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Research article

High-resolution mapping of Southern Ocean shipping emissions reveals policy-critical hotspots and post-pandemic rebound

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ABSTRACT

Antarctic shipping emissions are currently unregulated despite occurring in a sensitive environmental and geopolitical context. While previous studies have estimated tourism-related emissions, they lack the vessel type and spatial resolution necessary for effective mitigation strategies. This study integrates high-resolution Automatic Identification System (AIS) data with power-based modelling to quantify CO_2 emissions from all ship classes operating in the Southern Ocean between 2019 and 2022. The findings reveal that ships operating south of 60°S emitted 0.63 million tonnes of CO_2, with icebreakers (43.9 %), passenger vessels (28.7 %), and fishing ships (16.3 %) as the dominant contributors. Emissions were concentrated in the Antarctic Peninsula (60 %) and the Ross Sea (10 %), both critical biodiversity zones. The COVID-19 pandemic led to a 98 % reduction in tourism emissions in 2020–2021, while fishing ships remained largely unaffected, underscoring the sector's resilience to external disruptions. Four nations—the United States, Russia, Norway, and China—accounted for about 48 % of total emissions, highlighting disparities in polar operational footprints. These findings underscore the need for coordinated policy interventions, including region-specific emission regulations and strengthened clean fuel mandates under the IMO Polar Code, with the Antarctic Treaty System (ATS)-facilitated collaboration to advance national legislative and regulatory alignment—measures collectively aimed to align Antarctic shipping practices with Sustainable Development Goals (SDGs).

1. Introduction

Antarctica, the Earth's southernmost continent, remains one of the most isolated and least disturbed regions on the planet. However, rapid increases in human activities, primarily through scientific research, fishing, and tourism, have raised global concerns about their environmental impact. Ships serve as the primary mode of transportation to Antarctica, intensifying carbon emissions that contribute to climate change. The Southern Ocean is facing adverse effects from increasing maritime human activities, including marine ecological pollution (Aronson et al., 2011; McCarthy et al., 2019, 2022), marine traffic noise (Erbe et al., 2019), and greenhouse gas (GHG) emissions (Amelung and Lamers, 2007; Farreny et al., 2011; Li et al., 2022). Since the Industrial Revolution, human activities have significantly increased greenhouse gas emissions, impacting even remote environments like the Southern Ocean (Fogwill et al., 2020; Hauck et al., 2023). Globally rising carbon emissions accelerate the melting of ice sheets and shelves, thereby contributing to sea-level rise (Benn and Sugden, 2020). Additionally, ocean acidification from CO_2 absorption alters marine ecosystems, threatening biodiversity and disrupting climate patterns (Hancock et al., 2020; Rogers et al., 2020; Nissen et al., 2024). In contrast to the global consensus on carbon emission reduction, mitigating shipping's environmental impact in Antarctica necessitates strengthening the International Maritime Organization (IMO)'s governance

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framework—specifically by enhancing Carbon Intensity Indicator (CII) requirements under the Polar Code—to align with the Antarctic Treaty System (ATS)'s environmental objectives.

Under high-emission scenarios, Antarctica and its surrounding waters will undergo extensive transformations with far-reaching global consequences (Rintoul et al., 2018). The growing accessibility of Antarctic waters due to shrinking sea ice has intensified maritime traffic, raising the urgency of assessing its environmental footprint. While carbon emissions from Antarctic tourism have been extensively studied (Amelung and Lamers, 2007; Farreny et al., 2011; Li et al., 2022), emissions from other human activities remain poorly quantified (Leripio et al., 2012; Kakareka, 2020). Studies indicate that Antarctic cruise tourism contributes significantly to carbon emissions, with Amelung and Lamers (2007) estimating emissions of approximately 15 tonnes of CO_2 per tourist. Farreny et al. (2011) reported that 70 % of emissions from the tourism sector stemmed from cruise ships during 2008–2009. However, existing methodologies, which rely on statistical data from the International Association of Antarctica Tour Operators (IAATO), lack the precision required to map spatial emissions and assess their ecological impact comprehensively.

The development of Automatic Identification Systems (AIS) has revolutionized maritime research, providing unprecedented access to ship trajectory data. AIS-based studies have been widely employed for maritime surveillance, speed optimization, route planning, and emission analysis (Murray and Perera, 2021; Zhao and Shi, 2018; Yang et al., 2019; Rong et al., 2022). By integrating AIS data with ship parameters, researchers can estimate carbon emissions with high spatial and temporal accuracy, a methodology successfully applied in various global regions (Winther et al., 2014; Vicente-Cera et al., 2020; Weng et al., 2020; Toscano et al., 2021; Smit et al., 2022; Mou et al., 2024). However, despite its applicability, the use of AIS data for carbon emission assessments in the Antarctic region remains limited. Quantifying Southern Ocean maritime carbon footprints is nevertheless critical for developing evidence-based environmental policies and strengthening Antarctic governance frameworks. AIS data overcome these limitations by providing: (i) Real-time vessel trajectories, (ii) Engine power-linked emission modelling, and (iii) unified assessment across all ship classes.

The United Nations Sustainable Development Goals (SDGs) represent a universal call to action to foster balanced growth and forge a more equitable, sustainable future for both humanity and the planet. Our research contributes directly to the objectives of the SDGs, particularly SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 17 (Partnerships for the Goals), by providing a comprehensive assessment of maritime carbon emissions in the Antarctic region. By quantifying these emissions with high spatial and temporal precision, this study highlights the extent to which human activities impact one of the world's most fragile ecosystems. Understanding these emissions is essential for developing strategies to mitigate climate change effects and promote sustainable ocean management. Integrating AIS-based emission assessments into policy frameworks strengthens international efforts to reduce human-induced environmental degradation in Antarctica, offering a more data-driven foundation for decision-making.

Our 2019–2022 carbon emission inventory has direct implications for global and regional environmental governance. Our data contribute to ongoing revisions of the IMO Polar Code, particularly the extension of the CII, and provide valuable insights for the spatial design of marine protected areas under the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Additionally, by supporting national emission integration under SDG 13.2, our study reinforces the need for more effective international collaboration in addressing maritime emissions. The disparities in emissions among major stakeholder nations – including the United States (U.S.), China, and Russia – underscore the necessity of establishing burden-sharing mechanisms under the Protocol on Environmental Protection to the Antarctic Treaty. This approach is crucial for addressing potential impacts on the Antarctic environment and confirming a more equitable and responsible framework to regulate human activities in this rapidly changing region.

In this study, we estimated shipping carbon emissions in the Antarctic region by integrating AIS data with ship performance parameters. By analyzing maritime activity from 2019 to 2022, we reconstructed carbon emission trajectories, identified spatial and temporal emission patterns, and mapped emission hotspot regions. This study not only fills key knowledge gaps in polar emission research but also provides a blueprint for translating scientific insights into actionable conservation and climate strategies—ensuring the long-term sustainability of one of Earth's most vital ecosystems. The facts and figures gained from this research have direct implications for policymakers, researchers, and international regulatory bodies striving to develop effective strategies for environmental conservation in the Southern Ocean. By offering a data-driven perspective on carbon emissions, this study supports more informed decision-making processes within global and regional governance frameworks. As maritime traffic in Antarctica continues to grow, certifying that environmental policies are grounded in vigorous scientific evidence will be essential for the preservation of the region's ecological integrity while maintaining international commitments to sustainable development and climate action. Following the introduction, the study is further detailed in the subsequent sections. Section 2 describes the data and methodology, including AIS dynamic data, ship parameter data, and the approach used for calculating carbon emissions from shipping. Section 3 presents the results and analysis, examining temporal trends, country-wise emission comparisons, and the spatial distribution of emissions. Section 4 explores the broader implications of these findings, while Section 5 concludes the study by summarizing key comprehensions and their relevance to environmental policy and conservation efforts in the Antarctic region.

2. Data and methods

2.1. AIS-derived ship tracking data

The AIS data utilized in this study were obtained from the China Ocean Satellite Data Service Center (https://osdds.nsoas.org.cn), which provides global coverage. These data were acquired by five satellites equipped with AIS sensors, whose key specifications are summarized in Table 1. The dataset includes essential dynamic information, such as maritime mobile service identity (MMSI), geographic coordinates (longitude, latitude), speed over ground (SOG), course over ground (COG), heading, and universal time coordinated (UTC) timestamps. For this study, AIS Level 1b (L1b) data products from 2019 to 2022 were analyzed. To ensure data reliability, anomalous entries were removed following the method proposed by Zhao et al. (2018). Ship trajectories were then sampled at 30-min intervals to standardize the temporal resolution. The final dataset comprised more than 2.7 million recorded positions south of 50°S, with their spatial distribution illustrated in Fig. 1.

2.2. Ship parameter dataset and sources

The ship parameter data utilized in this study were primarily obtained from the Information Handling Services (IHS) Markit database (https://maritime.ihs.com), which provides comprehensive records of ocean-going vessels with a gross tonnage (GT) of 100 or more and

Table 1
Basic information of the satellites equipped with AIS sensors.

Launch year	Satellite	Orbital inclination	Swath width of AIS
2018	HY-1C	99°	≥950 km
2018	HY-2B	99°	≥1000 km
2020	HY-1D	99°	≥950 km
2020	HY-2C	66°	≥1000 km
2021	HY-2D	66°	≥1000 km

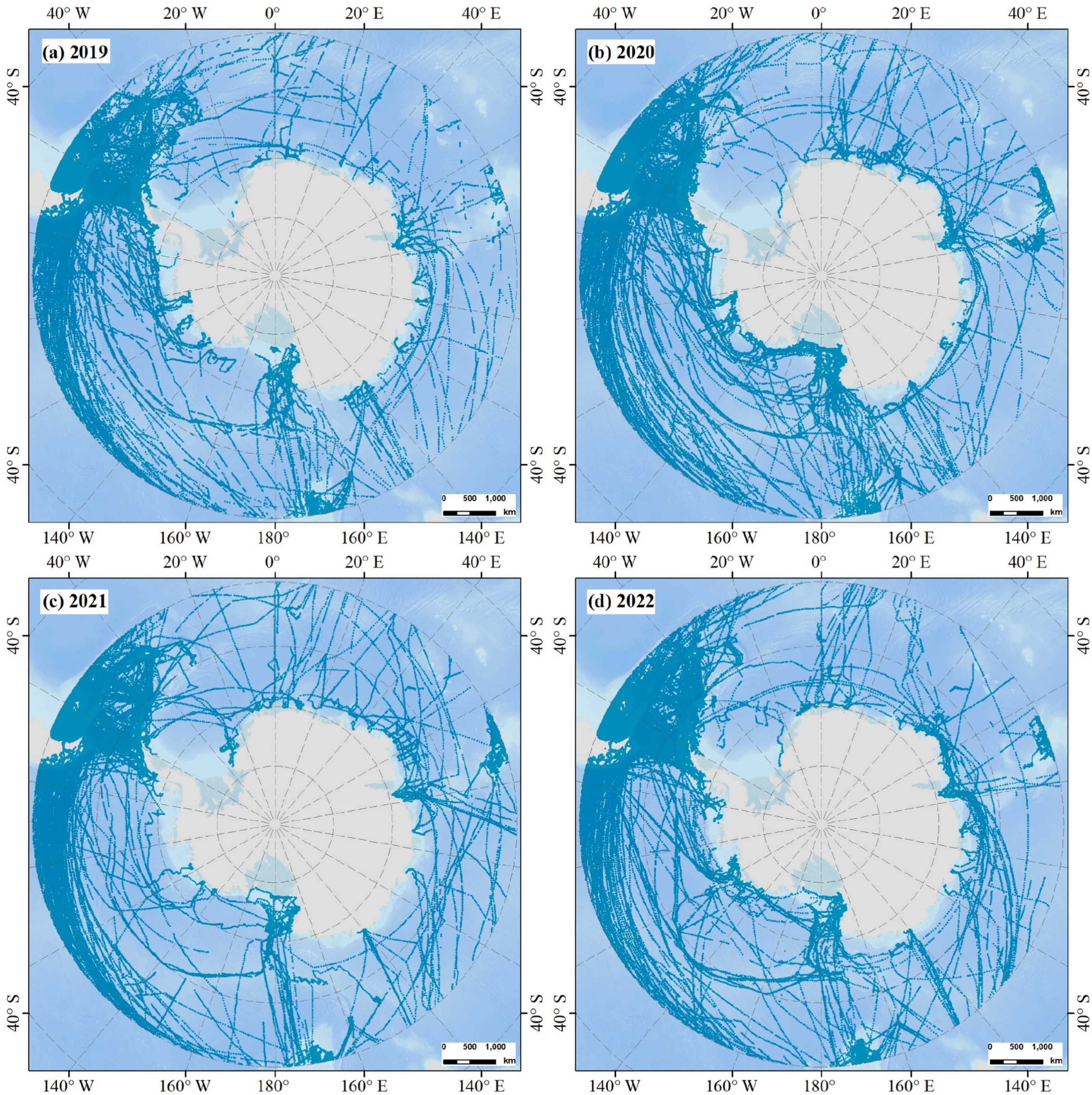

Fig. 1. Distribution of ships in the Southern Ocean. (a) 2019, (b) 2020, (c) 2021, and (d) 2022.

registered International Maritime Organization (IMO) numbers. This dataset includes key ship attributes such as vessel age, MMSI number, ship name, ship type, length, breadth, gross tonnage (GT), deadweight tonnage (DWT), service speed, maximum draught, main engine power (MEP), and auxiliary engine power (AEP). Since certain ship parameters were not available in the IHS Markit database, supplementary data were obtained from internet searches and static AIS data provided by the China Ocean Satellite Data Service Center. The final dataset comprises detailed parameters for 5068 ships operating in the Southern Ocean. The correlation coefficients among key ship parameters are illustrated in Fig. S1 (in the Supplementary Material).

Certain small and unidentified vessels often exhibit unreliable parameters and low-quality AIS data, as noted by Taconet et al. (2019). To address this issue, the analysis focused exclusively on ships with lengths greater than 20 m, which resulted in the exclusion of approximately 439 vessels. To estimate missing ship parameters, particularly gross tonnage (GT), regression formulas based on primary ship dimensions such as length and beam are frequently utilized, as outlined by Kristensen (2012, 2013). In the Southern Ocean, ships were categorized into various types, including bulk carriers, container ships, fishing vessels, general cargo ships, icebreakers, passenger ships, tankers, vehicle carriers, and other types. The relationship between ship length and GT was found to be strong, as illustrated in Fig. S1, where the correlation coefficient reveals a significant association between these two parameters.

Regression equations were subsequently developed to define the relationship between length and tonnage for each ship type, facilitating the estimation of missing GT values. The scatter plots shown in Fig. S2 illustrate the relationship between ship length and GT for different vessel categories, with each plot annotated with the corresponding regression equations. These plots demonstrate clear, distinct trends for each ship type, with R^2 values indicating the strength of the relationships. For instance, the regression model for bulk carriers showed a strong R^2 value of 0.96, indicating a very strong relationship between length and GT. Container ships and fishing vessels also showed strong correlations with R^2 values of 0.89 and 0.88, respectively. General cargo ships showed a very high R^2 value of 0.91, and icebreakers exhibited an R^2 of 0.76. Passenger ships and tankers had R^2 values of 0.98 and 0.99, respectively, while vehicle carriers showed an R^2 value of 0.93, and other types of ships also had an R^2 of 0.93. These high R^2 values across all ship types confirm the reliability and strength of the regression models used to estimate GT based on ship length.

To estimate the missing service speed of ships, we replaced absent values with typical service speeds derived from similar ships. These typical speeds were determined based on gross tonnage (GT) and ship type. Similarly, missing engine power values are often estimated using relationships between ship length or GT and engine power, as shown in previous studies (Zhang et al., 2019; Toscano et al., 2021). To further address missing data, we developed a support vector regression (SVR) model to estimate the missing main engine power (MEP) based on the relationships among GT, service speed, and MEP. Fig. S3 presents scatter plots illustrating the correlation between recorded MEP and estimated MEP for various ship types using the SVR method. These plots reveal a strong relationship, with high R^2 values indicating the robustness of the model's estimates across different ship categories. Specifically, bulk carriers showed an R^2 of 0.87, while container ships exhibited a much higher correlation with an R^2 of 0.94. Fishing vessels had an R^2 of 0.86, general cargo ships had an R^2 of 0.88, and icebreakers showed an R^2 of 0.64. Passenger ships and tankers had R^2 values of 0.9 and 0.91, respectively, while vehicle carriers and other ships demonstrated R^2 values of 0.89 and 0.71. Notably, the parameters for icebreakers were thoroughly documented, with no missing GT or MEP data. This comprehensive documentation enhances the reliability of the data for this specific ship type. Overall, these results highlight the effectiveness of the SVR model in estimating the MEP across various vessel types, ensuring the estimated values are reliable and consistent for further analysis.

The auxiliary engine power for ships can typically be obtained from the IHS Markit database; however, some records are missing. In the absence of this data, an alternative assumption is that the auxiliary engine power is a fraction of the main engine power, as suggested by Wang et al. (2019). To estimate the missing auxiliary engine power, we calculated the average ratio between the auxiliary engine power and the main engine power for different ship types. These ratios are summarized in Table S1, which shows the respective values for each ship type.

2.3. Method for calculating carbon emissions from shipping

In this study, AIS dynamic data were integrated with ship parameter data, including main and auxiliary engine data, to precisely calculate the energy consumption of ships. Subsequently, the fuel consumption was estimated by multiplying the baseline fuel consumption by the energy consumption. Finally, the derived fuel consumption was multiplied by the fuel emission factor, thereby providing a comprehensive and accurate estimation of carbon emissions considering the operation of the ship. This methodology, commonly known as the bottom-up approach, involves utilizing detailed ship parameters and activity information to estimate shipping emissions (Moreno-Gutiérrez et al., 2015). This comprehensive approach ensures a detailed and accurate assessment of emissions, relying on ship-specific characteristics and operational activities. In Eq. (1), the method for estimating fuel consumption is as follows:

$$F = T \times (MEP \times LF_{ME} \times BFC_{ME} + AEP \times LF_{AE} \times BFC_{AE}) \tag{1}$$

where T represents the time (h), MEP represents the main engine power measured in kilowatts (kW), LF_{ME} denotes the load factor of the main engine (%), BFC_{ME} is the main engine's baseline fuel consumption (g/kWh), AEP is the auxiliary engine power (kW), LF_{AE} is the load factor of the auxiliary engine (%), and BFC_{AE} is the auxiliary engine's baseline fuel consumption (g/kWh).

The load factor of the main engine is calculated by Eq. (2):

$$LF_{ME} = (\overline{V}/V_D)^n \tag{2}$$

where $\overline{V}$ represents the average speed between two trajectory points of the ship, measured in knots, and V_D is the designed speed of the ship, which is usually considered 1.064-fold greater than Lloyd's service speed (Moreno-Gutiérrez et al., 2015). The exponent n is the constant ship speed coefficient and represents the relationship between speed and main engine power. Under ideal conditions, n is typically 3, but due to other factors, values slightly greater or slightly less than 3 are also feasible (Moreno-Gutiérrez et al., 2015, 2019; Moreno-Gutiérrez and Durán-Grados, 2021). Considering the icebreaker as a special type of ship, we investigated the relationship between the speed of the Xuelong icebreaker, managed by the Polar Research Institute of China, and the load factor of its main engine, as shown in Fig. S4a. The study suggested that when calculating the main engine load factor of icebreakers, 1.52 is a more appropriate value of exponent n.

Generally, main engines achieve optimal operational efficiency when the main engine load factor reaches approximately 80 %. Conversely, at low load factors—particularly below 20 %—the engine operates sub-optimally, with diminished fuel efficiency. Under such conditions, baseline models frequently underestimate actual fuel consumption and carbon emissions, necessitating correction (IMO, 2020; CARB, 2022; Smit et al., 2022). To address this, the International Maritime Organization (IMO) recommends the correction factor (CLF) for main engines, defined in Eq. (3) as follows:

$$CLF = \left(0.455 \times LF_{ME}^2 - 0.71 \times LF_{ME} + 1.28\right) \tag{3}$$

The relationship between the CLF and LF_{ME} is depicted in Fig. S5. At an 80 % load factor, CLF approximates 1.0, indicating that the baseline fuel consumption estimate remains unadjusted—consistent with engines operating at their peak efficiency. By contrast, at a 20 % load factor, the CLF is approximately 1.16, meaning actual fuel consumption may be 16 % higher than the original model's estimate, thereby correcting for inefficiencies under low-load conditions. Therefore, when LF_{ME} falls below 80 %, the CLF is applied to refine the estimates: the main engine fuel consumption term in Equation (1) should be multiplied by the CLF to yield the corrected fuel consumption under such operational scenarios.

The operational status of a ship's power equipment varies depending on its navigation conditions. According to ship speed based on AIS data, a ship's navigation status can be categorized into three modes: cruise, at anchor and berth, and in manoeuvre. Carbon emissions from the ship are calculated separately for each navigation state. The cruising status is characterized by an average speed exceeding 4 knots, which typically indicates a higher main engine load (Ekmekçioğlu et al., 2020). In the anchoring and berthing state, when the main engine remains inactive, the ship's speed is less than 1 knot, while in the manoeuvring state, the speeds range between 1 and 4 knots. During the cruise mode, the load factor of the auxiliary engine is set at 30 %; during the manoeuvring state, it is 50 %; and during anchoring and berthing, it is 40 % (Ekmekçioğlu et al., 2020; Toscano et al., 2021). In the context of navigation in polar regions, auxiliary engines are employed to provide heating for fuel and domestic water supplies, resulting in additional power consumption; therefore, the power of auxiliary engines needs to be multiplied by a correction factor of 1.275 in our study region (Winther et al., 2014).

Different types of engines have varying fuel consumption rates, and it is essential to distinguish them when estimating a ship's fuel consumption. Typically, engines with a rated speed of less than 300 rpm are classified as slow-speed diesel (SSD), those with a speed between 300 and 1000 rpm are considered medium-speed diesel (MSD), and those with a speed greater than 1000 rpm are considered high-speed diesel (HSD) (Ekmekçioğlu et al., 2020). As heavy fuel oil (HFO) is not recommended for Antarctic waters, in the present study, it is assumed that liquefied natural gas (LNG) fuel, marine diesel oil (MDO), and marine gas oil (MGO) are used as ship fuels in our study region. According to the Fourth Greenhouse Gas Study (IMO, 2020), Table S2 shows the baseline fuel consumption (BSF) and emission factor (EF) of CO_2. The BSF for slow-speed diesel engines is 165 g/kWh, that for medium-speed diesel is 175 g/kWh, and that for high-speed diesel and auxiliary engines is 185 g/kWh. When ships use LNG fuel, the baseline fuel consumption of both the main and auxiliary engines is 156 g/kWh.

For the collected ship parameter data, a total of 2488 ships recorded daily fuel consumption at specific cruising speeds. These recorded fuel consumption values were compared to model-calculated daily fuel consumption, as shown in Fig. S4b. The estimated fuel consumption for most ships closely aligns with the recorded values. The MAPE is within 15 %, exhibiting the reliability of the fuel consumption model utilized in this study.

To further validate the fuel consumption model, we analyzed the fuel consumption statistics of the Xuelong and Xuelong 2 icebreakers during China's 39th Antarctic Research Mission. For Xuelong, the actual fuel consumption was recorded at 3255 tonnes, while the model-calculated consumption was 3442 tonnes, resulting in a difference of less than 7 %. For Xuelong 2, the actual consumption was 3391 tonnes, compared to a model-calculated value of 3041 tonnes, yielding a difference of 9 %. Additionally, we compared real fuel consumption data for parts of the voyages during China's 40th Antarctic Research Mission to model-calculated values, as illustrated in Fig. S6. While discrepancies were observed for Xuelong 2 on certain days, these variations may be influenced by weather conditions or differences in the daily statistical periods. Despite these occasional discrepancies, the daily fuel consumption estimates for both ships remain relatively reliable across most voyage states. Moreover, the model demonstrates strong predictive capability, with R^2 values of 0.85 for Xuelong and 0.49 for Xuelong 2, and MAPE of 12.57 % and 8.84 % (Fig. S6 ab), respectively, indicating a robust performance in estimating fuel consumption.

Once fuel consumption (F) has been determined using Equations (1)–(3), total carbon emissions (E) are calculated by multiplying the fuel consumption value (F) by the carbon emission factor (EF), as presented in Eq. (4).

$$E = F \times EF \tag{4}$$

where E represents carbon emissions and F is fuel consumption. EF denotes the fuel-based emission factors shown in Table S2, with MDO/MGO fuel having an EF of 3.206 g CO_2/g fuel and LNG fuel having an EF of 2.750 g CO_2/g fuel. Through the above formulas, the carbon emissions of each ship in the Southern Ocean were estimated, thereby revealing the spatiotemporal characteristics of ship emissions in the Southern Ocean.

3. Results and analysis

3.1. Analysis of the temporal characteristics

In this study, the carbon emissions from ships in geographic regions south of 50°S and 60°S from 2019 to 2022 were calculated, and the statistical results are presented in Table 2. From 2019 to 2022, a total of 4.06 million tonnes of CO_2 were emitted by ships located south of 50°S, with emissions of 0.63 million tonnes south of 60°S. Research revealed that between 2019 and 2021, shipping carbon emissions in the United States Exclusive Economic Zone (EEZ) exceeded 95 million tonnes (Mou et al., 2024), significantly higher than the carbon emissions observed in our study region. CO_2 emissions south of 60°S accounted for about 16 % of those observed south of 50°S, indicating lower intensity of human activities in high-latitude regions. However, owing to the vulnerability of the Antarctic ecosystem, any human activity has the potential to directly or indirectly impact the Antarctic environment, which is a factor that cannot be neglected. In the region south of 60°S, the year 2021 witnessed the lowest number of ships and carbon emissions in recent years, primarily attributed to the reduction in shipping activities due to coronavirus disease 2019 (COVID-19). The region south of 50°S had the highest number of ships in 2021, with lower CO_2 emissions than those in 2020 and 2022, indicating that shipping activities in this region were also affected by COVID-19. We observed that 135 more fishing ships were operating south of 50°S in 2021 compared to 2022. The COVID-19 pandemic impacted ship operations, resulting in a reduced operational range and frequency of activities, aside from fishing operations. This decrease in ship activities contributed to the lowest carbon emissions from ships in 2021.

Table 2
Ship count and carbon emissions from 2019 to 2022 in the Southern Ocean.

Date	Ship count		CO_2 (1000 tonnes)	
	50°S	60°S	50°S	60°S
2019	1852	168	939	142
2020	1892	162	1030	160
2021	2056	131	1000	122
2022	1928	171	1095	206

The monthly CO_2 emissions south of 50°S and south of 60°S during the period of 2019–2022 are illustrated in Fig. 2. Overall, carbon emissions south of 50°S were significantly greater than those south of 60°S. Bulk carriers, container ships, general cargo ships, tankers, and vehicle carriers can all be classified as cargo ships. According to Fig. 2a, the sea areas with lower latitudes serve as crucial maritime transportation routes, leading to a greater number of cargo ships traversing these areas. From 2019 to 2022, carbon emissions from cargo ships south of 50°S amounted to 2.15 million tonnes, accounting for approximately 53 % of total emissions. According to the monthly carbon emissions of different ships, seasonal variations in emissions were less pronounced among bulk carriers, container ships, and tankers due to their operation at lower latitudes with minimal seasonal influences, such as sea ice. In addition, these cargo ships seemed to be less impacted in the region south of 50°S during the pandemic. In contrast, passenger ships, icebreakers, and fishing ships showed distinct seasonal carbon emission patterns, and these ships were primarily active during the summer. According to Fig. 2b, due to the high latitudes and increased navigation costs, the region south of 60°S experienced fewer cargo shipping activities. Carbon emissions in this area were predominantly attributed to icebreakers, fishing ships, and passenger ships, which primarily operate in the Southern Ocean. These ships exhibited more distinct seasonal emission patterns, reflecting the seasonal nature of their activities in the region.

In the region south of 60°S, apart from the decline observed during the pandemic from 2020 to 2021, icebreakers exhibited relatively high levels of CO_2 emissions during summer seasons throughout our study period. Fishing ships exhibited a stable and regular trend of annual CO_2 emissions, with no significant decline observed during the pandemic. The optimal time for visiting Antarctica is between October and April (IAATO, 2022). CO_2 emissions from passenger ships are the highest in January, February, and December each year, with minimal tourism activities occurring annually from May to September. Additionally, during the 2019–2020 tourism period, CO_2 emissions from passenger ships were extremely high. However, emissions from passenger ships dropped by approximately 98 % during the 2020–2021 tourism period. Subsequently, during the 2021–2022 tourist season, emissions gradually

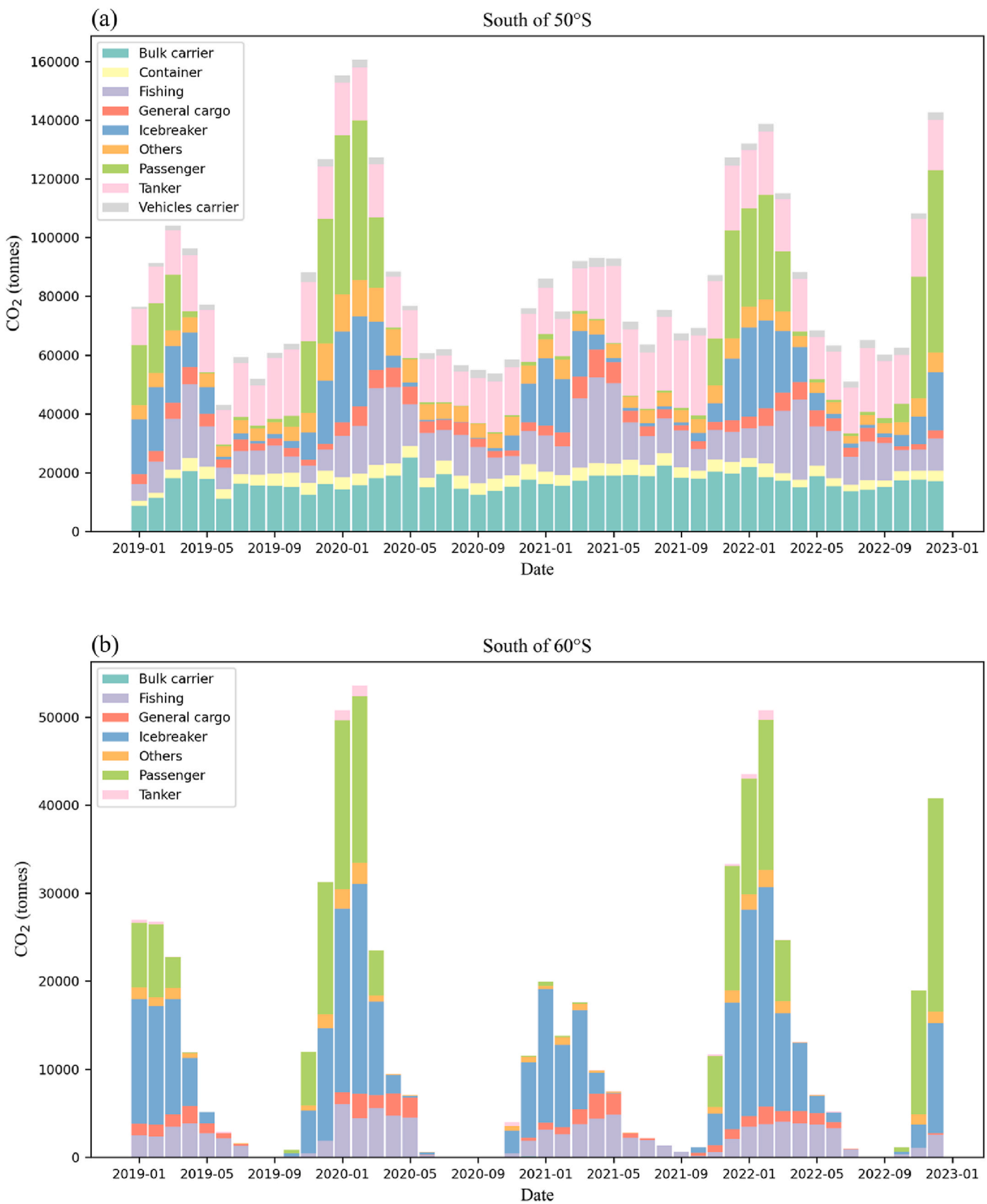

Fig. 2. Monthly CO_2 emissions from different types of ships in the regions south of 50°S (a) and 60°S (b).

increased. In December 2022, emissions reached their highest point during our study period. This phenomenon cannot be solely attributed to post-pandemic recovery but also stems from multifactorial drivers, including policy revisions and tourism demand resurgence. During the 2020 COVID-19 pandemic, global tourism experienced severe disruptions due to lockdowns, travel restrictions, and disease transmission impacts (Gössling et al., 2021). Government policies in Antarctic gateway states significantly impeded access to the continent through border closures and restrictions on transit via sovereign territories. New Zealand and Australia implemented stringent border controls that substantially reduced visits to East Antarctica and the Ross Sea region (Hughes and Convey, 2020; Liggett et al., 2024). By early 2021, global

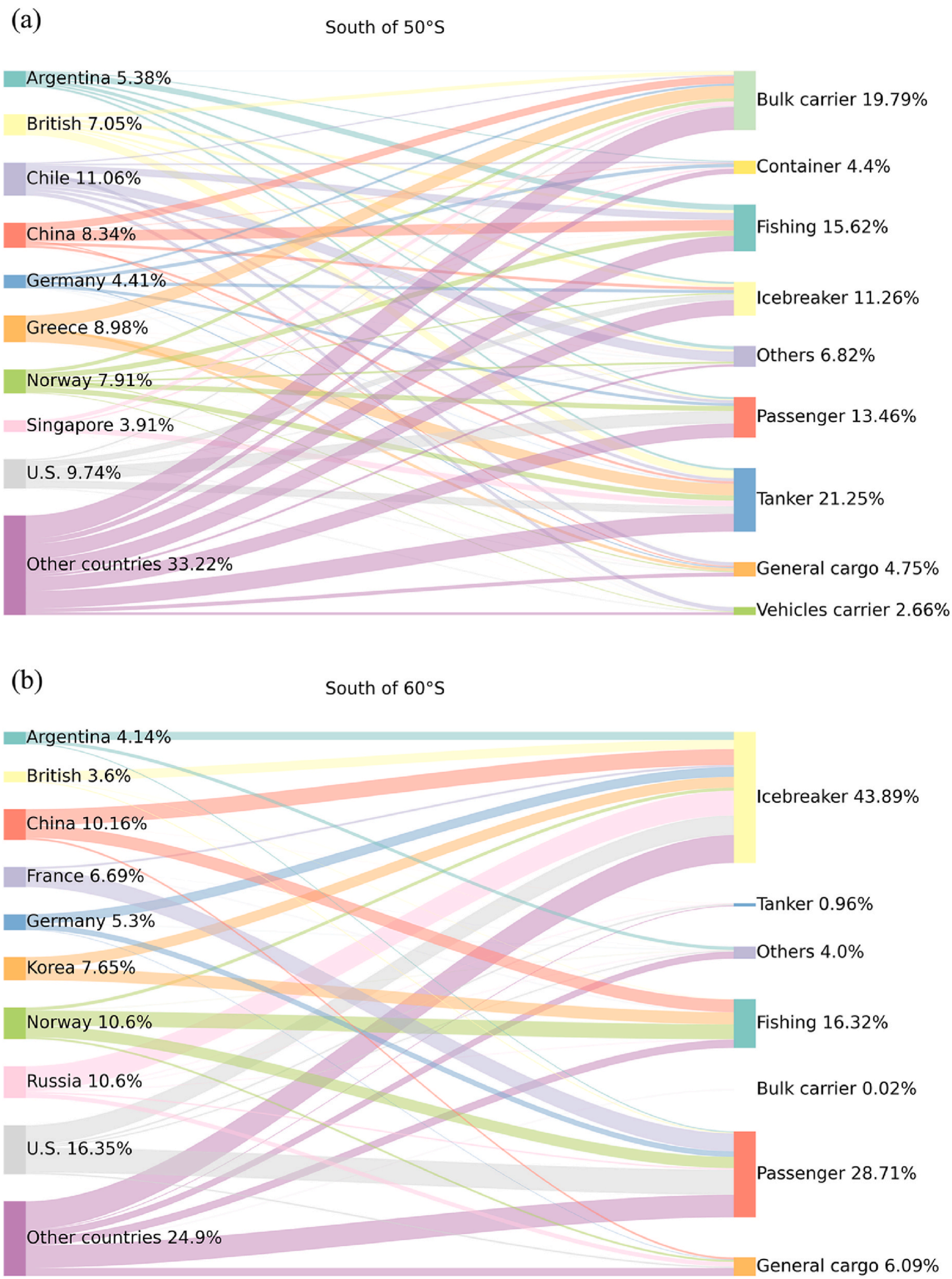

Fig. 3. Shipping CO_2 emission ratios among different ship types and countries in the regions south of 50°S (a) and 60°S (b).

pandemic conditions began to improve. Although Antarctic tourism partially resumed during the 2021–22 season, persistent low tourist willingness and operator reluctance to deploy vessels due to suboptimal occupancy rates constrained recovery (Makanse, 2024). Additionally, the delayed commissioning of vessels originally scheduled for 2021–22, caused by pandemic-induced supply chain disruptions, reduced operational capacity (IAATO, 2023). The 2022–23 season witnessed the deployment of these delayed vessels, coinciding with revived global tourism. Pent-up demand from prolonged travel restrictions triggered explosive growth in Antarctic visitation, exceeding pre-pandemic levels (IAATO, 2023).

3.2. Comparisons of carbon emissions between countries

Comparing the CO_2 emissions of different countries' ships can help to determine the sources of emissions and determine each country's activity levels in the Antarctic. Since the information on the flag state of a ship may not accurately align with its ownership and operator, we categorized ships by country based on the nationality of the operator. The ship operator information was gathered from the IHS Markit database and the Equasis (Electronic Quality Shipping Information System) database (https://www.equasis.org). We conducted a comparison of multiple countries that have high rankings in terms of carbon emissions from shipping. The CO_2 emission ratios of different countries and ship types from 2019 to 2022 are shown in Fig. 3. Chile's ports, which are situated south of 50°S, are essential maritime access points for Antarctica. South of 50°S, ships from Chile contributed the greatest proportion of CO_2 emissions, totalling 449,636 tonnes. The U.S. ranked second, with CO_2 emissions reaching approximately 395,743 tonnes during 2019–2022, which were driven primarily by passenger ships, icebreakers, and tankers. Greece ranked third, with approximately 364,947 tonnes of CO_2 emitted, predominantly from commercial cargo ships. China ranked fourth, with CO_2 emissions amounting to approximately 338,852 tonnes, driven by fishing ships, bulk carriers, and icebreakers.

South of 60°S, CO_2 emissions from shipping primarily originated from ship types such as icebreakers (43.9 %), passenger ships (28.7 %), and fishing ships (16.3 %). Ships from the U.S. contributed the most to CO_2 emissions, accounting for approximately 16.4 %, with emissions totalling 103,000 tonnes from 2019 to 2022. Ship activities from the U. S. predominantly involved icebreakers and passenger ships. Russia (~10.6 %), Norway (~10.6 %), and China (~10.2 %) had similar CO_2 emission proportions. Russia's emissions were primarily from icebreakers, while Norway's emissions predominantly resulted from fishing ships and passenger ships. In the case of China, emissions were mainly attributed to icebreakers and fishing ships.

Fig. 4 depicts the monthly CO_2 emissions from ships for different countries in the regions south of 50°S and south of 60°S. In the region south of 50°S, the monthly fluctuation in ship emissions from Chilean ships was not significant compared with that in other countries. The CO_2 emissions from U.S. ships rapidly increased starting in October and peaked in approximately February. In February 2020, the U.S. experienced the highest levels of emissions compared with all other months, with passenger ships accounting for approximately 60 % of emissions during that period. However, emissions from ships in the U.S. significantly declined in 2021, with a partial recovery at the end of the year. China experienced a later peak of CO_2 emissions in May 2021, surpassing the peak in March 2020, indicating that China's maritime activities in the Southern Ocean were also influenced by the pandemic but demonstrated a relatively swift recovery. Similarly, Greece experienced a later peak in CO_2 emissions in August 2021 than in 2020.

From an analysis of CO_2 emissions from shipping in the region south of 60°S, the reduction in CO_2 emissions from shipping by different countries was more significant between 2020 and 2021. The U.S. experienced significant disruptions in both icebreaker and passenger vessel operations due to pandemic-related challenges. Conversely, Russia, which is primarily involved in icebreaker activities, encountered comparatively minor disruptions. Additionally, during the Antarctic summer season of 2020–2021, most countries reduced and postponed their Antarctic activities, leading to a subsequent delay in the peak of CO_2 emissions from shipping. In general, maritime survey operations and tourism activities in Antarctica usually conclude after April. Nevertheless, China, Norway, and Korea sustained a small level of CO_2 emissions following April, primarily attributed to subsequent fishing shipping activities.

Emissions from Antarctic shipping are inherently a proxy for human activity intensity in this remote region. We further analyze the reasons for the disparities in ship-related carbon emissions among the above-mentioned countries. Fig. S7 shows spatial distribution of ship trajectories of different countries in the Southern Ocean during 2019–2022. The differences in national emissions reflect distinct operational priorities and geopolitical contexts. Chile, as a gateway nation to Antarctica, hosts ports south of 50°S that serve as critical maritime access points to Antarctica. Its ship activities are primarily concentrated in the area from southern South America to the Antarctic Peninsula, particularly between 50°S and 60°S, maintaining consistently high activity levels in this region.

Greece, recognized as a leading maritime power with the world's

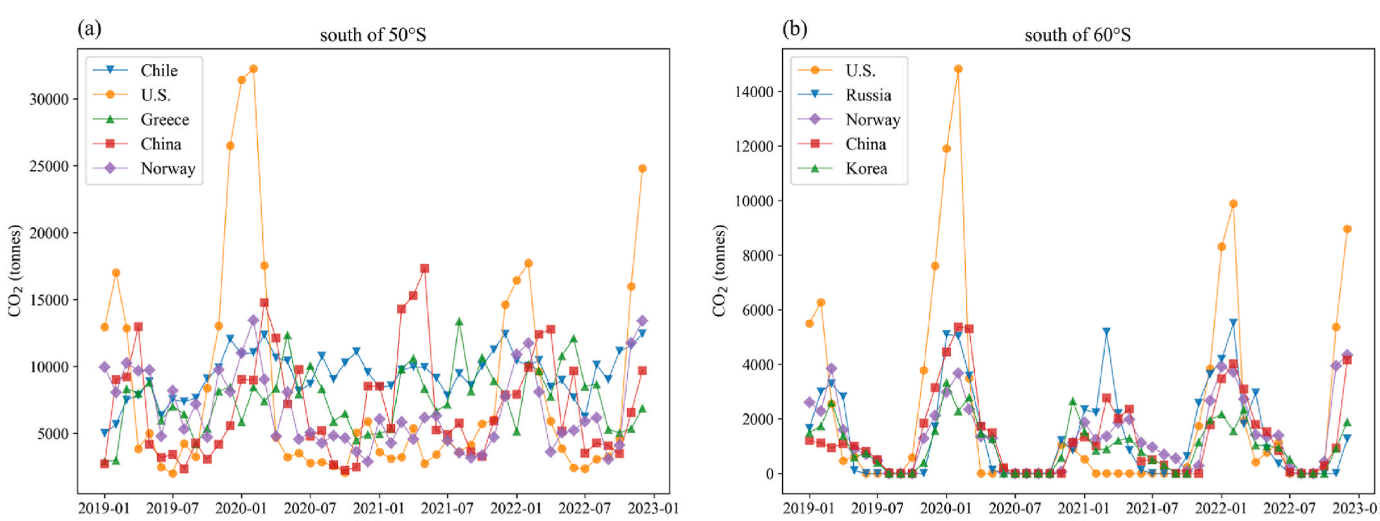

Fig. 4. Monthly CO_2 emissions of ships from different countries in the regions south of 50°S (a) and 60°S (b).

highest shipping fleet value (UNCTAD, 2024), operates a substantial number of merchant vessels. Its shipping routes frequently traverse the Southern Ocean (e.g., the Drake Passage) to connect the Atlantic and Pacific Oceans, but rarely engage in purposeful activities deep within the Southern Ocean. Consequently, Greece's ship-related carbon emissions are concentrated in the 50°S–60°S region, with minimal contribution from areas south of 60°S, and its activities are less dependent on seasonal factors.

In the Southern Ocean, U.S. maritime activities are predominantly driven by tourism, followed by scientific expeditions. Supported by a robust economy and advanced service sector, the U.S. has maintained long-term investments in Antarctic tourism through domestic tour operators, which manage a substantial fleet of Antarctic cruise vessels. The IAATO, founded in 1991 under the leadership of U.S. tourism enterprises, plays a pivotal role in coordinating and regulating Antarctic tourism. Additionally, U.S. tourists have consistently ranked among the top in terms of numbers in recent years. As a result, U.S. passenger ship activities are extremely frequent during the Antarctic summer. The COVID-19 pandemic (2020–2021) led to the suspension of tourism activities and consequently caused a sharp decline in passenger vessel emissions. By contrast, U.S. icebreaker operations, which are primarily dedicated to scientific missions and logistical resupply of major research stations such as Palmer Station (Antarctic Peninsula) and McMurdo Station (Ross Sea region), experienced only minor disruptions due to the persistent demand for scientific operations. Accordingly, the pronounced decline in emissions observed in Fig. 4 is primarily attributable

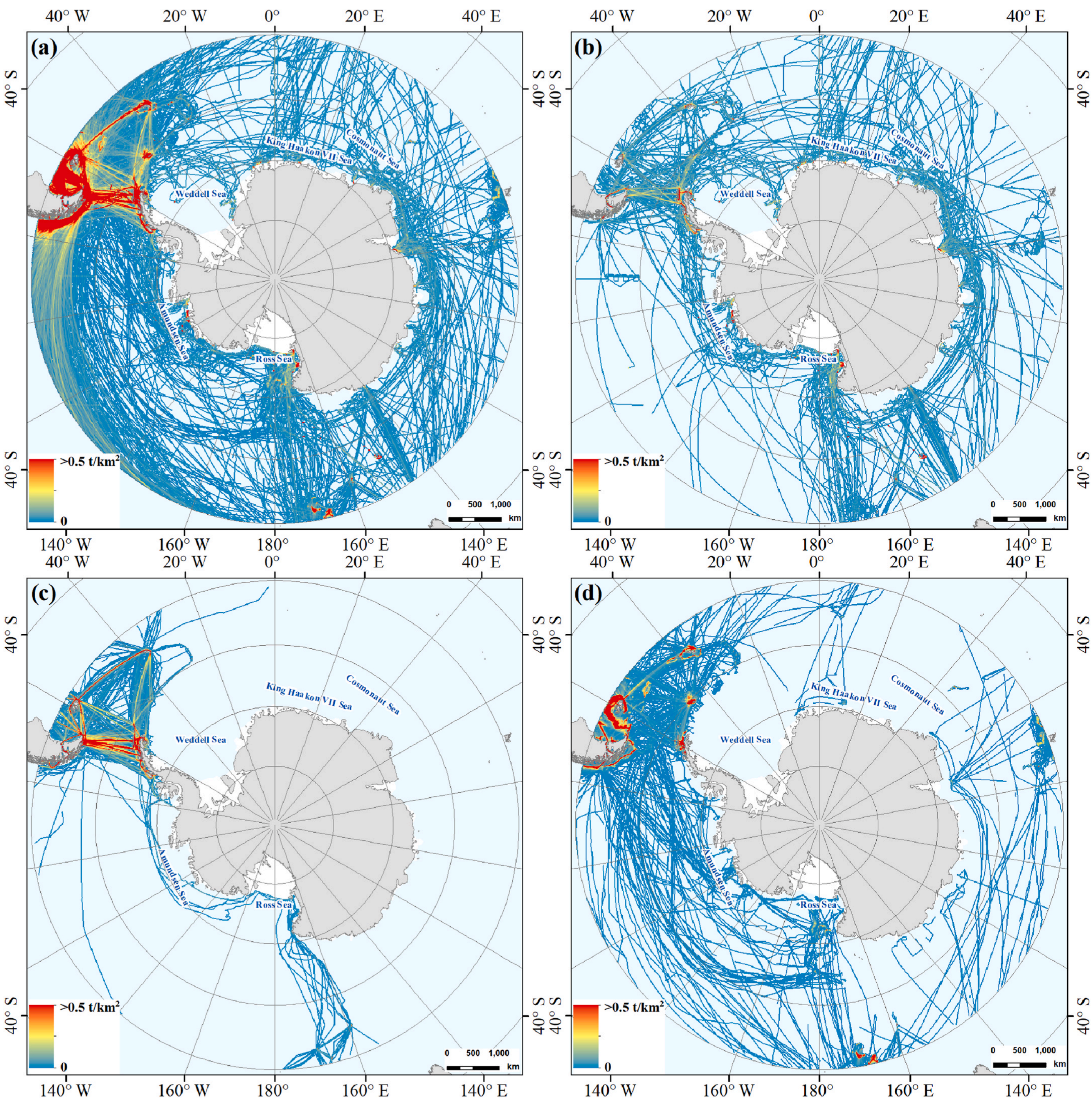

Fig. 5. Density of CO_2 emissions from all ships (a), icebreakers (b), passenger ships (c), and fishing ships (d) in the Southern Ocean during 2019–2022.

to reduced passenger vessel activity.

Russia's Antarctic shipping activities embody a geo-strategic calculus that prioritizes sustained scientific presence over economic gains. Its fleet operations are dominated by icebreakers tasked with maintaining year-round logistics for its network of research stations—exemplified by vessels supporting remote outposts like Vostok and Novolazarevskaya. Tourism remains minimal, with only occasional cruises such as the ship Professor Khromov's seasonal expeditions in the Ross Sea, while fishing activities are limited to small-scale krill harvesting near the Antarctic Peninsula. China, with a shipping fleet size second only to Greece globally, operates a large number of commercial vessels worldwide, resulting in substantial cargo ship traffic south of 50°S. China's emissions in this region are driven by state-funded polar research (e.g., the Xuelong and Xuelong 2 icebreakers) and krill fishing in the Scotia Sea. Collectively, Russia and China's icebreaker emissions align with their investments in polar logistics capabilities, supporting research station operations and asserting strategic presence in Antarctic governance.

Antarctica is rich in fishery resources, with krill being the most commercially valuable. Since the Soviet Union initiated trial krill fishing in Antarctica in the 1970s, countries such as Japan, Poland, and Chile have successively developed krill exploitation. Following the dissolution of the Soviet Union, Russia's commercial krill fishing in the Southern Ocean gradually declined. China joined the CCAMLR in 2007 and formally began commercial krill fishing in Antarctica in 2010 after multiple expeditions. Currently, krill fishing is dominated by a few nations, with Norway leading in catch volume, followed by China and South Korea (Nicol and Foster, 2016)—a pattern that reflects both economic and food security interests in the region. Consequently, higher activity intensity among these nations' fishing vessels contributes to their relatively higher fishing-related carbon emissions.

3.3. Characteristics of the spatial distribution of carbon emissions from shipping

In our exploration of spatial variations in CO_2 emissions from shipping in the Southern Ocean (2019–2022), a line density method with a 10 × 10 km grid resolution was employed for detailed analysis. As illustrated in Fig. 5, the density maps reveal the primary emission regions of ships and can help to determine the main shipping lanes. According to Fig. 5a, south of 50°S, ship emissions primarily originate from the waters around Chile and Argentina. The Drake Passage serves as a crucial pathway for ships to enter the Antarctic, resulting in high CO_2 emissions from shipping in the region between the Antarctic Peninsula and South America. Additionally, the Ross Sea exhibits relatively concentrated CO_2 emissions, primarily attributed to high-latitude shipping activities.

In the context of polar exploration, icebreakers play a crucial role in facilitating scientific research and maintaining essential logistical operations. These specialized vessels navigate between research stations and supply ports, providing vital support for scientific endeavours in harsh and demanding polar environments. Fig. 5b shows that the CO_2 emissions from icebreakers are significantly concentrated in the Drake Passage, the adjacent areas of the Antarctic Peninsula, and along the coastal regions of Antarctica. Notably, these emissions are particularly pronounced near research stations. Considering the accessibility of cruise ships, primary Antarctic tourism routes typically involve voyages from Argentina or Chile to the Antarctic Peninsula and from Australia or New Zealand to the Ross Sea. Fig. 5c shows that emissions from passenger ships are notably concentrated around the Ross Sea, with more significant concentrations extending from South America to the Antarctic Peninsula, which encompasses South Georgia Island. The density of CO_2 emissions from fishing ships, as shown in Fig. 5d, indicates that fishing ships mainly operate on fishing grounds. The intensity of their activities serves as a valuable indicator, elucidating the spatial distribution of fisheries resources. In the region north of 60°S, emissions from fishing ships are not as frequent in the Drake Passage region as emissions from other types of ships. The emissions are concentrated in the waters around Chile and Argentina, South Georgia Island, and Auckland Island. South of 60°S, their main activities occur around the South Shetland Islands, South Orkney Islands, and in the vicinity of the Ross Sea.

Fig. 5 shows that the water around the Antarctic Peninsula is a crucial region for maritime activities, with comparatively high CO_2 emissions from ships. According to the IAATO, the Antarctic Peninsula is a famous tourist destination, featuring 289 tourist locations and attracting more than 20,000 visitors during the 2021–2022 tourist season (IAATO, 2022). Through an assessment of CO_2 emissions from ships around the Antarctic Peninsula, we found that during the 2019–2022 period, all ships emitted 0.39 million tonnes of CO_2, constituting more than 60 % of the emissions in the region south of 60°S. As shown in Table 3, passenger ships were the primary contributors to shipping emissions, emitting approximately 173,139 tonnes from 2019 to 2022, constituting approximately 44 % of the total in the Antarctic Peninsula Region; icebreakers emitted 77,467 tonnes of emissions, accounting for approximately 20 %; and fishing ships emitted 86,886 tonnes of emissions, representing 22 %.

To reflect the variations in passenger shipping activities across different tourist seasons, we considered October through September as one coherent period. The analysis of CO_2 emissions from passenger ships around the Antarctic Peninsula during different periods is illustrated in Fig. 6, which reveals a pattern of concentrated shipping activities over time. Predominantly, emissions are observed around key regions, such as the South Shetland Islands, Bransfield Strait, the Palmer Archipelago, and the vicinity of Elephant Island. The CO_2 emissions from passenger ships around the Antarctic Peninsula reached 62,678 tonnes from October 2019 to September 2020. However, owing to the significant decline in Antarctic tourism caused by the COVID-19 pandemic, emissions from passenger ships sharply decreased to 980 tonnes from October 2020 to September 2021. During this period, only three passenger ships were operational. From October 2021 to September 2022, with the resumption of tourism activities, CO_2 emissions recovered to 52,062 tonnes. The pandemic negatively impacted the tourism industry and the global economy from 2020 to 2021, resulting in drastic reductions in Antarctic tourism and CO_2 emissions. With the dissipation of the pandemic and the recovery of the global economy, it is anticipated that Antarctic tourism will expand again.

In addition to the Antarctic Peninsula region, the Ross Sea region serves as a prominent region for maritime activities, featuring the world's largest marine protected area, namely, the Ross Sea region Marine Protected Area (RSrMPA). This area is dedicated to limiting fishing and other human activities, emphasizing its crucial scientific research value. Approximately 80 % of the protected area consists of General Protection Zones (GPZs), which strictly prohibit fishing activities and allow only research-oriented fishing for specific fish species. The Special Research Zones (SRZs) permit research-related fishing with restricted catch volumes, while the Krill Research Zone (KRZ) allows targeted research fishing for krill (Brooks et al., 2021; Grüss et al., 2024). Owing to the significant ecological and scientific value of the Ross Sea region, numerous countries have conducted research and monitoring activities in the Ross Sea region, establishing research stations such as McMurdo Station, which is operated by the United States and represents the largest scientific research station in Antarctica. Given its high latitude, shipping activities in the Ross Sea are dominated by icebreaker research expeditions. Additionally, there are occasional fishing and cruise shipping activities, along with sporadic cargo ships delivering supplies to the research stations. Table 4 shows the CO_2 emissions from ships in the Ross Sea sector in different years. Notably, the bulk carrier ships that passed through this sector were near 60°S and did not venture far into the Ross Sea. During the period from 2019 to 2022, a total of 68,556 tonnes of CO_2 were emitted in the Ross Sea sector, accounting for more than 10 % of the emissions in the Southern Ocean region located south of 60°S. Icebreaker ships emitted approximately 50,451 tonnes of CO_2, constituting approximately 74 % of the

Table 3
Ship count and CO_2 emissions from different types of ships from 2019 to 2022 in the Antarctic Peninsula region.

Ship type	Ship count				CO_2 (tonnes)			
	2019	2020	2021	2022	2019	2020	2021	2022
Fishing	24	27	18	20	16,394	23,725	24,390	22,377
General cargo	12	12	12	12	6438	9129	9309	5469
Icebreaker	19	14	15	18	22,456	14,752	14,461	25,798
Others	21	16	13	20	6216	5851	4625	5308
Passenger	52	53	33	63	40,104	41,359	20,765	70,911
Tanker	4	–	2	2	715	–	149	185

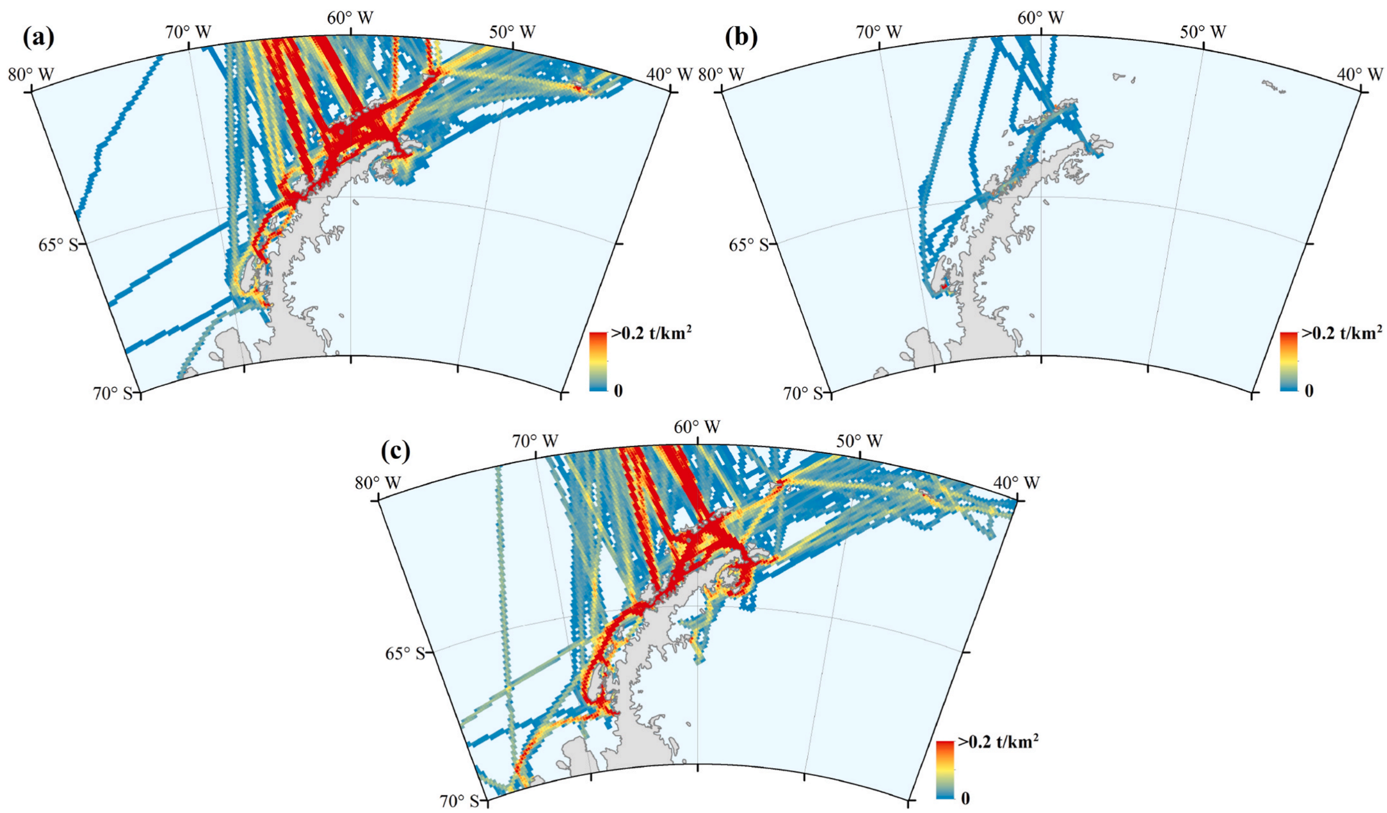

Fig. 6. Density of CO_2 emissions from passenger ships in the Antarctic Peninsula region during 2019–2022. (a) 2019.10–2020.09, (b) 2020.10–2021.09 and (c) 2021.10–2022.09.

Table 4
Ship count and CO_2 emissions from different types of ships in the Ross Sea sector from 2019 to 2022.

Ship type	Ship count				CO_2 (tonnes)			
	2019	2020	2021	2022	2019	2020	2021	2022
Bulk carrier	–	1	–	1	–	68	–	49
Fishing	19	20	19	18	1662	1873	2168	2128
General cargo	2	2	–	1	1470	1692	–	897
Icebreaker	10	10	7	6	9711	18,721	6139	15,880
Passenger	1	3	–	2	661	1530	–	1545
Tanker	–	1	–	1	–	1202	–	1160

total emissions in the Ross Sea sector. In addition, only icebreakers and fishing ships operated in this region in 2021.

Fig. 7 reveals the distribution of emissions from all ships in the Ross Sea sector during different periods. The emissions were mainly concentrated near the western coast of the Ross Sea, accompanied by a significant clustering of research stations within this region. Owing to the high latitudes and restrictions in protected areas, the overall CO_2 emission intensity was not high. The intensity of fishing activities in protected areas can be assessed by analyzing emissions from fishing vessels. From 2019 to 2022, approximately 1162 tonnes of CO_2 from fishing ships were emitted in the protected area, constituting approximately 15 % of the total CO_2 emissions from fishing ships in the Ross Sea sector. Specifically, the GPZ area contributed 573 tonnes, the SRZ area contributed 586 tonnes, and there were almost no emissions from fishing ships in the KRZ region. Through an analysis of the temporal changes shown in Fig. 7, we found that CO_2 emissions from vessels in the region amounted to 26,850 tonnes from October 2019 to September 2020, decreased to 6621 tonnes from October 2020 to September 2021, and

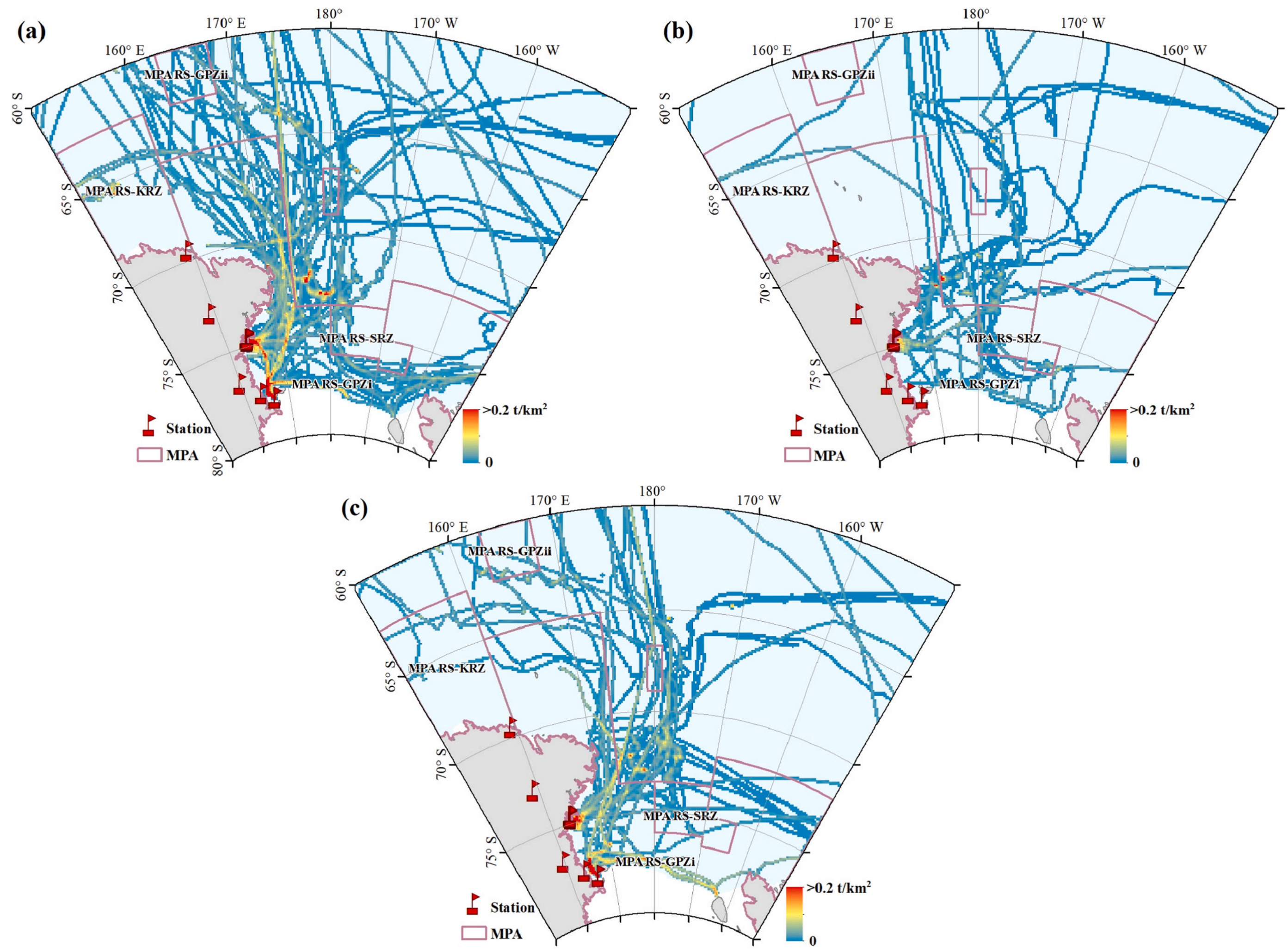

Fig. 7. Density of CO_2 emissions from all ships in the Ross Sea sector during 2019–2022. (a) 2019.10–2020.09, (b) 2020.10–2021.09, and (c) 2021.10–2022.09.

increased again to 20,822 tonnes from October 2021 to September 2022. This phenomenon indicates a decline of more than 75 % in maritime activities in the Ross Sea region from 2020 to 2021 due to the impact of the pandemic.

4. Discussion

4.1. Potential impacts of shipping activities on the Antarctic environment

Shipping activities in the Southern Ocean pose significant risks to Antarctica's fragile ecosystems through both physical disturbances and ecological disruptions. Propulsion systems and hull operations in ice-covered waters alter sea ice structure, threatening ice-dependent ecosystems (Kariminia et al., 2012), while anchoring at frequently visited sites such as the Antarctic Peninsula damages benthic communities on the seafloor (Aronson et al., 2011). Ship strikes further endanger marine mammals, often causing severe injury or mortality (Tejedo et al., 2022).

Maritime vessel operations constitute a significant environmental stressor in polar regions through multiple pollution pathways. Combustion of marine fuels emits greenhouse gases and particulate matter that accelerate climate change (Amelung and Lamers, 2007; Farreny et al., 2011), while black carbon deposition on cryospheric surfaces amplifies albedo reduction and melting dynamics, particularly in the Antarctic Peninsula (Cordero et al., 2022). Hydrocarbon spills from vessels introduce toxic compounds that disrupt marine trophic networks, impacting plankton to fish populations (Tin et al., 2009; Aronson et al., 2011). Similarly, discharge of untreated sewage introduces pathogens and nutrient loads that drive eutrophication and microbial dysbiosis (Tin et al., 2009).

Acoustic pollution from vessel engines and sonar systems generates noise that masks bioacoustic signals, impairing the communication and navigation behaviors of marine mammals (Erbe et al., 2019). Solid waste streams, including microplastics from packaging and synthetic microfibers from laundering, pose entanglement risks to avifauna and pinnipeds, causing injury and mortality through drowning or infection (do Sul et al., 2011; Waller et al., 2017). Vessels additionally serve as vectors for biological invasions via hull fouling communities and ballast water discharge, facilitating the introduction of nonnative species that alter benthic ecosystems (McCarthy et al., 2019).

According to the Global Carbon Project, global fossil CO_2 emissions in 2024 are projected to reach 37.4 gigatonnes (Gt), 0.8 % higher than in 2023. This growth will elevate atmospheric CO_2 concentrations by approximately 6.1 gigatonnes of carbon (GtC), equivalent to 2.87 ppm, extending the historical trajectory that has seen concentrations rise 51 % from pre-industrial levels (~278 ppm circa 1750) to 419.31 ppm in 2023 (Friedlingstein et al., 2025). These emissions drive systemic changes with projected repercussions on Antarctica, including impacts on sea ice extent, glacial retreat, ice shelf collapse, ice sheet collapse, and Southern Ocean acidification. Since the Industrial Revolution, oceanic CO_2 absorption has reduced global seawater pH by ~0.1 units (Raven et al., 2005), with the Southern Ocean experiencing amplified effects due to its unique oceanographic processes (Cao and Caldeira, 2008). The cumulative evidence underscores that anthropogenic carbon emissions demand concerted mitigation and policy intervention. This study quantifies shipping-related CO_2 emissions at 0.63 million tonnes south of 60°S from 2019 to 2022—significantly lower than global maritime emission hotspots. While current evidence indicates that localized carbon emissions have not yet induced detectable environmental impacts in the region, these emissions cumulatively exacerbate carbon sink saturation stress in the Southern Ocean. Unmitigated emissions risk triggering cascading effects on Antarctic ecosystems demands proactive governance.

4.2. Policy implications

Shipping emissions in the Southern Ocean are both a critical environmental stressor and a quantifiable indicator of human activity intensity, providing a benchmark for policy evaluation. Icebreakers (43.9 %), tourism vessels (28.7 %), and fishing ships (16.3 %) dominate CO_2 emissions south of 60°S but remain inadequately regulated. While the IMO Polar Code sets navigation rules, enforcement is hampered by poor monitoring and jurisdictional ambiguities, with Annex VI to the Antarctic Treaty's Environmental Protocol lacking effective implementation (Ferrada and Caldera, 2024).

Although flag states are primarily responsible for vessel operations, enforcement of IMO standards beyond territorial waters remains weak, particularly due to the widespread use of "flags of convenience" by Antarctic passenger vessels (e.g., Bahamas, Malta, Marshall Islands). This governance gap poses disproportionate risks for Antarctica (Todorov, 2024). Our analysis proposes an alternative approach that classifies vessels by operator nationality to account for emissions. Therefore, future regulations should mandate proactive declaration of responsible entities (state operators or organizations) prior to Antarctic entry, establishing clear liability matrices among vessel operators, flag states, and coastal authorities.

Globally, carbon reduction is a consensus goal. IAATO operators have pledged a 50 % reduction by 2050, yet this falls short of many national pledges and the IMO net-zero target by 2050 (Senigaglia et al., 2025); the British Antarctic Survey targets net-zero by 2040. Achieving such ambitions requires stricter regulatory alignment and technological innovation in ship decarbonization (e.g., clean fuels, vessel redesign). The Antarctic Treaty Consultative Meeting (ATCM), though lacking direct enforcement authority, can bridge this gap by fostering consensus and engaging with the IMO to integrate Antarctic-specific priorities into global emission frameworks and national legislation.

Our high-resolution emission map identifies compliance priority zones, with the Antarctic Peninsula contributing ~60 % of Southern Ocean shipping CO_2 emissions and the Ross Sea ~10 %. Elevated vessel activity in these sensitive areas highlights the need for spatially targeted management. Seasonal emission caps and landing restrictions in the Antarctic Peninsula, supported by pandemic-related evidence of ~98 % emission reductions from tourism, could align visitor surges with ecological capacity. Similarly, using the Ross Sea MPA zoning to restrict fishing emissions would reduce cumulative pressures.

Balancing environmental protection in Antarctica with scientific and economic activities demands policies that target emission hotspots, modernize liability frameworks, and leverage real-time monitoring to address climate change collectively. From a sustainability standpoint, polar regions hold pivotal significance for advancing global sustainable development (Li et al., 2025). This study contributes to key SDGs: it supports SDG 13.2 by providing vessel-specific emission benchmarks for national policy frameworks; aligns with SDG 14.4 through mapping fishing fleet emissions to inform sustainable marine resource management; and advances SDG 17.6 by offering an AIS-based emission estimation model, thereby fostering international cooperation and technology sharing in environmental monitoring.

4.3. Limitations and future work

This study estimated Southern Ocean shipping CO_2 emissions using an AIS-based power model, validated with icebreaker fuel consumption data, but faces several limitations. First, analyses were restricted to vessels longer than 20 m due to lower data quality for smaller ships. To assess the impact of excluding smaller vessels, we assigned a length of 20 m to ships lacking length parameters or measuring less than 20 m. Based on this approach, emissions from 439 small vessels (80,372 tonnes) accounted for only 2 % of total emissions, indicating that their exclusion introduces minor uncertainty. Second, AIS data quality affects the quantification of carbon emissions (Tian et al., 2022; Chen and Yang, 2024), with challenges including sparse 2019 trajectory data in this study due to data acquisition constraints. Third, potential minor geographical variations in fuel emission factors—such as those identified by Fan et al. (2023)—were not considered in this study. Despite these limitations, the AIS-based method remains the most effective approach for estimating shipping emissions, offering a valuable means of assessing ship activity intensity and environmental impacts. Furthermore, the power-based AIS approach is not limited to carbon emissions; it can be extended to other pollutants (e.g., NO_x, SO_x, black carbon) when their emission factors for different fuels are available.

Future research should prioritize three key areas: first, the expansion of AIS monitoring networks in the Southern Ocean to enhance data reliability; second, incorporating other pollutants into emission inventories to further quantify shipping's environmental impacts on Antarctica; and third, an assessment of the equity implications of emission controls, particularly concerning the accessibility of Antarctic research for developing countries. Addressing these research priorities will not only refine emission estimation methodologies but also strengthen the governance mechanisms necessary for ensuring the long-term sustainability of maritime activities in the Southern Ocean.

5. Conclusion

Shipping carbon footprints serve a dual innovative role: as a quantifiable metric of human activity intensity in Antarctica and thereby as a diagnostic tool for prioritizing conservation interventions. This study established a comprehensive framework for quantifying Southern Ocean shipping CO_2 emissions, addressing a critical gap in polar environmental research by integrating high-resolution AIS trajectory data with vessel-specific power modeling. In this study, we estimated CO_2 emissions from shipping activities in the Southern Ocean between 2019 and 2022, providing insights into the spatiotemporal distribution of emissions. The results highlight some key findings:

First, we present the first multi-year emission inventory of ships in the Southern Ocean. From 2019 to 2022, a total of 4.06 million tonnes of CO_2 were emitted from shipping activities south of 50°S, with cargo ships accounting for 53 % of the total emissions. The emissions were less influenced by the COVID-19 pandemic compared to other vessel types. In the region south of 60°S, emissions were 0.63 million tonnes, approximately 16 % of the total emissions from south of 50°S, with icebreakers contributing 43.9 %, passenger ships 28.7 %, and fishing ships 16.3 %. Emission patterns showed significant seasonal variation, with peak emissions occurring during the Southern Hemisphere summer months, especially between November and January each year. The pandemic led to a substantial reduction in emissions between 2020 and 2021, primarily affecting passenger ships, while fishing vessels experienced minimal disruptions. As the epidemic abated and the global economy recovered, tourism activities in Antarctica experienced a rapid rebound, which was reflected in the changes in CO_2 emissions from passenger ships.

Second, the analysis identified countries with high CO_2 emissions from their shipping operations in the Southern Ocean. In the region south of 60°S, the United States, Russia, Norway, and China were major contributors, with the United States primarily operating passenger ships and icebreakers, Russia focusing on icebreaker operations, Norway engaging in fishing and passenger ship operations, and China mainly involved in fishing and icebreaker activities. This granularity enables targeted policy design aligned with each nation's activity profile.

Third, we innovatively map emission hotspots at sub-regional scales, pinpointing the Antarctic Peninsula (60 % of emissions south of 60°S) and Ross Sea (10 %) as critical zones. Within these zones, passenger ships dominate emissions in the Antarctic Peninsula, whereas icebreakers are the primary contributors in the Ross Sea. These regions remain key shipping emission hotspots; by linking hotspots to distinct vessel types, our analysis underscores the need for differentiated management strategies to mitigate environmental impact.

The findings of this study underscore the importance of regulating emissions from shipping activities in the Southern Ocean to safeguard the region's fragile ecosystems. The Antarctic Peninsula and Ross Sea, as high-priority hotspots, demand targeted interventions—such as stricter environmental standards for tourism and icebreaker operations—while the pandemic-induced emission decline demonstrates the feasibility of demand-side policies in shaping maritime activity. By framing shipping carbon footprints as both a metric of human impact and a tool for conservation prioritization, this research advances polar environmental science. Methodologically, the integration of high-resolution AIS data with vessel-specific modeling facilitates robust and efficient emission quantification in polar regions. Practically, our findings support evidence-based governance, aligning with global goals such as UN Sustainable Development Goals (SDG 13 on climate action and SDG 14 on marine sustainability).

CRediT authorship contribution statement

Xi Ding: Writing – original draft, Methodology, Formal analysis. **Songtao Ai:** Investigation, Funding acquisition, Conceptualization. **Shoukat Ali Shah:** Writing – review & editing, Validation, Supervision. **Quan Shen:** Resources, Data curation. **Meng Cui:** Resources, Investigation. **Christo Pimpirev:** Writing – review. **Yi Cai:** Visualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126738.

Data availability

Data will be made available on request.

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