RESPONSE TO REVIEWERS

Journal: Atmospheric Chemistry and Physics
MS No.: egusphere-2026-1935
Manuscript Title: Addressing systemic underestimation in global ship emissions from fleet growth and fuel compliance

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. Please refer to the revised manuscript for the *page number and line number* mentioned in *italic*.

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.

Content

Response to Reviewer #1:

OVERALL

This paper presents an updated version of a ship activity model to better estimate the atmospheric emissions of CO2, SOX, BC, NOX and PM2.5 where both number of vessels, distance sailed and compliance option with respect to the IMO global sulfur cap is included. While presenting important new data, showing the underestimation of all emissions of atmospheric pollutants, it lacks a further discussion.

Response:

Thank you for your insightful and constructive feedback on our manuscript. We are glad that you recognize the value of our study in underestimation in global shipping emissions. Your comments have enlightened us with valuable perspectives on the broader implications of our work, and we greatly appreciate the thoughtful consideration you've given to our work.

We will seriously address these questions by reorganizing a more comprehensive and detailed description of the methodology and clarifying the assumptions on which the model is based. Further analyses were also conducted on the uncertainties and limitations of the results. These efforts are expected to strengthen the rigor and robustness of the conclusions of this study.

Thanks again for your time and effort in providing such thoughtful input.

DETAILS

Q1. Contribution analysis

If authors think it is the adoption to daily resolution, the data curation and/or the addition of more vessels to the model that have the greatest influence on the results?

Response:

We appreciate the opportunity to further clarify the relative contributions of the methodological improvements introduced in this study.

As introduced in the METHOD *(page4, line95)*, SEIMv2.3 differs from previous versions through three major improvements: (1) daily AIS collection and preprocessing, (2) daily updating of the Ship Technical Specification Database (STSD) by incorporating newly identified vessels, and (3) the Fleet Low Sulfur Compliance Choice Module (FLSCCM). Below we discuss the contribution of each improvement to the emission estimates.

First, the adoption of daily AIS data itself does not change the emission calculation results compared with annual AIS data, but changes the temporal resolution of the inventory from annual to daily and enables near-real-time emission estimation. To accommodate the characteristics of daily AIS data, we developed a dedicated preprocessing, or data curation framework which includes temporal anomaly removal, spatial anomaly removal, interpolation across long signal gaps, and route restoration. The data curation influenced the emission results in many ways. For example, filtering out spatial anomaly signals decreases the emissions while route restoration increases emissions.

Data curation provides the foundation for emission calculations, rather than constituting an improvement to the underlying emission calculation methodology. Therefore, we did not analyze the influence of data curation on the emission results, while we did evaluate its effectiveness by comparing the spatial distribution of AIS signals before and after preprocessing. As shown in Figure 1 for representative regions and Figure S1 for the global dataset, the preprocessing framework effectively removes abnormal signals while preserving realistic shipping activities.

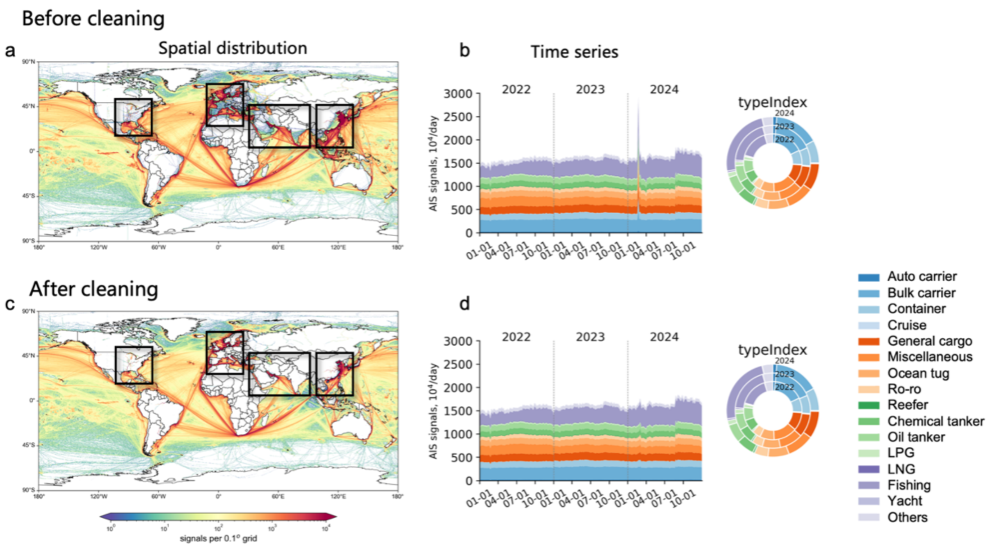


Figure S1. The spatial distribution and time series of AIS before and after preprocessing

Second, to quantitatively distinguish the contributions of the remaining two methodological improvements, namely the daily STSD update and the FLSCCM, we designed three numerical experiments for the 2024 emission inventory based on fully curated AIS dataset:

- We first calculated emissions using the previous SEIMv2.2 framework, which neither incorporates newly identified vessels nor includes the FLSCCM, yielding emission estimate E1.
- We then applied the complete SEIMv2.3 framework, including both the daily STSD update and the FLSCCM, yielding E2.
- Finally, we ran SEIMv2.3 with the FLSCCM disabled while retaining the updated STSD, yielding E3.

Accordingly, the difference E2 − E3 represents the contribution of the FLSCCM (labelled as FLSCCM-2024 in Figure 6), whereas E3 − E1 represents the contribution of the daily STSD update (labelled as STSD-2024 in Figure 6).

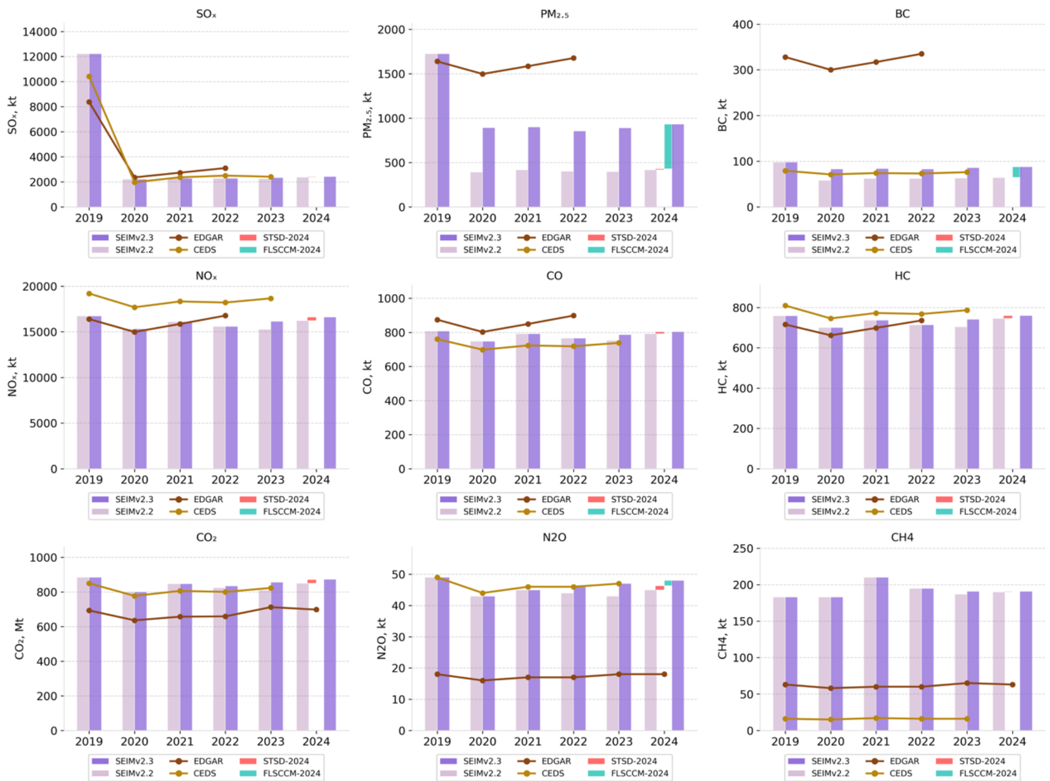


Figure 6: Comparison of annual global ship emissions results from SEIMv2.3, SEIMv2.2, and other studies. SEIMv2.2 results were sourced from (Yi et al., 2024). SEIMv2.3 represents the method presented in this paper. EDGAR represents the emission results from Emissions Database for Global Atmospheric Research, sourced from (Crippa M., 2025). CEDS represents the emission results from Community

Earth atmospheric Data Systems, sourced from (Hoesly, 2025).

The results demonstrate that the relative importance of these two improvements depends on the pollutant considered. For CO_2, NO_x, CO, HC, N_2O, CH_4, and most gaseous pollutants, the daily STSD update contributes the majority of the mitigated underestimation because it increases the completeness of the active fleet represented in the model. For example, failure to identify and characterize newly active ships would have resulted in an underestimation of global CO_2 emissions by 5.4% in 2023 and 2.6% in 2024. In contrast, the FLSCCM plays the dominant role for $PM_{2.5}$ and BC because their emission factors are highly sensitive to the fuel-compliance pathway adopted after implementation of the IMO global sulfur limit. Neglecting continued HFO use after 2020 would underestimate $PM_{2.5}$ and BC emissions by approximately 55% and 27%, respectively, of which approximately 97% is mitigated by the FLSCCM. For SO_2, both compliance pathways achieve substantial sulfur reductions, and the difference between their contributions is therefore less pronounced than for $PM_{2.5}$ and BC. These quantitative results are presented in Figure 6 and discussed in Sect. 3.2.

Based on your suggestion, we have further clarified the respective roles of daily AIS processing, the daily STSD update, and the FLSCCM in both the Methods and Results sections.

Revisions:

(1) In METHOD *(page4, line89)*, we have clarified whether the three improvements we introduced influence the emission results.

In SEIMv2.3, we collected daily AIS data and enhanced the pre-process accordingly to enable near-real-time ship emission calculation. Compared with collecting AIS annually, this operation does not change the emission results, but only changes the temporal resolution of the results. Detailed methods are provided in Sect. 2.1.

(2) In RESULTS *(page12, line264)*, we presented the analysis of the contributions of different factors on total emissions in a separate paragraph at the end of Sect.3.2 and added a description of the analytical methods and results:

To quantitatively distinguish the contributions of daily identification and characterization of new ships (denoted as STSD-2024 in Fig. 6) and the fleet low sulfur compliance choice module (denoted as FLSCCM-2024 in Figure 6), numerical experiments were conducted for the 2024 emission inventory. (i) SEIMv2.2 was applied without daily STSD updates or the FLSCCM; (ii) SEIMv2.3 was applied with the updated STSD but with the FLSCCM disabled; and (iii) the complete SEIMv2.3 framework was applied. Consequently, the difference between experiments (iii) and (ii) represents the contribution of the FLSCCM, whereas the difference between experiments (ii) and (i) represents the contribution of the daily STSD update. The results indicate that the dominant source of emission underestimation varies among pollutants. The daily STSD update contributes most to the reduction in underestimation for CO_2 and most gaseous pollutants by improving fleet completeness, whereas the FLSCCM plays a larger role for $PM_{2.5}$ and BC because these pollutants are highly sensitive to post-2020 fuel compliance pathways.

Q2. Implications for environment and health

Given the systematic underestimation (and 20% is a lot), what are the implications of the shipping fleet's impact on the environment and human health and what can be proposed as measures to improve reporting, data sharing and inclusion of global shipping in future climate/impact models?

Response:

We agree that the approximately 20% systematic underestimation in shipping emission can propagate into biases in environmental, climatic, and health-impact assessments based on bottom-up ship emission inventories. The implications differ across environmental pathways and geographical regions.

Ship-emitted primary PM and secondary particulate matter formed from SO_2 can alter marine aerosol concentrations and cloud condensation nuclei, thereby affecting cloud microphysical properties, cloud formation, and aerosol radiative forcing (Sofiev et al., 2018; Shi et al., 2023; Yi et al., 2026). Underestimated $PM_{2.5}$ and SO_2 emissions may therefore bias assessments of the climatic effects of shipping. Sulfur and nitrogen compounds deposited onto the ocean may also affect surface-water acidity and marine biogeochemistry, particularly along intensively trafficked shipping routes and in coastal or semi-enclosed waters, although the magnitude of these effects depends on seawater buffering capacity, circulation, and the spatial scale considered (Shi et al., 2023).

The implications for human health should be interpreted more cautiously. As described in the METHOD section, most of the additional emissions identified in this study originate from open-ocean regions outside Emission Control Areas, rather than near densely populated coastal areas. Therefore, the effect of the inventory correction on population exposure and associated health burdens is likely to be limited. Nevertheless, long-range transport may still influence coastal air quality. The spatially and temporally resolved inventory developed in this study can provide a basis for future modelling studies to quantify the resulting effects on climate, air quality, and human health.

Our results also highlight the need for improved data accessibility and observational validation. We therefore propose the following measures:

(i) Establishing more timely and accessible global databases for vessel technical specifications, new-build records, engine characteristics, and exhaust-gas cleaning system installations. At present, much of this information is available primarily through costly commercial providers, such as Clarksons Research, limiting its use in independent scientific research. Future data-sharing mechanisms should better balance commercial interests and confidentiality with scientific needs, for example by providing standardized, aggregated, or research-access versions of essential vessel data.

(ii) Conducting additional onboard, plume-based, remote-sensing, and port-based measurement campaigns covering different ship types, engine loads, operating conditions, fuels, and emission-control technologies. Such observations would support the validation and refinement of emission factors, fuel-compliance assumptions, and emission estimates at both individual-vessel and aggregated regional scales.

Together, these measures would improve the completeness, transparency, and reliability of global shipping emission inventories and strengthen their application in future assessments of climate, air quality, human health, and marine environmental impacts.

Revisions:

In DISCUSSION *(page16, line333)*, we expanded the discussion on the environmental and health impacts of the underestimated emissions:

Near-real-time emission inventories enable tracking of short-term emission changes and provide a data foundation for emission reduction policies (Xu et al., 2023). The systemic underestimation addressed in this study may affect assessments of the environmental and health impacts of global shipping. Underestimated $PM_{2.5}$ and SO_2 emissions may bias estimates of shipping-induced aerosol–cloud interactions and radiative forcing (Chen et al., 2017; Goldsworthy et al., 2019; Yuan et al., 2024). The deposition of sulfur and nitrogen compounds may also affect surface-water acidity and marine biogeochemistry, particularly along heavily trafficked routes and in coastal or semi-enclosed waters (Shi et al., 2023). The additional contribution to population exposure and health burdens may be limited, because the additional emissions identified in this study were mainly in open-ocean regions, distant from populated coastal areas.

In DISCUSSION *(page 17, line366)*, we combine our idea of how to improve data reporting with your last comment about uncertainties:

These uncertainties can be constrained at the inventory level through complete data curation and systematic sensitivity analyses, while future improvements in ship-specific technical databases and broader sharing of vessel technical specifications, scrubber installation records, and fuel-use or bunkering data would further reduce uncertainties at the individual-vessel level and facilitate the use of shipping emission inventories in future climate and impact models.

Q3. Distinguish between VLSFO, MGO, and ULSFO

The authors focus on two compliance options (low sulfur fuels and HFO + scrubber) but given the high temporal resolution of ship activity data, would it be possible to divide low sulfur options into VLSFO (in 0.5% areas) vs MGO (and ULSFO) (in 0.1% areas)? My guess is that emission factors are different but the question is if data is available to differentiate.

Response:

Thank you for this important comment. We agree that the low-sulfur fuel pathway should distinguish fuels used under the 0.5% and 0.1% sulfur limits because their emission factors differ. In the revised model description, VLSFO and MGO are represented as separate fuel categories, and all fuel categories and corresponding emission factors used in SEIMv2.3 are provided in Tables S2 and S3.

Specifically, high-resolution AIS data are used to determine the sulfur limit applicable to each vessel according to its operating time and location. For vessels following the fuel-switching pathway, fuel used in waters subject to the IMO 0.5% global sulfur limit is represented using VLSFO emission factors, whereas fuel used in ECAs and other waters (such as China DECA) subject to the stricter 0.1% sulfur limit is represented using MGO emission factors.

However, the model cannot reliably distinguish ULSFO from MGO within the 0.1% sulfur fuel category. AIS data identify vessel activity and location but not the actual fuel product consumed onboard, and globally consistent ship- or voyage-level data distinguishing ULSFO from MGO are unavailable. Although both fuels comply with the 0.1% sulfur limit and therefore have broadly similar SO_2 emission factors when their actual sulfur contents are comparable, residual-type ULSFO may have higher $PM_{2.5}$ and black carbon emission factors than distillate MGO. Representing all fuels used in 0.1% sulfur areas using MGO emission factors may therefore cause some underestimation of $PM_{2.5}$ and black carbon where ULSFO is used. We have clarified this assignment procedure and associated uncertainty in Sect. 2.3, the Discussion, and the Supplement.

Revisions：

(1) In METHOD *(page8, line193)*, we have expanded the description of the compliant fuel assignment strategy as follows:

For ships assigned to option (1), the specific compliant fuel is further determined according to the sulfur limit applicable to the operating year and geographical location. Their default fuel is represented using VLSFO emission factors, whereas fuel used in ECAs and other waters subject to the stricter 0.1% sulfur limit is represented using MGO emission factors. Admittedly, uncertainties and limitations exist in the fleet low sulfur compliance choice module. For example, ULSFO is not represented as a separate fuel category and fuels used in 0.1% sulfur areas are therefore represented using MGO emission factors. They will be explained in detail in Discussion section.

(2) In DISCUSSION *(page16, line359),* we have clarified the limitation regarding ULSFO and MGO:

Third, FLSCCM does not distinguish ULSFO and MGO, and fuels of 0.1% sulfur are represented using MGO emission factors. This simplification is expected to have limited influence on SO_2, but it may lead to some underestimation of $PM_{2.5}$ and BC emissions where residual-type ULSFO is used.

Q4. Emission factors

On emission factors, would it be possible to present these as ranges instead of absolute numbers to reflect the variability? Is engine load accounted for in the modelling, if not the authors could discuss the implications of including this? For many pollutants, emission factors are tested at different loads so it should be possible to do some estimations (present ranges as proposed in previous point).

Response:

Thank you for this helpful suggestion, which allows us to clarify how engine-load variability is represented in SEIMv2.3. Engine load and low-load adjustment factors are already explicitly considered in the emission calculations. Table S2 reports the baseline energy-based emission factors assigned according to fuel type, engine type, engine-speed category, and NO_x Tier. For each AIS record, the instantaneous main-engine load is estimated from vessel speed using the propeller law. When the estimated load is below 20%, the corresponding baseline emission factor is multiplied by a pollutant-specific low-load adjustment factor; at loads of 20% or higher, the baseline value is retained. Therefore, the effective emission factor applied in the calculation varies with the operating load rather than remaining constant.

We agree that presenting only the baseline values in the original Supplement did not adequately convey this load-dependent variability. However, we did not replace the baseline factors with a single minimum–maximum range. Instead, we retained the baseline factors in revised Table S2 and added the pollutant-specific LLAF curves and their applicable load range in Fig. S6. This allows the effective emission factor at any load below 20% to be reproduced directly, while preserving the signal-by-signal calculation framework.

We also reorganized the Supplementary Information so that revised Table S2 summarizes the baseline energy-based emission factors, whereas revised Table S3 summarizes the fuel properties, sulfur contents, and fuel-based emission factors used in the fuel-switching module. This reorganization, together with Fig. S6, more clearly shows both the baseline values and their load-dependent adjustment in SEIMv2.3.

Revision:
(1) In METHOD *(page4, line82)*, we added a sentence to clarify that engine load was considered in the calculation process:
Engine-load effects were explicitly considered by estimating the main-engine load for each AIS record and applying pollutant-specific low-load adjustment factors when the load was below 20%. Detailed factors are provided in Fig. S6.

(2) In Supplementary Information, we added Fig. S6. and a note.

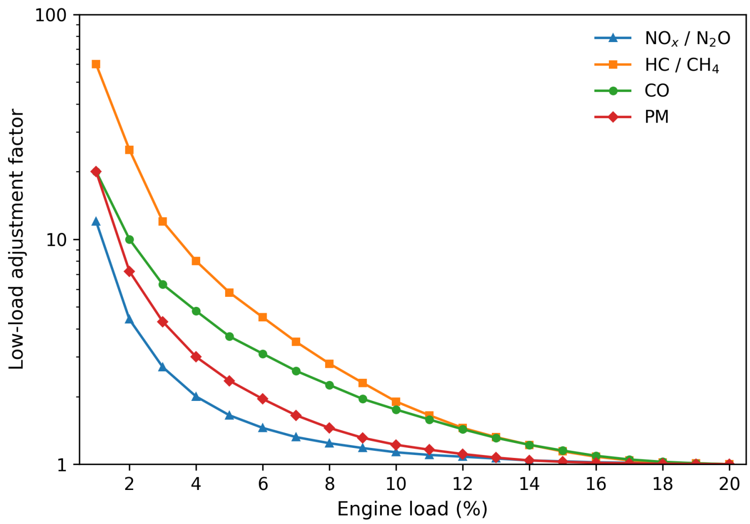


Figure S6. Low-load adjustment factors applied to main-engine emission factors in SEIMv2.3.

Notes. Low-load adjustment factors applied to main-engine emission factors as a function of estimated engine load. Baseline emission factors are retained at engine loads of 20% or higher. At engine loads below 20%, pollutant-specific low-load adjustment factors are applied to NOx/N_2O, HC/CH_4, CO, and PM according to (Icf International, 2009).

(2) In Supplementary Information, we reorganized Table S2 to summarize the baseline energy-based emission factors, whereas revised Table S3 to summarize the fuel properties, sulfur contents, and fuel-based emission factors used in the fuel-switching module. We also explained when and how LLAF was applied.

Table S2. Baseline energy-based emission factors applied in SEIMv2.3 (unit: g/(kWh))

Fuel	**Engine**	**Engine type**	**NOx**				**$PM_{2.5}$**	**SOx**		**HC**	**CO**	**CH4**	**N2O**	**CO2**	
			Tier 0	**Tier I**	**Tier II**	**Tier III**		**Tier 0**	**Tier I–III**					**Tier 0**	**Tier I–III**
HFO	ME	SSD	18.1	17.0	14.4	14.4	1.39	9.404	8.896	0.632	0.54	0.010	0.031	576.090	544.950
	ME	MSD	14.0	13.0	10.5	10.5	1.39	9.912	9.404	0.527	0.54	0.010	0.034	607.230	576.090
	ME	HSD	10.0	9.8	7.7	7.7	1.39	10.420	9.912	0.527	0.54	0.010	0.030	638.370	607.230
	AE	AE	11.2	11.2	11.2	11.2	1.40	10.420	9.912	0.400	0.54	0.010	0.040	638.370	607.230
	Boiler	BE	2.1	2.1	2.1	2.1	1.42	17.283	17.283	0.100	0.20	0.002	0.040	1058.760	1058.760
VLSFO (0.5% S)	ME	SSD	18.1	17.0	14.4	14.4	0.31	1.715	1.617	0.632	0.54	0.010	0.030	561.050	528.990
	ME	MSD	14.0	13.0	10.5	10.5	0.31	1.813	1.715	0.527	0.54	0.010	0.030	593.110	561.050
	ME	HSD	10.0	9.8	7.7	7.7	0.31	1.862	1.813	0.527	0.54	0.010	0.034	609.140	593.110
	AE	AE	11.2	11.2	11.2	11.2	0.31	1.862	1.813	0.400	0.54	0.010	0.036	609.140	593.110
	Boiler	BE	2.1	2.1	2.1	2.1	0.31	3.136	3.136	0.100	0.20	0.002	0.049	1025.920	1025.920
MGO (0.1% S)	ME	SSD	18.1	17.0	14.4	14.4	0.20	0.342	0.323	0.632	0.54	0.010	0.030	561.050	528.990
	ME	MSD	14.0	13.0	10.5	10.5	0.20	0.362	0.342	0.527	0.54	0.010	0.030	593.110	561.050
	ME	HSD	10.0	9.8	7.7	7.7	0.20	0.371	0.362	0.527	0.54	0.010	0.034	609.140	593.110
	AE	AE	11.2	11.2	11.2	11.2	0.20	0.371	0.362	0.400	0.54	0.010	0.036	609.140	593.110
	Boiler	BE	2.1	2.1	2.1	2.1	0.20	0.626	0.626	0.100	0.20	0.002	0.049	1025.920	1025.920
LNG	ME	SSD	1.3	1.3	1.3	1.3	0.02	0.005	0.004	0.500	1.30	2.500	0.020	475.750	335.500
	ME	MSD	1.3	1.3	1.3	1.3	0.02	0.005	0.004	0.500	1.30	5.500	0.020	475.750	335.500
	ME	HSD	1.3	1.3	1.3	1.3	0.02	0.005	0.004	0.500	1.30	5.500	0.020	475.750	335.500
	AE	AE	1.3	1.3	1.3	1.3	0.02	0.005	0.005	0.500	1.30	5.500	0.020	475.750	429.000
	Boiler	BE	1.3	1.3	1.3	1.3	0.03	0.009	0.009	0.105	0.20	0.040	0.020	783.750	783.750

Notes: The values listed in Table S2 are baseline energy-based emission factors. For each AIS record, the main-engine load was estimated from vessel speed using the propeller law. When the estimated load was below 20%, the baseline emission factor was multiplied by the pollutant-specific low-load adjustment factor shown in Fig. S6; at loads of 20% or higher, the adjustment factor was set to 1. Therefore, the effective emission factor used in the calculation varied with engine load.

Table S3. Fuel properties and fuel-based emission factors used for fuel switching

Fuel	Carbon content (m/m%)	$EFCO_2$,f (g/gfuel)	Sulfur content (m/m%)	$EFSO_2$,f (g/gfuel)
HFO (2.43% S)	0.8493	3.1140	2.6	0.0510
VLSFO (0.5% S)	0.8744	3.2060	0.5	0.0098
MGO (0.13% S)	0.8744	3.2060	0.13	0.0025
LNG	0.7500	2.7500	~0	0.0000317

MINOR COMMENTS

Q5. Graphical abstract

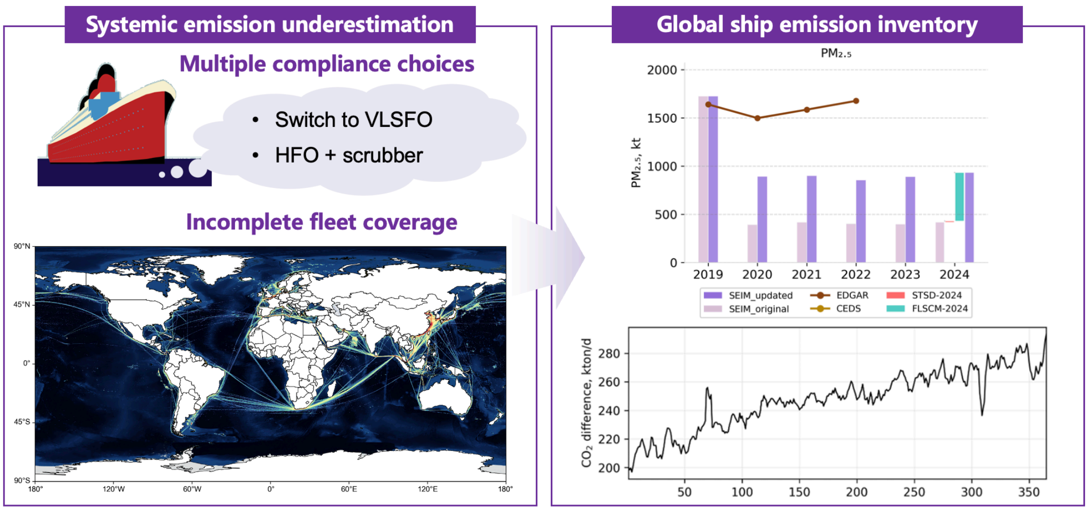
Objects in graphical abstracts need to be enlarged to allow for better illustration.

Response:

Thank you for this helpful suggestion. We have revised the graphical abstract by enlarging the main objects and simplifying the layout. Specifically, the ship-compliance illustration, fleet-description map, and inventory comparison panels were enlarged, while minor graphical elements and overly detailed labels were removed to improve readability.

Revision:

In page 2, we revised the graphical abstract:



Q6. Text revision

row 27: is the 1.7 rise of atmospheric emissions referring to CO2? specify.

Response:

Thank you for pointing this out. We confirm that the reported 1.7-fold increase refers specifically to global shipping CO_2 emissions, as reported in the cited study. To avoid ambiguity, we have revised the corresponding sentence in the manuscript to explicitly state “CO_2 emissions” instead of the more general term “atmospheric emissions”.

Revision:

In INTRODUCTION *(page2, line28)*, we changed ‘atmospheric’ to ‘CO_2’:

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 (CO_2) emissions from 1970 to 2021 (Wang et al., 2025).

Q7. Text revision

IMO should always be written in capital letters.

Response:

Thank you for pointing this out. We have corrected the capitalization of IMO throughout the manuscript to ensure that it is consistently presented in capital letters, including those in the citation.

Q8. Implications for missing new vessels

Row 54-57: the implications of missing new vessels are discussed but it is not really clear to me why this is a challenge and why this is relevant, please specify.

Response:

Thank you for this valuable comment. We agree that the implications of missing newly active vessels were not sufficiently explained in the original manuscript.

Ship emission estimation relies on combining AIS-derived activity data with vessel technical specifications, such as deadweight tonnage, build year, engine power, ship type, and fuel information, which are used to assign engine loads and emission factors. However, when newly active vessels are absent from ship technical databases, their missing specifications have to be filled using default or assumed values. These default values may differ substantially from the actual characteristics of individual vessels, leading to large errors in engine power estimation, emission factor assignment, and consequently ship-level emissions. This makes missing new vessels a relevant challenge for near-real-time emission inventories.

To reduce such errors, our framework supplements missing vessel parameters using machine-learning models based on available physical information, such as vessel length and width, to predict deadweight tonnage, engine power, and ship type. These predicted parameters provide more vessel-specific inputs than direct default assignment and thus help improve the accuracy of emission estimation for newly active vessels. We have revised the manuscript to clarify this point.

Revision:

(1) In INTRODUCTION *(page3, line60)*, we explained why missing new vessels would become a challenge in generating accurate emission inventory:

Unlike ship activity data, which can be updated daily, ship technical databases are generally supplemented at least one year later (Yi et al., 2024a). As a result, newly built ships often lack key technical specifications and have to be represented by proxy values, which can affect engine power estimation, load-factor correction, and emission factor assignment, thereby introducing uncertainties into shipping emission estimation.

(2) In METHOD *(page6, line149)*, we added the necessity of parameter completion:

(2) Static AIS lack main engine power and DWT information, which is also critical for matching emission factors. Without additional parameter completion, these missing specifications would have to be represented by default or proxy values, which may introduce considerable uncertainties in engine power estimation and subsequent emission factor assignment. Through extensive literature review,…

Q9. Emission calculation formula

row 74: authors say formula is largely consistent, what differed? what does this mean?

Response:

Thank you for pointing this out. We agree that the phrase "largely consistent" was ambiguous. Our intention was to indicate that the fundamental emission calculation equations remain identical to those in our previous study, whereas the methodological advances of the present work lie in the daily activity preprocessing, dynamic ship technical database, and fleet compliance module.

Revision:

(1) In METHOD *(page4, line79),* we have revised the corresponding sentence to explicitly state that the core emission calculation equations are identical to those in our previous study:

The specific formula used in this study to calculate ship emissions are identical to those reported by (Yi et al., 2024a) and provided in Supplementary Information.

(2) In Supplementary Information, we further highlighted that the core emission equations were identical to Yi et al. (2024a) and that the differences occurred in updated input data preprocessing and module-level assignments:

Emission calculation principles of SEIMv2.3

The mathematical formulation of the emission calculation is identical to that described by Yi et al. (2024a). Therefore, differences from Yi et al. (2024a) arise from updated input data preprocessing and module-level assignments rather than changes in the core emission equations. SEIMv2.3 calculates atmospheric emissions for every ship by every two subsequent AIS signals…

Q10. Annual data preprocess

row 103: Do the authors know how annual data is treated? is that unprocessed? how is the overlap handled?

Response:

Thank you for this valuable comment. We admitted that the preprocessing procedures for the annual AIS dataset were not clearly described in the original manuscript.

Annual AIS datasets are not used without preprocessing. Similar to the daily AIS datasets, they undergo ship identification and quality-control procedures before being used for emission estimation. The main difference lies in the characteristics of the two datasets and the corresponding preprocessing strategies. For the annual AIS dataset, the interval threshold used to identify temporally abnormal AIS signals is set to a much larger value because the data are collected less frequently. In addition, signal transmission delay is not considered during annual preprocessing, since annual datasets do not aim to preserve the exact temporal sequence of ship activities. In contrast, the daily AIS preprocessing framework is specifically designed for near-real-time applications and therefore includes additional procedures to identify delayed AIS transmissions and reconstruct the chronological sequence of ship movements.

We would also like to clarify that the annual and daily AIS datasets are processed independently and are used in different model applications. Only one dataset is used in each emission calculation; therefore, there is no overlap or double counting between the two approaches.

Based on your suggestion, we have clarified the differences between the preprocessing procedures for annual and daily AIS datasets in the revised manuscript.

Revision:

(1) In METHODS *(page4, line106)*, we have expanded the description of the preprocessing procedures for the annual and daily AIS datasets. We also further explained the difference between daily and annual AIS preprocessing:

Therefore, rigorous pre-processing was necessary especially for daily near-real-time emission calculation.
Annual AIS data used in previous SEIM were also preprocessed before emission calculation, while the present daily framework differs from the annual preprocessing mainly in its treatment of temporal anomalies and delayed signal transmission. For the annual AIS dataset, temporal anomaly filtering was conducted with a larger interval threshold because the signals were collected at lower frequency.
For the daily AIS dataset, firstly, to ensure the stability of daily input data, …

(2) In METHOD *(page4, line111)*, We also further clarified the difference between annual and daily AIS pre-processing, in handling the transmission delay:

Unlike annual AIS preprocessing, the daily framework explicitly accounts for transmission delays because daily AIS data received on a given day may contain signals with timestamps from both the current and previous days.

Q11. Implications for scrubber installation

Scrubber installations are also underreported, please discuss implications for this.

Response:

When scrubber-equipped vessels are not identified in technical databases, their use of high-sulfur fuel oil combined with exhaust gas cleaning may not be adequately represented, leading to biases in the assumed fuel mix and associated emission factors. This issue affects not only SO_2 estimates, but potentially also PM2.5, black carbon, and particle number.

Moreover, complete installation records alone cannot fully resolve this issue, because the actual operation of scrubbers may vary across voyages and operating conditions. Globally consistent and continuously available information on whether scrubbers are operating, particularly during ocean-going voyages, remains limited. Consequently, assuming that an installed scrubber is operated throughout all relevant periods may also introduce errors into emission estimates.

We have therefore added a discussion clarifying that incomplete scrubber installation and operational data may affect both atmospheric emission estimates and the broader environmental assessment of shipping emissions.

Revision:

In DISCUSSION *(page16, line361)*, we added a discussion clarifying that incomplete information on both scrubber installation and actual operation can affect the emission calculation:

Finally, incomplete scrubber installation records may bias $PM_{2.5}$, BC, and PN emission calculation because unidentified scrubber-equipped vessels may be treated as using low-sulfur fuels. Besides, installation records alone do not fully indicate whether scrubbers are actually operated during the whole voyages, which introduces further uncertainty.

Q12. Reference

row 150-152: add reference for the emission factors.

Response:

Thank you for this helpful suggestion. The sources of the emission factors were already provided in the Supplementary Information. However, we agree that the corresponding references were not explicitly indicated in the main text, which may have caused unnecessary ambiguity. We have therefore added the relevant references in the revised manuscript and clarified that the emission factors are primarily based on the IMO Fourth Greenhouse Gas Study(Imo, 2020) and the National Standard for General Diesel Fuel of the People's Republic of China.

Revision:

In METHOD *(page4, line79)*, we added the source and reference for emission factors:

… and provided in Supplementary Information. Emission factors for different ship types and fuels are listed in Table S2 and Table S3, primarily based on the IMO Fourth Greenhouse Gas Study (IMO, 2020), U.S. Environmental Protection Agency reports (Starcrest Consulting Group, 2022) and the National Standard for General Diesel Fuel of the People's Republic of China (GB 252-2015).

Q13. Scrubber installation determination

row 167-170: Does the DWT threshold ensure that cruise vessels are included. There is a DNV report on ship types with scrubbers showing that a large fraction of container vessels and cruise ships have installed scrubbers. Speed will also determine fuel consumption and thus motivate installation of scrubbers.

Response:

Thank you for this important comment. We agree that the current DWT threshold does not explicitly ensure the inclusion of cruise ships. The purpose of the fleet low-sulfur compliance choice module (FLSCCM) is not to reconstruct a complete ship-specific scrubber installation database, but to correct the major bias in emission estimation caused by neglecting the HFO + scrubber compliance pathway in previous global inventories. Therefore, the DWT-based criterion was designed for the ship categories contributing most to global HFO consumption and emissions, namely bulk carriers, container ships, and tankers.

We also agree with the reviewer that DNV data show substantial scrubber uptake in several ship types, including container vessels and cruise ships. However, cruise ships represent only a small fraction of the global fleet activity in our AIS dataset, as shown in Fig. S1. Therefore, although the omission of an explicit cruise-specific scrubber criterion may affect local estimates in cruise-intensive coastal regions, its influence on the global emission totals is expected to be limited.

Regarding vessel speed, we agree that speed strongly affects fuel consumption and may therefore influence the economic incentive for scrubber installation. In SEIMv2.3, speed is already used in the activity-based emission calculation. However, we did not use speed as a fixed criterion for scrubber assignment because voyage speed is highly dynamic and varies with route, weather, operational conditions, and ship status. In contrast, DWT is a stable and globally available vessel attribute, and the DWT threshold was calibrated against IMO fuel consumption statistics to reproduce the observed post-2020 HFO consumption share.

Based on this comment, we have clarified in the revised manuscript that the DWT threshold is an economic proxy for assigning the main HFO + scrubber pathway among major cargo ship types, rather than a ship-type screening criterion that explicitly captures cruise ships. We also added a discussion of the associated uncertainty for cruise-intensive regions.

Revisions:

(1) In METHOD *(page8, line187)*, we have clarified that the DWT threshold is used as an economic criterion for major cargo ships that contribute to a large proportion of shipping emissions:

For this study, a threshold of 40,000 DWT was applied (Fig. S4). The DWT threshold is used as a proxy for scrubber adoption among major HFO-consuming cargo ship types rather than as a ship-type screening criterion. Therefore, it does not explicitly capture scrubber adoption by passenger ships and service ships.

Q14. Figure 4

Figure 4 "fleet number by weight bin" , not possible to see the higher weight bins. Also, can the higher representation of new-found vessels in Bulk and container say

something about reporting/control of these segments in general? Oil tankers are perhaps rigorously documented with strict vetting procedures etc while bulk/container are less controlled?

Response:

Thank you for this helpful suggestion. In the revised Figure 4, we have therefore applied a logarithmic radial scale only to this subplot, which substantially improves the visibility and comparison of the less populated weight bins while preserving the original presentation of the other subplots. This modification improves the visualization of the fleet size distribution across weight classes while preserving the relative patterns presented in the original figure.

We agree that the higher representation of newly identified vessels in bulk carriers and container ships may provide information on reporting and operational visibility across ship segments.

However, we would not interpret this pattern as evidence that bulk carriers and container ships are less controlled. Bulk carriers and container ships are subject to general SOLAS requirements, including mandatory AIS carriage for cargo ships above relevant gross-tonnage thresholds. In addition, bulk carriers are covered by SOLAS Chapter XII on additional safety measures, while containerized shipping is subject to SOLAS requirements such as verified gross mass before loading (Imo, 2024b, a). Therefore, the observed pattern is more likely related to fleet growth and AIS-based detectability rather than weaker regulatory control.

In our framework, newly identified vessels are primarily captured from AIS signals and then supplemented with technical information, rather than being identified from reporting-based records alone. Therefore, the larger number of newly identified bulk carriers and container ships may reflect both their fleet growth and their relatively high detectability in AIS-based updating. Bulk carriers have a large baseline fleet size, so a similar relative increase can lead to a large absolute number of additional vessels. For container ships, the recent expansion of containerized shipping (Unctad, 2021) may also contribute to the larger number of newly identified vessels.

Conversely, recent studies suggest that shadow-fleet activities are predominantly associated with oil tankers, which may reduce their detectability in AIS-based fleet updating (Caprile, 2024; U.S. Department of the Treasury, 2025). Therefore, the smaller apparent increase in oil tankers should not necessarily be interpreted as evidence of more complete fleet records alone. Although this remains a plausible explanation, we do not have sufficient quantitative evidence to assess its contribution in the present study.

Revision:

In RESULTS *(page 10)*, we revised the ‘Fleet number by weightBin’ subplot on the top-right corner:

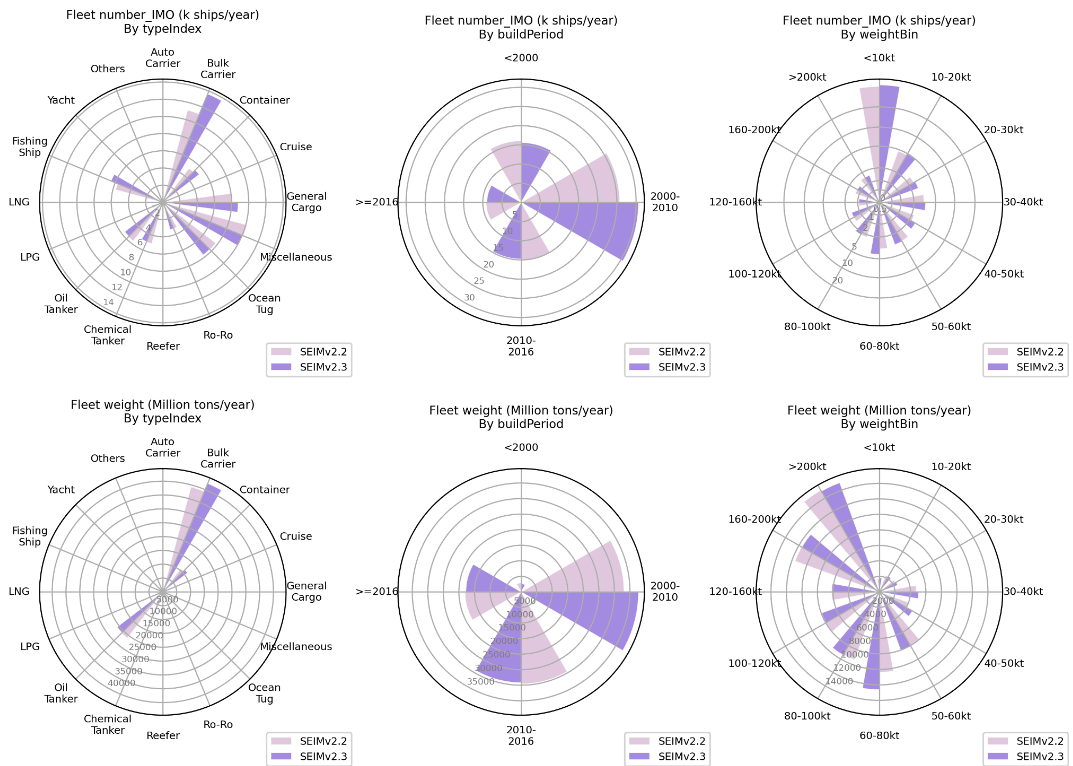


Figure 4: The composition of ship number and total weight of the active global fleet by SEIMv2.3 and SEIMv2.2. **For the “Fleet number by weight bin” subplot, the radial axis is displayed on a logarithmic scale to improve the visualization of categories with relatively small fleet sizes.**

Q15. Validation

EDGAR and CEDS should be described in text.

Response:

Thank you for this comment. We agree that EDGAR and CEDS were insufficiently introduced in the original manuscript. We have now defined both datasets at their first occurrence and briefly described their scope and relevance to the comparison. EDGAR, the Emissions Database for Global Atmospheric Research, is a global anthropogenic emission inventory that provides sector-resolved estimates of greenhouse gases and air pollutants. CEDS, the Community Emissions Data System, provides consistent historical anthropogenic emissions of reactive gases, aerosols, and greenhouse gases by sector. Their international shipping estimates were used here as independent global datasets for comparison with the temporal trends derived from SEIMv2.3.

Revision:

In RESULTS *(page11, line242)*, we added definitions and brief descriptions of EDGAR and CEDS at their first occurrence in the Results section. We also clarified that their international shipping estimates were used as independent global datasets for evaluating the temporal trends derived from SEIMv2.3.

… using different models from 2019 to 2024. For comparison, we used international shipping emissions from the Emissions Database for Global Atmospheric Research (EDGAR), a global sector-resolved inventory of anthropogenic greenhouse gases and air pollutants, and the Community Emissions Data System (CEDS), a consistent historical inventory of sectoral anthropogenic emissions. These datasets provide independent global estimates against which the temporal trends in SEIMv2.3 can be evaluated.

Q16. Text revision

The only GHG included is CO2 right? If yes, be specific and change to CO2 instead of GHG in text.

Response:

Thank you for pointing this out. In this study, greenhouse gas (GHG) emissions include not only CO_2 but also CH_4 and N_2O, which are estimated following the same emission calculation framework. Therefore, the use of the term GHG in the manuscript is intentional rather than referring exclusively to CO_2. To avoid potential ambiguity, we have revised the relevant text to explicitly clarify that GHG emissions in this study comprise CO_2, CH_4, and N_2O.

Revision:

In RESULTS *(page11, line241)*, we clarified that GHG emissions in this study comprise CO_2, CH_4, and N_2O at GHG's first appearance in the RESULTS Section:

Figure 6 shows the global ship emissions of nine atmospheric pollutants and greenhouse gases (GHG), including CO_2, CH_4, and N_2O, calculated using different models from 2019 to 2024.

Q17. Share of global shipping emissions

How does the increase of CO2 emission change the global shipping contribution of CO2-emissions? What is this equivalent to?

Response:

Thank you for this insightful comment. International shipping contributes approximately 2.9% of global anthropogenic CO_2 emissions. Therefore, a 5.4% increase in estimated shipping CO_2 emissions corresponds to an increase of approximately 0.16% in the contribution of shipping to global anthropogenic CO_2 emissions.

Although this change is relatively small from the perspective of the global carbon budget, this does not diminish the importance of accurately quantifying shipping emissions. A relatively small percentage correction corresponds to a substantial amount of CO_2 emissions at the global scale and is important for policy evaluation and tracking progress toward decarbonization targets. In addition, unlike CO_2, shipping emissions contribute disproportionately to air pollution in coastal regions; therefore, improving the completeness of ship emission inventories is particularly important for regional air-quality assessment.

Based on this suggestion, we have clarified these implications in the revised manuscript.

Revision:

In RESULTS *(page12, line262)*, we clarified the implication of the underestimated CO_2 emissions and emphasized that, although their share in total shipping emissions is relatively small, their inclusion improves the completeness of the inventory and supports policy-relevant emission tracking:

Although the proportion of underestimated emissions relative to total shipping emissions was relatively low, the inclusion of newly identified ships enabled us to capture emission changes caused by fluctuations in maritime trade and provided a more complete basis for monitoring shipping decarbonization and evaluating mitigation policies.

Q18. Text revision

row 252: should it really say "only 29%"? 29% sounds like a lot

Response:

Thank you for pointing this out. We agree that the word “only” was inappropriate in this context because an underestimation of 29% is still substantial. We have therefore revised the sentence to present the comparison in a neutral manner without implying that the underestimation in the South China Sea is negligible.

Revision:

In RESULTS *(page14, line292)*, we revised the sentence as follow:

For BC emissions, the underestimated portion reached 39% and 38% in the Indian Ocean and Red Sea, respectively, and was also as high as 29% in the South China Sea.

Q19. Text revision

row 259: air pollutants refer to what compounds? be specific instead.

Response:

Thank you for pointing this out. We agree that the term “other air pollutants” was too general. In the revised manuscript, we have explicitly specified the individual pollutants included instead of referring to them collectively.

Revision:

In RESULTS *(page14, line297)*, we removed the original sentence “For other air pollutants and GHG, the proportion is smaller, from 2% to 12.6%.” and specified it with:

For the remaining pollutants, the underestimated proportion was 9.1% for SO_2, 12.6% for NOx, 9.5% for CO, 11.2% for HC, 10.0% for CO_2, 1.9% for CH_4, and 7.6% for

N_2O.

Q20. Particular number

row 301: elaborate more on the particle number discussion, many more references on that topic and the impact of scrubbers on particle number.

Response:

Thank you for this valuable suggestion. We agree that the original discussion of particle number (PN) emissions was too brief and did not sufficiently explain the implications of the IMO 2020 sulfur regulation or the role of scrubbers.

In the revised manuscript, we substantially expanded this discussion from three aspects. First, we clarified that changes in PM cannot be directly translated into changes in PN or particle size distributions. Second, we reviewed recent studies on the response of PN emissions to sulfur regulation and fuel switching. These studies show that although sulfur reduction generally decreases PN emissions, the magnitude of the reduction depends strongly on fuel type and combustion conditions, and therefore remains less certain than the response of PM. Third, we expanded the discussion of scrubbers. Recent onboard and laboratory measurements indicate that scrubbers modify PN emissions in a particle-size-dependent manner, with different responses for total PN, nonvolatile PN, and larger soot-containing particles. Consequently, PM reductions cannot be directly used to infer PN reductions.

Based on these findings, we further clarified that the present study improves the representation of PM emissions through the fleet low sulfur compliance choice module, but does not explicitly simulate PN emissions or particle size distributions. We therefore identified explicit representation of PN emissions under different fuel-compliance pathways as an important direction for future development.

Revision:

In DISCUSSION *(page16, line344)*, we expanded the discussion of PN emissions and scrubbers' impact on them:

… His findings indicated that the IMO low sulfur regulation did not affect PM2.5 emissions. In addition to $PM_{2.5}$ mass emissions, PN emissions deserve further attention because ship exhaust contains large numbers of ultrafine particles that are not well represented by particle mass alone. Kuittinen et al. (2021) argued that ship emissions remain a significant source of anthropogenic PN emissions after 2020. Measurements in the Baltic Sea SECA showed that reducing fuel sulfur content from 1.5% to 0.1% decreased plume PN concentrations by 27% and ambient PN concentrations by 32% (Seppälä et al., 2021). Meanwhile, ship plumes can still contribute up to 19% of PN concentrations on days affected by shipping lanes (Kivekäs et al., 2014). The effect of scrubbers on PN is also size- and configuration-dependent. Onboard measurements on a modern cruise ship showed that a hybrid scrubber reduced total PN and nonvolatile PN, but no significant reduction was observed for particles larger than 50 nm, which commonly include BC and metal-containing particles (Kuittinen et al., 2024).

Admittedly, certain limitations exist in our methodology. On one hand, although SEIMv2.3 improves the representation of shipping PM2.5 emissions, the present inventory does not include PN emissions. Future development should incorporate PN emission factors and size-resolved particle information to better assess the climatic and health impacts of shipping emissions….

Q21. Uncertainties

row 302-307: this should be discussed earlier in discussion and elaborated on: why does uncertainties appear? How can they be reduced? Is there a way of validating at single-ship level?

Response:

Thank you for this valuable suggestion. We agree that the original uncertainty discussion was too brief. In the revised manuscript, we expanded the discussion about uncertainty on three aspects: (1) the main sources of uncertainty, (2) possible approaches to reduce them, and (3) the feasibility of single-ship validation.

Specifically, we explained that uncertainties mainly arise from machine-learning-based supplementation of missing ship specifications and from the statistical allocation of fuel-compliance pathways in the Fleet Low Sulfur Compliance Choice Module. We also discussed that these uncertainties could be reduced through improved ship specification databases, larger training datasets, more complete scrubber and fuel-use information, and better access to ship-level operational data. Finally, we clarified that direct single-ship validation remains challenging because onboard fuel-consumption records and continuous emission measurements are rarely publicly available, but future validation could use onboard measurements, noon reports, EU MRV, or IMO DCS data where available.

Revisions:

In DISCUSSION *(page16, line356)*, we expanded the discussion about uncertainties, taking into consideration about what you mentioned in Q2, Q3, and Q11:

…. On the other hand, uncertainties arise from multiple aspects. First, missing ship specifications supplemented by machine learning may introduce errors for individual vessels, although such errors are expected to decrease after aggregation to regional and global scales. Second, FLSCCM relies on statistical allocation of fuel consumption because actual ship-level fuel choices are generally unavailable. Third, FLSCCM does not distinguish ULSFO and MGO, and fuels of 0.1% sulfur are represented using MGO emission factors. This simplification is expected to have limited influence on SO_2, but it may lead to some underestimation of $PM_{2.5}$ and BC emissions where ULSFO is used. Finally, incomplete scrubber installation records may bias $PM_{2.5}$, BC, and PN emission calculation because unidentified scrubber-equipped vessels may be treated as using low-sulfur fuels. Besides, installation records alone do not fully indicate whether scrubbers are actually operated during the whole voyages, which introduces further uncertainty.

These uncertainties can be constrained at the inventory level through complete data curation and systematic sensitivity analyses, while future improvements in ship-specific technical databases and broader sharing of vessel technical specifications, scrubber installation records, and fuel use data would further reduce uncertainties at the individual-vessel level and facilitate the use of shipping emission inventories in future climate and impact models. Direct validation at the single-ship level remains difficult because such data are rarely publicly available. Future validation could use onboard measurements, EU MRV, or ship bunkering data. Nevertheless, comparisons with independent inventories and sensitivity analyses indicate that these uncertainties are unlikely to affect the main conclusions on the magnitude, temporal evolution, and pollutant characteristics of global shipping emissions.

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