



The impact of opening the Arctic Northeast Passage on the global maritime transportation network pattern using AIS data

Naixia Mou^{1,2} · Jie Li^{1,3} · Shuyue Sun¹ · Tengfei Yang^{4,5} · Lingxian Zhang¹ · Hengcai Zhang² · Wenbao Liu¹

Received: 13 May 2019 / Accepted: 15 May 2020 / Published online: 30 May 2020
© Saudi Society for Geosciences 2020

Abstract

Previous studies have shown that the existing maritime network presents unbalanced characteristics as reported by Mou et al. (Sustainability, 10(4): 977–989, 2018). The research in this paper shows that the network movement caused by the opening of the Arctic Northeast Passage will share part of the pressure of the Belt and Road passage, which will play a positive role in the global maritime transportation network. Based on the 2014 global container Automatic Identification System (AIS) data, this research constructs a global maritime transportation network and conducts scenario simulations on the opening of the Arctic Northeast Passage. An evaluation system based on a complex network index is established to evaluate changes in the geometric characteristics of maritime network and community characteristics, and PageRank is used to evaluate the status changes of ports in communities before and after the opening of the network. Finally, the impact of the opening of the Arctic Northeast Passage on the global maritime network pattern is analyzed and discussed. Results show that after opening the Arctic Northeast Passage, (1) the small-world features of the global maritime network are more obvious and the scale-free features are weaker, which indicates that the transportation efficiency of the global network is promoted; (2) the center of global maritime network moves northward with a latitude of 1.3° and eastward with a longitude of 4°; and (3) the importance of some ports, such as the Middle East, Mediterranean, and Southeast Asia communities, has reduced by 0.0073, 0.0078, and 0.0092 respectively. Conversely, the importance of some ports has increased, such as the Northeast Asia community and West Europe community, with increase values of 0.0074 and 0.0097 respectively. These findings are expected to provide advice on national strategies and regional port investments.

Keywords Arctic Northeast Passage · Automatic Identification System · Maritime transportation · Complex network · Scenario simulation · Network community

Responsible Editor: Amjad Kallel

✉ Jie Li
1763532140@qq.com

✉ Wenbao Liu
liuwenbao163@163.com

¹ College of Geomatics, Shandong University of Science and Technology, Qingdao 266590, China

² State Key Laboratory of Resources and Environmental Information System, Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

³ Department of Surveying and Planning, Shangqiu Normal University, Shangqiu 476000, China

⁴ Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100094, China

⁵ University of Chinese Academy of Sciences, Beijing 100094, China

Introduction

The Arctic Passage is a shipping way that crosses the Arctic Circle and connects the three economic centers, North America, East Asia, and Western Europe. As shown in Fig. 1, three passages are involved: the Northwest Passage, the Northeast Passage, and the Central Passage. Among them, the Northeast Passage is made up of the ship route that goes via the Russian Siberian region and Far East Area and connects the Atlantic Ocean and the Pacific Ocean. It spans five Arctic Oceans: the Barents Sea, the Kara Sea, the Laptev Sea, the Eastern Siberia Sea, and the Kage Sea (China MSA 2014). The opening of the Arctic Passage is an important part of the “Polar Silk Road” initiative and a useful complement to the Belt and Road initiative.

The Intergovernmental Panel on Climate Change (IPCC) fifth assessment report points out that the average annual

Fig. 1 Arctic Passage map



ocean temperature is rising at a rate of 0.11, and the amount of sea ice in the entire Arctic region is declining at a rate of about 9.4 to 13.6% per decade (Climate Change 2013; <https://www.ipcc.ch/report/ar5/wg1/>). With the acceleration of melting ice and the rise of temperature, coupled with the development of existing technology and polar marine equipment, ships are now able to sail in Arctic waters throughout the year (Hong 2012; Nam et al. 2013; Choi et al. 2015). The opening of the Arctic Passage, especially the Northeast Passage, will greatly shorten the maritime transport distance, transportation time, and fuel cost between Western Europe and Northeast Asia. For example, from St. Petersburg Port in western Russia to Vladivostok Port in the east, the route through the Arctic Passage is about 14,280 km, 8920 km less than through the Suez Canal and 15,120 km less than through the Cape of Good Hope (Jiang et al. 2012). The Arctic Passage can also make up for the shortcomings of the current traditional Passage through the Suez Canal and Malacca Channel. This way, Somali pirates and Indian Ocean pirates could be avoided and navigation risks will be reduced (Li and Sun 2011). Compared with the complex glacial topography and the nearly one-third of the fairway away from the offshore area in the Northwest Passage, the Northeast Passage is safer. In addition, United States Geological Survey (USGS) counts about 90 billion barrels of oil, 1669 trillion cubic feet of natural gas, and 44 billion barrels of natural gas liquid in the

Arctic. Russia in the Northeast Passage accounts for 52% in oil storage of the Arctic area and is also the country with the most abundant natural gas storage. The opening of the Northeast Passage provides a prerequisite for the export and utilization of Arctic resources such as natural gas and mineral products (USGS 2009; Miller and Ruiz 2014; Gautier et al. 2009). However, although the Arctic Passage has the demand and possibility of passing, it also faces some challenges, such as harsh polar climate, the demand of ice-breaking equipment in sea transportation, the extreme night, and the fragile ecological environment. Therefore, better technology and research need to be provided to support the development and protection of the Arctic region.

In the related research on the opening of the Arctic Passage, the contents mainly focus on two aspects: the navigation conditions of the Arctic Passage (Liu and Kronbak 2010; Aksenov et al. 2016; Wang et al. 2016) and the impact analysis after navigation (Ho 2010; Sun and Zheng 2016; Blunden 2012). According to different indicators, the risk assessment on the possibility of opening the Arctic passage is carried out. The impact of the opening is analyzed from the perspectives of economic interests, political status, and maritime transportation network. The data adopted in the research process of Arctic is mainly conducted from two perspectives: OD data (for a network border, O for origin, D for destination) and non-OD data, where non-OD data includes statistic data such as

navigation time (Liu and Kronbak 2010; Aksenov et al. 2016; Wang et al. 2016), navigation distance (Hong 2012; Sahin and Kum 2015), and navigation cost (Lindstad et al. 2015; Suárez de la Fuente et al. 2018) and natural geographic data such as meteorology (Smith and Stephenson 2013; Mao and Rychlik 2018), hydrology (Stephenson et al. 2014; Lei et al. 2015; Afenyo et al. 2017), as well as economic and trade statistic data (Ho 2010; Sun and Zheng 2016; Blunden 2012). For example, Bye and Aalberg (2018) make statistical analysis based on maritime accident data and finally determine the indicators that could be used as risk assessment of maritime accidents that were ship type, weather conditions, and flag state. Aksenov et al. (2016) use the RCP8.5 IPCC emission scenario to check the navigation of the Arctic route, arguing that the summer route in the Arctic route in the mid-twenty-first century would be as fast as the North Sea route. At present, based on OD data research, global maritime network research focusing on the global scale and the Belt and Road region is to be widely carried out. For example, Peng et al. (2018) analyze and compare the robustness of three global freight networks, oil tankers, container tanks, and bulk carriers, based on complex network methods and find that hub ports played a key role in the connectivity of marine transportation networks. Mou et al. (2018) use the complex network method to conclude that the maritime network of Maritime Silk Road had characteristics of uneven distribution. However, there is relatively little research in the Arctic area. The main research on the Arctic around OD data includes that of Li et al. (2015) and Li et al. (2017); they made a static analysis of the trade structure network of the Arctic route by using the structural hole theory and discussed the evolution process of the complex network structure of the sea after the navigation of the Arctic Passage. They think the opening will make the Arctic economic circle more closely linked. Based on ship route data and freight data, Lin and Chang (2018) use the spatio-temporal network method to conclude that navigation skills and fuel prices are the main factors affecting the commercial utility of NSR. Wang et al. (2017), based on the container shipping network study, find the average transportation cost of the Arctic channel is lower than that of the traditional passage.

In the existing research on the opening of the Arctic Passage, compared with the non-OD data such as statistical data, the network constructed on the basis of OD data extracted from ship's Automatic Identification System (AIS) trajectory can better reflect the characteristics of the maritime transportation network. But the research based on OD data is much less than that based on non-OD. Besides, most of the research based on OD data is static analysis of the maritime transportation network, such as network connectivity analysis and transportation efficiency analysis. The research lacks dynamic analysis based on network indicators to explore the maritime

transportation network, such as spatial and temporal changes of network structure, and transfer of ports between communities. In addition, most of these studies are directed at the analysis of the status quo, short of predictions for the future, or limited to the study of the Arctic Passage itself. In this paper, not only is Arctic Passage itself studied but also the whole of the global transportation network is put into consideration. The transportation network after the opening of the Arctic Northeast Passage is simulated on the basis of AIS data. The maritime routes from China, Japan, and Korea to Northwest Europe are shared by the Northeast Passage. The changes of the global maritime transportation network structure during the whole opening process, the changes of maritime transportation network community, and the changes of the status of its ports within the community are analyzed from the perspectives of qualitative assessment and quantitative analysis. The impact of the Arctic Northeast Passage on the global maritime transportation network is analyzed by using a complex network method that combines static structure features and the dynamic structure features of the maritime transportation network.

Research area and data

The opening of the Arctic Northeast Passage will greatly promote the connection between Northeast Asia and Northwest Europe. East Asia is the world's largest manufacturing center and the European Union's (European Union, EU) largest import market, and Europe is in turn East Asia's largest trading partner and import market. As the largest importer in East Asia, China is an important stakeholder in Arctic affairs. Geographically, it is a "Near-Arctic State" (Jian 2018). Since the establishment of the National Ocean Forecasting Center in 2010, it has provided ice forecasting for ice navigation and scientific investigation in the Arctic region many times (Li et al. 2018). Since 2013, COSCO SHIPPING Specialized Carriers Co., Ltd., has organized 22 sub-ships to carry out voyage missions on the Arctic Northeast Passage. China, Japan, and Korea are the top countries in Northeast Asia's economic development and coastal countries. Therefore, in this paper, the maritime trade transportation between the three Northeast Asian countries of China, Japan, and Korea, and Northwest Europe, is shared to simulate the situation after the opening of the Northeast Passage.

The Northwest Europe area includes 7 countries, i.e., Sweden, Norway, Finland, Denmark, Iceland, the Netherlands, and Belgium, with a total of 386 ports. China, Japan, and Korea cover a total of 247 ports. The distribution of research areas and ports is shown in Fig. 2. Combined with the information, such as the World Port Index published by NGA

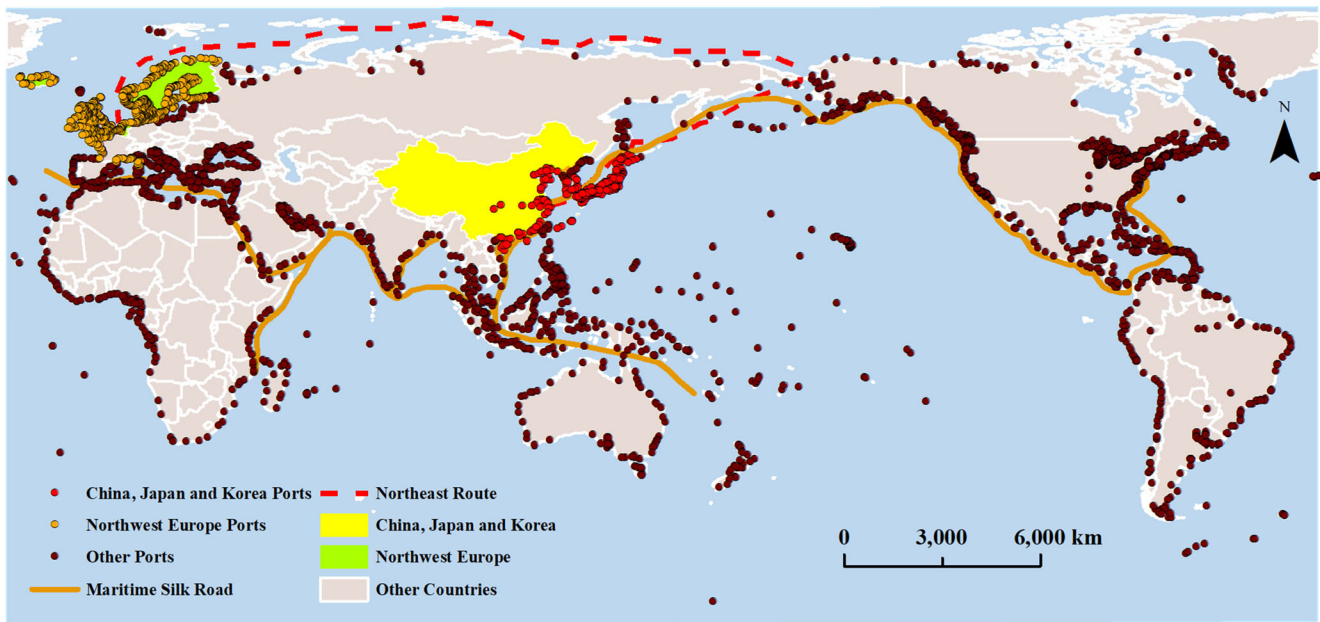


Fig. 2 The study areas and ports

(National Geospatial-Intelligence Agency) and the world port navigation guides, the whole year's container AIS data from January 1 to December 31, 2014, is used to match spatial location for trajectory data and extract OD data of ships traveling between ports. The processed AIS data includes ship ID, OD port index, and docking time. There are 2,930,28 pieces of OD data, including 4531 ships and covering 1346 ports worldwide. Among them, 2570 ships sail out of China, Japan, and Korea and 402 ships sail to the Northwest Europe region with a total of 1020 voyages.

Scenario simulation

Scenario simulation refers to the process of designing a scenario according to actual conditions and research purposes to predict and analyze the impact of the opening of the Arctic Northeast Passage. Broek and Den (2014) use the GSIM (global simulation model) method to infer the undeveloped port locations in the Arctic and calculate future traffic and trade volumes. This paper assumes that the Northeast Passage in the Arctic area is fully opened. Combining geo-indicators, such as terrain data, sea ice data, harbor size, and national Trade Complementarity Index (Kuang and Wang 2011; Sang and Yang 2015), appropriate Arctic port nodes are selected to form a new network connectivity border, and then traditional container maritime transportation from China, Japan, and Korea to Northwest Europe is shared into the simulated route. The scenario simulation process is shown in Fig. 3, mainly including two processes: network simulation and network sharing.

Network simulation

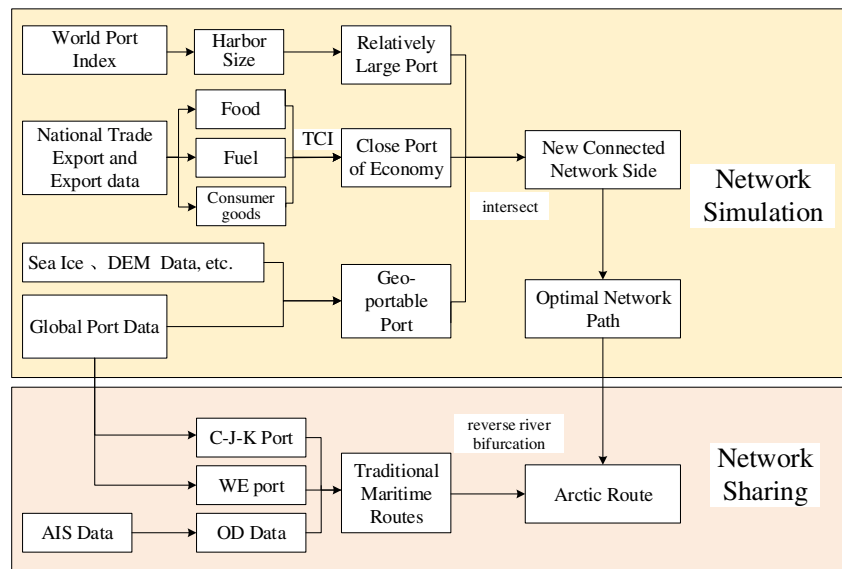
The harbor size information comes from the HARBORSIZE field in World Port Index (2017 version). Considering that the Arctic Passage is mainly used for transporting heavy cargo, such as natural gas, coal, and other natural resources (Gao et al. 2018), three types of ports *L* (large)/*M*(medium)/*S*(small) are selected in this paper, temporarily not considering the opening of *V* (very small) port.

TCI (Trade Complementarity Index) is used to measure the closeness of trade relations between two countries. Global import and export trade data in 2014 (data from the World Bank: <http://www.worldbank.org/>) are used to calculate the average of the Trade Complementarity Index (Yu 2009) among Arctic countries, according to the three trading items of food, fuel, and finished products. The computational formula is shown in Eq. (1):

$$E_{ijk} = RCA_{xik} \times RCA_{mjk} \times RCA_{xik} = \frac{X_{ik}/X_i}{X_{wk}/X_w}, RCA_{mjk} = \frac{M_{jk}/M_j}{M_{vk}/M_v} \quad (1)$$

In Eq. (1), E_{ijk} is the Trade Complementarity Index between country i and country j . RCA_{xik} is comparative advantages of export commodity k in country i . RCA_{mjk} is comparative disadvantages of import commodity k in country j . X_{wk} is world exports of product k and X_{ik} country i is exports of product k . X_w and X_i are world and country i exports of all the products respectively. M_{vk} and M_{jk} are world and country j imports of product k . M_v and M_j are world and country j imports of all the products. The greater the value of E_{ijk} is,

Fig. 3 Scenario simulation diagram(C-J-K means China, Japan, and Korea, WE means West Europe)



the more frequent trade between the two countries and the greater the possibility of navigation between ports it has. Generally speaking, when $E_{ijk} > 1$, the complementarity between the two countries is higher than the average of other markets, and the trade relationship between the two countries is relatively close. The countries that meet the conditions are shown in Table 1.

Among the countries with high national Trade Complementarity Index, three types of ports (*L/M/S*) with simple terrain and good ice conditions are selected. Finally, 179 ports are determined, including 27 ports in Russia, 37 ports in Sweden, 31 ports in Norway, 22 ports in Finland, 30 ports in Denmark, 21 ports in Iceland, 10 ports in Greenland, and 1 port in the USA. Thus, a total of 1090 network borders are added.

Network sharing

Existing literature studies show that in the Arctic Northeastern Passage, the area with the longest navigational time is the Chukchi Sea. The navigation period is from early July to

Table 1 Trade Complementarity Index of Northeast waterway countries

Country	Country	E_{ijk} (TCI)	Country	Country	E_{ijk} (TCI)
Russia	Norway	19.525	Norway	Sweden	2.269
Russia	Greenland	11.147	Denmark	Russia	1.971
Iceland	Norway	10.401	Denmark	Norway	1.839
Russia	Finland	3.241	Finland	Greenland	1.727
Finland	Norway	3.024	Greenland	Sweden	1.295
Russia	Sweden	2.432	Denmark	Greenland	1.050

mid-to-late November (Zhang et al. 2019; Niederdrenk and Notz 2018; Rodrigues 2008). It is estimated that in the route from Shanghai Port and Dalian Port to Russia’s Murmansk Port, the Arctic Passage will share 35% freight volume of the traditional passage (Gunnarsson 2012; Ragner 2000; Wu and Lang 2017). On the basis of existing Arctic port freight volume, taking Arctic strategies (Bechselica 2018; <http://www.arctic-lio.com/NSR>) of Russia into consideration and assuming that temperatures, glaciers, and other navigation conditions are ideal, the sharing rate in this study is selected as 35%, and the opening time is selected from July to November of each year. In the network sharing process, only 35% of the marine transportation in traditional passage during this period is shared.

When the ships pass through traditional passage, the routes from China, Japan, and Korea to Northwestern Europe can be represented as:

[Port 1(China, Japan, Korea), Port 2, Port 3, ..., Port *N* (Northwest Europe)]

where *N* is the total number of ports in each traditional route, and Port 2, 3 ... stand for intermediate ports of traditional passage in between the shipping routes which start from China, Japan, and Korea. After being shared, the route passing through the Arctic Northeast Passage should satisfy:

[Port 1(China, Japan, Korea), Port 2', Port 3', ..., Port *M* (Northwest Europe)]

where *M* is the total number of ports in each northeast route, and Port 2', 3'... stand for intermediate ports of the Northeast Passage in between the shipping routes which start from China, Japan, and Korea.

In addition, the northeast route that shares the traffic volume should be the optimal route between the starting port and ending point. In order to better measure the difference in the merits of each path, the maximum value of each path in the

Arctic is processed by maximum-minimum normalization to consider the impact brought by both existing maritime transportation and port berthing. First of all, the average weight value in the network path is calculated, as is shown in Eq. (2):

$$\bar{w}_i = \frac{\sum_{j=1}^k w_j}{k} \quad (2)$$

where w_j is the node weight in the calculated path, and k is the number of nodes in the path, and also number of berthing ports. Then, the path is standardized in Eq. (3):

$$W_i = \frac{\bar{w}_i - w_j^{\min}}{w_j^{\max} - w_j^{\min}} \quad (3)$$

where w_j^{\min} and w_j^{\max} are the minimum and maximum values of the node weights in the path, respectively, and W_i is the standardized value of the i th route. The larger the value of W_i is, the more obvious the advantage of the route is.

Based on the reverse river bifurcation principle (Yu 2014), the ports of Northwest Europe at the ending branch converge into the ports of China, Japan, and Korea at the source; therefore, the weights to be shared by each Arctic route are calculated and corresponding weights are subtracted from the traditional paths to be shared. The final opening maritime transportation network is shown in Fig. 4.

Functions

Based on the indicators of the maritime transportation complex network, the basic geometric characteristics and

connectivity changes of the network are analyzed, and the Modularity Index is used to obtain the community division status of the global maritime network. Combining the PageRank's method, the changes of port status in community are studied. The specific process is shown in Fig. 5.

Complex network indicators

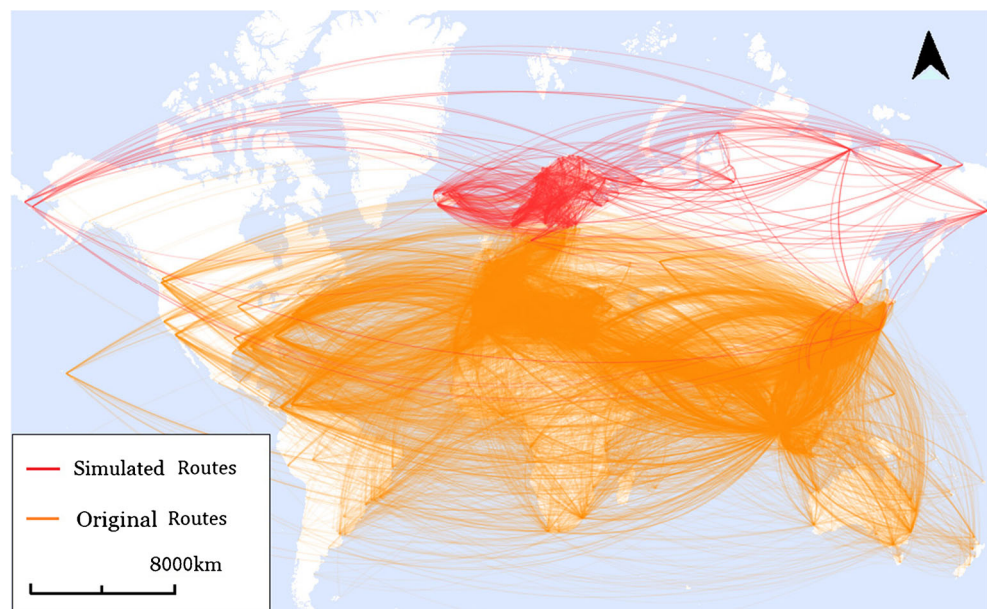
With the global ports as the nodes and the transportation routes between the ports as borders, a global maritime complex network is built. The overall geometric characteristics and connectivity of the network are represented by calculating the average path length, average clustering coefficient, and degree of the network.

The average path length is the average of the distance between any pair of nodes in the network, i.e., the average number of borders to go through from one node to another (Wang et al. 2006). The calculation method of this indicator is shown in Eq. (4), where d_{ij} refers to the distance between node i and node j , i.e., the number of borders on the shortest path connecting the two nodes, and n refers to the number of network nodes. In the maritime transportation network, the average path length L indicates the average number of ports where ships need to berth during transportation. The smaller the value is, the higher the transportation efficiency of the network is.

$$L = \frac{1}{\frac{1}{2}n(n+1)} \sum_{i \geq j} d_{ij} \quad (4)$$

The clustering coefficient indicates the degree of closeness of interconnection between nodes in the network, and the computational formula is shown in Eq. (5). The average

Fig. 4 Comparison of simulated routes and original routes



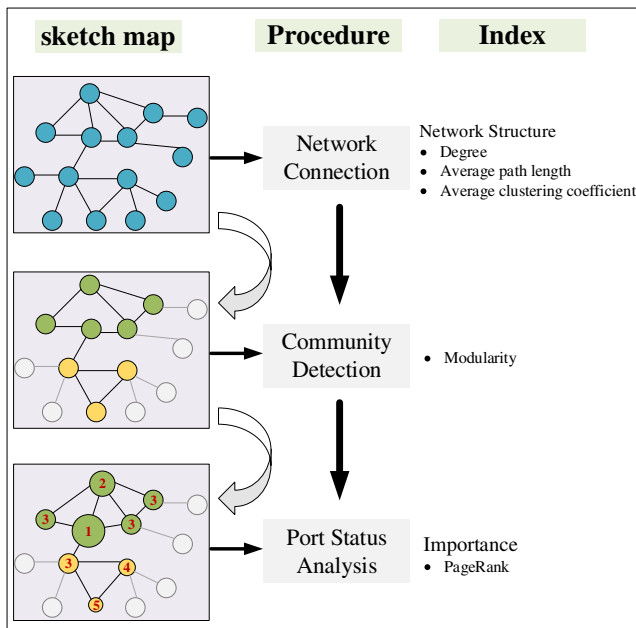


Fig. 5 The research framework map

clustering coefficient is the average of the clustering coefficients of all nodes in the network. The formula is shown in Eq. (6), which characterizes the tightness of the overall maritime transportation network (Newman 2003).

$$C = \frac{1}{n} \sum_{i \in V} C_i \tag{5}$$

$$C_i = \frac{2E_i}{(k_i(k_i-1))} \tag{6}$$

where C_i is the clustering coefficient of node i , n is the number of network nodes, V is the node collection, k_i is the adjacent node of node i , and E_i is the number of borders actually existing between nodes k_i .

Degree indicates the number of other ports with direct routes to the port. It is a basic index to measure the importance of a port (<http://www.arctic-lio.com/NSR>) and is often used to measure the scale-free features of the network. The computational formula of this indicator is shown in Eq. (7) (Zhong et al. 2012):

$$D_i = \sum_{j=1, j \neq i}^n L_{ij} \tag{7}$$

D_i is the degree value of node i . L_{ij} is the number of borders between node i and node j . n is the number of network nodes.

Defining port status

In this paper, the PageRank indicator is used to define the importance of the port so as to reflect the status of the port in the global network. As a classic web page-sorting algorithm in the Google engine, PageRank is used to measure the importance of a particular web page compared with other web pages in the search index. The PR value is calculated through links between nodes

(Lawrence et al. 1998; Kamvar et al. 2003; Wang and Ren 2016). Since network sharing in the paper is a process based on direction and weight, the study is based on a directed-weighted network model and uses a function that evaluates the node importance in the directed-weighted complex network based on PageRank proposed by Zhang et al. (2013) and Barrat et al. (2004). Through making weighted analysis for directed borders and ranking the importance of ports in each community, hub ports in the community are selected. The directed-weighted network model is represented by S , $S = (V, H)$. $V = \{v_1, v_2, \dots, v_n\}$ is the collection of network nodes and $H = \{h_1, h_2, \dots, h_m\} \subseteq V \times V$ is the collection of borders. The number of nodes in the network is $n = |V|$, i.e., the number of ports. The number of borders is $m = |H|$. $v_i \in V (i=1, 2, \dots, n)$ indicates a node in network, i.e., a port. $(v_i, v_j) \in H$, (v_i, v_j) indicates $v_i \rightarrow v_j$, i.e., a directional border from node v_i to node v_j . For example, (Shanghai Port, Hong Kong Port) means the route setting out from Shanghai Port to Hong Kong Port.

The formula to calculate the importance of port nodes based on the PageRank method is shown in Eq. (8):

$$PR(v) = \alpha \sum_{v_i \in V_v} \frac{w(v_i, v)}{\sum_{v_j \in V_{v_i}} w(v_i, v_j)} PR(v_i) + \frac{1-\alpha}{n} \tag{8}$$

In this formula, V_v indicates the node collection connecting with the original node v ; V_{v_i} indicates the node collection connecting with node v_i ; $w(v_i, v)$ is the weight between node v_i and original node v ; $\sum_{v_j \in V_{v_i}} w(v_i, v_j)$ is the strength of node v_i ,

i.e., the sum of the weights of other nodes that v_i points to directly; $PR(v_i)$ is the importance of node v_i ; $\alpha (0 < \alpha < 1)$ is the damping coefficient which indicates the probability that a ship will stop at a port and continue to go to the next port at any time. In general, the larger the damping coefficient is, the better the relative importance of the nodes can be distinguished. However, at the same time, the larger the damping coefficient is, the slower the speed of algorithm convergence is. Therefore, considering the above factors, the damping coefficient is set to 0.85.

Community detection

Community structure is a common feature in complex networks. Complex networks are composed of many different communities. The nodes in the community are closely connected, and the nodes between communities are relatively loose. In community detection, modularity is an indicator used to measure the strength of community structures in a network (Wang et al. 2006; Newman 2006), also known as modular metrics. The closer the modularity Q is to 1, the better the community partition

quality of the network is and the more obvious the community characteristics are. Therefore, the optimal network community partition can be obtained by maximizing the value Q . The formula to calculate the modularity is shown in Eq. (9):

$$Q = \frac{1}{2m} \sum_{i,j} \left[W_{ij} - \frac{k_i k_j}{2m} \right] \delta(c_i, c_j) \quad (9)$$

In this formula, m indicates the number of borders in the network; W_{ij} is the weight of borders between adjacent matrixes representing node i and node j ; k_i is the weight of all the borders that connect with node i ; and c_i represents the community number where the node is located. If node i and node j are in the same community, returned value $\delta = 1$; if not, $\delta = 0$.

In this paper, the greedy algorithm which can maximize the modularity is used to obtain the approximate optimal community partition (Newman 2004). The algorithm continuously traverses the nodes in the network, regards each node as an independent small community, and then calculates the modularity increment brought by the combination of the two connected communities. We select the two communities with the maximum increase or minimum decrease of modularity and merge them into one. We repeat the procedure until all nodes are merged into one community. The maximum value Q corresponding to network community partition in this process is the approximate optimal community partition. The specific steps of the algorithm are as follows:

1. Remove all network borders and use each node in the network as a separate community.
2. Make each connected part of the network a community, and then add the borders that are not joined to the network back to the network. Each time a border is added, if the borders added into network connect two different communities, the two communities should be merged. And calculate the modularity increment that forms the new community partition. Select the two communities with maximum increase or minimum decrease of modularity and merge them into one.
3. If the number of communities in the network is greater than 1, return to step 2 to continue the iteration, otherwise go to step 4.
4. Traverse the values Q corresponding to each community partition, and select the community with the largest value as the optimal partition of the network.

Results and discussion

Geometric feature analysis of maritime network

A topological structure chart of maritime network is constructed according to the connection matrix formed by port nodes and the connection frequency matrix composed of

transportation frequency between ports. The basic statistical indicators of complex networks before and after the opening of the Arctic Northeast Passage are calculated using Eqs. 4, 5, 6, and 7. The results are shown in Table 2.

It can be seen from Table 2 that the average value of port node degree after opening decreases from 21.051 to 18.876, indicating that the number of direct routes in any port in the network decreases from 21 to 19. It can be seen from Fig. 6 that the degrees of nodes in the maritime transportation network are mostly 2, 3, 4, and 5. Before opening, the port nodes with values of 2, 3, 4, and 5 account for 32.6%, and the proportion after opening is increased to 39.8%, which means that the number of ports with low values increases. Only a few nodes have large values. For example, Singapore Port has been no. 1 with a high value of 245 after opening, occupying the central position of the global maritime transportation network.

Curve fitting is performed on the node degree distribution in the maritime transportation network. It is found that degree distribution is in accordance with the distribution regularities of power exponent; the fitting effect is very good; and both have scale-free properties which are weakened after the simulation (Tovar et al. 2015). All indicates that the uneven distribution characteristics of global maritime transportation network are improved. The Arctic ports that opened in the Northeast Passage can reduce the pressure that maritime transportation concentrates too much on traditional passage such as the Maritime Silk Road, add new selection opportunities, and reduce waste of maritime resources.

It can be seen from Table 2 and Fig. 7 that the average path length of the maritime transportation network drops from 3.027 to 2.521, indicating that the routes where a ship needs to arrive at other ports from any port decrease from 3 to 2.5. It shows that during the transportation process, the number of transits between the global ports decreases; the global transmission efficiency of the shipping network increases; and the opening of the Northeast Passage reduces the topological distance between the ports to a certain extent and promotes the connectivity between the networks.

It can be seen from Table 2 and Fig. 8 that the average clustering coefficient of the maritime transportation network increases from 0.545 to 0.616. It indicates that the aggregation features of the maritime transportation network are more obvious after the opening of the Northeast Passage, the local transportation efficiency of the maritime transportation network improves,

Table 2 Network indicators before and after opening

Network indicator	Node	Border	Average path length	Average clustering coefficient	Average degree
Before	1346	293028	3.027	0.545	21.051
After	1525	296868	2.521	0.616	18.876

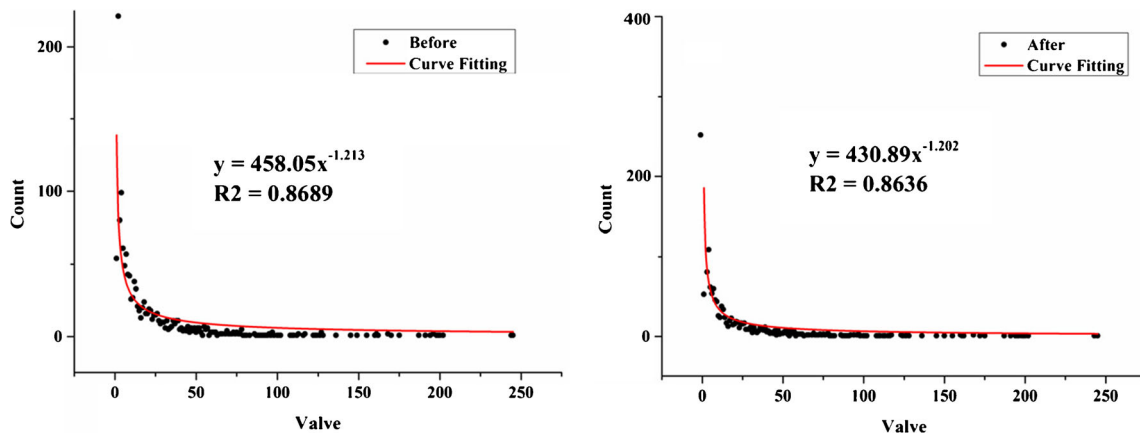


Fig. 6 Degree distribution

and the links between the ports become closer. There are a few ports with a small clustering coefficient, because these ports have a small flow of goods and there are few direct routes. Therefore, sea cargo is mostly transited from a hub port with a large value.

Through the above analysis of geometrical parameters, it is found that the global container maritime transportation network has both a small average path length and a large network clustering coefficient, indicating that the network has a small-world experiment. After opening, small-world features are more obvious than the original network. The connectivity between the networks is stronger, and the connection between ports is more efficient. The degree distribution and distribution regularities of power exponent reflect that the marine transportation network has scale-free features, the features after opening are slightly weakened, and the network distribution becomes balanced.

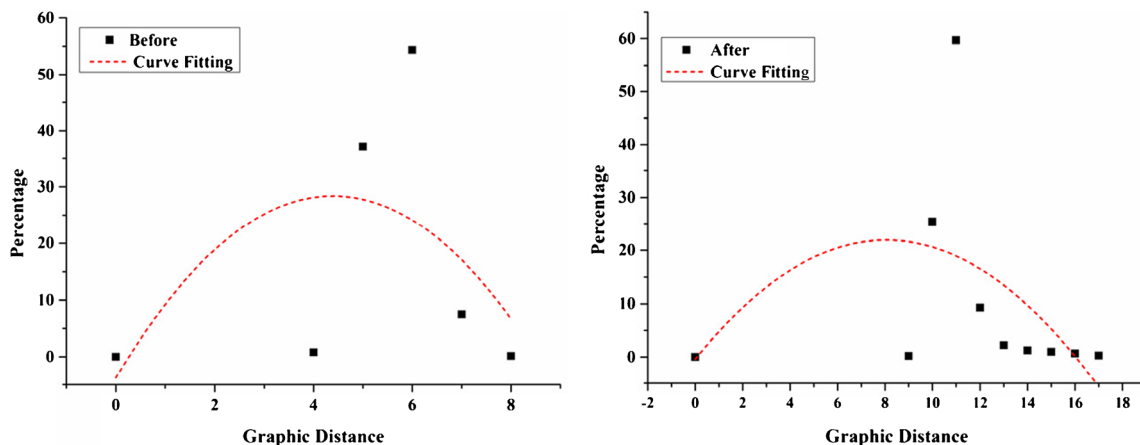
Analysis of port status in community

Community partition

The greedy algorithm is used to detect the communities of global maritime transportation network before and after the opening. After opening, Q in Eq. (9) is calculated as 0.551,

greater than the value of 0.537 before opening, which indicates that the port connection within the community is closer after the opening of the Arctic Northeast Passage and the division between communities in the maritime transportation network is more obvious. Besides, the center of the global maritime transportation network moves to the northeast, the north with latitude of about 1.3° and the east with longitude of 4° .

The final detection results are shown in Figs. 9 and 10. Due to the opening of the Arctic Northeast Passage, a link between Northwest Europe and Northeast Asia through the Arctic Ocean is established. Some ports in the north of West Europe, some ports in the north of Northeast Asia, and the ports in the Arctic Northeast Passage form a new Arctic community. The community originally based on the entire east coast of Atlantic is divided into two communities, West Europe community and West Africa community, due to the decline of traditional long-haul routes from the Cape of Good Hope and the Suez Canal to West Europe, as well as the increase of routes within West Europe. The West Europe community expands to the north. For example, Kirkenes Port in Norway has been categorized as part of the West Europe community.



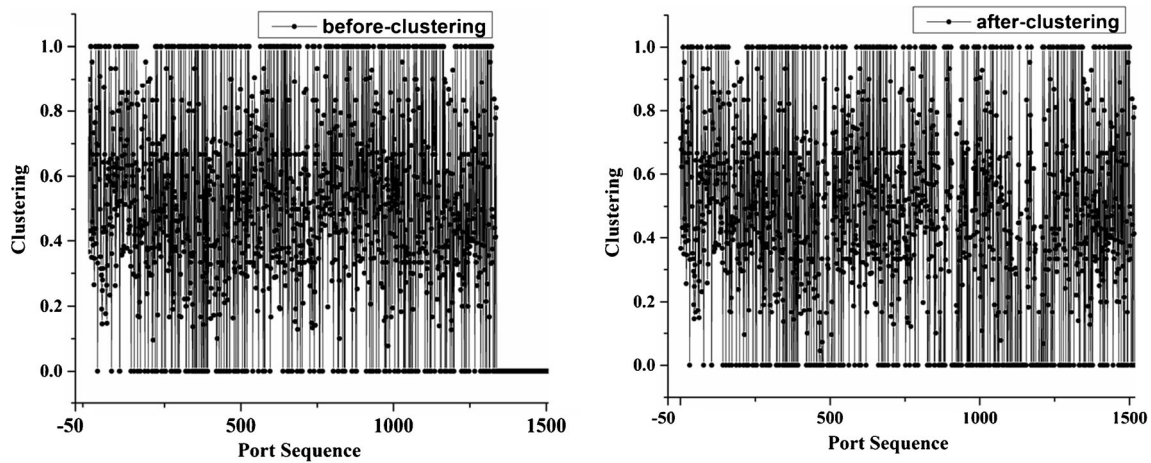


Fig. 8 Clustering coefficient distribution

The route migration caused by the opening of the Arctic Northeast Passage has led to a clearer border between the Northeast Asia community and Southeast Asia community. The geographical area of the Northeast Asia community expands, compared with the past. Some ports in northern China and some ports in Japan move from the Southeast Asia community to Northeast Asia community, such as the Yangzhou Port in China and Yokkaichi Port in Japan, and the community center moves northward with latitude of more than 1° . Because of the reduction of long-distance transportation to Africa and Europe through the Straits of Malacca, some ports near the Straits of Malacca which were originally parts of the Middle East community have less connection with ports along the Indian Ocean. Therefore, these ports are merged into the Southeast Asia community, such as the Phuket Port of Thailand. In addition, after the opening of the Northeast

Passage, the center of the Southeast Asia Community moves eastward with longitude of about 4.5° and northward with latitude of about 2° . And the boundary between the Southeast Asia community and the Middle East community has become clearer than before the passage was opened. After the network is shared, the routes from the coast of the Indian Ocean and passing the Suez Canal to the Mediterranean region also decrease, which leads to the ports of the Mediterranean region belonging to the Middle East community to be merged into the Mediterranean community, such as the Ain Sukhna Port in Egypt. Then, the Mediterranean community has a tendency to move towards the Atlantic Ocean, and the distance to the west is about 0.5° in longitude. After the opening of the Northeast Passage, the area of the Middle East community shrinks significantly. Many ports begin to move to other communities. In addition to the ports in the Mediterranean region and the

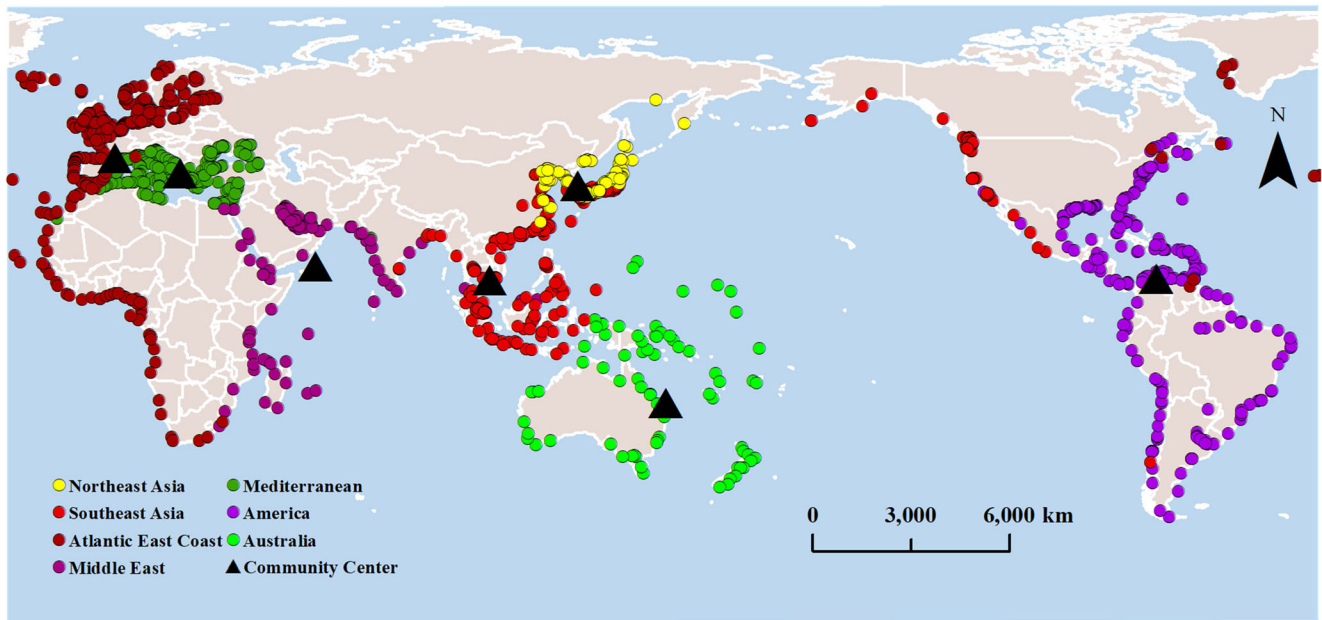


Fig. 9 Community probing map before opening

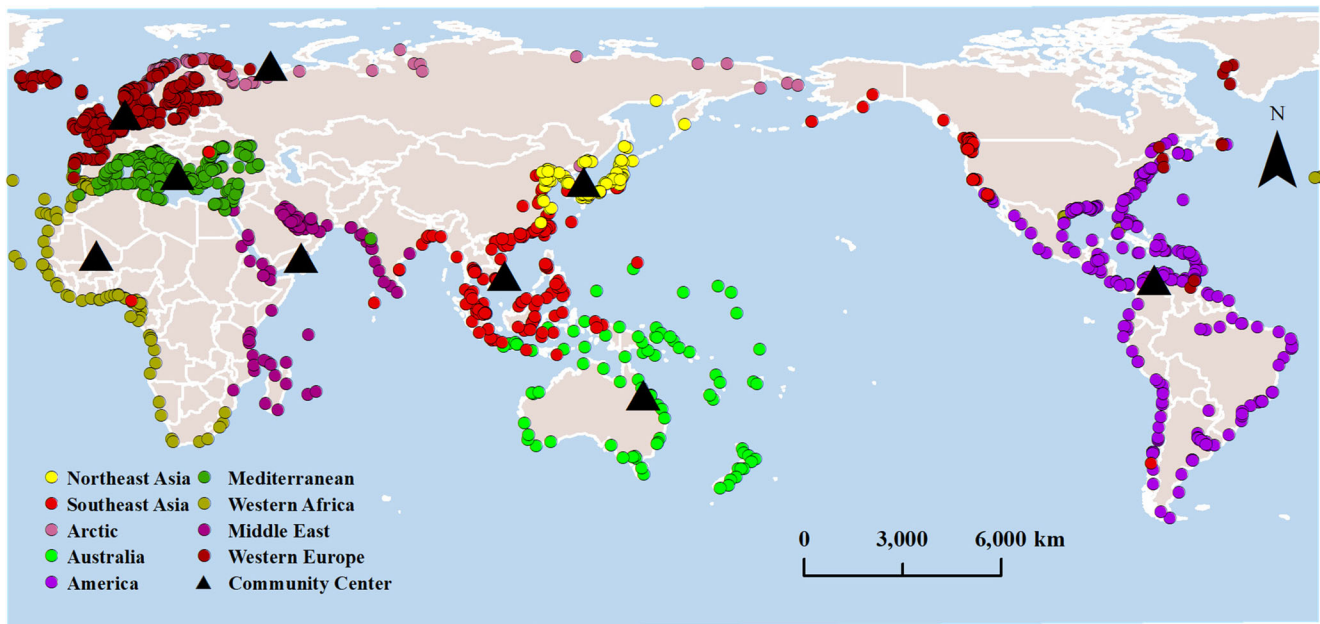


Fig. 10 Community probing map after opening

Straits of Malacca, those on the west coast of the Bay of Bengal, such as the Male Port in the Maldives, also move to the Southeast Asia community. The community clearly moves to the northwest. It moves westward with longitude of nearly 4° and northward with latitude of nearly 3° . In addition, the Australian community also moves to the northwest. It moves westward with longitude of more than 6° and moves northward with latitude of about 2.5° . Some ports located near the Straits of Malacca move away from the Southeast Asia community to the Australian community, such as the Semarang Port in Indonesia. However, contrary to other communities, the Australian community is in a tendency of dispersion and the connectivity of ports within the communities also declines.

Besides Asia, Africa, and Europe, the opening of the Arctic Northeast Passage has other impacts on the traditional passage. For example, it will bring some competition to the traditional passage passing the Panama Canal, which will lead to reduction in network transportation between Southeast Asia and North America. Some ports on the west coast of North America will move from the Southeast Asia community to America community, such as the Ensenada Port in Mexico.

Changes of port status

The PR value of each port is calculated through Eq. (8), and the change of the port status in each community is evaluated. The results are shown in Figs. 11 and 12. The Natural Breaks Algorithm (The Natural Breaks Algorithm is to set the boundary at a position where the data value difference is relatively large in the original data and divide the element into multiple categories (Dong and Wu 2016; Xu 2015) is used to divide the ports into five grades according to the PR value. The first

grade is small-sized ports, 0–0.0248. The second grade is medium-small-sized ports, 0.0249–0.0884. The third grade is medium-sized ports, 0.0885–0.1987. The fourth grade is medium-large-sized ports, 0.1988–0.3798 and the fifth grade is large-sized ports, 0.3799–0.7357. The higher the grade is, the greater the importance of the port is and the higher the port status is.

From the perspective of globe, although the opening of the Arctic Northeast Passage changes the community structure and the status of the ports within the community, the global maritime transportation center is not changed. Singapore Port and Hong Kong Port in Southeast Asia have significant status. Due to the large degree, most cargo transportation chooses to be transferred in these ports, which makes them important central hub ports in the world. It can be seen from Figs. 11 and 12 that the importance of ports in Asia, Africa, and Europe still shows a trend of “high-low-high” from east to west, and the average importance of ports in the Middle East community is significantly lower than that of the Southeast Asia community and Mediterranean community. The average importance of ports in the Middle East community decreases from 0.0666 to 0.0593, from 0.0736 to 0.0658 in the Mediterranean community, and from 0.0847 to 0.0755 in the Southeast Asia community. Therefore, after the opening of the Northeast Passage, the overall status of ports in the three communities declines. In addition, the opening of the passage has increased the port status of the Northeast Asia and West Europe communities. The average importance of ports increases from 0.0657 to 0.0754 in the West Europe community, from 0.0840 to 0.0766 in the Mediterranean community.

From the perspective of community, in the maritime transportation network before opening, compared with other

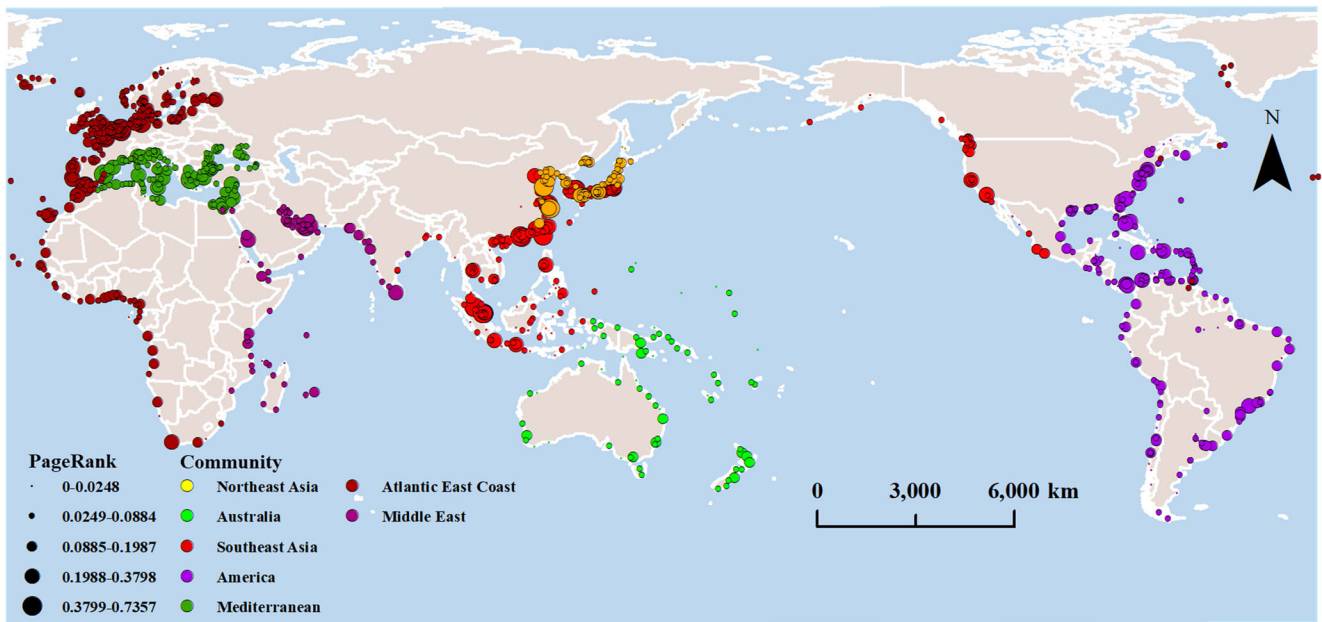


Fig. 11 Port status map within the community before opening

communities, the Southeast Asia community mainly has large ports; most ports in the Mediterranean community, Northeast Asia community, and West Europe community are medium-sized and medium-large-sized; the American community mainly has medium-sized ports; the distribution of medium-large-sized, medium-sized, and medium small-sized ports in the Middle East community is balanced; and the Australian community mainly has small-sized and medium-small-sized ports. After opening the Arctic Northeast Passage, the port status of each community is affected to some extent, as is shown in Table 3. The status of some ports in northern

China, Japan, and South Korea of the Northeast Asia community rises. Some medium-small-sized ports turn into medium-sized and even medium-large-sized ports, such as China’s Zhenhai Port. The status of most ports in the Southeast Asia community declines, such as the Shekou Port in southern China and Singapore Port in Singapore. Some medium-sized and medium-small-sized ports near the South China Sea turn into small-sized ports, such as China’s Shuidong Port. The status of ports near the Straits of Malacca significantly declines. Many medium-sized ports turn into medium-small-sized ports, such as the Davao Port in the Philippines. In the

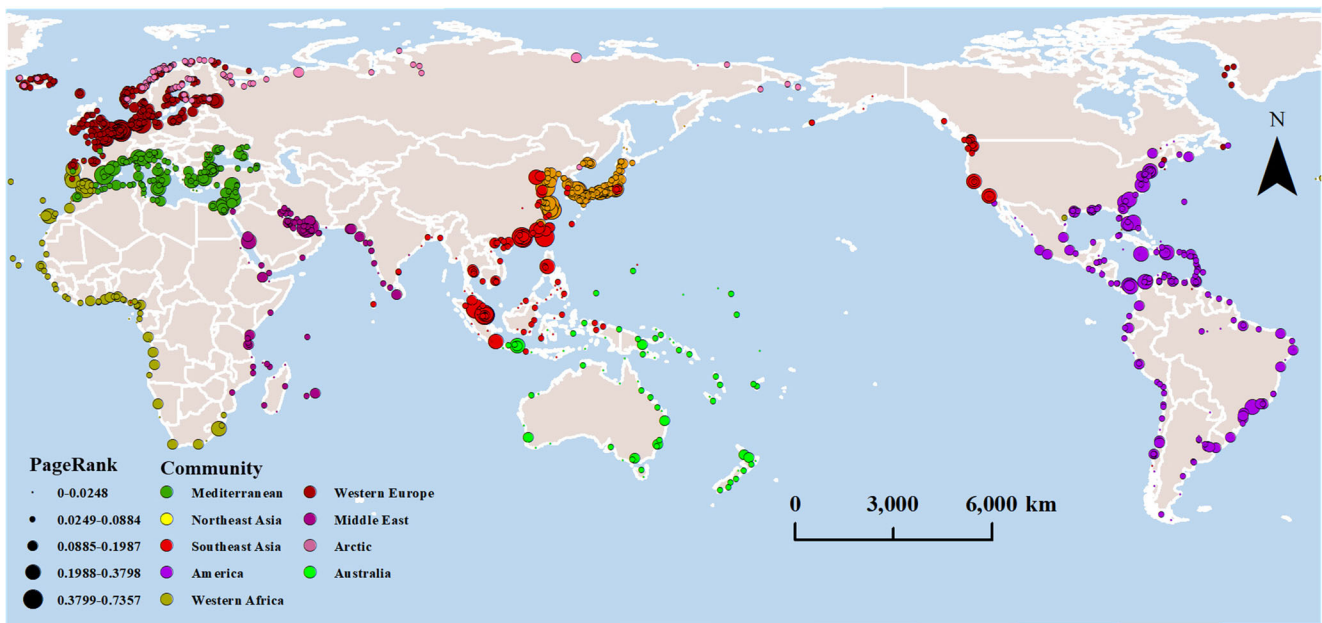


Fig. 12 Port status map within the community after opening

Table 3 Changes in status of some ports

Port	Community	Before	After
Zhenhai	Northeast Asia	0.0345	0.1997
Shekou	Southeast Asia	0.4666	0.4185
Singapore	Southeast Asia	0.7357	0.6584
Shuidong	Southeast Asia	0.0864	0.0219
Davao	Southeast Asia	0.0953	0.0852
Colombo	Middle East	0.2204	0.1985
Mumbai	Middle East	0.0901	0.0807
Berbera	Middle East	0.0305	0.0242
Algeciras	Mediterranean	0.5658	0.5153
Cagliari	Mediterranean	0.2204	0.1983
Cape Town	West Africa	0.2035	0.1829
Rotterdam	West Europe	0.0458	0.0492
Hamburger	West Europe	0.5121	0.5298
Skelleftehamn	West Europe	0.0172	0.0533

Middle East community, the Colombo Port in Sri Lanka has the most obvious change which turns from a medium-large-sized port into a medium-sized port. The status and importance of other ports, such as the ports in the West India and the Gulf of Aden, also decline, such as the Mumbai Port in India and Berbera Port in Somalia. The status of ports in the Mediterranean community has decreased, such as the port of Algeciras Port in Spain, and some medium-large-sized ports along the European coast began to switch to medium-sized ports, such as the Cagliari Port in Italy. After the community in east coast of Atlantic splits into two communities, West Europe and West Africa, the status of ports near the Cape of Good Hope and Strathro Straits declines. For example, the Cape Town Port of South Africa switches from a medium-large-sized port to a medium-sized port. In the West Europe community, the status of some ports rises, such as the Rotterdam Port in the Netherlands and Hamburg Port in Germany. Some ports in the north turn from small-sized ports into medium-small-sized ports and medium-sized ports, such as the Skelleftehamn Port in Sweden.

Discussion

Through the study on the static and dynamic trends of the global maritime transportation network, it is found that the global maritime transportation network shows a trend of moving northward. Previous studies have shown that the existing maritime transportation network presents unbalanced characteristics, such as congestion, long route, and long time in the Belt and Road area (Mou et al. 2018; Yang et al. 2018). The movement of network caused by the opening of the Arctic Northeast Passage will share some pressure for the Belt and Road, and this situation will also be improved.

After opening the Arctic Northeast Passage, resources in East Asia and South Asia begin to move to Russia and the EU through the Arctic Northeast Passage. During this period, a large number of cargoes need to be transferred to other ports. Some large ports in north China such as the Dalian Port and Qingdao Port and Yokohama port in Japan can easily become transfer ports and berthing ports, leading to a rise in the status of some ports in the northern part of the Northeast Asia community. In the case that the Arctic Northeast Passage competes with the traditional passage, the long-distance routes to the West Europe via coastal ports in the Belt and Road decrease, especially the routes passing the Cape of Good Hope. Therefore, the connection between the ports near the Bay of Bengal, Straits of Malacca, and the ports in Northeast Asia decreases, and the ports near the Cape of Good Hope contact less with the Middle East community and West Europe community, thus reducing their own status. In addition, the transportation of Maritime Silk Road will be partly transferred from sea to land in countries with convenient land transportation, such as Myanmar and India. After the routes are shared, because of the decrease in cargo handling capacity, the status of such ports declines, such as the Mumbai Port in India and Laem Chabang Port in Thailand.

This research can be used to detect maritime transportation communities, promote port planning, and provide services for container transportation worldwide. In addition, after the opening of the passage, in order to improve the operational efficiency of maritime cargo and reduce waste of resources, the following suggestions are proposed:

1. To open new Arctic ports. East Asia and West Europe, as the world's major maritime trading bases, have a large supply and demand of goods (Liu and Hu 2017). The northward movement of the community will inevitably bring unprecedented pressure to the ports in the polar regions. The number of existing ports in the Arctic is fewer, and construction of infrastructure is incomplete. There are no ports with deep water conditions suitable for large ship unloading. Therefore, it is recommended to open some new ports, especially in coastal areas of the Eastern Siberian Sea.
2. To increase investment in equipment and services of ports. As the routes move northward, as transitional ports, the ports in Northeast Asia and Northwest Europe are facing certain pressure because of sharp increase in transportation. The reduction of operation efficiency, crowded routes, and insufficient berths appear in ports due to the excessive burden (Hu and Zhu 2008). Also, most countries in Northeast Asia and Northwest Europe have many ports, such as Sweden with 93 ports. Therefore, it is recommended to increase the investment in medium-small-sized and small-sized ports with potential in Northeast Asia and Northwest Europe, such as China's Dandong

- Port, Penglai Port, Sweden's Skelleftehamn Port, so as to share pressure for some important hub ports such as the Pusan Port, Yokohama Port, Dalian Port, and Antwerpen Port; provide the transit for ships; improve transportation efficiency; and reduce waste of resources.
3. To appropriately adjust the number of delivered ships. For coastal ports in traditional passage, such as the ports in Mediterranean and Middle East, the increase in medium- and short-distance transportation and the reduction of long-distance transportation mean that the number of routes as berthing ports decreases, which can increase the input of medium- and small-sized ships, avoid imbalance between bearing capacity and cargoes of ships, and reduce resource waste.
 4. To adopt multi-modaling logistics. The Arctic area that belongs to Russia which is rich in natural resources. Countries with few such resources, such as China, need to import a lot of resources, especially oil and natural gas. However, the existing Arctic ports in Russia are fewer and the equipment is incomplete. Therefore, it is recommended to increase land transportation between Asia and Russia to reduce the pressure of Arctic maritime transportation.
 5. To make new economic and trading policies. During the opening of the passage, the connection between many ports becomes frequent. For example, China, Japan, Korea, and Russia will import and export a large number of natural resources. Therefore, it is recommended that relevant countries make corresponding trade policies to promote cooperation and development between countries.

Conclusion

Based on the AIS trajectory data of global containers, 35% routes of traditional passage from China, Japan, and South Korea to northwest Europe are shared to the Northeast Passage. The changes of the global maritime transportation pattern after the opening of the Arctic Northeast Passage are explored. Related conclusions are as follows:

First, after the opening of the Arctic Northeast Passage, the average topological distance between ports decreases by 0.506 and the average clustering coefficient increases by 0.071. The small world features of the global maritime transportation network are more obvious. The scale-free features of the network decrease with an average from 21.051 to 18.876. The ports with low node values of 2, 3, 4, and 5 account for 39.8% from 32.6%. All these show that the opening of the passage will greatly increase the connectivity of the global maritime transportation network, play an important role in promoting the transportation efficiency of the global network, and improve the uneven distribution of the original network.

Second, after the route is shared, the network community partition will be more obvious, the internal communication within the community will become tight, and the global maritime transportation network will move to the northeast: the north with a latitude of 1.3° and the east with longitude of about 4° . With the migration of marine transportation to the Northeast Passage, new communities will emerge in the Arctic area. Community on the east coast of the Atlantic will begin to split into two communities: West Europe and West Africa. Community features of Northeast Asia, Southeast Asia, Middle East, and Mediterranean will be more obvious. The borders between communities are clearer. The Mediterranean community has a tendency of moving westward and the other three communities moving northward. The Australian community will expand and tend to spread northwestward.

Third, from the global perspective, the importance of ports in Asia, Africa, and Europe still show a trend of "high-low-high" from east to west. The maritime transportation status of some ports in the Southeast Asia community such as the Singapore Port and Hong Kong Port is significantly higher than that in other communities. The average importance of ports decreases by 0.0073 in the Middle East community, 0.0078 in the Mediterranean community, and 0.0092 in the Southeast Asia community. From the perspective of community, the status of ports in the Northeast Asia community and the northern part of the West Europe community rises and declines in the Malacca Strait of the Southeast Asia community, the west Mediterranean community, the junction between the West Europe community and West Africa community, as well as the most of the Middle East community. Some small ports in the northern part of the West Europe community turn into medium-sized and medium-small-sized ports. Some large-sized and medium-large-sized ports in the European coast of the Mediterranean community convert into medium-sized ports.

In this paper, on the basis of AIS data, a simulation of the real situation for the opening of the Arctic Northeast Passage is conducted, and the maritime transportation network is constructed and compared. In the future, the transportation volume of trade and the pollution of the ship in the Arctic Passage will be estimated based on AIS data. This study provides a research method for how to construct a maritime transportation network and a hub port on the Arctic Passage, and provides a scientific basis for exploring the impact of opening the Arctic passage on traditional passage even on global networks based on maritime trajectory data. It also plays a significant role in promoting the Belt and Road initiative of the twenty-first century and the Polar Silk Road initiative.

Author contributions Conceptualization, Naixia Mou; methodology, Jie Li and Hengcai Zhang; software, Jie Li and Wenbao Liu; validation, Tengfei Yang and Lingxian Zhang; writing—original draft preparation,

Naixia Mou and Jie Li; writing—review and editing, Shuyue Sun and Wenbao Liu; project administration, Tengfei Yang and Lingxian Zhang.

Funding information This research is supported in part by the Key Project of the Chinese Academy of Sciences (ZDRW-ZS-2017-4-3), the National Natural Science Foundation of China (41771476), and Natural Science Foundation of Shandong Province (ZR2016DM02).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Afenyo M, Khan F, Veitch B, Yang M (2017) Arctic shipping accident scenario analysis using Bayesian network approach. *Ocean Eng* 133:224–230
- Aksenov Y, Popova EE, Yool A, Nurser AJG, Williams TD, Bertino L, Bergh J (2016) On the future navigability of Arctic sea routes—high-resolution projections of the Arctic Ocean and sea ice. *Mar Policy* 7:300–317
- Barrat A, Barthélemy M, Vespignan A (2004) Modeling the evolution of weighted networks. *Physical Review. E, Statistical, Nonlinear & Soft Matter Physics* 70(2):1–13
- Bechselica F (2018) The characteristics and influence of Russian Arctic strategy. *Border Econ Cult* 2:19–21
- Blunden M (2012) Geopolitics and the Northern Sea Route. *Int Aff* 88(1): 115–129
- Broek RP, Den V (2014) The economic impact of open Arctic routes on global maritime LNG trade. *Maritime Economics and Logistics*
- Bye RJ, Aalberg AL (2018) Maritime navigation accidents and risk indicators: An exploratory statistical analysis using AIS data and accident reports. *Reliab Eng Syst Saf* 176:174–186
- China MSA (2014) Arctic Northeast Passage navigation guide. People's Communications Press Co. Ltd, Beijing
- Choi M, Chung H, Yamaguchi H, Nagakawa K (2015) Arctic sea route path planning based on an uncertain ice prediction model. *Cold Reg Sci Technol* 109(109):61–69
- Climate Change (2013) The Physical Science Basis. <https://www.ipcc.ch/report/ar5/wg1/>.
- Dong YC, Wu J (2016) A comparative study on tourism competitiveness of vice-province cities in China. *Journal of Shandong Normal University (Natural Science)* 31(4):103–107
- Gao SL, Liu JZ, Zhang X (2018) Economic analysis of the Arctic navigation of merchant ships on the Silk Road in the ice. *Practice in Foreign Economic Relations and Trade* 01:26–29
- Gautier DL, Bird KJ, Charpentier RR, Grantz A, Houseknecht DW, Klett TR, Moore TE, Pitman JK, Schenk CJ, Schuenemeyer JH, Sørensen K, Tennyson ME, Valin ZC, Wandrey CJ (2009) Assessment of undiscovered oil and gas in the Arctic. *Science* 324(5931):1175–1179
- Gunnarsson B (2012) NSR transit voyages in 2011 and 2012 (YTD). Kirkenes, Norway: center for High North logistics
- Ho J (2010) The implications of Arctic sea ice decline on shipping. *Mar Policy* 34(3):713–715
- Hong N (2012) The melting arctic and its impact on China's maritime transport. *Res Transp Econ* 35(1):50–57
- Hu YH, Zhu DL (2008) Empirical analysis of the worldwide maritime transportation network. *Physica A: Statistical Mechanics & Its Applications* 388(10):2061–2071
- Jian Y (2018) An Interpretation of China's Arctic Policy. *Pac J Theol* 26(03):1–11
- Jiang XM, Zhu XM, Wang ZL, Dou B (2012) Analysis of Russian Arctic strategy based on Arctic route. *World Regional Studies* 21(3):45–49
- Kamvar, S.D., Haveliwala, T.H., Manning, C.D., 2003. ACM Press the twelfth international conference - Budapest, Hungary 2003.05.20-2003.05.24 Proceedings of the twelfth international conference on World Wide Web, - WWW '03 - Extrapolation methods for accelerating PageRank computations, pp. 261-270.
- Kuang WF, Wang JG (2011) Research on the complementarity and potential of Sino-French bilateral trade—easy complementarity index and ARIMA model measurement. *Soc Sci Hunan* 1:137–141
- Lawrence P, Sergey B, Rajeev M, Terry W (1998) The PageRank citation ranking bringing order to the Web. *Stanford Digital Libraries Working Paper* 9(1):1–17
- Lei R, Xie H, Wang J, Leppäranta M, Jónsdóttir I, Zhang ZH (2015) Changes in sea ice conditions along the Arctic Northeast Passage from 1979 to 2012. *Cold Reg Sci Technol* 119:132–144
- Li ZF, Sun JP (2011) Analysis of criterion game mechanism of Arctic routes geopolitical. *World Regional Studies* 20(01):56–62
- Li ZF, Jiang SF, Xu MQ, Shi YL, Zhang XL (2015) On the shipping network evolution under the Arctic route. *Complex Systems and Complexity Science* 12(4):55–60
- Li ZF, Miao Y, Chen J (2017) Analysis on the economic circle trade work of Arctic shipping routes based on structural holes theory. *J Central China Normal Univ*
- Li M, Yang QH, Zhao JC, Sun XY, Tian ZX, Shen H, Hao GH, Li CH, Zhang L (2018) Arctic sea ice concentration numerical forecasting and its evaluation. *Acta Oceanol Sin* 40(11):46–53
- Lin DY, Chang YT (2018) Ship routing and freight assignment problem for liner shipping: application to the Northern Sea Route planning problem. *Transportation Research Part E: Logistics and Transportation Review* 110:47–70
- Lindstad H, Bright RM, Strømman AH (2015) Economic savings linked to future Arctic shipping are at odds with climate change mitigation. *Transp Policy* 45:24–30
- Liu, C.J., Hu, Z.H., 2017. Hierarchy system research about the Maritime Silk Road shipping network. *Economic Geography. Economic Geography*, 37(7), 27-32.
- Liu MJ, Kronbak J (2010) The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. *J Transp Geogr* 18(3):434–444
- Mao WG, Rychlik I (2018) Stochastic spatio-temporal model for wind speed variation in the Arctic. *Ocean Eng* 165:237–251
- Miller AW, Ruiz GM (2014) Arctic shipping and marine invaders. *Nat Clim Chang* 4(6):413–416
- Mou NX, Liu CX, Zhang LX, Fu X, Xie YC, Li Y, Peng P (2018) Spatial pattern and regional relevance analysis of the Maritime Silk Road shipping network. *Sustainability* 10(4):977–989
- Nam J-H, Park I, Lee HJ, Kwon MO, Choi K, Seo Y-K (2013) Simulation of optimal arctic routes using a numerical sea ice model based on an ice-coupled ocean circulation method. *International Journal of Naval Architecture and Ocean Engineering* 5(2):210–226
- Newman MEJ (2003) The structure and function of complex networks. *SIAM Rev* 45(2):167–256
- Newman MEJ (2004) Fast algorithm for detecting community structure in networks. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics* 69(6 Pt 2):066133
- Newman MEJ (2006) Modularity and community structure in networks. *Proc Natl Acad Sci U S A* 103(23):8577–8582
- Niederdrenk AL, Notz D (2018) Arctic sea ice in a 1.5 °C warmer world. *Geophys Res Lett* 45(4):1963–1971
- Northern sea route information office (n.d.) <http://www.arctic-lio.com/NSR>.
- Peng P, Cheng SF, Chen JH, Liao MD, Wu L, Liu XL, Lu F (2018) A fine-grained perspective on the robustness of global cargo ship transportation networks. *J Geogr Sci* 28(07):881–899

- Ragner CL (2000) Northern Sea Route cargo flows and infrastructure: present state and future potential (FNI Report). Fridtjof Nansen Institute
- Rodrigues J (2008) The rapid decline of the sea ice in the Russian Arctic. *Cold Reg Sci Technol* 54(2):124–142
- Sahin B, Kum S (2015) Risk assessment of Arctic navigation by using improved fuzzy-AHP approach. *Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering* 157(4):241–250
- Sang BC, Yang LZ (2015) China's trading relations with the countries of "One Belt And One Road": based on the trade competitiveness and trade complementarities. *On Economic Problems* 8:1–5
- Smith LC, Stephenson SR (2013) New trans-Arctic shipping routes navigable by mid-century. *Proc Natl Acad Sci* 10(13):1191–1195
- Stephenson SR, Brigham LW, Smith LC (2014) Marine accessibility along Russia's Northern Sea Route. *Polar Geogr* 37(2):111–133
- Suárez de la Fuente S, Larsen U, Pawling R, García Kerdan I, Greig A, Bucknall R (2018) Using the forward movement of a container ship navigating in the Arctic to air-cool a marine organic Rankine cycle unit. *Energy* 159:1046–1059
- Sun Z, Zheng J (2016) Finding potential hub locations for liner shipping. *Transp Res B Methodol* 93:750–761
- Tovar B, Hernández R, Rodríguez-Déniz H (2015) Container port competitiveness and connectivity: the Canary Islands main ports case. *Transp Policy* 38(C):40–51
- USGS, 2009. Geological survey (USGS) circum-Arctic resource appraisal: estimates of undiscovered oil and gas north of the Arctic Circle.
- Wang XY, Ren G (2016) Improved PageRank algorithm based on user behavior and page analysis. *Comput Eng* 42(2):164–168
- Wang XF, Li X, Chen GR (2006) Theory and applications of complex networks. Tsinghua University Press
- Wang N, Yan B, Wu N, Zhao WJ (2016) Comments on "Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector" [Transp. Res. Part A: Policy Pract. 66 (2014) 144–161]. *Transport Res Part A: Policy Pract* 94:699–702
- Wang N, Yan B, Wu D, Wu N (2017) The spatio-temporal pattern of China-EU shipping route under the background of Arctic navigation. *Econ Geogr* 37(12):9–16
- Wu J, Lang CJ (2017) Research on the traffic assignment of the Arctic LNG transport routes. *Journal of Central China Normal University (Natural Sciences)* 51(3):364–369
- Xu XZ (2015) Comment on the multi-center system of Wuhan urban development zone, in China Urban Planning Association. Guizhou, China
- Yang R, Mou NX, Peng P, Liu XL, Zhang HC, Lu F (2018) Evaluation on competitiveness of important ports along the Maritime Silk Road. *J Geo-Inf Sci* 20(5):623–631
- Yu ZJ (2009) Evaluating Chinese trade competitiveness: theory and method exploring based on G-L & RCA index. *Statist Res* 26(05): 94–99
- Yu WB (2014) Research on spatio-temporal features and extraction of digital watershed based on DEM. Zhejiang University
- Zhang K, Li PP, Zhu BP, Hu MY (2013) Evaluation method for node importance in directed-weighted complex networks based on PageRank. *Journal of Nanjing University of Aeronautics & Astronautics* 45(3):429–434
- Zhang ZH, Huisingh D, Song M (2019) Exploitation of trans-Arctic maritime transportation. *J Clean Prod* 212:960–973
- Zhong K, Xiao Y, Xu J, Ma FG, Liu Y, Wu L (2012) Measuring city centralities based on the train network of China. *J Geo-Inf Sci* 14(1): 85–93