frontiers | Frontiers in Environmental Science

ORIGINAL RESEARCH
published: 06 June 2022
doi: 10.3389/fenvs.2022.907868

Unexpected Methane Emissions From Old Small Fishing Vessels in China

Lizhi Wang[1,2,3], *Wei Du*[2,4], *Huizhong Shen*[5,6]*, *Yuanchen Chen*[7], *Xi Zhu*[2], *Xiao Yun*[2], *Guofeng Shen*[2], *Yilin Chen*[5,6], *Junfeng Liu*[2], *Xuejun Wang*[2] *and Shu Tao*[2,5,6]

[1]*Key Laboratory of Agro-Forestry Environmental Processes and Ecological Regulation of Hainan Province, Hainan University, Haikou, China,* [2]*Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Sino-French Institute for Earth System Science, Peking University, Beijing, China,* [3]*College of Ecology and Environment, Hainan University, Haikou, China,* [4]*Key Laboratory of Geographic Information Science of the Ministry of Education, School of Geographic Sciences, East China Normal University, Shanghai, China,* [5]*School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, China,* [6]*Guangdong Provincial Observation and Research Station for Coastal Atmosphere and Climate of the Greater Bay Area, Southern University of Science and Technology, Shenzhen, China,* [7]*College of Environment, Research Centre of Environmental Science, Zhejiang University of Technology, Hangzhou, China*

Diesel-fueled ships have long been considered to contribute a marginal fraction of the global methane (CH_4) emission budget compared to liquified natural gas (LNG)-fueled ships. Here, based on real-world measurements, we find that a specific yet-overlooked group of diesel-fueled ships–the old small fishing vessels (OSFVs)–is associated with high levels of CH_4 emissions. The emission factors of CH_4 from OSFVs is on average 5.2 ± 6.4 g CH_4 per 1 kg fuel consumed, approaching EF_{CH4} of LNG-fueled ships (5.3–30.1 g/kg) and being at least six times EF_{CH4} of other types of diesel-fueled ships (0.0–0.9 g/kg). We estimate that CH_4 emissions from OSFVs in China amount to 570–2,240 t per year, which is comparable to the total CH_4 emission from all LNG-fueled ships worldwide. Our results thus call for revision of the global CH_4 emission inventory for shipping.

Keywords: methane emission, old small fishing vessel, emission factor, climate change, China

OPEN ACCESS

Edited by:
Haofei Yu,
University of Central Florida, United States

Reviewed by:
Junwen Liu,
Jinan University, China
Congmeng Lyu,
University of Colorado Boulder, United States

Correspondence:
Huizhong Shen
shenhz@sustech.edu.cn

Specialty section:
This article was submitted to Atmosphere and Climate, a section of the journal Frontiers in Environmental Science

Received: *30 March 2022*
Accepted: *11 May 2022*
Published: *06 June 2022*

Citation:
Wang L, Du W, Shen H, Chen Y, Zhu X, Yun X, Shen G, Chen Y, Liu J, Wang X and Tao S (2022) Unexpected Methane Emissions From Old Small Fishing Vessels in China. Front. Environ. Sci. 10:907868. doi: 10.3389/fenvs.2022.907868

INTRODUCTION

Methane (CH_4) is a powerful greenhouse gas with radiative forcing on average 80.8–82.5 times that of carbon dioxides of an equal mass over 20 years and 27.2–29.8 times over 100 years. (Forster et al., 2021). CH_4 is an important precursor of tropospheric ozone which has adverse effects on human health and vegetation growth (Crutzen, 1973). CH_4 emissions from shipping have gained growing attention due to the expansion of maritime transportation in the context of globalization (Olmer et al., 2017; Ushakov et al., 2019). Past studies on shipping emissions of CH_4 have been focused on liquified natural gas (LNG)-powered ships because substantial CH_4 can escape unburned at the exhaust from low-pressure LNG-fueled engines of these ships, as is called "CH_4 slip" (Ushakov et al., 2019). Diesel-powered ships, on the other hand, have typically much lower levels of CH_4 slip (two orders of magnitude lower than LNG-powered ships) (Nielsen and Stenersen, 2010), and their CH_4 emissions are considered to be negligible (Nielsen and Stenersen, 2010).

However, not all the diesel engines are CH_4 free. Engines subject to old technology or under poor maintenance may release high levels of CH_4 because, in addition to direct slip, CH_4 is produced by incomplete combustion that occurs more frequently in old engines or during abnormal engine operation (Nam et al., 2004; Amous, 2000; Karakurt et al., 2012). It was found, for example, that emission factors of CH_4 (EF_{CH4}, i.e., the amount of CH_4 emitted per unit mass of fuel consumed) for on-road vehicles with a model year of 1980 were six times the EF_{CH4} for those with a model year of 2000 (Nam et al., 2004). Similar differences are expected for ships, with poorly-maintained old ships being associated with higher levels of CH_4. However, investigations on CH_4 emissions from old ships are scarce.

Old small fishing vessels (OSFVs, defined as small fishing vessels over ten-year age) in China are a typical group of vessels privately owned by local fishermen in low-income community. Most OSFVs are under poor maintenance conditions and absent from regular official emission inspection. China Fishery Statistical Yearbook reported a total of 370 thousand small fishing vessels which account for half of the fishing fleet in China (Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2020), but their aging rate (i.e., the fraction of OSFVs among the small fishing vessels) is not known. Assuming an aging rate between 12 and 47% based on other types of ships on record (including dry bulk cargo ship, container vessel, and liquid cargo) (Ministry of Transport of the People's Republic of China, 2021a), OSFVs may account for 6–24% of the fishing fleet in China—the top fishery country of the world. The tonnage of China's OSFVs (140,000–550,000 tonnes) could be comparable with that of the entire fishing fleet in some world's leading fishery countries, such as the United States (271,000 tonnes), Norway (392,000 tonnes), Vietnam (445,000 tonnes), Korea (512,000 tonnes), Philippines ($495,000 tonnes), or Japan (936,000 tonnes) (Organisation for Economic Co-operation and Development, 2019). Despite the large number and high emission potentials, EF_{CH4} of OSFVs have not yet been investigated, and their share of China's total shipping emission is unclear.

In this study, we measured EF_{CH4} of typical OSFVs in China. To the best of our knowledge, this is the first time to report EF_{CH4} of OSFVs. We further compared OSFVs' EF $_{CH4}$ with EF_{CH4} of other ships that were measured in this study or reported in literature. Based on our measurements, we estimated the CH_4 emissions from OSFVs and discussed the importance of OSFVs for CH_4 emissions from shipping in China.

METHODS

On-Site Measurements

On-site measurements were conducted on three OSFVs which were all more than 10 years old and less than 12 m in length (**Supplementary Table S1**). The OSFVs were all wooden boats whose tonnages ranged from 10 to 15 t. Each OSFV was equipped with a diesel engine. The engine capacities of these three OSFVs were 8.8, 16, and 108 kW, respectively. For comparison, other types of marine vessels were also tested, including three medium fishing boats, three tug boats, one ferry, one cargo, and two engineering vessels. The tonnages of these vessels were much larger than those of OSFVs, ranging from 69 t for medium fishing boats to 6,000 t for one of the engineering vessels. All vessels were fueled with marine light diesel. The compositions and properties of light diesel from local gas stations were analyzed and summarized in **Supplementary Table S2**. Note that the light diesel used by the vessels may not meet the China's national standards because inferior cheap diesel may be provided and distributed by illegal suppliers in local areas (Long and Shi, 2020). More details about the OSFVs and other tested vessels, including their age, tonnage, engine power, length, etc., are provided in **Supplementary Table S1** with the vessels' photographs shown in **Supplementary Figure S1**.

On-site emission sampling was conducted in May 2016 and August 2017 in three harbors, i.e., Yangpu, Haikou, and Sanya in Hainan Province, China (**Supplementary Figure S2**). The on-site sampling system consisted of a sampling probe (with the inner diameter of 10 mm), a residence chamber, a particulate matter pre-filter, a gas sensor box, an online nondispersive infrared analyzer (GXH-3051, Beijing Junfang Lihua Institute of Science & Technology, China), and an active pump (SKC, PA, United States) (**Supplementary Figure S3**). During sampling, the gas pump was operated at a flow rate of ~2.0 L/min. Exhaust gases were extracted through the sampling probe placed near the centers of the engine exhaust ports (or chimneys for large vessels). The sampled gases were then directed into the residence chamber to facilitate better mixing and subsequently went through the particulate matter filter to avoid excessive particulate loading and through silica gel to remove water vapor. Filtered dry gases were collected in the gas sensor box where CH_4, carbon dioxide (CO_2), and carbon monoxide (CO) concentrations were measured using the online nondispersive infrared analyzer. All the instruments were checked and calibrated prior every sampling cycle. The flow of the gas pump was calibrated both before and after sampling, using a primary flow calibrator (Bios Defender 510, United States). The layout of the sampling system is shown in **Supplementary Figure S3**. Similar sampling systems have been used to measure shipping emissions of particulate- and gaseous-phase pollutants, as described in detail in previous studies (Wang et al., 2022a; Wang et al., 2022b).

The on-site measurements covered an array of driving modes, including cruising, operating, manoeuvring, and berthing. For cruising and berthing modes, each sampling cycle lasted for about 10 minutes when the vessels ran under stable engine loads. For maneuvering and operating modes, each sampling cycle covered a whole activity period. During most sampling cycles, repetitive samples were collected simultaneously, from which the averages and variations of the measurement results were taken.

Calculation of Emission Factors

We calculated fuel-based EF_{CH4} in the unit of g × (kg fuel)$^{-1}$ based on the widely-used carbon mass balance method (Zhang et al., 2000), assuming that carbon in fuel is mainly emitted in the form of CO_2, CO, and CH_4. EF_{CH4} is calculated as follows,

$$EF_{\mathrm{CH_4}} = \frac{1000 \times C_{\mathrm{CH_4}} \times f_{C-\mathrm{fuel}}}{C_{\mathrm{CO_2}} \times f_{C-\mathrm{CO_2}} + C_{\mathrm{CO}} \times f_{C-\mathrm{CO}} + C_{C-\mathrm{CH_4}} \times f_{\mathrm{CH_4}}}$$

where C_{CH4}, C_{CO2}, and C_{CO} are measured concentrations of CH_4, CO_2, and CO in exhaust gas, respectively; $f_{C\text{-}CH4}$, $f_{C\text{-}CO2}$, and f_{CO} denote carbon contents in CH_4, CO_2, and CO, respectively, and are 12/16, 12/44, and 12/28, respectively; $f_{C\text{-}fuel}$ denotes the carbon content in fuel and was measured to be 86.5% in this study. Following previous studies, (Zhang et al., 2018; Wang et al., 2022b) integrated EF_{CH4} of each type of vessel, representing a daily average level, was calculated by integrating EF_{CH4} under different driving modes with corresponding time-driving mode patterns. Detailed procedures for calculating integrated EF can be found in previous studies. (Zhang et al., 2018; Wang et al., 2022b)

TABLE 1 | Integrated emission factors of methane (EF_{CH4}) from different types of vessels measured in this study.

Vessel type	Number of vessels	Number of sampling cycles	EF_{CH4}, g/kg Mean (Standard deviation)
OSFV	3	8	5.23 (6.40)
Fishing vessel, median	5	12	0.02 (0.03)
Tug boat	3	20	0.05 (0.11)
Ferry	1	2	0.93 (1.21)
Cargo	1	3	0.00 (0.00)
Engineering vessel	2	13	0.04 (0.13)

Note: The EF_{CH4} listed in this table integrates EF_{CH4} under different driving modes with corresponding time-driving mode patterns (Zhang et al., 2018; Wang et al., 2022b). "OSFV" denotes old small fishing vessel.

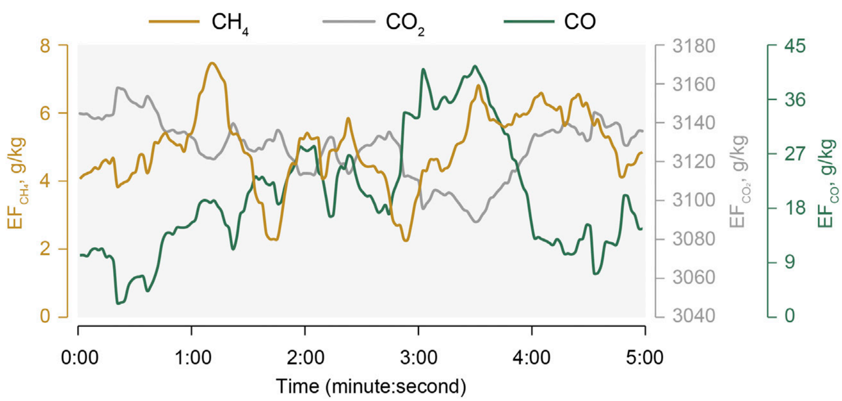

FIGURE 1 | The measured temporal variation in instantaneous EF_{CH4}, EF_{CO2}, and EF_{CO} of a typical OSFV during cruising.

RESULTS AND DISCUSSION

Average EF_{CH4} of OSFVs and Variations

The average EF_{CH4} of the 58 measurements is 0.9 g/kg (g CH_4 emitted per kg fuel burned), varying among individual measurements from 0 to 14.8 g/kg. When considering time-driving mode patterns, the integrated EF_{CH4} range from 0 g/kg for cargoes to 5.2 g/kg for OSFVs. **Table 1** shows the integrated EF_{CH4} values and standard deviations of different types of vessels, which reveals considerable differences in EF_{CH4} levels. Median fishing vessels (0.02 g/kg), tugs (0.05 g/kg), cargoes (0.00 g/kg), and engineering ships (0.04 g/kg) have much lower EF_{CH4} than ferries (0.9 g/kg) and OSFVs (5.2 g/kg).

Factors Affecting EF_{CH4}

The average EF_{CH4} of the 58 measurements (0.90 g/kg) was more than one order of magnitude higher than the EF_{CH4} proposed by the International Maritime Organization (IMO) in their latest GHG study (0.04–0.05 g/kg) (Faber et al., 2020). This difference was mainly driven by the high levels of EF_{CH4} from OSFVs which were on average over 100 times the IMO proposed levels. Note that the IMO's EF_{CH4} (0.04–0.05 g/kg) was used to represent a fleet-average level for estimating global emissions from diesel-fueled ships and was based on measurements conducted on four ships only (Cooper and Gustafsson, 2004; Faber et al., 2020). Among the four ships, none were OSFVs.

Despite the high average of OSFVs' EF_{CH4}, EF_{CH4} of individual OSFVs vary widely and fluctuate in time during each driving cycle. The three OSFVs we measured have EF_{CH4} of 0.0, 1.6, and 12.3 g/kg, respectively. The near-zero EF_{CH4} of the first OSFV is likely associated with its installation of a different type of engine which has a much higher capacity (108 kW) than those of the other two OSFVs (16 and 8.8 kW, respectively). The third OSFV shows the highest EF_{CH4}, which may be a result of its being the oldest (15 years) among the three OSFVs (10 years for the other two). High temporal resolution of the measurement data allows for further investigation into the instantaneous EF_{CH4} during sailing. **Figure 1** shows the temporal variation of EF_{CH4} over 5 minutes in the middle of a typical sailing cycle. EF_{CH4} are found to be changing by a factor of three (from 2.3 to 7.2 g/kg) within this short period, which are more variable than the EFs of CO_2, as expected, but less variable than the EFs of CO (varying by a factor of 18) (**Figure 1**). The ratio of CH_4/CO_2 in OSFV exhaust is on average 1.5×10^{-3}, which is much larger than the other types of diesel-fueled ships measured in this study (6.1×10^{-4} on average) but lower than LNG-fueled ships as reported in literature (typically 0.6–0.9%) (Ushakov et al., 2019).

CH_4 emissions from LNG-fueled ships have been of great concern due to substantial CH_4 slipping from LNG-fueled ships—LNG typically contains more than 90% CH_4 which is subject to potential leakage during engine operation (Guo and Ghalambor, 2014; Ushakov et al., 2019). CH_4 content in diesel, on the other hand, is neglectable, and diesel-fueled ships are associated with EF_{CH4} levels typically two orders of magnitude lower than those of LNG-fueled ships (Faber et al., 2020). Surprisingly, the average measured EF_{CH4} of OSFVs (5.2 g/kg) in this study, which are fueled by diesel, is over six times EF_{CH4} of other diesel-fueled ships measured in this study and approaches those of LNG-fueled ships reported in literature (5.3–30.1 g/kg) (Ushakov et al., 2019; Faber et al., 2020). As we measured, the composition of fuel collected from nearby gas stations represents common diesel composition (**Supplementary Table S2**). Therefore, such high levels of CH_4 are very likely a result of combustion by-products under abnormal engine operation rather than slipping of unburned fuel. This presumption is strengthened by similarly higher levels of emissions from OSFVs of other incomplete by-products reported in previous studies (Wang et al., 2022a; Wang et al., 2022b). Nevertheless, the underlying mechanisms leading to the high EF_{CH4} of OSFVs warrant further investigation.

CH_4 Emissions From Domestic OSFVs and Implications

Assuming that the fraction of OSFVs among small fishing vessels fall within the range of 12–47% (note that the range is based on the reported aging rates of other types of ships in China) (Ministry of Transport of the People's Republic of China, 2021a), we estimate that the oil consumption by OSFVs in China is 4.7–18.3 PJ year^{-1} in 2020. In comparison, the global consumption of LNG by shipping estimated by the International Energy Agency is 12.7 PJ year^{-1} in the same year (International Energy Agency, 2019). OSFVs in China alone amounts to an annual CH_4 emission of approximately 570–2,240 t, which is similar in magnitude to the CH_4 emission from all LNG-fueled ships globally (2,610 t) (Faber et al., 2020).

The robustness of the current study is affected by both the limited number of ships investigated and the high variability of EF_{CH4} among OSFVs. As for the OSFVs monitored, only one exceeds significantly from the average EF_{CH4} (0.90 g/kg), reaching a mean value of 12.3 g/kg, while the other two show limited emissions (0.0 and 1.6 g/kg), which warrants more measurements for further investigation. We also note that the literature-reported EF_{CH4} data for diesel-fueled ships are very scarce. For example, IMO uses data from merely four ships to approximate the average EF_{CH4} of the global diesel-fueled fleet. The measured EF_{CH4} of the three OSFVs and 12 diesel-fueled ships of other types in this study, therefore, represent a significant addition to the current EF_{CH4} dataset.

In recent years, China has made great efforts to reduce pollutants emissions from various sources (Zheng et al., 2018; Xie, 2020), including domestic shipping (Ministry of Ecology and Environment of the People's Republic of China, 2018). OSFVs are being phased out due to stringent regulations and incentives to promote replacement of OSFVs (Ministry of Agriculture and Rural Affairs, 2019; Ministry of Transport of the People's Republic of China, 2021b). In a follow-up investigation, we conducted an expanded survey on the actual share of OSFVs operating in Hainan in 2021, 4 years after our emission measurements were carried out. The survey investigated 67 small fishing vessels in eight main harbors in Hainan and revealed an aging rate of 16% among the small fishing vessels, which is close to the lower bound of our estimated aging rate (12–47%). The difference between the survey-based local aging rate and the estimated nationwide aging rate is reasonable, given that Hainan together with some other leading ocean fishing provinces pioneers the phasing-out of OSFVs (Department of Agriculture and Rural Affairs of Hainan Province, 2018). Considering the high emission levels of CH_4, as revealed in this study, and other incomplete combustion by-products (Wang et al., 2022a; Wang et al., 2022b), the phasing-out of OSFVs driven by stringent regulations may yield significant climate and health cobenefits.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

LW: Methodology, Investigation, Formal analysis, Writing—review and editing. WD: Methodology, Investigation, Writing—review and editing. HS: Investigation, Formal analysis, Writing—original draft, Writing—review and editing, Funding acquisition. YC: Methodology, Investigation. XZ: Methodology, Investigation. XY: Methodology, Investigation. GS: Methodology, Investigation, Funding acquisition. YC: Methodology, Investigation, Formal analysis. JL: Conceptualization, Methodology. XW: Methodology, Investigation. ST: Conceptualization, Methodology, Writing—review and editing, Funding acquisition.

FUNDING

This research is supported by the National Natural Science Foundation of China (Grants 41991312, 41821005, 41922057, 41830641, and 42192510), Department of Science and Technology of Guangdong Province (Grant 2021B1212050024), Department of Education of Guangdong Province (2021KCXTD004), Shenzhen Environmental Monitoring Center (Grant 0722-216FE4812SZF-2), and Center for Computational Science and Engineering at Southern University of Science and Technology.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.907868/full#supplementary-material

Supplementary Figure S1 | On-site photographs of the old small fishing vessels **(A)**, medium fishing boats **(B)**, tug boats **(C)**, ferries **(D)**, cargo **(E)**, and engineering vessels **(F)** tested in this study.

Supplementary Figure S2 | The map of the sampling locations.

Supplementary Figure S3 | Schematic of the on-site sampling system.

Supplementary Table S1 | Summary of the key information on the tested vessels.

Supplementary Table S2 | Summary of the content of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) in local light diesel at Yangpu port.

REFERENCES

Amous, S. (2000). "Non-CO_2 Emissions From Stationary Combustion," in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. IPCC, 41–54.

Cooper, D., and Gustafsson, T. (2004). *Methodology for Calculating Emissions from Ships: 1. Update of Emission Factors*. Norrköping, Sweden: SMHI Swedish Meteorological and Hydrological Institute.

Crutzen, P. (1973). A Discussion of the Chemistry of Some Minor Constituents in the Stratosphere and Troposphere. *Pageoph* 106-108 (1), 1385–1399. doi:10.1007/bf00881092

Department of Agriculture and Rural Affairs of Hainan Province (2018). Announcement of the Proposed Subsidy for the Renewal and Transformation of Marine Fishing Fishing Vessels in Hainan Province in 2018. Available at: https://agri.hainan.gov.cn/hnsnyt/xxgk/0200/0202/201901/t20190124_2267113.html (accessed 2021/8/13).

Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B., Hauerhof, E., et al. (2020). Reduction of GHG Emissions from Ships—Fourth IMO GHG Study 2020—Final Report. *IMO MEPC* 75 (7), 15.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., et al. (2021). "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Editors V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Cambridge, United Kingdom, New York, NY: Cambridge University Press), 923–1054. doi:10.1017/9781009157896.009

Guo, B., and Ghalambor, A. (2014). *Natural Gas Engineering Handbook*. Houston, TX: Gulf Publishing Company.

International Energy Agency (2019). World Energy Statistics 2019. Available at: https://www.iea.org/data-and-statistics/data-product/world-energy-statistics (Accessed 05/04/2021).

Karakurt, I., Aydin, G., and Aydiner, K. (2012). Sources and Mitigation of Methane Emissions by Sectors: A Critical Review. *Renew. energy* 39 (1), 40–48. doi:10.1016/j.renene.2011.09.006

Long, W., and Shi, J. (2020). *Hainan Investigated and Punished 13 Cases of Illegal Use of Over-standard Fuel Oil in a Year*. Wuhan, China: China Water Transport News. Available at: http://www.zgsyb.com/news.html?aid=533559 (accessed 11 202113.

Ministry of Agriculture and Rural Affairs (2019). Fishing Vessel Renovation Subsidy Standard. Available at: https://www.sohu.com/a/348651794_769126 (accessed 2021/12/25).

Ministry of Agriculture and Rural Affairs of the People's Republic of China (2020). *China Fishery Statistical Yearbook*. Beijing, China: China Agriculture Press.

Ministry of Ecology and Environment of the People's Republic of China (2018). *Limits and Measurement Methods for Exhaust Pollutants from Marine engines (CHINA I, II)*. Available at: http://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/dqhjbh/dqydywrwpfbz/201608/t20160830_363272.shtml (Accessed 05/04/2021).

Ministry of Transport of the People's Republic of China (2021). An Analysis Report on the Capacity of Coastal Inter-provincial Freight Ships in 2020. Available at: https://xxgk.mot.gov.cn/2020/jigou/syj/202102/t20210219_3526026.html (accessed 2021 07/08/2021).

Ministry of Transport of the People's Republic of China (2021). Decision of the Ministry of Transport on Amending the "Regulations on the Administration of Old Transport Ships. Available at: http://www.gov.cn/zhengce/zhengceku/2021-08/26/content_5633472.htm?_zbs_baidu_bk (accessed 2021/12/25).

Nam, E. K., Jensen, T. E., and Wallington, T. J. (2004). Methane Emissions from Vehicles. *Environ. Sci. Technol.* 38 (7), 2005–2010. doi:10.1021/es034837g

Nielsen, J., and Stenersen, D. (2010). Emission Factors for CH_4, NOX, Particulates and Black Carbon for Domestic Shipping in Norway, Revision 1. *Marinted Report MT22 A10-199* (Marintek: Klima og forurensningsdirektoratet). Available at: https://www.miljodirektoratet.no/globalassets/publikasjoner/klif2/publikasjoner/2746/ta2746.pdf (Accessed 05/04/2021).

Olmer, N., Comer, B., Roy, B., Mao, X., and Rutherford, D. (2017). *Greenhouse Gas Emissions from Global Shipping, 2013–2015 Detailed Methodology*. Washington, DC, USA: International Council on Clean Transportation, 1–38.

Organisation for Economic Co-operation and Development (2019). *OECD.Stat: Fisheries and Aquaculture Statistics*. Available at: https://stats.oecd.org/ (Accessed 05/04/2021).

Ushakov, S., Stenersen, D., and Einang, P. M. (2019). Methane Slip from Gas Fuelled Ships: A Comprehensive Summary Based on Measurement Data. *J. Mar. Sci. Technol.* 24 (4), 1308–1325. doi:10.1007/s00773-018-00622-z

Wang, L., Du, W., Chen, Y., Wang, W., Chen, Y., Zhu, X., et al. (2022). High PM2.5 Emission from Typical Old, Small Fishing Vessels in China. *Environ. Sci. Technol. Lett.* 9 (3), 199–204. doi:10.1021/acs.estlett.1c00927

Wang, L., Du, W., Yun, X., Chen, Y., Zhu, X., Shen, H., et al. (2022). On-site Measured Emission Factors of Polycyclic Aromatic Hydrocarbons for Different Types of Marine Vessels. *Environ. Pollut.* 297, 118782. doi:10.1016/j.envpol.2021.118782

Xie, Z. (2020). China's Historical Evolution of Environmental Protection along with the Forty Years' Reform and Opening-Up. *Environ. Sci. Ecotechnology* 1, 100001. doi:10.1016/j.ese.2019.100001

Zhang, F., Chen, Y., Chen, Q., Feng, Y., Shang, Y., Yang, X., et al. (2018). Real-world Emission Factors of Gaseous and Particulate Pollutants from Marine Fishing Boats and Their Total Emissions in China. *Environ. Sci. Technol.* 52 (8), 4910–4919. doi:10.1021/acs.est.7b04002

Zhang, J., Smith, K. R., Ma, Y., Ye, S., Jiang, F., Qi, W., et al. (2000). Greenhouse Gases and Other Airborne Pollutants from Household Stoves in China: A Database for Emission Factors. *Atmos. Environ.* 34 (26), 4537–4549. doi:10.1016/s1352-2310(99)00450-1

Zheng, B., Tong, D., Li, M., Liu, F., Hong, C., Geng, G., et al. (2018). Trends in China's Anthropogenic Emissions since 2010 as the Consequence of Clean Air Actions. *Atmos. Chem. Phys.* 18 (19), 14095–14111. doi:10.5194/acp-18-14095-2018

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.