Response to Reviewers #1's Comments

Summary:

This paper presents the development of an emissions inventory for ship emissions from the costal and river waters around China, based on the Ship Emission Inventory Model (SEIM), using a comprehensive set of AIS data to produce a high temporal and spatial resolution inventory. It uses the inventory, along with changes in emissions due to policy interventions as part of the domestic ship emission control (DECA) policy, to assess how ship emissions around China have changed from 2016 to 2019. Emission from ships play an important role in air pollution in China (as they do globally) and as a result studies like this are important in order to fully understand the effect. This work is novel, interesting and reasonably well written. I believe it should be published in ACP if the authors can address the following minor points.

Response:

Thank you very much for spending time to give us so many constructive comments. Upon learning through them, we improved our manuscript and tried our best to address all the concerns in this revision.

General comments:

Q1. Description of AIS data

I found the description of how the AIS data of number and position of ships is actually turned into emissions of air pollutant a bit lacking. What emission factors are used for this? Connected to this, the authors use the China domestic ship emission control (DECA) policy to alter emissions throughout the study period but do not quote any evidence as to how effective the policy has been or how much compliance there has been with the emission reductions. Are there any measurement studies that could be quoted to show whether ships are sticking to the DECAs?

Response:

Thank you for the comment.

(1) Emission factors

The emission calculation process within SEIM model has been introduced in our previous study (*Liu et al., 2016; Fu et al., 2017; Liu et al., 2018*) in detail, including the data collection and cleaning, calculation formula, emission factor (EF) adoption as well as default parameter setting. This article inherited the original SEIM model and upgraded it to the SEIM v2.0. To better guide readers, we added more descriptions related the calculation methods and the data in the Supplementary

Methods, including:

a) **General calculation formula in SEIM v2.0;**
b) **Automatic Identification System (AIS) data;**
c) **Ship technical specifications database (STSD);**
d) **Emission factors (EFs) connected with the DECA policy.**

Correspondingly, we also added **Fig. S1** to examine the temporal and spatial coverage of AIS data, and **Table S2** to show the emission factors applied in the SEIM v2.0. Thank you for your kind remainder.

(2) Compliance of DECA policy

DECA policy came into effect guaranteed by the authority of Chinese government, which 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 (*Liu et al., 2018; Zhang et al., 2019; Zhao et al., 2020; 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 cause uncertainties in this study. Therefore, an explanation was added in the revised manuscript to address this uncertainty.

Revisions in Manuscript:

1) Lines 108-109: The general calculation formula of the SEIM model is summarized in the Supplementary Methods.
2) Lines 290-297: The details about the emission factors regarding different fuel types were introduced in the Supplementary Methods. 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.

Revisions in Supplement:

General calculation formula in SEIM v2.0

The emission calculation in this study was made for each individual vessel, with a breakdown into three different engine types (main engine, auxiliary engine, and boiler) and four operation modes (At berth, at anchorage, maneuvering, and at sea). Transient emissions are calculated by multiplying emission factors (per unit power) by engine load ratios, with adjustment factors for fuel type and sulfur content. Total emissions are aggregated using transient emissions multiplied by time durations. The equations (1), (2) and (3) provide the emission calculation for main engine (ME) auxiliary engine (AE) and boiler in SEIM v2.0 model.

$$E^{\mathrm{ME}} = \sum_{t=1}^{n} \mathrm{MCR} \times \mathrm{EF}_{p,i,j,k}^{\mathrm{ME}} \times \mathrm{LF}_t \times \mathrm{LLAF}_p \times \Delta T_t \times 10^{-6} \tag{1}$$

$$E^{\mathrm{AE}} = \sum_{t=1}^{n} P_{v,s,m}^{\mathrm{AE}} \times \mathrm{EF}_{p,i,k}^{\mathrm{AE}} \times \Delta T_t \times 10^{-6} \tag{2}$$

$$E^{\mathrm{Boiler}} = \sum_{t=1}^{n} P_{v,s,m}^{\mathrm{Boiler}} \times \mathrm{EF}_{p,i}^{\mathrm{Boiler}} \times \Delta T_t \times 10^{-6} \tag{3}$$

Where MCR is the maximum continuous rated power (kW) for each vessel; $\mathrm{EF}_{p,i,j,k}^{\mathrm{ME}}$ is the emission factor for fuel type *i*, engine type *j*, emission standard *k* and species *p* (g/kW·h); LF_t is the load factor in time interval *t*, LLAF_p is the low load adjust factor for species *p*, which is applied when the load factor is less than 20%; ΔT_t is the time interval of the *t*-th continuous AIS signal (h); *n* is the total number of AIS signal time intervals under each category. $P_{v,s,m}^{\mathrm{AE}}$ and $P_{v,s,m}^{\mathrm{Boiler}}$ is the operating power (kw) of AEs and boiler of ship type *v* and size bin *s* (divided by dead weight tonnage) under operating mode *m* (kW); $\mathrm{EF}_{p,j,k}^{\mathrm{AE}}$ is the emission factor of pollutant *p* for AEs using fuel type *i* and complying with emission standard *k* (g/kW·h); $\mathrm{EF}_{p,i}^{\mathrm{Boiler}}$ is the emission factor of pollutant *p* for boilers using fuel type *i* (g/kW·h). Detailed description was provided in the Methods of our previous study (Liu et al., 2016).

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.

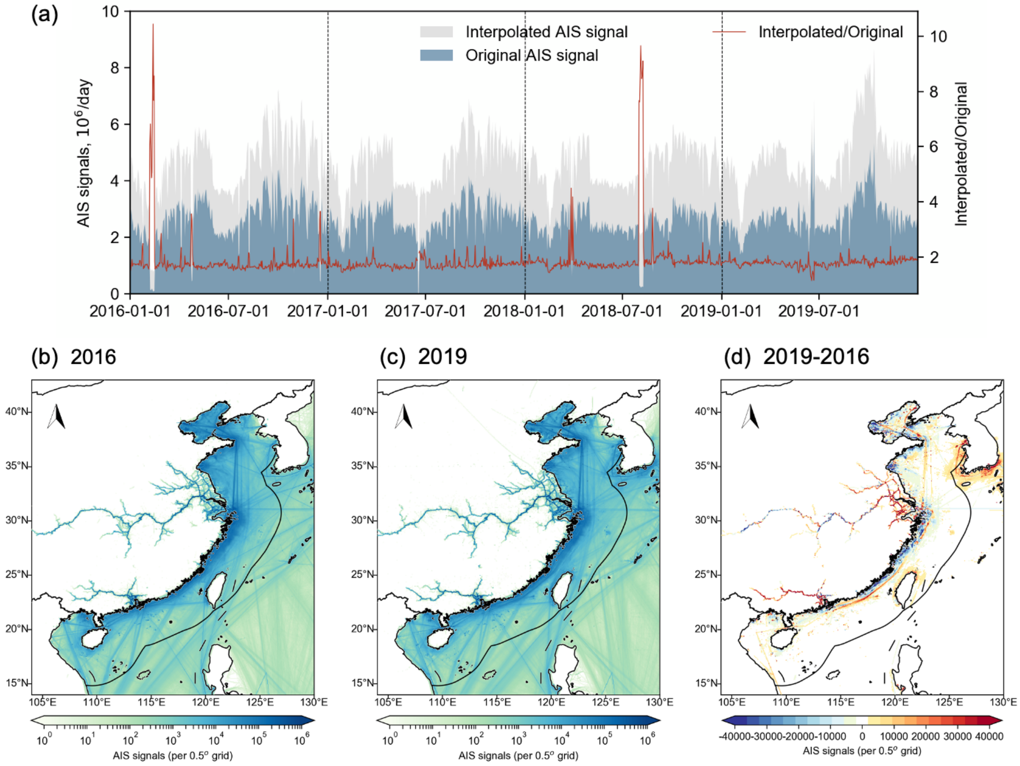

Fig. S1 Temporal and spatial coverage of AIS data in rivers and 200 Nm coastal zone of China from 2016 to 2019. (a) Daily evolution of AIS signals. (b) Spatial distribution of AIS signals in 2016. (c) Spatial distribution of AIS signals in 2019. (d) Spatial difference between 2016 and 2019.

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. 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.

Emission factors (EFs) in line with the DECA policy

In this study, the average fuel sulfur content for heavy fuel oil (HFO) was assumed to be 2.43% and that for maritime gas oil (MGO) was 1.3%. These assumptions were consistent with our previous studies based on the investigation of global fleet from *IMO Greenhouse Gas Study* (IMO, 2014; IMO, 2020). The implementation of China's domestic emission control area (DECA) required low sulfur fuel, i.e., MGO with sulfur content <0.5% m/m for ships entering the area. Despite the mandatory date, some regions actually implemented the DECA policy ahead of time, such as Shenzhen port and ports in Yangtze River Delta (YRD). Meanwhile, fuel consumed by river vessels are demanded to use general diesel oil (GDO) with phased requirements, with sulfur content followed by 0.035%, 0.005% and 0.001%. Table S1 summarizes the actual performance of DECA from 2016 to 2019 and the corresponding fuel type in different area, including both the coastal seas and inland rivers. Emission factors for different fuel types are shown in Table S2, which were either directly obtained from *Third IMO Greenhouse Gas study 2014* and related studies, or converted by the ratio of fuel sulfur content to the baseline, as illustrated in our previous work (Liu et al., 2016). In SEIM v2.0, a two-step method for was applied for ship emission estimation to be in line with the policy requirements, including the baseline EF selection and fuel correction factor (FCF) application:

- At the first stage, the baseline ship emissions were calculated for each two consecutive AIS signals based on the vessel's instantaneous power and the power-based baseline emission factors. The baseline EFs were selected according to fuel type of vessel recorded in STSD, including the liquified natural gas (LNG), HFO and MGO-0.13%. The GDO was only applied for river vessels, and the sulfur content for GDO was determined by time of AIS signals.
- In the policy-abutted modification module, the final ship emission would be further adjusted by the FCF. Due to the complexity of the DECA boundary, it would be time-consuming to judge whether it is in the DECA polygon for each AIS signal point. Thus, the intermediate output resulted from the first stage was grouped and aggregated by desired spatial resolution (e.g., 0.05° × 0.05°)

and other fields to reduce computing costs. For each aggregated emission record, vessels would be judged weather it was operating inside the DECA and needed to switch oil based on the signal time, geographical locations (latitude and longitude coordinates) and operating status. If the result of judgment is that the oil needs to be switched, the FCF, resulted from the quotient of the emission factors of the switched fuel and original fuel, would be further multiplied in the emission calculation formula.

Table S2. Emission factors for different fuel types used in this study (Unit: g/kW·h)

Fuel type	Emission Source	Engine type	PM	NO_x (Tier 0[d])	NO_x (Tier I)	NO_x (Tier II)	SO_2	HC
HFO (2.43% S)	ME	SSD[a]	1.335	18.1	17	15.3	9.261	0.6
		MSD[b]	1.33	14	13	11.2	10.215	0.5
	AE		1.339	14.7	13	11.2	10.782	0.4
	Boiler		2.1	14.85	14.85	14.85	0.1	0.1
MGO (0.05% S)	ME	SSD	0.31	17.01	15.98	14.38	1.81	0.6
		MSD	0.31	13.16	12.22	10.53	1.98	0.5
	AE		0.32	13.82	12.22	10.53	2.12	0.4
	Boiler		0.2	1.974	1.974	1.974	3.1	0.1
MGO (0.13% S)	ME	SSD	0.199	17.01	15.98	14.38	0.515	0.6
		MSD	0.2	13.16	12.22	10.53	0.568	0.5
	AE		0.202	13.82	12.22	10.53	0.599	0.4
	Boiler		0.112	1.974	1.974	1.974	0.825	0.1
GDO (0.035 %S)	ME	SSD	0.0192	17.01	15.98	14.38	0.133	0.6
		MSD	0.0192	13.16	12.22	10.53	0.147	0.5
	AE		0.0193	13.82	12.22	10.53	0.155	0.4
GDO (0.05% S)	ME	SSD	0.0028	17.01	15.98	14.38	0.019	0.6
		MSD	0.0027	13.16	12.22	10.53	0.021	0.5
	AE		0.0028	13.82	12.22	10.53	0.022	0.4
GDO (0.001% S)	ME	SSD	0.001	17.01	15.98	14.38	0.004	0.6
		MSD	0.001	13.16	12.22	10.53	0.004	0.5
	AE		0.001	13.82	12.22	10.53	0.004	0.4
LNG		Otto[c]	0.03	1.3	1.3	1.3	0.003	0.5

[a, b, c] mean slow speed diesel engine (SSD), medium speed diesel engine (MSD) and Otto-cycle LNG-fueled engine, respectively.

[d]Tier 0 refers to all ships constructed prior to January 1, 2000 which did not have an IMO Tier requirement at the time of construction.

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Q2. Ship emission impact

Could the authors comment on how much the emission from ships actually affects air pollution in populated areas in China? They quote percentage contribution to emissions but a more useful number would be how concentrations are affected. I realise this is not part of this studies but maybe there is some literature on the subject?

Response:

Thank you for your comments. In this study we give a high-resolution ship emission inventory from 2016-2019, but air quality simulation is not the topic of this study. However, there has been a significant number of studies on impacts of shipping emissions on air pollution in China during previous decades. Some of results are summarized as follows:

- On a national scale, ship emissions increased the annual average $PM_{2.5}$ concentration in eastern China to 5.2 μg/m^{-3}, while the influence range of coastal ships can reach as far as 960 km inland *(Lv et al., 2018*).
- At the regional scale, the average annual $PM_{2.5}$ concentration in the Bohai Rim Area (BRA) increases by 5.9% due to ship emissions, and the contribution in summer is as high as 12.5% (*Chen et al., 2018)*; shipping emissions contributed 0.60 μg/m^{-3} to the land ambient $PM_{2.5}$ in Pearl River Delta (PRD) region, and the maximum contribution reached up to 2.54 μg/m^{-3} in Hong Kong *(Liu et al., 2018)*; the annual contribution of ship emissions to $PM_{2.5}$ concentration in the Yangtze River Delta (YRD) could reach 4.62 μg/m^{-3} in summer (*Feng et al. 2019*).
- At the port scale, previous studies have showed that ships contributed 20-30%

to $PM_{2.5}$ in the coastal and riverside areas of Shanghai during the influence of ship plume (*Fan et al. 2016*); the contribution rate of ship emissions to $PM_{2.5}$ concentration in summer in Qingdao is as high as 13.1%, while the that near the port may exceed 20% (*Chen et al. 2017*).

In the revised manuscript, this part has been reorganized to underline the effect of ship emission on air pollution in populated areas in China.

Revisions in Manuscript:

Line 48-55: The influence of coastal ships to annual average $PM_{2.5}$ concentration (> 0.1 μg/m^3) can reach as far as 960 kilometers inland in China (Lv et al., 2018). Exhaust emissions from ships contributed significantly to air pollution in major port clusters, e.g., Bohai Rim Area (BRA), Yangtze River Delta (YRD) and Pearl River Delta (PRD) regions, and the maximum increase of annual $PM_{2.5}$ concentrations reaches up to 2 ~ 5 μg/m^3, with the greatest impact on YRD region (Chen et al., 2018; Liu et al., 2018; Lv et al., 2018; Feng et al., 2019). During ship-plume-influenced periods, ships can even contribute over 20% of the total $PM_{2.5}$ concentrations in port centers, e.g., Shanghai Port, Qingdao Port (Fan et al., 2016; Chen et al., 2017b).

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Q3. Resolution of inventory

The authors consistently talk about the high spatial and temporal resolution inventory without actually stating clearly what the resolutions are. Please add this prominently in the manuscript.

Response:

Thank you for your kind reminder. The spatial resolution is 0.05° longitude and latitude grid, as illustrated in Figure 11, Figure 12, Figure 13, and the temporal evolution could be traced down to one single day (Figure 10) in this study. This information has been added to the Abstract and the Introduction section.

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 83-85: In this study, we developed the ship emission inventory **(0.05° × 0.05°, daily)** for the inland rivers and the 200 Nm coastal zone of China from 2016 to 2019 based on the global AIS data and the updated version of Shipping Emission Inventory Model (SEIM v2.0).

Minor editorial points:

Q4. Line 8: pollutions should be pollution.

Response:

Thank you for the comment. The word has been corrected.

Revisions in Manuscript:

Line 8: Ship emissions and coastal air **pollution** around China are expected to be alleviated with the gradually implemented of domestic ship emission control (DECA) policy.

Q5. Line 107: use different language to 'figure out'.

Response:

Thank you for the comment. We adopted the word "fill" instead of "figure out".

Revisions in Manuscript:

Line 117: The 10-minute linear interval interpolation method was used to ~~figure out~~ **fill** long-distance AIS signal gaps.

Q6. Line 129: 'hardly unified standard' does not make sense.

Response:

Thank you for the comment. We have modified this expression.

Revisions in Manuscript:

Lines 142-143: Due to the complexity brought by the inconsistency of the ships' flag state, operating country and activity location, ~~there is hardly unified standard~~ **it is hard** to determine the attribution country of ship emissions.

Q7. Line 150: replace 'averagely' with 'on average'.

Response:

Thank you. The word has been corrected.

Revisions in Manuscript:

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

Q8. Line 381: 'proportions' does not need the 's'.

Response:

Thank you. The word has been corrected.

Revisions in Manuscript:

Line 440: The **proportion**~~s~~ of ship SO_2 emission from 12-50 Nm rose from 17.5% in 2016 to 35.3% in 2019, becoming the major spatial contributor in 2019.

Q9. Line 472: replace 'on' with 'to' and 'effect' with 'effects'.

Response:

Thank you. These words have been corrected.

Revisions in Manuscript:

Line 535: This reminds us to pay attention ~~on~~ **to** additional environmental ~~effect~~ **effects** brought by detouring ships during the continuous implementation of DECA 2.0 policy.

Q10. Throughout the whole manuscript NOx needs to have a subscript x.

Response:

Thank you. The "NO_x" has been revised throughout the whole manuscript.