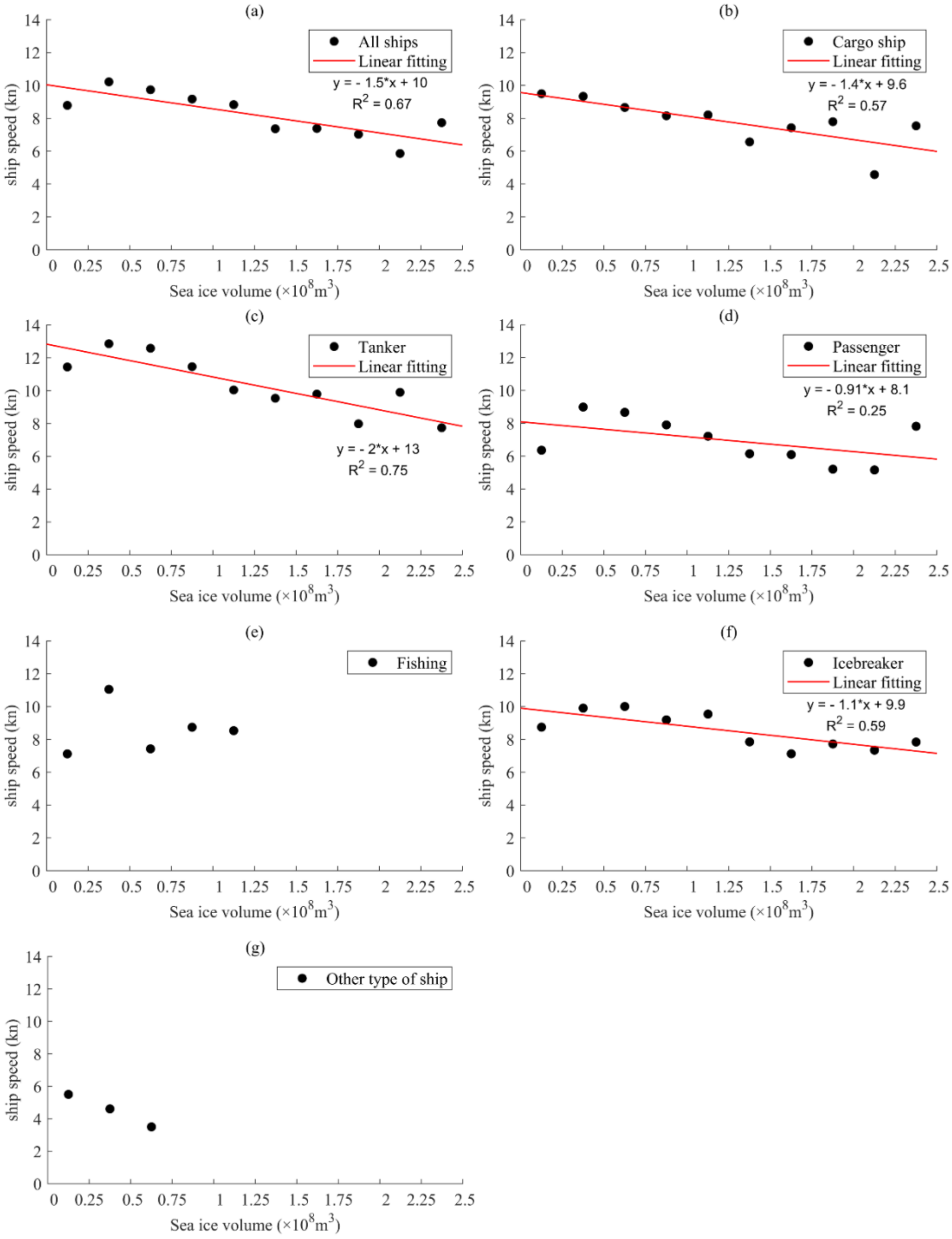

Fig. 17. Correlation between SIV and ship speed: (a) all ship, (b) cargo ship, (c) tanker, (d) passenger ship, (e) fishing, (f) Icebreaker, (g) other type of ship.

Further analysis of the SIV's impact on ship speed reveals notable trends (see Fig. 17). The linear fitting of all ships with SIV shows a clear decreasing trend in ship speed, with an R^2 value of 0.67, indicating a strong correlation. Cargo ships and tankers also exhibit significant correlations with SIV (R^2 of 0.57 and 0.75 respectively), demonstrating a decrease in speed with worsening ice conditions. Passenger ships, however, show an increasing trend in speed with SIC and SIT, but a decreasing trend with SIV. This underscores the scientific validity of using SIV to describe sea ice's effect on ship speed. For fishing vessels, removing data points in the lower SIV interval notably increases the average speed, suggesting a bias towards slower speeds in thicker ice conditions. Icebreakers show the strongest correlation with SIV (R^2 of 0.59), with a notable decrease in speed as ice conditions worsen. Conversely, other ship types exhibit decreasing speeds with increasing ice conditions.

In summary, SIV proves to be a more comprehensive indicator of sea ice impact on ship navigation compared to SIC and SIT. Across all ship types, the conclusion remains consistent: ice conditions significantly influence ship speed.

4. Discussion

The increasing accessibility and significant economic benefits of the NEP have led to a rise in ships opting to navigate along this route (Wu et al., 2024). However, sea ice remains a critical factor affecting the safety of ship transportation in this region, with current observation and forecasting capabilities falling short of meeting navigation needs (Wu et al., 2022). Ships traversing the NEP often encounter sea ice, leading to potential collisions and risks such as hull damage and ice entrapment if ice conditions surpass the ship's structural strength and ice resistance (Tseng and Cullinane, 2018).

Given the harsh Arctic climate, accidents in the NEP pose significant threats to crew safety and incur substantial economic costs (Browne et al., 2021).

This study addresses these challenges by analyzing the impact of sea ice on ship navigation behavior through the integration of sea ice data with actual navigational information. The findings are crucial for guiding ship navigation in icy waters. Specifically, the study examines the effects of SIC, SIT, and SIV on ship trajectories and speed. It compares spatial and temporal variations in the coupling of different sea ice parameters with ship trajectories and speed, revealing insights into how ship routes and speeds influence Arctic Sea ice distribution. Ultimately, the study unveils the impact and distribution patterns of Sea ice on ship trajectories and speed, providing valuable guidance for safer navigation in icy regions.

4.1. Distribution of sea ice and ships

The findings highlighted distinct seasonal patterns in ship navigation along the NEP, closely tied to sea ice conditions. In 2022, the navigation season commenced in July, peaking in September, and extending through October. This period witnessed lighter sea ice conditions, facilitating a total of 115 ship transits along the NEP, with September registering the highest activity, accommodating 83 crossings. Compared to previous studies on NEP sea ice conditions over the past four decades (Ji et al., 2021; Liu et al., 2024; Min et al., 2023), our results indicate an extended navigation window for ships, coinciding with improved sea ice conditions, which has enhanced the navigability of merchant vessels (Mahmoud et al., 2024; Pang et al., 2023).

Data from the CHNL Information Office's report on Shipping traffic at the North Sea Route (NSR) in 2022 revealed a notable surge in transit ship traffic, escalating from 18 voyages in 2015 to 85 voyages in 2021 (CHNL Information Office, 2023). Our study recorded 121 ship transits along the NEP in 2022, with transit traffic concentrated between July and October, mirroring a distinct seasonality observed in NEP navigation (Gunnarsson, 2021). These findings underscore that even slight improvements in NEP sea ice conditions can catalyze a rapid upsurge in ship traffic, with international shipping companies capitalizing on the commercial opportunities offered by the NEP.

4.2. Influence of sea ice on ship routes

This study reveals distinct variations in the distribution of ship routes under the influence of sea ice along the NEP, a finding consistent with prior research (Eguíluz et al., 2016). Notably, cargo ships and tankers exhibited similar route distributions along the NEP, primarily comprising coastal and transit routes (Rodríguez et al., 2024). Sea ice conditions and destination ports emerged as key factors influencing ship route distribution in the NEP (Wang et al., 2021; Zhao et al., 2024), elucidating the differing trajectory distributions observed for cargo ships and tankers across different periods in our study. For passenger ships, catering primarily to Arctic tourism, uncertain sea ice conditions limited their trajectory distribution along the NEP (Chen et al., 2021), with some vessels navigating to popular tourist destinations like the Svalbard archipelago (Long et al., 2023). Additionally, the trajectory distribution of fishing vessels is influenced by the location of fishery resources (Tian et al., 2022). However, our research indicates that under the influence of sea ice, fishing vessels tend to assume transportation roles along the NEP. Areas, where icebreaker trajectories were distributed, denote the presence of impassable sea ice conditions, necessitating icebreaker assistance for navigation. While icebreakers facilitate passage through ice-covered waters, they alter the trajectory of following ships beyond their icebreaking class (Duan et al., 2024). Given the unique trajectory distribution characteristics of different ship types under the influence of sea ice, accounting for ship types is essential.

4.3. Influence of sea ice on ship speed

Both SIC and SIT are correlated with changes in ship speed and have been widely utilized in studies examining the impact of sea ice on ship speed (Sibul et al., 2023). Furthermore, this study categorizes ship types to systematically analyze the influence of sea ice on ship speed along the NEP. Contrary to findings in the Baltic Sea by Löptien and Axell (2014), ship speed in our study did not exhibit a noticeable downward trend with increasing SIC and SIT. However, significant speed variations were observed when SIC exceeded 85% and SIT exceeded 0.2m. While the correlation coefficients of tanker speed with SIC and SIT in our study were lower than those reported for tankers in the East Siberian Sea (Nakanowatari et al., 2018), the decreasing trend of tanker speed with increasing SIT outweighed that with SIC, consistent with our findings. Additionally, the correlation coefficients between icebreaker speed and SIC, as well as SIT, were lower than those observed for the XUE LONG in six polar voyages (Chen et al., 2023). Notably, the R^2 for the linear fit of all ships to SIV was 0.67, surpassing that for SIC (0.17) and SIT (0.2), indicating the importance of considering SIV in studies of Arctic ship trajectories and speed.

4.4 Policy Implication

This study observed that ships adhered to the IMO's recommended speed limits for navigating in icy regions during actual voyages. The IMO's POLARIS guidelines categorize ship navigation in ice areas into three levels: normal operation, elevated operational risk, and operation subject to special considerations (IMO, 2016). Ships are required to adhere to speed limits and recommended speeds under elevated operational risk conditions. We verified the speed of cargo ships and tankers sailing independently and the pilotage of an icebreaker in ice areas. As per the POLARIS guidelines and the risk values for PC6 ice-class ships (see Table 2), the recommended speed limit for PC6 ice-class ships is 3kn when the SIC exceeds 80% and the SIT is above 1.2 meters, meeting the elevated operational risk criteria. Our result revealed that independent cargo ships and tankers all sailed under the speed limit of the guidelines. However, the average speeds of cargo ships and tankers escorted by icebreakers in January in elevated operational risk waters were 6.93kn and 5.99kn, respectively. Consequently, independently navigating ships demonstrated better compliance with the POLARIS regulations for navigating in icy waters by maintaining lower speeds, with icebreakers leading their way.

Our result elucidated a strong inverse relationship between Sea Ice Volume (SIV) and ship movements by employing data fusion methodologies for spatial-temporal monitoring and analysis of sea ice and maritime activities. This finding could be implemented in decision making process and tools to better guide the shipping navigation in the NEP. Policy makers could consider setting up standards to regulate the shipping speed and shipping route under different SIV conditions to enhance navigation safety in the NEP. Additionally, incorporating pertinent climate data enables the derivation of a more realistic depiction of ship route and speed distributions within icy zones (Akdağ et al., 2024; Luo et al., 2023), serving as fundamental groundwork for navigation planning and policy formulation in such environments.

5. Conclusion

The paper delves into the crucial role of sea ice conditions in shaping the navigational behavior and safety of ships traversing the NEP. Through an in-depth analysis of SIC, SIT, SIV, and AIS data from 2022, the study investigates how sea ice affects ship routes and speeds along the NEP, employing spatiotemporal correlations. The findings hold significant implications for governmental entities and ship pilots, offering valuable insights for optimizing Arctic shipping activities and policies. By aiding ship pilots in crafting voyage plans—covering both routes and speed design—the study contributes to safer and more efficient navigation practices. Moreover, governments and organizations can leverage the research outcomes to refine existing policies and regulations, potentially culminating in the establishment of a comprehensive guide for Arctic ship navigation.

The study highlights the NEP's navigation window, extending from July to October, coinciding with the period of lightest sea ice conditions. Notably, this timeframe witnesses the highest ship traffic along the NEP, with 115 ships recorded. Analysis reveals that ships tend to avoid ice-laden areas whenever feasible, as evidenced by a substantial percentage of ship trajectories being distributed in waters with SIC below

10% and SIT below 0.1m. Furthermore, the study underscores the inverse relationship between ship speed and sea ice conditions, with ship speeds predominantly clustered in the 6kn-14kn range, with 10kn-12kn being the most prevalent. Variations in trajectory and speed distribution among different ship types underscore the nuanced impact of sea ice on navigation behavior.

Moreover, the research underscores the significance of SIV in understanding the effects of sea ice on ship navigation, with the coefficient of determination (R^2) for the linear fitting of SIV to all ship speed reaching 0.67—significantly higher than the values obtained for SIC and SIT. This underscores the importance of considering SIV alongside traditional parameters when assessing Arctic ship navigation.

While the study sheds light on crucial aspects of Arctic ship navigation, it acknowledges certain limitations. These include challenges in gathering data on the ice class of all ships navigating Arctic waters and the absence of consideration for environmental factors like wind, snow depth, and visibility. Future research endeavors will focus on leveraging the study findings to refine ship navigation models in ice-covered waters and explore the impact of icebreakers on ship formations' navigational behavior.

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