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Quantifying and Mapping the Spatiotemporal Characteristics of High Seas Shipping and the Pollution

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Abstract. Global shipping plays a crucial role in international trade. It is responsible for 2-3% of global greenhouse gas emissions. Emissions from maritime transportation on the high seas show considerable variation over time and across different locations. The volume of emissions from ships is closely linked to the level of shipping activity. This study utilizes global shipping Automatic Identification System (AIS) data from 2015 to 2024 to analyze the spatial and temporal patterns and trends of maritime activities in various countries, offering insights and guidance for the targeted development of marine environmental management strategies.

Keywords: Ship emission; High seas; Automatic identification System; Marine pollution.

1. Introduction

In recent years, international shipping, which serves as a fundamental component of global trade, has been responsible for transporting over 80% of the volume of international trade[1] and constitutes a significant source of greenhouse gas emissions[2]. Data from the International Maritime Organization (IMO) indicate that the global shipping sector emits approximately 105.6 million tons of carbon dioxide annually, representing roughly 2.89% of anthropogenic greenhouse gas emissions, 9% of global sulfur oxide emissions, and 17% of nitrogen oxide emissions[3]. The ongoing increase in anthropogenic greenhouse gases is recognized as the primary driver of climate change and its associated detrimental impacts on both human and natural systems[4]. In April 2025, the IMO approved a regulation mandating that all countries achieve net-zero emissions in shipping by no later than 2050, thereby presenting new challenges to the global shipping industry[5].

The volume of emissions generated by ships is closely correlated with the intensity of shipping activities[2]. Compared to other pollution sources, ship emissions remain among the least regulated. Moreover, the spatial and temporal distribution of major shipping freight hubs varies significantly across countries. The principle of common but differentiated responsibilities and respective capabilities, as enshrined in the legal framework of the United Nations Framework Convention on Climate Change (UNFCCC), is widely acknowledged as a foundational guideline for addressing global climate change[5]. Consequently, examining the shipping activities and pollution profiles of key maritime nations across different sea regions, along with their evolving trends, is critically important for the effective reduction of carbon emissions from shipping. Notably, existing literature lacks comprehensive research focusing on country-specific characteristics and temporal trends related to this issue.

2. Materials and Methods

2.1 Data sources and preprocessing

In this study, a time series data covering a 10-year period (from 2015 to 2024) of Containers, bulk carriers, and oil tankers is used. These data comes from the Automatic Identification System (AIS) for ships. AIS is an automatic tracking system for ocean going vessels that can forward the geographic location of each vessel to maritime authorities and other vessels. At the beginning of the proposal of AIS data, it was usually used for inter ship communication, enhancing ship collision prevention capabilities, avoiding collisions, improving ship radar functions, managing maritime vessel traffic, and improving fishery activity supervision[6]. The International Convention for the

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Safety of Life at Sea, issued by the International Maritime Organization (IMO), requires cargo ships with a load capacity of 300 tons or more for international navigation, cargo ships with a total weight of 500 tons or more for domestic navigation, and all passenger ships to be equipped with AIS signal transmission devices[8]. With the improvement of AIS data availability and the continuous expansion of information coverage, it has also been widely used in deep-sea research fields such as analyzing ship activity patterns. Due to the AIS transmitter reporting the ship's speed, heading, and position every 2 to 10 seconds, according to the data processing method adopted in the past study, a linear ship trajectory can be generated by connecting continuous AIS signal transmission base station position reporting points corresponding to the ship's Maritime Mobile Service Identification (MMSI) number[8].

This section focuses on the three main types of ships in freight transportation: container ships, oil tankers, and dry bulk carriers. The AIS data of these three types of ships from 2015 to 2024 will be used as the accounting basis. The basic data of AIS comes from the open-source database "Ship Information Network"（http://www.shipxy.com/）”, including ship name, speed, country of registry, source and destination countries, load capacity, vessel number, and location information. AIS data is first cleaned and filtered to remove location points located on land or in areas with obvious anomalies, and all data points are converted to universal time (the UTC time zone) to eliminate missing records and anomalies with ship speeds exceeding 30 knots. Subsequently, based on the characteristics of ship names, call signs, and ship types, the AIS data was cleaned, integrated, and formed into a dataset of activity lines for different ships in the region. The above data cleaning and preprocessing process was completed using Python 3.10.

The intrinsic characteristics of international maritime shipping activities constitute a critical consideration in the development of analytical models. Under international law, merchant vessels are mandated to be registered in a host country, thereby granting them the right to fly the civilian flag of that nation, commonly referred to as the country of registry. These vessels are subject to the legal framework of their country of registry, which also bears the responsibility for conducting periodic inspections. In accordance with international shipping conventions, many vessels engage in the practice of flying flags of convenience, registering under open registry countries such as Panama, Barbados, and the Cayman Islands. This practice is primarily motivated by the desire to minimize operational costs, evade taxation, and circumvent stringent safety regulations and labor protections related to wages and working conditions that would otherwise apply in the shipowner’s home country. The term "flag of convenience" denotes the registration of a vessel in a country distinct from that of the shipowner’s residence or citizenship. Consequently, the country of registry parameter within Automatic Identification System (AIS) data is an unreliable indicator for accurately representing a nation’s genuine maritime shipping interests[9]. Therefore, in identifying principal countries engaged in shipping activities, this study employs the countries of departure and destination as the primary criteria, rather than the country of registry. Using 2024 as the reference year, six countries exhibiting the highest intensity of global shipping activities—namely China, Japan, South Korea, the United States, Indonesia, and India—were selected for an in-depth analysis of their maritime activities and trends over the preceding decade.

2.2 Methodology

2.2.1 Density analysis

The density analysis tool within ArcGIS Pro facilitates the identification of high-density regions and the examination of data hotspots by partitioning the study area into grid layers, each assigned distinct density values. Specifically, line density analysis quantifies the density of linear features within the vicinity of each output grid cell. This is achieved by delineating a circular search area centered on each grid cell; the length of the line segments intersecting this circle is multiplied by their respective weight values, and the product is then divided by the circle’s area to derive the density value for that grid cell. The density calculation is expressed by the following formula:

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$$\text{Density} = \sum_{i=1}^{n} L_i V_i / A \tag{2}$$

Where, A denotes the area of the circle, n represents the number of line segments within the circle, L and V correspond to the length and weight value of the line segments falling within the circle, respectively. In the implementation of the line density analysis function in ArcGIS Pro version 3.3, the grid cell dimensions employed in this study were uniformly set to 0.1°× 0.1°.

2.2.2 Mann Kendall trend test

The Mann-Kendall (M-K) test is extensively utilized in research for assessing trends in time series data[10][11], offering robustness in handling missing values and partial outliers[12]. The result of M-K test reflects the presence of linear or nonlinear trends within the data sequence. In its computation, S is the summation of the differences between data values, with the sign function sgn(x) represents the sum of the differences in the value x, that values -1,+1, and 0 based on the sign of x.

$$S = \sum_{I=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}\big(x(i) - x(j)\big). \tag{2}$$

When the following conditions are met, the corresponding value as follows:

$$\begin{cases} \text{if } x > 0,\ \mathrm{sgn}(x) = 1 \\ \mathrm{sgn}(0) = 0 \\ \text{if } x < 0,\ \mathrm{sgn}(x) =- 1 \end{cases} \tag{3}$$

The positive or negative of S respectively reflect the upward or downward trend of the data.

To obtain more accurate results, the variance VAR (S) of S is calculated as follows, where n represents the number of data points.

$$\mathrm{VAR(S)} = \frac{n(n-1)(2n+5)}{18} \tag{4}$$

The calculation of Kendall's standardized test statistic Z is as follows, where Z>0 and Z<0 respectively indicate an increasing and decreasing trend. The outcomes of this analysis provide insights into the temporal dynamics of ship activities and associated pollution levels across various high-sea regions.

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{VAR(S)}}},\ S > 0 \\ 0,\ S = 0 \\ \frac{S+1}{\sqrt{\mathrm{VAR(S)}}},\ S < 0 \end{cases} \tag{5}$$

On the basis of calculating Z, the confidence test of the results is performed using P. The calculation principle of P is as follows:

$$P = 2 \times (1 - \varphi(|Z|)) \tag{6}$$

In the testing process, P represents the probability of observing the current or more extreme trend when the null hypothesis (H_0 the time series does not have a monotonic trend) is true. The smaller the P-value, the less likely it is that the observed trend is caused by random fluctuations, thus giving more reason to reject the null hypothesis and believe that the trend change is significant. A significance threshold of 0.05 is conventionally adopted.

All data processing was conducted using the "trend" package in R version 4.3. The year 2024 was designated as the reference point for trend calculations in the subsequent analyses.

3. Results and Discussion

3.1 Results

Maritime shipping fundamentally functions as a facilitator of trade. Consequently, the principal global production hubs (notably East Asia and Southeast Asia), consumer markets (including North America and Europe), and resource extraction regions (such as the Middle East, Australia, and Brazil) inherently establish the most heavily trafficked shipping corridors, exemplified by the busy

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routes across the Pacific and Indian Oceans. The demand for shipping services is directly influenced by patterns of economic expansion and contraction.

The spatial distribution of areas with high shipping activity and associated pollution emissions is markedly uneven, predominantly concentrated along international trade routes and major port locations (see Fig. 1). Over the last decade, the intensity of maritime traffic in key global waterways has steadily increased, resulting in elevated pollutant emissions from vessels. The shipping lanes in East Asia, Europe, and North America exhibit the highest traffic density and relative emission levels, with emissions particularly concentrated in critical maritime chokepoints such as the Strait of Malacca, the Suez Canal, and the Baltic Sea.

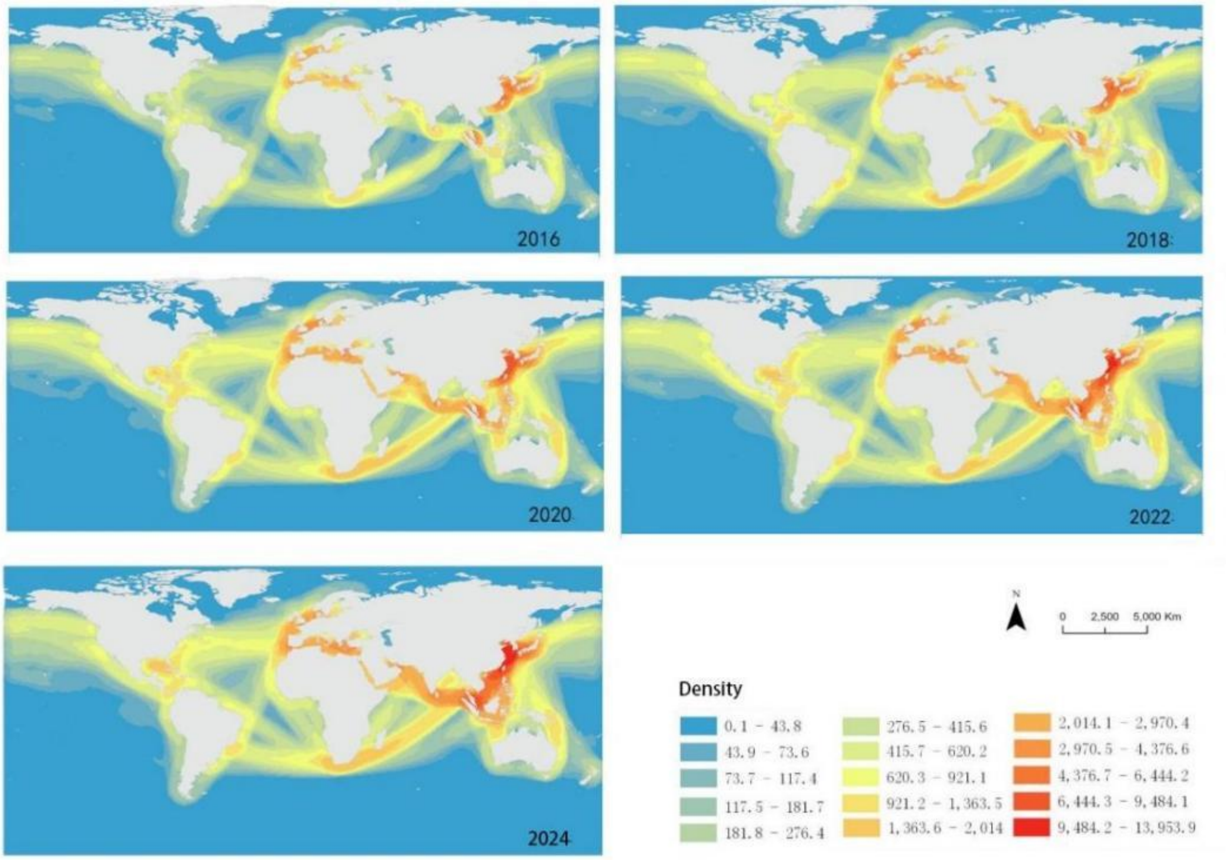

Fig. 1 Hotspots of ship activities from 2016 to 2024

The examination of spatio-temporal patterns reveals that the primary nations involved in maritime shipping activities are predominantly located in East Asia and South Asia (see Fig. 2). Notably, there exists considerable spatio-temporal variability in the environmental impacts exerted by vessels from different countries on marine environments.

Over the past decade, China has exhibited the most intensive maritime activities, with maritime trade across the Indian Ocean, Pacific Ocean, and Atlantic Ocean demonstrating statistically significant upward trends at a 95% confidence level, thereby rejecting the null hypothesis. Maritime trade remains a critical component of China's current and prospective maritime interests. Conversely, Japan's maritime activities have experienced a marked decline in South America over the same period, also significant at the 95% confidence interval, while showing pronounced increases in regions such as the North Atlantic and the Arabian Sea. This pattern suggests that the future maritime interests of Japan are increasingly focused on sea passages connecting to Europe. The maritime trade of South Korea within the Pacific and Indian Ocean regions has shown significant growth at the 95% confidence level, indicating heightened future interest in these areas. The maritime interests of United States are predominantly concentrated along the Pacific and North Atlantic shipping routes, with a notable upward trend observed in the North Atlantic, but no

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significant activity detected in other maritime regions. In comparison, Indonesia’s maritime interests are most pronounced in the South India Passage, where a clear upward trend is evident at the 95% confidence interval, although interest in certain Pacific regions has declined. The maritime activities of India reveal a significant upward trajectory extending from the Arabian Sea to the eastern coast of North America, rejecting the null hypothesis at the 95% confidence level, while simultaneously exhibiting a significant downward trend in engagement with East Asia and South America.

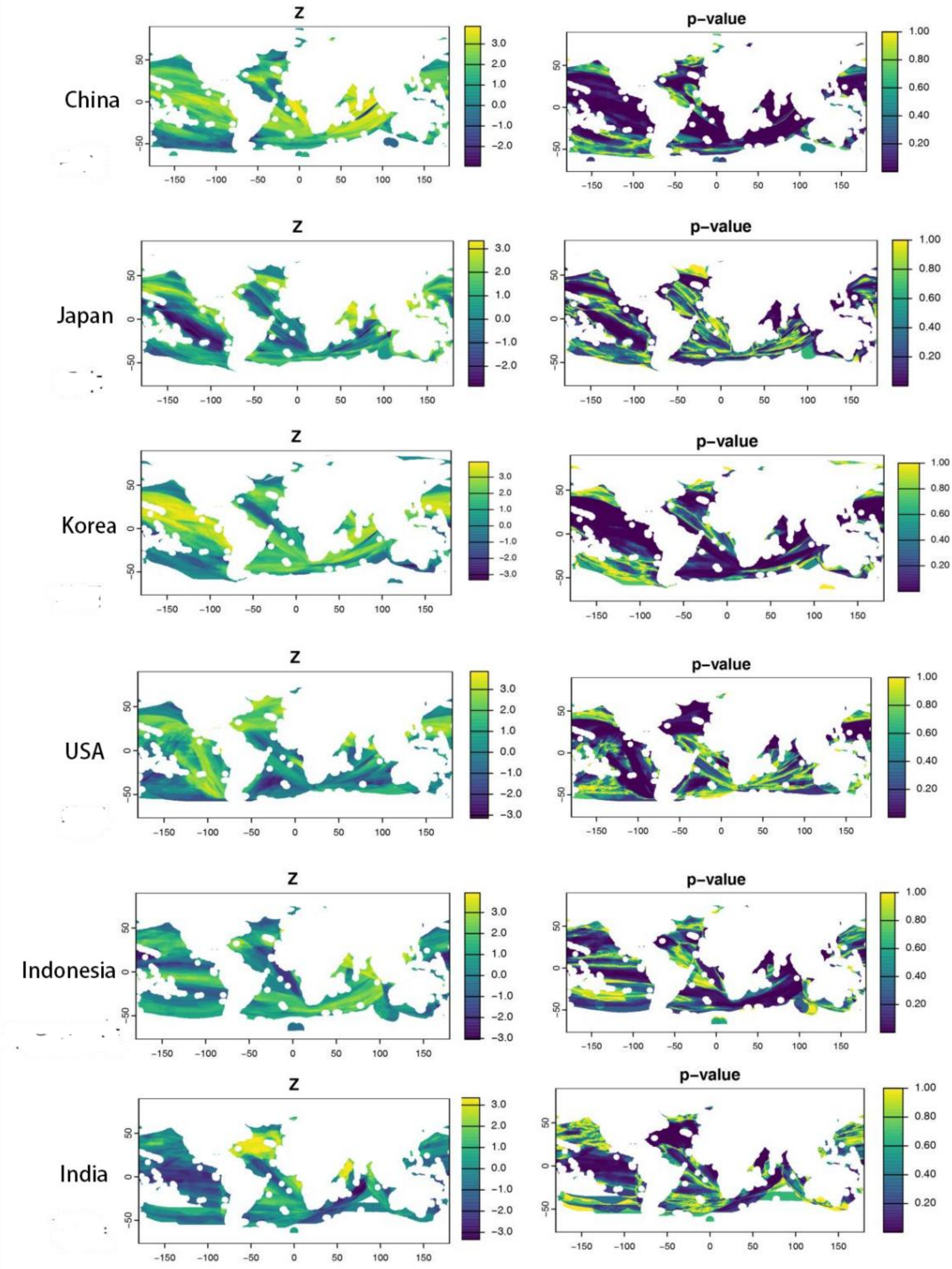

Fig. 2 The changing trends of high seas shipping in different countries

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3.2 Disscussion

The Chinese maritime shipping sector constitutes a critical component of global commerce, with shipping serving as the predominant mode of transportation, accounting for approximately 95% of China’s import and export trade volume. International shipping activities originating from China represent nearly one-third of the worldwide total. China’s freight routes extend globally, primarily emanating from East Asia and forming dense networks across the Pacific and Indian Oceans characterized by substantial cargo volumes and high operational frequency. The IMO emission reduction mandates for global shipping vessels are poised to exert considerable influence on China’s maritime supply chain. Consequently, it is imperative to promptly develop and implement pertinent environmental management strategies, enhance pollution control standards for ships and ports, and advance the deployment of intelligent and environmentally sustainable marine technologies to safeguard the stability of China’s maritime supply chain.

4. Conclusions

Utilizing quantitative analysis and spatial mapping derived from AIS data, this study examines the principal spatial and temporal patterns of high seas shipping activities across various nations. It further offers recommendations for the formulation of region-specific marine environmental protection policies. The spatial distribution of shipping emissions exhibits significant heterogeneity, predominantly concentrated along major international trade corridors and key port areas. Given these regional disparities, tailored policy interventions are essential to effectively mitigate ship emissions and preserve marine ecosystem productivity. Accordingly, the research advocates for encouraging individual countries to devise emission reduction strategies aligned with their unique spatial and temporal maritime activity profiles. In distinct maritime zones, the implementation of targeted regulatory measures aims to minimize adverse impacts on socio-economic activities while addressing climate change and environmental pollution. This approach seeks to balance the costs and benefits of such interventions, thereby fostering the sustainable development of oceanic resources.

5. Funding

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