Maritime Policy & Management

The flagship journal of international shipping and port research

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tmpm20

Implications of Arctic shipping emissions for marine environment

Qiong Chen, Ying-En Ge, Adolf K.Y. Ng, Yui-yip Lau & Xuezong Tao

To cite this article: Qiong Chen, Ying-En Ge, Adolf K.Y. Ng, Yui-yip Lau & Xuezong Tao (2022) Implications of Arctic shipping emissions for marine environment, Maritime Policy & Management, 49:2, 155-180, DOI: 10.1080/03088839.2021.1990427

To link to this article: https://doi.org/10.1080/03088839.2021.1990427

Published online: 25 Oct 2021.

MARITIME POLICY & MANAGEMENT
2022, VOL. 49, NO. 2, 155–180
https://doi.org/10.1080/03088839.2021.1990427

Routledge
Taylor & Francis Group

Check for updates

Implications of Arctic shipping emissions for marine environment

Qiong Chen[a], Ying-En Ge[a,b], Adolf K.Y. Ng[c,d], Yui-yip Lau[e] and Xuezong Tao[a]

[a]Lloyd's Register Foundation International Institute for Transport and Environment, College of Transport & Communications, Shanghai Maritime University, Shanghai, China; [b]College of Transportation Engineering, Chang'an University, Xi'an, Shannxi, China; [c]Division of Business and Management, Beijing Normal University-Hong Kong Baptist University United International College, Zhuhai, China; [d]St. John's College, University of Manitoba, Winnipeg, MB, Canada; [e]Division of Business and Hospitality Management, College of Professional and Continuing Education, the Hong Kong Polytechnic University, Hong Kong, China

ABSTRACT

To investigate the distribution and behaviour of ocean vessels in the Arctic region and determine the impacts of their emissions, we examine vessel characteristics in conjunction with a series of Automatic Identification System (AIS) data between 2012 and 2016. These datasets, combined with a bottom-up model for estimating pollution emissions, enable us to analyse the level of pollution generated by vessels in the Arctic region. The results indicate that the movements of the vessels and their emissions increase in frequency and continue to do so unless clean energy or technologies are adopted. More than 80% of the emissions are found to be concentrated in the Norwegian and Barents Seas. Emissions from the Northern Sea Route are comparatively low and those from the Northwest Passage are similarly insignificant. Besides, an empirical analysis of the emissions in the Arctic region is carried out following the more restrictive International Maritime Organization (IMO)'s regulations on sulphur emissions that is implemented in 2020. This investigation supplements the literature analysing Arctic's pollution emission inventory.

KEYWORDS

Arctic region; pollution emissions; ais; bottom-up pollution emission model

1. Introduction

The Arctic Circle (latitude at 66 degrees 33 minutes N) is rich in wildlife and oil resources (Lasserre 2011), with a number of ports and sizeable population bases located in this region. Accordingly, this region has received a wide attention from scholars, policy makers, industrial practitioners, and environmentalists as the temperature in the Arctic increased at a rate almost twice as much as that of the global average over the past century (AMAP 2011). Climate change has resulted in a significant rise in temperature and a continuous reduction in the level of ice coverage in the Arctic region, which has brought economic opportunities to the Arctic as indicated by more and more Arctic shipping routes to unfold in the past decades. These Arctic routes greatly reduce operational costs due to the decreased fuel consumption as well as shortened journey time spent in transit (Faury and Cariou 2016; He et al. 2020; Lin and Chang 2018). However, the Arctic marine environment poses a huge challenge to vessel operations and fleet management due to its extreme weather conditions and its loose regulatory framework. This paper investigates the behaviour of vessels navigating in the Arctic and estimates their pollutant emissions into

CONTACT Ying-En Ge yege@chd.edu.cn College of Transportation Engineering, Chang'an University, Middle-section of Nan'er Huan Road, Xi'an, Shannxi 710064, China

Note: This article is a revised and expanded version of a paper entitled 'Implications of Arctic shipping emissions for marine environment' presented at the 2nd CCAPPTIA conference (online), 28–30 June 2021.

the local environment based on Automatic Identification System (AIS) data and vessel characteristics. The purpose of this investigation is to gain valuable insights and constructive advice into impacts of pollutant emissions on the marine environment in the Arctic region.

Shipping is one of the most significant sources of emissions in the Arctic (Winther et al. 2014), as it releases a large amount of pollution into the environment, such as Nitrogen Oxides (NO_X), Sulphur Oxides (SO_X), particulate matters (PM) and greenhouse gases (Corbett 2003; Goldsworthy and Goldsworthy 2015; Liu et al. 2016). Many studies have revealed the detrimental impacts of these pollutants on human health and the marine environment, particularly in the Arctic (Corbett 2003; Maragkogianni and Papaefthimiou 2015).

In general, top-down and bottom-up approaches are the two main ways to calculate the pollutant emissions from ships (Miola and Ciuffo 2011; Nunes et al., 2017). The top-down approach, also known as the fuel consumption-based approach, allows for the estimation of emission inventories by means of ship fuel sales data and fuel emission factors (Endresen et al. 2005; Nunes et al., 2017). It may also adopt fleet activity-based models with the fuel consumption result for emission inventory calculations (Eyring et al. 2010). Capaldo et al. (1999) predicted sulphur emissions based on the fuel consumption of ocean-going vessels in the Southern Pacific Ocean and the Northern Hemisphere Ocean. Similarly, Endresen et al. (2007) created a global vessel emissions inventory through the use of an improved fuel consumption modelling approach. The top-down approach is commonly used to calculate global greenhouse gas emissions inventories (Fourth IMO GHG Study 2020). The bottom-up approach, also known as an activity-based approach, is considered more accurate in the calculation of emission inventories. However, it requires a series of data on vessel traffic, such as vessel characteristics (e.g., type, length, engine power, design speed, International Maritime Organisation (IMO) number) and navigational data (e.g., sailing speed, port of calls, the distances travelled, sailing time), to construct an emission model (Goldsworthy and Goldsworthy 2015; Nunes et al., 2017). The wide availability of AIS data makes this approach feasible. Tichavska and Tovar (2015) integrated AIS data with a bottom-up modelling approach to assessing pollutant emissions from passenger ships in the port of Las Palmas in 2011. Yau et al. (2012) complied speed data with a bottom-up approach to creating an emissions inventory for the Hong Kong port in 2017. In the recent years, Chen et al. (2017), Johansson, Jalkanen, and Kukkonen (2017) and Liu et al. (2018) investigated the combination of a bottom-up model and the AIS data to obtain more accurate calculation of emission inventories.

Recent research on shipping routes in the Arctic has been largely carried out from an economic and operational perspective (Faury and Cariou 2016; Lin and Chang 2018). Paxian et al. (2010) used a global bottom-up vessel emissions estimation model along with vessel movement data to calculate fuel consumption, emissions and vessel traffic density for the then-current scenario and set up two possible future scenarios for 2050. By means of the data from the Arctic Marine Shipping Assessment database, Corbett et al. (2010) used an activity-based model of 5 km × 5 km grid cells to generate Arctic emissions inventories of key greenhouse gases, Black Carbon (BC) and other pollutants, which created current scenarios and projected future scenarios for 2050. They investigated the growth of shipping activities in the region, the potential diversion of vessel traffic through new and emerging routes and a number of possible emissions control measures. Peters et al. (2011) also used a bottom-up model combined with a detailed global energy market model to project the emissions inventories of Arctic shipping and petroleum activities for 2030 and 2050. They also estimated the extent of the sea ice in their future scenarios. Dalsøren et al. (2013) used the data from the Arctic vessel emissions inventories in high-resolution areas to quantify the changes in the concentration of pollutants. Additionally, they considered radiative forcing to be responsible for the short-lived atmospheric pollutants from shipping emissions of NO_X, SO_X, Carbon Monoxide (CO), BC, and organic carbon. Browse et al. (2013) integrated Arctic shipping emissions inventories from 2004 with both a global aerosol microphysics model and a chemical transport model to quantify the potential contribution of future Arctic shipping activities to high-latitude BC deposition in 2050. Similarly, for vessels in the Arctic region, Winther et al. (2014) organised a detailed BC, NO_X, and Sulphur dioxide (SO_2) emissions inventory for 2012 based on AIS data, vessel engine power functions and technology-stratified emission factors. The data enabled them to predict a series of trends for 2020, 2030, and 2050.

These studies have provided a good set of insights into shipping pollution in the Arctic and most have predicted and examined future pollution scenarios. However, with insufficient empirical data to analyse the impact of environmental pollution in the Arctic region, the work in the existing literature perhaps represents only a fraction of research in this area. To our best knowledge, there have been few empirical studies that have been specifically based on a combination of AIS data for consecutive years and a bottom-up model to examine the impact of shipping pollution in the Arctic. In our study, the AIS data between 2012 and 2016 are combined with a bottom-up model to evaluate the impact of Arctic shipping on the regional environment, which initially quantifies the pollution emissions from vessels in the Arctic Circle from 2012 to 2016 and then examines the amount and trend of pollution when the new restrictions on the amount of sulphur content in fuel came into effect in 2020. It is expected that the shift of global shipping from the traditional routes to the Arctic routes due to climate change, which reduces the total emissions from global shipping. Consequently, as this shift carries on, shipping emissions may be more concentrated in the Arctic, which is an environmentally vulnerable region. Therefore, it is necessary to tighten rules and regulations governing Arctic shipping in a timely manner to prevent this from happening in the Arctic region.

The intellectual merits of this work lie in quantifying ship emissions in the Arctic from 2012 to 2016, supplementing the Arctic ship pollutant emission inventory, and predicting ship emissions in the Arctic when sulphur policy changes in 2020.

The rest of this paper is structured as follows. Section 2 describes the scenario settings for the analysis. Section 3 introduces the sources of the data and presents the methodology for this analysis. The results of our numerical analysis are presented and analysed in Section 4. Section 5 offers policy recommendations based on the results of our numerical analysis. The last section is to present a set of concluding remarks with a discussion on implications of this investigation.

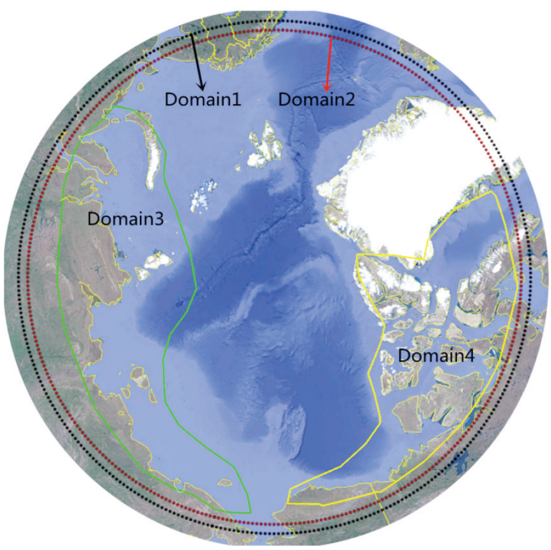

Figure 1. Chosen domains in the Arctic for the investigation (Source: adapted by Authors from Google Earth).

2. Scenario settings

Four geographical domains are identified and selected to investigate implications of Arctic shipping emissions for marine environment in the Arctic region. As shown in Figure 1, domain 1 covers a wide range (66.57° N to 90° N,—180° W to 180° E), Domain 2 (67.57° N to 90° N,—180° W to 180° E) represents the target region to be used for vessel emissions calculation, Domain 3 constitutes the NSR area (mainly including the Russian coastline, Kara, Laptev and East Siberian Seas), and Domain 4 represents the NWP area (mainly including the coastline of the United States and Canada, Beaufort Sea, Baffin Bay and Davis Strait). We used the vessel statistical data and the AIS data to calculate the emissions in Domain 1. The vessel emissions data are used for Domains 2, 3 and 4. We chose two nested domains (Domains 1 and 2) instead of a single layer to remove uncertainty due to the boundary effects and to improve the accuracy of the average vessel speed by calibrating the abnormality identified in the AIS data (see Sub section 3.2.3 and Appendix D) (Liu et al. 2016).

3. Data and methodology

3.1. Data sources and data description

We used the information from 3 databases: the AIS, the static Arctic database and the model databases. These comprise the data on marine traffic obtained from the China Classification Society (CCS), the Korean Register of Shipping (KR), the Nippon Kaiji Kyokai (NKK), the Russian Register of Shipping (RS), and BLM-Shipping. The static Arctic database provides the fixed data for vessel characteristics, such as the IMO number, vessel type, length, width, the rated engine power, the design speed, the gross tonnage (GT), the deadweight tonnage, the flag, the year the vessel was built, the fuel type, among others. If the data on some characteristics were missing, we made predictions using the model databases of the four societies (i.e., the CCS, KR, NKK, RS), which included the information on more than 10,000 vessels.

3.2. Data processing methods

3.2.1. Model database

A database of vessel models was created based on the data obtained from the four classification associations. However, critical vessel characteristics, such as the power of the main engine and the design speed, could not be accessed (see Table A.1 in Appendix A). We accordingly predicted the GT, the design speed and the rated power of the engines. Entec (2010) and Chen et al. (2017) both used a nonlinear regression analysis of the rated engine power of the main engine as a function of its GT. Liu et al. (2016) adopted a gradient boosting regression tree approach to predicting missing data. In this investigation, we used machine learning algorithms to predict the GT, the rated engine power and the design speed (see Appendix B), for which the coefficients of determination (R^2) of the regression functions were greater than or equal to 0.70; if $R^2 < 0.70$, the average value was used instead of the rated engine power and the design speed.

3.2.2. Static Arctic database

The vessels were categorised into 9 main types in terms of what is carried or purpose: general cargo, bulk carrier, container, tanker, fishing, tug, passenger, pleasure craft, and sailing. The annual number of vessels for each vessel type during 2012–2016 is listed in Table A.2 in Appendix A. During this period, fishing and general cargo contributed the largest number of vessels, and the least contributor is containerships. The data showed that the annual numbers of vessels in the Arctic were 4798 in 2012, 6639 in 2013, 5864 in 2014, 6204 in 2015 and 6878 in 2016, which shows an increasing trend in Arctic traffic although there was a big increase in 2013.

Table 1 shows the calculated average GT, average speed, and average rated engine power of vessels in 2016 alongside a comparison of the average power values reported in previous studies. In terms of the average GT, the bulk carrier was the largest type of vessels, followed by container ships and tankers.

Table 1. Calculated average GT, average speed and average power with a comparison of the average power with those reported in the literature.

Vessel Type	Average GT	Average Speed (knots)	Average Power (kW)	Average power reported in previous study	Difference average power with this study
Bulk Carrier	43,944.83	15.72	9,902.19	8,206 (Liu et al. 2016)	−17.13%
General Cargo	7,777.97	12.79	3,051.99	3,845 (Liu et al. 2016)	25.98%
Container	23,202.60	21.49	22,045.40	33,460 (Liu et al. 2016)	51.78%
Tanker	27,484.81	12.26	6,485.64	10,032 (Liu et al. 2016)	54.68%
Fishing	1,120.21	12.37	1,243.38	1,032 (Fourth IMO GHG Study 2020)	−17.00%
Tug	729.24	12.18	1,240.23	1302 (Fourth IMO GHG Study 2020)	4.98%
Passenger	11,740.99	22.48	2,326.70	3,960 (Chen et al. 2017)	70.20%
Pleasure Craft/ Sailing	288.02	12.75	2,409.15	3,137 (Third IMO GHG Study 2014)	30.21%
Other	5,407.28	13.56	3,308.00	3,415 (Liu et al. 2016)	3.23%

Pleasure crafts and sailing vessels had the smallest GT. Regarding the average rated engine power of vessels, containers ships were the largest, followed by the bulk carriers, with tugs and fishing vessels having the smallest rated engine power. Most vessels had an average speed of 10–15 knots. Container and passenger vessels were found to have higher than average speed, which was between 20 and 30 knots. A comparison of the average power values revealed that the values for the different vessel types included in this study were lower than those reported in the literature on ship emissions outside the Arctic area, except for bulk carriers and fishing ships. Due to the heavy coverage of ice and snow, the severe environment is not favourable for vessel navigation. In this framework, it is not surprising that the average rated engine power was lower than the rates reported in the existing literature.

3.2.3. The AIS database

The AIS database was designed to facilitate the automatic exchange between the vessels themselves and the coastal authorities regarding vessel information, such as the Maritime Mobile Service Identity (MMSI) codes, the vessel coordinates (their longitude and latitude), and the actual vessel speeds and trip durations. Such information can be used to analyse the movements and activities of the vessels (IMO 2020). The IMO's International Convention for the Safety of Life at Sea (SOLAS) requires that AIS be installed on international voyage vessels with a GT of 300 or higher, and on all passenger ships regardless of size (Chen et al. 2021; IMO 2020).

To calculate the levels of emissions, we applied the complete AIS dataset of the period from 2012 to 2016, which contained the information on 30,383 vessels and included 159,691,613 AIS messages related to the Arctic region. Based on the AIS dataset, we calculated the average vessel speed, which was equal to the distance between two adjacent recording points and divided by the duration of the journey (Goldsworthy and Goldsworthy 2015). However, the average operational speed is often less than the design speed due to various factors, such as the age of the vessel, the vessel specifications (i.e., draught, hull surface, propellers), and sea conditions (Babicz, 2015). However, when we analysed the vessel data, there were numerous instances of the average speed that are higher than the design speed. During the period between 2012 and 2016, the record of the average speed totals was 0.31% in 2012, 5.69% in 2013, 0.4% in 2014, 29.76% in 2015, and 1.98% in 2016. To this end, we identified as abnormal scenario. To reconcile these abnormal average speeds and to ensure that they were not higher than the design speeds, we used a grid-based average AIS speed completion algorithm (see Algorithm 1 in Appendix D).

To apply Algorithm 1, we selected a container ship in the Arctic region with the MMSI code of 352,212,000. As demonstrated in Figure 2, the red line indicates the design speed of the container ship, with a value of 26.45 knots, and the grey line represents the average speed of the vessel that was not specially treated. It was evident, however, that some of the average speed values were higher than the design speed. On this occasion, these speeds dangerously exceeded 175 knots. The green line represents

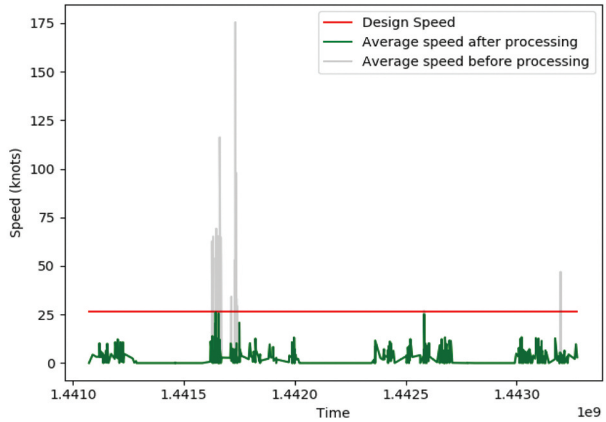

Figure 2. The AIS average speed completion as demonstrated by Algorithm 1.

the average speed processed by Algorithm 1, which was consistently less than the design speed. Following their treatment with Algorithm 1, the average speeds of the vessels in the Arctic amounted to 2.16 knots in 2012, 1.36 knots in 2013, 1.67 knots in 2014, 1.99 knots in 2015 and 2.02 knots in 2016.

3.3. Emissions parameters

3.3.1. Auxiliary engine power and boiler power

The auxiliary engines (AEs) of a vessel are used to generate electricity. It has been shown (Liu et al. 2016; Port of Los Angeles 2014) that, if the AEs are in continual use, they may generate the largest loads while the vessel is in a hotelling period (at berth or at anchorage). The AE data constitute a significant gap in the data collected by the classification associations (i.e., CCS, KR, NR, RS), as it is nearly impossible to directly access accurate AE information. To estimate the AE power of individual vessels, we adopted the AE-to-ME power ratios (where ME refers to the main engine) reported by the Environmental Protection Agency (EPA) (2009) and Port of Richmond (2010) (see Table C.1 in Appendix C,).

As demonstrated in Table C.2, we adopted the AE load factor for different vessel types reported in the EPA's report (Environmental Protection Agency (EPA) 2009), wherein a higher load factor indicates that a vessel requires more electrical energy.

As with the examinations of AE power, there are similarly a few data sources providing information on the power of vessel boilers, which are used to heat fuel, water and steam. We obtained boiler power values from the classes and modes of vessels from the EPA documentation (Environmental Protection Agency (EPA) 2009) (see Table C.3 in Appendix C). We used the values in Ng et al. (2013) to account for the boiler powers of fishing, pleasure craft and sailing vessels. For the data on the boiler powers of passenger vessels, we used the values reported by Nunes et al. (2017).

3.3.2. Vessel operation modes

We defined the vessel movement activity modes using the vessel speed range, which were congruent with the methods of the previous vessel emission inventory studies (Ng et al. 2013). The average speed is used to categorise vessel activities into four key modes: hotelling, manoeuvring, slow cruise, and fairway cruise (see Table C.4 in Appendix C).

3.3.3. Engine and fuel types

The types of main engines include high-, medium-, and slow-speed ones. These classifications are made based on the dominant GT and engine speed for each vessel type (Entec 2010) (see Table C.5 in Appendix C). Moreover, it is assumed that these vessels mainly use three types of fuel: residual, marine diesel, and marine gas oil (Port of Los Angeles 2014, 2015).

3.3.4. Emission factors and adjustment factors

Emissions data for vessels remain relatively scarce due to the complexity of emissions test procedures and the related costs to produce them. The baseline emission factors of the main engines (MEs) used in this study (see Appendix C, Table C.6) are obtained from (Environmental Protection Agency (EPA) 2009). When the diesel-cycle engines operated at 20% or less of the power requirements, their emissions factors tended to increase, as these engines are less efficient at a low load level. Table C.7 in Appendix C provides the low-load adjustment multipliers for the emission factors, based on the data provided by the port of Los Angeles (Port of Los Angeles 2014). The emission factors of the AEs and the boilers are accordingly provided in Tables C.8 and C.9 in Appendix C, respectively (Environmental Protection Agency (EPA) 2009; Port of Los Angeles 2014).

3.4. Methodology

We adopted the bottom-up method based on the AIS data (Liu et al. 2016). The AIS data, vessel characteristics data and the power-based emission factors are used in our study. We list the equations used in the bottom-up method below.

$$E = \sum_{n=1}^{M} E_n \tag{1}$$

$$E_n = E_{main} + E_{auxiliary} + E_{boiler} \tag{2}$$

$$E_{main} = P \times EF_{main} \times \sum_{T} LF_t \times A_{LF,t} \times \Delta T_t \tag{3}$$

$$LF_t = \left({}^{v_t}/_{v_{max}} \right)^3 \tag{4}$$

$$E_{auxiliary} = EF_{auxiliary} \times \sum_{T} (P_{auxiliary,i,j} \times \Delta T_t) \tag{5}$$

$$P_{auxiliary,i,j} = P \times R_j \times ALF_{i,j} \tag{6}$$

$$E_{boiler} = EF_{boiler} \times \sum_{T} (P_{boiler,i,j} \times \Delta T_t) \tag{7}$$

where E represents the total emissions of each pollutant (i.e., CO, CO_2, HC, NO_X, PM_{10}, $PM_{2.5}$, SO_X) from all the types of vessels in the Arctic Circle. We list and define the other notations below

E_n	:	Total emissions of a certain pollutant from a single vessel *n*;
M	:	Total number of vessels;
E_{main}, $E_{auxiliary}$ and E_{boiler}	:	Emissions from the main engines, the auxiliary engines, and the boilers, respectively.
P	:	Maximum continuous rated power of the main engines, which is unique to each vessel.
EF_{main}	:	Emissions factor of the main engine when using fuel with a certain sulphur content, as described in Table C.6 in Appendix C.
LF_t	:	The load factor (*LF*) for the main engine at time t.
$A_{LF,t}$		Emissions adjustment factors (A) when LF is lower than 20%, as described in Table C.7 in Appendix C.
ΔT_t	:	Time interval between two adjacent velocity points, which are the AIS points.
V_t	:	Vessel speed.
V_{max}	:	Vessel design speed, which is unique to each vessel.
$EF_{auxiliary}$	:	Emissions factor of the auxiliary engine when using fuel with a particular sulphur content, as described in Table C.8 in Appendix C.
$P_{auxiliary,i,j}$	:	The power of the auxiliary engine, which is constant for a vessel type *j* in mode *i*.
R_j	:	Ratio of the auxiliary engine power to the main engine power for vessel type *j*, as described in Table C.1 in Appendix C.
$ALF_{i,j}$	:	Auxiliary engine load factor, which is constant for a vessel type *j* in mode *i*, as described in Table C.2 in Appendix C.
EF_{boiler}	:	Emissions factor of the boiler when using fuel with a particular sulphur content, as described in Table C.9 in Appendix C.
$P_{boiler,i,j}$	:	The power of the boiler, which is constant for a vessel type *j* in mode *i* (see Table C.3 in Appendix C).
i	:	Mode *i*, dependent on the vessel speed (see Table C.4 in Appendix C).

4. Numerical analysis

4.1. Arctic vessel distribution

We analysed the distribution of vessels in the Arctic region between 2012 and 2016. Figure 3 demonstrates that most vessels were concentrated in the Norwegian and Barents Seas, followed by some vessels along the Siberian coastline. The NWP area (see Domain 4) and the gradual expansion to the Chukchi Sea had the least number of vessels. However, there has been an increased number of vessels navigating in the Arctic, some of which have even attempted to cross the North Pole.

4.2. Pollution over the Arctic circle

4.2.1. Arctic emissions

Using SO_X emissions as the sample, the total vessel emissions in the Arctic region in 2012, 2013, 2014, 2015, and 2016 are estimated to be 34,139.72 t, 50,846.26 t, 51,502.03 t, 58,540.22 t, and 65,604.29 t, respectively. The year-on-year growth rates are 48.94% (2013 relative to 2012), 1.29% (2014 relative to 2013), 13.67% (2015 relative to 2014), and 12.07% (2016 relative to 2015) (see Figure 4(A)). The total emissions of the other pollutants are listed in Appendix E. As demonstrated in Figure 4(A), the emissions increased annually regardless of pollutant type.

However, when compared with the 2013 data, the emission growth rate of some pollutants (i.e., CO, HC, NOx and $PM_{2.5}$) showed a slightly decrease in 2014 (see Figure 4(A) and Table E.2 in Appendix E). The negative annual total growth rate for some pollutants in 2014 is due to an 11.7% decrease in the number of Arctic vessels comparing with 2013 (see Table A.2). The total emissions reached a maximum value in 2016. Among the seven pollutants (CO, CO_2, HC, NO_X, PM_{10}, $PM_{2.5}$ and SO_X), the emissions of CO_2, SO_X and NO_X accounted for 96.96%, 1.63% and 1.03% in 2016, respectively. The total emissions of these pollutants over the NSR and the NWP regions are shown in Figure 4(B), which is to be discussed in more detail in Section 5.

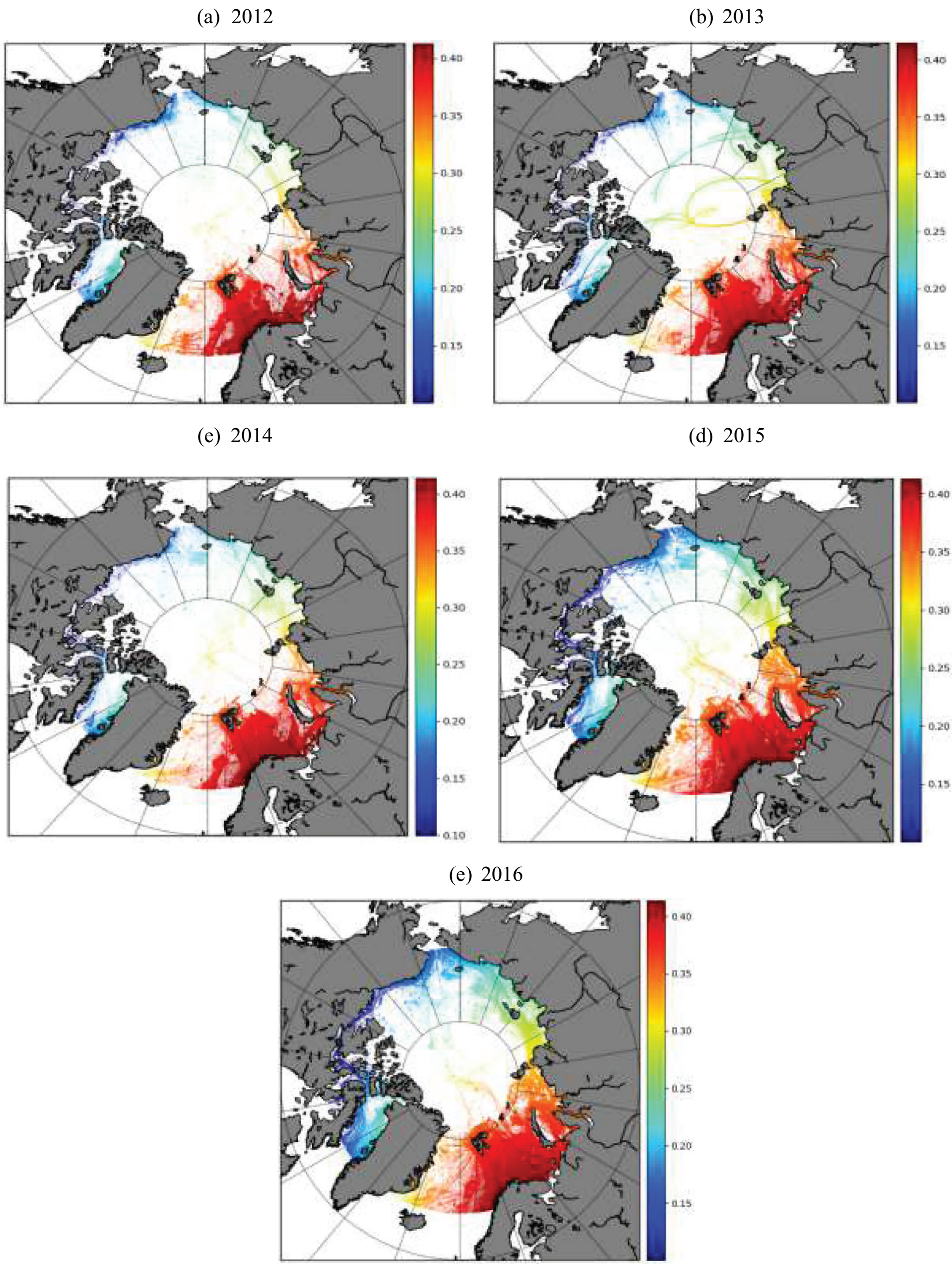

Figure 3. The annual vessel track distribution in the Arctic region [The colours closest to red indicate higher frequencies of maritime activities compared to the other locations (Source: Authors based on Python 3)].

The emissions associated with the different operational modes in the Arctic region are shown in Figure 4(D). Because the Arctic region is a large area covered by ice and snow, vessel speed in that region was much slower than the speeds observed in other sea areas. The results revealed that the highest emissions resulted from hotelling activities, followed by emissions from manoeuvring, slow

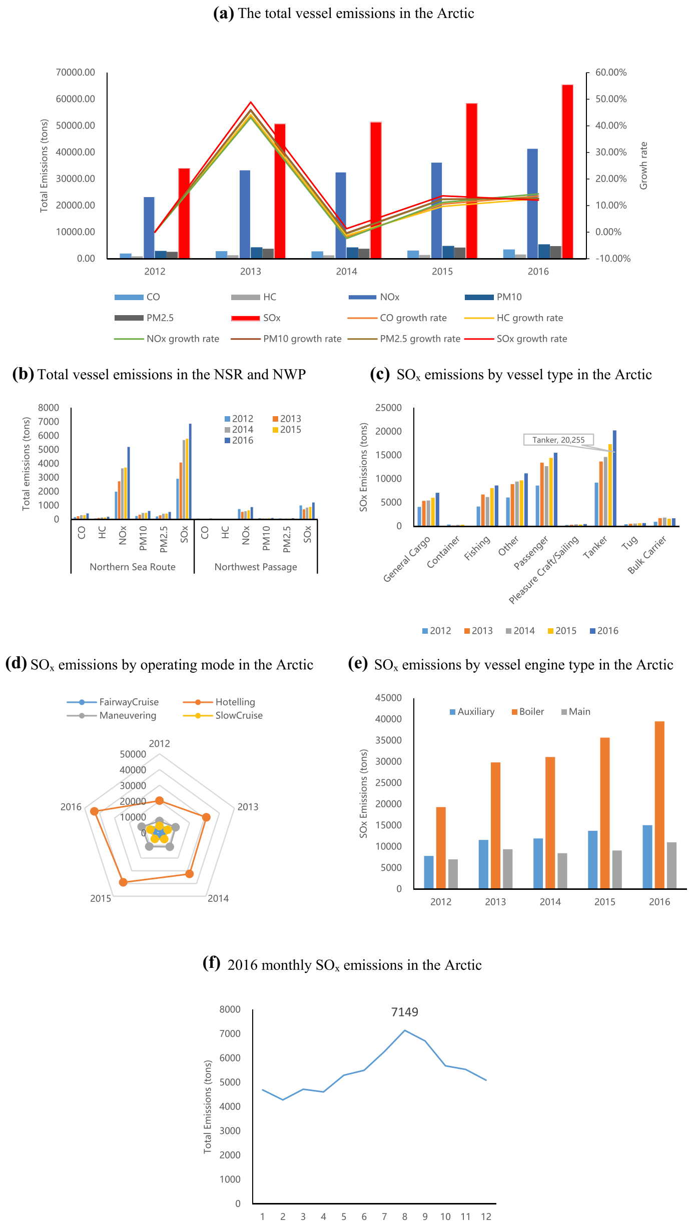

Figure 4. (C) outlines the emissions contributions across the different types of vessels. These results revealed that the emissions increased annually, with only a small number of vessel types not conforming to this finding. Using levels of SO_X as the sample, tankers, passenger vessels, fishing vessels, cargo vessels, and vessels in the 'other' category are the main sources of emission in the Arctic region, with tankers being the largest emitter. The total estimated vessel emissions in 2016 in the Arctic region for tankers, passenger vessels, fishing vessels, cargo vessels, and 'other' vessels are 20,254.98 t, 15,550.25 t, 8,628.86 t, 7,068.35 t, and 11,175.99 t, respectively. These levels account for a respective 30.87%, 23.70%, 17.03%, 13.15%, and 17.04% of the total emissions.

cruise and fairway cruise. Figure 4(E) outlines the annual emissions from the MEs, the AEs and the vessel boilers. Boiler emissions accounted for most SO_X emissions, followed by the AEs and the MEs.

Also, there have been significant monthly variations in vessel emissions. Outlining the emissions from the Arctic region in 2016, Figure 4(F) demonstrates these monthly variations. July, August, September, and October have high levels of emissions, with the highest amounts occurring in August. Those months comprise the summer and autumn seasons when most of the ice and snow has melted and more vessels can navigate through the Arctic region. SO_X emissions in July, August, September, and October are 6,278.86 t, 7,149.48 t, 6,714.94 t, and 5,689.26 t, respectively, accounting for 9.57%, 10.90%, 10.24%, and 8.67% of the total vessel emissions. The minimum level of emissions, 4,285.09 t, occurred in February, with the highest levels of emissions in August being 1.67 times higher than the levels observed in February.

Figure 4. Vessel emissions in the Arctic Circle (A) The total vessel emissions in the Arctic. (B) Total vessel emissions in the NSR and NWP. (C) SO_x emissions by vessel type in the Arctic. (D) SO_x emissions by operating mode in the Arctic (E) SO_x emissions by vessel engine type in the Arctic. (F) 2016 monthly SO_x emissions in the Arctic

4.2.2. Spatial distribution

Based on the geographical coordinates in the AIS data, we aggregated the annual vessel emissions for the Arctic region from 2012 to 2016 into 0.1° × 0.1° grid cells. Although the overall emission intensities of SO_X, CO_2, and NO_X are notably higher than those of the other pollutants, the spatial distributions are roughly the same across all the pollutants, as they largely correspond to the vessels' navigational trajectories and operating modes. Figure 5 shows the spatial distributions of SO_X emissions from vessels in the Arctic region. The high emission intensities are distributed in the regions where the vessels are most active, most notably in the Norwegian and Barents Seas.

Due to the ocean currents, the southern part of the Barents Sea is ice-free for the whole year. This encourages various vessels (e.g., tankers, container ships, bulk carriers, general cargo ships and fishing vessels) to operate in this area. Consequently, a higher intensity of emissions generates a greater pressure on the marine environment. In contrast to the high Arctic area, the less vessel activities mitigate the impact on the environment. Vessel emissions are also clearly identified on the main waterways of the Kara Sea. The effects of snow and ice make the vessel activities of 2012 and 2013 concentrated along the main routes, as are the emissions. However, the navigability of the Arctic has gradually been enhanced as a result of the ever-melting ice and increasingly smaller snow coverage. We noted that ship owners have been crossing the North Pole since 2013, and their four main routes are outlined in Figure 5(B). Starting in 2014, vessels conducted a wider range of maritime-related activities in the Arctic and have used more routes. As such, the emissions are allocated to more grid cells and the emission intensity in some areas have correspondingly dropped.

4.3. 2020 Arctic inventory forecasting

To reduce the emissions of SO_X, NO_X and particulate pollutants, the IMO made a worldwide effort to harness the pollution emissions of vessels. An important measure is to establish a global limit on the sulphur content in fuel oil, i.e., 0.50% m/m (mass by mass), which started to take into effect on 1 January 2020. To predict the 2020 Arctic emissions inventories, we assume two scenarios, P1 and P2, as shown in Table 2. The vessels navigating in the P1 scenario continue to use fuel with a 2.7% sulphur content whereas the vessels in the P2 scenario use a 0.5% sulphur fuel.

Emissions from vessels using low-sulphur fuel are given in Eq. (8) (Liu et al. 2018):

$$E_{LS} = E_{RO} \cdot \left(\frac{EF_{LS}}{EF_{RO}} \right) \tag{8}$$

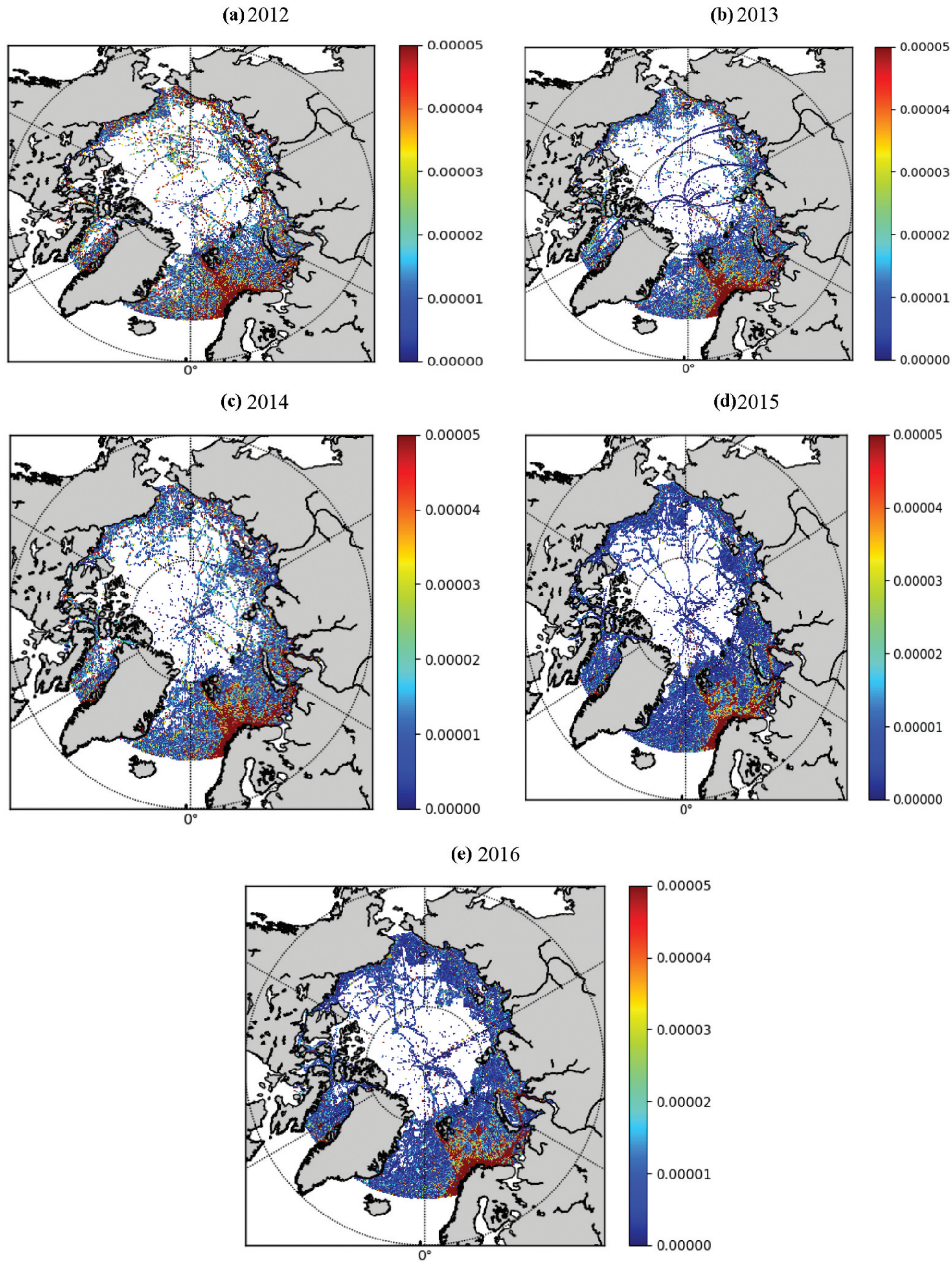

Figure 5. The spatial distributions of annual SO_X vessel emissions in the Arctic region [The red areas indicate a higher density of emissions compared to the other locations (Source: Authors based on Python 3)].

where E_{LS} (t) represents the emissions associated with low-sulphur fuel; E_{RO} (t) refers to the emissions associated with residual fuel; and EF_{LS} and EF_{RO} (g/kWh) refer to the emissions factors respectively for residual and low-sulphur fuels, which are derived from the documentation as shown in Table C.6 in Appendix C (Environmental Protection Agency (EPA) 2009).

Table 2. Scenario settings for 2020 Arctic inventory forecasting.

Scenario	Fuel Type	Sulphur %	SOx Emission Factors (g/kWh)	Total Emissions (tons)	% Reduction (P1 to P2)
P1	heavy fuel oil (HFO)	2.7%	10.29	94,499.67	-
P2	marine diesel oil (MDO)	0.5%	1.81	16,622.39	82.41%

SO_X is taken as an example to perform a regression analysis to predict the SO_X emissions for 2020 using the following model:

$$y = 7062.31x - 14171366.53, R^2 = 0.91$$

where y is the total emissions and x is the year. In the P1 scenario, the total emissions are predicted to be 94,499.67 t. In the P2 scenario, Eq. (8) is used to calculate the total emissions value of 16,622.39 t (Table 2). According to the results, and relative to the P1 scenario, the pollutants from the vessels are expected to dramatically decrease by 82.41%.

4.4. Uncertainty analysis

There are multiple factors involved in calculating pollution emissions, such as vessel classification, engine power, activities, and emissions factors. These factors have a direct impact on the accuracy of the emissions inventory. The uncertainty in the estimation of vessel emissions in this study are derived from the following aspects:

(1) Incomplete data on the vessel characteristics, such as the vessel type, GT, the engine power, the design speed, the fuel type, the construction time, the AE power, and the boiler power, among others.
(2) Vessel classification: Maritime traffic is used as a reference in this investigation.
(3) Uncertainty regarding the vessel fuel: The statistical analysis of interest is based on fuel with 2.7% sulphur content.
(4) Two factors can induce inaccuracies in processing the AIS data. One is missing AIS tracks. Although an interpolation algorithm may be used to generate the missing tracks, the error will inevitably be occurred. The other factor is the calculated average AIS speed higher than the design speed.
(5) The influence of waves, wind and other weather conditions on the vessel operations, which are not considered in this investigation.
(6) The uncertainty in the bottom-up approach, which may affect determination of auxiliary and boiler powers and differentiation of operation modes.

Table 3. Differences in 2015 Arctic ship results in Comer et al. (2017) th**an those in this study.**

	Comer et al. (2017)	This study	Difference with this study
Study area	above 58.95°N	above 67.57° N	-
AIS data source	IHS data	BLM-Shipping data	-
Number of ships	10,099	6,204	−38.57%
SOx emissions (t)	62,560	58,540	−6.43%

Table 4. Vessel emissions in 2015 (10^3 t).

	Arctic Circle	NSR	NWP	Global (Johansson, Jalkanen, and Kukkonen 2017)
SO_x	58.54	5.79	0.91	9690.00
CO_2	3476.29	344.01	53.86	831,300.00

To address these factors that may create uncertainty in estimating vessel emissions, we may collect additional vessel attribute information to improve the AIS ship-processing process although it may greatly complicate the resulting computation procedure.

5. Discussion and policy recommendations

From the vessel trajectory distribution, we found that vessels navigating in the Arctic region mainly travel in the Norwegian and Barents Seas. Vessels have recently become more active in the NSR due to Russia's strong support for the development of the NSR as well as the increasingly improved natural conditions due to the melting of the snow and ice. Many multinational energy companies are actively participating in the development and expansion of this area (Sulyandziga 2019). Vessels in the NWP area, particularly high-power vessels, are less active, with only a few small vessels tending to use this route (Figure 3). This lower activity level is due to complicated straits, pingos, and multiyear ice makes navigation in this area extremely challenging. The Canadian federal government's attitude towards the development of the Arctic region is committed to protecting the interests of the Arctic's indigenous people (Thorsell and Leschine 2016). Canada introduced their Arctic region policy in 2019, which prioritised protecting the interests of indigenous people over the development of the Arctic route.[1] Accordingly, vessels navigating in the Arctic (e.g., the NSR and NWP) exhibit different degrees of activity (Figure 3) due to the difference in attitude between Russia and Canada towards Arctic development. When compared to the Russian counterparts, Canada has a much more conservative view on the development of Arctic shipping routes. Such a difference explains the increases in the level of use of the NSR.

To verify the accuracy of the Arctic emission results, this paper uses the SOx emissions in 2015 as an example to compare with those results in Comer et al. (2017), which is given in Table 3, from the four main aspects: study area, AIS data source, Number of ships, and SOx emissions. Comer et al. (2017) choose a relatively large region as its study area and more vessels are active in this region. The difference in the number of vessels and SOx emissions between them are 38.57% and 6.43%, respectively. Regarding the SOx emissions, the vessels use residual and distillate fuel according to Comer et al. (2017). The emission of SOx is 62,560 tons. In this study, we assume that all vessels use the HFO fuel. The emissions of vessels in the Arctic generate 58,540 tons. The ship operators make the decisions on using the fuel to operate the vessels ships in the Arctic are uncertain. The results suggest that the SOx emission is close to what it is reported in Comer et al. (2017). As expected, the results of this study performed at an acceptable accuracy degree which can further used by researchers and industrial practitioners.

Pollutant emissions in the NSR are thus significantly greater than those in the NWP (see Figure 4 (B)). Moreover, there is an annual upward trend due to the increased traffic level in the NSR. Alternatively, in the NWP, emissions have changed very little, irrespective of the type of pollution. If the level of SO_X in 2015 is used as an example, the emissions of vessels in the Arctic Circle, the NSR and the NWP are 58.54×10^3 t, 5.79×10^3 t and 0.91×10^3 t, respectively (see Table 4). These results suggest that the NSR and NWP areas only generate 9.90% and 1.55% of the total emissions in the Arctic Circle. The remaining 88.7% are concentrated in the Norwegian and Barents Seas. Globally, Arctic emissions account for 0.60% of the total world emissions. Emissions from the NSR region accounted for only 0.06% of the total world emissions, and those from the NWP are even lower. Although the Arctic ecological environment is sensitive to maritime activities and the resulting emissions (Liang and Aherne 2019), these emissions to date have yet posed any notable impacts to the region. Moreover, emissions in the Arctic region are projected to be lower after the implementation of the IMO's 2020 limit on global sulphur emissions. Accordingly, we do not anticipate these emissions to have any serious effects on the Arctic environment. If the environment is successfully protected, more vessels should be encouraged to navigate in the Arctic region. In fact, as shown in

Zhu et al. (2018), under certain conditions, shipping along the NSR 'can benefit from lower operational and environmental costs, which will lead to higher market and social welfare.' Therefore, the development of the Arctic region need not necessarily be questioned negatively.

As the Arctic region is rich in natural gas, oil, and other mineral resources (Lasserre 2011), its strategic importance has been globally recognised (Becker et al. 2018; Thorsell and Leschine 2016). Although there are around 400 tankers in the Arctic simultaneously, they are the most active vessels emitting the most pollutants into the region (see Figure 4(C)). The previous analysis indicated that these tankers are mainly distributed in the Norwegian Sea, the Barents Sea, or along the NSR, with an annual average of 411 tankers. They are not the largest vessels of the type but emitted the highest volume of pollutants, as they are more active in the region than the other types of ships. Due to the large coverage of ice and snow, in the case of a tanker's oil spill, it is extremely difficult to accommodate the pollutants and therefore the oil spill can generate serious damages to the Arctic environment. Further restrictions are necessary for tankers to entre the region, which should be based both on the existing policies and potential effects of new policies specifically designated to protect the Arctic environment.

Based on the available data and the IMO's policy or regulations, we are proposing the following recommendations:

- It is essential to improve the shipping conditions in the Arctic region so that ships may sail at a higher speed or decrease demand for power, which then reduces energy consumption and emissions from Arctic shipping.
- It is essential to closely monitor tankers sailing in the Arctic and vessels operating in the Norwegian Sea by enforcing more stringent measures if they have adverse environmental impacts. Previously reported data indicate that there were frequent tanker activities in the Arctic. The occurrence of oil spill would be ecologically disastrous to the region. In addition, the heat map of vessel pollution shows that emissions from the vessels in the Arctic are mainly in the Norwegian Sea. Therefore, we propose to make a close monitoring of oil tankers in the Arctic and vessels in the Norwegian Sea.
- The total emissions from global shipping may be reduced because the shift from the traditional routes to the Arctic routes greatly reduces the journey distance and time and energy consumption. This shift is happening as climate change makes the Arctic suitable for shipping longer during a year.

6. Conclusions

The existing literature on the Arctic has offered varied investigations of the current data on Arctic shipping and predicted future scenarios of pollution emissions from the vessels shipping in the Arctic region. However, the urgent need for an empirical analysis of environmental impacts of Arctic shipping remained. To address this need, this paper has explored the navigational distribution of vessels and evaluated environmental impacts of their emissions in the Arctic region by means of a bottom-up method combined with high-frequency AIS data for 2012–2016. It is found that most vessels were concentrated in the Norwegian and Barents Sea areas and that tankers, passenger vessels, fishing vessels, cargo vessels, and those in the 'other' vessel type in Table 1 constituted the main sources of emissions in the Arctic region. The hotelling operational mode accounted for most of the emissions, followed by manoeuvring, slow cruise, and fairway cruise. Regarding engine types, it is found that the boilers created the highest volume of emissions, followed by auxiliary engines (AEs) and main engines (MEs). Therefore, it is essential to improve the shipping conditions in the Arctic region so that ships may sail at a higher speed or decrease demand for power, which then reduce energy consumption and emissions from Arctic shipping.

Emissions are found to be the highest in July, August, September, and October of a year during 2012–2016 when the Arctic region was the busiest during a year. As the sulphur content in fuel was restricted to 0.5% as of 2020, the total emissions are predicted to be 16,622.39 tons in the Arctic region. This investigation accordingly enriches the existing literature on emissions inventory contributed by Arctic shipping. As climate change makes the Arctic suitable for shipping longer during a year, more and more shipping traffic is shifting from the traditional routes to the Arctic routes, which will certainly reduce the journey distance and time and energy consumption and, accordingly, decrease the total emissions from global shipping.

This paper calculated the emissions inventory for vessels operating in the Arctic, in conjunction with the levels of emissions from vessels sailing along the NSR and the NWP. The highest levels of global maritime emissions occurred in the Norwegian and Barents Seas. Although the shift from the traditional routes to the Arctic routes reduces the total emissions from global shipping, shipping emissions may be more concentrated, as this shift carries on, in the Arctic, which is an environmentally vulnerable region. Therefore, it is necessary to tighten rules and regulations governing Arctic shipping in a timely manner to prevent this from happening in the Arctic region.

It is essential to carry out further research to gain a richer understanding of key factors in developing sustainable Arctic shipping. For example, in addition to the application of the AIS data, we may generalise the findings reported in this paper to conduct in-depth interviews with a range of practitioners, policymakers, government bodies, vessel operators, and other relevant stakeholders. It is desirable to consider other key factors that determine vessel operations in Arctic waters, including ice safe speed restrictions, the water-depth restrictions to manage vessel sizes, and the ice requirements for vessel class designs (i.e., size, GT). Third, based on Olmer et al. (2017) and Fourth IMO GHG Study (2020), a more precise classification of vessels is provided. Besides, key parameters, such as information on the auxiliary engines and boilers of the vessels, can be applied in subsequent studies. Finally, we believe that this study offers significant contributions to this increasingly important area in the shipping and maritime industries.

Note

1 Arctic Policy Framework. https://www.eia.gov.nt.ca/en/arctic-policy-framework, retrieved on 4 August 2021.

Acknowledgments

The authors would like to thank the anonymous referees for their very helpful comments and suggestions. This work was supported by the National Natural Science Foundation of China (Grants#: 72031005, 72074141) and the National Social Science Foundation of China (Grant#: 18ZDA052). The authors are also grateful for the support of the Lloyd's Register Foundation (Grant: G\100111), a charity that helps to protect life and property by supporting engineering-related education, public engagement, and the application of research.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Natural Science Foundation of China [72031005, 72074141, 71671110]; National Social Science Foundation of China [18ZDA052]; Lloyd's Register Foundation [G\100111].

ORCID

Ying-En Ge http://orcid.org/0000-0002-8435-0483
Adolf K.Y. Ng http://orcid.org/0000-0002-7869-8328

Yui-yip Lau http://orcid.org/0000-0002-4011-5625

References

AMAP. 2011. The Impact of Black Carbon on Arctic Climate. *AMAP Technical Report No. 4(2011). Arctic Monitoring and Assessment Programme (AMAP)*, edited by P. K. Quinn, A. Stohl, A. Arneth, T. Berntsen, J. F. Burkhart, J. Christensen, M. Flanner, et al., Oslo. 72.

Babicz, J. 2015. *Encyclopedia of Ship Technology*. Second. Publisher: Wärtsilä Corporation. 02.09.2019 Helsinki, Finland. https://maddenmaritime.files.wordpress.com/2017/04/wartsila-o-marine-encyclopedia.pdf

Becker, A., A. K. Y. Ng, D. McEvoy, and J. Mullett. 2018. "Implications of Climate Change for Shipping: Ports and Supply Chains." *Wiley Interdisciplinary Reviews: Climate Change* 9 (2): e508.

Browse, J., K. S. Carslaw, A. Schmidt, and J. J. Corbett. 2013. "Impact of Future Arctic Shipping on High-latitude Black Carbon Deposition." *Geophysical Research Letters* 40 (16): 4459–4463. doi:10.1002/grl.50876.

Capaldo, K., J. J. Corbett, P. Kasibhatla, P. Fischbeck, and S. N. Pandis. 1999. "Effects of Ship Emissions on Sulphur Cycling and Radiative Climate Forcing over the Ocean." *Nature* 400 (6746): 743–746. doi:10.1038/23438.

Chen, D., X. Wang, Y. Li, J. Lang, Y. Zhou, X. Guo, and Y. Zhao. 2017. "High-spatiotemporal-resolution Ship Emission Inventory of China Based on AIS Data in 2014." *Sci Total Environ* 609: 776–787. doi:10.1016/j.scitotenv.2017.07.051.

Chen, Q., Y. Y. Lau, Y. E. Ge, M. A. Dulebenets, T. Kawasaki, and A. K. Y. Ng. 2021. "Interactions between Arctic Passenger Ship Activities and Emissions." *Transportation Research Part D: Transport and Environment*. 97 Article number: 102925 10.1016/j.trd.2021.102925

Comer, B., N. Olmer, X. Mao, B. Roy, and D. Rutherford, 2017. Prevalence of Heavy Fuel Oil and Black Carbon in Arctic Shipping, 2015 to 2025. Available online: https://theicct.org/sites/default/files/publications/HFO-Arctic_ICCT_Report_01052017_vF.pdf [2021 March 25].

Corbett, J. J. 2003. "Updated Emissions from Ocean Shipping". *Journal of Geophysical Research* 108(D20). Article number: 4650. doi:10.1029/2003JD003751.

Corbett, L., D. A. Winebrake, J. J. Harder, S. Silberman, and J. A. M. Gold. 2010. "Arctic Shipping Emissions Inventories and Future Scenarios." *Atmospheric Chemistry and Physics* 10 (19): 9689–9704. doi:10.5194/acp-10-9689-2010.

Dalsøren, S. B., B. H. Samset, G. Myhre, J. J. Corbett, R. Minjares, D. Lack, and J. S. Fuglestvedt. 2013. "Environmental Impacts of Shipping in 2030 with a Particular Focus on the Arctic Region." *Atmospheric Chemistry and Physics* 13 (4): 1941–1955. doi:10.5194/acp-13-1941-2013.

Endresen, Ø., E. Sørgård, H. L. Behrens, P. O. Brett, and I. S. A. Isaksen. 2007. "A Historical Reconstruction of Ships' Fuel Consumption and Emissions." *Journal of Geophysical Research* 112 (D12): D12. doi:10.1029/2006JD007630.

Endresen, Ø., J. Bakke, E. Sørgård, T. Flatlandsmo Berglen, and P. Holmvang. 2005. "Improved Modelling of Ship SO2 Emissions—a Fuel-based Approach." *Atmospheric Environment* 39 (20): 3621–3628. doi:10.1016/j.atmosenv.2005.02.041.

Entec, 2010. Defra UK Ship Emissions Inventory Final Report, London, UK. 02.09.2019].

Environmental Protection Agency (EPA), 2009. Current Methodologies in Preparing Mobile Source Port-related Emission Inventories. Final Report. https://www.epa.gov/sites/production/files/2016-06/documents/2009-port-inventory-guidance.pdf [2021 March 25].

Eyring, V., I. S. A. Isaksen, T. Berntsen, W. J. Collins, J. J. Corbett, O. Endresen, R. G. Grainger, J. Moldanova, H. Schlager, and D. S. Stevenson. 2010. "Transport Impacts on Atmosphere and Climate: Shipping." *Atmospheric Environment* 44 (37): 4735–4771. doi:10.1016/j.atmosenv.2009.04.059.

Faury, O., and P. Cariou. 2016. "The Northern Sea Route Competitiveness for Oil Tankers." *Transportation Research Part A: Policy and Practice* 94: 461–469.

Goldsworthy, L., and B. Goldsworthy. 2015. "Modelling of Ship Engine Exhaust Emissions in Ports and Extensive Coastal Waters Based on Terrestrial AIS Data – An Australian Case Study." *Environmental Modelling & Software* 63: 45–60. doi:10.1016/j.envsoft.2014.09.009.

He, J., C. Tan, W. Yan, W. Huang, M. Liu, and H. Yu. 2020. "Two-stage Stochastic Programming Model for Generating Container Yard Template under Uncertainty and Traffic Congestion." *Advanced Engineering Informatics* 43: 101032. doi:10.1016/j.aei.2020.101032.

IMO, 2020. Regulations for Carriage of AIS. https://www.imo.org/en/OurWork/Safety/Pages/AIS.aspx. 02.09.2019].

Johansson, L., J.-P. Jalkanen, and J. Kukkonen. 2017. "Global Assessment of Shipping Emissions in 2015 on a High Spatial and Temporal Resolution." *Atmospheric Environment* 167: 403–415. doi:10.1016/j.atmosenv.2017.08.042.

Lasserre, F. 2011. "Arctic Shipping Routes." *International Journal: Canada's Journal of Global Policy Analysis* 66 (4): 793–808. doi:10.1177/002070201106600409.

Liang, T., and J. Aherne. 2019. "Critical Loads of Acidity and Exceedances for 1138 Lakes and Ponds in the Canadian Arctic." *Sci Total Environ* 652: 1424–1434. doi:10.1016/j.scitotenv.2018.10.330.

Lin, D.-Y., and Y.-T. Chang. 2018. “Ship Routing and Freight Assignment Problem for Liner Shipping: Application to the Northern Sea Route Planning Problem.” *Transportation Research Part E: Logistics and Transportation Review* 110: 47–70. doi:10.1016/j.tre.2017.12.003.

Liu, H., M. Fu, X. Jin, Y. Shang, D. Shindell, G. Faluvegi, C. Shindell, and K. He. 2016. “Health and Climate Impacts of Ocean-going Vessels in East Asia.” *Nature Climate Change* 6 (11): 1037–1041. doi:10.1038/nclimate3083.

Liu, H., Z.-H. Meng, Y. Shang, Z.-F. Lv, -X.-X. Jin, M.-L. Fu, and K.-B. He. 2018. “Shipping Emission Forecasts and Cost-benefit Analysis of China Ports and Key Regions’ Control.” *Environ Pollut* 236: 49–59. doi:10.1016/j.envpol.2018.01.018.

Maragkogianni, A., and S. Papaefthimiou. 2015. “Evaluating the Social Cost of Cruise Ships Air Emissions in Major Ports of Greece.” *Transportation Research Part D: Transport and Environment* 36: 10–17. doi:10.1016/j.trd.2015.02.014.

Miola, A., and B. Ciuffo. 2011. “Estimating Air Emissions from Ships: Meta-analysis of Modelling Approaches and Available Data Sources.” *Atmospheric Environment* 45 (13): 2242–2251. doi:10.1016/j.atmosenv.2011.01.046.

Ng, S. K. W., C. Loh, C. Lin, V. Booth, J. W. M. Chan, A. C. K. Yip, Y. Li, and A. K. H. Lau. 2013. “Policy Change Driven by an AIS-assisted Marine Emission Inventory in Hong Kong and the Pearl River Delta.” *Atmospheric Environment* 76: 102–112. doi:10.1016/j.atmosenv.2012.07.070.

Nunes, R. A. O., M. C. M. Alvim-Ferraz, F. G. Martins, and S. I. V. Sousa. 2017. “The Activity-based Methodology to Assess Ship Emissions - A Review.” *Environ Pollut* 231 (Pt 1): 87–103. doi:10.1016/j.envpol.2017.07.099.

Olmer, N., B. Comer, B. Roy, X. Mao, and D. Rutherford, 2017. Greenhouse Gas Emissions from Global Shipping, 2013-2015 Detailed Methodology. Available online: https://theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf [2021 March 25].

Paxian, A., V. Eyring, W. Beer, R. Sausen, and C. Wright. 2010. “Present-day and Future Global Bottom-up Ship Emission Inventories Including Polar Routes.” *Environ. Sci. Technol* 44 (4): 1333–1339. doi:10.1021/es9022859.

Peters, G. P., T. B. Nilssen, L. Lindholt, M. S. Eide, S. Glomsrød, L. I. Eide, and J. S. Fuglestvedt. 2011. “Future Emissions from Shipping and Petroleum Activities in the Arctic.” *Atmospheric Chemistry and Physics* 11 (11): 5305–5320. doi:10.5194/acp-11-5305-2011.

Port of Los Angeles, 2014. Port of Los Angeles Inventory of Air Emissions 2013. https://www.portoflosangeles.org/environment/air-quality/air-emissions-inventory [2021 March 25].

Port of Los Angeles, 2015. Port of Los Angeles Inventory of Air Emissions 2014. https://www.portoflosangeles.org/environment/air-quality/air-emissions-inventory [2021 March 25].

Port of Richmond. 2010. “SF BAY Area Seaports Air Emissions Inventory Port Of Richmond 2005 Emissions Inventory.” *Environ*. 71.

Study, F. I. M. O. G. H. G., 2020. Fourth IMO GHG Study Final Report, Delft, CE Delft, July 2020. Available online: https://imoarcticsummit.org/wp-content/uploads/2020/09/MEPC-75-7-15-Fourth-IMO-GHG-Study-2020-Final-report-Secretariat.pdf [2021 March 25].

Study, T. I. M. O. G. H. G., 2014. Third IMO GHG Study 2014 Executive Summary and Final Report, June 2014. Available online: https://www.imo.org/en/OurWork/Environment/Pages/Greenhouse-Gas-Studies-2014.aspx [2021 March 25].

Sulyandziga, L. 2019. “Indigenous Peoples and Extractive Industry Encounters: Benefit-sharing Agreements in Russian Arctic.” *Polar Science* 21: 68–74. doi:10.1016/j.polar.2018.12.002.

Thorsell, D. E., and T. M. Leschine. 2016. “An Evaluation of Oil Pollution Prevention Strategies in the Arctic: A Comparison of Canadian and U.S.” *Approaches. Marine Policy* 72: 255–262. doi:10.1016/j.marpol.2016.04.042.

Tichavska, M., and B. Tovar. 2015. “Port-city Exhaust Emission Model: An Application to Cruise and Ferry Operations in Las Palmas Port.” *Transportation Research Part A: Policy and Practice* 78: 347–360.

Winther, M., J. H. Christensen, M. S. Plejdrup, E. S. Ravn, Ó. F. Eriksson, and H. O. Kristensen. 2014. “Emission Inventories for Ships in the Arctic Based on Satellite Sampled AIS Data.” *Atmospheric Environment* 91: 1–14. doi:10.1016/j.atmosenv.2014.03.006.

Yau, P. S., S. C. Lee, J. J. Corbett, C. Wang, Y. Cheng, and K. F. Ho. 2012. “Estimation of Exhaust Emission from Ocean-going Vessels in Hong Kong.” *Science of the Total Environment* 431: 299–306. doi:10.1016/j.scitotenv.2012.03.092.

Zhu, S. D., X. W. Fu, A. Ng, M. Luo, and Y. E. Ge. 2018. “The Environmental Costs and Economic Implications of Container Shipping on the Northern Sea Route.” *Maritime Policy & Management* 45 (4): 456–477. 2018. doi10.1080/03088839.2018.1443228.

Appendix A.

See Tables A.1 and A.2

Table A.1 The Level of Completeness of the Static Information of each Data Source

Data source	IMO	Vessel Type	Length	Width	GT	Rated Engine Power	Design Speed	Year of Built
RS	√	√	√	√	√	√	√	√
NK	√	√	√	√	√	√	√	√
KR	√	√	√	√	√	√	√	√
CSS	√	√	√	√	√	√	√	√
Marinetraffic	√	√	√	√	√			√

Table A.2 2012-2016 Arctic Vessel Types and Vessel Numbers

	2012a	2013	2014	2015	2016
Bulk Carrier	169	264	283	222	270
General Cargo	1169	1849	1290	1473	1569
Container	15	23	20	21	21
Tanker	332	486	392	404	443
Fishing	1718	2243	2185	2503	2686
Tug	211	281	258	270	325
Passenger	266	338	296	292	317
Pleasure Craft/Sailing	390	435	490	397	485
Other	528	720	650	621	762

a: except January and February (due to two months data are not available to the public).

Appendix B.

See Tables B.1, B.2, B.3 and B.4

Table B.1 GT Forecast Model

Vessel Type	Sample Size	R2	RMSE	ML	Properties
Bulk Carrier	3896	0.99	0.05	RFR	Length, width
General Cargo	1227	0.97	0.17	XBT	Length, width
Container	968	0.99	0.07	ETR	Length, width
Tanker	1678	0.99	0.07	RFR	Length, width
Fishing	1028	0.98	0.14	SVR	Length, width
Tug	1044	0.98	0.12	ETR	Length, width
Passenger	258	0.86	0.37	SVR	Length, width
Pleasure Craft/Sailing	259	0.89	0.39	ETR	Length, width
Othera	120	0.95	0.21	SVR	Length, width

a: includes Icebreakers, SARs, Dredgers, Law Enforcement vessels, Pilot Vessels, Military Ops, Safe Water, Unspecified, Dive Vessels, Special Crafts, Light Vessels, Medical Transports, Reserved, Local Vessels, High Speed Crafts and Port Tenders.

Random Forest Regression: RFR. Support Vector Regression: SVR. Extra Trees Regression: ETR. Extreme Gradient Boosting: XBT. RMSE: Root Mean Square Error.

Table B.2 The Rated Engine Power Forecast Model

Vessel Type	Sample Size	R2	RMSE	ML	Properties
Bulk Carrier	3896	0.95	0.22	GBRT	GT
General Cargo	1227	0.85	0.38	SVR	GT, Length, width
Container	968	0.97	0.16	XBT	GT, Length, width
Tanker	1678	0.98	0.14	GBRT	GT, Length, width
Fishing	1028	0.81	0.43	SVR	Length, width
Tug	668	0.83	0.41	ETR	GT, Length, width
Pleasure Craft/Sailing	233	0.77	0.48	XBT	GT, Length, width
Other	102	0.82	0.41	GBRT	GT, Length, width

Table B.3 The Design Speed Forecast Model

Vessel Type	Sample Size	R2	RMSE	ML	Properties
General Cargo	1227	0.87	0.35	SVR	Power, width
Container	968	0.92	0.28	XBT	GT, Length, width, Power
Tanker	1678	0.85	0.39	SVR	GT, Length, width, Power
Fishing	1009	0.81	0.43	SVR	GT, Length, width, Power
Passenger	213	0.84	0.39	ETR	Length, width, Power

Table B.4 The Average Rated Engine Power and the Average Design Speed

Vessel Type	Bulk Carrier	Passenger	Tug	Pleasure Craft/Sailing	Other
Sample Size	3848	219	995	226	118
Average Rated Engine Power (kw)		2348.16			
Average Design Speed (knots)	15.64		12.14	12.75	13.58

Appendix C.

See Tables C.1, C.2, C.3, C.4, C.5, C.6, C.7, C.8 and C.9.

Table C.1 Auxiliary Engine Power Ratios by Vessel Type

Vessel Type	AE Power Ratio
Bulk Carrier	0.222
General Cargo	0.191
Container	0.220
Tanker	0.211
Fishing	0.222
Tug	0.222
Passenger	0.16
Pleasure Craft/Sailinga	0.222
Other	0.222

a: Take the largest proportion of AE Power Ratio

Table C.2 Auxiliary Engine Load Factor Assumptions

Vessel Type	Fairway Cruise	Slow Cruise	Manoeuvring	Hotelling
Bulk Carrier	0.17	0.27	0.45	0.22
Container Ship	0.13	0.25	0.48	0.19
General Cargo	0.17	0.27	0.45	0.22
Passenger	0.80	0.80	0.64	0.16
Tanker	0.24	0.28	0.33	0.26
Othersa	0.17	0.27	0.45	0.22
Fishinga	0.17	0.27	0.45	0.22
Tug	0.17	0.27	0.45	0.22
Pleasure Craft/Sailinga	0.17	0.27	0.45	0.22

aBy the auxiliary Engine Power Ratios speculation

Table C.3 Boiler Power by Vessel Class and Model

Vessel Type	Manoeuvring	Hotelling
Bulk Carrier	109	109
General Cargo	106	106
Container	506	506
Tanker	371	3000
Fishing	0	0
Tug	0	0
Passengera	1393	1393
Pleasure Craft/Sailing	0	0
Other	371	371

a: Passenger vessels have a higher rate of boiler usage due to the number of passengers and the need for hot water.

Table C.4 Vessel Operation Mode Definition by Vessel Speed

Operation Mode	Description	Vessel Speed (knots)
Fairway Cruise	Vessel operating at a speed higher than slow cruise speed, inside (fairway cruise) or outside (cruise)	[12,)
Slow Cruise	Vessel operating at a reduced speed inside waters, in line with speed limit requirements	[8, 12)
Manoeuvring	ManoeuvringVessel operating at a lower speed as it approaches the berth/pier/dock or anchorage	[1, 8)
Hotelling	Vessel at berth or anchored with the propulsion engines switched off	[0, 1)

Table C.5 Engine Type by Gross Tonnage of each Vessel Type

Vessel Type	≤5 000 GT	5 000–25,000 GT	>25,000 GT
Bulk Carrier	MSD	SSD	SSD
Container	MSD	MSD	SSD
General Cargo	MSD	SSD	SSD
Passenger	HSD	MSD	MSD
Tanker	MSD	SSD	MSD
Others	MSD	MSD	SSD
Fishinga	MSD	SSD	SSD
Tuga	MSD	SSD	SSD
Pleasure Craft/Sailinga	MSD	MSD	SSD

a: The Engine Type with the largest proportion has been taken

Table C.6 Main Engine Emission Factors (g/kWh) for Vessels

Engine Type	Fuel Type	sulphur	Emission Factors (g/kWh)						
			NO_X	PM_{10}	$PM_{2.5}$	HC	CO	SO_X	CO_2
SSD	RO	2.70%	18.10	1.42	1.31	0.60	1.40	10.29	620.62
	MDO	1.00%	17.00	0.45	0.42	0.60	1.40	3.62	588.79
	MGO	0.50%	17.00	0.31	0.28	0.60	1.40	1.81	588.79
	MGO	0.10%	17.00	0.19	0.17	0.60	1.40	0.36	588.79
MSD	RO	2.70%	14.00	1.43	1.32	0.50	1.10	11.24	677.91
	MDO	1.00%	13.20	0.47	0.43	0.50	1.10	3.97	646.08
	MGO	0.50%	13.20	0.31	0.29	0.50	1.10	1.98	646.08
	MGO	0.10%	13.20	0.19	0.17	0.50	1.10	0.40	646.08

Table C.7 Low Load Adjustment Multipliers for the Main Engine Emission Factors

Load	PM	NO_X	SO_X	CO	HC	CO_2
≤0.02	7.29	4.63	1.00	9.68	21.18	1.00
0.03	4.33	2.92	1.00	6.46	11.68	1.00
0.04	3.09	2.21	1.00	4.86	7.71	1.00
0.05	2.44	1.83	1.00	3.89	5.61	1.00
0.06	2.04	1.60	1.00	3.25	4.35	1.00
0.07	1.79	1.45	1.00	2.79	3.52	1.00
0.08	1.61	1.35	1.00	2.45	2.95	1.00
0.09	1.48	1.27	1.00	2.18	2.52	1.00
0.10	1.38	1.22	1.00	1.96	2.18	1.00
0.11	1.30	1.17	1.00	1.79	1.96	1.00

(*Continued*)

Load	PM	NO_X	SO_X	CO	HC	CO_2
0.12	1.24	1.14	1.00	1.64	1.76	1.00
0.13	1.19	1.11	1.00	1.52	1.60	1.00
0.14	1.15	1.08	1.00	1.41	1.47	1.00
0.15	1.11	1.06	1.00	1.32	1.36	1.00
0.16	1.08	1.05	1.00	1.24	1.26	1.00
0.17	1.06	1.03	1.00	1.17	1.18	1.00
0.18	1.04	1.02	1.00	1.11	1.11	1.00
0.19	1.02	1.01	1.00	1.05	1.05	1.00
0.20	1.00	1.00	1.00	1.00	1.00	1.00
>0.20	1.00	1.00	1.00	1.00	1.00	1.00

Table C.8 Auxiliary Engine Emission Factors (g/kWh) for Vessels

		Emission Factors (g/kWh)						
Fuel Type	sulphur	NO_X	PM_{10}	$PM_{2.5}$	HC	CO	SO_X	CO_2
RO	2.70%	14.7	1.44	1.32	0.40	1.10	11.98	722.54
MDO	1.00%	13.9	0.49	0.45	0.40	1.10	4.24	690.71
MGO	0.50%	13.9	0.32	0.29	0.40	1.10	2.12	690.71
MGO	0.10%	13.9	0.18	0.17	0.40	1.10	0.42	690.71

Table C.9 Boiler Emission Factors (g/kWh) for Vessels

Fuel Type	sulphur	SO_X	NO_X	PM_{10}	$PM_{2.5}$	HC	CO	CO_2
HFO	2.70%	16.50	2.10	0.80	0.64	0.10	0.20	970
MGO	0.50%	3.10	2.00	0.20	0.18	0.10	0.20	922

Appendix D.

See Algorithm 1.

The grid-based AIS average speed completion algorithm is as follows:

Hypothesis 1: Vessels of the same type have a similar track and a similar average speed.

Hypothesis 2: The average speed between two points of the vessel's AIS data is not greater than the design speed of the vessel (Babicz, 2015).

The purpose of this algorithm is to correct the AIS records wherein the AIS average speed is higher than the design speed. The AIS data of one type of vessel is denoted as $\{\langle Vavg_i, V_i, AreaID_j, VareadID_j \rangle | \mathrm{i} = 1, 2, 3, \cdots, \mathrm{m}; \mathrm{j} = 1, 2, 3, \cdots, \mathrm{n}; \mathrm{m} < \mathrm{n}\}$, where $Vavg_i$ is the AIS average speed, V_i is the vessel design speed, $AreaID_j$ is 0.1° × 0.1° the grid cells, is the speed of grid cells. In Algorithm 1, $AIS'_{Domain1}$ and $AIS'_{Domain2}$ are the two regions of the AIS records. According to Hypothesis 1 and Hypothesis 2, algorithm 1 uses in Domain1 to correct the records of AIS the average speed abnormity in Domain2.

Algorithm 1. Grid-based AIS average speed completion algorithm.

Input: $AIS'_{Domain1} = \{Vavg_i, V_i, AreaID_j, VareadID_j > | \mathrm{i} = 1, 2, 3, \cdots, \mathrm{n}; \mathrm{j} = 1, 2, 3, \cdots, \mathrm{m}; \mathrm{n} < \mathrm{m}\}$
(Trajectory data of one type vessel)

Output: $AIS'_{Domain2} = \{Vavg_z, V_z, AreaID_h, VareadID_h > | \mathrm{z} = 1, 2, 3, \cdots, \mathrm{k}; \mathrm{h} = 1, 2, 3, \cdots, \mathrm{l}; \mathrm{k} < \mathrm{l}\}$

Initialise: $VareadID_i \leftarrow \emptyset$; $VareadID_z \leftarrow \emptyset$; $Domain2 \in Domain1$

(1) Get $VareadID_j$ in Domain1

fori ← 1ton − 1doif$Vavg_i \leq V_i$ *then*forj ← 1tom − 1do$VareadID_j \leftarrow \sum^V avg_i / Count(Vavg_i)$endendend

(1) Complete AIS average speed in Domain2, where in the AIS average speed is higher than the design speed

forz ← 1tok − 1doif$Vavg_z \leq V_z$ *then*
forh ← 1tol − 1do
$VareadID_h \leftarrow \sum^V avg_z / Count(Vavg_z)$end
endif$Vavg_z > V_z$ *then*if$AreaID_h == VareadID_j$ *then*$Vavg_z \leftarrow VareadID_j$else
$Vavg_z \leftarrow \sum^V areadID_h / Count(VareadID_h)$endendforh ← 1tol − 1do$VareadID_h \leftarrow \sum^V avg_z / Count(Vavg_z)$end

Appendix E.

See Table E.1 and Table E.2.

Table E.1 Annual Vessel Emissions in the Arctic (tons)

	CO	CO_2	HC	NO_X	PM_{10}	$PM_{2.5}$	SO_X
2012	1972.97	2,029,591.35	907.24	23,407.45	2945.73	2597.54	34,139.72
2013	2836.93	3,021,151.23	1308.54	33,492.33	4302.06	3783.68	50,846.26
2014	2785.35	3,058,759.21	1291.72	32,701.93	4287.47	3762.38	51,502.03
2015	3079.64	3,476,289.23	1416.79	36,358.54	4819.79	4225.11	58,540.22
2016	3498.18	3,896,505.52	1595.16	41,585.86	5429.48	4763.95	65,604.29

Table E.2 The growth rate of different pollutants

	2012 to 2013	2013 to 2014	2014 to 2015	2015 to 2016
CO	43.79%	−1.82%	10.57%	13.59%
CO_2	48.86%	1.24%	13.65%	12.09%
HC	44.23%	−1.29%	9.68%	12.59%
NO_X	43.08%	−2.36%	11.18%	14.38%
PM_{10}	46.04%	−0.34%	12.42%	12.65%
$PM_{2.5}$	45.66%	−0.56%	12.30%	12.75%
SO_X	48.94%	1.29%	13.67%	12.07%