Russia-Ukraine war has altered the pattern of carbon dioxide emissions from shipping in the Black Sea region

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Recent geopolitical crises have reshaped global shipping patterns, profoundly impacting related carbon emissions. Here, we utilize automatic identification system data from March 2021 to February 2024 and the ship traffic emission assessment model to investigate changes in carbon dioxide emissions from shipping in the Black Sea region before and during the Russia-Ukraine war. We find that shipping carbon dioxide emissions in Ukraine's Black Sea exclusive economic zone decreased by an average of 17.88% annually, while those in Romania's and Turkey's Black Sea exclusive economic zones increased by 36.30% and 16.08% annually, respectively. At the voyage level, shipping carbon dioxide emissions from maritime trade between Russia and the European Union obviously decreased, while those from maritime trade with certain Asian and Middle Eastern countries have obviously risen. The findings uncover the challenges to the climate change goal in the global shipping sector due to regional geopolitical crises.

Maritime transport plays an essential role in global economic and social development. According to the International Maritime Organization (IMO), maritime transport handles ~80% of world trade[1] and contributes 3% of global carbon dioxide (CO_2) emissions[2]. In the EU, shipping is the third largest transport source of emissions after road transport and aviation, accounting for 13.5% of total transport greenhouse gas emissions[3]. Without intervention, this share will continue to rise. Shipping CO_2 emissions impacts global climate change and human health[4–6]. As global greenhouse gas emissions rise, ocean temperatures are gradually increasing, exacerbating ocean acidification and causing negative impacts on marine ecosystems[7]. The global warming trend driven by human greenhouse gas emissions has also increased the frequency and intensity of extreme weather events[8]. The increasing prevalence of high-temperature weather has led to more frequent heatwaves, which not only result in a large number of direct deaths but also worsen air pollution[9]. This places additional strain on public health, particularly with respect to respiratory and cardiovascular diseases[5]. Therefore, reducing carbon emissions from global shipping is crucial in the effort to mitigate climate change and improve public health.

In order to achieve the targets set by the Paris Agreement, the IMO developed an initial strategy for reducing greenhouse gas emissions in shipping in 2018, with a target to reduce greenhouse gas (GHG) emissions by at least 50% by 2050, compared to 2008[10]. In 2023, the IMO adopted its GHG strategy, aiming for a reduction of at least 20% in greenhouse gas emissions by 2030, with the ultimate goal of achieving net-zero emissions by 2050[11]. Specifically, shipping CO_2 emissions must be reduced by at least 40% by 2030, compared to 2008 – The carbon intensity should be reduced by 40%. Analysing the temporal and spatial patterns of shipping CO_2 emissions holds practical value for policy development and global shipping emissions management[12,13]. Understanding the distribution of emissions over time and space not only helps identify shipping areas most impacted by geopolitical events but also offers valuable data to support future emission reduction policies. By pinpointing these critical periods and regions, policymakers can design more targeted measures to minimise the impact of unforeseen geopolitical crises on emission reduction targets.

Maritime transport is highly susceptible to external political and crisis events[14]. Changes in maritime transport patterns inevitably lead to shifts in the spatiotemporal distribution of shipping CO_2 emissions. Understanding these variations is crucial for global emission reduction and achieving net-zero GHG emissions[15]. This includes the designation of emission control areas[16], shipping route planning[17], and green energy replacement strategies[18]. There has been extensive research on shipping CO_2 emissions including modelling and analysis[19,20], impacts on ecology and human health[5,6], emission predictions[21,22] and decarbonisation. However, few studies have analysed the impact of geopolitical conflict on shipping CO_2 emissions.

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Since the Russia–Ukraine war began in February 2022, it has not only reshaped the geopolitical landscape, but also affected global shipping routes and energy markets[23,24]. Recently, a few macroeconomic studies have investigated the change of global trade patterns during the Russia–Ukraine war[25,26] and examined the effects of the war and sanctions on the global shipping network[27,28]. Fluctuations in energy prices and rerouted transport paths have impacted shipping costs and altered the global shipping network[29], affecting the spatial distribution of CO_2 emissions. However, the changes in shipping CO_2 emissions before and during the war remain unclear. Thus, it is necessary to explore these spatiotemporal changes since the start of the Russia–Ukraine war using global shipping data.

Here, we analyse the changes in global shipping CO_2 emissions during the Russia–Ukraine war using automatic identification system (AIS) data from March 2021 to February 2024 and the bottom-up ship traffic emission assessment model (STEAM)[30]. We examine the overall trends and spatiotemporal patterns of ship CO_2 emissions before and during the war, focusing on changes in the Black Sea's shipping CO_2 emissions from three perspectives: exclusive economic zones (EEZs), shipping routes, and ports (Supplementary Fig. 1). In the context of the global efforts to reduce CO_2 emissions and achieve sustainable development goals, this study, to the best of our knowledge, provides new insights into the change in global shipping CO_2 emission patterns during geopolitical conflicts, and it supports the development of more effective carbon reduction policies for the shipping industry. As global concerns about climate change intensify, our findings will aid in promoting a more sustainable future for maritime transport.

Results

Changes in global shipping CO_2 emissions

We use a bottom-up approach to estimate the monthly shipping CO_2 emissions from the number of active ships for 96057 ships globally from March 2021 to February 2024, covering 1 year before and 2 years after the onset of the Russia–Ukraine war (Supplementary Table 1). We find that global shipping CO_2 emissions increased by an average of 1.63% annually during the 2 years following the start of the war, compared to the year prior (Fig. 1), and that shipping CO_2 emissions are predominantly concentrated in the Yellow Sea, East China Sea, Arabian Sea, Mediterranean Sea, Gulf of Mexico, and several major international maritime trade routes (Supplementary Fig. 2). The container ships, oil tankers, and bulk carriers constitute the primary sources of global shipping CO_2 emissions, with the majority of these emissions arising from the main engines of the ships. The most obviously increases in shipping CO_2 emissions were observed in oil tankers (3.79%), liquefied gas tankers (2.43%), and container ships (1.43%). Prior to the Russia–Ukraine war, the three ship types with the highest CO_2 emissions globally were container ships, oil tankers and bulk carriers. However, following the onset of the war, the CO_2 emissions from oil tankers and liquefied gas tanker experienced a notably higher growth rate, resulting in an increased share of global shipping emissions from these ship types. This surge is attributed primarily to the sanctions imposed by Western countries on Russian oil and natural gas, which have profoundly altered the structure of global energy trade. Additionally, with the easing of pandemic restrictions, the global economic recovery has spurred rapid growth in international maritime trade, further exacerbating the upward trend in CO_2 emissions[31]. Geopolitical crises, including the Russia–Ukraine conflict and the Red Sea crisis, have compelled many ships to adopt longer detour routes to avoid high-risk areas. To mitigate the delays caused by these extended routes, some ships have increased their operating speeds, which has elevated fuel consumption and CO_2 emissions. As a result, CO_2 emissions associated with specific ship types have experienced an obvious increase, starting from November 2023.

CO_2 emissions from shipping come from the main engine, auxiliary engine, and boiler in the STEAM. The power of the main engine, auxiliary engine, and boiler varies under different operational phases (see detail in 'Method'). Therefore, the ship's CO_2 emission vary depending on its operational phases (Supplementary Tables 2–4). We analyse the CO_2 emission proportions of the main engine, auxiliary engine, and boiler across

various ship types (Supplementary Fig. 3). The results show that for bulk carriers, container ships, general cargo ships, and liquefied gas tankers, the main engine emissions account for more than 50% of total emissions, followed by auxiliary engine emissions, while boiler emissions account for the smallest proportion. This is mainly because these four vessel types operate longer at sea, where the differences in the engine power across various operational phases are small, resulting in the dominant emissions from the main engine. In contrast, chemical and oil tankers exhibit clearly higher boiler power at berth, often exceeding the power of auxiliary engines. As a result, their boiler emissions account for a larger proportion than auxiliary engine emissions. Specifically, for oil tankers, boilers serve multiple critical functions, including heating to maintain cargo temperature, providing onboard heating, and meeting other operational energy requirements. When an oil tanker at berth, its main engines are usually inactive, and its boilers increase their output to meet the vessel's energy demands. The boiler engine power of the oil tankers at berth is ~5–10 times higher than at other operational phases (Supplementary Table 4). Additionally, maintaining the required cargo temperature at sea is indeed an obvious contributor to boiler emissions. This process results in considerable energy consumption and associated CO_2 emissions, particularly during long voyages. Thus, the proportion of boiler emissions for oil tankers is close to that of the main engine emissions for oil tankers.

Shipping CO_2 emissions have changed noticeably in the Black Sea region since the start of the Russia–Ukraine war (Fig. 2). Following the war's outbreak in February 2022, shipping CO_2 emissions obviously decreased 55.64% and 36.13% annually between Ukraine and the Bosphorus, and between the Kerch Strait and the Bosphorus, respectively. In contrast, emissions on routes between Russia and the Bosphorus continued to rise. Additionally, a prolonged drought in the second half of 2023 led to congestion in the Panama Canal, reducing trade volume between Panama and the United States and obviously reducing CO_2 emissions in this area. Concurrently, the Red Sea crisis forced many ships to detour around the Cape of Good Hope, increasing emissions on routes between the Malacca Strait and the Cape of Good Hope. As a result, shipping CO_2 emissions in the maritime region surrounding the Cape of Good Hope have surged by over 50% since November 2023 (Supplementary Fig. 4).

With the post–pandemic economic recovery, annual average ship CO_2 emissions increased in the EEZs of most countries during the 2 years following onset of the Russia–Ukraine war compared to the year before (Fig. 3). Shipping CO_2 emissions in the Democratic Republic of the Congo, Romania, and Kazakhstan increased by over 20% annually, while maritime emissions in Benin, Ukraine, Azerbaijan, and Finland decreased by over 12% annually (Supplementary Table 5). The monthly trend of emissions by country shows that after the onset of the war, shipping CO_2 emissions in Ukraine's EEZ declined sharply, while the CO_2 emissions of Romania, Finland, Germany and Netherlands short-term increased apparently, then the CO_2 emissions of Finland, Germany and Netherlands began to decline. Following the European Union (EU) and Japan's sanction on Russian seaborne crude oil and petroleum products on December 5, 2022[32], shipping CO_2 emissions in the EEZs of EU countries like Finland, as well as in Japan, began to decline. Additionally, a surge in trade along the Trans-Caspian International Transport Route caused short-term increases in emissions in Kazakhstan's and Azerbaijan's EEZs[33]. The Democratic Republic of the Congo's emissions also rose notably after it joined the Intergovernmental Standing Committee on Shipping (ISCOS), a regional organisation promoting maritime interests, in March 2022[34].

We extracted voyages of six primary ship types between countries using AIS data and generated an interaction showing CO_2 emissions from maritime voyages among major countries (Fig. 4). We found that since the onset of the Russia–Ukraine war, CO_2 emissions from the six primary ship types in maritime trade between Russia and the EU have shown a marked annual decline. Conversely, CO_2 emissions from these ship types in maritime trade between Russia and Turkey, and between Turkey and the EU, have increased apparently year by year. We further analysed the five countries with the highest CO_2 emissions from the six primary ship types in
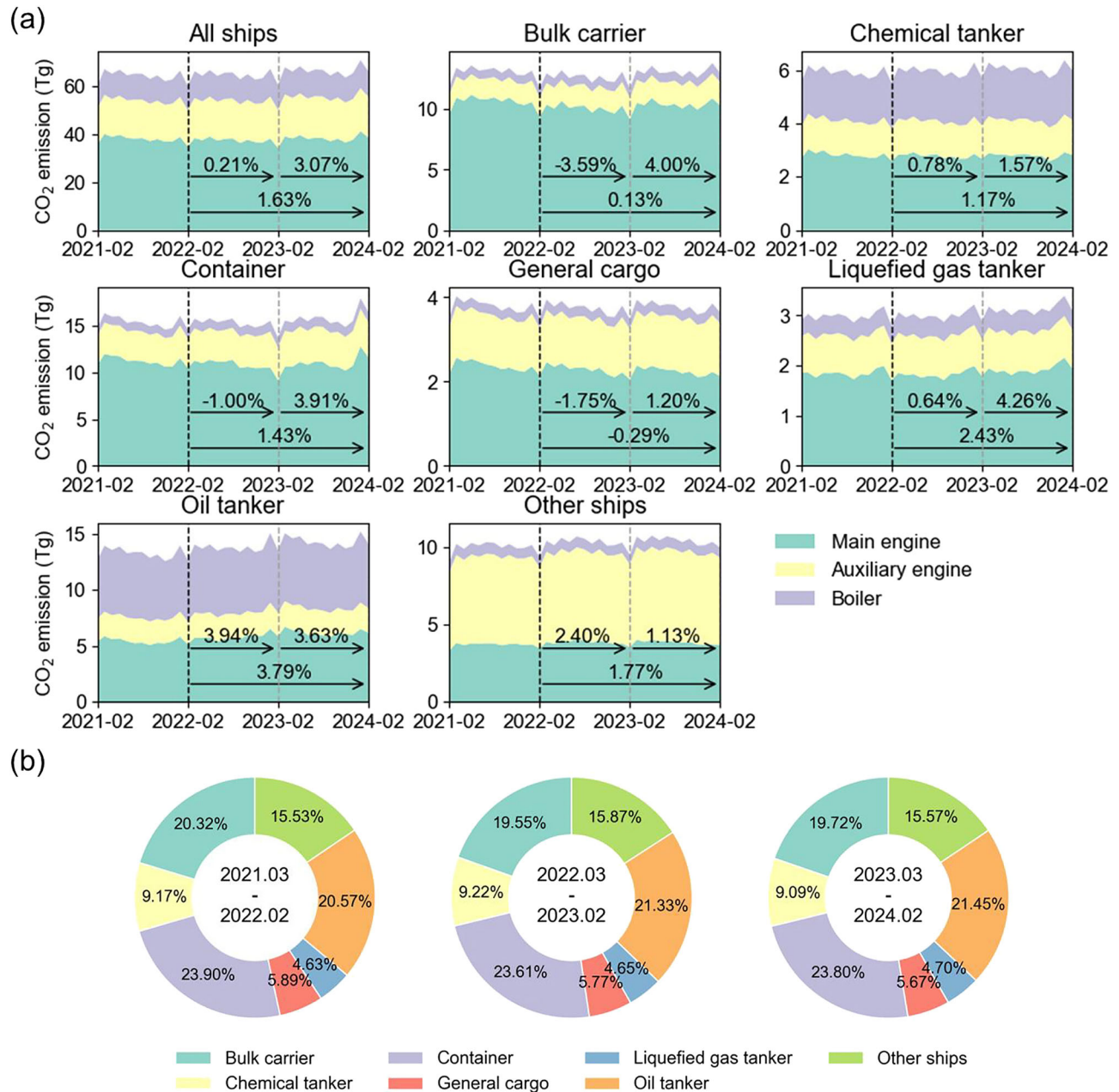
Fig. 1 | Global shipping CO$_2$ emissions from March 2021 to February 2024. a Global monthly shipping CO$_2$ emissions from March 2021 to February 2024, including main engine, auxiliary engine and boiler. **b** CO$_2$ emissions from primary ship types account for the proportion of total CO$_2$ emissions.

trade with Russia (Supplementary Fig. 5). The results reveal that after the start of the Russia–Ukraine war, the rankings of the five countries with the highest CO$_2$ emissions from voyages originating in Russia changed substantially. Shipping CO$_2$ emissions from Russia to the EU in the second year after the war decreased by 61.33%, compared to the year before the war. Before the war, shipping CO$_2$ emissions from voyages from Russia to the EU accounted for 31.89% of total shipping CO$_2$ emissions generated by Russia's export maritime trade, but this figure dropped to 9.45% during the war. The shipping CO$_2$ emissions from Russia to the United States also decreased, from 8.52% to 1.04%, dropping the United States out of the top five highest emitters. In contrast, shipping CO$_2$ emissions from Russia to China, Turkey, and India increased from 11.08%, 7.77%, and 2.22% to 17.47%, 14.15%, and 12.72%, respectively, making these three countries the top three destinations in terms of CO$_2$ emissions from Russian exports. Particularly, the three countries with the highest growth rates are India, China and Turkey (Supplementary Fig. 6).

After the onset of war, shipping CO$_2$ emissions from EU to Russia continued to represent the largest share of the total CO$_2$ emissions generated by Russia's import maritime trade. However, shipping CO$_2$ emissions from the EU to Russia in the second year after the war decreased by 54.52%, compared to the year before the war. The proportion of shipping CO$_2$ emissions from the EU to Russia also fell apparently, from 41.73% to 17.90% of total shipping CO$_2$ emissions generated by Russia's import maritime trade. Meanwhile, emissions from voyages originating in China, Turkey, and India to Russia increased from 9.52%, 8.81%, and 1.42% to 17.16%, 13.38%, and 10.76%, respectively. Particularly, the three countries with the highest growth rates are India, China and Singapore (Supplementary Fig. 6). These findings suggest that the Russia–Ukraine war led to considerable shifts in Russia's maritime trade patterns, with trade with China, Turkey, and India intensifying, while trade with regions such as the EU and the United States declined. Additionally, increased shipping distances driven by changes in Russia's maritime trade patterns resulted in a 6.03% increase in
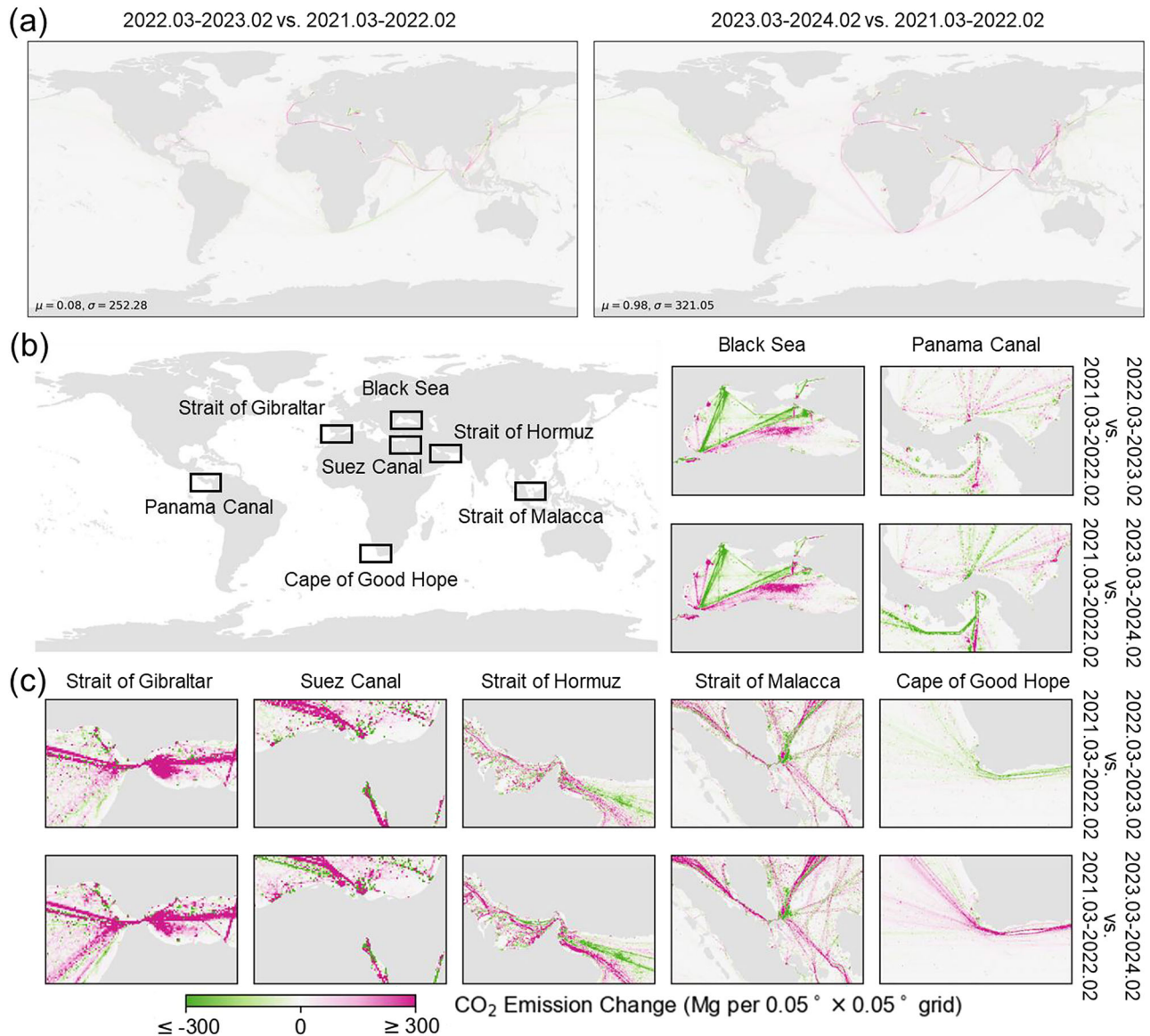
Fig. 2 | Spatial changes in shipping CO$_2$ emissions. a Spatial distribution of shipping CO$_2$ emissions in the first and second years of the Russia–Ukraine war compared with the year before the war. **b** Seven shipping chokepoints. **c** Spatial changes in shipping CO$_2$ emissions for seven shipping chokepoints in the first and second years of the Russia–Ukraine war compared with the year before the war.

shipping CO$_2$ emissions from Russia's maritime imports, and a 30.49% increase in shipping CO$_2$ emissions from Russia's maritime exports in the second year of the war, compared to the period before the war.

Shipping CO$_2$ emissions of the EEZs in the Black Sea region

Figure 5 illustrates the monthly changes in shipping CO$_2$ emissions at the EEZ level. After the outbreak of the war in February 2022, the annual average shipping CO$_2$ emissions in the Black Sea region increased by 1.42%, with the largest increases in general cargo, and bulk carrier. The CO$_2$ emission patterns in the Black Sea EEZs showed obvious variation among countries. In the first year of the war, shipping CO$_2$ emissions in the EEZs of Ukraine, Russia, and Bulgaria generally decreased, with Ukraine seeing the most obvious drop of 43.57% (Supplementary Fig. 7). This was mainly due to reduced emissions on the routes between Ukraine and the Bosphorus, and the Kerch Strait and the Bosphorus. As the war continued, maritime trade adjusted to its effects. In the second year, shipping CO$_2$ emissions in Ukraine's EEZ remained 32.56% below pre-war levels, while emissions in Russia's Black Sea EEZ dropped by 10.10%, underscoring the war's greater impact on Ukraine than Russia (Supplementary Fig. 8).

The Western sanctions on Russia disrupted its trade. However, Russia mitigated these effects by rerouting trade and finding new markets and supply chains[28]. Furthermore, geopolitical shifts and increased global demand for natural gas led Russia to boost energy exports through the Bosphorus. Additionally, shipping CO$_2$ emissions on routes between Romania and the Bosphorus surged in first the two years of the war, with growth rates in Romania's EEZ reaching 57.15% and 85.79%. Emissions from oil tankers, general cargo, chemical tankers, and liquefied gas carriers all exceeded 100% in the second year of the war, reflecting shifts in trade routes and patterns.

The monthly shipping CO$_2$ emissions in the EEZs of Black Sea countries highlight changes before and during the Russia–Ukraine war (Supplementary Figs. 9–13). Before the war, shipping CO$_2$ emissions in these EEZs were on the rise. During the war, emissions temporarily dropped. In Ukraine's EEZ, emissions fell by nearly 50% compared to the same period in 2021, a trend that started to ease only in June 2022. Western sanctions slowed the growth rate of emissions in Russia's EEZ from May to September 2022, with some months recording lower emissions than in 2021. Among Russia's EEZs, the Black Sea EEZ saw the most obvious change, with a nearly
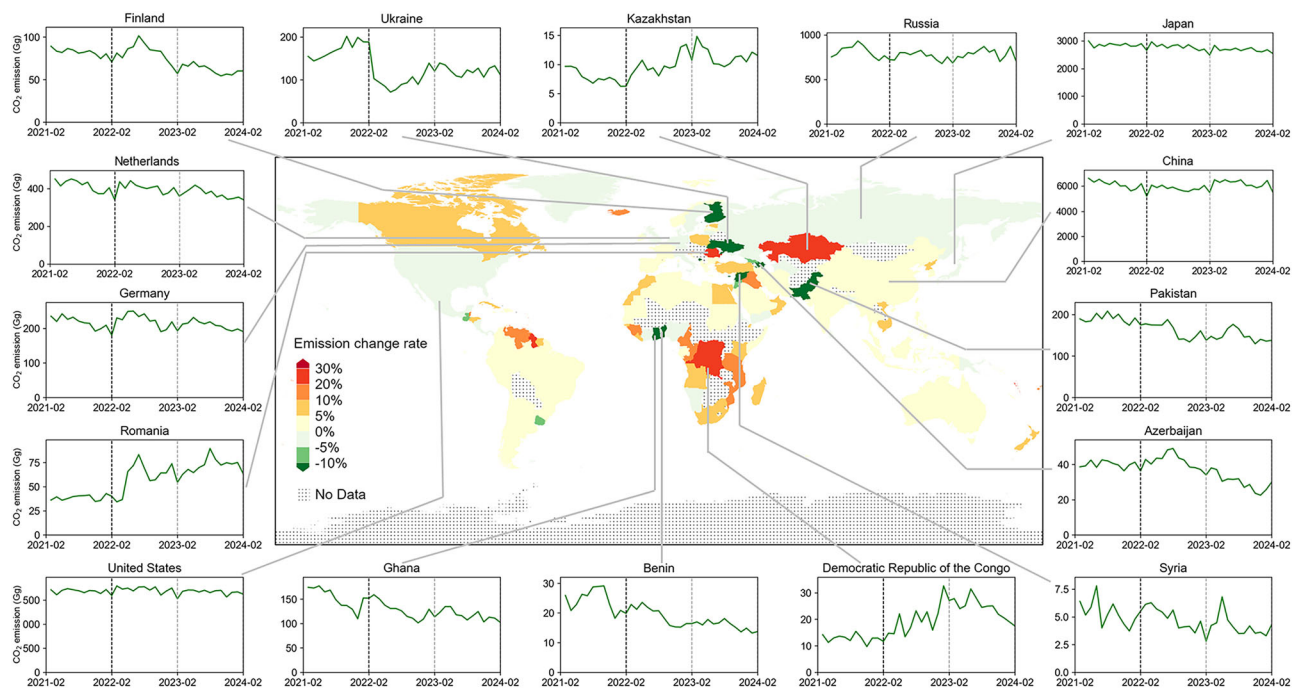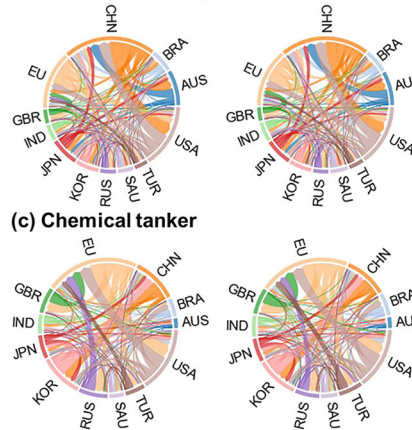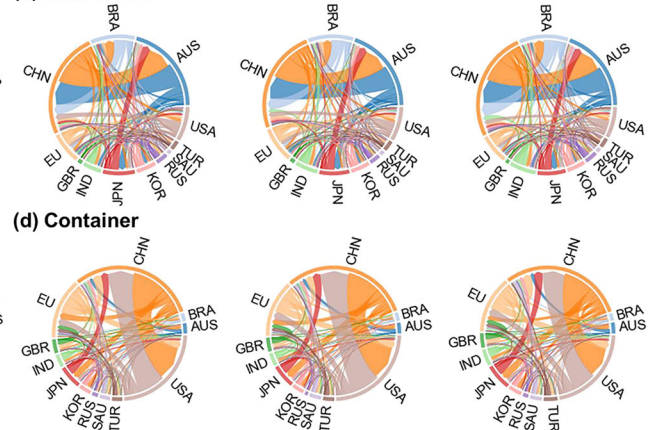
Fig. 3 | Spatial distribution of the annual average change rate in shipping CO$_2$ emissions across EEZs before and during the Russia–Ukraine war. The subgraphs are the monthly shipping CO$_2$ emission in the EEZs of some countries before and during the Russia–Ukraine war.
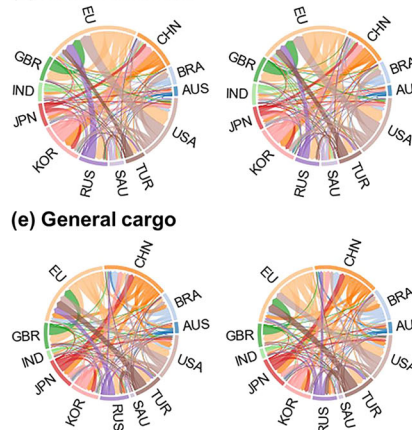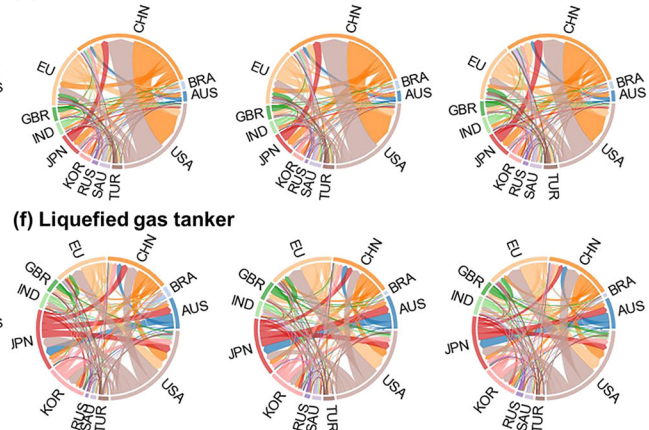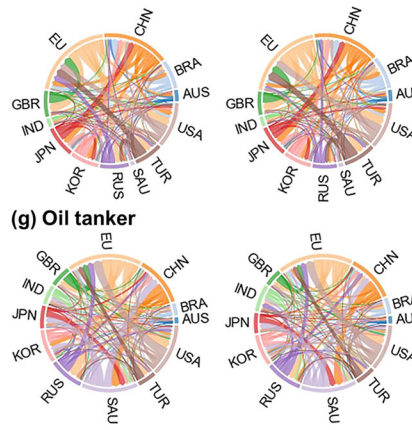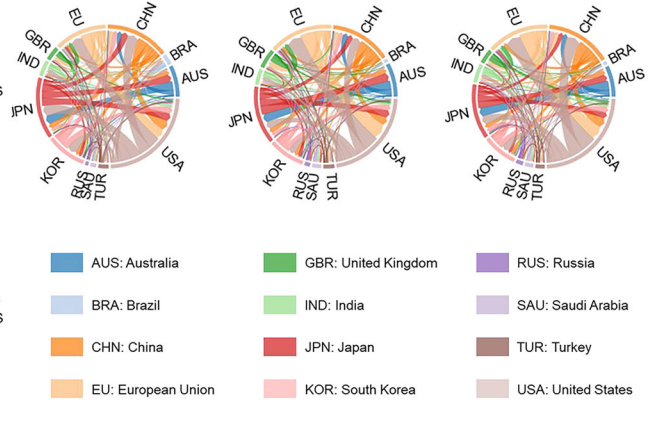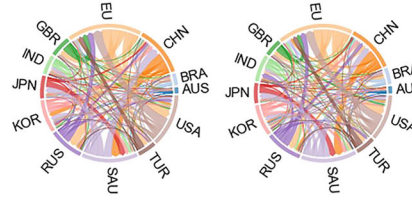

Fig. 4 | Changes in voyage CO$_2$ emissions among major countries from March 2021 to February 2024. Left: 2021.03–2022.02, Centre: 2022.03–2023.02, Right: 2023.03–2024.02. In each subplot, line colours represent the origin countries of the voyages.
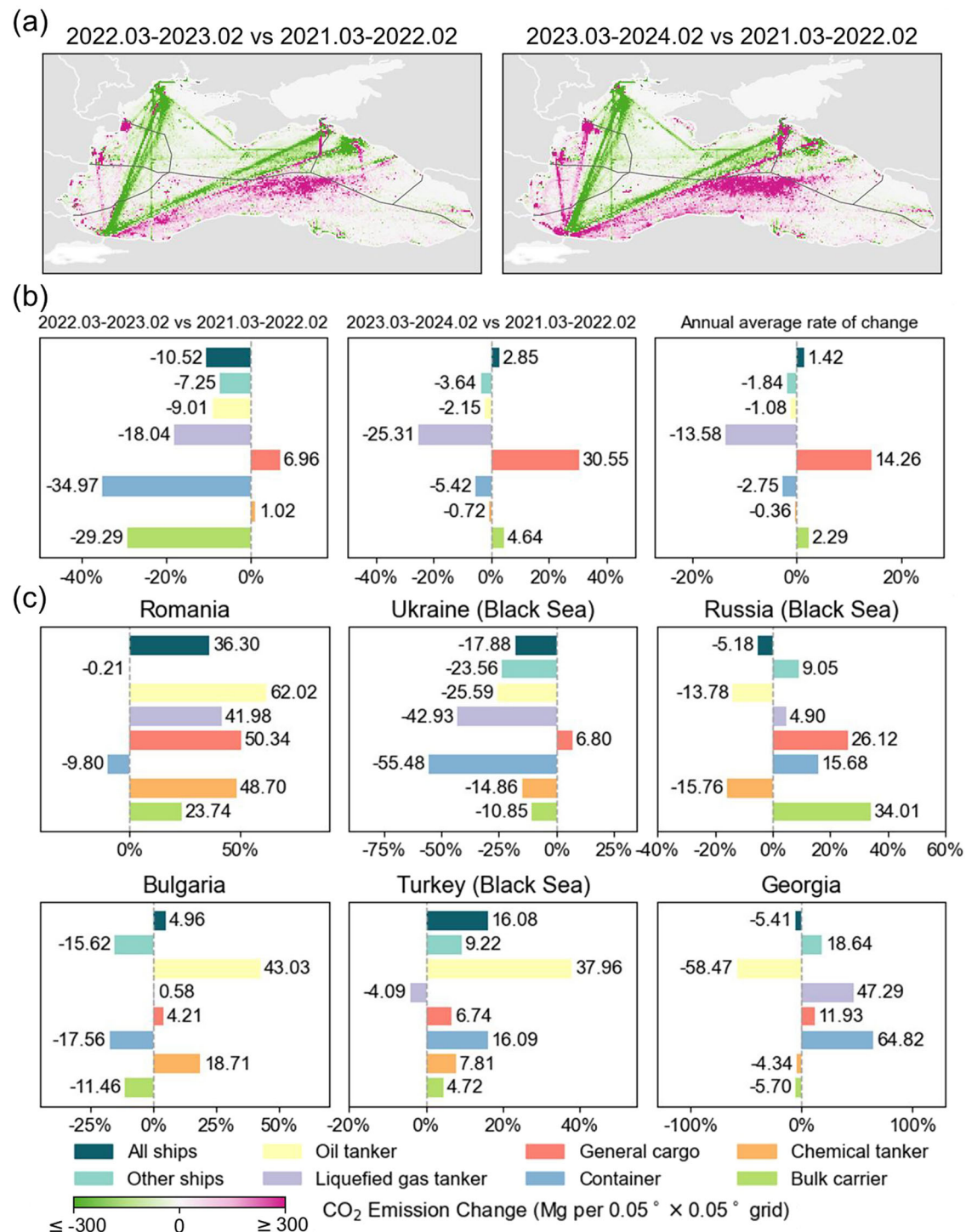
Fig. 5 | Shipping CO₂ emissions in the Black Sea and EEZs of six countries in the first and second years of the Russia–Ukraine war compared with the year before the war. a Spatial distribution of shipping CO_2 emissions in the Black Sea in the first and second year of the Russia–Ukraine war compared with the year before the war. The black solid line is the boundary of EEZs. **b** The change rate of CO_2 emissions from different ships in the Black Sea in the first and second years of the Russia–Ukraine war compared with the year before the war. **c** Average annual change rate of CO_2 emissions from different ships in the EEZs of six countries compared to the pre-war year.

30% decrease in emissions, although they gradually began to recover, showing a year-on-year decrease of 15.29% in the first year of the war.

Notably, shipping CO_2 emissions in Romania's EEZ surged from April 2022, with several months (July 2022 and August 2023) exceeding 100% of pre-war levels (Supplementary Fig. 9). This increase was likely due to Ukrainian goods being rerouted through Romanian ports, boosting ship activity and emissions. Conversely, reduced trade on the route between

Ukraine and the Sea of Marmara via Bulgaria's EEZ led to lower emissions in Bulgaria's EEZ.

After the war began, shipping CO_2 emissions obviously increased near the Turkish EEZ boundary adjacent to Russia, while emissions within the neighbouring Russian EEZ did not see a similar rise. This could be attributed to ships lingering in the Turkish EEZ due to Western sanctions, waiting for transshipment by Russia's shadow fleet[35]. Additionally, some ships may
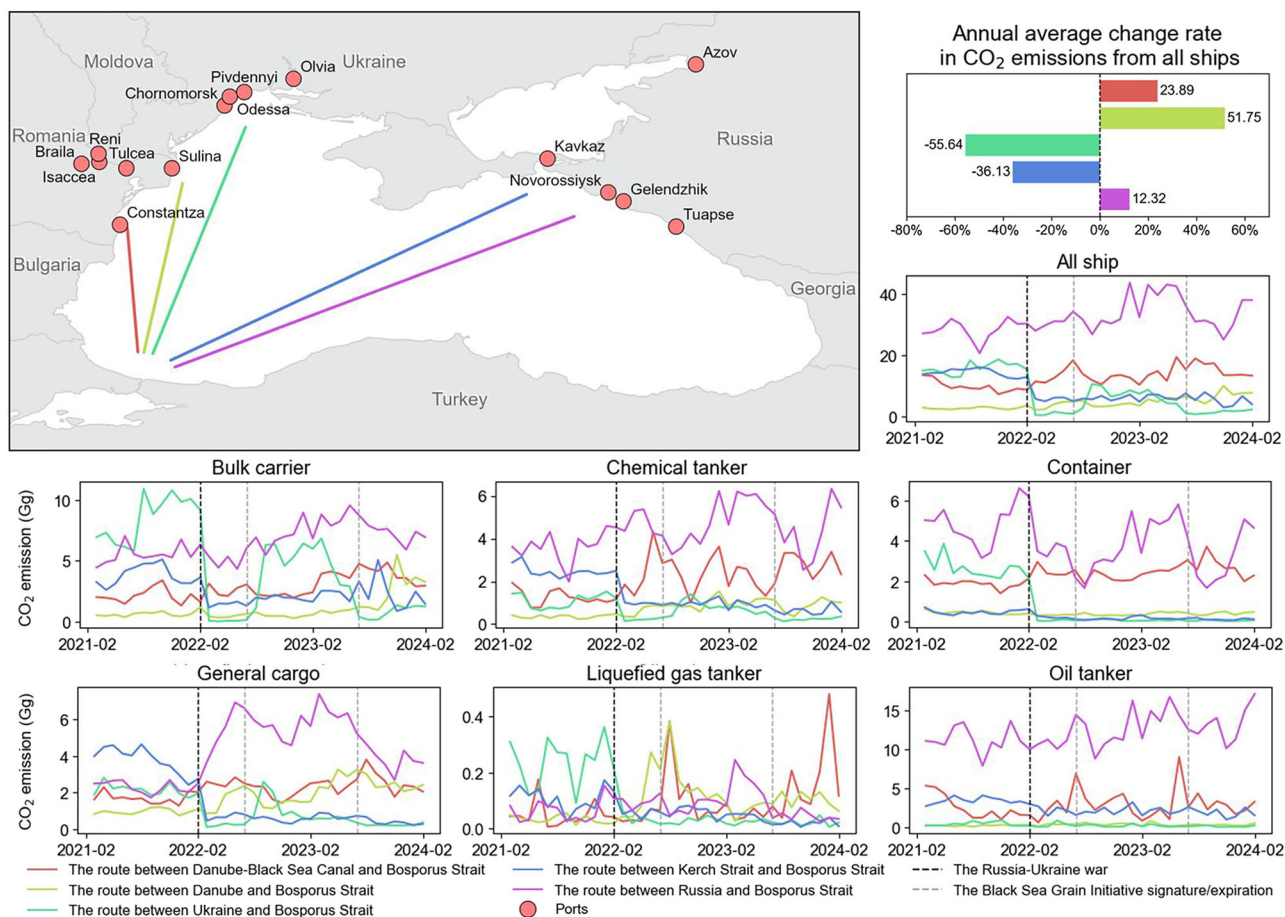
Fig. 6 | The map shows the locations of the five major shipping routes. The bar graph shows annual average change rate in CO_2 emissions from all ships on the five major shipping routes. The line graph shows the monthly CO_2 emissions of different ship types on the five major shipping routes from March 2021 to February 2024.

have turned off their AIS before entering the Russian EEZ, resulting in unrecorded emissions. Consequently, emissions within the Russian EEZ might be underestimated.

Shipping CO_2 emissions of major shipping routes in the Black Sea region

We selected the five major shipping routes in the Black Sea region and established a 10-kilometre buffer zone around these routes to calculate and analyse shipping CO_2 emissions before and after the start of the Russia–Ukraine war (Fig. 6). We observed that the war led to an obvious reduction in shipping CO_2 emissions on the major routes connecting Ukraine to the Bosphorus and the Kerch Strait to the Bosphorus, with decreases of 55.64% and 36.13%, respectively. This reduction likely resulted from safety concerns and potential blockades reducing vessel traffic. Conversely, shipping CO_2 emissions on the routes between Romania and the Bosphorus and between Russia and the Bosphorus increased obviously, with growth rates of 23.89%, 51.75%, and 12.32%, respectively. This increase reflects heightened shipping activity due to rerouting or increased trade demands in these areas. These results highlight an obvious change in shipping CO_2 emissions in the Black Sea following the start of the Russia–Ukraine war, and they illustrate the adaptability of shipping routes in response to geopolitical tensions.

By analysing monthly shipping CO_2 emissions for six major ship types on the five major shipping routes in the Black Sea region, we observed that during the early stages of the Russia–Ukraine war, shipping activities between Ukraine and the Bosphorus changed drastically due to safety concerns and Russian blockade measures, causing emissions to drop by over 90% for all ship types. However, the Black Sea Grain Initiative allowed Ukraine to export grain and other agricultural products from Black Sea ports, boosting trade

activities of bulk carriers, chemical tankers, general cargo, and oil tankers, and increasing their emissions during the agreement period. Despite this, emissions began to decline again before the agreement expired in July 2023 due to ongoing geopolitical tensions and economic uncertainty.

Obvious increases in shipping CO_2 emissions were noted on routes between Romania and the Bosphorus. On the Danube–Black Sea Canal to the Bosphorus route, CO_2 emissions from liquefied gas tankers rose by an average of 57.58% annually, chemical tankers by 41.62%, and bulk carrier by 35.84% (Supplementary Fig. 14). On another route between the Danube and the Bosphorus, emissions for bulk carrier increased by an average of 77.30% annually, liquefied gas tankers by 65.34%, chemical tankers by 63.29%, and general cargo by 62.05%. During the Black Sea Grain Initiative, emissions on these routes reduced, but they rose again after the agreement expired, showing the high sensitivity of shipping activities to international policies and geopolitical changes. This also underscores Romania's key role as a transit point for shipping between Ukraine and the Bosphorus. These changes highlight that complex geopolitical factors, market demand shifts, and international trade policies can change regional shipping activities.

After the outbreak of the Russia–Ukraine war, shipping CO_2 emissions on the route between the Kerch Strait and the Bosphorus decreased obviously due to safety concerns and Russian blockade measures, with CO_2 emissions from general cargo dropping by an average of 62.54% annually, and liquefied gas tankers, chemical tankers and container ships by nearly 50%. The obstruction of the Kerch Strait, a crucial waterway between the Black Sea and the Sea of Azov, disrupted shipping activities between Ukrainian ports and the strait. Conversely, emissions on the route between Russia and the Bosphorus rose obviously, except for container ships, with CO_2 emissions from liquefied gas tankers increasing by an average of 16.83% annually. This increase was driven by a surge in European LNG demand
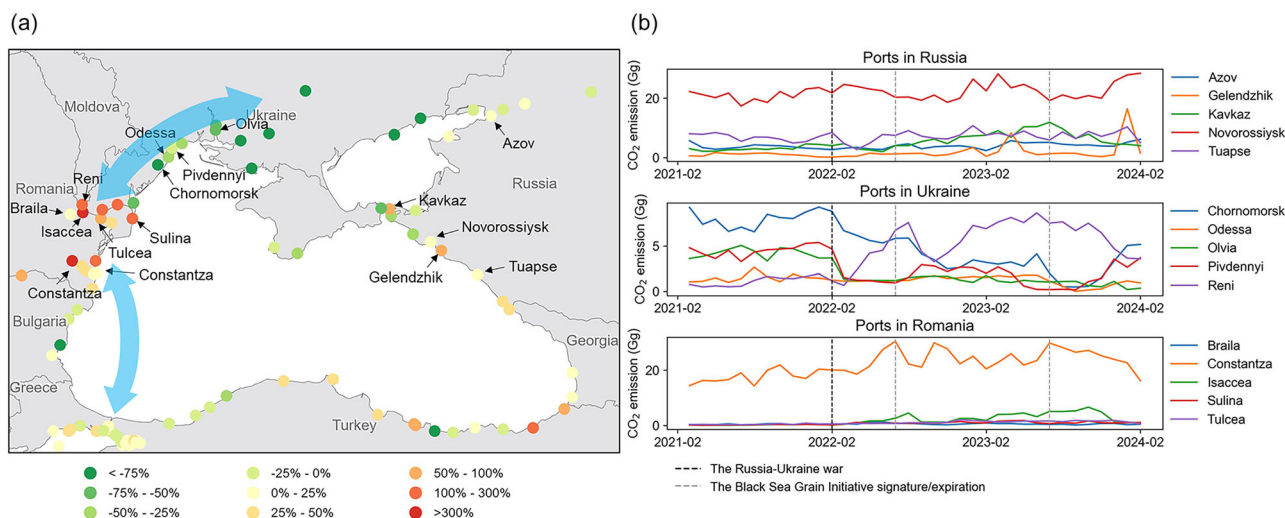
Fig. 7 | Shipping CO$_2$ emissions of major ports in the Black Sea. a Monthly shipping CO$_2$ emissions for the major ports in the Black Sea after the start of the Russia–Ukraine war compared with before the war. The blue bidirectional arrows mean that Ukraine may engage in transshipment trade via Romania. **b** Monthly shipping CO$_2$ emissions of five major ports in Russia, Ukraine and Romania from March 2021 to February 2024.

following the Nord Stream pipeline explosion, leading Russia to boost energy exports through the Bosphorus. The rise in CO$_2$ emissions from general cargo, bulk carrier, chemical tankers, and oil tankers also indicates Russia's adjustments in maritime trade strategy to sustain economic growth amid Western sanctions. These observations reveal how regional shipping activity changes following geopolitical events and illustrate how market demand and international policies influence dynamic changes in shipping CO$_2$ emissions.

Shipping CO$_2$ emissions of the ports in the Black Sea region
Using a 10-kilometre buffer zone centred on port coordinates, we calculated the CO$_2$ emissions of Black Sea ports before and after the start of the Russia–Ukraine war, as shown in Fig. 7. The war resulted in a clear spatial distribution pattern of changes in port emissions. Most Ukrainian coastal ports experienced a reduction of over 50% in shipping CO$_2$ emissions due to the Russian blockade. As the Ukraine's largest grain and passenger port, Odessa saw increased shipping CO$_2$ emissions over the subsequent 2 years. Inland ports near Romania, such as Ukraine's Reni port and Romania's Isaccea port, showed obvious increases in shipping CO$_2$ emissions. This reflects a shift in maritime trade from affected Ukrainian coastal ports to inland ports for transshipment through Romania. Consequently, Romania's coastal port emissions also rose apparently. The OECD[36] reported that Ukraine's trade through inland ports with neighbouring countries increased obviously during the war, supporting our findings.

Analysis of five ports in Russia, Ukraine, and Romania revealed that the Black Sea Grain Initiative allowed Ukraine to export grain and other agricultural products from Odessa, Chornomorsk, and Pivdennyi, leading to increased shipping CO$_2$ emissions from these ports starting in July 2023. However, emissions declined again as the agreement expired. Russian ports such as Sevastopol, Kavkaz, Gelendzhik, and Azov experienced temporary emission decreases after the attacks but recovered to pre-war levels within 4 months, showing Russia's efficiency in maintaining port infrastructure for trade continuity. Emissions at Russian ports in the northeastern Black Sea also increased, indicating less impact on ports farther from the war zone. These findings highlight the complex impact of regional war on shipping CO$_2$ emissions and the varied strategies countries employ to address these challenges.

Discussion
This study quantitatively analysed the changes in shipping CO$_2$ emissions since the start of the Russia–Ukraine war across four levels: world, EEZs, shipping routes, and ports. We observed that the economic sanctions imposed by Western countries changed Russia's shipping industry,

particularly reducing CO$_2$ emissions from chemical tankers, container ships, liquefied gas tankers and oil tankers (Supplementary Fig. 11). These reductions are mainly due to sanctions on goods such as raw materials and refined oil, leading to reduced transportation demand and thus lower CO$_2$ emissions. Despite facing a ban on crude oil imports from Western countries, CO$_2$ emissions from oil tankers in Russia's EEZ increased obviously in the second year of the Russia–Ukraine war, reflecting Russia's shift towards new trade partners and markets, especially in Asia[37]. This shift likely led to longer routes and increased transport frequency, thereby raising emissions. Additionally, some transactions may be conducted through informal channels or shadow fleets[35,38]. These fleets often use inefficient technologies, resulting in higher emissions, and frequently disable AIS to evade regulation, potentially underestimating overall emissions in Russia's EEZ. Including this data could reveal higher emission levels, crucial for developing effective international policies and responses.

The blockade of Ukrainian seaports by Russia led to a sharp decline in CO$_2$ emissions in Ukraine's EEZ and its main shipping routes, almost reaching a 60% and 100% reduction during the early stages of the Russia–Ukraine war. Ukraine, known as the breadbasket of Europe, has a particularly urgent need for grain transportation, especially during the war, which has heightened global concerns about food security[26,39]. Although emissions from bulk carriers between Ukraine and the Sea of Marmara initially dropped nearly 100%, this figure later reduced to about 30%, reflecting some recovery in transport activity after international intervention and alternative logistics solutions[40]. Therefore, in the face of geopolitical conflict challenges, the international community, the shipping industry, and policymakers need to work together to find effective strategies to mitigate the war's impact, ensuring the stability of global supply chains and environmental sustainability.

The results show that the IMO's goal of achieving net-zero greenhouse gas emissions by 2050 faces challenges caused by geopolitical crises. Geopolitical crises may compel countries to reassess and realign their supply chains in response to sanctions and security risks[41]. The need to evade sanctions and security concerns have forced some shipping companies to replan shipping routes and select alternative ports, which lead to increased transportation distances and fuel consumption, resulting in higher CO$_2$ emissions[42,43]. During geopolitical crises, nations frequently prioritise their own economic and security interests, which can undermine their commitment to environmental protection. In addition, sanctions triggered by geopolitical crises have led some companies, when facing stringent restrictions, to resort to illegal or semi-legal measures to minimise compliance costs. The emergence of shadow fleets is particularly concerning, as these ships, which often do not comply with international regulations, may

use inefficient fuels and low-standard emission technologies, exacerbating the carbon emission problem[44]. These activities not only add to the global shipping carbon emission burden, but also pose additional difficulties for international regulatory and environmental measures. Geopolitical crises not only disrupt the global operational framework of the shipping industry but also influence the operational strategies of shipping companies across different regions. Armed conflicts have resulted in fluctuations in energy prices, disruptions in supply chains, and the realignment of shipping routes, all of which have collectively contributed to an increase in shipping emissions. Furthermore, shifts in the international political landscape have led to a concentration of shipping activities in certain countries and regions, thereby exacerbating emissions growth in these specific areas. Therefore, the changes in shipping routes, increased operational costs, and activities of shadow fleets caused by the geopolitical crises need to be considered fully in future global shipping policies and strategic planning.

IMO has set an ambitious GHG emission reduction strategy for 2023. However, we find that, despite the strengthened climate change mitigation efforts by international regulatory bodies such as the IMO and the European Union, including the EU Emissions Trading System and the IMO's existing Energy Efficiency Existing Ship Index as well as the Carbon Intensity Indicator[45], global shipping emissions still grew at an average annual rate of 1.63% from 2021 to 2024. Additionally, during the Russia–Ukraine war, emissions from specific ship types such as oil tankers, liquefied gas tankers, and container ships obviously increased. Nevertheless, when assessed using the vessel-based Annual Efficiency Ratio (AER), carbon intensity decreased by 22% in 2018 compared to 2008[1]. Based on the dataset used in this study, the vessel-based AER in 2023 decreased by 9.67% compared to 2021 (Supplementary Fig. 15), consistent with the overall trend reported in the 83rd session of the Marine Environment Protection Committee (MEPC 83)[46]. If this downward trend continues, carbon intensity is expected to fall below 60% of 2008 levels by 2028, achieving the IMO's 2023 strategic target 2 years ahead of schedule, although 3 years later than projected based on MEPC 83 data. Additionally, we observed that the decline in the vessel-based AER accelerated in 2023 compared to 2022, possibly due to changes in shipping routes driven by geopolitical events leading to longer voyages[47] and further contributed to the reduction in the vessel-based AER[46]. However, the increase in voyage distances also led to reduced overall transport efficiency, resulting in a rise in total global maritime CO_2 emissions. It should be noted that the data used by the IMO and MEPC are derived from the Data Collection System (DCS), which is based on reported data from shipping of 5,000 gross tonnage or above. In contrast, this study utilises AIS trajectory data and ship technical specifications data, covering a larger number of ships, although with potentially lower data precision than DCS. This difference is a primary reason why the vessel-based AER values calculated in this study are higher than those reported by the IMO and MEPC.

While climate change policies and technological advancements contribute to emission reductions, geopolitical factors often have an obvious, unpredictable impact on global shipping CO_2 emissions. This impact is particularly pronounced when geopolitical crises disrupt key shipping routes, energy supplies, or trade patterns. Geopolitical crises that result in route adjustments and longer voyages[47] can rapidly alter shipping emissions trends, leading to deviations from established emission reduction targets[46]. Therefore, global climate change policies and emission reduction targets must take into account the potential effects of such unforeseeable geopolitical events on shipping emissions. Future policies should not only address the challenges posed by climate change but also incorporate more flexible and adaptive strategies in response to the complexities of geopolitical conflicts. We recommend integrating more risk assessments and scenario simulations into the long-term greenhouse gas strategies for the shipping industry to enhance its adaptability when responding to geopolitical crises. This will help policymakers quickly adjust shipping emission policies in the face of unforeseen events, such as wars, ensuring the achievement of emission reduction targets. Undeniably, the impacts of geopolitical crises on global shipping CO_2 emissions bring new pressures and demands to the IMO, which must take stronger regulatory measures[48] and vigorously promote cleaner fuels[49] to ensure the global shipping industry can continue to progress toward the net-zero emissions goal.

Methods
Dataset
In this study, we use four datasets: (1) over 20 billion terrestrial and satellite AIS data points per year, (2) the ship technical specifications data for above 96057 ships, (3) the world EEZs dataset[50], and (4) the world ports dataset. The AIS data are categorised into static AIS data and dynamic AIS data. Dynamic AIS data includes detailed information such as each ship's unique MMSI number, current location, time, speed, draft, and course, which is essential for accurately estimating each ship's CO_2 emissions. Static AIS data, on the other hand, contains information such as the ship's IMO number, MMSI number, and time. The IMO mandates that ships navigating international waters with a gross tonnage of over 300, as well as all passenger ships regardless of tonnage, must be equipped with AIS. The ship specifications data from the IHS database provide information such as unique identifiers, maximum speed, beam, gross tonnage, engine type, and fuel type. By integrating these datasets, we employ a bottom-up approach to estimate the annual emissions of each ship.

Ship characteristics, such as type, size, and power facilities, are crucial parameters for calculating CO_2 emissions. In this study, we first matched the ships in the raw AIS data with the technical specifications data using their IMO codes. When a vessel is leased or its AIS equipment is replaced, the vessel's MMSI number may change, while the IMO number remains constant. Therefore, we use the IMO number as the primary identifier to match AIS data with technical specification data. Dynamic AIS data contains only the MMSI information of the vessel, without the IMO number, making direct association with the technical specification data unfeasible. In contrast, static AIS data includes both the IMO and MMSI numbers, allowing us to establish matching pairs based on these identifiers. For vessels whose MMSI changes multiple times within a year, we retain only the first MMSI-IMO pair, after removing trajectory data that includes fewer than 10 ship tracks. To address the issue of decreased matching rates when applying previous years' ship profiles to the new year, we create a separate MMSI-IMO matching relationship table for each year. This ensures more accurate matching between dynamic AIS data and technical specification data by using the IMO number from the respective yearly matching table.

However, some ships lacked technical specification data. Deleting these ships would have led to errors in CO_2 emissions calculations. To address this, we followed the Fourth IMO Greenhouse Gas Study[1] guidelines and implemented the following four steps to fill in the missing data:

(1) We selected ships identified as in service from the IHS database and categorised them into 17 ship types and different sizes defined by the IMO[1]. Missing values for breadth (beam), dead weight (DWT), and draught were filled using the median values for each type and size. We then used multiple linear regression models to estimate the length overall and capacity based on each type and size[1].

(2) For ships missing maximum speed data, we trained a random forest regression model using ship build year, type, length overall, beam, gross tonnage (GT), and max speed and used it to estimate the missing maximum speeds[51]. The model's estimation accuracy is shown in Supplementary Table 6.

(3) For ships lacking maximum continuous rating (MCR) but having DWT and GT, we used a regression model to estimate the MCR for 17 ship types[52,53]. The model's estimation accuracy is shown in Supplementary Table 7.

(4) For ships missing revolutions per minute (RPM) but having max speed, MCR, and DWT, we used a multiple linear regression model to estimate RPM for 17 ship types[1].

To ensure the accuracy and reliability of shipping CO_2 emission, it was necessary to filter out erroneous data in the raw AIS data, caused by signal interference, equipment failure, or improper operation. Firstly, to ensure the validity of AIS data, we only retain data that meet all of the following

conditions: (1) The ship's IMO or MMSI must conform to the relevant standards. (2) The ship's longitude must be within the range of −180° to 180°, and latitude within −90° to 90°. (3) The AIS data must fall within the time frame from March 2021 to February 2024. (4) The trajectory data for the same IMO number must contain more than 10. Then, if a ship's speed in the AIS data exceeded 1.5 times its maximum speed from the technical specifications, the speed was replaced. Finally, the AIS data for each ship were sorted chronologically, and the average speed between adjacent points was calculated. If this average speed exceeded 1.5 times the maximum speed, the later trajectory point was deemed erroneous and deleted.

Estimation of global shipping CO_2 emissions

For the AIS trajectory sequence of ship s, denoted as Traj_s, $\text{Traj}_s = \{p_0, p_1, \ldots, p_m\}$, where m is the number of trajectory points, and each point p_i is a quadruple $(t_i, v_i, \text{lat}_i, \text{lon}_i)$, representing time, speed, latitude, and longitude. This study uses a bottom-up method to calculate the shipping CO_2 emissions. a ship has only one main engine, one auxiliary engine and one boiler. The CO_2 emissions of ship s are primarily produced by the main engine, auxiliary engine, and boiler. The total emissions E_s of ship s are given by:

$$E_s = E_s^{main} + E_s^{auxiliary} + E_s^{boiler} \qquad (1)$$

where E_s^{main} is the CO_2 emission produced by main engine of the ship s, $E_s^{auxiliary}$ is the CO_2 emission produced by auxiliary engine of the ship s, and E_s^{boiler} is the CO_2 emission produced by boiler of the ship s. The units of E_s, E_s^{main}, $E_s^{auxiliary}$ and E_s^{boiler} are grams.

CO2 emissions from shipping are depend on the engine type, ship type, ship size, operational phase and emission factor of the ship. The main engine emissions E_s^{main} of ship s are calculated as:

$$E_s^{main} = MCR \times EF^{main} \times \sum_{i=1}^{m} LF_i \times A_i \times (t_{i+1} - t_i) \qquad (2)$$

where MCR is the maximum continuous rating power of ship's main engine, which can be obtained from the IHS database. The unit of MCR is kw. EF^{main} is the emission factor of the main engine determined by the fuel type and engine type of ship s, which is described in Supplementary Table 2. The unit of EF^{main} is g kw-1 h-1. t_{i+1} and t_i are the times of the adjacent AIS trajectory points of ship s, which are derived from AIS dataset. The units of t_{i+1} and t_i are hour. The units of A_i is the adjustment factor for the load ratio coefficient LF_i of the main engine. For CO_2 emissions from shipping, A_i is equal to 1[1]. The load ratio coefficient LF_i is the ratio of an engine's power output to its MCR, which is calculated by:

$$LF_i = (v_i / v_{\max})^3 \qquad (3)$$

where v_i is the instantaneous speed of the ship s at time t_i, which can be obtained from AIS dataset. $v_{\max}$ is the maximum speed of the ship s, which can be obtained from HIS database. The units of v_i and $v_{\max}$ are knot. The auxiliary engine emissions $E_s^{auxiliary}$ are calculated as:

$$E_s^{auxiliary} = EF^{auxiliary} \times \sum_{i=1}^{m} P_{phase}^{auxiliary} \times (t_{i+1} - t_i) \qquad (4)$$

where $EF^{auxiliary}$ is the emission factor of the auxiliary engine determined by the fuel type and engine type of ship s, which is is described in Supplementary Table 2. $P_{phase}^{auxiliary}$ is the power of the auxiliary engine in a certain ship type and a certain operational phase, which is obtained from fourth IMO GHGs study (Supplementary Table 3). The unit of $P_{phase}^{auxiliary}$ is kw. The boiler emissions E_s^{boiler} are calculated as:

$$E_s^{boiler} = EF^{boiler} \times \sum_{i=1}^{m} P_{phase}^{boiler} \times (t_{i+1} - t_i) \qquad (5)$$

where EF^{boiler} is the emission factor for the boiler (Supplementary Table 2), determined by the RPM of the main engine. P_{phase}^{boiler} is the power of the boiler in a certain ship type and a certain operational phase, which is obtained from fourth IMO GHGs study (Supplementary Table 4). The unit of P_{phase}^{boiler} is kw.

The emission factors for ships vary under different operational phases and the main engine fuel type. Based on the ship's speed and main engine power, we classify the operational phase into the following four categories:

- At berth: The phase when a ship is docked at a pier or berth, or during the loading or unloading of cargo, where the speed of the ship is less than 1 knot.
- Anchored: The phase when a ship is slowly approaching a pier or berth, where the speed of the ship is between 1 and 3 knots.
- Manoeuvring: The phase when a ship requires precise control for tasks such as docking, undocking, turning, or navigating narrow channels or port areas, where the speed of the ship is greater than 3 knots and the main engine power is less than 20% of MCR.
- At sea: The phase when a ship is operating at a steady, economic speed along its planned route in open waters, where the speed of the ship is greater than 3 knots and the main engine power is greater than 20% of MCR.

The main engine fuel type is one of the key parameters in the STEAM, directly influencing the emission factor (Supplementary Table 2). According to the Fourth IMO GHG Study, we utilise the main engine description field from the IHS database to categorise the main engine fuel types into three categories: heavy fuel oil (HFO), marine diesel oil (MDO), and liquefied natural gas (LNG). For main engines using HFO and MDO, it is assumed that they operate on a diesel cycle, and they are further categorised as follows:

- Slow-speed diesel (SSD): engine speed lower than or equal to 300 RPM.
- Medium-speed diesel (MSD): engine speed between 300 and 900 RPM.
- High-speed diesel (HSD): engine speed above 900 RPM, or the field includes petrol.

For main engines using LNG, they are categorised as follows:

- LNG-Otto medium-speed (MS): four-stroke, medium-speed, dual-fuel engines that operate on the Otto cycle.
- LNG-Otto slow-speed (SS): two-stroke, slow-speed, dual-fuel engines that operate similar to the Otto cycle.
- LNG-Diesel (Diesel): two-stroke, slow-speed, dual-fuel engines that operate on the Diesel cycle.

For ships lacking a main engine description in the IHS database, we fill the missing data using the mode of the main engine fuel type from similar ships of the same type and size.

Voyage identification

The draught information of a ship, which reflects its loading status, allows for voyage identification based on changes in draught[54]. However, because the draught data recorded in the AIS are manually entered by crew members, any operational errors may result in inaccurate draught records. Therefore, relying solely on draught data for identifying ship voyages introduces uncertainty in extraction results. To address this issue, we use a method that combines ship speed, travel time, and distance information to enhance voyage identification accuracy[55]. Since cargo loading and unloading primarily occur within ports, draught changes should be recorded in port areas. Based on this approach[55], we further refine the voyage identification method by incorporating port information, thereby improving identification precision. The method for voyage identification is as follows:

- The draught difference between consecutive time points exceeds 3 metres, and the ship's speed is below 2 knots.
- The draught change occurs within a 10-kilometre radius of a port.
- The time interval before and after the draught change is at least 12 h.
- The distance covered before and after the draught change is at least 30 kilometres.

- The number of trajectory data points recorded before and after the draught change is no fewer than 120.

Uncertainty analysis

This study has several uncertainties and limitations. First, the incomplete ship data may lead to an underestimation of CO_2 emissions. Some small or older ships lack AIS devices resulting in the exclusion of these ships from the dataset. For example, ~400 oil tankers, which form shadow fleets, have disabled their AIS devices to evade international monitoring and restrictions, thereby facilitating Russia's energy exports[56,57]. Consequently, the ship count in this study is lower than the actual value, which could thus lead to an underestimation of CO_2 emissions, especially the shipping CO_2 emissions of Russia. However, by comparing the CO_2 emissions results of this study with the emission trends reported by UNCTAD for the corresponding period[31], it was found that the trends are consistent, suggesting that the CO_2 emissions estimates in this study are both reasonable and reliable.

Secondly, the STEAM method of shipping CO_2 emissions involves numerous factors, such as ship size, ship type, fuel type, engine type, cargo carrying capacity, emission reduction measures, and weather and ocean conditions, all of which can impact the results of the CO_2 emissions. In this study, we may not fully capture the complexities of actual conditions. Although this study applies the method provided by the IMO to classify ship size, ship type, fuel type, and engine type[1], and employs linear regression and random forests to estimate the relevant missing factors, with most of the estimated results yielding an R^2 value greater than 0.7, discrepancies may still exist between the estimated and actual values, potentially resulting in errors in the CO_2 emissions.

Finally, the route data extracted from AIS trajectory data is subject to uncertainty. Factors such as signal delay, reception anomalies, and manual input errors may lead to inaccuracies in the trajectory point coordinates, timestamps, and draft information, which may impact the accuracy of route extraction. To address this uncertainty, we use port data for calibration; however, the uncertainty in the definition of port service areas introduces an additional source of error.

Data availability

The automatic identification system data and technical specifications data are restricted to the third party (http://www.shipxy.com/) and used under license for the current study. The world exclusive economic zones (EEZ) data can be found in Flanders Marine Institute[50]. The world ports data can be found in http://www.shipxy.com. Source data are provided in Supplementary Data 1.

Code availability

The codes for shipping CO_2 emissions estimation model in this paper are available at https://doi.org/10.5281/zenodo.15625076.

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Y.X. contributed to methodology, data curation, result interpretation, writing—original draft, and funding acquisition. P.Z. contributed to conceptualisation, methodology, writing—review and editing, supervision and funding acquisition, T.K. contributed to methodology, result interpretation, writing—review and editing, K.Q. contributed to result interpretation.

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