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Health and climate impacts of ocean-going vessels in East Asia

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East Asia has the most rapidly growing shipping emissions of both CO_2 and traditional air pollutants, but the least in-depth analysis. Full evaluation of all pollutants is needed to assess the impacts of shipping emissions. Here, using an advanced method based on detailed dynamic ship activity data, we show that shipping emissions in East Asia accounted for 16% of global shipping CO_2 in 2013, compared to only 4–7% in 2002–2005. Increased emissions lead to large adverse health impacts, with 14,500–37,500 premature deaths per year. Global mean radiative forcing from East Asian shipping is initially negative, but would become positive after approximately eight years for constant current emissions. As a large fraction of vessels are registered elsewhere, joint efforts are necessary to reduce emissions and mitigate the climate and health impacts of shipping in the region.

Emissions from ships and ports include both long- and short-lived climate pollutants (SLCP), for example, CO_2, CH_4 and black carbon (BC), and criteria pollutants, such as SO_2, NO_X and $PM_{2.5}$ (refs 1–3). Attention on ships and ports has increased as seaborne trade has grown significantly in recent decades. Asia's share of world seaborne trade reached 38.7% and 49.4% for goods loaded and unloaded in 2013, and eight of the top ten global container ports are located in East Asia, as the region continues to dominate the league table for port throughput[4]. Shipping volume in East Asia is expected to grow in the near future, mainly due to the 21st Century Maritime Silk Road strategy, which is designed to go from China's coast through the South China Sea to Europe via the Indian Ocean in one route, and to the South Pacific in the other.

However, the climate and air quality impacts from shipping are not well understood in this region. A full evaluation of all pollutants, including CO_2, BC, CH_4, and substances that cool the climate (especially sulfate, organic carbon and nitrate), is critical to understanding both short-term and long-term climate change effects. For this region, there are several global-scale studies, most of which use fuel-based approaches[2,5–8]. These methods provide a reasonable estimate of global emissions, but less accuracy at the regional level due to systematic misallocation of marine fuels[9]. For example, a study in Europe[10] found that top-down estimates account for only 20 to 70% of regional estimates. Analysis for Asia has been limited; for example, a previous study estimated SO_2 emissions from ships between 1988 and 1995 based on trade data, but focused on large cargo ships only[11]. Research in later years has been at port or city levels, all in Shanghai or Hong Kong[12–14], with little progress specifically at the regional level in the past 20 years. Although Asian emissions are of course included in global inventories, the regional bias, as described above, leads to inaccuracy of inventory in this region.

Bottom-up methods (voyage route/port call statistics, or real-time ship movement-based) were used recently in Europe and North America and in the global Third International Maritime Organization (IMO) Greenhouse Gas Study[9,15–19], providing the most detailed information on activity. However, the availability of shipping activity data for research was limited in some areas[17], especially in Asia. Many fewer Automatic Identification System (AIS) messages were recorded for research purposes in Asia—even within the latest IMO study—than in Europe or North America, which is inconsistent with seaborne trade data[9]. This has greatly hampered understanding of the Asian contribution to global emissions.

This study provides an important regional supplement to global shipping emission studies by introducing high-quality AIS data and a ship technical specification database. In total, emissions are calculated based on 78 million hours of vessel operation, equivalent to 177 operating days for each vessel, from AIS-derived activity data in East Asia. The total number of vessels observed in 2013 in this region is 18,324. We present ship emissions, followed by an analysis of their climate and human health impacts, along with a discussion of these results.

Shipping emissions in East Asia

In this study, we calculate CO_2, SO_2, NO_X (as NO_2), particulate matter (PM), CO, non-methane volatile organic compounds (NMVOCs), BC (as a fraction of PM), organic carbon (OC, as a fraction of PM), CH_4 and N_2O emissions from ocean-going vessels (OGV) for East Asia in 2013. The resulting total CO_2 emissions are $126 \pm 4\,Tg\,yr^{-1}$. Regional pollutant emissions are estimated to be $1.85 \pm 0.07\,Tg\,yr^{-1}$ (SO_2), $2.8 \pm 0.1\,Tg\,yr^{-1}$ (NO_X), $0.240 \pm 0.009\,Tg\,yr^{-1}$ (PM), $0.100 \pm 0.004\,Tg\,yr^{-1}$ (NMVOC), $0.108 \pm 0.005\,Tg\,yr^{-1}$ (CO), $50 \pm 3\,Gg\,yr^{-1}$ (CH_4) and $6.8 \pm 0.3\,Gg\,yr^{-1}$ (N_2O). The BC and OC fractions of PM are set to 6.6% and 20.2%, respectively (Supplementary Information).

Figure 1 illustrates the spatial distribution of CO_2 emissions from East Asian shipping. The chosen region reflects our focus on

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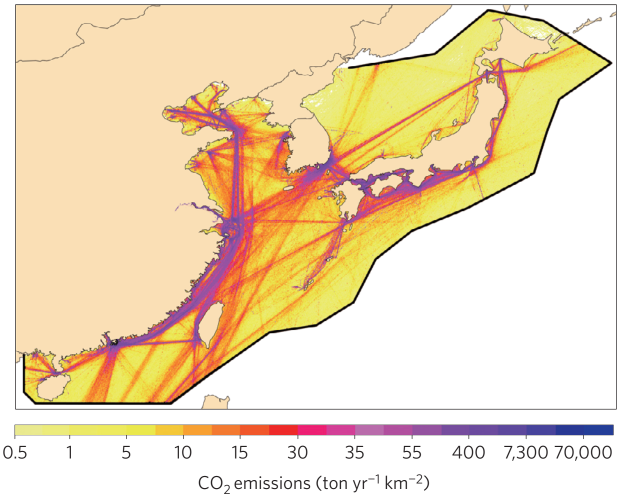

Figure 1 | Spatial distribution of CO_2 emissions from East Asian shipping.

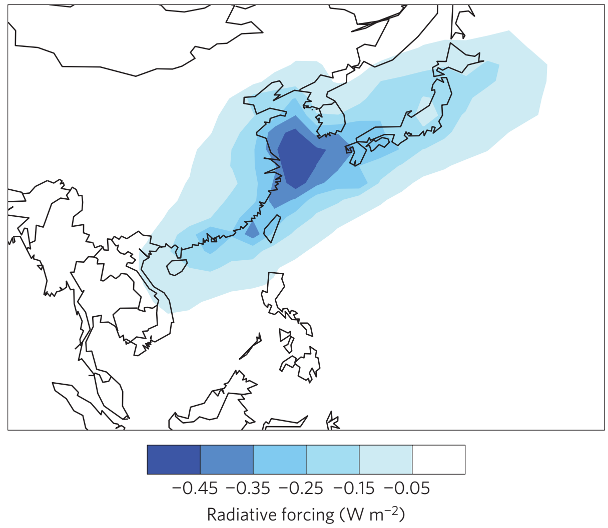

Figure 2 | Radiative forcing ($W\,m^{-2}$) attributable to aerosols and ozone from East Asian shipping. Values include aerosol–cloud interactions. Negative values (blue) mean that shipping emissions have a cooling impact on climate near East Asia. The forcing shown here is dominated by sulfate and ozone, for which the global mean industrial era uncertainties are 50–60% (a reasonable estimate for this case, as emissions are better known but regional forcing is more uncertain than global).

densely populated areas, and is not intended to endorse any national boundaries. The spatial distribution is generated by adding up the emissions for each grid box from all routes for all ships. Spatial distributions for SO_2, NO_X, CO, NMVOC, CH_4 and N_2O emissions are fairly similar to that for CO_2, with only minor differences near shore. By using this AIS-based method, all waterways with high emission intensity are clearly identified. It is evident that the highest traffic density occurs within a small fraction of the total area, for example, in the Taiwan Strait. In general, areas near all the major East Asian ports have high emission intensities.

Of the total emissions in East Asia, about 31% were from the East China Sea, which reflects high traffic to and from the Yangzi River Delta (YRD) region and in the Taiwan Strait. The Western Pacific share is about 22% of total emissions, which are mainly from shipping activity along the trans-Pacific and north–south routes from Japan. The South China Sea (northern part) is another area with high emissions, contributing about 16%. Three busy ports are located in this area, including Hong Kong, Shenzhen and Guangzhou. Most of the north–south routes from China start from this area. Although the total emissions in the Bohai Sea are the smallest of the six sea areas, the emission intensity there is among the highest, reaching 70 ton km^{-2} for CO_2 emissions. In contrast, the CO_2 emission intensity is 55 ton km^{-2} in the Yellow Sea, 51 ton km^{-2} in the East China Sea, 29 ton km^{-2} in the South China Sea, 22 ton km^{-2} in the Western Pacific Sea, and 16 ton km^{-2} in the Sea of Japan. More details related to the aggregated emissions for various regions are shown in Supplementary Fig. 1.

A previous study[20] showed that roughly 70% of the emissions from international shipping occur within 400 km (equivalent to 216 nautical miles (nm)) of the coast. To further characterize the emission distribution, we choose areas near the Chinese and Japanese coasts to analyse the accumulated share of total emissions versus distance to the shore (Supplementary Fig. 2). Taking CO_2 as an example and setting emissions within 140 nm as the total, we find that 60% of total emissions happen within 20 nm of shore in the East Asia region. Comparing the coasts of China and Japan, 80% of emissions occur within 60 nm of shore in the YRD region and within 40 nm of shore on Japan's east coast. This difference represents the impact of the differing distribution of voyage routes. The Japanese routes are mostly from the south along the coast, while the Chinese routes near YRD are from Japan, Korea or the Pacific Ocean, from east to west. The emission intensity changes with distance are provided in Supplementary Fig. 2.

Container carriers and bulk carriers are the main contributors in East Asia for all pollutants, except CH_4. Container ships contribute 24–27% of emissions, and bulk carriers contribute 26–27%. Emissions from tankers, RORO (roll-on roll-off cargo) and general cargo account for about 18%, 13% and 10%, respectively. CH_4 is mainly from liquefied gas tankers. The proportions of container ships, tankers and bulk carriers in East Asia are comparable to global and European fleets. The role of passenger ships (cruise vessels) is relatively small in East Asia, where it is only 2%, as compared with 11% globally and 29% in Europe[21]. The majority of OGV emissions are associated with main engines. The auxiliary engine and boiler shares are 26 and 8% of the total CO_2 emissions; however, significantly higher than previous global-scale results (for example, 10% for auxiliary engines[22]). This reflects the fact that the cruise distances in East Asia are much shorter than those during global voyages. Thus the emission share attributable to main engines is smaller at the regional level. More details on the contributions from each ship category and engine type are provided in Supplementary Table 1.

Two sources of uncertainty in regional shipping emissions estimation are considered: the completeness of ship observations and the estimates of annual emissions from the observed fleet of ships. A Monte Carlo method with 100,000 simulations was used to evaluate the uncertainty for our bottom-up emission inventories. In total, the uncertainty for CO_2 is about 3%, and for the other pollutants is about 4–6%. These confidence ranges are similar to other activity-based inventories[9]. Additional details of the uncertainty analysis are in the Supplementary Information.

Climate change impact of ship emissions

Using the East Asian ship emissions to drive the GISS-E2 global chemistry–climate model, we find that they lead to a near-term radiative forcing that is strongly negative off much of the Chinese, Japanese and Korean coasts ($<-0.3\,W\,m^{-2}$; Fig. 2). Globally averaged, the forcing due to East Asian emissions is also negative in the years immediately following emissions, owing to the large net regional aerosol (direct + indirect) plus ozone forcing. However, the accumulating, nearly uniform CO_2 forcing takes on greater importance with time. Similarly, there is a nearly uniform negative forcing from methane owing to an NO_x-emission driven reduction

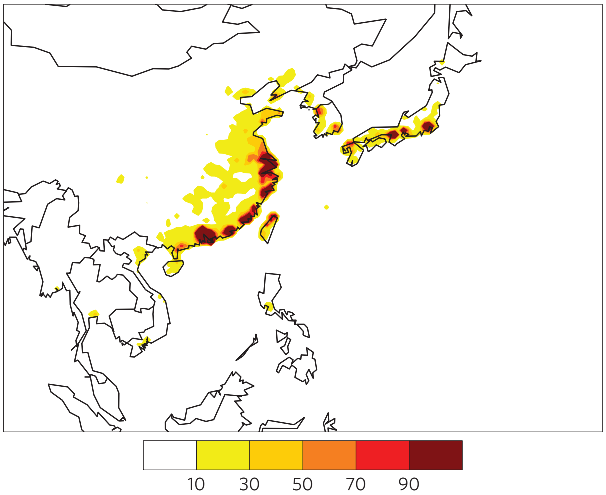

Figure 3 | Premature deaths per year attributable to East Asian shipping emissions in each 0.5° × 0.5° grid box. Positive values mean that shipping emissions damage human health.

in methane's chemical lifetime which outweighs the small methane emissions from ships, but the positive CO_2 forcing is always larger. Hence, although global mean net forcing is initially negative, it becomes zero in year 7, and reaches 0.003 W m^{-2} by year 75. Thus the emissions may at least temporarily mask a portion of the warming due to greenhouse gases in East Asia, although in the long term the CO_2 emissions from OGVs would have a greater worldwide impact. Prior studies[23,24] found similar short-term cooling and long-term warming from shipping in other regions.

Health impact of ship emissions

Using our modelling of atmospheric chemistry and transport, we also examine the impact of ship emission-derived $PM_{2.5}$ and ozone on human health via respiratory disease, cardiovascular disease and lung cancer. We find the ship emissions have a substantial impact on human health (Fig. 3). Impacts are especially large near shore, but extend inland a considerable distance. Although emissions were perturbed only within the domain described above, long-range transport of pollution leads to substantial effects in urban centres outside the domain, such as Bangkok and Hanoi. Using a recently published health methodology incorporating 1,000 relative risk functions per cause[25] and reporting their mean and 95% confidence intervals, the ship emissions analysed here lead to more than 24,000 premature deaths annually in East Asia, with the largest impacts in mainland China (18,000 ± 8,600), Japan (3,600 ± 1,200), Taiwan + Hong Kong + Macau (1,100 ± 400), South Korea (800 ± 300) and Viet Nam (600 ± 200). Worldwide totals attributable to these shipping emissions are 17,100 ± 8,400 premature deaths due to $PM_{2.5}$ and 8,900 ± 3,100 due to ozone, an important though small fraction of the more than 1 million total premature deaths attributable to ambient air pollution in the same region[26]. Our range for $PM_{2.5}$ of 8,700 to 25,500 is within the very large range of 1,000–32,000 found in an earlier study for East Asian shipping $PM_{2.5}$ (ref. 27). This results from offsetting influences of our use of higher emissions estimates and more causes of mortality (the prior work did not include respiratory diseases), but also newer exposure–response functions that reduce the impact of $PM_{2.5}$ at the very high exposure levels typical of East Asia.

Emission share by flags and destinations

Figure 4 shows the breakdown of CO_2 emissions by the ships' registered country/region (ship flag) and by where CO_2 was emitted (affected region). Examination of CO_2 emissions also serves as a proxy for other pollutants, whose effects are regional rather than global. The top three maritime countries/regions for flag of registry in East Asia are Japan (13.9%), mainland China (8.86%) and Hong Kong (6.14%). The CO_2 emission from ships registered in countries outside East Asia is about 65.2%, which shows that it is very important to reduce emissions not only from local vessels, but also from foreign-registered ships. In the Bohai Sea, which has the highest emission intensity, as mentioned previously, ships registered in countries outside the region (63.0%) and in mainland China (31.3%) are the two largest contributors. Neighbouring South Korea's portion increases significantly in the Yellow Sea, but is still small (6.9%). In the East China Sea, which has the largest total emissions in East Asia, the contribution from out-of-region vessels reaches 76.6%, while the contribution of ships from China, Hong Kong and Japan are similar. In the Sea of Japan, emissions from vessels registered in other countries and in Japan are much higher than any other. In the South China Sea, emissions are mainly from vessels of other countries (74.6%), Hong Kong (11.9%) and mainland China (11.4%). In the Western Pacific, vessels from other countries and Japan are major contributors, about half and half.

Discussion

We find a clear and plausible increasing trend in East Asian shipping emissions over the past ten years (Fig. 5). Compared with global international shipping emissions for 2012 in the Third IMO Greenhouse Gas Study[9], the contribution of shipping in East Asian waters to CO_2 emissions is roughly 16% (ignoring the one year difference between 2012 and 2013). East Asian contributions to global NO_X and SO_2 emissions from shipping are approximately 16% and 19%, respectively.

Comparing these ratios with previous studies, significant increases in East Asia's share of all pollutants are observed. In 2000, 4.5% of worldwide shipping emissions were in this region based on merged Automated Mutual-assistance Vessel Rescue system (AMVER) and International Comprehensive Ocean–Atmosphere Data Set (ICOADS) data[1]. The AMVER or ICOADS proxy[10], based on data from 2002 to 2005, assigned 6.7% to this region. The EDGAR V4.2 assigned 12.5% of the global shipping CO_2 total to this region, while the later publicly available geospatial data from EDGAR (HTAP V2 for 2010) assigned only 6.3% of the global shipping CO_2 total to this region[28]. This study updates the contribution of East Asia to 14–19% (for different pollutants) in 2013.

This increasing emission trend was further examined by comparison with trade growth. Seaborne trade (indicated by containers) in East Asia increased by a factor of 2.62 from 2003 to 2013 (from 90,003,566 to 236,285,057 Twenty-Foot Equivalent Units)[29]. The EDGARv4.2 FT2010 (ref. 30) global inventory for 2003 was aggregated in the same East Asian domain, yielding 73.8 Tg CO_2 emissions. Our estimate is 1.7 times higher. We also compare with the global emission inventory for 2001[31] (including main and auxiliary engines), distributing those emissions using the AMVER/ICOADs combined proxy. When excluding boiler emission, our CO_2 estimation is 2.0 times higher. Both of these emission increases are slower than the trade increase, probably reflecting improvements in engine efficiency and loss of information on some small ships. For the other pollutants, the emission increases relative to the estimates for earlier years are not consistent with CO_2 (1.85 times for NO_x, 2.7 times for SO_2, when excluding boiler emissions). This is because of differences in the regional distribution proxy. Previous work used the same CO_2 spatial distribution proxy for all pollutants. In our study, the bottom-up method accounts for differences among pollutant distributions. For example, because high sulfur fuels are used in this region, the East Asian SO_2 share of the world fleet emissions is higher than the CO_2 share. Also, in near-shore regions, the fraction of emissions from main engines

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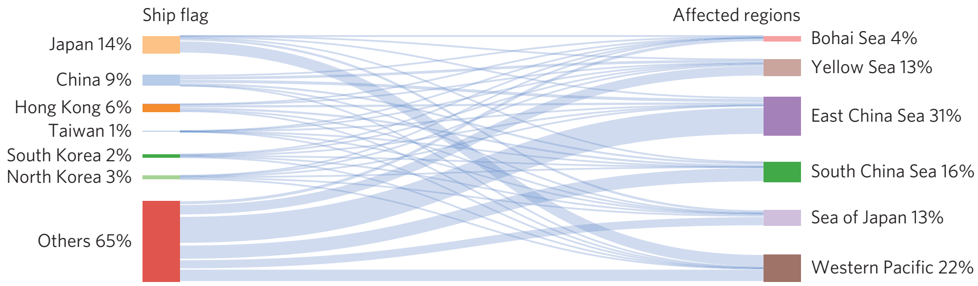

Figure 4 | Statistics of CO_2 emissions by the ship registration and emission location. Left vertical axis is the ships' registered country/region (ship flag) that produced these emissions. Right vertical axis is the location where pollutants were emitted (affected regions). The grey rows between the left and right vertical axes are the CO_2 emissions percentages. Right vertical axis percentages total 99% as a result of rounding.

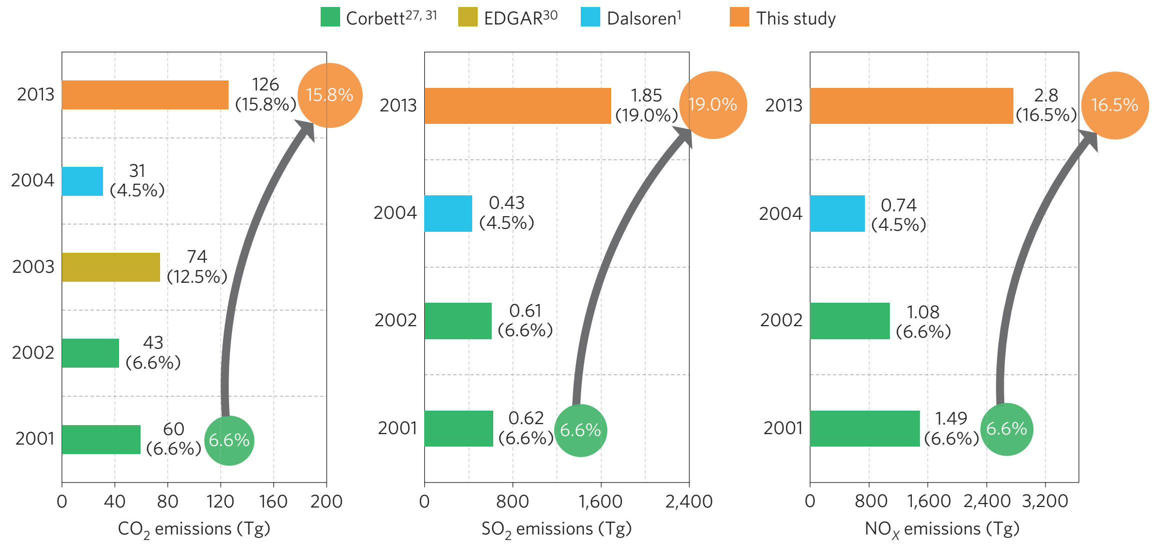

Figure 5 | Comparison of this study and other studies analysed for the same East Asia region. The vertical axis is the model year from 2001 to 2013. The percentages represent the ratios of East Asia to global shipping emissions. The percentage of this study is compared with the IMO inventory for 2012, while the others are global studies with both global totals and regional emissions.

is reduced, whereas the portion from boilers is increased, and boilers have much lower NO_x emissions than main engines. Detailed comparison between previous studies and this work are provided in the Supplementary Information.

The shipping emissions were compared with all sector emissions in East Asia using the Regional emission inventory in ASia (REAS) 2.1 inventory[32]. The sectors in REAS 2.1 include: fuel combustions in power plants, industry, transport, and residential sectors; industrial process; agricultural activities (fertilizer application and livestock); and others. Emissions in 2008, the latest update in REAS 2.1, are 35.0 Tg(SO_2), 31.0 Tg(NO_X), 22.2 Tg(PM), 30.1 Tg(NMVOC), 213.6Tg(CO), 1.7 Tg(BC), 3.1 Tg(OC), and 10,887 Tg(CO_2). Since neither REAS nor our estimates are based exclusively on energy consumption, it is not reasonable to project emissions in another year using activity growth rates. We therefore compare our estimate with the 2008 inventory, acknowledging that this comparison is imperfect. OGV emissions are about 5.3% of the SO_2 emissions, 9.0% of the NO_X, 1.1% of the PM, 1.2% of the CO_2, 0.3% of the NMVOC, and 0.1% of the CO from all sources in the same region.

Shipping as a significant pollution source

Our study shows that shipping emissions in East Asia have increased from 4 to 7% of global shipping emissions in the early 2000s to 16% in 2013. This emissions growth parallels, although is slightly slower than, growth in seaborne trade in this region. Compared with other sources, emissions from shipping are ~9.0% of the total NO_x and ~1.2% of the total CO_2 from all sectors in the same domain. Analysis of the emission share by flag shows that ships registered outside East Asia contribute about two-thirds of all shipping emissions in East Asia.

The climate impacts from ship emissions vary with time and location. Global mean forcing from East Asian shipping is initially negative, but would become positive after approximately eight years for constant current emissions. However, net radiative forcing would remain negative locally over East Asian waters for more than a century if emissions were to remain constant. Actual future forcing will depend on the relative emissions of short-lived cooling agents and CO_2, which may be affected by policies targeting air pollution, climate change, or both.

We also find the ship emissions have a substantial impact on human health. The ship emissions have the largest impacts in mainland China, Japan, Taiwan + Hong Kong + Macau, South Korea and Vietnam, with secondary impacts of more than 100 deaths in North Korea, Myanmar, Thailand, India, Bangladesh and Pakistan. The worldwide total of 14,500–37,500 premature deaths is primarily due to $PM_{2.5}$, but ozone pollution also plays a substantial role.

Thus, our findings contribute to the understanding of the comprehensive impacts of multiple pollutants from shipping, supporting the view that ocean-going vessels in East Asia have become a significant source of both climate change and local air pollution. Controlling ship emissions is a necessary component of addressing both long-term greenhouse gas emissions and also SLCPs, as well as air pollution for coastal areas.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

H.L. designed the study and wrote the paper. D.S. designed and wrote the climate and health impact sections. M.F., X.J. and Y.S. conducted the emissions modelling work. G.F. conducted the composition–climate modelling. G.F. and C.S. performed the health impact analyses. K.H. provided insights on ship emission inventory and discussion. All authors contributed to interpretation of the data and provided comments on the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to H.L., D.S. or K.H.

Competing financial interests

The authors declare no competing financial interests.

Methods

The emissions methodology used here considers a great number of fleet segments, introduces AIS data, which enable the positioning of ship emissions with a high spatial resolution, and includes modelling of shipping emissions. The AIS data in this study has sufficient coverage and frequency to accurately characterize voyages (Supplementary Information). A ship technical specification database (STSD) was built by merging an international ship database with local ship information, and was then improved by use of a Gradient Boosting Regression Tree (see Supplementary Information).

We match AIS data with the STSD to calculate emissions from each ship. The emission calculation in this study was made for each individual vessel, belonging to ten different ship types (Supplementary Table 1), with a breakdown into three different engine types (Main engine, Auxiliary engine, and Boiler) and four operation modes ('At berth', 'At anchorage', 'manoeuvring', and 'At sea'; see Supplementary Table 8).

The equations below provide the emission calculation used in our bottom-up method:

$$E=\sum_{n=1}^{18324} E_n \quad (1)$$

$$E_n=E_{\text{propulsion}}+E_{\text{auxiliary}}+E_{\text{boiler}} \quad (2)$$

where E represents total emission for a certain pollutant from all vessels in this region. E_n represents total emission for a certain pollutant of a single vessel n; $E_{\text{propulsion}}$, $E_{\text{auxiliary}}$, and E_{boiler} are, respectively, the emissions from propulsion engines, auxiliary engines and boilers.

Transient emissions are calculated by multiplying emission factors (per unit power) by engine load ratios, with adjustment factors for fuel type and sulfur content. Total emissions are aggregated using transient emissions multiplied by time durations. The average sulfur content of heavy fuel oil (HFO) was set as 2.43% and for distillate fuel oil as 0.13%, according to the IMO survey for 2013[33].

$$E_{\text{propulsion}}=\text{MCR}\times \text{EF}_{\text{propulsion\_base}}\times\sum_{T}\text{LF}_t\times A_{\text{LF},t}\times\Delta T_t \quad (3)$$

where MCR is the maximum continuous rated power of the propulsion engines. This value is unique for each vessel. $\text{EF}_{\text{propulsion\_base}}$ are the base emission factors of the propulsion engine using a certain sulfur content fuel, as described in Supplementary Table 9. LF_t, $A_{\text{LF},t}$ and ΔT_t are respectively the instantaneous load factor for the propulsion engine, emission adjustment factors when LF is lower than 20%, and the operation duration time at time t. A is a constant for each LF, as described in Supplementary Table 10. ΔT_t is the time interval between each pair of the two adjacent speed points, both the original AIS points and the interpolation points. The instantaneous speed is used to calculate the instantaneous engine load for each ship using the propeller law.

$$\text{LF}_t=(v_t/\text{MDS})^3 \quad (4)$$

where v_t is the instantaneous speed at time t and MDS is the maximum designed speed of vessel type j. Instantaneous speed can be obtained from the online AIS platform directly, or using interpolation for large time interval data. MDS of each ship is shown in Supplementary Fig. 7.

$$E_{\text{auxiliary}}=\text{EF}_{\text{auxiliary}}\times\sum_{T}(P_{\text{auxiliary},i,j}\times\Delta T_t) \quad (5)$$

where $\text{EF}_{\text{auxiliary}}$ are the emission factors of the auxiliary engine using a certain sulfur content fuel, as described in Supplementary Table 11. $P_{\text{auxiliary},i,j}$ is the power of the auxiliary engine, which is a constant for a vessel type j in one mode i, in Supplementary Table 6. The mode i is judged by using instantaneous speed and load at time t using Supplementary Table 8.

$$E_{\text{boiler}}=\text{EF}_{\text{boiler}}\times\sum_{T}(P_{\text{boiler},i,j}\times\Delta T_t) \quad (6)$$

where $\text{EF}_{\text{boiler}}$ are the emission factors of the boiler using a certain sulfur content fuel, as described in Supplementary Table 12. $P_{\text{boiler},i,j}$ is the power of boiler, which is a constant for a vessel type j in one mode i, in Supplementary Table 7. The mode i is judged by using instantaneous speed and load at time t using Supplementary Table 8.

The advantage of the time sequence is that if there are duplicate messages then the total duration time remains the same, and so the total emissions are not influenced. To deal with the AIS interruption near the boundary, which usually causes extremely long time durations, two nested domains were used. At least a 360 km boundary distance from domain 1 to 2 was kept to ensure there are multiple AIS messages within this distance. The chosen region reflects our focus on densely populated areas, and does not represent any national boundaries.

We use the shipping emission inventory as input for simulations with the NASA Goddard Institute for Space Studies (GISS)-E2 global chemistry–climate model. Results are based on the difference in surface pollutants and radiative forcing between simulations using the 2013 emissions presented here and those using zero shipping emissions in this region, with all other parameters set to 2010 values. Radiative forcing includes direct effects of sulfate, carbonaceous (black and organic carbon), nitrate, dust and sea-salt aerosols, aerosol-induced cloud-albedo effects and ozone. Impacts of CO_2 changes are calculated using an offline set of analytic equations representing the multiple timescales involved in the carbon cycle, as in the 2007 IPCC Assessment. Methane forcing is also computed offline based on the chemical lifetimes calculated in the composition-climate model simulations.

Health impacts of surface pollution changes are calculated using established methodologies. Premature deaths are calculated as $M=M_b\times P\times \text{AF}$, where M is the number of premature deaths due to $PM_{2.5}$ or ozone, M_b is the cause-specific baseline mortality rate, P is population, and AF is the attributable fraction of deaths due to $PM_{2.5}$ or ozone. We perform a large suite of calculations incorporating the range of reported relationships between $PM_{2.5}$ exposure and AF using 1,000 variants for each cause-specific relative risk[25] (see Supplementary Information). Health impacts of ozone are based on assessments of the association between both long-term and short-term exposures and relative risk of respiratory and cardiovascular disease.

References

33. *Report of the Marine Environment Protection Committee on its Sixty-seventh Session* (IMO, 2014).