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Emissions and health impacts from global shipping embodied in US–China bilateral trade

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Global shipping activity emits 938 million tonnes of carbon dioxide annually, surpassing the eighth highest emitting country. Although the impacts from the shipping industry have been investigated over the past three decades, allocating responsibilities remains a difficult issue. Numerous parties should share the responsibility and quantitative analysis is therefore required when considering the interaction between the global economy, shipping and ecological connectivity. Here, beginning with our shipping emission inventory model based on satellite-observed vessel activities, we evaluated trade-embodied shipping emissions and their impacts on human health. Combined with international trade databases, we traced shipping impacts back to responsible bilateral trade and proposed an integrated trade–shipping–air quality–health impact nexus. Quantitative analysis shows that the US–China bilateral trade is responsible for 2.5% of the global shipping carbon dioxide emissions and 4.8% of ship-related global premature deaths caused by air pollution. Our research provides the methodology to allocate intercontinental responsibilities to trade pairs and ships.

The past 40 years have witnessed tremendous development opportunities and improvements in human well-being brought about by international production fragmentation[1]. As a low-cost, high-volume transport method, maritime transport plays an invaluable role in the global supply chain. However, exhaust emissions from ships bring about adverse impacts on climate and human health. Global shipping emissions were responsible for approximately 2.6% of global greenhouse gas (GHG) emissions in 2012 (refs. [2,3]), which could increase to 17% in 2050 if unregulated[4]. Criteria pollutants, such as fine particulate matter ($PM_{2.5}$, particulates with an aerodynamic diameter of ≤2.5 μm), sulfur oxides (SO_x) and nitrogen oxides (NO_x) from ships, could lead to premature mortality (increasing from ~60,000 in 2002 (ref. [5]) to ~250,000 deaths in 2020 (ref. [6])) and morbidity.

Although the climate and health impacts of global shipping are well documented[2,5–16], assigning climate mitigation responsibility remains a challenge. Related regulation was intentionally set outside the national allocation schemes in the Kyoto Protocol and Paris Climate Agreement[15,17]. Scholarly and political dialogues for the past three decades[7,15,18–26] focused on a United Nations Framework Convention on Climate Change (UNFCCC)-based[27] approach to regulate international shipping emissions. For the UNFCCC-based approach, eight options were compared and finally five options were recommended: (1) no allocation, or allocate the ship's transnational activity emissions to individual countries according to: (3) bunker fuel sale, (4) company or vessel registration or operator, (5) departure or destination of vessel or (6) cargo. Numerous efforts have been made to compare these options[7,19,20,28–30], including quantitative assessments of options 3 (refs. [22,23]), 4 (refs. [22,24]) and 5 (ref. [24]) and case studies for option 6 (refs. [15,18]).

Although studies based on the supply chain have recently made progress in accounting for consumer-based emissions instead of production-end emissions[31–34], when calculating total emissions caused by global trade, emissions during the transportation process have not been included. Offshoring separates consumers and producers, bringing about pollutants emitted by shipping, which can be transported over the busiest sea-lanes or even to inland areas hundreds of kilometres away from the consumers and producers[14,35].

All these features indicate the importance to expand the current sector-based emission analysis by trade-driven analysis. Option 6 can be used for both the allocation and supply-chain research. At present, case studies related to option 6 rely on the macroeconomic distance-multiplication approach[18] or sea-waybill-based approach[15,18]. The macroeconomic approach relies on input–output tables, which could facilitate time-series analysis, but the poor linkage with ship activities hindered validation and regulation[18]. The sea-waybill-based approach provides clear and accurate emission assessments, but waybill data is not yet globally available[15]. Both approaches are limited by data accessibility for large-scale application.

Here, beginning with our previous shipping emission inventory model based on the observed vessel automatic identification system (AIS) signals in 2016 (ref. [14]), we traced shipping emissions of 4,482 vessel calls back to the US–China bilateral trade of 12,346 subcategories. Using the chemical transport model GEOS–Chem, we further tracked the globally distributed impacts on ambient $PM_{2.5}$ concentrations from shipping emissions related to the US–China trade. Health consequences were then evaluated based on the exposure level to $PM_{2.5}$. An integrated trade–shipping–air quality–health impact nexus was built to allocate shipping impacts to responsible bilateral trade and commodity sectors. The nexus enlarges the intension of 'responsibility' from traditional carbon dioxide (CO_2) emissions to both CO_2 emissions and human health impacts caused by air pollutants. It also bridges the gap in the transport-related emissions in the supply chain for bilateral trade. The new methodology breaks through the obstacles introduced by the lack of detailed waybills in most countries and enables global feasibility for responsibility allocation.

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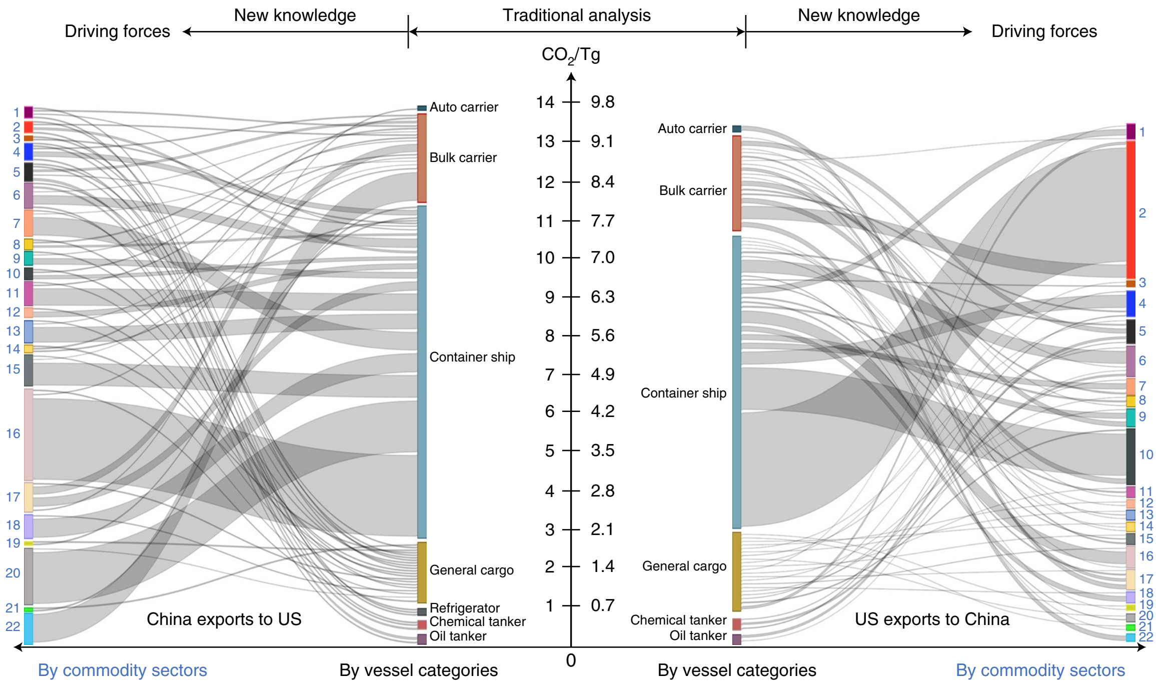

Fig. 1 | US–China trade-embodied shipping emissions. Commodity breakdown (left and right bars), ship breakdown (bars in the middle) and combined commodity–ship breakdown (shadow curves). Commodity sector numbering (in blue): 1, Animals and their products; 2, Vegetable products; 3, Animal or vegetable fats, oil or waxes; 4, Foodstuff, beverages, vinegar and tobacco; 5, Mineral products; 6, Chemical products; 7, Plastics, rubber and articles thereof; 8, Hides, skins, leather, furskins and their products; 9, Wood, charcoal, cork, straw and articles thereof; 10, Wood pulp, paper and articles thereof; 11, Textiles and textile articles; 12, Articles of daily use; 13, Articles of stone, plaster, cement, mica, glass and ceramic; 14, Pearls, precious metals and jewellery; 15, Base metals and articles thereof; 16, Machinery and electrical equipment; 17, Transport equipment; 18, Instruments and apparatus, clocks and watches; 19, Arms and ammunition; 20, Miscellaneous manufactured articles; 21, Works of art, collectors' pieces and antiques; 22, Special or unclassified products.

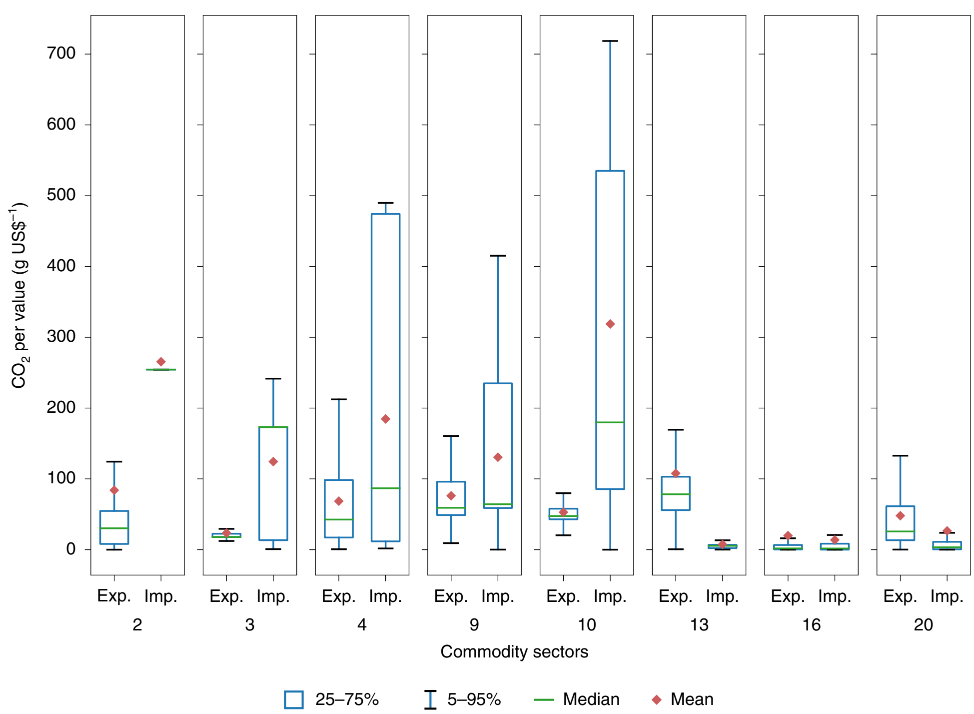

Fig. 2 | CO_2 emissions per value embodied in sea-transport for typical commodity sectors. Exp., China's exports; Imp., China's imports. Commodity sector numbering as in Fig. 1. The interval between the upper and lower cap line represents the 5–95% sample distribution. The box represents the 1/4 to 3/4 quantile (25–75%) sample distribution.

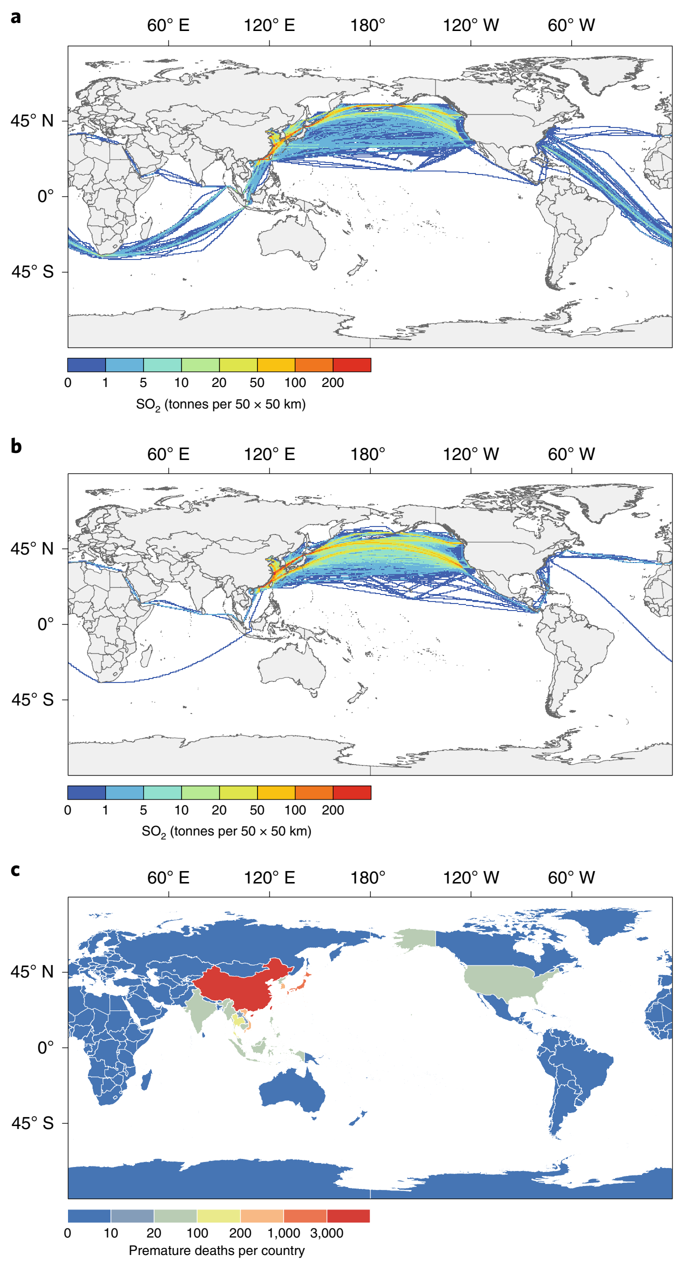

Fig. 3 | Geographic distribution of shipping emissions and related premature deaths embodied in the US–China trade in 2016. a, SO_2 emissions from US exports. **b**, SO_2 emissions from Chinese exports. **c**, Premature deaths related to US–China bilateral trade. Credit: Base maps from Natural Earth (https://www.naturalearthdata.com/).

Results

Trade-related shipping emissions. Sea transport is responsible for 99.1% of the US–China trade if counted by weight (71.5% if counted by value)[36,37], of which about 120 million tonnes (Mt) of products shipped from China to the United States by 2,441 vessel calls (defined as a non-stop single-trip) and 104 Mt from the United States to China by 2,041 vessel calls. These vessel calls included 513 container ships, 979 bulk carriers, 156 general cargos, 108 chemical/oil tankers and 70 other ships. The capacity of this ship fleet, defined by the ship's deadweight tonnage (DWT) retrieved from our global ship technical specification database (STSD)[14], is higher than the total weight of commodities from the trade dataset, indicating a 66% use rate of the ship fleet. The use rate is reasonable compared to the reported average rate for each vessel category in the International Maritime Organization's MEPC 68/INF 24 (ref. [38]). The details of the ship database and ship-commodity matching methods are in Supplementary methods 2–4. Trade data obtained from the US Census Bureau[36] were also compared to our trade/ship datasets as a top-down validation. All three datasets used in this study—the trade database, ship fleet DWT and the trade data from the US Census Bureau—are comparable, indicating the reliability of the trade/ship datasets in the Supplementary methods 1–3 and 8.

In 2016 trade between the United States and China constituted 3.4% of the world's trade[37,39] and resulted in 321 kilotonnes (kt)SO_2, 23 MtCO_2, 450 ktNO_x, 41 ktPM and 18 ktCO in shipping emissions, which accounted for 2.5% of global shipping emissions[2]. As shown in the middle part of Fig. 1, for traditional analysis the emission amounts based on ship categories indicated that the major contributor was the container ship. However, when driving forces were considered, new information identified substantial differences between the US and China trade emission structures, as shown in the left and right parts of Fig. 1, respectively. The total amount of commodities in sector 2 (vegetable products) and 10 (wood pulp and recovered paper) accounted for nearly half of the total US–China maritime trade emissions. The transportation of vegetable products (the US soybean accounted for 79.3% of the weight in sector 2) resulted in over 40% of the total emissions, but only 12.4% of the value from the US to China. Another main driving force was the waste in sector 10, which accounted for 15.2% (1,416 ktCO_2) of the total emissions from US–China transportation, but only 3.2% of the total trade value of US exports. The waste transported from the US to China included the waste paper or paperboard (1,309 ktCO_2, 92.4% of sector 10), plastic waste, parings and scrap (59 ktCO_2, 4.2% of sector 10) and metal waste and scrap (48 ktCO_2, 3.4% of sector 10). China was once one of the largest importers of foreign waste in the world, importing over 50% of global plastic waste in 2016 (ref. [40]). In 2017 the Chinese government decided to completely ban the import of 24 types of solid foreign waste, which is of great importance for improving trade efficiency and benefitting other countries along the shipping routes in terms of reducing shipping emissions[41]. In Chinese exports to the United States, machinery and electrical equipment (sector 16, 25% of total emissions), miscellaneous manufactured articles (sector 20, 16% of total emissions) and special or unclassified products (sector 22, 8% of total emissions) were the main driving forces of shipping emissions. More details related to emission calculations and results are discussed in Supplementary methods 5.

Shipping emissions embodied in China–US exports are 41–48% higher than US–China exports. Compared to the trade surplus (300% based on Chinese statistics and 400% based on US statistics[37]), the differences in emissions were rather small, indicating higher CO_2 emission per value trade from US exports. Figure 2 uses boxplots to show the CO_2 emissions per value for typical sectors. Overall, the commodities exported from China to the US have an equivalent CO_2 emission of 35.7 g US\$$^{-1}$, while the value of the commodities exported from the US to China is 68.6 g US\$$^{-1}$. The CO_2 emissions per value of soybean is 254 g US\$$^{-1}$ (included in sector 2) and the CO_2 emissions per value of solid waste is 325 g US\$$^{-1}$ (contained in sector 10). When sector 2 and sector 10 were removed, the CO_2 emission ratio from the US to China was drastically reduced to 28.3 g US\$$^{-1}$. If these low-value but large-weight cargos could be controlled with sea transport, the emissions per value would be greatly improved. Chinese machinery, equipment and high-tech intermediate products (sector 16) have a low CO_2 emissions per value ratio (25.4 g US\$$^{-1}$). Targeted reduction of ship energy consumption or changes in trade standards and structure might notably improve the emission reduction efficiency according to this diagram. These advantages may not have been revealed in previous top-down forecasts on shipping emissions.

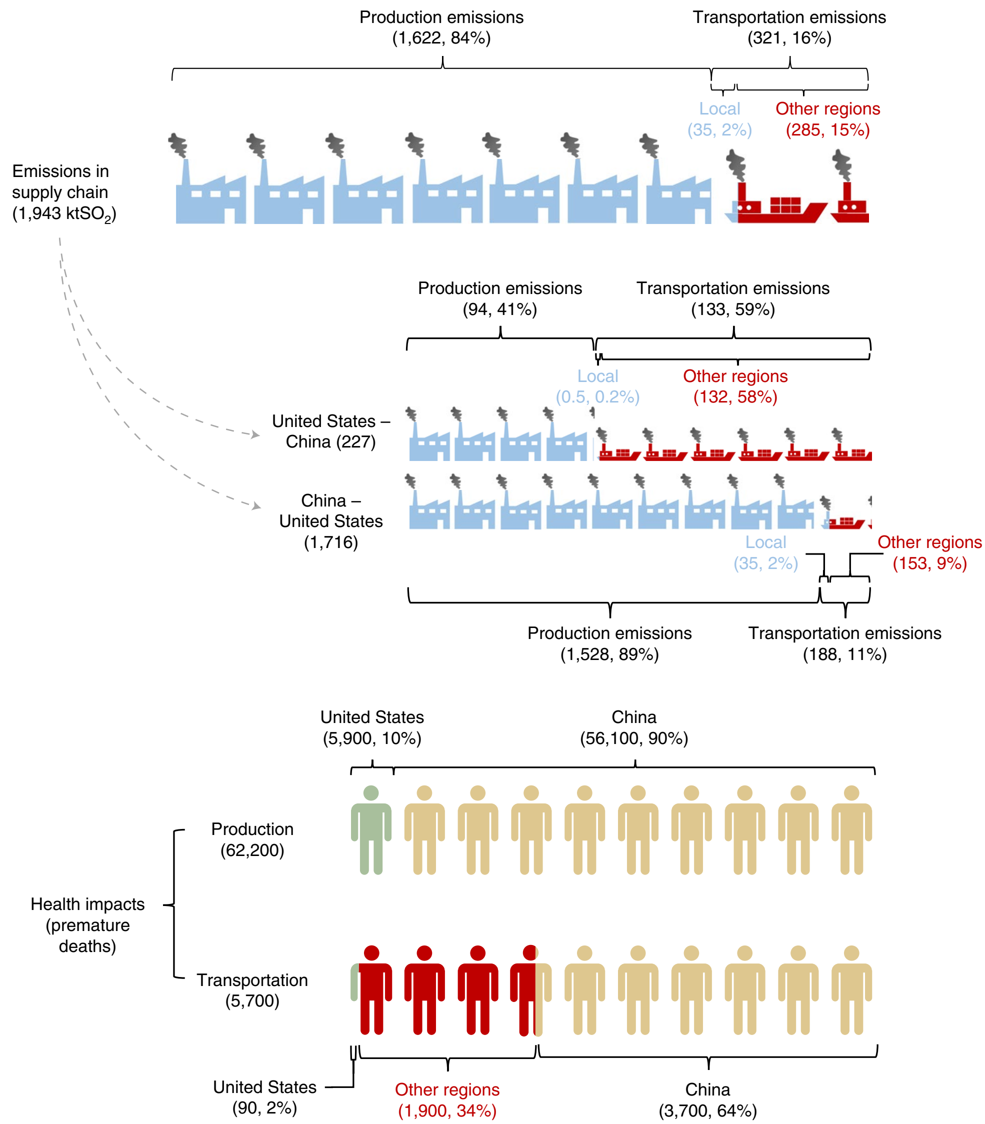

Fig. 4 | Emissions and health consequences in the supply chain for the US–China bilateral trade in 2016. Production-end versus transportation processes and local versus remote regions. Blue, emissions in the United States plus China; red, emissions and health impacts in other regions; green, health impacts in the United States; yellow, health impacts in China.

Shipping-related pollution and health impacts embodied in US–China trade. US–China trade-related shipping emissions distributed not only in Chinese and US coastal areas, but also in other regions, as shown in Fig. 3. Chinese exports mainly go through the Pacific shipping lane. For US exports, although the Pacific shipping lane still dominates west coast exports, considerable emission signals in the Atlantic Ocean, Cape of Good Hope and the Indian Ocean are also detected from east coast export routes. We found that emissions (SO_2, NO_x, primary PM and volatile organic compounds as precursors for the $PM_{2.5}$ formation) embodied in the US–China bilateral trade led to an increase in $PM_{2.5}$ concentrations of up to 1.1 $\mu g\,m^{-3}$, with fairly high contributions to coastal regions of China and Japan (Supplementary Fig. 10). The global premature deaths of ambient $PM_{2.5}$ due to shipping emissions in US–China trade reached ~5,700 (95% confidence interval (CI), 2,700–6,600 deaths) (see Supplementary Table 7). The mortality in China accounted for 64.4% of the total global deaths induced by shipping emissions in the US–China trade, while little impact (less than 100 deaths) was found in the United States because of the sparser population compared to China. The North American Emission Control Area (ECA), where low sulfur fuel oil was used to control SO_2 and PM shipping emissions, benefitted the US through the reduction of $PM_{2.5}$-related premature deaths. We also found that the shipping emissions embodied in the bilateral trade of these two countries caused a total of ~1,900 premature deaths (95% CI, 800–2,100) in regions outside China and the United States. The mortalities in Japan (1,000 mortalities, with a 95% CI, 500–1,100), South Korea (200 mortalities, with a 95% CI, 100–300) and Vietnam (200 mortalities, with a 95% CI, 100–300) were all higher than that in the United States. The US–China trade shipping-related pollution also caused health impacts in Southeast Asia.

Emissions in supply chain: transportation versus production. Figure 4 provides a comparison of shipping emissions versus production-end emissions[33] embodied in the US–China bilateral trade. Using SO_2 as an example, we found that the maritime transport could increase the traditional trade-related emissions with an increment of 20% in the US–China bilateral trade. For the US-export

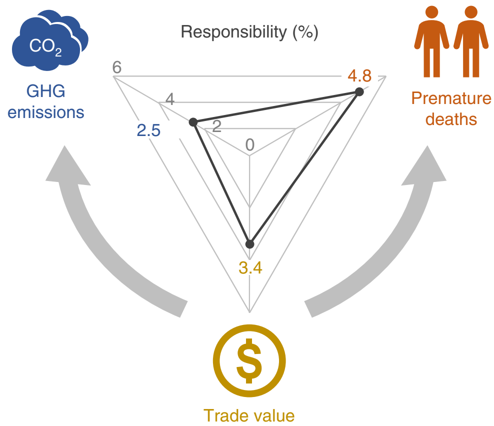

Fig. 5 | US–China trade-related global share from different perspectives. Percentage responsibility by trade value, CO_2 emissions and premature deaths.

commodities, the emissions generated in production activities (which mainly influenced the local environment) accounted for 41% of the aggregate emissions in the supply chain. The remaining 59% of the total emissions originate from transport activities, and nearly all of them occur in regions outside the United States and China, which exceeds the totals of production emissions. For Chinese exports, the proportion of transportation emissions are relatively small (11%) due to the large number of production emissions. Similar to the US exports, most emissions are produced in other regions. In terms of the health impacts, China suffers more health consequences than other countries because of its large population is concentrated along the eastern coast. However, 34% of the premature deaths caused by shipping emissions occurs in countries not directly related to the US–China bilateral trade. This phenomenon is substantially different from production-related emissions, in which nearly all premature deaths occur at the producing area, and indicates that shipping emissions are not negligible in the estimation of supply-chain-related emissions.

Discussion

Our research developed analysis methodology to allocate shipping impacts to bilateral trade pairs (as responsibility parties) based on the intensive bottom-up analysis for both the transportation demand, including trade volume and structure, and also the emission level of recruited ships for this trade. To facilitate mitigation of trade-embodied shipping emissions, the stakeholders involving trade pairs and shipowners should all take responsibility. The trade pairs could reduce the trade volume, optimize trade structure (for example, reducing low-value large-weight commodities in trade) or recruit 'cleaner' ships. Compared to the option for reducing trade demand, countries may choose to employ 'cleaner' ships instead of 'dirty' ships when this can be counted towards their credits. Our methodology can accelerate the market-driven strategy in the process of cleaning the ship fleet, and hence help to achieve the 50% carbon emission reduction target by 2050 (ref. [42]). The fact that emissions and impacts could be brought to other regions outside the bilateral trade pairs should also be taken into consideration to guarantee the fairness of responsibility counting. When more 'victims' were included in the system, the definition of 'responsibility' could influence the results. From a GHG emission perspective, the US–China bilateral trade is responsible for 2.5% of the global shipping CO_2 emissions[2]; from a criteria pollutants perspective, the US–China bilateral trade is responsible for 4.8% of ship-related global premature deaths[6]. Neither the GHG nor the criteria pollutants responsibility share is equal to the trade share, which is 3.4% of the global total trade value[39] (Fig. 5). These unequal shares indicate the complexity of the responsibility allocation and the need for systematic quantitative analysis to allocate responsibility. For example, higher trade efficiency and shorter routes could contribute to the reduction of GHG responsibility. Cleaner ships, ECA, regional air quality, population density and distance from ship emissions to coastal areas could influence the allocation of criteria pollutants-related responsibility.

Methods

Trade database. We acquired the US–China bilateral trade data (country level, but not specific to port or region level) in 2016 from the China Customs Statistics Yearbook 2016 (ref. [43]), which contains the value and weight information of 12,346 commodity subcategories. The trade data in our dataset was comparable to the aggregated data from the US Bureau of the Census[36] (Supplementary Fig. 1). Due to the location of China and the US, commodities must be transported by air or sea. Here, we assumed that all commodity weights were transported by sea. The reason for this assumption was that only 0.3% (US–China) and 1.8% (China–US) of the total commodity weight was transported by air based on data from the US Bureau of the Census[36]. Supplementary methods 1 discusses the data sources and categories for the US–China bilateral trade database, and the quality assurance and quality control for the bilateral trade database, respectively.

Ship database. An updated STSD from our previous research[14] provided detailed technical specification information for each ship, including vessel type, DWT, maximum continuous rating and so on. Among these parameters, the vessel type was used to link to the cargo type, while DWT was used to check the total freight weight by comparing the vessel fleet total with the trade commodity total. Compared to the global in-service vessel fleet, our new STSD had better coverage (Supplementary Table 1). The AIS data in this study had sufficient coverage and frequency to accurately characterize voyages and identify trade transport vessels (Supplementary Fig. 2). Supplementary methods 2 provides further information on STSD and AIS data.

Method for identifying shipping voyages related to the China–US bilateral trade. Identification of the US–China trade-related vessels was based on global AIS data. The identification standards for the trade vessels from China to the US were as follows: (1) the departure point and arrival point were in the Chinese research domain and the US research domain, respectively, (2) vessels did not sail back into the Chinese research domain after departure before arriving at the US research domain and (3) vessel departure was defined as being anchored (with a sailing speed of <1 knot) in the previous AIS message and not anchored in the following AIS message. Vessel arrival was defined as for the vessel departure. The uncertainties considering different scenarios were also assessed, for example including or excluding stop-over situations. The advantage of our method was that it could avoid double counting when used globally. Supplementary methods 3 describes the detailed approach, results and uncertainties for vessel call identification.

Linkage between the transport vessel fleet and commodities. As noted above, vessel types were linked to cargo types. A general list of commodity categories carried by different vessel types was obtained from the International Chamber of Shipping[44]. Within the different vessel types, the commodity type carried by auto carriers, refrigerator ships, chemical tanker and oil tankers was relatively clear because of their unique characteristics; however, the cargo categories related to bulk and container ships were more complicated. To reduce the uncertainty of bulk and container ship-related cargo and to determine the commodities carried by bulk carriers we collected over 10,000 real logistics for commodity types carried by bulk carriers from a marine logistics information platform (http://company.shipping.jctrans.com/AskOfferList/; Supplementary Fig. 8). The commodities carried by each vessel category are summarized in Supplementary Table 5. Every subcategory commodity was connected to a certain type or several types of vessel fleets. In the overlap situation, in which a commodity may carried by multiple vessel fleet categories, we assumed that the commodity amount was distributed within each vessel fleet by weighting the total DWT in the whole trade vessel fleet. For details, please refer to Supplementary methods 4.

Shipping emissions. All ship emissions were calculated using our shipping emission inventory model[14], which was based on AIS data. This model was similar to the method used in the International Maritime Organization's third GHG study[2], but was updated using a time interval calculation that decreased the uncertainty of the emission calculation and spatial distribution (Supplementary methods 5). We chose the year 2016 as the base year when the North American ECA policy had been implemented and while China's Domestic ECA policy was in its preparation. The PM, NO_x, SO_2, carbon monoxide, hydrocarbon, CO_2, nitrous oxide and methane emission results are summarized in Supplementary Table 6. With the linkage between vessel fleets and commodity, the emissions due to transporting each commodity type could be calculated.

Air quality. The GEOS–Chem chemical transport model was employed to estimate the global air quality impacts from shipping emissions in the China–US trade with a zero-out approach. Briefly, the difference between the simulation results with and without US–China trade shipping emissions, with other model parameters set the same, was used for our air quality analysis. More details about model configuration and evaluation are described in Supplementary methods 6.

Health models. Premature deaths associated with exposure to $PM_{2.5}$ were calculated as $M = M_b \times P \times AF$, where M is the number of premature deaths due to $PM_{2.5}$; M_b is the cause-specific baseline mortality rate; P is population and AF is an attributable fraction of deaths due to $PM_{2.5}$. The integrated exposure–response (IER) model and the linear C–R function were both applied to estimate the AF[45,46]. The median and the 95% CI were provided in our results to represent the uncertainties in health models. We used 1,000 variants for each cause-specific relative risk in the IER model and a 95% CI for the β parameter when evaluating the relative risk in the linear concentration–response (C–R) function (see Supplementary information). For consistency with the recent Global Burden of Disease Study[47], only the results from the IER model were discussed and shown in the main text. Detailed methods are introduced in Supplementary methods 7.

Uncertainty analysis. This work was subjected to several uncertainties and limitations. First, the total identified ships for the US–China bilateral trade in this study could be biased due to the undercount or overcount of more-than-bilateral trade-related voyages. We quantified the uncertainties in vessel call identification results by comparing the identified vessel fleets capacity with the US–China bilateral trade weight for each vessel category (Supplementary methods 3). The results were acceptable when compared to the reported use rate by the International Maritime Organization's MEPC 68/INF 24 (ref. [38]). We also tested a set of voyage identification procedures that included the stopping-over situation and the results indicated that our original identification criteria was more credible (Supplementary methods 3). Second, linking commodities to ship categories could be biased, despite using both an International Chamber of Shipping report[44] and a realistic shipping manifest information platform. Taking into account that the CO_2 US^{-1} results could be affected by the commodity–ship matching process, we evaluated the uncertainties by comparing the magnitudes of ship-related differences with commodity-related differences (Supplementary methods 4). Although commodity-related differences could reach thousands of times (0.1–2492.7 g US^{-1}), the ship-related differences were only restricted to three times (0.03–0.09 tonnes of CO_2 per tonne of capacity). Furthermore, the uncertainty would not be transferred to the total emissions because they were calculated using AIS data and were independent of the commodity–ship matching progress. We also compared the CO_2 emission per weight per nautical mile in this study to a manifest-based bottom-up study[15], and the results were comparable (17 g of CO_2 per tonne of cargo per nautical mile in our study versus 18–24 g of CO_2 per tonne of cargo per nautical mile in the manifest-based study). Third, there were many uncertainties of the health assessment and they were subject to the limits of C–R functions. We quantified the uncertainties in parameters of both the IER model and the linear model, providing the median and the 95% CI of estimates (Supplementary methods 7). The global premature deaths due to shipping in US–China trade reached 5,700 (95% CI, 2,700–6,600 deaths) and 19,500 (95% CI, 9,900–29,400 deaths) using the IER model and the linear model, respectively (Supplementary Table 7). Although the national ranking of mortality number was similar in these two methods, the linear C–R function produced three to five times higher health burden estimates than those using the IER model. The detailed uncertainty of each method is discussed in the Supplementary information and summarized in Supplementary Table 8. The results validation is summarized in Supplementary Table 9.

Data availability
Data are constrained to third-party restrictions. The AIS data and the trade commodity data between China and the US are used under licence for the current study and are not publicly available. Emission data are available from the corresponding author upon request.

Code availability
Python codes used during the current study are available from the corresponding author on reasonable request.

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Author contributions

H.L. conceived and led the study. Z.-H.M. established the model and the connections between emissions and commodities. Z.-F.L. and F.-Y.D. helped with data processing. Q.Z. and Y.L. performed the GEOS–Chem model simulation. X.-T.W. and Y.-N.Z. helped collect the marine logistics information and process the massive data matching. M.-S.S. worked on the trade dataset. Q.Z. and K.-B.H. provided important views on the study.

Competing interests

The authors declare no competing interests.

Additional information

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