RESPONSE TO REVIEWERS

Journal: Atmospheric Chemistry and Physics
MS No.: egusphere-2026-1935
Manuscript Title: Addressing systematic underestimation in a global ship emission inventory through improved fleet representation and fuel compliance characterization

Dear reviewer,
Many thanks to you for the positive comment and interest in our work. All of the comments are very professional and valuable for the revision and improvement of our research. We have carefully addressed all the comments and revised the manuscript accordingly. The correction details are listed below point by point.

The revision notes are as follows:

Reviewers' comments are in red and in bold font.

Authors' responses are in indent and in black normal font.

Revisions on manuscript are in indent and in blue normal font.

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Response to Reviewer #1:

OVERALL

I want to thank the authors for addressing most of my comments, the methodological approach is much clearer now. However, this has raised some questions regarding the novelty and focus of the paper. In my opinion, the authors should focus more on the development of the "Fleet low sulfur compliance choice model (FLSCCM)" (and how this can be developed moving towards alternative fuels) as the addition of "new vessels" and daily resolution appears to be something that can be produced using annual data (with less computational power?). If I understand it correct, the "new vessels" may be included in other models if their ship specific databases are more developed (i.e. include more ships?). Could you compare the respective datasets? Or at least number of ships? I think there are some interesting findings contributions in this manuscript (the FLSCCM module, the intercomparisons of different emission models, the problem of underestimation when data is lacking/not publicly available and the risks associated if models have too low accuracy), but the authors have slightly missed that and instead focus on their internal model-comparison.

Response:

We sincerely thank the reviewer for the constructive and insightful comments. These suggestions are highly valuable for clarifying the novelty, focus, and broader significance of our study. We have carefully considered your suggestions and incorporated them into the revised manuscript. In the following point-by-point responses, we address these issues from three main perspectives:

(1) a multi-dimensional comparison with other maritime datasets and emission inventories;
(2) a more explicit discussion of the necessity and advantages of daily-resolution emission inventories, and
(3) a deeper discussion of the implications and broader significance of our findings.

We are particularly grateful for these suggestions, which have encouraged us to move beyond comparisons among different versions of our own model and to better articulate the methodological and scientific contributions of the study.

Major Specific Comments

Comparison and validation

Q1. Comparison with other maritime datasets for ship technical information

Line 170: When using machine learning to fill STSD, have you checked whether there are other databases available, e.g. Seaweb, where this information is already available?

Response:

We thank the reviewer for pointing us to Sea-web. We investigated this database and confirmed that it provides extensive vessel-level information, covering more than 200,000 vessels of 100 GT and above, with a large number of technical and operational fields needed for STSD, such as ship type, dead wight tonnage (DWT), and year of build.

However, Sea-web and our STSD are not fully equivalent in terms of either fleet coverage or the technical variables required by our emission modelling framework. In particular, we found that the Sea-web fields available to us do not include main engine power, which is a key input required for our ship-level emission estimation and the selection of appropriate emission factors. Thus, although Sea-web provides many relevant vessel characteristics, it does not by itself eliminate the need to reconstruct missing parameters for our modelling framework.

In addition, Sea-web is a proprietary commercial database, whereas our objective in developing the machine-learning-based completion approach was to provide a more accessible, scalable, and reproducible way of completing missing vessel characteristics within an inventory constructed from accessible data sources. The ML approach is therefore not intended to replace comprehensive commercial databases such as Sea-web, but rather to reduce dependence on proprietary data and to improve the completeness of the specific parameters required for our emission and activity calculations.

To make this distinction clearer, we have added a comparison of the fleet boundaries, vessel coverage, and key technical variables between STSD and Sea-web, together with an external comparison of our fleet estimates against UNCTAD statistics. These comparisons help clarify both the scope of our inventory and the motivation for the ML-based completion procedure.

Revisions:

(1) In DISCUSSION *(page18, para1)*, we mentioned commercial databases such

as Sea-web and why we still need to introduce our ML-based approach:
First, missing vessel specifications supplemented through machine learning … global scales. Commercial databases such as Sea-web provide extensive ship-level information(S&P Global, 2026), but the fields available to this study did not include main engine power, a key input to SEIM. Our machine-learning framework therefore supplements accessible data to complete model-relevant ship characteristics; it is not intended to replace proprietary databases. Second, …

(2) In Supplementary Information *(page3, para4)*, we presented:
To assess whether an alternative vessel database could provide the technical information required by SEIMv2.3, we compared the STSD with Sea-web in terms of fleet coverage and the availability of key variables (Table S5 and Table S6). The comparison shows that Sea-web provides extensive vessel-level information, but its fleet definition and the fields available to this study do not fully match the requirements of the STSD/SEIMv2.3 inventory. In particular, main engine power, a key input to ship-level emission estimation, was not available among the Sea-web fields examined in this study. Thus, Sea-web provides complementary vessel information but cannot directly replace the STSD for our emission calculations.

Table S5. Availability of ship technical variables required by SEIMv2.3 in the STSD before and after machine-learning completion and in Sea-web

Variable required by our model	**STSD before ML**	**STSD after ML**	**Sea-web**
Ship type	Partial	✓	✓
GT	Partial	✓	✓
DWT	Partial	✓	✓
Year built	Partial	✓	✓
Main engine power	Partial	✓	X

Table S6. Fleet coverage, temporal scope, size, and accessibility of the STSD, SEIMv2.3 fleet subset, Sea-web, and UNCTAD data

Database	**Vessel coverage**	**Temporal scope**	**Approx. number**	**Accessibility**
STSD	Historical and current vessel records used to	Current + historical	440,000	Based on accessible /public

	construct SEIM			sources
Ships extracted from STSD for SEIM calculation	Active vessels in the target year	2024	132,000	Research inventory
Sea-web	Propelled seagoing merchant ships ≥100 GT, including active, newbuildings, casualties and lost/broken-up vessels	Current + historical	>200,000	Commercial subscription
UNCTAD	Merchant fleet ≥100 GT	2024	108,789	Public

Q2. Comparison with other maritime datasets for scrubber installation

Line 211-213: could you confirm if ships did not have a scrubber, i.e. by specifying fuel use? Or were all ships larger than DWT50000 and construction year after 2006 assumed to have a scrubber if nothing else was defined? Many scrubbers are installed on vessels as retrofit, how is that reflected in the assumptions made? There are databases, e.g. Seaweb and IMO gisis, that contain some information on scrubber installations that could be worth looking into.

Response:

Thanks for this detailed comment. We address the four questions raised in this comment in turn below:

First, voyage-level fuel use and scrubber operation cannot be directly observed at the global scale, so we cannot confirm the absence of a scrubber from observed fuel use for every vessel. We therefore assume that all ships comply with the IMO 2020 sulfur regulation and reconstruct their compliance pathways within FLSCCM. Ships identified as using low-sulfur fuels are treated as not requiring a scrubber, whereas ships classified by FLSCCM as continuing to use HFO are assumed to comply through an exhaust gas cleaning system (EGCS/scrubber). Accordingly, ships not assigned to the HFO-with-scrubber pathway are assumed to comply through the use of low-sulfur fuel.

Second, ships were not classified solely on the basis of DWT > 50,000 and construction year after 2006. These criteria were combined with ship type and the

fuel-compliance logic described above. The construction-year threshold was introduced as a statistical screening criterion rather than as an assumption that vessels built before 2006 could not be retrofitted. As shown in the Supplementary Information, relatively few scrubber-equipped ships in our installation dataset were built before 2006, and this fleet-age pattern was therefore used as one of the empirical criteria for reconstructing additional likely scrubber-equipped vessels.

Third, retrofit installations are explicitly reflected in the observed scrubber records. The Clarksons dataset provides both vessel construction year and scrubber installation year. For ships with direct installation records, whether a scrubber is considered in use in a given emission year depends on whether its recorded installation year precedes or coincides with that year. Thus, vessels built before the screening threshold can still be represented as scrubber-equipped if a retrofit installation is recorded.

Finally, following the reviewer's suggestion, we examined the IMO GISIS database. We agree that GISIS does not provide a complete registry of all scrubber-equipped vessels, but it is well suited as an independent external reference. After restricting the comparison to vessels explicitly recorded as EGCS/scrubber and active in the 2024 SEIM fleet, FLSCCM identified 1,740 of the 2,000 GISIS-recorded vessels (87.0%). The remaining 260 GISIS-only vessels represented only 1.75% of the relevant fleet DWT and 2.55% of fuel consumption. In addition, the reconstructed scrubber fleet showed broadly similar DWT and vessel-age distributions to the GISIS-recorded fleet. We therefore use GISIS as an external validation of the fleet-level reconstruction rather than as a complete vessel-level ground truth. These assumptions, the treatment of retrofit installations, and the GISIS comparison have now been clarified in the revised manuscript.

Revisions:

(1) In METHODS *(page9, para2)*, we presented:

Because globally complete ship-level compliance information is unavailable, FLSCCM reconstructs fleet sulfur compliance pathways by combining ship-level scrubber installation records with constrained statistical gap filling. All ships were assumed to comply with the IMO 2020 sulfur limit. ~~First, scrubber-equipped ships recorded in the Clarksons Research database are identified and matched with the SEIM fleet using ship MMSI. Ships were considered to have observed scrubber capability only when they were identified as fitted with scrubbers and the installation was effective before the corresponding emission calculation period.~~ For ships with Clarksons installation records, scrubber availability was determined

from the reported installation year; retrofits were therefore included from the year of installation onward. These records indicate scrubber installation availability rather than voyage-level operation. In this study, ships with effective installations were assumed to follow the HFO-with-scrubber pathway during the corresponding period.

For ships without available scrubber installation records, FLSCCM applies structurally constrained gap filling based on characteristics ~~derived from scrubber-equipped vessels identified from the installation database. Analysis of the scrubber installation database in Supplementary Information showed that … The threshold settings were determined based on the characteristics of the observed scrubber-equipped fleet.~~ of the observed scrubber fleet. Because scrubber installations were concentrated among larger ships and major cargo ship categories, gap filling was restricted to bulk carriers, container ships, oil tankers, and chemical tankers. Unmatched ships were eligible only if their DWT was at least 50,000 tonnes and, where reliable information was available, they were built after 2006. These size and age thresholds were empirical screening criteria, not assumptions that older ships could not have been retrofitted. Accordingly, ships not identified by FLSCCM as following the HFO-with-scrubber pathway were assumed to achieve compliance through the use of low-sulfur fuel. For ships identified or assigned as following the HFO-with-scrubber pathway, SEIMv2.3 applied a baseline $PM_{2.5}$ removal efficiency of …

(2) In Supplementary Information *(page5, para2)*, we presented:

To further evaluate the FLSCCM reconstruction against an independent source, we examined the DWT and age distributions of ships recorded in IMO GISIS and assigned to the HFO-with-scrubber pathway by FLSCCM in the 2024 SEIM fleet (Fig. S10). The two datasets show broadly similar DWT distributions and are both dominated by ships aged 5–19 years. However, differences remain in ship-age composition, and GISIS itself does not provide a complete global scrubber registry. The comparison therefore serves as a fleet-level structural check of the reconstructed compliance pathway rather than validation of the absolute number or scrubber status of every individual ship.

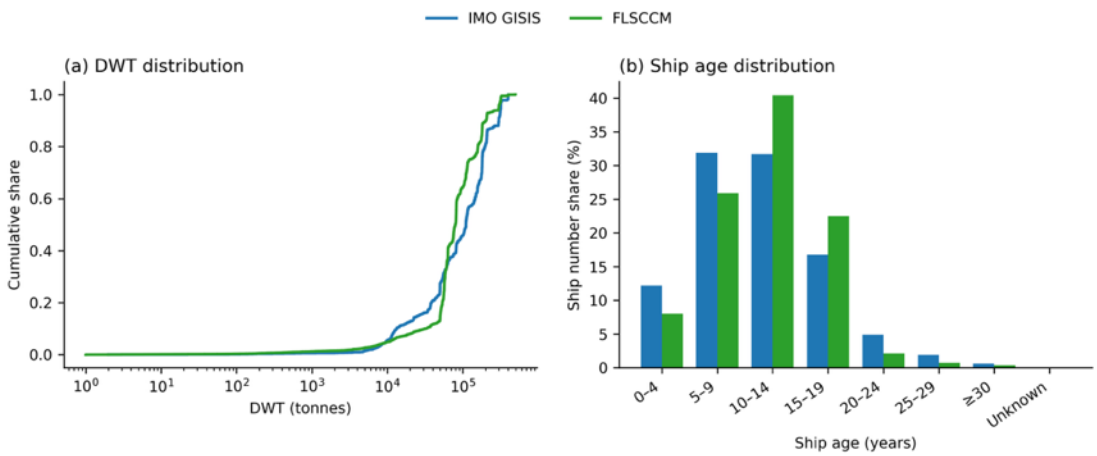


Figure S10. Comparison of the DWT and age distributions of scrubber-equipped vessels recorded in IMO GISIS and identified by FLSCCM in the 2024 SEIM fleet. (a) Cumulative distributions of vessel DWT. (b) Vessel-number shares by age category.

Q3. Comparison with other ship emission inventories for deeper discussion

Line 288-295: A bit of a mixture of method and results? Yous should also compare the other emissions (based on STEAM) with SEIM as these seem to deviate the most in figure 6. Why is STEAM3 showing so much higher PM2.5 and BC compared to SEIM (although they might not include scrubbers)? Why are CO2, N2O and CH4 deviating the way they do. I think figure 6 can give you many interesting discussion points beyond the internal comparison of SEIM versions.

Response:

We agree that the original paragraph mixed the design of the numerical experiments with interpretation of the results. We have therefore moved the description of the three experiments to the Methods section and expanded the Results/Discussion to discuss the differences between SEIMv2.3 and the external inventories shown in Fig. 6.

For $PM_{2.5}$ and BC, the higher estimates in the STEAM-based inventory are likely related in part to differences in the representation of fuel-compliance pathways and scrubber-related particle removal. STEAM incorporates information on emission-abatement technologies, including exhaust-gas cleaning systems, whereas SEIMv2.3 explicitly reconstructs the HFO-with-scrubber pathway and applies pollutant-specific removal assumptions for $PM_{2.5}$ and BC. Recent onboard measurements also show that particle removal by scrubbers is strongly dependent on particle size and composition. We therefore identify differences in scrubber and particulate-emission treatment as one plausible contributor to the divergence, rather than assuming that STEAM does not consider scrubbers.

We also clarified the provenance of the greenhouse-gas comparison. The CH_4 and N_2O values shown in Fig. 6 were obtained from EDGAR, whose spatial and temporal representation of international shipping is based on STEAM-related activity information. We therefore now refer to this comparison as "EDGAR (STEAM-based)", rather than attributing CH_4 and N_2O directly to the original STEAM3 inventory. Differences in CO_2 are mainly associated with differences in fleet/activity representation and fuel-consumption estimates. CH_4 is additionally sensitive to the representation of LNG-fuelled vessels, engine technology, and methane-slip emission factors, while N_2O is more strongly affected by fuel- and engine-specific emission factors and corresponding energy-consumption estimates. These additional comparisons and interpretations have now been incorporated into the revised Discussion.

Revisions:

(1) We removed line 288-292 to METHOD *(page9, para3)* and revised them:

To isolate the contributions of daily STSD updates and FLSCCM, three numerical experiments were conducted for the 2024 inventory: (i) SEIMv2.2 without either update, (ii) SEIM with the updated STSD but without FLSCCM, and (iii) the complete SEIMv2.3 framework. The difference between experiments (ii) and (i) represents the contribution of daily STSD updates, whereas that between experiments (iii) and (ii) represents the contribution of FLSCCM.

(2) In RESULTS *(page13, para1)*, we added:

Comparison between SEIMv2.3 and SEIMv2.2 shows that the absence of daily ship technical database updates would underestimate CO_2 emissions by 5.4% in 2023 and 2.6% in 2024. The 2024 attribution experiments further showed that daily STSD updates accounted for most changes in CO_2 and gaseous-pollutant estimates, whereas FLSCCM had the larger effect on $PM_{2.5}$ and BC (Fig. 6).

(3) In RESULTS *(page13, para2)*, we added:

Comparison with external inventories also revealed pollutant-specific differences. EDGAR (STEAM-based) generally reported higher $PM_{2.5}$ and BC emissions than SEIMv2.3, while differences in CO_2, CH_4, and N_2O were smaller or followed different patterns. Because STEAM3 also accounts for exhaust-gas cleaning systems, the higher $PM_{2.5}$ and BC estimates cannot be attributed simply to omission of scrubbers (Johansson et al., 2017). Instead, differences in fleet representation, fuel-compliance pathways, emission factors, and scrubber removal efficiencies

may contribute to the observed discrepancies. For GHGs, CO_2 is mainly affected by vessel activity and fuel consumption, whereas CH_4 and N_2O are more sensitive to LNG representation, methane slip, and fuel- or engine-specific emission factors (Heikkilä et al., 2024; Yi et al., 2024a).

(3) In the caption of Figure.6, we revised:

Figure 6: Comparison of annual global ship emissions results from SEIMv2.3, SEIMv2.2, and other emission inventories from 2019 to 2024. SEIMv2.2 results were sourced from (Yi et al., 2024). SEIMv2.3 represents the method presented in this paper. EDGAR (STEAM-based) represents international-shipping emission estimates from EDGAR (Crippa et al., 2025), whose spatial and temporal allocation of shipping emissions draws on STEAM-based activity information.

Q4. Comparison with other maritime datasets for ship emission results

Line 366: Here you can refer to IMO gisis and Seaweb and many other studies with global focus as well.

Response:

We have expanded the Discussion to include additional global-scale sources of scrubber information, including IMO GISIS, commercial vessel databases such as Sea-web and Clarksons, and previous global assessments combining vessel-level scrubber information with AIS data. These sources provide valuable independent information but differ in reporting scope, fleet coverage, and accessibility, and no single source can be treated as a complete vessel-level registry of scrubber installations.

Following the reviewer's suggestion, we also examined IMO GISIS as an independent external reference for our reconstructed scrubber fleet. After restricting the comparison to vessels explicitly identified as EGCS/scrubber and active in the 2024 SEIM fleet, FLSCCM identified 1,740 of 2,000 GISIS-recorded vessels (87.0%). The remaining 260 GISIS-only vessels accounted for 1.75% of the relevant fleet DWT and 2.55% of fuel consumption. The reconstructed fleet also showed broadly similar vessel-age and DWT distributions to the GISIS-recorded fleet. We therefore use GISIS as an external validation of the fleet-level reconstruction while acknowledging that individual-vessel scrubber status cannot always be determined with certainty. This discussion and the additional global references have been added to the revised manuscript and Supplementary Information.

Revisions:

In DISCUSSION *(page18, para3)*, we added:

Future reductions in uncertainty require improved ship-specific technical databases, broader sharing of scrubber installation ~~records~~ and fuel-use data, and additional validation data.~~sets such as onboard measurements, EU MRV, or ship bunkering records. Direct single-ship validation remains challenging because such data are rarely publicly available. Nevertheless, comparisons with independent inventories and sensitivity analyses indicate that these uncertainties are unlikely to alter the main conclusions regarding the magnitude and characteristics of global shipping emissions.~~ IMO GISIS provides an important official source of EGCS information, although its coverage is incomplete, while commercial databases and onboard or operational records can provide complementary evidence. Direct single-ship validation remains challenging because comprehensive fuel-use and compliance information is rarely public. However, comparisons with independent inventories and sensitivity analyses indicate that these uncertainties are unlikely to alter the main conclusions.

Justification for daily resolution

Q5. Need for daily-resolution ship emission inventories

Line 46: Here you refer to policy making and timely emission inventories, I think policy is often made on annual basis? Again, is there a need for daily resolution?

Response:

We agree that many emission-control policies are formulated and evaluated over annual or longer timescales. We have therefore revised the manuscript to avoid implying that daily-resolution inventories are primarily needed for day-to-day policy formulation.

The main value of daily-resolution emission inventories lies instead in applications that depend on short-term variations in emissions, including pollution-episode analysis, air-quality simulation and forecasting, and source attribution. Previous studies have highlighted the need to move beyond static annual inventories toward inventories that better represent temporal variations in activity and emissions, particularly for high-temporal-resolution source-apportionment and air-quality applications (Sokhi et al., 2022; Jia et al., 2022). More recently, researchers from China showed that daily emission estimates can improve the representation of short-term emission changes and their air-quality impacts (Gu et al., 2026).

This need is particularly relevant to shipping because vessel locations, speeds, operating states, and traffic intensity can vary substantially from day to day. A daily

ship-emission inventory therefore preserves these activity-driven variations rather than deriving daily emissions from an annual inventory using prescribed temporal profiles. We have revised the Introduction to clarify this motivation and reduced the emphasis on daily-resolution inventories as a direct tool for policymaking.

Revisions:

In INTRODUCTION *(page3, para1)*, we added:

Accurate and timely emission inventories are key to evaluating air quality and climate impacts ~~and facilitating future policymaking~~ (Im et al., 2018; Luo et al., 2024; Liu et al., 2024; Goldsworthy et al., 2019; Huang et al., 2020; Li et al., 2024). While long-term policy assessments often rely on annual inventories, high-temporal-resolution inventories are particularly important for pollution-episode analysis, source attribution, and air-quality modelling, where short-term variations in source activity need to be represented explicitly(Gu et al., 2026; Jia et al., 2022; Sokhi et al., 2022). Bottom-up models…

Q6. Need for daily-resolution STSD

Line 157-159: Since you are only updating STSD every two years, how will the daily resolution help? This is related to my previous comments asking for a clearer motivation for the daily resolution.

Response:

We realize that the original wording may have caused confusion regarding the update frequency of STSD. The statement that STSD is "updated once every two years" refers to the original STSD maintenance scheme used in earlier versions of SEIM. In SEIM v2.3, this limitation is specifically addressed by introducing a daily updating framework.

Each day, static AIS records are used to identify vessels present in the activity database but absent from the STSD. These vessels are then characterized and incorporated before the daily emission calculation. This daily synchronization keeps the fleet-characteristic database consistent with AIS activity records and reduces emission underestimation caused by delayed inclusion of newly observed vessels. We have revised the manuscript to clarify that the biennial update refers to the previous STSD scheme, whereas SEIM v2.3 enables daily identification and supplementation of missing ships.

Revisions:

In METHODS *(page6, para2)*, we added:

The STSD in SEIM contains vessel-specific attributes, including ship type, deadweight tonnage (DWT), and main engine power. In previous versions of SEIM, the STSD was updated approximately every two years, potentially missing vessels newly appearing in the daily AIS activity database (Yi et al., 2024). SEIM v2.3 therefore introduces a daily update framework that identifies AIS-observed vessels absent from the STSD, supplements their technical characteristics, and incorporates them into daily emission calculations.

Clarification of existing methods and assumptions

Q7. Methodology

Line 96: what do you mean with "disaggregated dynamic method"?

Response:

We agree that the term "disaggregated dynamic method" was not sufficiently explicit. We have therefore removed this term from the revised manuscript and replaced it with a direct description of the SEIM methodology. Specifically, we now clarify that SEIM performs emission calculations at the individual AIS-signal level and accounts for variations in vessel operating conditions, including vessel speed and corresponding operating power, based on vessel activity and ship-specific technical characteristics. This wording more directly describes the methodological features intended by the original term.

Response:

In METHOD *(page4, para3)*， we removed the phrase and replaced it with:

SEIM was first established by Liu et al. (2016) based on AIS data and ship-specific technical information to simulate ship emissions at the individual AIS-signal level. This signal-level approach enables ship-by-ship reconstruction of ship activity and emissions, suitable for …

Q8. Ship identification

Line 123: Don't you use IMO-number to identify and match ships?

Response:

Thanks for pointing this out. Our original wording was unclear. Static AIS records contain both MMSI and, where available, IMO numbers, and both identifiers are used in our vessel-matching procedure. IMO numbers are particularly useful for identifying oceangoing vessels because they are permanent ship identifiers, whereas MMSI provides broader coverage of AIS-observed vessels, including vessels for which no IMO number is available. We have revised the manuscript to clarify this point.

Revisions:

In METHODS *(page5, para2)*, we added:

Static AIS contains ship identifiers, including MMSI and, where available, IMO numbers, together with technical information such as ship type, length, width, and draft, and is used for the daily identification and characterization of newly observed ships.

Q9. Figure 3

Figure 3: Is it correct that you assume a fuel consumption that is 30% higher than the IMO numbers? Why is this? Is IMO data also determined from models or is data collected from bunker fuel sold?

Response:

We did not assume that total fuel consumption should be approximately 30% higher than the IMO values. Notably, the HFO consumption estimated by SEIM in 2019 is close to the IMO DCS value, indicating that the difference in total fuel consumption is not a uniform scaling bias across all fuel types.

The IMO reference is based on the mandatory Data Collection System (DCS), which covers ships of 5,000 GT and above, whereas SEIM reconstructs fuel consumption for a broader AIS-observed fleet. One plausible contributor to the higher SEIM total is therefore the broader fleet coverage. Smaller vessels and vessels operating in coastal waters are more likely to use distillate fuels such as MDO/MGO, whereas HFO use is concentrated more strongly among larger oceangoing commercial vessels (Celik et al., 2020). Extending the fleet beyond the IMO DCS reporting threshold can therefore increase total fuel consumption without producing a proportional increase in HFO consumption. Differences in fuel-category definitions and model-based fuel assignment may also contribute to the remaining discrepancy.

We have clarified in the revised manuscript that the IMO values are reported DCS data rather than bunker-sales or purely model-derived estimates, and that the difference should be interpreted in light of fleet coverage and fuel classification rather than as an imposed 30% uplift.

Revisions:

In METHODS *(page9, para4)*, we added:

The close agreement in HFO consumption, particularly in 2019, suggests that the higher total fuel consumption in SEIM is not a uniform scaling effect but is more likely associated with its broader fleet coverage and differences in fuel composition

relative to the IMO DCS reporting fleet. Therefore, IMO statistics were used as an independent fleet-level reference …

Q10. Ship identification by IMO number

Line 237: What do you men with "If we identified ship number by unique IMO…", didn't you do that?

Response:

We did use IMO numbers in the vessel-identification and matching process. Our intention in this sentence was to compare the growth of STSD under two different counting conventions: unique MMSI and unique IMO number. MMSI provides broader coverage of AIS-observed vessels, including vessels without an IMO number, but it may change during a vessel's lifetime. In contrast, the IMO number is a permanent ship identifier and therefore provides a more stable basis for tracking oceangoing vessels over time. Consequently, the total number of vessels differs depending on whether unique MMSI or unique IMO numbers are used. We have revised the text to make this distinction explicit.

Revisions:

In RESULTS *(page10, para1)*, we replaced the original sentences with:

Over the study period, ~~the number of ships (identified by unique MMSI) in the STSD increased from 418,000 to 440,000, representing a growth of 5.3%. If we identified ship number by unique IMO number (primarily for oceangoing ships), the STSD exhibited more significant growth, expanding from 105,000 to 126,000 ships—a notable increase of 20.0%, underlining that dynamic update of STSD effectively enhanced the coverage of oceangoing ships.~~ the number of vessels in STSD increased from 418,000 to 440,000 when counted by unique MMSI, corresponding to a 5.3% increase. When counted by unique IMO number, which provides a more stable identifier for oceangoing vessels, the number increased from 105,000 to 126,000, corresponding to a 20.0% increase. The difference between the two counts reflects their different coverage and identifier characteristics: MMSI provides broader coverage of AIS-observed vessels, whereas IMO numbers are permanent identifiers but are not available for all vessels.

Q11. Air quality implications

Line 367-369: In this particular study, little differences are shown in air quality. What if you consider port cities with less other industries? How has air quality changed then?

Response:

We agree that our original wording may have been unclear. The Busan study did not show little change in air quality overall; rather, it reported a pronounced decrease in SO_2 following the sulfur regulation, while the change in ambient $PM_{2.5}$ was not statistically significant (Song et al., 2022). Our intention was therefore to highlight the contrasting responses of gaseous sulfur pollution and bulk particulate matter, rather than to suggest that the regulation had little air-quality benefit.

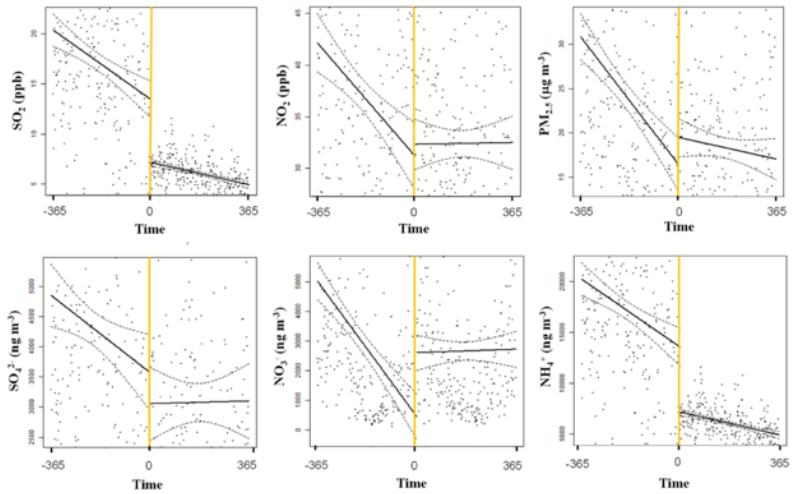


Fig. 4. RDD results for SO_2, NO_2, $PM_{2.5}$, and SIA (SO_4^{2-}, NO_3^-, and NH_4^+) in $PM_{2.5}$ at BS2 port.

Figure R1. RDD results for SO_2, NO_2, $PM_{2.5}$ and SIA in $PM_{2.5}$ at Busan port (Song et al., 2022)

We have now expanded this discussion by considering additional port studies. Similar results have been reported in Shanghai, where SO_2 decreased substantially after implementation of ship-emission controls, while the response of $PM_{2.5}$ and its components was more heterogeneous (Zhang et al., 2019). Studies in Canadian port cities also found that $PM_{2.5}$ decreased less markedly than SO_2 following marine sulfur regulations (Anastasopolos et al., 2021). Together, these studies suggest that SO_2 responds more directly to sulfur-control measures, whereas ambient $PM_{2.5}$ is influenced by a broader mixture of sources and atmospheric processes.

We also agree with the reviewer that examining ports with fewer competing industrial sources would be informative. However, major ports are commonly co-located with industrial, transport, and urban emission sources, making it difficult to isolate the shipping contribution to ambient $PM_{2.5}$ using observational data alone. We have therefore revised the manuscript to clarify this limitation and to avoid over-interpreting the Busan results.

Revisions:

In DISCUSSIONS *(page17, para2)*, we revised and added:

Song et al. (2022) ~~analyzed $PM_{2.5}$ concentrations near Busan Port before and after the IMO 2020 sulfur regulation and found limited changes in ambient $PM_{2.5}$,~~

~~highlighting the complexity of evaluating shipping impacts based solely on particle mass concentrations.~~ reported a pronounced reduction in SO_2 at Busan Port following the IMO 2020 sulfur regulation, while no statistically significant change was observed in bulk $PM_{2.5}$. Similar patterns have been reported in Shanghai, and studies in Canadian port cities also found that $PM_{2.5}$ reductions were smaller than those of SO_2 (Anastasopolos et al., 2021; Zhang et al., 2019). These contrasting responses reflect the stronger direct link between sulfur regulation and SO_2, whereas ambient $PM_{2.5}$ is influenced by multiple emission sources and atmospheric processes.

Q12. PN emissions with scrubbers

Line 373-377: There are also studies showing an increase of PN with scrubbers, e.g. Winnes et al 2020, Grigoriadis et al 20204 and Santos et al 20204 discuss this.

Response:

Thank you for pointing out these studies. We agree that our original discussion did not sufficiently reflect the variability in reported particle-number responses to scrubbers. The available evidence indicates that the effect of scrubbers on PN is not unidirectional and depends strongly on particle size, volatility, scrubber configuration, fuel properties, engine operating conditions, and measurement methodology.

For example, Winnes et al. (2020) reported a substantial reduction in total PN downstream of the scrubber, although the reduction in the solid particle fraction was limited and particle emissions remained higher than those obtained with low-sulfur fuel. In contrast, onboard measurements by Grigoriadis et al. (2024) showed higher PN concentrations downstream of an open-loop scrubber than at engine-out, which were attributed to condensational growth, salt particles, and the formation of sulfuric-acid particles in the smaller size range. Santos et al. (2024) further showed that wet scrubbing reduced total PN but shifted the sulfate mode toward larger particle sizes, increasing particle-mass emission factors and cloud-condensation-nuclei emissions. An earlier experiment by Santos et al. (2022) also reported an increase in PN following wet scrubbing.

We have revised the Discussion accordingly to emphasize that scrubber effects on particle emissions cannot be represented by a single PN removal efficiency and that both particle number and size-dependent characteristics should be considered in future ship-emission inventories.

Revisions:

In DISCUSSION *(page17, para3)*, we added:

However, the influence of scrubbers on PN is highly variable. Some measurements have reported substantial reductions in total PN downstream of scrubbers (Winnes et al., 2020; Kuittinen et al., 2024), while others have observed increased PN associated with the formation or growth of ultrafine sulfur-containing particles (Grigoriadis et al., 2024). Santos et al. (2024) further showed that reductions in total PN can coincide with shifts toward larger sulfate particles and increases in particle mass or cloud-condensation-nuclei emissions. These contrasting responses indicate that future ship emission inventories should consider PN size distributions and scrubber-specific particle characteristics in addition to $PM_{2.5}$ mass emissions.

Q13. Reference to IMO GISIS for scrubber use

Line 397: when discussing databases, you should refer to IMO gisis with respect to scrubber-use (it is not complete but it is official).

Response:

Thanks for this suggestion. We have added IMO GISIS to the Discussion as an official regulatory source of information on approved equivalent compliance methods, including EGCS/scrubber installations, while noting that it does not provide a complete global registry of scrubber-equipped vessels.

Following the reviewer's suggestion, we also used GISIS as an independent external reference for the reconstructed scrubber fleet. After restricting the comparison to vessels explicitly identified as EGCS/scrubber and active in the 2024 SEIM fleet, FLSCCM identified 1,740 of 2,000 GISIS-recorded vessels (87.0%). We have added this comparison to the Supplementary Information and revised the Discussion accordingly.

Revisions:

In DISCUSSION *(page18, para3)*, we added:

Future reductions in uncertainty require improved ship-specific technical databases, broader sharing of scrubber installation and fuel-use records, and additional validation datasets. IMO GISIS provides an important official source of vessel-level information on approved equivalent compliance methods, including EGCS installations, although its coverage is not complete. Commercial databases and complementary observations, such as onboard measurements, EU MRV data, and ship bunkering records, could further support vessel-level validation. Direct single-ship validation nevertheless remains challenging because comprehensive fuel-use and compliance information is rarely publicly available. Nevertheless, comparisons with independent inventories and sensitivity analyses suggest that

these uncertainties are unlikely to alter the main conclusions.

MINOR COMMENTS

Q14. Wording and terminology in ABSTRACT

Response:

Thanks for these detailed comments on wording and terminology. We have carefully revised the manuscript throughout the Abstract, Introduction, Methods, Results, and Discussion to improve precision, consistency, and readability.

Revisions:

Line 15: why are ship emission inventories "indispensable"?

~~To evaluate emission control effects and conduct rapid response air quality simulations, accurate and timely ship emission inventories are indispensable.~~

Accurate and timely ship emission inventories are **essential** for evaluating emission control effects and conducting rapid-response air quality simulations.

Line 23: "persistent impact", I propose to change wording. Perhaps "remaining issue"?

The resulting emission discrepancies gradually accumulated over 2024, ~~demonstrating the persistent impact of delayed fleet information updates on ship emission estimates.~~ indicating that delayed fleet information updates remain an important source of uncertainty in ship emission estimates.

Q15. Wording and terminology in INTRODUCTION

Revisions:

Line 30: define "hard-to-abate" as you do in abstract.

As one of the hard-to-abate sectors (Sharmina et al., 2021), global shipping experienced a threefold increase in cargo turnover and a 1.7-fold increase in carbon dioxide (CO2) emissions from 1970 to 2021 (Wang et al., 2025).

As a sector characterized by high energy demand, long-lived assets, and limited near-term low-carbon alternatives, global shipping is considered hard to abate (Sharmina et al., 2021). From 1970 to 2021, global shipping experienced a threefold increase in cargo turnover and a 1.7-fold increase in carbon dioxide (CO_2) emissions (Wang et al., 2025).

Line 57: add CO2.

In particular, distinguishing Heavy Fuel Oil (HFO) use with scrubbers from low-sulfur fuel switching remains challenging at the global ship level, despite their substantially different implications for $PM_{2.5}$, and BC emissions. For CO_2 and

pollutants such as NO_x, incomplete fleet information can also lead to biased emission estimates through missing ship activity and fuel consumption penalty.

Line 60: write out ECA abbreviation.

From January 1, 2020, the global sulfur limit for ship fuel oil was reduced from 3.50% to 0.50%, while a stricter limit of 0.10% applies within emission control areas (ECAs).

Line 72: using "therefore" seems a bit strange here.

~~Therefore, neglecting HFO-with-scrubber pathways may introduce substantial uncertainty into post-2020 estimates of $PM_{2.5}$, and BC emissions.~~

This limitation highlights the potential uncertainty introduced by neglecting HFO-with-scrubber pathways in post-2020 estimates of $PM_{2.5}$ and BC emissions.

Line 76: you have not explained the static database yet.

In this study, newly identified ships include both newly delivered vessels and existing vessels absent from the ~~original static database.~~ ship technical database used for bottom-up emission estimation. ~~Unlike ship activity data that can be processed at daily resolution, ship technical databases are generally updated with substantial delays~~ Such databases are typically updated less frequently than AIS-based activity data (Yi et al., 2024a), creating a temporal mismatch between fleet information and observed ship activity.

Line 84: "remains lacking" sounds wrong.

However, an integrated framework that simultaneously updates ship activity and technical information with quality control remains ~~lacking~~ limited.

Line 90: With "AIS-derived information" the authors mean IMO-numbers right? Be more explicit.

Second, newly identified ships are dynamically detected from ~~AIS activity records and incorporated into the static ship technical database, with missing specifications supplemented through AIS-derived information and machine-learning-based reconstruction.~~ AIS records using ship identifiers such as MMSI and IMO number, and incorporated into the ship technical database. Missing technical specifications are then reconstructed using available static AIS attributes, including ship type, length, width, and draft, together with machine-learning models.

Q16. Wording and terminology in METHODS

Revisions:

Line 146: what do you mean with "short delay"? Give a time (span).

This preprocessing window is required for trajectory reconstruction from delayed AIS transmissions, while SEIMv2.3 enables near-real-time emission updates ~~with~~

~~a short delay~~ approximately three days after AIS data acquisition.

Line 185: and CO2

...with different implications for fuel consumption, SO_2 emissions, $PM_{2.5}$, ~~and~~ BC, and, to a lesser extent, CO_2 emissions.

Q17. Wording and terminology in RESULTS

Line 230: I think it is misleading to say 20 ships per day detected. The "per day" indicates that we see 20 ships per day entering the market/fleet but as you have already shown you include old ships (most of them being rather old). So the increase you detected is a model/database improvement right and would give the same result if you looked at annual data? Same comment for sentence on line 338.

Response:

We agree that the expression "20 ships per day" could be misleading. We have revised the sentence to avoid misunderstanding. We also agree that a retrospective analysis of a complete year of AIS data could identify many of the same missing ships. The purpose of the daily procedure, however, is to identify and characterize such ships when they first appear in the incoming AIS data, allowing them to be incorporated into subsequent three-day-delay emission calculations without waiting for an annual or periodic fleet-database update.

Revisions:

~~An average of 20 ships (identified by MMSI number) previously absent from the STSD are detected per day,~~ Daily AIS processing identified approximately 20 previously unrepresented ships on an average processing day, which were subsequently incorporated into the STSD.

Figure 5: is this distribution on an annual basis or daily?

Figure 5: Annual spatial distribution of newly detected ship signals.

Line 271: Define pollutants.

Comparisons were limited to pollutants ~~with~~ available ~~and comparable estimates.~~ across inventories. $PM_{2.5}$ was excluded from the CEDS comparison because corresponding estimates were unavailable.

Figure 7: do you mean differences between SEIM versions here?

Figure 7. Regional differences in ship PM2.5, BC, CO2, and NOx emissions between SEIMv2.3 and SEIMv2.2 ~~underestimation mitigated by SEIMv2.3 in different ocean regions~~ in 2024.

Q18. Wording and terminology in DISCUSSION

Line 364: "Our conclusions are supported..." which conclusions?

~~Our conclusions are~~ The continued importance of HFO-with-scrubber pathways after IMO 2020 is also supported by independent evidence from IMO fuel consumption statistics, scrubber installation records, and ambient particle observations.

Q19. Supporting literature for scrubbers' impact on CO2 emissions

Line 38-40: what about increase/change in CO2 emissions? Using a scrubber comes with a fuel penalty of approx.. 2% (depending on vessel type etc).

Response:

Thanks for this important point. Following the reviewer's suggestion, we examined the literature on the additional energy demand associated with scrubber operation and found support for a fuel-consumption penalty of approximately 2%, with the exact value depending on vessel type and scrubber configuration. We have added this evidence to the revised manuscript and now clarify that, although scrubbers are effective for sulfur compliance, their operation can lead to a small increase in fuel consumption and associated CO_2 emissions.

Revisions:

In INTRODUCTION *(page2, para1)*, we added:

Previous research showed that after the International Maritime Organization (IMO) low sulfur regulation came into force in 2020, ship SO_2 emissions dropped by 81.3% globally (Yi et al., 2024a) and by 71% in Southern China (Feng et al., 2023). The regulation has a comparatively small effect on CO_2 emissions. For ships equipped with scrubbers to comply with the regulation, additional energy is required, commonly resulting in an approximately 2% fuel-consumption penalty (Lunde Hermansson et al., 2024). Studies evaluating regional sulfur regulations have demonstrated their effectiveness in reducing ship-related SO_2 emissions...

Q20. Supporting references

Line 66: "Nevertheless, multi-source evidence indicates that HFO-based compliance pathways remained important after 2020." Needs reference.

Response:

This sentence was intended as a topic sentence summarizing the evidence presented immediately afterward. To make the support explicit, we have added references to the sentence while retaining the subsequent discussion of IMO fuel statistics, regional bunker data, and scrubber-equipped vessels.

Revisions:

Nevertheless, multi-source evidence indicates that HFO-based compliance

pathways remained important after 2020 (IMO, 2024; Lunde Hermansson et al., 2024).

Q21. Supporting references

Line 69-71: the 800 vessels with scrubbers in Baltic Sea in presented Lunde Hermansson et al 2024 was detected using STEAM

Response:

Thanks for directing us to the STEAM-based methodology underlying the analysis of Lunde Hermansson et al. (2024). We revisited the study and confirmed that the reported scrubber-equipped vessels in the Baltic Sea were identified and analysed using STEAM v4.3.0, with the methodology referring to Jalkanen et al. (2021). We have therefore revised the manuscript to describe this evidence more precisely as a STEAM-based regional assessment of continued scrubber operation after 2020.

Revisions:

Moreover, a STEAM-based assessment (Jalkanen et al., 2021; Lunde Hermansson et al., 2024) ~~Lunde Hermansson et al. (2024)~~ identified more than 800 scrubber-equipped ships operating in the Baltic Sea after 2020...

Q22. Supporting literature

Line 105: add examples of other bottom-up models

Response:

Representative AIS-based bottom-up models, including STEAM, MariTEAM, and MoSES, had already been introduced earlier in the Introduction. To avoid repetition while making the reference explicit, we now briefly refer back to these examples at Line 105.

Revisions:

Similar to other AIS-based bottom-up models introduced above (e.g., STEAM, MariTEAM, and MoSES), SEIM reconstructs ship activity…

Q23. General formatting

Remove brackets around references where they are listed in sentences (e.g. line 96 and Line 100).

Response:

We have revised all such in-text citations throughout the manuscript so that references incorporated into sentences are presented without unnecessary brackets.

Q24. Reference to SI

Refer to supplementary information where applicable but avoid writing out sentences like "detailed factors are provided in Fig S4".

Response:

We have revised these sentenses throughout the manuscript so that Supplementary Information is cited more concisely.

Q25. Removing Summary part

Why do you have a separate summary followed by conclusion? Incorporate summary part in results and shorten the conclusion (see comment in point by point list e.g. move line 380-395 to result/discussion)

Response:

We have removed the separate Summary section, incorporated the relevant content into the Results and Discussion, and shortened the Conclusion accordingly.

Q26. Code and data availability

Regarding Code and data availability: is the STSD data set available?

Response:

The STSD was constructed using several underlying data sources, including commercially purchased ship technical data that are subject to licensing restrictions. Therefore, the complete STSD cannot be made publicly available. However, the dataset may be made available from the corresponding author upon reasonable request, subject to the applicable data-use and licensing conditions. We have clarified this point in the Code and Data Availability section.

Response to Reviewer #2:

OVERALL

The paper was improved considerably. The authors took almost all of my comments appropriately into account. I have two remaining issues that should be addressed.

Response:

We sincerely thank the reviewer for the careful and constructive comments in the first round, which helped us substantially improve the manuscript. We are also very pleased to see that the revised version has addressed most of the previous concerns and that only two issues remain. We appreciate these final comments and have addressed them carefully below.

Major Specific Comments

Q27. Title and abstract modification

When reading the title and the abstract, it is still not sufficiently clear that the paper describes updates in a specific ship emission model, namely the update from SEIM v2.2 to SEIM v2.3. I propose to modify the title into "Addressing systematic underestimation in a global ship emission inventory through improved fleet representation and fuel compliance characterization" and to mention SEIM in the abstract.

Response:

We have revised the title accordingly and modified the Abstract to explicitly state that this study updates the Ship Emission Inventory Model from SEIM v2.2 to SEIM v2.3. The major updates, including improved fleet representation and sulfur-compliance characterization, are now clearly introduced in the Abstract.

Revisions:

In ABSTRACT *(page1)*, we changed the sentence into:

Here, we ~~established a dynamically~~ updated the Ship Emission Inventory Model to SEIMv2.3 by introducing an improved representation of post-2020 fuel sulfur compliance pathways and enabling ~~that allows~~ near-real-time emission calculation within three days of AIS data acquisition.

Q28. Validation for scrubber installation

The model artificially increases the number of ships that use scrubbers from 4,285 to 11,932. It is rather unrealistic that the STSD misses more than 7,000 ships with scrubber installations. The authors should find out what a realistic number for large ocean-going vessels with scrubber installations is and make clear how much their numbers deviate from this.

Response:

Thanks for raising this important concern. We agree that increasing the number of vessels assigned to the HFO-with-scrubber pathway from 4,285 to 11,932 through statistical reconstruction introduces uncertainty and is a limitation of the present approach. These additional vessels should therefore not be interpreted as confirmed scrubber installations.

A key difficulty is that no globally complete ship-level scrubber database is currently available. In the present revision, following a suggestion from Reviewer 1, we additionally examined the IMO Global Integrated Shipping Information System (GISIS), an official IMO source containing records of approved equivalent compliance methods, including scrubbers. We compared these records with the commercial Clarksons scrubber dataset and found substantial but incomplete overlap between the two sources. Within the 2024 SEIM active fleet, Clarksons recorded 4,392 scrubber-equipped ships and IMO GISIS recorded 2,000, of which 1,489 were common to both datasets (Figure R2). This corresponds to about 74% of the GISIS-recorded ships but only 34% of the Clarksons records. When considering the broader scrubber records available up to 2024, Clarksons contained 6,138 ships and IMO GISIS 2,028, with only 1,492 ships recorded in both datasets (Figure R3). Thus, even an official regulatory source and a major commercial database provide substantially different ship-level coverage. This inconsistency highlights the difficulty of defining a complete global scrubber fleet from any single existing database and motivates the use of a fleet-level proxy rather than treating either source as complete ground truth.

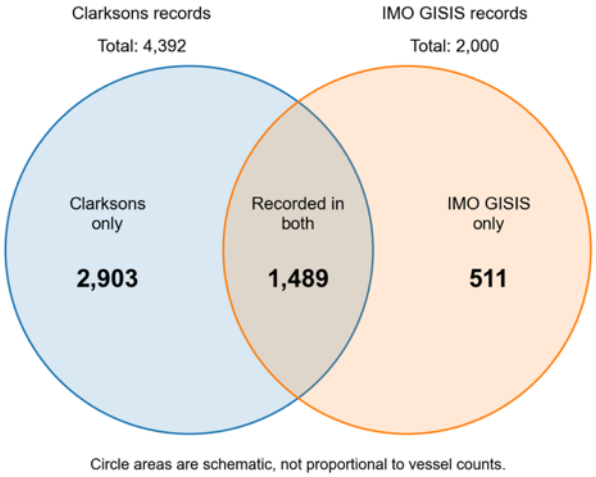


Figure R2. Overlap between Clarksons and IMO GISIS scrubber records within the 2024 SEIM active fleet.

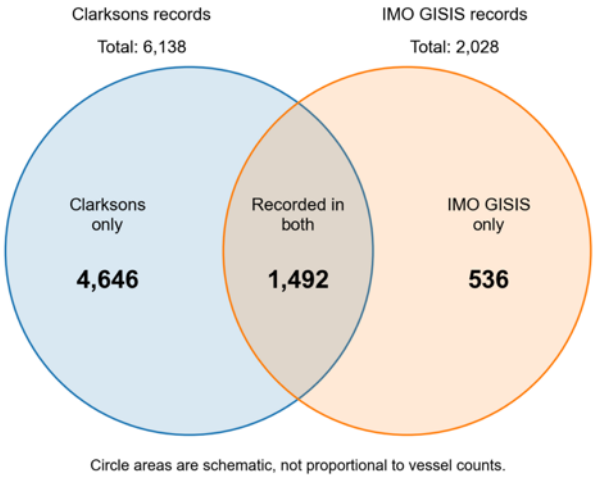


Figure R3. Overlap between Clarksons and IMO GISIS scrubber records

FLSCCM was therefore developed as a fleet-level proxy for reconstructing sulfur-compliance pathways rather than as a ship-by-ship scrubber registry. We nevertheless evaluated the reconstruction using several independent checks. Among 2,000 vessels explicitly recorded as EGCS/scrubber-equipped in IMO GISIS and active in the 2024 SEIM fleet, FLSCCM identified 1,740 (87.0%), and the reconstructed fleet showed broadly similar DWT and vessel-age distributions. Because the objective of FLSCCM is emission estimation, we also compared the reconstructed fuel structure with IMO fleet-level fuel-consumption statistics, for which HFO consumption showed good agreement.

In addition, sensitivity analyses showed that uncertainty in the reconstructed fleet size had a comparatively small influence on the resulting emissions. Varying

the DWT threshold changed inferred scrubber-vessel numbers substantially, while $PM_{2.5}$ and BC emissions changed by only −3.1% to +2.1% and −0.5% to +0.3%, respectively. Alternative construction-year treatments changed the reconstructed fleet size from 9,950 to 11,931 vessels, while $PM_{2.5}$ and BC emissions changed by only 5.4% and 1.0%.

We have revised the manuscript and Supplementary Information to clarify the proxy nature of FLSCCM, introduce the IMO GISIS comparison suggested by Reviewer 1, and explicitly acknowledge the uncertainty associated with the exact number of vessels assigned to the HFO-with-scrubber pathway.

Revisions:

In DISCUSSION, *(page18, para1)*, we added:

Second, FLSCCM reconstructs sulfur compliance pathways using ship-level scrubber records combined with constrained statistical allocation because global ship-specific fuel-use observations are unavailable. The exact number of ships assigned to the HFO-with-scrubber pathway therefore remains uncertain and should be interpreted as a fleet-level proxy rather than a census of confirmed scrubber installations. However, sensitivity tests show that substantial changes in the reconstructed fleet size produce only limited changes in global $PM_{2.5}$ and BC emissions.

In S3. Characteristics of observed scrubber-equipped vessels, we added a paragraph:

To further evaluate the FLSCCM reconstruction against an independent source, we examined the DWT and age distributions of ships recorded in IMO GISIS and assigned to the HFO-with-scrubber pathway by FLSCCM in the 2024 SEIM fleet (Fig. S10). The two datasets show broadly similar DWT distributions and are both dominated by ships aged 5–19 years. However, differences remain in ship-age composition, and GISIS itself does not provide a complete global scrubber registry. The comparison therefore serves as a fleet-level structural check of the reconstructed compliance pathway rather than validation of the absolute number or scrubber status of every individual ship.

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