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Linking ship-associated emissions and resource development in the Arctic: Trends and predictions along the Northern Sea Route

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ABSTRACT

Arctic ship traffic has increased significantly due to continuous sea ice loss and resource extraction. The shipping sector is an important contributor to atmospheric emissions of nitrogen oxides (NO_x) and sulphur dioxide (SO_2), and an increase in ship activity will lead to significant increases in these emissions. However, there is a lack of studies linking ship activities and the associated emissions with recent Arctic resource development activities. This study aims to assess the relationship between sector-specific developments (fishing, tourism, trade, oil, gas, mining, and "others") and ship traffic, and the associated emissions from 2013 to 2023 along the Northern Sea Route (NSR), using time series analysis and linear regression. In addition, the relationships were further used to predict future ship-associated emissions by 2030, utilizing a combination of regression models and Holt-Winters' trend and seasonal forecast. Results showed a 61% increase in distance travelled, 115% increase in NO_x emissions, and 68% increase in SO_2 emissions from 2013 to 2023. A strong positive linear relationship between oil and gas production and the ship-associated emissions of NO_x and SO_2 was found, with a coefficient of determination as high as 0.97. The oil sector emerged as the largest contributor to emissions from 2017 onward. Projections indicate that NO_x and SO_2 emissions will be more than doubled, reaching 12,400 and 1200 tonnes, respectively, by 2030, of which the oil sector accounts for 45 and 61% of the total emissions. This highlights the need for further emissions reduction measures, especially with expanding Arctic oil projects, in order to mitigate the environmental impact of increased resource-driven shipping along the NSR.

1. Introduction

The continuous melting of sea ice has led to increased shipping activities in the Arctic due to improved navigability (Berkman et al., 2020; Li et al., 2021). In addition, the region's abundant natural resources and growing global demand for natural resources such as fish, oil, natural gas, and minerals, along with increased interest for Arctic tourism and trans-Arctic shipping of goods, have sparked global attention (Gritsenko and Efimova, 2020). The number of unique registered vessels within the International Maritime Organization (IMO) Polar Code area increased 25% from 2013 to 2019 (PAME, 2020a). The total distance travelled within the same area increased by 75%, reaching 10.7 million nautical miles (PAME, 2020a), while shipping in the Canadian Arctic tripled since the 1990s (Dawson et al., 2020). A recent study indicated a 7 % annual growth in shipping days within the IMO Polar Code area, with the Northern Sea Route (NSR) experiencing the most significant increase (Müller et al., 2023).

The NSR, stretching from the Kara Sea in the west to the Bering Strait in the east, falls within the Russian Arctic Zone of development and has witnessed substantial investments in infrastructure and development projects, particularly in new oil and gas fields (Gunnarsson, 2021; Gunnarsson and Moe, 2021; Li et al., 2021). From 2016 to 2019, voyages along the NSR increased by 58 %, and cargo transported quadrupled, with notable contributions from dry cargo ships from NorNickel, oil tankers from Novy Port, and liquefied natural gas (LNG) carriers from Yamal LNG (Boylan, 2021; Gunnarsson and Moe, 2021; Li et al., 2021). Projections suggest that if Russian development projects proceed as planned, annual cargo volume along the NSR could grow from 10.7 million tonnes in 2017 to 100 million tonnes in 2025 (Li et al., 2021). The ongoing increase in cargo volume underscores the crucial role of natural resources, particularly oil and gas, in the future growth of ship traffic in the Arctic region. However, most studies link increasing ship traffic to decreasing sea ice (Berkman et al., 2020; Dawson et al., 2022; Eguíluz et al., 2016; Silber and Adams, 2019; Stocker et al., 2020).

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Therefore, studying the connection between Arctic resource activities and the associated ship traffic is of high importance.

Increasing ship traffic raises concerns about emissions of air pollutants, as the shipping sector is a major contributor to nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter (PM) pollution in the Arctic (Marelle et al., 2016; Raut et al., 2022). Although bottom-up studies have estimated emission inventories and assessed future emission scenarios (Chen et al., 2024; Corbett et al., 2010; Dalsøren et al., 2013; Peters et al., 2011; Winther et al., 2014), these studies are typically based on limited data from a single year rather than consecutive years and focus primarily on diversion/trans-Arctic routes (Chen et al., 2024; Winther et al., 2017). Few studies address air emissions from destinational and resource-driven shipping along the NSR. Given the ongoing and planned resource-driven development along the NSR, it is crucial to provide new empirical data on the region's recent and future developments and to assess the impact on ship-associated emissions.

To address these shortcomings, the primary objective of this study is to establish a connection between resource-driven activities along the NSR, and ship-associated emissions of NO_x and SO_2, and predict future ship-associated emissions by 2030. This study contributes in the following ways. 1) It provides new and high temporal resolution data on ship traffic and associated NO_x and SO_2 emissions, showcasing the dynamic developments in the region. 2) It presents recent and future metrics on oil, gas, and mining production in a rapidly developing region in the Arctic, highlighting their impact on ship-associated emissions. 3) The combination of linear regression and Holt-Winters' trend and seasonal forecast provides a robust prediction while incorporating seasonality. Ultimately, this study provides important insight into how sector-specific developments may impact regional emissions of NO_x and SO_2 in the future. All of these contributions are essential for enabling stakeholders to facilitate sustainable Arctic shipping.

2. Study area

In literature, the NSR is commonly referred to as the Northern Sea Route Water Area (NSRWA) (Gunnarsson, 2021). However, since accessing the NSR involves navigating through the Barents Sea, or the Bering Sea and eastern part of the Chukchi Sea, which are subject to varying levels of ship traffic, we include them in our analysis hereafter refer to the entire route as the NSR (Fig. 1).

The NSR holds particular interest due to numerous development projects that have been completed or are planned, particularly in the Russian Arctic Zone of Development, leading to increased cargo volumes transported by ships (Gunnarsson and Moe, 2021; Li et al., 2021). Notable projects on the Norwegian side include Hammerfest LNG (operational since 2007), Goliat oil field (operational since 2016), and Johan Castberg oil field (scheduled to start production in 2024) (Fig. 1) (Equinor, n.d., 2021; Norwegian Petroleum, n.d.). On the Russian side, significant projects include NorNickel (year-round mineral shipping since 2009), Prirazlomnoye oil field (operational since 2014), Novy Port oil field (operational since 2016), Yamal LNG (operational since 2017), and Taymyr coal (operational since 2020) (Fig. 1) (Global Energy Monitor, n.d.-b; Li et al., 2021; NorNickel, n.d.; Northern Star, n.d.). Future projects include Arctic LNG 2 and Vostok oil (expected to commence production from 2024), Arctic LNG 1 (planned for 2027), and Murmansk LNG (anticipated in 2028). Additionally, titanium extraction from the Pizhemskoye field is projected to begin in 2027, alongside plans for a new deepwater port in Indiga (Fig. 1) (Global Energy Monitor, n.d.-a; Humpert, 2023a; Offshore Technology, 2024; Ross, 2023; Seligman, 2021; TASS, 2023).

3. Materials and methods

3.1. Data collection and processing

3.1.1. Ship traffic data

Ship traffic data spanning from January 2013 to October 2023 was obtained from the Arctic Ship Traffic Database (ASTD), administrated by the Protection of the Arctic Marine Environment (PAME). Vessels operating in the Arctic region are logged in the database via Automatic Identification System (AIS) signals, which contain information such as geographical coordinates, vessel type, and size. The ASTD data is stratified into three accessibility tiers, with this study utilizing ASTD level 3. Level 3 access contains limited vessel information, including an ASTD-assigned unique identifier per ship per month, vessel type, size classification, flag registration, ice-class designation, and fuel quality (PAME, 2023). To mitigate data inaccuracies, only geographic point-based ship identifiers within the study area with operational durations exceeding 1 h (comprising over 10 registrations) were considered, and rows containing null values were excluded.

In this study, distance travelled, measured in Nautical Miles (NM), serves as the metric for evaluating ship activity, which has been used in

Fig. 1. Overview of the study area of this study, exhibiting various transport routes, important ports and resource development projects. Adapted from Figenschau and Lu (2022).

other studies (Dawson et al., 2022; Silber and Adams, 2019). Distance travelled between each unique ship's registration was calculated using the haversine formula (Mahmoud and Akkari, 2016), and subsequently aggregated into monthly sums.

3.1.2. Shipping sector identification

Economic development activities play a significant role in shaping shipping activity within the region. To interpret the relationship between economic development and shipping, each vessel's registered ship type was categorized into distinct economic sectors. These sectors include fishing, tourism, trade, oil, gas, mining, and "others" as shown in Table 1.

3.1.3. Emission data

Emissions data of NO_x and SO_2 from 2013 to 2023 were collected from the ASTD system. The system employs a bottoms-up algorithm, as outlined in the IMO 4th Greenhouse Gas Study (2020) and Olmer et al. (2017), to calculate emissions. These calculations integrate each vessel's AIS data, along with its characteristics provided by S&P Global, specific fuel consumption data from Det Norske Veritas (DNV), and emission factors from IMO (IMO, 2020), as outlined in the ASTD data documentation (PAME, 2023). Monthly emissions of SO_2 and NO_x were aggregated for each economic sector in Table 1. PM emission data in the ASTD system was available only from January 2013 to December 2019, due to the new fuel regulations (>0.5 % m/m sulphur ban after the IMO 2020 fuel oil sulphur limit implementation in January 2020 (hereafter IMO 2020)). The lack of continuous data on PM emissions and ship-specific details from the ASTD level 3 access made further estimations of PM difficult, as the pollutant is dependent on both sulphur content and energy consumption (specific fuel consumption). PM emissions was therefore not included in the study. However, even in the absence of continuous PM data, NO_x emissions can provide insights into energy consumption, while SO_2 can provide insights into the sulphur content of fuels used. Furthermore, both NO_x and SO_2 are important precursor to secondary formation of particles, such as nitric and sulphuric acid (HNO_3 and H_2SO_4). Thus, focusing on NO_x and SO_2 emissions allows readers to infer potential changes of PM. Future research could further explore these relationships to better understand PM dynamics in the Arctic.

3.1.3.1. Emission adjustments for gas tankers.

Emission adjustments for ships labelled as "Gas tankers" were necessary due to assumptions made by the ASTD system, which assumes that all gas tankers are fuelled solely by Heavy Fuel Oil (HFO) or residual fuel. However, recent studies show that gas tankers are primarily fuelled by LNG Boil-off Gas (BOG) (Comer et al., 2020, 2024; Pavlenko et al., 2020). Similar to the study by Comer et al. (2020), this study assumes that all gas tankers within the study area operate solely on LNG. To rectify emissions from gas tankers, the total monthly energy consumption (in megajoules (MJ) and kilowatt-hours (kWh)) for each fuel type was calculated using the formula:

$$P = FC * 1000 * VLHV_f \quad \text{Equation 1}$$

where P is the total energy consumption in MJ, FC is the fuel consumption in m^3, 1000 is used to convert from m^3 to litres (L), and $VLHV_f$ is the volumetric lower heating value in MJ/L for the respective fuel type f (Marine Diesel Oil (MDO) = 37.5, HFO = 39.1 and LNG = 20.8) (Foretich et al., 2021). The monthly energy consumption was converted to kWh using the conversion rate 1 MJ = 0.277778 kWh, allowing for further calculation of NO_x emissions by adjusting emission factor for LNG-Otto cycle slow speed dual fuel engines:

$$EM_{NO_x} = \frac{P_{kWh} * EF_{NOx}}{1000000} \quad \text{Equation 2}$$

Where EM_{NO_x} is the total monthly NO_x emissions in tonnes, P_{kWh} is the monthly power consumption in kWh, and EF_{NOx} is the emission factor of 1.3 g CH_4/kWh, as assumed in the IMO 4th Greenhouse Gas Study (IMO, 2020). The emissions were divided by 1,000,000 to convert from grams to tonnes.

For SO_2 emissions, which are fuel-based pollutants, the monthly energy consumption was converted into LNG-equivalents, assuming that one LNG equivalent was 50 MJ/kg LNG. The SO_2 emissions were calculated using the equation:

$$EM_{SO_2} = \frac{FC_{LNG} * EF_{SO_2}}{1000000} \quad \text{Equation 3}$$

Where EM_{SO_2} is the total monthly SO_2 emission in tonnes, FC_{LNG} is the calculated fuel consumption in LNG equivalents, and EF_{SO_2} is the emission factor of $3.17*10^{-5}$ g SO_x/g LNG, as assumed in IMO 4th Greenhouse Gas Study (IMO, 2020). The emissions were divided by 1,000,000 to convert from grams to tonnes.

3.1.3.2. Emission factor adjustment for SO_2.

Due to the implementation of the IMO 2020 in January 2020 (IMO, n.d.), the use of HFO with sulphur content exceeding 0.5 % was significantly reduced in ships associated to the economic sectors tourism, trade, mining, "others", and oil. Therefore, future SO_2 emissions are based on historic and projected fuel consumption, multiplied by the mean emission factor for the years 2020–2023 ($EM_{SO_{2-Future}} = FC_{Future-Sector} * EF_{uSO_2-Sector}$) (see Fig. A1 in appendix for time series of each ship sectors monthly emission factors and the calculated 2020–2023 mean SO_2 emission factor ($EF_{uSO2\text{-}Sector}$). The calculated mean emission factors for the different sectors are as follows: $EF_{uSO2\text{-}Tourism} = 0.0067$ g/m^3

$EF_{uSO2\text{-}Trade} = 0.0050$ g/m^3

$EF_{uSO2\text{-}Mining} = 0.0092$ g/m^3

$EF_{uSO2\text{-}Others} = 0.0028$ g/m^3

$EF_{uSO2\text{-}Oil} = 0.0080$ g/m^3.

The fishing sector relies solely on MDO as fuel, while the gas sector is assumed to be 100 % fuelled by LNG. Therefore, future emissions for these sectors are based on historical SO_2 emissions.

Table 1
Aggregation of ship types into economic sectors.

Fishing	Tourism	Trade	Oil	Gas	Mining	"Others"
Fishing vessels	Cruise ships Passenger ships	Refrigerated cargo ships Container ships Chemical tankers Oil product tankers[b] General cargo ships	Crude oil tankers Offshore supply ships[a]	Gas tankers	Bulk carriers	Ro-Ro cargo ships Other activities Other services

[a] Offshore supply ships attributed to oil, as most gas activities are land-based installations.
[b] Oil product tankers are attributed to trade, as they transport a wide range of refined oil products (ranging from diesel to vegetable oil) from refineries to various destinations along the study area, similar to general cargo ships. Unlike crude oil tankers, these ships cannot be directly attributed to the production of crude oil and are therefore separated from the oil sector.

3.1.4. Resource production data in different economic sectors

Based on the research conducted by Gunnarsson and Moe (2021) and Li et al. (2021), it is anticipated that the transportation volumes of oil, gas, and minerals will increase in the near future. To further evaluate the potential impact of these sectors on ship-associated emissions in the region, the relationship between historical and projected production of oil, gas, and minerals with ship-associated emissions is analysed. A dataset on historical and projected production for oil, gas, and minerals was compiled by reviewing articles, reports, and documents related to identified Norwegian and Russian Arctic development projects within the study area, as summarized in Tables 2 and 3.

Table 2
Overview of the sources, production facilities, resource type and reported production years for all identified planned oil, gas, and mineral projects, as highlighted in the study area (Fig. 1). Annual sectorial production numbers can be found in Table 3 in the results section.

Source	Field/Plant	Resource	Reported production year
Oil & Gas Journal (2016)	Prirazlomnoye	Oil	2014 & 2015
Staalesen (2018)			2016 & 2017
Global Energy Monitor (n.d.)			2019–2021
Krylov State Research Centre (2017), Borshchevskaia et al. (2022)			2022–2030 (expected)
*			*2018 not found, assumed median of 2017 and 2019 (2.84 mt).
Norwegian Petroleum (n.d.-b)	Goliat	Oil	2016–2021 and onwards
Equinor (n.d.)	Johan Castberg	Oil	2024–2030 (expected)
Li et al. (2021)	Novy Port	Oil	2016, 2017 2018 & 2020–2030 (expected)
Staalesen (2023b)	Vostok Oil	Oil	2030 (expected)
Ross (2023)			2024–2030 (adjusted).
Li et al. (2021)	Yamal LNG	Gas	2017 & 2018
Yamal LNG (2020, 2021)			2019 & 2020
Reuters (2022)			2021 and assumed until 2030.
Staalesen (2023a)	Arctic LNG 2	Gas	2024 (expected)
Norways and Elliot (2024), Global Energy Monitor (n. d.-a)			2025, 2026–2030 (expected)
Seligman (2021)	Arctic LNG 1	Gas	2027–2030 (expected)
(Humpert, 2023b; Offshore Technology, 2024)	Murmansk LNG	Gas	2027–2030 (expected)
Equinor (2021)	Hammerfest LNG	Gas	2013–2019 and 2023–2030 (expected)
Equinor (2022)			Assume ~3 mt production in 2020 due to fire. No production in 2021 and half production in 2022 (~2 mt).
NorNickel (2017, 2018, 2019, 2020, 2021, 2022)	NorNickel	Nickel	2013–2022. Used 2030 goal according to growth estimate in 2019 Annual Report and interpolated production in 2023–2029.
Northern Star (n.d.)	Taymyr Coal	Coal	2021–2030
Humpert (2023a), TASS (2023)	Pizhemskoye Titanium	Titanium	Assuming gradual scale-up towards 30 mt in from 2027 to 2030

3.2. Data analysis

3.2.1. Error-Trend-Seasonality analysis

Monthly data for sector-specific distance travelled, NO_x, and SO_2 emissions were subjected to Error-Trend-Seasonality (ETS) decomposition analysis using the Statsmodels python module *seasonal_decompose* to identify the 12-Month Moving Average (12MMA) trend (T), seasonal patterns (S), and error component (E) of each ship sector's time series (Seabold and Perktold, 2010). Considering the additive nature of the time series data and a seasonal periodicity of 12 months, the model assumed an additive structure:

$$y = T + S + E \qquad \text{Equation 4}$$

For ship sectors lacking specific development projects, such as fishing and tourism, the results of ETS decomposition were utilised for forecasting using the Holt-Winters' trend and seasonal forecast, detailed in in section 3.3.3.

3.2.2. Regression analysis

Linear regression was employed to analyse the relationship between NO_x and SO_2 emissions from oil, gas, and mining sector, and their respective resource production activities. The regression model is represented as follows:

$$y = \beta * X + \beta_0, \qquad \text{Equation 5}$$

Here, y represents the dependent variable, while X represents the independent variable, corresponding to annual production figures of oil, gas, or minerals. The coefficients β_0 (intercept) and β (slope) are estimated by the regression model. For the gas sector, the dependent variable y comprised annual mean NO_x and SO_2 emissions from shipping in gas sector, as the gas tankers were assumed to run solely on LNG. For NO_x emissions from the mining and oil sector, annual mean NO_x emissions were used as the y. For SO_2 emissions from these two sectors, fuel consumption was used as the dependent variable y. This assumption is based on the expectation that ships operating beyond 2023 will comply with the IMO 2020 regulations, which limit the use of fuel oils with more than 0.5 sulphur content (as described in section 3.1.3.2).

3.2.3. Holt-Winters' trend and seasonality forecast

For forecasting future NO_x and SO_2 emissions from the fishing, tourism, trade, mining, and "others" shipping sectors, the Holt-Winters' trend and seasonality forecast was employed. This method generates forecasts using three smoothing equations: one for level l_t, one for growth b_t, and one for seasonality s_t, which comes in two variations, a Holt-Winters' additive seasonal component (A, A method) and the Holt-Winters' multiplicative seasonal component (A, M method).

The A, A method is defined as follows:

$$\text{Level}: l_t = \alpha(y_t - s_{t-m}) + (1-\alpha)(l_{t-1} + b_{t-1}) \qquad \text{Equation 6.1}$$

$$\text{Growth}: b_t = \beta^*(l_t - l_{t-1}) + (1-\beta^*)b_{t-1} \qquad \text{Equation 6.2}$$

$$\text{Seasonal}: s_t = \gamma(y_t - l_{t-1} - b_{t-1}) + (1-\gamma)s_{t-m} \qquad \text{Equation 6.3}$$

$$\text{Forecast}: y^*_{t+h|t} = l_t + b_t h + s_{t-m+h_m^+}), \qquad \text{Equation 6.4}$$

where m represents the length of seasonality, l_t denotes the level at time t of the series, b_t represents the growth at time t, s_t represents the seasonal component at time t, $y^*_{t+h|t}$ denotes the forecast for h periods, and $h_m^+ = \lfloor (h-1) \bmod m \rfloor + 1$, which ensures the forecast is based on the number of complete cycles since the last year of the observed data. The parameters α, β^* and γ control the smoothing factor for the level, growth and seasonal components, respectively, and vary between 0 and 1 with the constraint that $\alpha + \beta^* + \gamma \leq 1$ (P. R. Hyndman et al., 2008). The A, M method is defined as follows:

Table 3
Reported and future production of oil, gas, and ore/metals from the identified resource development projects along the NSR.

Oil Production						
Year	Novy Port Oil	Prirazlomnoye Oil	Vostok Oil	Johan Castberg	Goliat	Total Oil
2013	0		0	0	0	0
2014	0	0.30	0	0	0	0.3
2015	0	0.80	0	0	0	0.8
2016	2.92	2.20	0	0	2.48	7.60
2017	5.95	2.60	0	0	2.11	10.66
2018	7.26	2.84	0	0	3.12	13.22
2019	8.00	3.08	0	0	1.98	13.06
2020	8.50	3.38	0	0	1.94	13.82
2021	8.50	3.60	0	0	1.70	13.80
2022	8.50	3.60	0	0	1.59	13.69
2023	8.50	3.60	0	0	1.11	13.21
2024	8.50	5	23.80	9.20	1.68	48.18
2025	8.50	5	36.40	9.20	1.68	60.78
2026	8.50	5	44.80	9.20	1.68	69.18
2027	8.50	5	52.50	9.20	1.68	76.88
2028	8.50	5	57.40	9.20	1.68	81.78
2029	8.50	5	560	9.20	1.68	80.38
2030	8.50	5	55.30	9.20	1.09	79.09
Gas Production						
Year	Sabetta LNG (mt)	Arctic LNG 2	Arctic LNG 1	Murmansk LNG	Hammerfest LNG	Total Gas
2013	0	0	0	0	4.65	4.65
2014	0	0	0	0	4.65	4.65
2015	0	0	0	0	4.65	4.65
2016	0	0	0	0	4.65	4.65
2017	0.30	0	0	0	4.65	4.95
2018	8.30	0	0	0	4.65	12.95
2019	18.40	0	0	0	4.65	23.05
2020	18.80	0	0	0	3.00	21.80
2021	21.00	0	0	0	0	21.00
2022	21.00	0	0	0	2.00	23.00
2023	21.00	0	0	0	4.65	25.65
2024	21.00	6.60	0	0	4.65	32.25
2025	21.00	13.20	0	0	4.65	38.85
2026	21.00	19.80	0	0	4.65	45.45
2027	21.00	19.80	6.60	0	4.65	52.05
2028	21.00	19.80	13.20	6.80	4.65	65.45
2029	21.00	19.80	19.80	13.60	4.65	78.85
2030	21.00	19.80	19.80	20.40	4.65	85.65

Mineral Production				
Year	NorNickel	Pizhemskoye Titanium	Taymyr Coal	Total Ore/Metals
2013	0.80	0	0	0.80
2014	1.20	0	0	1.20
2015	1.20	0	0	1.20
2016	1.20	0	0	1.20
2017	1.20	0	0	1.20
2018	1.30	0	0	1.30
2019	1.40	0	0	1.40
2020	1.40	0	0	1.40
2021	1.60	0	0.30	1.90
2022	2.00	0	1.25	3.25
2023	2.10	0	2.50	4.60
2024	2.10	0	5.00	7.10
2025	2.20	0	7.50	9.70
2026	2.30	0	10.00	12.30
2027	2.30	7.00	10.00	19.30
2028	2.40	15.00	10.00	27.40
2029	2.40	25.00	10.00	37.40
2030	2.50	30.00	10.00	42.50

$$\text{Level}: l_t = \alpha\left(\frac{y_t}{s_{t-m}}\right) + (1-\alpha)(l_{t-1} + b_{t-1}) \quad \text{Equation 7.1}$$

$$\text{Growth}: b_t = \beta^*(l_t - l_{t-1}) + (1-\beta^*)b_{t-1} \quad \text{Equation 7.2}$$

$$\text{Seasonal}: s_t = \gamma\left(\frac{y_t}{l_{t-1} - b_{t-1}}\right) + (1-\gamma)s_{t-m} \quad \text{Equation 7.3}$$

$$\text{Forecast}: y^*_{t+h|t} = (l_t + b_t h)s_{t-m+h_m^+)} \quad \text{Equation 7.4}$$

This method is identical to the first variation, except the seasonal component is expressed as a ratio. In this study, the length of seasonality m was set to 12 and forecast period h was set to 86.

Future NO_x emissions from the shipping sectors fishing, tourism, trade, mining, and "others" were forecasted based on historic NO_x emissions between January 2013 and October 2023. For SO_2, future emissions from tourism, trade, mining, "others", and oil were calculated based on future fuel consumption (m^3) and each sector's respective $EF_{uSO2\text{-}Sector}$. SO_2 emissions from the fishing sector, however, were based on historic SO_2 emissions, as they mainly use MDO as fuel.

3.2.3.1. Holt-Winters' model selection. In order to evaluate which forecasting method to use, the root mean squared error (RMSE) was employed as the performance metric. The method with the lowest RMSE was selected for forecasting, calculated using the equation:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}, \qquad \text{Equation 8}$$

where n denotes the number of data points (n = 130), y_i denotes the real value at given data point (i), and $\hat{\boldsymbol{y}}_i$ is the predicted value at the data point (i).

4. Results

In this section, the temporal variations and trends in distance sailed and associated emissions of NO_x and SO_2 from different shipping sectors from 2013 to 2023 are presented (Fig. 2). It also includes the historical and projected resource production data (Table 3), examining their relationship with relevant shipping activities (Fig. 3). The performance statistics of the Holt-Winters' forecast models for model selection are provided (Table 4). Lastly, future NO_x and SO_2 emissions by 2030 are presented, using a combination of the chosen Holt-Winters' method, and linear regression analysis (Fig. 4).

4.1. Sector-specific ship traffic and associated emissions

4.1.1. Sector-specific ship traffic

A notable increase and distinct seasonal variations in the distance travelled was observed throughout the study period (Fig. 2). The overall distance travelled increased 61 % from 0.90 million NM in 2013 to 1.45 million NM in 2023, as determined by the 12-MMA. The fishing sector and trade sector accounted for a substantial portion of the distance travelled, constituting 11–25 % of the total distance travelled and 13–30 % of the total distance travelled, respectively. The distance travelled in these two sectors range between 0.26 and 0.68 million NM and between 0.11 and 0.50 million NM, respectively. In addition, the "others" category exhibited a notable activity, particularly after March 2021, encompassing distances between 0.18 and 0.45 million NM, which accounts for approx. 15–27 % of the total distance travelled. The remaining sectors, including tourism, trade, oil, and gas, contributed relatively smaller portions to the total distance travelled, with each sector primarily representing less than 10 % of the overall distance travelled. Notably, all economic sectors except the oil and gas sector, displayed strong seasonality, with amplified activity typically observed between June and October. In contrast, the oil and gas sector remained relatively stable since 2019, fluctuating between 0.15 and 0.30 and 0.07 and 0.10 million NM, respectively.

4.1.2. Sector-specific NOx emissions

The ship-associated NO_x emissions displayed a continuous growth throughout the study period. The overall NO_x emissions surged by 115 %, from 2500 tonnes in 2013 to 5380 tonnes in 2023, as evidenced by the 12-MMA. Before 2017, NOx emissions were primarily attributed to

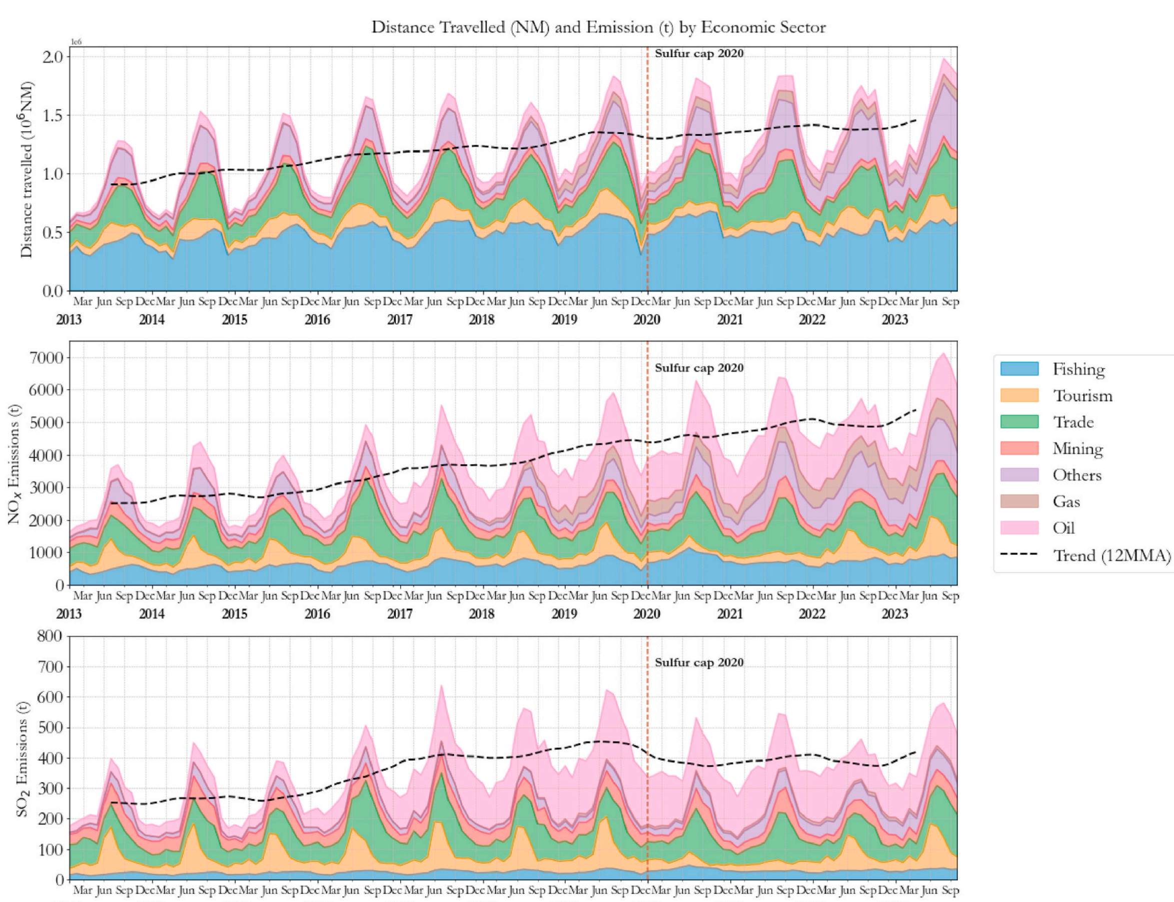

Figure SEQ Figure * ARABIC 2. Stacked time series for distance travelled, NO_x and SO_2 emissions from 7 Arctic economic sectors from January 2013–October 2023. The 12MMA for the total distance and emissions are also presented (black dashed line).

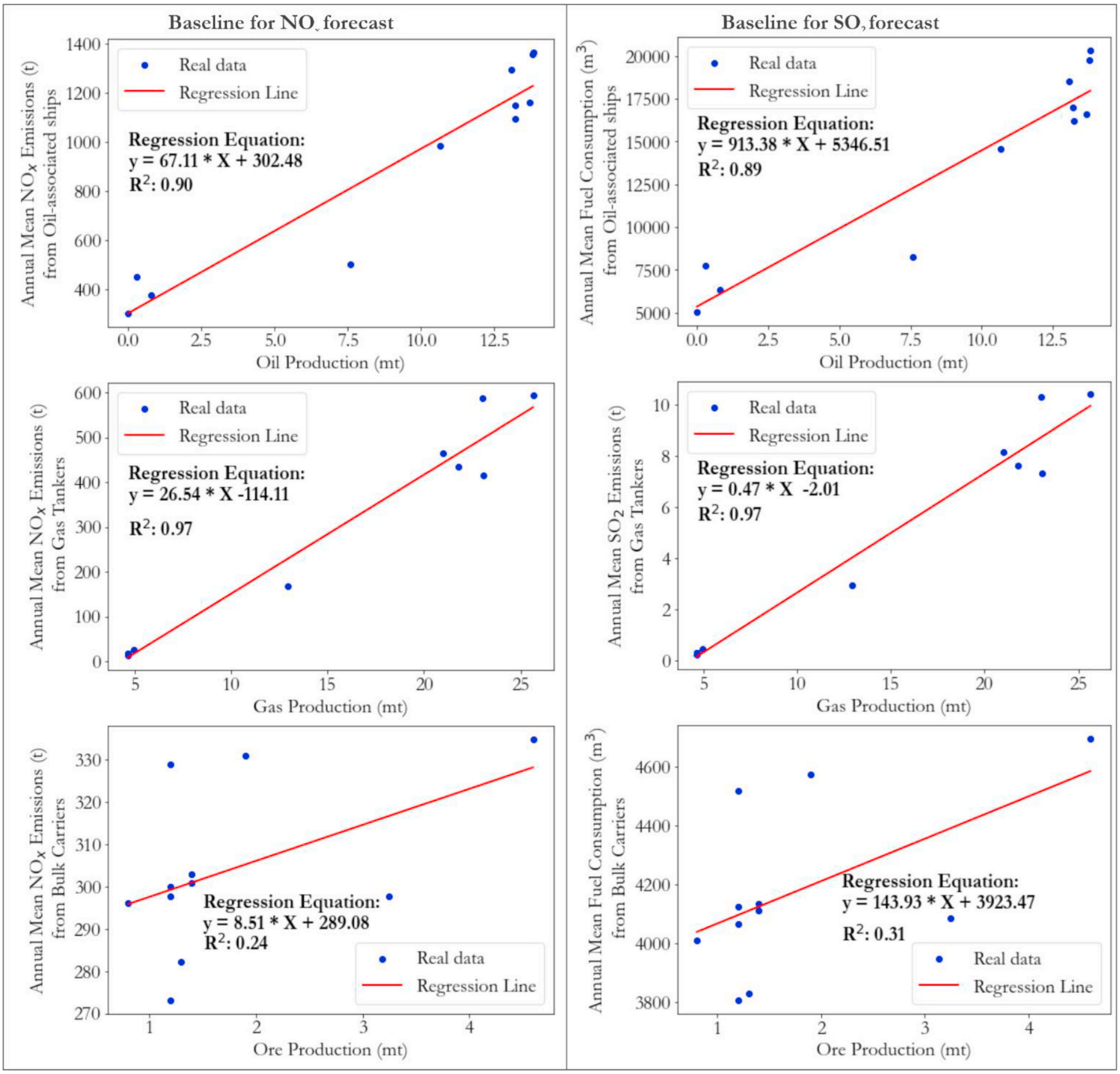

Fig. 3. Scatter plots with baseline regression model equation and R-squared for oil-, gas- and mining-related annual mean emissions and annual production in the study area (see Fig. A2 in appendix for normality tests).

four sectors: fishing, trade, oil, and "others". The fishing sector contributed between 300 and 750 tonnes (12–28 % of total emissions), trade ranged between 400 and 1900 tonnes (18–40 %), oil ranged from 170 to 780 tonnes (10–20 %), and "others" sector emitting 500–800 tonnes (up to 22 %). Notably, the tourism sector contributed significantly to NO_x emissions during the summer months June, July, and August, with tourism emitting between 500 and 1020 tonnes (up to 28 % of total emissions). During 2017, the oil sector emerged as the primary driver of NO_x emissions, contributing between 25 and 36 % of the total emissions, ranging from 900 to 1600 tonnes monthly. Additionally, an increase in NO_x emissions from the gas sector was observed from 2018 onwards, stabilizing between 400 and 600 tonnes a month. The absence of June–August peak tourism emissions in 2020 and 2021, along with the overall decrease in NO_x emissions in 2022, are notable observations.

4.1.3. *Sector-specific SO2 emissions*

From 2013 to 2023, the SO_2 emissions increased 68% from 250 to 420 tonnes, according to the 12MMA. The development in SO_2 emissions can be delineated into three phases: pre-2017, 2017–2019 and post-2020 phase. Before 2017, SO_2 emissions remained relatively stable, with a 16 % increase observed from 2013 to January 2016, reaching 290 tonnes according to the 12MMA. However, a notable 34 % increase occurred in January 2017, with emissions averaging 390 tonnes. During this period, trade, mining, and tourism sectors were the main contributors to SO_2 emissions, ranging from 40 to 199, 26–75 tonnes, and 20–164 tonnes, respectively. The spike in SO_2 emissions was primarily driven by a significant increase in emissions from the trade sector, compounded by rising SO_2 emissions from the oil sector. From 2017 to 2019, the oil sector drove a 15 % overall increase in SO_2 emission, contributing between 30 and 52 % of total emissions by December 2019. Notably, excluding the oil sector, SO_2 emissions would have decreased below 400 tonnes in 2018 and 2019. The final phase saw a 17 % decrease from 450 tonnes in September 2019 to 370 tonnes in September 2020, aligned with the IMO 2020. SO_2 emissions remained relatively stable thereafter, ranging between 370 and 410 tonnes, with a temporary dip observed in 2022. Both the fishing and gas sector made minimal contributions to SO_2 emissions, accounting for less than 10 and 3 %, respectively, contrasting with the significant contributions observed for distance travelled and NO_x, particularly in the case of fishing. The absence of peaking SO_2 emissions from tourism in 2020 and 2021 are similar to that observed in NO_x emissions.

Table 4
RMSE values for Holt-Winters' A, A method and A, M method for the fishing, tourism, trade, mining and "others" sector. The model with the lowest RMSE value was chosen as the forecasting method.

Holt-Winters Model Performance for NO_x Emission Forecast					
Sector	Holt-Winters Method	RMSE	Sector	Holt-Winters Method	RMSE
Fishing	A, A	62.53	Trade	A, A	105.97
	A, M	61.86		A, M	97.77
Tourism	A, A	92.05	Mining	A, A	55.68
	A, M	67.25		A, M	55.43
Others	A, A	84.63			
	A, M	119.71			
Holt-Winters Model Performance for SO_2 Emission Forecast					
Sector	Holt-Winters Method	RMSE	Sector	Holt-Winters Method	RMSE
Fishing	A, A	2.41	Trade	A, A	1661.18
	A, M	2.37		A, M	1518.65
Tourism	A, A	1395.02	Mining	A, A	771.48
	A, M	1077.87		A, M	750.78
Others	A, A	1663.25			
	A, M	2328.94			

4.2. *Historic and future oil and gas production and its impact on emissions*

4.2.1. *Historic and future oil, gas, and mining production in the study area*

The production of oil, gas and minerals has been systematically mapped, as detailed in Section 3.1.4, and summarized in Table 3 below. The initial oil production commenced in 2014, with significant acceleration occurring in 2016 following the operationalization of Novy Port. Since 2018, annual production has stabilised above 13 million metric tonnes (mt). The most significant increase in oil production is anticipated to more than triple from 2023 to 2024 if the Vostok Oil project proceeds as planned. The peak in oil production is forecasted for 2028, coinciding with the anticipated peak production of the Vostok Oil project.

Gas production was at 4.95 mt per year from 2013 to 2017 with the full operation of Hammerfest LNG. In 2018, the production increased to 12.95 mt upon the full operationalization of Yamal LNG. Steady growth has characterised gas production, reaching 25.65 mt in 2023. This upward trajectory is expected to persist, driven by the commencement of operations of Arctic LNG 2, 1 and Murmansk LNG projects. By 2030, the target is to achieve a gas production of 85.65 mt.

Ore production has demonstrated relative stability, climbing from 0.8 mt in 2013 to 1.9 mt in 2021, primarily comprising processed nickel and copper from NorNickel. The uptick in 2022 and 2023 can be attributed to increased production at the Taymyr coal project, projected to yield 10 mt of coal by 2026. Further expansion in the mining sector is anticipated, driven by the Pizhemskoye Titanium project, expected to

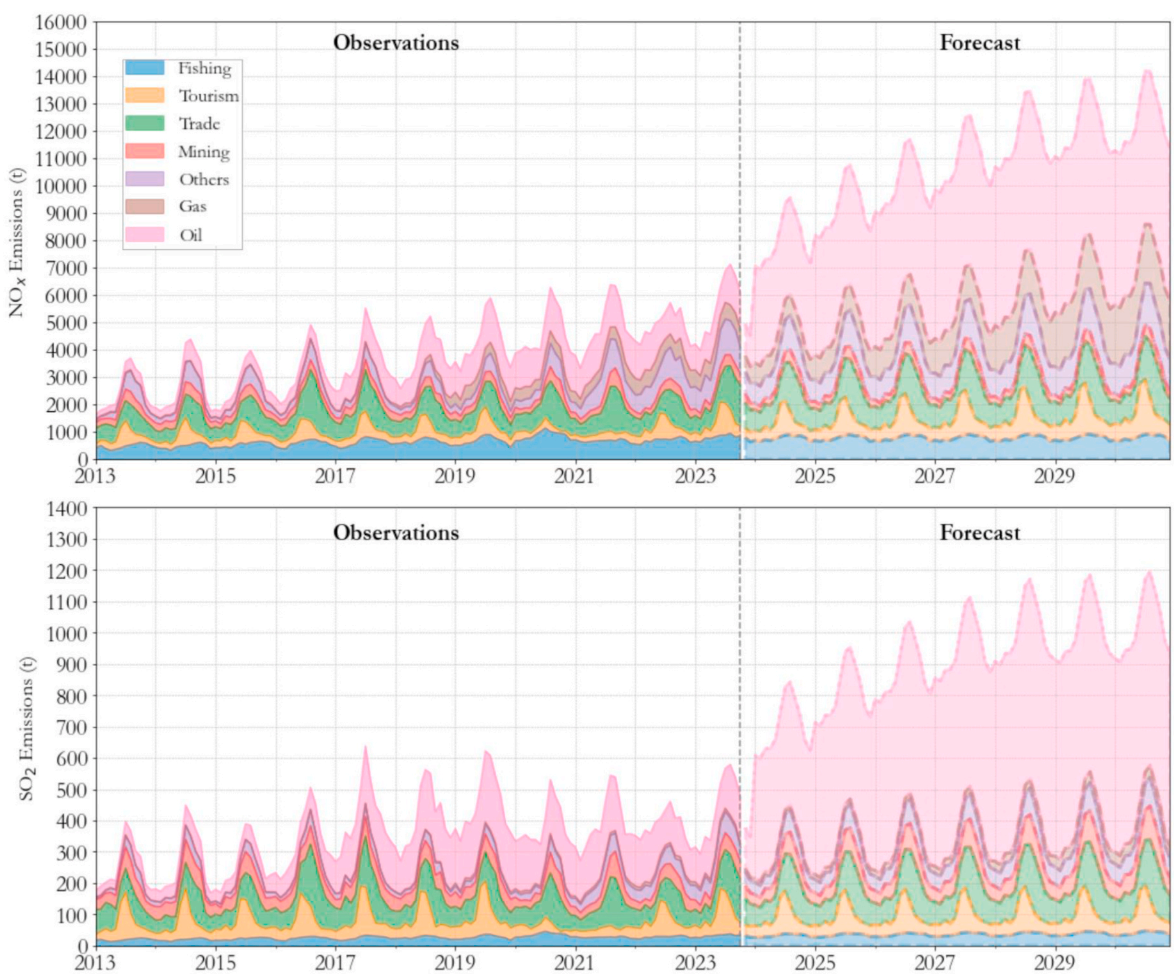

Fig. 4. Historic and future emissions of NO_x and SO_2 by 2030 using a combination of linear regression and Holt-Winters' trend and seasonality forecast.

export up to 30 mt by 2030. In sum, these activities will contribute to a total production of 42.5 mt processed ore by 2030.

4.2.2. The impact of oil, gas, and mining activities on ship-associated emissions

The relationship between oil, gas, and mining production, and the annual mean NO_x and SO_2 emissions from corresponding ship sectors are presented in Fig. 3. A robust linear relationship was observed between annual oil production (X) and NO_x emissions from oil tankers (y), with 90 % of the variance in NO_x emissions explained by changes in oil production. The fitted model suggests an increase of 67.11 t of NO_x emissions per mt increase in oil production. Similarly, 89 % of the variance in fuel consumption (y), the baseline for future SO_2 emissions, was explained by changes in oil production. The model suggests a 913.38 m^3 increase in fuel consumption per mt of oil produced (X). These findings suggest that the developments in oil sector are set to be a significant contributor to future emissions.

The gas sector exhibited an even stronger linear relationship than the oil sector, with 97 % of the variance in both NO_x and SO_2 emissions (y) explained by changes in annual gas production (X). NO_x emissions increased by 26.54 t per mt increase in gas production. The model suggests a minor increase of only 0.47 t in SO_2 emissions (y) per mt increase in gas production (X). Despite the significant contribution of NO_x emissions from the gas sector to overall emissions, SO_2 emissions are expected to be negligible.

In contrast to oil and gas, the relationship between historic emissions and fuel consumption in mining related shipping and reported activity showed a weak linear relationship. The fitted model could only account for 24 % of the variance in NO_x emissions and 34 % of the variance in fuel consumption, with respect to changes in ore production. Due to the poor relationship, future forecasts based on dry bulk cargo ships were discarded and included in the Holt-Winters' forecast as explained under section 3.3.3.

4.3. Holt-Winters trend and seasonality model performance

The calculated RMSE for forecasting the shipping sectors using either the Holt-Winters' A, A method or the A, M method are presented in Table 4. For NO_x emissions, the A, M method is generally preferred, except for the "others" sector, which performs best with the A, A method. The mining sector show little difference between the methods, but the A, M method is chosen. Similar results are observed for predicting SO_2 emissions, with all sectors except "others" preferring the A, M method. This suggest that the seasonal variation changes over time (R. J. Hyndman and Athanasopoulos, 2019). For a detailed summary of the Holt-Winters models, see appendix Table A1, A2, A3 and A4.

4.4. Projected future ship-associated emissions

Historic and projected NO_x and SO_2 emissions, based on a combination of regression analysis and Holt-Winters' forecast are presented in Fig. 4. In 2023, the mean emission of NO_x and SO_2 was at 5600 and 440 tonnes, respectively. According to the forecast, NO_x emissions are projected to increase by 121 %, reaching an annual mean of 12,400 tonnes by 2030, while SO_2 emissions are forecasted to increase by 127 %, reaching and stabilizing at an annual mean of 1000 tonnes by 2028 onwards. Emissions of NO_x and SO_2 may reach up to 14,200 and 1200 tonnes, respectively. Oil will continue to be the largest contributor to NO_x, accounting for 45 % in 2030, followed by gas, trade, and "others", contributing with 17 %, 10 % and 10 %, respectively. Fishing, tourism, and mining will in combination account for the remaining 18 % of the overall NO_x emissions. Regarding SO_2 emissions, the oil sector will remain the predominant contributor, accounting for 61 % of the total emissions in 2030. Trade is expected to contribute 11 % by 2030, while the "others" sector will contribute with 7 %. Fishing, tourism, mining, and gas account for the remaining 21 % of the overall SO_2 emissions. Interestingly, the SO_2 emissions appear to stabilise in 2028, when the peak in oil production is reached.

5. Discussion

5.1. Significant contribution of atmospheric emissions from shipping in oil sector

The results from this study reveal a significant increase in both ship activity and associated emissions of NO_x and SO_2 from 2013 to 2023, with projections indicating a rise to 12,400 and 1000 tonnes for NO_x and SO_2 emissions, respectively, by 2030. Notably, emissions do not align proportionately with distance travelled across economic sectors, particularly evident in the oil and fishing sectors (Fig. 2). The oil sector is the dominant contributor to the overall emissions from shipping, which aligns with previous research by Peters et al. (2011). This sector's higher emissions intensity is attributed to factors such as larger ship sizes, higher power demand, and the use of relatively sulphur-rich fuels (DNV GL, 2019a; IMO, 2020; PAME, 2020b; Peters et al., 2011). Conversely, the fishing sector, characterised by smaller vessels and the use of MDO, exhibits significantly lower emissions, particularly for SO_2 (Winther et al., 2017). Unlike previous projections, our study highlights the distinct emission profiles from gas transportation, which due to the utilisation of LNG as a fuel leads to substantially reduced NO_x and SO_2 emissions (Pavlenko et al., 2020; Winther et al., 2017). The results from this study underscore the pressing need for the oil sector to intensify efforts in mitigating emissions, especially as Arctic oil projects continue to expand.

5.2. Uncertainties

5.2.1. Uncertainties in future oil and gas projects

With oil and gas activities being an important driver to increased ship activity along the NSR, the future forecast heavily depends on the future developments in these sectors. However, it is uncertain whether the future development of the various oil and gas projects in Arctic Norway and Russia will go as planned (Table 2). Following the Russian full-scale invasion of Ukraine, sanctions on Russian oil and gas projects, especially the halt in delivery of Western technology and components, it is likely planned progress of the various Russian Arctic LNG and oil projects is postponed several years (Gunnarsson and Lasserre, 2023). Furthermore, the sanctions may limit access to available ships for transporting produced oil and gas to the market, as western sanctions stall the production of new Arc7 oil and gas tankers, as well as replacing contracted shipping services delivered by Western companies (Gunnarsson and Lasserre, 2023). Ultimately, the planned production may stagnate in the short-term and result in a less dramatic increase as suggested by the forecast (Fig. 4).

5.2.2. Mining sector fleet

The regression model's poor performance in explaining emissions from bulk carriers and ore production (R2 = 0.21 and 0.31; see Fig. 3) suggests that mining-related products may be transported by other types of vessels. While raw materials from the Mary River Mine in the Canadian Arctic are predominantly transported by bulk carriers (Baffinland, n.d.; PAME, 2020a), NorNickel primarily ships its products with multi-purpose Arc7 container ships (Gunnarsson and Moe, 2021). These container ships are categorized as "General cargo ships" in the ASTD system and are attributed to the trade sector. Therefore, the moderate contribution from the mining sector depicted in Fig. 4 may be an underestimation of the true contribution. Further investigation into emissions from mining-related shipping and the ongoing expansion of mining activities in the region is suggested.

5.2.3. Uncertainties in gas tanker emission adjustments

This study adjusted emissions from gas tankers based on assumed fuel usage in the ASTD system. While the original emission calculations are conducted using a bottom-up methodology (PAME, 2023), the adjustment in emissions using LNG as a fuel was derived from LNG-equivalents calculated from monthly HFO usage. This approach introduces uncertainties as it overlooks important factors such as environmental conditions, engine loads, specific fuel consumption (SFC), and manoeuvring modes, which are considered in other bottom-up studies (IMO, 2020; Winther et al., 2017). Since the presence of gas tankers in the Arctic region is relatively new, a more detailed study on emissions from the Arctic gas sector is advised.

5.3. Future fuel mix

While this study does not consider the fuel mix of the economic sectors, the observed decrease and stabilisation of ship-associated SO_2 emissions in 2020 and onwards can be attributed to a decrease in the use of high-sulphur fuel oil due to the implementation of the IMO 2020 (IMO, n.d.). Similar changes in emissions can be expected as new regulations and policies, such as the European Union's Maritime Emission Trading Scheme (METS), Arctic HFO fuel ban and the IMO Revised GHG strategy (Bilgili and Ölcer, 2024; DNV, 2023; European Comission, 2024) are being put into force. While most of the new policies address decarbonisation, it is likely that they will facilitate an increased use of alternative fuels such as LNG, biofuels, hydrogen and ammonia, which can significantly reduce energy-based emissions such as NO_x and fuel-based emissions such as SO_2 (Bengtsson et al., 2012; Foretich et al., 2021; Gilbert et al., 2018; Huan et al., 2019). A recent survey suggest that the global fuel mix by 2030 will consist of 66 % fuel oils, 10 % LNG, 10 % biodiesel, 4 % bio-/E-methane, 3 % biomethanol, 3 % ammonia and 4 % others (Global Maritime Forum, Global Center for Maritime Decarbonisation, & Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023). If this global fuel mix is applied to the Arctic fleet, the potential for emission mitigation is high. However, high uncertainties regarding fuel pricing, demand, compatible infrastructure and technical readability may put the attainability of the 2030 fuel transition target in question (Foretich et al., 2021).

5.4. Potential mitigation measures

The observed emission profiles of gas tankers suggest that oil tankers could effectively reduce emissions of both NO_x and SO_2 by transitioning to using LNG as fuel. Depending on the engine system, NO_x can be reduced by 40–85 %, whereas SO_2 emissions can be completely removed (DNV GL, 2019b). While LNG effectively reduces air pollutants, it also has significant climate implication, due to significantly increased methane slip and exhaust emissions (Comer et al., 2024; Pavlenko et al., 2020). Therefore, incentivising oil tankers to increase the use of low- or sulphur-free fuels such as MDO or biodiesel to mitigate SO_2 emissions could be an effective measure (Deng et al., 2021). Furthermore, a fuel switch in combination with the use of exhaust gas treatments systems (EGTS) such as Selective Catalytic Reduction (SCR) or Exhaust Gas Bypass (EGB) can reduce NO_x emissions by 80–95 % (Deng et al., 2021; Kostova et al., 2023). As discussed above, the use of alternative fuels will heavily depend on availability and price, whereas SCR systems are space-demanding and have a high cost, raising doubts about achievability by 2030 (Deng et al., 2021; Foretich et al., 2021).

6. Conclusion

This study has highlighted significant increases in ship traffic and associated emissions along the NSR, closely linked to the rise in resource-driven activities. While the fishing and trade sectors accounted for substantial portions of the distance travelled, the oil sector has emerged as the primary contributor to emissions since 2017. Projections indicate a notable surge in emissions, with the oil sector expected to contribute almost half of the total NO_x emissions and more than half of the total SO_2 emissions by 2030. Developments in oil-related activities will be the main driver for increased shipping and associated emissions in the near future along the NSR.

Addressing emissions from the oil-related ships and closely monitoring future developments in regional oil activity are crucial steps to mitigate the continuous rise in emissions of air pollutants in the Arctic. While this study provides valuable insights into how ship-associated emissions are affected by economic activities, it's essential to acknowledge limitations such as the poorly performing model for the mining sector, geopolitical influence, and changes in fuel mix and operational efficiency. Future research should focus on assessing these factors, particularly changes in the fuel mix and exhaust gas cleaning systems, to provide comprehensive understanding of emission dynamics along the NSR.

CRediT authorship contribution statement

Nikolai Figenschau: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Jinmei Lu:** Writing – review & editing, Supervision, Conceptualization. **Bjørn-Morten Batalden:** Writing – review & editing, Supervision, Conceptualization. **Giuliana Panieri:** Supervision, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used OpenAI's ChatGPT 3.5 for checking grammar and increase readability. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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