Response to Reviewers #2's Comments

Review of the paper

Annual ship emissions around China under gradually promoted control policies from 2016 to 2019
by Xiaotong Wang and co-authors

The paper describes changes in shipping emissions around the Chinese coast between 2016 and 2019. The existing and previously published ship emission inventory model (SEIM) was updated and applied to AIS ship position data for 4 years and the results are analyzed for the effects of policy measures on ship emissions for different ship types and different distances to the coast.

The paper presents interesting results that can be of use for subsequent air quality simulations but also for policy measures to further reduce ship emissions along the Chinese coast. The papers needs significant language improvements, it is sometimes quite difficult to understand what the authors want to say. This should be done by a native speaker or through a professional language check. I will not mention all sentences that need improvements and clarification, because they are simply too many. However, these corrections need to be done before the paper can be published.

The paper also suffers from imprecise descriptions and some open questions concerning the results, but those can be treated in a revision. I recommend publication of this article in ACP after moderate revisions of the contents and major revisions of the language.

Response:

Thank you very much for the positive comment and interest in our work. All 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. All grammatical problems in the revised manuscript have been carefully checked and vague expressions have been clarified to the most extent. As a matter of fact, we have learned that the language of this article will be polished and checked again before publication on Atmospheric Chemistry and Physics. The correction details for other problems are listed below point by point.

Major comments:

Q1. Lines 8-28:

In the abstract and throughout the paper it needs to said clearly which area is considered, when relative emission changes are given. I assume that the numbers mostly refer to the 200 nm zone along the Chinese coast, however, the area under investigation is much bigger, as shown in Fig. 11.

Response:

Thank you for your reminder. This study aims to evaluate the ship emissions targeting at the inland rivers and 200 Nm zone along the coast of China. Except for special explanation, the statistical results are all carried out for the inland rivers and the 200 Nm zone. As we applied a double-nested domain for emission estimation (see Q3 for detailed explanation), the spatial maps of shipping emissions (Fig. 5, Fig. 10, Fig. 11 and Fig. 12) could be given according to the domain 2 in Fig. 2.

Revisions in Manuscript:

1) Lines 13-15: In this model, NO_x, SO_2, PM and HC emissions from ships in **China's inland rivers and the 200 Nm coastal zone** were estimated in every single day with a spatial resolution of 0.05×0.05 degrees, based on a combination of Automatic Identification System (AIS) data and the Ship Technical Specifications Database (STSD).

2) Lines 143-145: In this study, the target area for developing ship emission inventory is **the navigable inland rivers and the coastal waters approximately within 200 Nm away from the Chinese mainland's territorial sea baseline (hereinafter referred to as 200 Nm zone),** as shown in Fig. 2.

Q2. Lines 76-89:

The number of 30 billion AIS signals does not say much about how complete the data is. You should say something on possibly missing data during certain times and how homogeneous the data is in time and space. In addition, you should give some information on the STSD, even though it might be described elsewhere, already. This could be done in the supplementary material. It is essential to know which technical information about the ships is typically available and which not. It is also surprising that 3.5 million vessel profiles are included given the fact that the number of large ocean going vessels is typically given as approx. 100,000. Is the rest of the data sets about small fishing boats (which won't have AIS in most cases) or about Chinese river vessels? This information can also be provided in section 2.3.

Response:

Thank you for your suggestions. These clear instructions helped improve our research and is very valuable for the revision.

(1) AIS data

The 30 billion AIS signals is the amount for global AIS data, which include both satellite-based signals and terrestrial-based signals. As we reduced the data and removed redundant signals, the data used in this study for China is about 100

million. We examined the AIS coverage and how homogeneous the data is in time and space after reducing. Results show that there exist missing signals or anomalies in particular days (Fig. S1), but the coverage of AIS data coverage has improved from 2016 to 2019. After the adoption of the 10-minute interpolation method, the AIS signal is expanded to about twice the original, and some periods with long intervals have been obviously supplemented. This part was added in the Supplementary Methods (see specific revisions below).

(2) STSD Ship technical specifications database (STSD)

At the same time, we carefully checked the total number of ships STSD covered and confirmed that the number of ship profiles included is about 350 thousand instead of 3.5 million. We assume that there should be a clerical error in the previous manuscript. The major sources of STSD are data from Lloyd's Register, China Classification Society (CCS) and Global Fishing Watch (GFW). And technical specifications of ships include MMSI number, IMO number, length, width, draft, rated power, built year, type, max speed, registered country, engine speed, dead water tonnage, etc. One of the improvements of STSD in this study is that it has been enriched, incorporated data from GFW, CCS as well as Classification Societies of other East Asian countries. We have cleaned the data by eliminating duplicated ships, ships with apparently faulty or too many missing properties. 350 thousand ships remained at last. In current STSD, there are 101,638 ocean-going vessels (OGVs, defined here as vessel having an IMO number), a bit more than that recorded by United Nations Conference on Trade and Development (UNCTAD), e.g., 97,136 in 2019 (https://unctadstat.unctad.org/wds), probably due to the difference in OGV definition. Other ships are mostly smaller than 500 Gt and usually don't have IMO numbers. In the revised manuscript, we also added a brief introduction to STSD in the Supplement.

Revisions in Manuscript:

1) Lines 85-87: The global AIS database with annually ~30 billion signals, together with Ship Technical Specifications Database (STSD) covering over **350 thousand individual vessels** were combined as fundamental data for emission calculation.

2) Lines 164-166: The global dynamic AIS data for the whole year of 2016-2019 (from January 1st to December 31st) with on average 30 billion signals per year, include both **satellite-based signals and terrestrial-based signals,** were collected to build a ship activity database.

3) Lines 175-180: After reducing, the AIS coverage in our study area has been examined in terms of time and space **(see Supplementary Methods and Fig. S1).** Short period drops probably result from missing or abnormal AIS signals

due to many reasons, such as disruption to satellites, equipment maintaining, data transmission fault, ships sailing beyond terrestrial station receiving range etc, which is a common phenomenon that has been pointed out by previous studies (Goldworthy et al., 2019; Johansson et al., 2017; IMO, 2020). To assure the reliability of total emissions, it's important to have whole year data instead of using several weeks and then multiplied to annual total.

4) Lines 182-187: The STSD describes ship properties such as vessel type, dead weight tonnage (DWT) and engine power, designed speed, flag state, etc., which has also been updated to 2019. The extended STSD currently contains over 350 thousand vessels, in which 101,638 are OGVs, which is consistent with the statistics of the United Nations (UNCTAD, 2019). Besides the ship data collected from Lloyd's Register and the Classification Societies of various countries, we have also incorporated fishing ships and smaller ships that don't have IMO numbers from Global Fishing Watch (GFW) (Kroodsma et al., 2018). These ships were observed to be quite active along China's coast. A further introduction to the updated STSD was provided in the Supplementary Methods.

Revisions in Supplement:

Automatic Identification System (AIS) data

The temporal and spatial coverage of AIS data were examined to guarantee the quality of ship emission inventories. The full year AIS data including both satellite signals and territorial signals from 2016 to 2019 were used for our emission calculations in this study. Fig. S1a showed the homogeneity of the AIS signals in this study in terms of time. It is noticeable that during February (Spring Festival Holiday in China) and May to August (Fishing-off Season in China), the number of daily AIS signals is lower than average (approx. 5 million/day). Missing signals or anomalies occasionally exist, which could due to multiple factors, such as disruption to satellites, equipment maintaining, data transmission fault etc., Besides, Bad weather could be a reason for interference of signal transmission. After the adoption of the 10-minute interpolation method, the AIS signal is expanded to about twice the original, and some periods with long intervals have been obviously supplemented. Fig. S1 (b) and (c) exhibited the change of spatial coverage of AIS signals in inland waters and coastal waters around China. The number of AIS messages transmitted per year is increasing over the span of this study's years of interest. This is evident from Fig. S1 (d) which demonstrates the improvement in AIS coverage between 2016 and 2019.

Ship technical specifications database (STSD)

In this study, the extended Ship Technical Specification Database (STSD) was applied for ship emission calculation (Liu et al., 2016). The data from Lloyd's Register, China Classification Society (CCS) and Global Fishing Watch (GFW) (Kroodsma et al., 2018) were the most significant sources. In the current STSD,

there are 101,638 ocean-going vessels (OGVs, defined here as vessel having an IMO number), a bit more than that recorded by United Nations Conference on Trade and Development (UNCTAD), e.g., 97,136 in 2019 (https://unctadstat.unctad.org/wds), which might due to the difference in OGV definition. The STSD provides static data which describes ship properties including vessel type, rated engine speed, rated engine power, length, width, height, design max speed, dead weight tonnage (dwt), maximum draught, build year, etc. Since STSD has incorporated data from GFW, CCS as well as Classification Societies of other East Asian countries, it also includes ships that are smaller than 500 Gt and usually don't have IMO numbers along China's coast, which take a large part in terms of the number of ships.
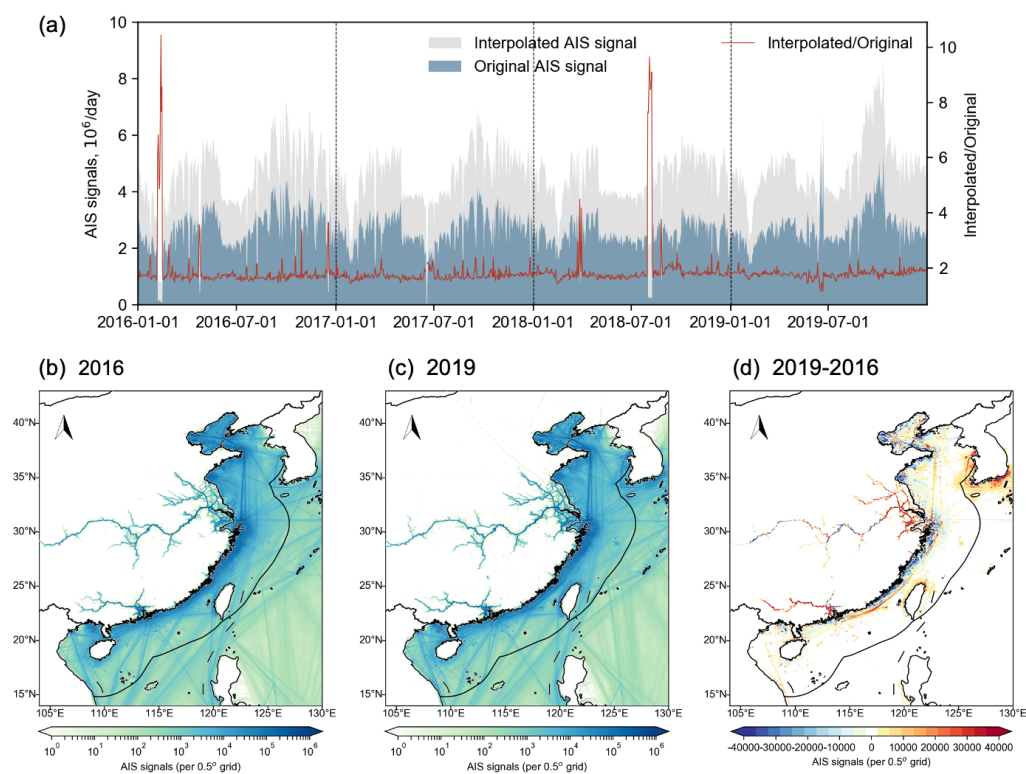
Fig. S1 Temporal and spatial coverage of AIS data in rivers and 200 Nm coastal zone of China from 2016 to 2019. (a) Daily evolution of AIS signals. (b) Spatial distribution of AIS signals in 2016. (c) Spatial distribution of AIS signals in 2019. (d) Spatial difference between 2016 and 2019.

Q3. Line 104/105:

What is the purpose of the "double nested domain"? What are the potential "boundary effects"?

Response:

The "double-nested domain" method was introduced in the Supplementary Information of our work published in 2016 (Liu et al., 2016). To put it simply, "boundary effects" refer to the sharp increase/decrease on the boundary when calculating the emission inventory in a defined region. The "double nested domain"

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is dedicated to solving the error caused by the "boundary effects".

The improvements can be explained by two example cases, as indicated by the green and purple curves in **Fig. Q3.1** below. For case 1, a ship moves following the green curve and sends AIS signals at point A and point B. If only D2 was used for calculation, the starting point for this ship would be point B, which is the first AIS signal after entering the D2. Thus, the emissions from the boundary to point B would be overlooked. By using the new method with two nested domains, the actual emission between point A and B was calculated and evenly distributed along the straight line between A and B. Then the emissions from the boundary to point B were included for the grid boxes inside the region. In contrast, case 2 indicated by the purple line, would overestimate emissions in a region without applying the two-nested domain. The AIS data shows that some vessels voyage across the research boundary, going out of the region and then sailing back into the region. With only D2 is set, all the navigation time between AIS signal C and D would be used to calculate emissions and then the emission would be distributed along a straight line between points C and D (as shown by the dotted line). However, the truth is that most of the emissions happen outside the regional boundary. Our new method successfully avoids these errors by introducing an extra domain with broader boundaries.
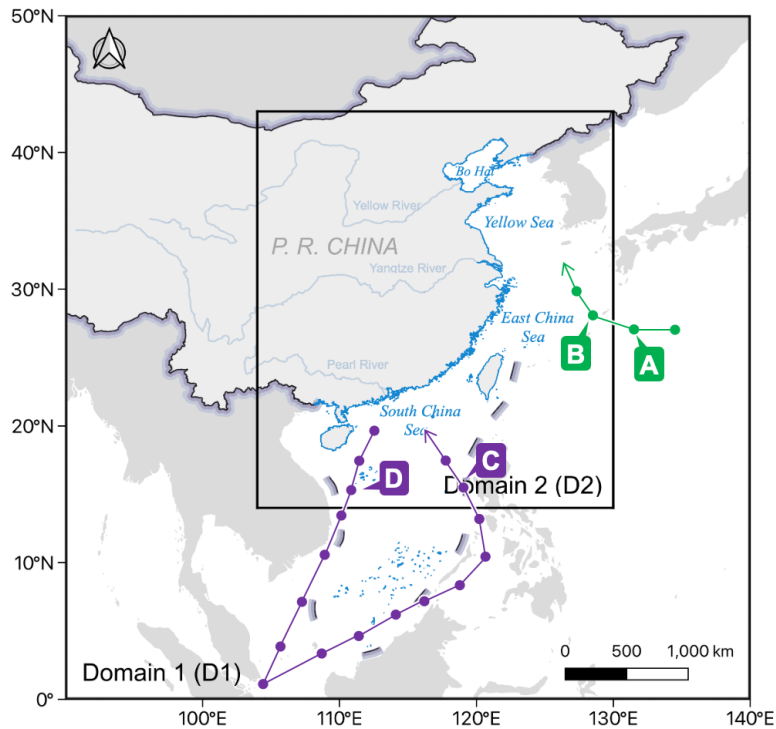
Fig. Q3.1 Schematic diagram of the method of double-nested domain to solve the boundary effect in AIS-based shipping emission inventory.

In this revised manuscript, we added the citation of our previous work and added a brief introduction of the "boundary effects".

Revisions in Manuscript:

Lines 112-114: To reduce the uncertainties of emission calculation, we have previously introduced several techniques in SEIM v1.0 (Liu et al., 2016): 1) a double-nested research domain was applied to reduce the boundary effects (i.e., **sharp increase/decrease on the boundary when calculating the emission inventory in a defined region**); …

Q4. Line 105/106:

What is the GBRT method? In how many cases do the default values have to be estimated because of missing ship properties?

Response:

GBRT (Gradient Boosting Regression Tree) is a machine learning method used for predicting missing values of ship properties, e.g., engine power, dead weight tonnage, maximum designed speed, etc., based on the available information in Ship technical specifications database (STSD). Details of the GBRT method has also been introduced in the Supplementary Information of our previous work (Liu et al., 2016). This method previously applied for approximately 30% of the total ocean-going vessels in East Asia. However, as we updated the STSD to involved more than 350 thousand vessels, this kind of vessels only account for approximately 5% in terms of amount.

In the revised manuscript, we made a little revision to the original sentence.

Revisions in Manuscript:

Lines 114-116: 2) the Gradient Boosting Regression Tree (GBRT) method was adopted to ~~estimate the default~~ **predict missing values of ship properties**;

Revisions in Manuscript:

Ship technical specifications database (STSD)
…However, the data is sometimes incomplete. Either excluding those particular ships from our computation or assigning default values to the property will lead to substantial inaccuracies. To correct the static data and reduce the error, we applied a machine learning method, Gradient Boosting Regression Tree (GBRT) to predict missing values based on other completed properties (Liu et al., 2016). This method previously applied for approximately 30% of the total ocean-going vessels in East Asia. However, as we updated the STSD to involved more than 350 thousand vessels, this kind of vessels only account for approximately 5% in terms of amount.

Q5. Line 111-114:

This is a nearly exact repetition of a text from the introduction. You should avoid such repetitions.

Response:

Thank you for your kind reminder. We have modified the similar sentences in the introduction section. We will tend to avoid repetitions in following works.

Revisions in Manuscript:

Lines 87-88: The technical details of upgrading the previous SEIM v1.0 to SEIM v2.0 were introduced in the Methods.

Q6, Line 118:

How long is "long time gap"? So, in which cases is the restoration method applied?

Response:

Thank you for the question. The "long time gap" we mentioned previously might not be accurate. The application situations and implement steps have been described by a sketch map in section 2.4.1 and Fig. 4. For each two consecutive AIS point A and B, if line AB intersects the continent and is not contained in the continent (considering this might be inland river), the route restoration method would be applied. However, the complex coastline makes it rather time-consuming to judge the geographical relationship between the trajectory line and the continent polygon one by one, we thus added an additional distance threshold of 50 km in the model, i.e., the restoration method would only be applied **when the distance of "cross-land trajectory" is over 50 km**. This setting would skip some cases when ships were sailing in the estuaries, crossing the coastlines.

In the revised manuscript, the "lone time gap" was replaced with "cross-land trajectory with long distance", and the statement of distance threshold was added to section 2.4.1.

Revisions in Manuscript:

1) Lines 131-133: Second, a route restoration module is applied for ~~long time gap~~ **cross-land trajectory with long distance** in AIS data, in which the 10-minute linear interpolation will be applied on the shorted paths instead.
2) Lines 237-241: However, as it was rather time-consuming to judge the geographical relationship between the trajectory line and the continent polygon, an additional distance threshold of 50 km was finally added in the model, i.e., the restoration method would only be applied for "cross-land trajectory with long distance". This setting would skip some cases when ships

were sailing in the estuaries, crossing the coastlines.

Q7. Line 160 and Table 1:

How are the total main engine power and the total dead weight tonnage calculated?

Response:

Thank you for your question. The main engine power and dead weight tonnage (DWT) for each particular ship are recorded in the STSD. The total main engine power and total DWT in **Fig. 3** and **Table 1** are both the accumulated values of all ships appears in the 200 Nm zone of China for each year, regardless of the counts of AIS signals or voyages. To avoid misleading, we removed the statistical result regarding the main engine power and total dead weight tonnage in the revised manuscript. The number of vessels and total operating hours in Table 1 would be more useful to reflect the ship activities.

Revisions in Manuscript:

Lines 191-195: Table 1 shows the statistical results of the AIS messages and active ships for different years in this study. From 2016 to 2019, an annual average of about 90,000 vessels were observed in in inland rivers and the 200 Nm zone of China, and the number of vessels showed a downward trend year by year. ~~The increasing trend of total vessel DWT and decreasing trend of the number of identified ships operating around China indicate the improvement of average loading capacity per ship. Detailed processing method of data collection, cleaning, matching and verification are described in our previous works (Liu et al., 2016).~~

Table 1: Statistics of AIS messages and active ships in China in 2016–2019.

Statistical items		2016	2017	2018	2019
Global	Archived AIS messages (10^9)	26	35	31	45
	Active ships with unique MMSI (10^3)	523	635	754	824
China (River and 200 Nm zone)	Number of identified ships (10^3)	96	92	88	85
	Total operating hours (10^6 hours)	196	197	195	202

Q8. Line 165 – 169 and Figure 3:

In Figure 3 it looks like there are short periods of one or few days during which the activity drops significantly (e.g. mid June, beginning of July, beginning of August). What is the reason for this? Is this bad weather, non-working days or something similar? Or are these periods with missing AIS data?

Response:

Thank you for your question. We checked the AIS data used in this study and discovered that in different years, AIS gaps appeared at different time. This indicates that these short period drops probably result from missing AIS signals. Because AIS data are obtained from both Satellite-based AIS and terrestrial AIS. Disruption to satellites, equipment maintaining, data transmission fault, ships sailing beyond terrestrial station receiving range etc. can cause missing or abnormal signals in AIS data. The data gap is a common phenomenon that occasionally occurs in AIS, which has also been pointed out by previous studies (*Goldworthy et al., 2019; Johansson et al., 2017; IMO, 2020*). So, it's important to provide day-by-day results and then estimates the annual total, instead of picking several typical days or weeks. In this revision, we kept the Fig. 3 to give temporal profile of vessel operating time and added more explanations regarding the coverage of AIS data in both the manuscript and the Supplementary Methods.

Revisions in Manuscript:

Lines 175-180: After reducing, the AIS coverage in our study area has been examined in terms of time and space (see Supplementary Methods and Fig. S1). Short period drops probably result from missing or abnormal AIS signals due to many reasons, such as disruption to satellites, equipment maintaining, data transmission fault, ships sailing beyond terrestrial station receiving range etc, which is a common phenomenon that has been pointed out by previous studies (Goldworthy et al., 2019; Johansson et al., 2017; IMO, 2020). To assure the reliability of total emissions, it's important to have whole year data instead of using several weeks and then multiplied to annual total.

Revisions in Supplement:

Automatic Identification System (AIS) data (See Q2)

References:

Goldsworthy, B., Enshaei, H., and Jayasinghe, S.: Comparison of large-scale ship exhaust emissions across multiple resolutions: From annual to hourly data, Atmospheric Environment, 214, 10.1016/j.atmosenv.2019.116829, 2019.
Johansson, L., Jalkanen, J.-P., and Kukkonen, J.: Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution, Atmospheric Environment, 167, 403-415, https://doi.org/10.1016/j.atmosenv.2017.08.042, 2017.
IMO: Fourth IMO GHG Study - Final Report, CE Delft, 2020.

Q9. Line 182:

You should consider that a method very similar to the route restoration method described here was already introduced by Aulinger et al. in 2016 (Atmos. Chem. Phys., 16, 739–758).

Response:

Thank you for your comments. We have read this work and supplement it to our

manuscript as a reference in Line. In the works done by Aulinger et al. (2016) and Johansson et al. (2017), route regeneration algorithm was applied to solve the long-time gap in consecutive AIS signals. Several factors would affect whether this method works well or not: AIS data's quality, the accuracy and fineness of predefined sea routes, time span between two consecutive interpolation points, etc. In this study, technical details of route regeneration algorithm applied around China sea was introduced in detail, including specific routes that are predefined, time gaps between interpolated points and the algorithm flow for peer review, comparison and reference.

Revisions in Manuscript:

Lines 214-215: Similar methods but with featured details has been previously experimented by **Aulinger et al. (2016) on a regional scale and Johansson et al. (2017) on a global scale.**

References:

Aulinger, A., Matthias, V., Zeretzke, M., Bieser, J., Quante, M., and Backes, A.: The impact of shipping emissions on air pollution in the greater North Sea region – Part 1: Current emissions and concentrations, Atmospheric Chemistry and Physics, 16, 739-758, 10.5194/acp-16-739-2016, 2016.

Johansson, L., Jalkanen, J.-P., and Kukkonen, J.: Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution, Atmospheric Environment, 167, 403-415, https://doi.org/10.1016/j.atmosenv.2017.08.042, 2017.

Q10. Line 222:

What are the criteria for a method to be "basically satisfactory"?

Response:

Thank you for the comment. Our original intention is that the result of spatial distribution results of AIS signals of OGVs, CVs and RVs is basically consistent with experience, i.e., they showed different navigation range, with OGVs mainly at seas, CVs near the coast and RVs in inland waters. Thus, we modified this improper expression.

Revisions in Manuscript:

Lines 258-260: The spatial distribution of AIS signals of OGVs, CVs, and RVs **were basically consistent with experience, with OGVs mainly at seas, CVs near the coast and RVs in inland waters.** ~~indicate that the identification method is basically satisfactory~~.

Q11. Line 253:

Can you say something about how well the emission inventory might agree with real world emissions? Despite possible methodological problems, which might be difficult to avoid (e.g. because of missing technical information about the ships), can you say something about the percentage of ships that do not follow the DECA rules (i.e. the

non-compliance rate)?

Response:

Thank you for your comments.

Two sources of uncertainty in regional shipping emissions estimation were considered: 1) the completeness of ship observations and 2) the estimates of annual emissions from the observed fleet of ships. In our previous work (Liu et al., 2016), a Monte Carlo method was also used to evaluate the uncertainty for our bottom-up emission inventories, which was estimated to be among 3% to 6%. In this study, completeness of both AIS data and STSD has been improved and SEIM has also been upgraded. These efforts all contributed to the consistency of the model to the real world and to some extent alleviated uncertainties. But inevitably there are still several uncertainties in this model, including AIS data gap and anomaly (influenced by methodological conditions, equipment maintaining, etc.), accuracy and coverage of STSD information, accuracy of RVs, CVs and OGVs classification, route restoration algorithm, obedience of ships under DECA policy, etc. We have added sentences in revised manuscript addressing the uncertainties of our emission inventory in this article.

Guaranteed by the authority of Chinese government, DECA policy was endowed it with the power to restrict the fuel ship-owners uses. Several investigations, using whether field measurements or simulations, have showed that with DECA policy, not only ship fuels have been found to be cleaner, but also air pollution caused by shipping activities have been evaluated to be less in important ports alongside Chinese coast *(Zhang et al., 2019b; Zhang et al., 2018a; Zou et al., 2020).* However, there are not sufficient evidence indicating all vessels stick to DECA's regulation or the violation rate of DECA policy from year to year. This could undoubtably cause uncertainties in emission estimation. In the revised manuscript, an explanation was added to address this potential uncertainty.

Revisions in Manuscript:

1) Lines 122-126: These improvements contributed to the consistency of the model to the real world and to some extent alleviated the uncertainties in our model. But inevitably several uncertainties still exist in this model, including AIS data gap and anomaly (influenced by methodological conditions, equipment maintaining, etc.), accuracy and coverage of STSD information, accuracy of RVs, CVs and OGVs classification, route restoration algorithm, obedience of ships under DECA policy, etc.

2) Lines 291-297: It is worth noting that as far as we know, there has not been

sufficient evidence showing all vessels are sticking to DECAs or the violation rate each year. But there are studies indicating the effectiveness of DECAs in recent years (Liu et al., 2018; Zhang et al., 2019; Zhao et al., 2020; Zou et al., 2020). Not only have fuels been found to be cleaner (Zhang et al., 2019), but also air pollution caused by shipping activities has been less in important ports alongside Chinese coast (Zou et al., 2020). Guaranteed by the authority of Chinese government, we assume that the DECA policy should mostly be effective, but lack of evidence about the violation of DECAs added to uncertainties in this model.

References:

Liu, H., Fu, M., Jin, X., Shang, Y., Shindell, D., Faluvegi, G., Shindell, C., and He, K.: Health and climate impacts of ocean-going vessels in East Asia, Nature Climate Change, 2016.

Zhang, X., Zhang, Y., Liu, Y., Zhao, J., Zhou, Y., Wang, X., Yang, X., Zou, Z., Zhang, C., Fu, Q., Xu, J., Gao, W., Li, N., and Chen, J.: Changes in the SO2 Level and PM2.5 Components in Shanghai Driven by Implementing the Ship Emission Control Policy, Environmental Science & Technology, 53, 11580-11587, 10.1021/acs.est.9b03315, 2019b.

Zhang, Y., Deng, F., Man, H., Fu, M., and Liu, H.: Compliance and port air quality features of ship fuel switching regulation: by a field observation SEISO-Bohai, Atmospheric Chemistry and Physics, 1-28, 2018a.

Zou, Z., Zhao, J., Zhang, C., Zhang, Y., and Zhou, B.: Effects of cleaner ship fuels on air quality and implications for future policy: A case study of Chongming Ecological Island in China, Journal of Cleaner Production, 267, 122088, 2020.

Q12. Line 283/284:

Can you say why the SO2 emissions you calculate might be higher than those in Li et al. (2018)? I understood that RVs have very low sulfur emissions which would means that they won't contribute a lot to the total emissions, even when they sail in coastal waters. Or could they switch fuel when leaving the river?

Response:

Thank you for your comments.

We would like to explain the fuel settings for RVs sailing in coastal waters first. In the SEIM v2.0 model, RVs were assumed to use general diesel oils (GDOs, sulfur content gradually decreased from 350 ppm to 10 ppm) complying with Chinese standards, so RVs would not switch fuels even when they sail in coastal waters. By the Article 65 of Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution issued in 2015 and revised version 2018, *it is prohibited to sell residual oil and heavy oil for non-road mobile machinery, as well as inland and river-to-sea vessels*. Thus, the fuel types and emission factors for RVs would keep unchanged regardless of the vessel location, within the period of the certain fuel standard.

As for the comparison with Li et al. (2018)'s study, the different of emission results for RVs might come from multiple aspects. Table Q12.1 lists the difference of RVs regarding the activity data, identification method of RVs, emission estimation method, emission factors and typical results. Due to the great differences in data sources and methods between this study and Li et al. (2018), it might be hard to make rigorous comparisons. We currently consider two major reasons causing the differences:

- We identified RVs based on AIS signals distribution in this study. Given the fact that CVs and even OGVs sail at inland waters sometimes, there exists possibilities that some CVs and OGVs are mistakenly identified as RVs, adding to the number of RVs in this study. Thus, the identified numbers of RVs might be higher than that in Li et al., (2018).

- We applied fuels with sulfur content complied with the national standards, for which the emission factors of SO_2 and PM would be much lower than CVs or OGVs. Thus, the emission shares of SO_2 and PM appeared to be lower in this study that in Li et al., (2018), but it was opposite for NO_x and other pollutants.

Table Q12.1 Comparison of ship emission estimation of RVs in China.

	This study	**Li et al. (2018)**
Targe year	2016-2019	2013
Activity data	Satellite- and terrestrial-based global AIS data (approx. 90,000 vessels)	National and local maritime department (MD), AIS sample (700 vessels)
Identification method of RVs	AIS trajectory distribution	Registration information in MD
Emission estimation methods	For each AIS signal, estimate emissions by vessel installed engine power, transient load factor and the time interval to the next signal	For each vessel arrived at port, estimate emissions by vessel installed engine power, average load factor and operating time in different modes
Emission factor	Power-based emission factor (g/kW·h)	Fuel-based (g/kg fuel) emission factor and fuel consumption rate (g fuel/kW·h)
Sulfur content	0.035% in 2016	0.5% in 2013
Emission shares of RVs	SO_2 (<1%), PM (1.1%), NO_x (13.2%), HC (19.3%)	SO_2 (2%), PM (3%), NO_x (6%), HC (12%)

Given the above reasons, we modified the explanations for the difference in the manuscript.

Revisions in Manuscript:

Lines 329-337: The emission shares of RV may differ from that by Li et al. (2018), considering the two major reasons. One the one hand, as we identified RVs based on spatial frequency distribution of ship trajectories in AIS, which allows vessels sometimes operating in coastal waters. Given the fact that CVs and even OGVs sail at inland waters sometimes, there exists possibilities that some CVs and OGVs are mistakenly identified as RVs. Thus, the identified vessels of RVs might be higher than that in Li et al., (2018). One the other hand, since we applied GDOs with sulfur content up to the national standard to RVs, for which and the emission factors of SO_2 would be much lower, the emission shares of SO_2 appeared to be lower than that in Li et al., (2018), but it was opposite for NO_x and other pollutants.

References

Li, C., Borken-Kleefeld, J., Zheng, J., Yuan, Z., Ou, J., Li, Y., Wang, Y., and Xu, Y.: Decadal evolution of ship emissions in China from 2004 to 2013 by using an integrated AIS-based approach and projection to 2040, Atmos. Chem. Phys., 18, 6075-6093, 10.5194/acp-18-6075-2018, 2018.

Q13. Line 295-308.

In my opinion, this investigation w.r.t. flag state does not add much information. Because shipping is international and the flag state does not even say something about the vessel owner, this analysis does not tell much.

Response:

Thank you for your comments. We adopted your suggestion and removed the analysis of shipping emission contributed by different flag states in the original section 3.1.2, as well as corresponding results in Abstract and Discussion. At the same time, we retained the comparison of OGV emission in the 200 Nm zone of China v.s. global shipping emissions and inserted into the original section 3.1.1 (now 3.1).

Revisions in Manuscript:

1) Lines 324-327: Compared to a recent estimation of global ship emissions (IMO, 2020), it is striking that OGVs in the 200 Nm zone of China contributed to 9.7 ~ 14.3% of global OGV emission (Table S3), despite only <1% of the world's sea area. Such result suggests the substantial concentration of shipping emissions from global fleet around China.

2) Line 22: ~~Although ocean-going vessels (OGVs) contributed to approximately 2/3 of ship emissions in Chinese waters, 2/3 of them came from ships registered in other countries~~.

3) Line 520: ~~In addition, although OGVs contributed approximated two-thirds of ship emissions in the 200 Nm zone of China, two-thirds of them come from ships registered in other countries~~.

Q14. Figure 9:

Short term drops in emissions are apparent in the time series, which do not correspond to the spring festival, e.g., mid of 2017, approx. Sept 2018. What is the reason for them?

Response:

Thank you for the question. The short-term drops in emissions for certain days (Jan. 1, 2017 and Aug. 1-9, 2018) are possibly caused by the overlong time gap in AIS data. To illustrate this, we put the time series of AIS signals and the emissions together, as shown in **Fig. Q14.1**. It can be observed that there are occasionally missing AIS signals in the whole time series, which might due to occasional disruption to satellites, equipment maintaining, data transmission fault etc., as we explained in **Q8**. We consider this the systematic error of the method, but it generally has minor influence on daily variations of ship emissions from 2016 to 2019. Moreover, the gap of AIS signal will not lead to the same degree of reduction of ship emissions, as the 10-minute interpolation method in SEIM v2.0 model could effectively avoid the emission deviation caused by duplicate or missing AIS signals.
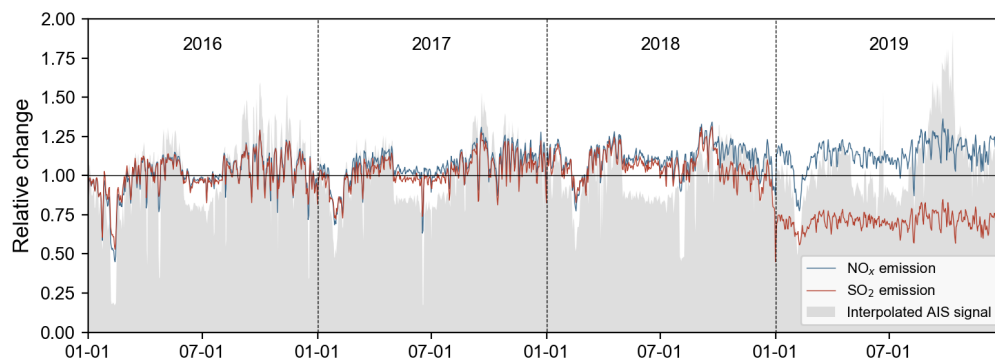
Fig. Q14.1 Daily changes of AIS signals and ship emissions of China in 2016-2019. The y=1 line refers to the daily average value of 2016 for each item.

In the revised version, we added a supplementary figure to show the temporal coverage of AIS data and added corresponding descriptions (see **Q2** for revisions).

Q15. Figure 10:

What is the reason for the steep short-term increase in emissions in some ports in 2018 (Tianjin, Ningbo Zhoushan, Shenzhen)?

Response:

Thank you for your question. We checked the data and found that the steep short-term increase of ship emissions in Tianjin, Ningbo-Zhoushan and Shenzhen ports occurred during approximately Sep. 2-25, 2018. This may be due to the change of ship dynamic information (e.g., navigation speed) caused by the interference of external factors (e.g., typhoon), resulting in upward biases of ship emission

estimation.

First, we checked the number of AIS signals and operating time of ships for these ports, but no sharp increase was found during the same period, when steep short-term increase was noticeable in SO_2 emissions. This eliminated the possibility of sudden change in ship activities being the reason for unusual SO_2 emissions. Second, we checked the time series of ship emissions and operating time from multiple aspects, e.g., vessel type, vessel age, flag country, size bin, operating mode, and found that the steep short-term increase was mostly related to the vessel type and operating mode. As shown in **Fig. Q15.1(a)**, the emissions from containers increased significantly during Sep. 2-25, 2018, while that from bulk carriers and tankers slightly increased. When divided according to the operating status, we found that emissions from containers at sea and maneuvering were higher than before, while that from ships at berth were lower, as illustrated in **Fig. Q15.1(b)**. The operating time of containers under different operating modes present similar characteristics, as shown in **Fig. 15.1(c).** Due to the relatively high main engine power, container ships would generate higher emission intensity under cruising mode compared to berthing, during the same operating time. Thus, the ship emissions for containers appeared to increase more significantly during Sep. 2-25, 2018, compared to other vessel types **(Fig. 15.1a)**. Moreover, major container ports such as Tianjin port, Ningbo-Zhoushan port and Shenzhen port were also observed to have more notably emissions during Sep. 2-25, 2018, among all ports in **Fig. 9** in the manuscript.

Given the fact that the operating mode was defined by navigation speed and load condition, we speculate that the most likely reasons causing the unusual change in operating mode would be the abnormal dynamic data (e.g., speed) in AIS signals, which could somehow be interfaced by external factors. According to China's meteorological data (http://www.typhoon.org.cn/), "Super Typhoon Mangkhut" formed on the Northwest Pacific Ocean in early September in 2018 and landed in China in mid-September. We speculate that the navigation speed of vessels might be affected by the typhoon passing through, thus affecting the judgement of operating mode in the model, i.e., ships at berth or anchorage were recognized as maneuvering or cruising. Due to the great difference between the emission intensities of ships in berthing and cruise mode (especially container ships), the emissions increased sharply from Sep. 2 to 25. However, more evidence is needed to verify the influence of extreme meteorological conditions on AIS signal.
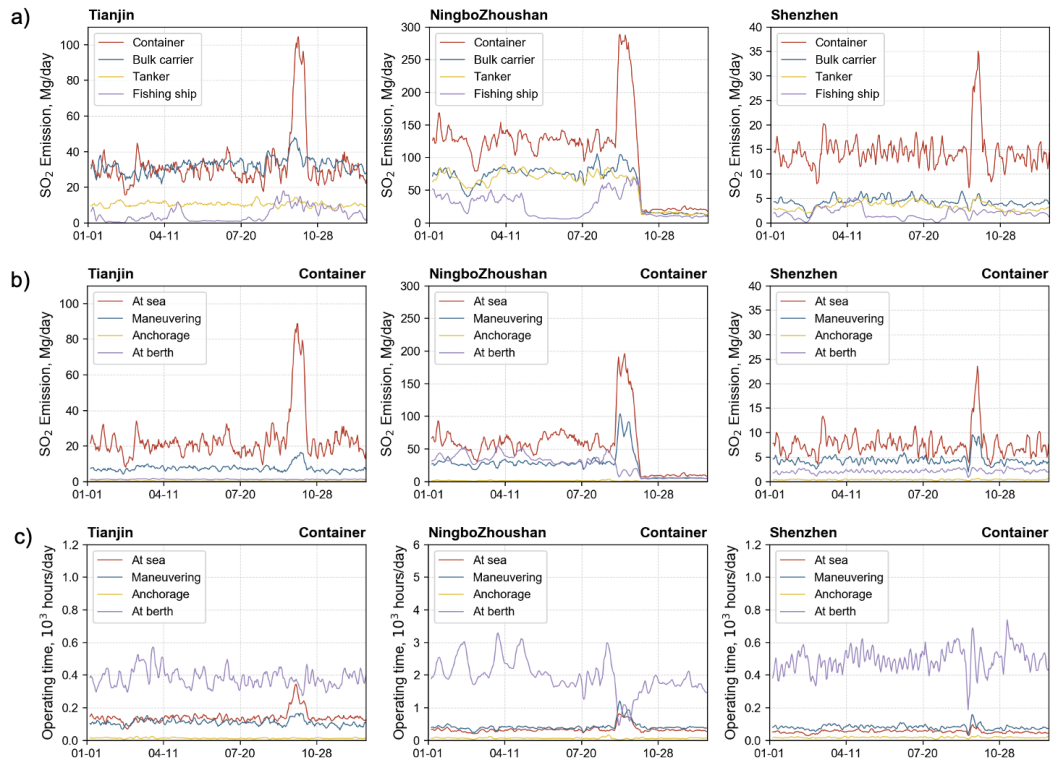
Fig. Q15.1 The 5-day moving average of SO₂ emissions for Tianjin, Ningbo-Zhoushan and Shenzhen port in 2018. (a) Ship emissions from typical vessel types. (b) Container emissions classified by operating mode. (c) Operating time of containers under different modes.

The calculation method has been applied in the whole period from year 2016-2019, but the steep short-term increase in emissions only appeared in certain period and certain ports. However, smoothing or removing could not guarantee that these biases did not occur in other time periods. They could neither be simply corrected as the true value is not known. So, we kept the original results without correction while admitting the uncertainties of the method on the fine time scale.

Revisions in Manuscript:

Lines 414-418: In addition, steep short-term increases in SO₂ emissions were observed for Tianjin, Ningbo Zhoushan, Shenzhen ports in September, 2019. These peaks were speculated to be due to the inaccurate vessel dynamic information in AIS signals caused by the interference of adverse weather, i.e., "Super Typhoon Mangkhut". However, more evidence is needed to verify the influence of extreme meteorological conditions on AIS signal.

Q16. Line 336/337:

Could you explain which role wind direction plays for ship activities?

Response:

Thank you for your question. Ship activities are mostly scheduled, which could somehow be affected by extreme events or weather, but they are not supposed to be strongly affected by the wind direction. In terms of the ship emissions, wind direction could act as a resistance or a propulsion to dynamically affect the ship emission intensity. Under headwind conditions, additional power was wasted to counter the wind power, so the fuel consumption of shipping increases and emissions rise. But this impact is independent of the ship's activities. Taking these factors into account, in the revised manuscript we removed this misquoted sentence from Chen et al. (2019b). Thank you again for your careful review valuable comments.

Revisions in Manuscript:

Line 412: …~~ship emissions in PRD region were higher in in spring and summer since wind direction were more advantageous for ship activity in spring and summer (Chen et al., 2019b);~~…

Q17. Line 374:

How can the improved emissions reduce uncertainties in an air quality model? It might improve the results of an air quality model application.

Response:

Thank you for pointing out this vague expression. We revised the sentence according to your suggestion.

Revisions in Manuscript:

Lines 432-433: This spatial improvement of ship emissions with the route restoration method is expected to ~~reduce uncertainties in the air quality model~~ **improve the results of an air quality model application**.

Q18. Line 398:

I cannot see how a North Atlantic shipping route would be visible in this emission inventory. Perhaps you mean a North Pacific route? A similar argument holds for the mentioned Asia-Europe routes: Do you know from the AIS data where the ships are heading?

Response:

Thank you for your kind reminder. The "North Atlantic Route" is a mistake and what we meant is indeed the "North Pacific Route". To illustrate the major routes of OGVs, we provide Fig. Q18.1 to show the spatial distribution of AIS signals in Domain 1 of the study area. Although the satellite-based signals in the open sea may be sparse than terrestrial -based ones closer to the coast, it is still clearly visible

that higher density of AIS signals on major routes could extend eastward to the Pacific Ocean, which is regarded the North Pacific Route. However, we also found that Asia-Europe routes stated here may not be proper, as it only show the legs between Chinese ports to Malacca Strait. Thus, in the revised manuscript, we changed "North Atlantic Route" to "North Pacific Route", and replaced the "Asia-Europe routes" with "routes from Chinese ports to Malacca Strait".
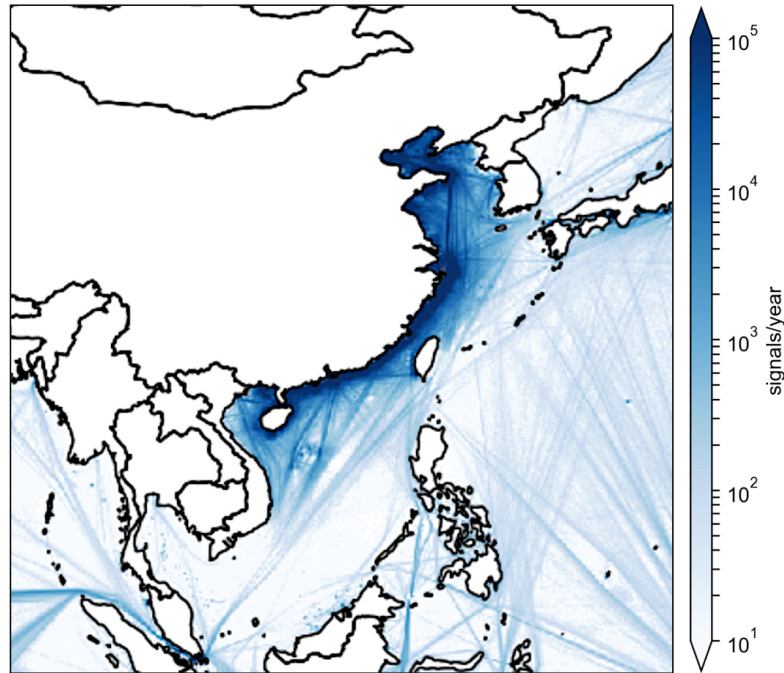

Fig. Q18.1 Spatial distribution of AIS signals in Domain 1 of the study area.

Revisions in Manuscript:

Lines 458-460: The most intensive near-sea routes included China-Korea, China Mainland-Taiwan, the North ~~Atlantic~~ **Pacific** Route, ~~Asia-Europe Route~~ **routes from Chinese ports to Malacca Strait** and routes between busy ports of China, such as main ports in BRA, YRD and PRD (Fig. 12a).

Q19. Line 424:

There is just one scenario defined (the No-DECA scenario). I would not call the emission calculation for the years 2016-2019 that consider all regulations in place a scenario. Therefore, you do not define "another" scenario.

Response:

Thank you for your kind reminder. We replace "another scenario" to "a scenario" throughout the manuscript.

Revisions in Manuscript:

1) Line 93: In addition, ~~another~~ **a** scenario without the DECA policy was performed to evaluate the effect of China's gradually implemented DECA

policy, considering the actual change of interannual ship activities.

2) Line 300: …we designed ~~another~~ **a** scenario (No-DECA scenario) in SEIM v2.0, as listed in Table 2.

3) Line 485: …we designed ~~another~~ **a** scenario without DECA policy to evaluate the emission reduction effect considering the annual change of ship activities.

Q20. Line 455:

Here you should make clear that the numbers refer to the 200 nm zone (if I am not mistaken):

Response:

Thank you for your kind reminder. We have added "in 200 Nm zone of China" in this sentence.

Revisions in Manuscript:

Lines 516-517: As a result, SO_2 and PM emissions from ships decreased by 29.6% and 26.4%, respectively, **in 200 Nm zone of China** in 2019 compared to 2016.

Q21. Line 471/472:

The sentence is repeated from lines 393/394. You should avoid such replications

Response:

Thank you for your kind reminder. We rewrote this sentence.

Revisions in Manuscript:

Lines 533-534: However, this elongated the sailing distance and resulted in more air pollutant emissions.

Minor comments:

Q22. Line 86:

Modify to "In addition, a scenario …"

Response:

Thank you. We have replaced "another scenario" with "a scenario".

Revisions in Manuscript:

Line 93: In addition, ~~another~~ **a** scenario without the DECA policy was performed to evaluate the effect of China's gradually implemented DECA policy, considering the actual change of interannual ship activities.

Q23. Line 122:

What is a "multidimensional analysis"?

Response:

Thank you. We have revised "multidimensional" to "from multiple perspectives".

Revisions in Manuscript:

Line 135-136: Finally, the ship emission inventory datasets will be established and used for visualization and ~~multidimensional~~ analysis **from multiple perspective**.

Q24. Line 162:

Replace "improvement" with "increase".

Response:

Thank you. This sentence has been removed (see **Q7** for revisions).

Q25. Line 196.

Skip "diagrammatic sketch".

Response:

Thank you. We have removed the words.

Revisions in Manuscript:

Line 229: Figure 4 illustrates ~~the diagrammatic sketch of~~ the ship route restoration algorithm, taking a segment of AIS positions as an example.

Q26. Line 225 and several other places:

Replace "implement" with "implementation".

Response:

Thank you. We have adopted the replacement throughout the manuscript.

Q27. Line 314:

What do you mean with "ship emission intensity"? Isn't this just daily emissions?

Response:

Thank you. We have removed the "intensity".

Revisions in Manuscript:

Line 368: The maximum daily ship emission ~~intensity~~ of SO_2 reached 6.4×10^3 Mg/day on September 22nd, 2018, 2.9 times of the lowest point, 2.2×10^3 Mg/day on January 1st, 2019.

Q28. Line 335:

What is meant with the "updating iteration speed of fleet"?

Response:

Thank you. The "updating iteration speed of fleet" was meant to express the "The

speed of vessel fleet renewal". We have deleted this expression as it might be redundant.

Revisions in Manuscript:

Lines 388-390: However, even though the newly-built, large-scale ships as well as ships using clean fuel oil are all taking an increasingly large part in emission structure, ~~the updating iteration speed of fleet is not enough to reverse~~ the rising trend of NOx emission is not yet reversed.

Q29. Line 350:

Avoid expressions like "dramatically".

Response:

Thank you. It has been changed to "sharply"

Revisions in Manuscript:

Line 404: Fortunately, in 2019, when most rigorous DECA 2.0 policy was implemented, it is clearly illustrated in Fig. 9 that all ports' SO_2 emissions were ~~dramatically~~ **sharply** reduced.

Q30. Line 394 and line 472:

I think "aggrandized" is not the right expression here.

Response:

Thank you. The "aggrandized" in Line 394 has been changed to "increased", and the sentence in Line 472 has been re-written.

Revisions in Manuscript:

1) Line 453: However, several ships detoured outside the scope of DECA 2.0 to save the cost on more expensive clean fuel oil, which further elongated the sailing distance and thus ~~aggrandized~~ **increased** emissions in farther maritime areas.
2) Lines 533-534: However, this elongated the sailing distance and resulted in more air pollutant emissions.

Q31. Line 487:

What do you mean with "complexity of registration and operation"?

Response:

Thank you. The "complexity" here referred to the fact that there were normally multiple countries involved for a particular ship, including the state of registration, ship owner and actual operator, etc. Thus, the shipping emission reduction might need multi-party cooperation.

Revisions in Manuscript:

Lines 547-549: Meanwhile, the international cooperation is also urgently called for to jointly control ship emissions due to ships' strong spatial mobility and the **intricate relations between the state of registration, ship owner and actual operator.**

Q32. Author contributions:

Initials are sometimes used in different order as in the list of authors. Who did the SEIM model runs? Who extended the model? What are "multiple analytical perspectives"?

Response:

Thank you for pointing out this. The section of "Author contributions" has been modified.

Revisions in Manuscript:

Lines 566-571: XW and WY contributed equally. XW extended the SEIM model and did the model runs. WY did the data analysis. XW and WY are responsible for writing the manuscript and figures and tables presented in this paper. ZL and FD provided valuable ideas on data analysis of this research. SZ and HX helped collect and clean the ship data. JZ assisted in the model development work. HL and KH provided guidance on the research and revised the paper. All authors contribute to the discussion and revision.

Q33. References:

Skip the test articles by Aman

Response:

Thank you. These articles have been removed.

Q34. Figure 4b

Figure 4b includes several spelling errors.

Response:

Thank you. We have corrected all spelling errors in Figure 4b.
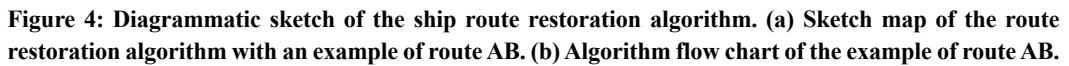
Revisions in Manuscript:

Figure 4: Diagrammatic sketch of the ship route restoration algorithm. (a) Sketch map of the route restoration algorithm with an example of route AB. (b) Algorithm flow chart of the example of route AB.

Q35. Figure 6

Figure 6: the y-axis does not fit to the RV sulfur content, in particular after 2017/07.

Response:

Thank you. We have modified the y-axis and added the legends to Fig. 6.

Revisions in Manuscript:

Figure 6: Evolution of sulfur content requirements for fuels in DECAs and inland rivers in China. The percentages refer to the sulfur content of the fuel. The italics refer to the operating mode constrained by DECA policy. The y-axis is unevenly distributed to show the standard of fuel sulfur content.

Q36. Figure 7

Figure 7, b and c: blue bars for 2013 should be included in the legend. Does the 2013 bar represent the sum of OGV, CV and RV or are RV missing?

Response:

Thank you. We have added the legend for blue bars for 2013. It represent the sum of shipping emissions from OGV and CV, i.e., RV was excluded (Fu et al., 2017).
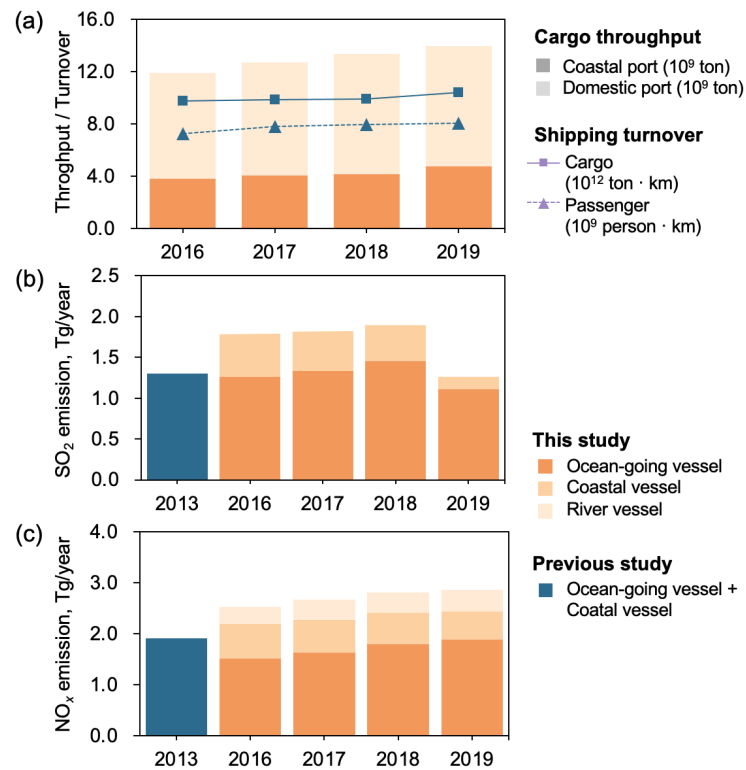
Revisions in Manuscript:

Figure 7: Annual changes of (a) seaborne trade and ship emissions of (b) SO$_2$ and (c) NO$_x$ from 2016 to 2019. Data in (a) are collected from Chinese Statistical Yearbook (NBS, 2020). Emissions of 2013 are derived from our previous work for comparison (Fu et al., 2017).

References:

Fu, M., Liu, H., Jin, X., and He, K.: National- to port-level inventories of shipping emissions in China, Environmental Research Letters, 12, 114024, 10.1088/1748-9326/aa897a, 2017.

Q37. Figure 8

Figure 8 might be skipped because of its low contribution to the scientific value of the paper.

Response:

Thank you for your suggestion. We have dropped the previous Fig. 8 and corresponding analysis in the manuscript (see **Q13**).

Q38. Figure 13

Replace "comparation" with "comparison"

Response:

Thank you. We have corrected this spelling error in Fig. 12 (previously Fig. 13).

Revisions in Manuscript:

Figure 12: Interannual spatial change of NO_x and SO_2 emissions from ships over China from 2016 to 2019. Annual average spatial distribution **comparison** of NO_x emission for (a) OGVs, (b) CVs and (c) RVs. Interannual variations of NO_x and SO_2 emission in different geographic regions for (d) OGVs, (e) CVs and (f) RVs.

Q39. Figure 14

Mention that this refers to the 200 nm zone.

Response:

Thank you. We have added the description of "in inland rivers and the 200 Nm zone of China" in the legend of Fig. 13 (previously Fig. 14).

Revisions in Manuscript:

Figure 13: Monthly variation of ship SO_2 emissions i**n inland rivers and 200 Nm zone of China** under Base condition and No-DECA scenarios in 2016-2019. The Base condition refer to the real condition. The No-DECA scenario reflect the emission based on the real ship activities without the DECA policy.

Q40. Figure 15

The horizontal bars giving the changes in % should be aligned along a vertical zero-line.

Response:

Thank you. Figure 15 is designed to be presented in the form of a **waterfall chart** (https://en.wikipedia.org/wiki/Waterfall_chart). The waterfall chart was developed by McKinsey & Company. It is used to show the cumulative process of results by allowing the columns suspending in mid-air to represent the contribution of each positive and negative value to the total amount. In a waterfall chart, each of the suspended bar starts with the end value of its previous bar. In recent years, this chart has been widely applied to present the driving forces of emission reduction or air quality and health benefits (*Zhang et al., 2019; Wang et al., 2020; Milovanoff et al., 2020; Shan et al., 2021*).

In this case, the horizontal bar refers to the absolute emission change compared to the previous year, while the percentages refer to the change rate in emissions relative to the previous year. Therefore, we hope to keep the form of the waterfall chart, but added the axes and labels in this revised version.
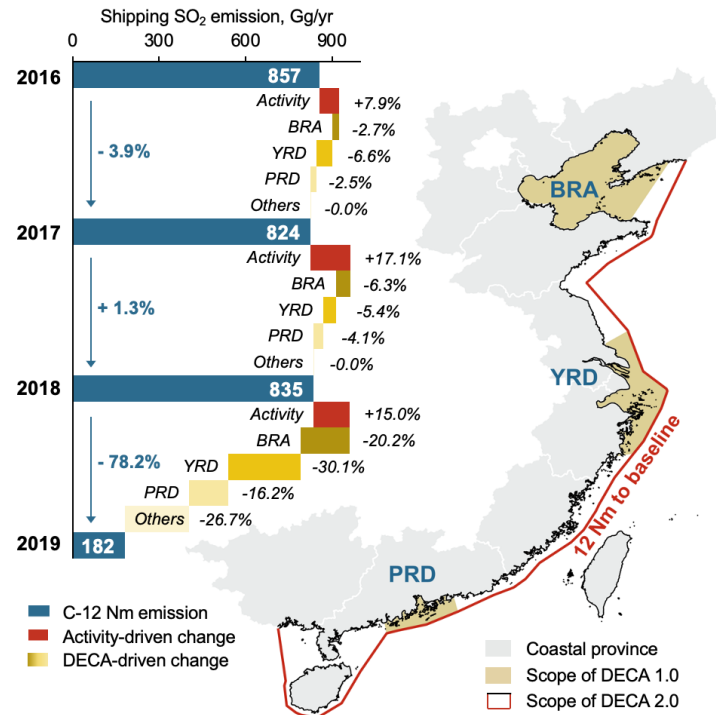
Revisions in Manuscript:

Figure 14: Regional contributions to annual reduction SO$_2$ emissions from ships within 12 Nm of the baseline of China's territorial sea. The figures inside the blue bars refer to the annual emissions, and the percentages refer to the relative change of emissions due to total ship activity change in C-12 Nm region or the DECA policies in each region.

References:

Zhang, Q., Zheng, Y., Tong, D., Shao, M., Wang, S., Zhang, Y., Xu, X., Wang, J., He, H., Liu, W., Ding, Y., Lei, Y., Li, J., Wang, Z., Zhang, X., Wang, Y., Cheng, J., Liu, Y., Shi, Q., Yan, L., Geng, G., Hong, C., Li, M., Liu, F., Zheng, B., Cao, J., Ding, A., Gao, J., Fu, Q., Huo, J., Liu, B., Liu, Z., Yang, F., He, K., and Hao, J.: Drivers of improved PM2.5 air quality in China from 2013 to 2017, Proc Natl Acad Sci U S A, 116, 24463-24469, 10.1073/pnas.1907956116, 2019.

Wang, H., He, X., Liang, X., Choma, E. F., Liu, Y., Shan, L., Zheng, H., Zhang, S., Nielsen, C. P., Wang, S., Wu, Y., and Evans, J. S.: Health benefits of on-road transportation pollution control programs in China, Proc Natl Acad Sci U S A, 117, 25370-25377, 10.1073/pnas.1921271117, 2020.

Milovanoff, A., Posen, I. D., and MacLean, H. L.: Electrification of light-duty vehicle fleet alone will not meet mitigation targets, Nature Climate Change, 10, 1102-1107, 10.1038/s41558-020-00921-7, 2020.

Shan, Y., Ou, J., Wang, D., Zeng, Z., Zhang, S., Guan, D., and Hubacek, K.: Impacts of COVID-19 and fiscal stimuli on global emissions and the Paris Agreement, Nature Climate Change, 11, 200-206, 10.1038/s41558-020-00977-5, 2020.