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Physical Sciences - Article

Keywords: High seas, International shipping, GHG emission, Policy evaluation, Emission drivers

Posted Date: January 28th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1300753/v1>

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The Climate Impact of High Seas Shipping

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Abstract

Strict carbon emission regulations are set with respect to countries' territorial seas or exclusive economic zone shipping activities to meet their climate change commitment under the Paris Agreement. However, no shipping carbon mitigation policies are proposed for the world high sea regions, which results in carbon intensive shipping activities on high seas. In this paper, we propose a Geographic-based Emission Estimation Model (GEEM) to estimate shipping GHG emission patterns on high sea regions. The results indicate that annual shipping CO₂-e emissions on high seas reach 211.60 million metric tonnes in 2019, accounting for about one-third of all shipping emissions globally and exceeding annual GHG emissions of countries such as Spain. The average emission from shipping activities on high seas is growing at approximately 7.26% per year, which far surpasses the global shipping emission growth rate of 2.23%. We propose the implementation policies on each high seas region with respect to the main emission driver of each high seas identified from our results. Our policy evaluation results show that carbon mitigation policies could reduce 25.46 and 54.36 million tonnes CO₂-e in the primary intervention stage and overall intervention stage respectively, with 12.09% and 25.81% reduction rates in comparison to the 2019 annual high seas shipping GHG emission.

Keywords: High seas; International shipping; GHG emission; Policy evaluation; Emission drivers

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35 Over the past decades, accelerated international and regional maritime trading activities have boosted
36 worldwide ocean-going shipping industry development. The associated shipping greenhouse gas
37 emission, however, has gradually become a non-neglectable issue against worldwide decarbonation
38 and climate change goals¹. As estimated by the International Maritime Organization (IMO) voyage-
39 based method², international shipping accounts for 755 million metric tonnes annual GHG emissions
40 in 2018. In order to improve emission reduction in maritime industry and to meet climate change
41 commitment under the Paris Agreement, many countries have submitted concrete plans and
42 implemented strict carbon emission regulations for shipping activities in their territory waters or
43 exclusive economic zones, such as emission controlled areas, alternative fuel substitution, electric or
44 nuclear propulsion adoption and renewable energy propulsion assistance etc.^{3,4,5} Previous maritime
45 related studies focus on the territory waters and exclusive economic zones carbon mitigation policy
46 effectiveness evaluation and improvement^{6,7}. While the Paris Agreement clearly outlines the emission
47 reduction plans for each country's territorial sea, little attention has been paid to the fast-growing
48 emission on the international high seas. Due to the non-sovereign property of high seas, no signatories
49 are directly responsible for high seas carbon emission reduction under the Paris Agreement and thus,
50 there have been no carbon mitigation policies or environmental regulations proposed or implemented
51 in these regions. As a result, ships travelling on the high seas often operate in economically efficient
52 manners, such as utilizing heavy fuel oil and travelling at high speeds, without any environmental
53 concerns^{8,9}. Since the high seas account for more than two-thirds of the world ocean regions, the
54 carbon intensive shipping activities on the high seas could become a potential barrier against the
55 worldwide carbon mitigation and sustainability efforts.

56
57 In comparison to the top-down approaches utilized by previous maritime GHG inventory estimation
58 studies, bottom-up approaches enable more accurate estimation results by summing up detailed
59 individual ship emission outputs^{10,11}. There are currently two bottom-up approaches used in the
60 existing literature to calculate shipping GHG emission for certain regions or countries, namely vessel-
61 based and voyage-based. However, these methods heavily rely on their assumptions: the vessel-based
62 method assumes that vessels with similar type and age have uniform shipping behaviors; the voyage-

63 based method assumes that international shipping emissions are those occurring on a voyage between
64 two ports in different countries^{2,12}. In this paper, we propose a new Geographic-based Emission
65 Estimation Model (GEEM) to estimate international shipping GHG emission patterns on high seas
66 regions. By incorporating the IHS Market Maritime & Trade vessel technical specification data and
67 Automatic Identification System (AIS) data as our GEEM static and dynamic datasets respectively,
68 our GEEM method can be viewed as a bottom-up approach that identifies GHG inventories through
69 the broadly covered individual ship navigation information. In comparison to the existing two bottom-
70 up GHG emission approaches, our GEEM method utilizes real-time geographic coordinates data,
71 which enables more accurate and robust high seas emission estimation by relaxing the
72 aforementioned assumptions. In particular, we exclude international vessels that navigate between
73 two countries' exclusive economic zones from high seas GHG emissions, and we include domestic
74 vessels whose route cover high seas regions in high seas GHG emissions. In essence, our GEEM
75 approach collects shipping navigation and emission data for those only occurring on high seas
76 geographically, and accordingly estimate our high seas shipping GHG emission results.

77
78 Our GEEM results indicate that the annual shipping CO₂-e emissions on high seas reach 211.60
79 million metric tons per year (Mmt/yr) in 2019, accounting for about one-third of all shipping
80 emissions globally. The high seas shipping emission in 2019 exceeds annual greenhouse gas
81 emissions of countries such as Spain, Argentina and United Arab Emirates. More alarmingly, the
82 average emission from shipping activities on the high seas is growing at approximately 7.26% per
83 year, which far surpasses the global shipping emission growth rate of 2.23% per year. By classifying
84 the worldwide high seas into 8 geographic regions and incorporating detailed vessel dynamic data of
85 all ships from all routes, we find that there exists a great degree of heterogeneity in key factors that
86 drive the shipping emission patterns across different high seas regions. As suggested by commonly-
87 adopted maritime carbon mitigation regulations, we propose the primary implementation policies on
88 each high seas region with respect to the main emission driver of each high seas identified from our
89 results. Our evaluation results show that carbon mitigation policies could reduce 25.46 and 54.36
90 million tonnes CO₂-e in the primary intervention stage and overall intervention stage respectively,

with 12.09% and 25.81% reduction rates in comparison to the 2019 annual high seas shipping GHG emission. Indeed, to regulate high seas shipping activities via the global maritime industry effort, international high seas shipping can contribute to the world trading and economic growth in a more environmentally-friendly manner.

Fig. 1| High seas classification and shipping allocation, according to the United Nations Convention on the Law of the Sea and the International Hydrographic Organization division standard (www.marinerregions.org), we divide the worldwide high seas into 8 geographic regions and calculate their shipping miles respectively, namely North Pacific Ocean High Seas (a), South Pacific Ocean High Seas (b), North Atlantic Ocean High Seas (c), South Atlantic Ocean High Seas (d), Arctic Ocean High Seas (e), Southern Ocean High Seas (f), Indian Ocean High Seas (g), and Other High Seas (h). The yellow bars in each subfigure indicate the annual shipping miles (million miles) of each high seas from 2015 to 2019.

Shipping Activities and Emissions on High Seas. In this study, we follow the high seas division standard provided by the International Hydrographic Organization and classify the worldwide high seas into 8 geographic regions, namely the North Pacific Ocean High Seas, South Pacific Ocean High Seas, North Atlantic Ocean High Seas, South Atlantic Ocean High Seas, Arctic Ocean High Seas, Southern Ocean High Seas, Indian Ocean High Seas, and Other High Seas. Using an AIS-based method, we first calculate the annual shipping activities of each region from 2015 to 2019 by adding up the distance travelled (in nautical miles) from all routes for all ships within the respective areas. Figure 1 illustrates the longitudinal and latitudinal boundaries and the respective shipping activities of each high seas region. Of the total shipping activities in 2019, about 23.43% were from the North Atlantic Ocean High Seas, which reflects the high traffic between European, North American, and South American countries. As shown in Figure 2, the shipping activities between the United States and the United Kingdom, Brazil and Spain, as well as United States and Brazil are amongst the busiest routes in the region. The Indian Ocean High Seas accounted for approximately 20.98% of the total shipping activities, which can be mainly attributed to the shipping activities along Asian countries. In particular, the shipping route between China and Australia is responsible for nearly 30% of the traffic in the region. The North Pacific Ocean High Seas is another region with significant shipping activities, contributing about 20.55% as most of the shipping routes between Asia and North America passes through this area. In particular, the shipping route from China to the United States, Korea to the United States, and Japan to the United States exhibits the most amount of traffic in the region. Overall, the resulting total shipping mileage in the high seas has exceeded a total of 1.56 billion nautical miles (nm) in 2019 with an average annual growth rate of 6.81% in the past 5 years. The review of maritime transport by UNCTAD indicate that international maritime trade expanded at 4.7%-6.7% annually from 2015 to 2019, with total volumes amounting to 11 billion tons in 2018¹³. The accelerated international maritime trade volumes boost shipping activities on the high seas, especially for those rapidly developed shipping routes such as South–South trade, Belt and Road Initiative by China, Panama Canal and Suez Canal related seaborne trade^{13,14,15}.

Fig. 2| High seas shipping mileage distribution, based on our GEEM calculation results, **a-f** report the average top 10 shipping mileage routes for North Pacific Ocean High Sea (**a**), South Pacific Ocean High Sea (**b**), North Atlantic Ocean High Sea (**c**), South Atlantic Ocean High Sea (**d**), Indian Ocean High Sea (**e**), and Other High Seas (**f**). The specific percentage in **a-f** indicate shipping mileage proportion of each high seas region during our GEEM sample period.

We collect and process 79613 vessels' high seas shipping records in total, which represent a majority of the international shipping fleet. We also utilize the 3-minute frequency AIS data spanning from January 2015 to December 2019, which accounts for a total of 5.03 TB raw AIS dataset. Using the detailed AIS messages transmitted by all ships from all routes, we calculate CO₂, SO₂, NO₂, particulate matter 2.5 (PM_{2.5}), particulate matter 10 (PM₁₀), CO, non-methane volatile organic compounds (NMVOCs), CH₄ and N₂O emissions generated by all vessels for each of the eight world high seas regions from 2015 to 2019. We calculate the carbon dioxide equivalent (CO₂-e) by switching other pollutants to CO₂ to standardize the climate impact of high seas GHG emission. The results indicate that the rapid development of shipping activities has resulted in a significant increase in emissions in the identified high seas regions. During this time, the total CO₂-e emissions rose from 163.98 Mmt/yr to 211.60 Mmt/yr, accounting for about one-third of all shipping emissions globally.

150 At the international level, the total high seas shipping-related CO₂-e emission in 2019 exceeds the
151 total annual greenhouse gas emissions of countries such as Spain, Argentina and United Arab
152 Emirates (countries' emission data are available at www.globalcarbonatlas.org). More alarmingly, the
153 average emission from shipping activities on the high seas is growing at approximately 7.26% per
154 year, which far surpasses the average total global emission growth rate of 0.09% per year and the
155 global shipping emission growth rate of 2.23% per year¹. That is to say, international shipping GHG
156 emission on high seas could become an increasing barrier against the worldwide carbon mitigation
157 and sustainability efforts.

158

159 Figure 3 illustrates the changes in CO₂-e emission output and carbon emission intensity across all
160 high seas regions from 2015 to 2019. In terms of total emissions, the results reflect, to some degree,
161 the intensity in shipping activities over the different high seas regions. Although the North Pacific
162 Ocean High Seas ranks third in total mileage travelled, it is responsible for more than 25% of the total
163 emissions generated. In fact, the North Pacific Ocean High Seas has the highest carbon emission
164 intensity at 0.1481 tonne/nm, which suggests that the shipping activities on the North Pacific Ocean
165 High Seas are more carbon intensive. The North Atlantic Ocean High Seas share is approximately
166 22%, while the Indian Ocean High Seas contributes about 18%. In terms of the average emission
167 growth rate, the top three fastest growing emitting regions are the Other High Seas (14.56%), the
168 North Atlantic Ocean High Seas (9.90%), and the South Pacific High Seas (9.11%). In particular, the
169 North Atlantic Ocean High Seas ranks in the top three regions for both total emissions generated and
170 emission growth rate, which indicates that the emission problem in one of the most heavily polluted
171 regions has become increasingly severe. Although the South Atlantic High Seas only contributes 13%
172 to the total emissions, the emission intensity there is among the highest, reaching 0.1450 tonne/nm
173 for CO₂ emissions. Indeed, Figure 3 shows the different GHG emission patterns of each high seas
174 shipping activities in terms of total emission, emission growth rate and intensity. We provide more
175 in-depth investigation on emission drivers of high seas shipping in the next Section.

176

Fig. 3| High seas shipping emission outputs and operational efficiencies, a-h provide the monthly carbon dioxide equivalent emissions and energy efficiency operational indicator for North Pacific Ocean High Seas (a), South Pacific Ocean High Seas (b), North Atlantic Ocean High Seas (c), South Atlantic Ocean High Seas (d), Arctic Ocean High Seas (e), Southern Ocean High Seas (f), Indian Ocean High Seas (g), and Other High Seas (h). The carbon intensity indicator (CII) is defined by IMO as carbon dioxide emissions per actual cargo mile. The annual emission and efficiency growth rate are shown on the x-axis, with blue and red arrows respectively.

Emission drivers on High Seas. By incorporating detailed vessel and dynamic data of all ships from all routes, we find that there exists a great degree of heterogeneity in key factors that drive the shipping emission patterns across different high seas regions. As shown in Figure 4, the degree of heterogeneity is mainly driven by the differences in key characteristics of ships active on each high seas regions, namely, the ship type, capacity, age and engine usage. Since the emissions in the Arctic

191 and Southern Ocean High Seas are nearly negligible (account for 0.02% and 0.08% of total high seas
192 GHG emission in 2019 respectively), we disregard them in the emission driver analysis. As a result,
193 the results are shown for the six emission significant high seas regions.

194

195 In terms of ship type, although there are nineteen official types of vessels defined by the IMO, the
196 top six most dominant ship types were responsible for nearly 80% of the total emissions while the
197 other thirteen types combined together for the rest. Thus, for the ease of analysis, we classify each
198 vessel into one of seven major types based on its usage, namely bulk carrier, chemical tanker,
199 container, general cargo, liquefied gas tanker (LG Tanker), oil tanker, and others. According to the
200 Energy Efficiency Operational Indicator (EEOI) defined in the IMO study, general cargo, liquefied
201 gas tanker and container are the top three most carbon-intense ship types^{2,16}. Figure 3(a) illustrates
202 the distribution of CO₂ equivalent emissions across different ship types in each high seas region. We
203 find that the emission patterns of the North Pacific Ocean High Seas and North Atlantic Ocean High
204 Seas are alarmingly different from those of the other high seas regions. In particular, the top 3 carbon
205 intense ship types were responsible for 62% and 54% of the emission in the aforementioned two
206 regions, respectively, while they were only responsible for 19-25% in the rest of the regions. The high
207 proportion of emission from the carbon intense ships can be mainly attributed to the rapid growth in
208 emissions of containers and liquefied gas tankers in these regions. Specifically, in the North Pacific
209 Ocean High Seas, the emission contribution from liquefied gas tankers spiked from 2% to 13%
210 between 2015 and 2019, resulting in a 175% growth in its amount of emissions in the region.
211 Moreover, the annual emission growth rate for containers in the North Atlantic Ocean High Seas is
212 25%, which is much higher than the 5% average in the other regions. In contrast, we find that in
213 regions such as the South Atlantic Ocean High Seas and Indian Ocean High Seas, low carbon intense
214 ships such as bulk carriers and oil tankers are the dominant source of emissions.

215

216 In terms of ship capacity, we classify all the vessels into five dead-weight tonnage (dwt) groups as
217 defined by the IMO, namely, 0-25000 dwt, 25000-50000 dwt, 50000-75000 dwt, 75000-100000 dwt,
218 and 100000+ dwt. It is important to note that according to the EEOI defined in the IMO study and

219 previous studies, smaller ships (under 50000 dwt) typically exhibit a higher carbon intensity than
220 larger ships^{2,17}. Figure 3(b) illustrates the distribution of CO₂ equivalent emissions across different
221 ship capacities. Out of all the high seas regions, the emission pattern in the South Atlantic High Seas
222 stands out from the rest. In particular, the smaller, carbon intense ships under 50000 dwt are
223 responsible for over 21% of the total emissions in the South Atlantic High Seas. In fact, the relatively
224 small-sized shipping pattern is consistent with the short shipping routes and varied goods demand for
225 berthing ports in the South Atlantic High Seas. In contrast, the proportion of emissions attributed to
226 ships of the same weight classes is only 10% in regions such as the North Pacific Atlantic High Seas.
227

228 In terms of ship age, we classify all the vessels into five age classes – 0-5 years, 5-10 years, 10-15
229 years, 15-20 years, and 20+ years. It is a fact that most new-build ships install engines with a better
230 EEDI and specific fuel consumption than ships with older construction year². As illustrated in Figure
231 3(c), there are two distinct emission patterns distributions across all the high seas regions. On the one
232 hand, the North Pacific, South Atlantic, Indian and the Other High Seas have relatively newer ships
233 as the dominant emission source. In particular, ships with service age less than 10 years contribute
234 42% of emissions for the North Pacific Ocean High Seas, 48% South Atlantic High Seas, 43% for the
235 Indian High Seas, and 42% for the Other High Seas. Moreover, the oldest ships (20+ years) only
236 account for an average of 10.71% of emissions in these regions over the five-year period. On the
237 other hand, emission sources in the South Pacific Ocean High Seas primarily consist of older ships
238 with service age greater than 15 years. In particular, the ships with service age over 20 years contribute
239 26% of emissions for the South Pacific, which is much higher than the average contribution rate in
240 the other four high seas regions. In fact, in comparison to the top 3 carbon emission high seas regions,
241 shipping emission regulations on territory water and EEZ for countries along the shipping routes in
242 the South Pacific Ocean are relatively loose due to less significant emission output. From a policy
243 regulation perspective, shipping companies would allocate their older ships on the South Pacific
244 Ocean and new-built ships on other Oceans, which results in the ships with service age over 15 years
245 the major emission sources in the South Pacific High Seas.

Fig. 4| High seas shipping carbon emission drivers, the carbon dioxide equivalent emission compositions and structural changes of each high seas region are identified and classified by ship type (column **a**), ship capacity (column **b**), ship age (column **c**) and ship engine (column **d**). The dark blue bars indicate the annual individual high seas shipping emissions of carbon dioxide equivalent (million tonnes). The bars in bright colors (labeled in the legend) represent the annual emission contribution of the associated unit categories, which are noted with their respective emission outputs.

253

254 In terms of ship engine usage, the majority of CO₂ equivalent emissions are associated with main
255 engines¹⁸. However, the Other High Seas stand out from the rest of the regions as the growth rate in
256 main engine emission contribution reaches 10.2% annually, which is more than twice the average
257 growth rate in emission contribution in other regions. Moreover, the auxiliary engine emission
258 contribution in the Other High Seas is growing at 12.89% annually, far exceeding the 4.94% annual
259 growth rate in other regions. This reflects the fact that the cruise distances in the Other High Seas
260 region are much shorter than the rest of the high seas regions. Thus, the growth in emission share
261 attributable to auxiliary engines is much higher.

262

263 **Shipping carbon mitigation policies evaluation.** The Fourth IMO GHG Emission Study and
264 previous works evaluate territory water or EEZ shipping GHG emission mitigation policies'
265 effectiveness with respect to the mid-term (2030) and long-term (2050) reduction targets^{2,19,20}.
266 Following the current mid- and long-term policy settings on territory water or EEZ, we examine the
267 high seas GHG reduction effectiveness in both primary policy implementation stage and overall
268 implementation stage. We propose the primary carbon mitigation policies to be implemented on each
269 high seas region based on its main emission driver identified in our results (in Table 1). Specifically,
270 in the ship type (ST) policy, we target the top 3 carbon-intense ship types (general cargos, liquefied
271 gas tankers, and containers) by substituting the heavy fuel oil (2.43% Sulfur content) used in these
272 ships with alternative fuel such as marine diesel oil and marine gas oil (0.13% Sulfur content)²¹. Since
273 the carbon emission contribution and emission growth rate of the carbon-intense ships in the North
274 Pacific Ocean High Seas and North Atlantic Ocean High Seas far exceed those in other high seas
275 regions, we directly implement the ST policy in these two regions; for the ship capacity (SC) policy,
276 we intend to improve the average international shipping capacity by shifting the shipping activities
277 conducted through ships with relatively small capacities (<50000 dwt) to ships with larger
278 capacities²². Since the proportion of emissions attributed to small-capacity ships in the Indian Ocean
279 High Seas and South Atlantic High Seas are more than twice as much as that of other high seas regions,
280 we directly implement the SC policy in these two regions; for the ship age (SA) policy, we raise the
281 in-service ship standard by implementing compulsory scrapping of active ships with service age

greater than 20 years and substitute them with newly-built ships for high seas shipping activities²³. Since the emission contribution rate of ships with service age over 20 years in the South Pacific far exceeds that in other high seas regions, we directly implement the SA policy in this region; for the ship engine (SE) policy, we set speed reduction at 10% for all ship types on high seas shipping for main engine carbon emission mitigation²⁴. Since the emission growth rate of main engines used in the Other High Seas is significantly higher than that in other regions, we directly implement the SE policy in this region.

Table 1| High seas shipping carbon mitigation policies and implementation strategies

Ship categories	Intended carbon mitigation policies	Measures	Primary high seas area
Ship type	High emission ship type supervision	Alternative fuel adoption for general cargo, liquefied gas tankers and container	North Pacific Ocean High Seas; North Atlantic Ocean High Seas
Ship capacity	Shipping capacity intervention	Improve the average international shipping capacity	Indian Ocean High Seas; South Atlantic Ocean High Seas
Ship age	New-build ships substitution	Raise the in-service ship standard; Compulsory scrapping policy for old ship	South Pacific Ocean High Seas
Ship engine	Main engine improvements	High sea shipping speed reduction	Other High Seas

Note: Extensive shipping carbon mitigation policies are proposed by International Maritime Organization and previous works. We collect the specific policies that target to foster maritime industry decarbonization through ship type, capacity, age and engine categories. We define the primary implementation policy with respect to the main shipping carbon emission driver of each high seas derived from our results. As a result. we evaluate the high seas carbon mitigation policy effectiveness in both primary implementation stage and overall implementation stage.

Fig. 5| High seas shipping carbon mitigation policy effectiveness evaluation, a-f provide the estimated carbon mitigation effectiveness of North Pacific Ocean High Seas (a), South Pacific Ocean High Seas (b), North Atlantic Ocean High Seas (c), South Atlantic Ocean High Seas (d), Indian Ocean High Seas (e) and Other High Seas (f). The primary and overall stage indicate the primary and overall policy implementation indicated in Table 1. The carbon reduction amount (million tonnes) and percentage of each high seas region are presented above each bar respectively.

The policy effectiveness assessment is conducted through two stages. In the primary stage, each of the carbon mitigation policy is implemented separately in the target high seas regions. After 2030, we enter the overall stage, where the carbon mitigation policies are implemented together across all the high seas regions. As illustrated in Figure 5, our evaluation results indicate that implementing tailored carbon mitigation policies in different high seas regions could reduce 25.46 and 54.36 million tonnes of CO₂ equivalent emission in the primary intervention stage and the overall intervention stage, respectively, with 12.09% and 25.81% reduction rates in comparison to the 2019 annual high seas

307 shipping GHG emission. In particular, it is worth noting that the regions with the greatest emission
308 reduction rate in the primary stage are the regions with the greatest high seas shipping emission
309 contribution rate overall, namely the Indian Ocean High Seas (13.82%), North Pacific Ocean High
310 Seas (12.79%), and North Atlantic Ocean High Seas (11.43%). Moreover, the tailored carbon
311 mitigation policy implemented through the primary stage shows the greatest emission reduction
312 percentage in each of the high seas regions (at average 46.84% of the total emission reduction), which
313 indicates that it is the most effective policy in reducing emissions in the particular region compared
314 to other policies. Thus, by identifying the key factors driving the emission patterns in different high
315 seas regions and accordingly designing tailored carbon mitigation policies for each region, it allows
316 international high seas shipping to contribute to the world trading and economic growth in a more
317 environmentally-friendly manner.

318

319 **Discussion**

320 Climate change is a global issue that requires international cooperation and solutions. To alleviate the
321 negative impact of climate change, the Paris Agreement was signed by world leaders in 2015 to foster
322 global greenhouse gas emission reduction across national borders²⁵. Signatories are committed to
323 reduce GHG emission from all industries and human activities, and all the countries' climate efforts
324 are monitored and reviewed by United Nations every 5 years²⁶. In terms of maritime industry, strict
325 carbon emission regulations are set with respect to countries' territory water or exclusive economic
326 zone shipping activities, such as emission controlled areas, alternative fuel substitution, electric or
327 nuclear propulsion adoption and renewable energy propulsion assistance etc^{27,28}. For example,
328 emission controlled areas are proposed to limit SO₂, NO₂ and particulate matter emissions in world
329 major countries' territory sea shipping²⁹; Ships are required to use low Sulfur content fuel such as
330 marine diesel oil and marine gas oil to reduce carbon emissions when the shipping activities occur at
331 berth or at exclusive economic zone of US and East Asia area^{30,31}. As a result, the Fourth IMO GHG
332 Emission Study suggests that the annual international shipping GHG emission growth gradually slow
333 down at a 2.23% average annual rate from 2015 to 2018 due to the associated maritime and
334 international shipping carbon mitigation policy interventions.

335

336 However, current shipping carbon mitigation policies are effective and implemented only in territory
337 seas and exclusive economic zone as part of certain country's carbon reduction policies. Due to the
338 non-sovereign property of high seas regions, no shipping carbon mitigation policies or environmental
339 regulations are proposed or implemented for the world high seas regions, regarding that no signatories
340 are responsible for high seas carbon reduction under the Paris Agreement^{32,33}. For a lower operational
341 cost of international shipping, ships usually navigate in an economically efficient manner on high
342 seas by utilizing heavy fuel oil and travelling with high speed without environmental concern. As a
343 result, our GEEM estimation results indicate that the carbon intensive shipping activities have
344 resulted in a significant increase in emissions on high seas regions. The total CO₂-e emissions reach
345 211.60 Mmt/yr in 2019, which exceeds the total annual greenhouse gas emissions of countries such
346 as Spain, Argentina, and United Arab Emirates. In addition, the average emission from shipping
347 activities on the high seas is growing at approximately 7.26% per year, which far surpasses the global
348 shipping emission growth rate of 2.23% per year. In essence, without policy intervention,
349 international shipping GHG emission on high seas could become a tragedy of the commons in the
350 global maritime industry: individual ships behave on their own interests to maximize their high seas
351 shipping profits, ignoring the negative externality and climate change impact of their carbon intensive
352 shipping patterns on high seas.

353

354 Utilizing our GEEM bottom-up vessel dynamic statistics of all ships from all routes, we find
355 heterogeneity in key factors that drive the shipping emission pattern across different high seas regions
356 in terms of ship type, capacity, age and engine categories. In order to evaluate the effectiveness of
357 different carbon mitigation policies on high seas shipping, we collect the specific policies that target
358 to foster maritime industry decarbonization in territory seas and exclusive economic zones and
359 propose the primary implementation policy with respect to the main emission driver of each high seas
360 region identified from our results. Specifically speaking, we set and evaluate ship type policies on the
361 Other High Seas, ship capacity policy on the Indian High Seas and South Atlantic High Seas, ship
362 age policy on the South Pacific High Seas, ship engine policy on the North Pacific High Seas and
363 North Atlantic High Seas. The evaluation results indicate that carbon mitigation policies could reduce

364 25.46 and 54.36 million tonnes CO₂-e in the primary intervention stage and overall intervention stage
365 respectively, with 12.09% and 25.81% reduction rates in comparison to the 2019 annual high seas
366 shipping GHG emission.

367

368 Although our evaluation results indicate that the carbon mitigation policies can effectively reduce
369 shipping GHG emissions on the high seas, implementing these policies may be difficult as no
370 signatories are directly responsible for these regions. To facilitate international cooperation and the
371 development of targeted regional high seas emission control agreement between countries, we also
372 identify the major emission-contributing shipping routes and the key signatories involved in each
373 high seas region as shown in Figure 2. Specifically, the trading activities between China, the United
374 States, Korea, Japan, and Canada generate contribute to nearly 50% of the emissions generated in the
375 North Pacific Ocean High Seas. In the South Ocean Pacific High Seas, the shipping routes between
376 Japan, Australia, and New Zealand are the most carbon emission intensive, generating 36% of the
377 emissions in the region. In the North Atlantic Ocean High Seas, the trading routes with the heaviest
378 traffic and carbon emissions involve countries such as the United States, the United Kingdom, Brazil,
379 Spain, Canada, the Netherlands, and Germany. In the South Atlantic Ocean High Seas, the top 3 most
380 carbon-intensive trading route is from Singapore to Brazil, Brazil to China, and India to Brazil,
381 contributing 13%, 6%, and 5%, respectively. In the Indian Ocean High Seas, the shipping routes
382 between China and Australia are especially carbon intensive, contributing to over 35% of the
383 emissions in the region. In the Other High Seas Region, some of the most carbon intensive trading
384 routes involve countries such as China, Saudi Arabia, Singapore, Australia, New Zealand, United
385 Arab Emirates, and South Africa. By identifying these emission-intensive trading routes, it can
386 promote the key countries involved to form regional high seas emission control agreement and impose
387 the carbon mitigation policies discussed above on the vessels operating along these trading routes.
388 After all, by regulating high seas shipping activity via the international cooperation and global
389 maritime industry effort, international high seas shipping can contribute to the world trading and
390 economic growth in a more environmentally-friendly manner in the future.

391

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Acknowledgement

This work was supported by grants from the National Natural Science Foundation of China (71988101, 72174035, 71774018 and 71831002), and LiaoNing Revitalization Talents Program (XLYC2008030).

Competing Interests

The authors declare no competing interests.

469 **Methods**

470

471 **GEEM static database.** In this study, a new Geographic-based Emission Estimation Model (GEEM)
472 static database is created using the vessel technical specification dataset provided by the IHS Market
473 Maritime & Trade and AIS static database. The IHS & AIS static database contains ships
474 characteristics for ships as of 2020. The ships range from 100 GT fishing ferries and service vessels
475 to the largest bulk carriers and cargo ships, covering both ships that engage in international as well as
476 domestic navigation. In this study, the combined IHS & AIS static database contains all the data
477 collected and updated to 2020. Thus, we checked each vessel's status against a timestamp of the most
478 recent change in status separately to ensure that only "in service" vessels are included in our GEEM
479 static database.

480

481 The GEEM static database provides detailed ship characteristics including the IMO number, vessel
482 type, build year, length, width, height, capacity, design speed, fuel type, installed engine power,
483 engine RPM, maximum draught, dead weight tonnage (dwt) etc. This wide range of metrics is
484 essential for estimating fuel consumption and emission from ships. However, the data is sometimes
485 incomplete so that one or more technical information was found to be missing for some ships in the
486 IHS dataset. In our data, 0.06% of the ships are missing capacity, 2.4% of the ships are missing build
487 year, 3.0% of the ships are missing fuel type, 20.7% of the ships are missing design speed, and 26.4%
488 of the ships are missing engine RPM. Simply excluding those particular ships with missing technical
489 information from our calculation or assigning default values to the missing property will lead to
490 significant computation inaccuracies. To correct the data and address the uncertainty, we designed a
491 robust method to infill these missing technical specifications. Following the guidelines recommended
492 by the Fourth IMO GHG Study³⁴, we create a multilinear regression for each ship type by taking into
493 account individual vessel's known design parameters such as beam, draught and capacity. Since both
494 beam and draught serve as the basis in the estimation of other metrics, the missing values for these
495 metrics are first filled based on median values per type and size category. After this essential
496 information is infilled, we apply individual regressions on each of the other metrics. Finally, for

individual ships that could not be infilled due to too many missing entries, we replace the missing information with the median values of their respective type and size class.

In this analysis, the technical specification data were collected and pre-processed for 79613 vessels, which represents a majority of the international shipping fleet. The fleet scale is reasonable compared with the previous literature^{35,36}. The original vessels collected are categorized into 19 vessel type categories according to the IMO ship types classified in the Fourth IMO GHG Study. In addition, the vessels collected are also classified into 4 age groups based on their build years. Supplementary Table 1 lists the classified vessel types, and the number of vessels counted in each category. Supplementary Table 2 lists the classified engine tier groups, vessel capacity group and the number of vessels counted in each group.

Supplementary Table 1| GEEM static dataset vessel types

Ship type	This study
Bulk Carrier	11981
Oil Tanker	7403
Container	5366
General Cargo	13196
Chemical Tanker	5145
Ro-Ro	1162
Cruise	475
Refrigerated Bulk	684
Liquefied Gas Tanker	2011
Other Liquids Tankers	34
Ferry - Pax Only	1272
Ferry - Ro-Pax	2120
Vehicle	842
Service - Tug	5172
Service - Other	4799
Miscellaneous Fishing	8942
Miscellaneous - Other	1727
Offshore	5068
Yacht	2214

Supplementary Table 2| Sample vessel classification and statistics

Vessel capacity category		
Vessel type	capacity	count
Bulk Carrier	0-9999	524
	10000-34999	1603
	35000-59999	2912
	60000-99999	3305
	100000-199999	1049
	200000-+	538
Chemical Tanker	0-4999	1274
	5000-9999	777
	10000-19999	1595
	20000-39999	1058
	40000-+	2066
	0-999	72
Container	1000-1999	75
	2000-2999	82
	3000-4999	197
	5000-7999	205
	8000-11999	209
	12000-14499	49
General cargo	14500-19999	213
	20000-+	1074
	0-4999	2777
	5000-9999	838
	10000-19999	4058
	20000-+	1359
Liquefied gas tanker	0-49999	4816
	50000-99999	2964
	100000-199999	132
	200000-+	0
	0-4999	1394
	5000-9999	70
Oil tanker	10000-19999	50
	20000-59999	364
	60000-79999	684
	80000-119999	2761
	120000-199999	1621
	200000-+	2337
Others	0-+	34511

Engine tier category	
Tier 0 (engine construction date before 2000)	29058
Tier 1 (engine construction date between 2000-2010)	21614
Tier 2 (engine construction date between 2011-2015)	15695
Tier 3(engine construction date after 2016)	13246

Dynamic Ship Movement Database. One of the advantages of this study is the superior quality Automatic Identification System (AIS) data in the high seas regions across the globe. In 2002, the AIS was introduced by the IMO International Convention for the Safety of Life at Sea (SOLAS) to improve maritime safety. Acting as a dynamic tracking and monitoring system, the AIS provides broad coverage and delivers detailed real-time information on the ship, including a ship's identity, position, speed, and draught at a given timestamp. Following the mandate set by IMO SOLAS, all ships over 300 GT engaged in international voyages, cargo ships over 500 GT engaged in national voyages and all passenger ships are required to install AIS transceiver. According to the most recent study^{37,38,39}, the number of ships equipped with AIS and the number of AIS messages transmitted per year has experienced a significant growth over the years, which suggests that the introduction of the automatic vessel position reporting system has significantly reduced the uncertainty concerning ship activities and their geographical distribution.

Supplementary Table 3| AIS message broadcast frequency

Transponder Type	Vessel's Moving Status (Transponder ON)	Transmission Rate
Class A	Anchored / Moored	Every 3 Minutes
Class A	Sailing 0-14 knots	Every 10 Seconds
Class A	Sailing 14-23 knots	Every 6 Seconds
Class A	Sailing 0-14 knots and changing course	Every 3.33 Seconds
Class A	Sailing 14-23 knots and changing course	Every 2 Seconds
Class A	Sailing faster than 23 knots	Every 2 Seconds
Class A	Sailing faster than 23 knots and changing course	Every 2 Seconds
Class B	Stopped or sailing up to 2 knots	Every 3 Minutes
Class B	Sailing faster than 2 knots	Every 30 Seconds

531 This study utilizes AIS dataset to construct our GEEM dynamic database. That is to say, our GEEM
532 dynamic database includes metrics that are essential for the analysis of vessel movement and activity,
533 such as the IMO identification number, Maritime Mobile Service Identify (MMSI) code, vessel
534 coordinate (longitude and latitude), vessel actual speed, voyage draught, and time information. As
535 shown in Supplementary Table 3, the AIS transmission rate is consistent with vessel's moving status
536 and transponder type. All the AIS data are transmitted with a broadcast frequency of one message no
537 more than 3 minutes. As a result, the study utilizes the full year 3-minute frequency AIS data spanning
538 from January 2015 to December 2019, which accounts for a total of 5.03 TB raw AIS dataset.

539

540 **Research domain identification.** As suggested by the United Nations Convention on the Law of the
541 Sea, high seas can be defined as all parts of the sea that are not included in the exclusive economic
542 zone (EEZ). In this study, we first identify the worldwide high seas by subtracting the world country's
543 exclusive economic zones from the world sea boundary. In addition, following the high seas division
544 standard provided by International Hydrographic Organization, we divide the worldwide high seas
545 into 8 geographic regions and define each high seas region's longitude and latitude based on
546 Geographic information system (GIS) database (namely the North Pacific Ocean High Seas, South
547 Pacific Ocean High Seas, North Atlantic Ocean High Seas, South Atlantic Ocean High Seas, Arctic
548 Ocean High Seas, Southern Ocean High Seas, Indian Ocean High Seas, and Other High Seas).
549 Supplementary Fig. 1 presents the research domain of this study and the geographic boundary of each
550 high seas region. GHG emission of vessels are collected and aggregated to respective high seas region
551 by 0.05° grid box based on their AIS messages. By dividing the worldwide high seas into 8 geographic
552 regions, we are able to investigate the different GHG emission pattern and emission driver of each
553 high seas, and the policies can be designed and evaluated in a more specific and effective manner.

554

Supplementary Fig. 1| High seas boundary and classification. According to the United Nations Convention on the Law of the Sea and the International Hydrographic Organization division standard and, by subtracting the world country's Exclusive Economic Zones from the world sea boundary, this study divides the worldwide high seas into 8 geographic regions, namely North Pacific Ocean High Seas (a), South Pacific Ocean High Seas (b), North Atlantic Ocean High Seas (c), South Atlantic Ocean High Seas (d), Arctic Ocean High Seas (e), Southern Ocean High Seas (f), Indian Ocean High Seas (g), and Other High Seas (h).

Previous studies use bottom-up vessel-based or voyage-based methods to calculate shipping GHG emission for certain regions or countries^{34,40,41}. In essence, these methods heavily rely on their assumptions: the vessel-based method assumes that vessels with similar type and age have the uniform shipping behaviors; the voyage-based method distinguishes international and domestic shipping emissions as those which occurred on a voyage between two ports in different or same countries.

In this paper, we propose a new geographic-based method for estimating the high seas shipping GHG inventory. As illustrated in Supplementary Fig. 2, no matter the vessel type, age or the shipping destination, AIS messages are collected only when shipping occurred on high seas geographically. Based on the bottom-up approach, this paper uses the spatial join method in GIS spatial superposition analysis to identify ship trajectory points located in different high seas regions. We then obtain high seas emissions by accumulating ship trajectory emissions in each high seas region. In comparison to the existing two bottom-up GHG emission approaches, the geographic-based method enables more accurate and robust high seas emission estimation due to the following aspects: international vessels navigate between two countries' exclusive economic zone are excluded from high seas GHG inventory (such as Port A Country A to Port A Country B in Supplementary Fig. 2); domestic shipping

580 would be accounted as high seas GHG emission if the shipping route covers high seas region (such
581 as Port A Country A to Port C Country A in Supplementary Fig. 2).
582

583
584 **Supplementary Fig. 2| Geographic-based high seas shipping allocation.** In comparison to the existing
585 bottom-up shipping estimation approaches such as vessel-based and voyage-based shipping calculation
586 method, we collect AIS messages for both international and domestic shipping routes and all kinds of vessel
587 types if and only if the AIS messages are reported from high seas regions (yellow bar in Supplementary Fig.
588 2). As a result, exclusive economic zones AIS messages and shipping emission (grey bar in Supplementary
589 Fig. 2) are excluded in this study.
590

591 **Geographic-based Emission Estimation Model.** The technical strategy of our proposed
592 Geographic-based Emission Estimation Model (GEEM) is illustrated in Supplementary Fig. 3. As
593 discussed above, we utilize the IHS raw database and vessel AIS messages to construct our GEEM
594 static and dynamic database. We design a geographic-based AIS messages collection method to
595 classify and categorize high seas shipping route and associated GHG emission. In this section, we
596 demonstrate the detailed GEEM high seas emission calculation method, the specifications of emission
597 equation settings and the updated emission factors used in this study.
598

Supplementary Fig. 3| Technical strategy for Geographic-based Emission Estimation Model (GEEM)

In international shipping, the GHG emission of each vessel is produced by three types of vessel engines, namely the main engine (propulsion engine), the auxiliary engine and the boiler. Since the main engine and the auxiliary engine are the moving power source of shipping, the emission intensities of the main and auxiliary engine are determined by a variety of shipping characteristics such as the vessel movement modes, instantaneous load factors, and maximum continuous rated power etc. Boiler is used for hot water production and fuel heating. Its emission intensity is mainly associated with vessel fuel types. We next show how our GEEM approach calculate and collect the GHG emission of the above three engines and formulate the total emission of high seas from a bottom-up approach.

612 The GHG emission of each vessel i can be calculated as the sum of vessel main engine, auxiliary
 613 engine and boiler emission:

$$614 \quad E = E_{main} + E_{auxiliary} + E_{boiler} \quad (1)$$

615
 616 In this study, we formulate the total GHG emission TE of each high seas region by summing up the
 617 individual vessel's emission occurring in high seas region geographically:

$$618 \quad TE_i = \sum_{i=1}^n E_{ij}, \quad (2)$$

619 In terms of the vessel main engine, the GHG emission of main engine can be expressed as follows:

$$620 \quad E_{main} = MCR \times EF_{main} \times \sum_{j=1}^m LF_j \times AF_j \times \Delta T_j, \quad (3)$$

621 where MCR is the maximum continuous rated power; EF_{main} represents the emission factor of
 622 vessel main engine; LF_j is the instantaneous load factor at time j , AF_j is the emission adjustment
 623 factors when the vessel's instantaneous load factor is lower than 20%. ΔT_j is the time span of the
 624 two adjacent AIS messages. It is worth noting that the emission factor for vessel main engine and
 625 auxiliary engine provided by the previous studies lack the High Speed Diesel (HSD) and Slow Speed
 626 Diesel (SSD) emission factors, respectively. In this study, we update the overall vessel main and
 627 auxiliary engine emission factors based on IMO Fourth GHG Emission Study. In addition, we also
 628 calculate the Tier 3 (vessel construction date after 2016) vessel's GHG emission intensities for both
 629 the main and auxiliary engine. The emission factors for main engine are reported in Supplementary
 630 Table 4.

631

632 **Supplementary Table 4| Emission factors for vessel main engine (g/kwh)**

Engine	Fuel	Tier	Model	PM _{2.5}	PM ₁₀	NO _x	SO ₂	CO	NM	CO ₂	N ₂ O	CH ₄
Type	Type		Year						VOC			
SSD	HFO	Tier 0	≤1999	1.28	1.39	18.1	8.751	0.54	0.632	576	0.031	0.012
MSD				1.28	1.39	14.0	9.224	0.54	0.527	607	0.034	0.01
HSD				1.29	1.4	10.0	9.697	0.54	0.527	638	0.030	0.01
SSD	(2.43% Sulfur)	Tier 1	2000- 2010	1.28	1.39	17.0	8.278	0.54	0.632	545	0.031	0.012
MSD				1.28	1.39	13.0	8.751	0.54	0.527	576	0.034	0.01
HSD				1.28	1.39	9.8	9.224	0.54	0.527	607	0.030	0.01
SSD				1.28	1.39	14.4	8.593	0.54	0.632	545	0.031	0.012

MSD		Tier	2011-	1.28	1.39	10.5	9.084	0.54	0.527	576	0.034	0.01
HSD		2	2015	1.28	1.39	7.7	9.575	0.54	0.527	607	0.030	0.01
SSD				1.28	1.39	14.4	8.890	0.54	0.632	545	0.031	0.01
MSD		Tier	≥ 2016	1.28	1.39	10.5	9.398	0.54	0.527	576	0.034	0.01
HSD		3		1.28	1.39	7.7	9.906	0.54	0.527	607	0.030	0.01
SSD				0.17	0.18	18.1	0.508	0.044	0.632	561	0.030	0.012
MSD		Tier	≤ 1999	0.17	0.18	14.0	0.537	0.046	0.527	593	0.030	0.01
HSD		0		0.17	0.18	10.0	0.551	0.54	0.527	609	0.034	0.01
SSD	MDO/			0.17	0.19	17.0	0.479	0.044	0.632	529	0.030	0.012
MSD	MGO	Tier	2000-	0.17	0.18	13.0	0.508	0.046	0.527	561	0.030	0.01
HSD		1	2010	0.17	0.18	9.8	0.537	0.54	0.527	593	0.034	0.01
SSD	(0.13%			0.17	0.19	14.4	0.446	0.044	0.632	529	0.030	0.012
MSD	Sulfur)	Tier	2011-	0.17	0.18	10.5	0.473	0.046	0.527	561	0.030	0.01
HSD		2	2015	0.17	0.18	7.7	0.500	0.54	0.527	593	0.034	0.01
SSD				0.17	0.19	14.4	0.231	0.044	0.632	529	0.030	0.01
MSD		Tier	≥ 2016	0.17	0.18	10.5	0.245	0.046	0.527	561	0.030	0.01
HSD		3		0.17	0.18	7.7	0.259	0.54	0.527	593	0.034	0.01
Otto	LNG	Tier	<2016	0.03	0.03	1.3	0.003	1.3	0.5	457	0.018	8.5
Otto (MS)		0-2		0.02	0.02	1.3	0.003	1.3	0.500	457	0.02	5.5
Otto (SS)	LNG	Tier	≥ 2016	0.02	0.02	1.3	0.003	1.3	0.500	457	0.02	2.5
Diesel		3		0.01	0.01	3.4	0.003	1.04	0.400	457	0.03	0.2

Note: 1) SSD: Slow Speed Diesel; MSD: Medium Speed Diesel; HSD: High Speed Diesel; HFO: Heavy Fuel Oil; MDO: Marine Diesel Oil; MGO: Marine Gas Oil; LNG: Liquefied Natural Gas; Otto: Otto-cycle LNG-fueled engine. 2) According to the Fourth IMO GHG Study, we set Heavy Fuel Oil (HFO) average sulfur content at 2.43%, Marine Diesel Oil (MDO) and Marine Gas Oil (MGO) at 0.13%. In addition, we collect and update all types of emission factors (PM_{2.5}, PM₁₀, NO_x, SO₂, CO, NMVOC, CO₂, N₂O, CH₄) reported in Fourth IMO GHG Study.

633

634 The instantaneous load factor LF_j in Equation (4) at time j can be formulated as follows:

635
$$LF_j = \left(\frac{v_j}{MDS} \right)^3, \quad (4)$$

636 where v_j is the vessel's instantaneous speed at time j and MDS is the vessel's maximum designed
637 speed. The base emission factors for vessel main engine would decrease by about 20 percent load. As
638 a result, according to the adjusted emission factor statistics of Energy and Environmental Analysis,
639 Supplementary Table 5 shows the adjusted emission factors AF_j for vessel main engines at low loads.

640

641

Supplementary Table 5| Adjusted emission factors for vessel main engines at low loads (%)

Load Factor (%)	PM	NO _x	SO ₂	CO	NMVOC	CO ₂	N ₂ O	CH ₄
2	7.29	4.63	1	9.7	21.18	1	4.63	21.18
3	4.33	2.92	1	6.49	11.68	1	2.92	11.68
4	3.09	2.21	1	4.86	7.71	1	2.21	7.71
5	2.44	1.83	1	3.9	5.61	1	1.83	5.61
6	2.04	1.6	1	3.26	4.35	1	1.6	4.35
7	1.79	1.45	1	2.8	3.52	1	1.45	3.52
8	1.61	1.35	1	2.45	2.95	1	1.35	2.95
9	1.48	1.27	1	2.18	2.52	1	1.27	2.52
10	1.38	1.22	1	1.97	2.18	1	1.22	2.18
11	1.3	1.17	1	1.79	1.96	1	1.17	1.96
12	1.24	1.14	1	1.64	1.76	1	1.14	1.76
13	1.19	1.11	1	1.52	1.6	1	1.11	1.6
14	1.15	1.08	1	1.41	1.47	1	1.08	1.47
15	1.11	1.06	1	1.32	1.36	1	1.06	1.36
16	1.08	1.05	1	1.24	1.26	1	1.05	1.26
17	1.06	1.03	1	1.17	1.18	1	1.03	1.18
18	1.04	1.02	1	1.11	1.11	1	1.02	1.11
19	1.02	1.01	1	1.05	1.05	1	1.01	1.05
20	1	1	1	1	1	1	1	1

642

643 In terms of vessel auxiliary engine, the GHG emission of auxiliary engine can be expressed as follows:

$$644 \quad E_{auxiliary} = EF_{auxiliary} \times \sum_{j=1}^m P_{aux_j} \times \Delta T_j, \quad (5)$$

645 Where $EF_{auxiliary}$ is the emission factor of vessel auxiliary engine at certain fuel types, P_{aux_j} is
 646 the auxiliary engine power output at time j , and the ΔT_j is the time span of the two adjacent AIS
 647 messages. Emission factors for auxiliary engine are reported in Supplementary Table 6. In fact, the
 648 vessel auxiliary engine P_{aux_j} and boiler have different power outputs when the vessel movement
 649 mode changes. Vessel movement modes can be categorized into 4 types by their speed and maximum
 650 continuous rated power (MCR), namely At berth (speed less than 1 knot), At anchorage (speed
 651 between 1 knot-3 knot), Maneuvering (speed great than 3 knots and less than 20% MCR) and At sea
 652 (speed above 20% MCR). As a result, Supplementary Table 7 provides adjusted auxiliary engine and
 653 boiler power outputs for different vessel movement modes.

654

Supplementary Table 6| Emission factors for auxiliary engine (g/kwh)

655

Engine Type	Fuel Type	Tier	Model Year	$PM_{2.5}$	PM_{10}	NO _x	SO _x	CO	NM VOC	CO ₂	N ₂ O	CH ₄
SSD				1.29	1.4	11.2	9.697	0.54	0.421	638	0.040	0.01
MSD		Tier 0	≤1999	1.29	1.4	11.2	9.697	0.54	0.421	638	0.040	0.01
HSD				1.29	1.4	11.2	9.697	0.54	0.421	638	0.040	0.01
SSD				1.28	1.39	11.2	9.224	0.54	0.421	607	0.040	0.01
MSD	HFO	Tier 1	2000-2010	1.28	1.39	11.2	9.224	0.54	0.421	607	0.040	0.01
HSD				1.28	1.39	11.2	9.224	0.54	0.421	607	0.040	0.01
SSD	(2.43%			1.28	1.39	11.2	9.575	0.54	0.421	607	0.040	0.01
MSD	Sulfur)	Tier 2	2011-2015	1.28	1.39	11.2	9.575	0.54	0.421	607	0.040	0.01
HSD				1.28	1.39	11.2	9.575	0.54	0.421	607	0.040	0.01
SSD				1.28	1.39	11.2	9.906	0.54	0.421	607	0.040	0.01
MSD		Tier 3	≥ 2016	1.28	1.39	11.2	9.906	0.54	0.421	607	0.040	0.01
HSD				1.28	1.39	11.2	9.906	0.54	0.421	607	0.040	0.01
SSD				0.17	0.18	11.2	0.551	0.54	0.421	609	0.036	0.01
MSD		Tier 0	≤1999	0.17	0.18	11.2	0.551	0.54	0.421	609	0.036	0.01
HSD				0.17	0.18	11.2	0.551	0.54	0.421	609	0.036	0.01
SSD				0.17	0.18	11.2	0.537	0.54	0.421	593	0.036	0.01
MSD	MDO/	Tier 1	2000-2010	0.17	0.18	11.2	0.537	0.54	0.421	593	0.036	0.01
HSD	MGO			0.17	0.18	11.2	0.537	0.54	0.421	593	0.036	0.01
SSD	(0.13%			0.17	0.18	11.2	0.500	0.54	0.421	593	0.036	0.01
MSD	Sulfur)	Tier 2	2011-2015	0.17	0.18	11.2	0.500	0.54	0.421	593	0.036	0.01
HSD				0.17	0.18	11.2	0.500	0.54	0.421	593	0.036	0.01
SSD				0.17	0.18	11.2	0.259	0.54	0.421	593	0.036	0.01
MSD		Tier 3	≥ 2016	0.17	0.18	11.2	0.259	0.54	0.421	593	0.036	0.01
HSD				0.17	0.18	11.2	0.259	0.54	0.421	593	0.036	0.01
Otto	LNG	Na	all	0.02	0.02	1.3	0.005	1.3	0.5	429	0.018	5.5

Note: The emission factor of engine tier 3 NO_x can only be used within the North Sea and Baltic Sea NO_x Emission Control Area (NECA). We substitute the engine tier 3 NO_x emission factor with engine tier 2 NO_x emission in other high seas.

GHG emission of vessel boiler can be expressed as follows:

$$E_{boiler} = EF_{boiler} \times \sum_{j=1}^m P_{boiler_j} \times \Delta T_j, \quad (6)$$

Where EF_{boiler} is the emission factor of vessel boiler at certain fuel types, P_{boiler_j} is the boiler power output at time j , and the ΔT_j is the time span of the two adjacent AIS messages. In fact, the emission intensity of vessel boiler can generally be determined by sulfur content of vessel fuels. As suggested by IMO Maritime Environment Protection Committee (www.imo.org), we identify 3 sulfur content categories by different fuel types. Supplementary Table 8 summarizes the emission factor for vessel boiler in this study.

Supplementary Table 7| Adjusted auxiliary engine and boiler power output (kw)

Ship Type	Size	Auxiliary Boiler Power Output				Auxiliary Engine Power Output			
		At berth	Anchored	Maneuvering	Sea	At berth	Anchored	Maneuvering	Sea
Bulk carrier	0-9,999	70	70	60	0	110	180	500	190
	10,000-34,999	70	70	60	0	110	180	500	190
	35,000-59,999	130	130	120	0	150	250	680	260
	60,000-99,999	260	260	240	0	240	400	1,100	410
	100,000-199,999	260	260	240	0	240	400	1,100	410
	200,000-+	260	260	240	0	240	400	1,100	410
Chemical tanker	0-4,999	670	160	130	0	110	170	190	200
	5,000-9,999	670	160	130	0	330	490	560	580
	10,000-19,999	1,000	240	200	0	330	490	560	580
	20,000-39,999	1,350	320	270	0	790	550	900	660
	40,000-+	1,350	320	270	0	790	550	900	660
Container	0-999	250	250	240	0	370	450	790	410
	1,000-1,999	340	340	310	0	820	910	1,750	900
	2,000-2,999	460	450	430	0	610	910	1,900	920
	3,000-4,999	480	480	430	0	1,100	1,350	2,500	1,400
	5,000-7,999	590	580	550	0	1,100	1,400	2,800	1,450
	8,000-11,999	620	620	540	0	1,150	1,600	2,900	1,800
	12,000-14,499	630	630	630	0	1,300	1,800	3,250	2,050
	14,500-19,999	630	630	630	0	1,400	1,950	3,600	2,300
	20,000-+	700	700	700	0	1,400	1,950	3,600	2,300
	0-4,999	0	0	0	0	90	50	180	60
General Cargo	5,000-9,999	110	110	100	0	240	130	490	180
Cargo	10,000-19,999	150	150	130	0	720	370	1,450	520
	10,000-+	150	150	130	0	720	370	1,450	520
	0-49,999	1,000	200	200	100	240	240	360	240

Liquefied gas tanker	50,000-99,999	1,000	200	200	100	1,700	1,700	2,600	1,700
	100,000-199,999	1,500	300	300	150	2,500	2,000	2,300	2,650
	200,000-+	3,000	600	600	300	6,750	7,200	7,200	6,750
	0-4,999	500	100	100	0	250	250	375	250
	5,000-9,999	750	150	150	0	375	375	560	375
	10,000-19,999	1,250	250	250	0	690	500	580	490
Oil tanker	20,000-59,999	2,700	270	270	270	720	520	600	510
	60,000-79,999	3,250	360	360	280	620	490	770	560
	80,000-119,999	4,000	400	400	280	800	640	910	690
	120,000-199,999	6,500	500	500	300	2,500	770	1,300	860
	200,000-+	7,000	600	600	300	2,500	770	1,300	860
Fishing	0-+	0	0	0	0	200	200	200	200

Note: Vessel movement modes can be categorized into 4 types by their speed and maximum continuous rated power (MCR). Specifically, At berth = vessel speed less than 1 knot, At anchorage = vessel speed between 1 knot-3 knot, Maneuvering = vessel speed great than 3 knots and less than 20% MCR, At sea = vessel speed above 20% MCR. Vessels with different movement modes and types have heterogenous boiler power output, auxiliary engine power output and GHG emission patterns.

Supplementary Table 8| Emission factor for boiler (g/kwh)

Fuel type	PM _{2.5}	PM ₁₀	NO _x	SO ₂	CO	NMVOC	CO ₂	N ₂ O	CH ₄
HFO (2.43%Sulfur)	1.31	1.42	2.1	14.85	0.2	0.105	1059	0.040	0.002
MDO/MGO (0.13%Sulfur)	0.13	0.14	2.1	0.825	0.2	0.105	970	0.049	0.002
LNG	0.03	0.03	1.3	0.00269	0.2	0.105	457	0.020	0.04

Emissions Uncertainty Analysis. The uncertainty in our global high seas shipping emissions estimation mainly originates from the following sources: (1) the uncertainty of the static dataset; (2) the uncertainty of dynamic dataset in the sampling of AIS data. (3) the uncertainty of emission factors of the observed fleet ships.

The uncertainty of the static dataset mainly includes the ship specification parameters and ship coverage. In this study, the ship specifications are obtained from the official IHS database and improved using our adaptive infilling algorithm. As shown in Supplementary Table 9, we compare our static dataset to the official IMO dataset in terms of numbers and coverage. Although we exclude ships that have no high seas shipping records, our GEEM static dataset collects 79613 vessels for all types in sum, and the majority of 19 ship types covers 80% higher of the IMO dataset. In terms of the top 6 GHG emission contributors of ship type on high seas shipping, namely Bulk Carrier, Chemical

683 Tanker, Container, General Cargo, Liquefied Gas Tanker and oil tanker, our dataset covers 94.9% of
 684 the IMO dataset. That is to say, the GHG estimation results of our proposed GEEM method is built
 685 on a well-covered static dataset.

686 **Supplementary Table 9| Static dataset comparison**

Ship type	IMO dataset	This study	% of IMO dataset
Bulk Carrier	11672	11981	96.5%
Oil Tanker	8177	7403	90.5%
Container	5182	5366	103.6%
General Cargo	14994	13196	88.0%
Chemical Tanker	5506	5145	93.4%
Ro-Ro	2002	1162	58.0%
Cruise	612	475	77.6%
Refrigerated Bulk	895	684	76.4%
Liquefied Gas Tanker	1953	2011	102.9%
Other Liquids Tankers	179	34	18.9%
Ferry - Pax Only	3459	1272	36.77%
Ferry - Ro-Pax	3148	2120	67.3%
Vehicle	828	842	101.7%
Service - Tug	20251	5172	25.5%
Service - Other	6180	4799	77.6%
Miscellaneous Fishing	23911	8942	37.4%
Miscellaneous - Other	645	1727	267.7%
Offshore	7555	5068	67.8%
Yacht	2477	2214	89.4%

687
 688 The data quality of the dynamic database is evaluated according to three aspects: the AIS data
 689 coverage rate, AIS time interval frequency, and redundant data. The first step in calculating the AIS
 690 coverage rate is to check the GEEM static database and determine all the vessels that are active during
 691 the given period of this study. To do so, a set of rules are applied based on each vessel’s build year,
 692 the current ship status, and the year that the vessel’s ship status was last updated. Next, all the active
 693 vessels are matched with the messages in the AIS database. Supplementary Table 10 describes the
 694 size of the total fleet classified as in service with the percentage that also appears in the AIS database.
 695 For top 6 high seas emission ship type, 94.6% of the 6 type ships are observed with AIS.

696
 697 **Supplementary Table 10| AIS dataset coverage**

Ship type	2015	2016	2017	2018	2019	Ships in service	% if in-service ships observed on AIS
Bulk Carrier	10544	10877	11286	11258	11981	12327	97.2%
Oil Tanker	5807	5940	6293	6403	7403	8044	92.0%
Container	5100	5187	5377	5328	5366	5367	99.9%
General Cargo	12166	12282	12463	13196	13196	13940	94.7%
Chemical Tanker	4400	4593	4785	4837	5145	5843	88.1%
RoRo	1033	1055	1110	1098	1162	1631	71.2%
Cruise	399	404	416	417	475	481	98.8%
Refrigerated Bulk	686	670	677	651	684	792	86.4%
Liquefied Gas Tanker	1696	1802	1912	1909	2011	2136	94.1%
Other Liquid Tankers	33	33	33	32	34	87	39.1%
Ferry-PaxOnly	1161	1181	1206	1202	1272	1400	90.8%
Ferry-RoPax	1815	1879	1950	1946	2120	2798	75.8%
Vehicle	774	793	825	784	842	873	96.4%
Service Tug	4620	4752	4903	4834	5172	5569	92.9%
Service Other	4647	4642	4709	4642	4799	5267	91.1%
Miscellaneous Fishing	8393	8547	8682	8632	8942	9761	91.6%
Miscellaneous Other	1541	1569	1637	1599	1727	2553	67.6%
Offshore	5157	5107	4998	4838	5068	5638	89.9%

698

699 Supplementary Table 11 shows the time interval statistics for our AIS data. Among all the archived
700 messages, 96.77% of our AIS data have a time interval of less than 2 minutes. Only about 0.05% of
701 our AIS data have a time interval of more than 30 minutes, which may be caused by extreme weather
702 situations, complicated geographical condition interferences and other uncertain reasons. For these
703 long interval messages (two signals have interval longer than 600s), speeds between each two of the
704 AIS signals were generated by interpolation for every 600 seconds along the voyage trajectory.

705

706

Supplementary Table 11| the time interval statistics for AIS data

Time interval	Percentage
30 seconds	92.28%
60 seconds	3.33%
90 seconds	0.85%
120 seconds	0.31%
20 minutes	2.99%

30 minutes	0.19%
> 30 minutes	0.05%

707

708 In addition to the successfully matched vessels, AIS messages received from other vessels could not
709 be matched due to a lack of technical data. Although omitting emissions from these unmatched ships
710 introduces uncertainty, the existing studies have shown that its impact on emission estimation is rather
711 negligible as most of these ships are relatively small^{42,43}. Another concern for matching the AIS data
712 with the GEEM static database is message duplication. Since AIS data are reported from multiple
713 AIS transceivers, both terrestrial and satellite based, there exist a possibility that duplicated messages
714 may be received and recorded. To eliminate the occurrence of this phenomenon, we first put all the
715 AIS messages collected for each individual ship in a sequential manner. When each ship's AIS data
716 are ranked according to time sequence, the duplicated messages will have a time interval of 0, and
717 therefore can be easily discovered and discarded. Thus, the duplicated messages will not affect our
718 final emission calculation result.

719

720 The uncertainties of emission factors include the main engine, the auxiliary engine and the boiler. As
721 discussed in previous section, we update the overall vessel main and auxiliary engine emission factors
722 based on the official IMO Fourth GHG Emission Study. In addition, we also calculate the 2019
723 vessel's GHG emission intensities for all engine types. As reported by the Fourth IMO GHG emission
724 study, the results from the Monte Carlo analysis for international shipping CO₂-equivalent emissions
725 indicate that the uncertainty in the average CO₂-equivalent emission factor is relatively small and set
726 as 2.68% standard deviation of mean. However, international fleets have different carbon emission
727 factor as for some pollutants such as SO₂, PM_{2.5} and PM 10 during our sample period. As a result,
728 we update the yearly emission factors for the above three pollutants based on IMO Fourth GHG
729 Emission Study. Supplementary Tables 12 and 13 demonstrate the updated PM₁₀ (The emission
730 factors of PM_{2.5} are 92% of PM 10) and SO₂ emission factor for all engine and fuel types respectively.

731

732

Supplementary Table 12| updated emission factors for PM₁₀ (g/kwh)

Generation	Engine	Fuel	2015	2016	2017	2018	2019
1	SSD	HFO	1.35	1.39	1.4	1.4	1.4
		MDO	0.18	0.18	0.18	0.18	0.18
	MSD	HFO	1.35	1.39	1.4	1.4	1.4
		MDO	0.18	0.18	0.18	0.18	0.18
	HSD	HFO	1.35	1.39	1.4	1.4	1.4
		MDO	0.18	0.18	0.18	0.17	0.17

2	Boiler	HFO	1.34	1.41	1.42	1.42	1.42
		MDO	0.15	0.15	0.15	0.14	0.14
		LNG	0.03	0.03	0.03	0.03	0.03
	AE	HFO	1.35	1.39	1.4	1.4	1.4
		MDO	0.18	0.18	0.18	0.17	0.17
	SSD	HFO	1.35	1.38	1.39	1.39	1.39
		MDO	0.19	0.19	0.19	0.18	0.18
	MSD	HFO	1.35	1.39	1.39	1.39	1.39
		MDO	0.18	0.18	0.18	0.18	0.18
	HSD	HFO	1.35	1.39	1.4	1.4	1.4
		MDO	0.18	0.18	0.18	0.18	0.18
	Otto-MS	LNG	0.02	0.02	0.02	0.02	0.02
		HFO	1.34	1.41	1.42	1.42	1.42
		MDO	0.15	0.15	0.15	0.14	0.14
	Boiler	LNG	0.03	0.03	0.03	0.03	0.03
		HFO	1.35	1.39	1.4	1.4	1.4
		MDO	0.18	0.18	0.18	0.18	0.18
	AE	LNG	0.02	0.02	0.02	0.02	0.02
		HFO	1.36	1.34	1.35	1.35	1.35
		MDO	0.2	0.2	0.2	0.19	0.19
	MSD	HFO	1.36	1.34	1.35	1.35	1.35
		MDO	0.2	0.2	0.2	0.19	0.19
	HSD	HFO	1.37	1.34	1.35	1.35	1.35
		MDO	0.2	0.2	0.2	0.18	0.18
3	Otto-SS	LNG	0.02	0.02	0.02	0.02	0.02
	Otto-MS	LNG	0.02	0.02	0.02	0.02	0.02
		LNG	0.01	0.01	0.01	0.01	0.01
		LNG-Diesel	0.01	0.01	0.01	0.01	0.01
	Boiler	HFO	1.38	1.33	1.35	1.34	1.34
		MDO	0.18	0.17	0.17	0.15	0.15
		LNG	0.03	0.03	0.03	0.03	0.03
	AE	HFO	1.37	1.34	1.35	1.35	1.35
		MDO	0.2	0.2	0.2	0.18	0.18
		LNG	0.02	0.02	0.02	0.02	0.02

Note: SSD: Slow Speed Diesel; MSD: Medium Speed Diesel; HSD: High Speed Diesel; HFO: Heavy Fuel Oil; MDO: Marine Diesel Oil; MGO: Marine Gas Oil; LNG: Liquefied Natural Gas; Otto: Otto-cycle LNG-fueled engine. Generations 1 to 3 indicate engine built before 1984, between 1984 and 2000 and after 2000 respectively.

Supplementary Table 13| updated emission factors for SO₂ (g/kwh)

Engine Type	Fuel Type	2015	2016	2017	2018	2019
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SSD	HFO	8.383	8.820	8.890	8.890	8.890
	MDO	0.264	0.264	0.264	0.231	0.231
MSD	HFO	8.862	9.324	9.398	9.398	9.398
	MDO	0.280	0.280	0.280	0.245	0.245
HSD	HFO	9.341	9.828	9.906	9.906	9.906
	MDO	0.296	0.296	0.296	0.259	0.259
LNG-Otto (MS)	LNG	0.005	0.005	0.005	0.005	0.005
LNG-Otto (SS)	LNG	0.006	0.006	0.006	0.006	0.006
LNG-Diesel	LNG	0.014	0.014	0.014	0.013	0.013
Boiler	HFO	16.286	17.136	17.272	17.272	17.272
	MDO	0.512	0.512	0.512	0.448	0.448
	LNG	0.009	0.009	0.009	0.009	0.009
Auxiliary Engines	HFO	9.341	9.828	9.906	9.906	9.906
	MDO	0.296	0.296	0.296	0.259	0.259
	LNG	0.005	0.005	0.005	0.005	0.005

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