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ORIGINAL PAPER

Effect of the low sulphur regulations of maritime fuels on ambient air quality: a case study in the Bosphorus strait

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Abstract

The maritime transportation sector poses a significant environmental risk due to its reliance on fossil fuels and its proximity to coastal areas. To address this issue, the International Maritime Organization, authorized by the IPCC, is responsible for reducing and preventing ship-borne emissions. The International Maritime Organization regularly updates emission prevention measures through annual MEPC meetings, particularly under the MARPOL 73/78 Convention, to adapt to changing conditions. In this study, we utilized a bottom-up approach to calculate the emissions of NO_X, SO_2, CO, and PM_{10} emitted by ships transiting through the Istanbul Bosphorus from 2014 to 2021. We employed the AERMOD air quality dispersion model to generate SO_2 spatial distribution maps, focusing on the year 2014 with the highest pollutant release. The obtained results were compared with measurements from air quality monitoring stations, allowing us to evaluate the contribution of maritime SO_2 emissions to overall Bosphorus pollution. Furthermore, we also examined the impact of low sulfur fuel usage after the sulphur was reduced from 3.5 to 0.5% by mass, in accordance with the regulations put into effect by IMO in 2020.

Keywords Maritime emissions · Desulphurization · Modelling · AERMOD

Introduction

The maritime transportation sector significantly impacts the environment due to its reliance on fossil fuels and proximity to coastal areas. Ship emissions, particularly those containing Sulphur oxides (SOx), contribute heavily to air pollution in coastal regions (Ekmekçioğlu et al. 2021a). The International Maritime Organization (IMO), authorized by the IPCC, plays a crucial role in regulating and preventing ship-borne emissions. The IMO establishes forward-looking, comparable, and classifiable high standards for both shipbuilding and ship operations, aiming to strengthen the protection of the marine environment and atmosphere. This focus on environmental sustainability in the maritime industry is commonly referred to as 'green maritime'. International regulations and sanctions are imposed on ships that pose environmental hazards, prompting numerous scholars to focus their academic research on these crucial issues.

According to Ekmekçioğlu et al. (2021a), emissions from ships arriving at Türkiye's four major ports were estimated using two bottom-up methods: ENTEC (ENTEC 2010) and Environmental Protection Agency (EPA) (EPA—Office of Transportation Air Quality 2020). The researchers developed emission estimation equations based on the ship gross tonnage (GRT) for the container ship type, specifically targeting the cruising, manoeuvring, and port operation modes. Ekmekçioğlu et al. (2021b) focused on estimating the emissions of various pollutants (NOx, NMVOC, PM, SOx, CO, and CO_2) released by a container ship during a 37-day voyage. Top-down and bottom-up (Trozzi 2013) methods were utilised to make the estimations and the two methods were compared. Additionally, Ekmekçioğlu et al. (2019) analyzed emissions from ships arriving at İzmir and Mersin ports of Türkiye. The calculations included ship recordings for a whole year along with actual port durations. Schwarzkopf

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et al. (2021) presented a modular Ship Emission Modeling System (MoSES) with scenario capabilities based on ship position data recorded by AIS. They used the bottom-up approach in the calculations. Yang et al. (2021) calculated the emissions from ships arriving at Tianjin port for 2018 by using the AIS-based bottom-up method. Simonsen et al. (2019) calculated CO_2, NO_x, and $PM_{2.5}$ emissions from 81 cruise ships operating in Norwegian waters in 2017 for cruise and port positions. A new model was used for the estimation of fuel consumption in the study, in which a fuel-based calculation method was used by using AIS data (Simonsen et al. 2018). Kılıç et al. (2020) analyzed the port emissions of ships arriving at the İskenderun Port of Türkiye in 2013 and compared the environmental performance of using port electricity. They proved that using shore electricity instead of diesel generators in ports provides environmental and economic benefits. Bilgili and Çelebi (2018) estimated the emissions from 9 bulk carriers using 3 years of data from 3 different methods, available in the literature. Nunes et al. (2017) calculated emissions from ships arriving at 4 Portuguese ports (Leixoes, Setúbal, Sines and Viana do Castelo) between 2013 and 2014. They used the activity-based calculation method from the Emission Inventory Guidebook for Air Pollutants (EMEP/EEA) 2016 guidebook (Trozzi and De Lauretis 2016). They used main engine powers from EMEP/EPA as a function of GT, and auxiliary engine powers as a function of main engine power from Trozzi's work (Trozzi 2010). Gutierrez and Grados (2021) proposed a model called SENEM (Ship's Energy Efficiency Model) for ship-sourced emission calculation. The model presented in the study was tested and validated on four RO-Pax vessels operating in the Strait of Gibraltar. Mamoudou et al. (Mamoudou et al. 2018) collected $PM_{2.5}$ samples at Yangshan Port in 2016 and estimated the effects of ship emissions on ambient air. Murena et al. (2018) utilized CALPUFF to determine ground-level air pollutants, which originated from port emissions in Naples, Italy. Toscano et al. (2021) evaluated emissions from cruise ships arriving at the port of Naples using physical and numerical methods. The effects of emissions from the port position of three cruise ships were investigated using wind tunnel and computational fluid dynamics (CFD) models. Ekmekçioğlu et al. (2020) calculated ship-borne emissions arriving at Ambarlı and Kocaeli ports for a one year data using the ENTEC method. The study utilized atmospheric dispersion modelling (AERMOD) to assess the impact of emissions, calculating PM_{10}, NO_x and SO_2 concentrations. Kuzu et al. (2021) utilised AERMOD in order to predict the air pollutants from port operations in Bandırma port. As it is listed from the literature survey list, there are numerous studies aiming to calculate maritime emissions. They rely on different approaches. Less is focused on both emission calculation and their modelling to calculate the ground-level concentration over land.

Despite existing research on calculating maritime emissions (Ekmekçioğlu et al. 2019, 2021a, b; Kılıç et al. 2020; Bilgili and Çelebi 2018; Nunes et al. 2017; Mamoudou et al. 2018), a gap exists in studies that combine emission calculations with air quality modeling to assess the impact on specific locations (Murena et al. 2018; Toscano et al. 2021; Ekmekçioğlu et al. 2020; Kuzu et al. 2021). IMO reduced Sulphur content of marine fuels to 0.5% outside SECA area as of 2020 (Bilgili 2021). This study aims to calculate ship emissions in the Bosphorus Strait from 2014 to 2021 and conduct air quality modelling for the year 2014 and 2021 to assess the impact of the 2020 sulphur regulation on SO_2 concentrations in a populous city.

Materials and methods

Study area

The Bosphorus Strait, depicted in Fig. 1, is a roughly 30-km-long waterway separating Europe and Asia. It connects the Black Sea to the Sea of Marmara and bisects Istanbul into the European and Asian sides. For countries bordering the Black Sea, the Bosphorus serves as a crucial trade route, providing access to the Mediterranean Sea via the Marmara Sea (Ünlü et al. 2018).

Istanbul, Türkiye's most populous city, is also the country's economic and trade center. However, ship traffic through the Bosphorus Strait poses environmental threats. Maritime transport pollution can be categorized as air and marine pollution (Ünlü et al. 2018). Emissions from the main and auxiliary engines of these ships pollute the air, negatively impacting the Bosphorus, the Istanbul coastline, and the health of local organisms (Kutluk 2018).

Emission calculation

Scientific literature offers various methods for calculating ship emissions. Two primary approaches are top-down and bottom-up. The top-down approach relies on ship fuel consumption data, while the bottom-up approach uses the ship's installed engine power and activity data for calculations.

In this study, the calculations were made in line with the "Methodologies For Estimating Port-Related and Goods Movement Mobile Source Emission Inventories, 2020" publication published by EPA using the bottom-up approach (EPA—Office of Transportation Air Quality 2022). The emissions are calculated according to Eq. 1.

$$E = P \times A \times EF \times LF \quad (1)$$



Fig. 1 Location of the study area

where E is the emissions per ship (in g), P is the engine power (in kW), A is the engine running hour (in h), EF is the emission factor (in g/kWh), LF is the load factor. Load factor expresses the ratio of actual energy consumption. It is expressed as percentage.

The main engine load factor was calculated as the ratio of the Bosphorus passage speed of the ships and their transit time. For the auxiliary engine load factor, it is assumed that 2 auxiliary engines are active and working at 50% load while the ships are passing through the strait. The data obtained from the Directorate General of Coastal Safety were used in the calculations. The data included strait passage dates, speeds, and times, IMO numbers and basic dimensions of the ships. Auxiliary engine powers, main engine powers, and speed data were used from marine traffic (Marine Traffic—Global Ship Tracking Intellligence 2023) and Information Handling Services (IHS) marine database (IHS Maritime database 2022). All the engine powers used in the study are the real engine powers of the ships. It is also assumed that the main engine uses heavy fuel oil (HFO) before 2020 and low sulfur fuel oil (VLSFO) after 2020 during the passage through the Bosphorus. Auxiliary engines are assumed to be medium speed diesel (MSD) and use marine diesel oil (MDO).

In the calculations, the construction year, strait passage time, speed, type of fuel used, main engine power, number of revolutions per minute (rpm), and auxiliary engine power data of the ships were used. We gathered the data of approximately 22,000 different ships passing through the Bosphorus between 2014 and 2021 and calculated the amount of NO_x, SO_2, PM_{10} and CO pollutants emitted by 331,027 ships in total using real technical data of all.

Dispersion model

In this study, we used US EPA's recommended stead state Gaussian plume model AERMOD. The emissions calculated in the previous section was used as the mass input of the pollutants. The emissions were divided to 50 m × 50 m area emissions along the fleet route of the ships. Emissions were area type and the path of the ships are shown in Fig. 2.

The second input to the model was the surface topography. It was gathered by 250 m × 250 m grids. USGS –DEM 7.5 min data was used to prepare the surface map (Kuzu 2018). The grid intersection of the surface map was

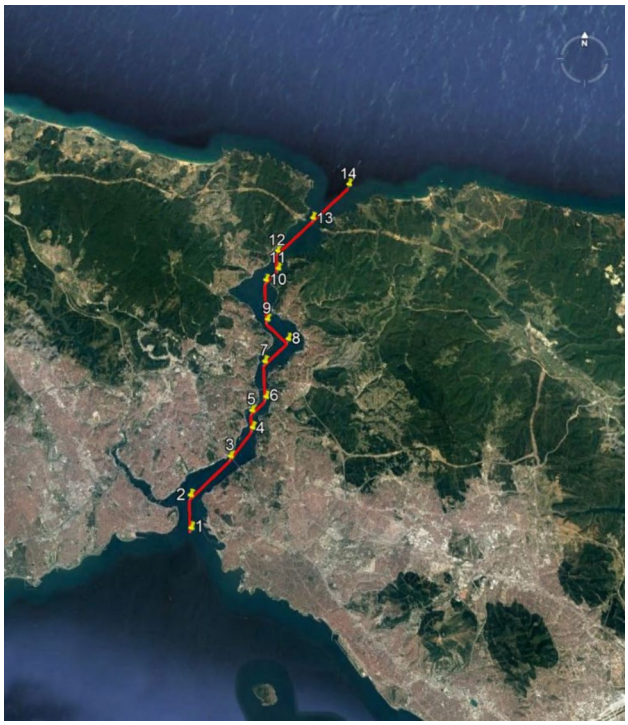


Fig. 2 Route of the vessels in the Bosphorus Strait

the ground-level receptor points of the model where the concentrations of the pollutants were estimated.

The modelled concentrations were compared against measurement data for one discrete location apart from the prepared grid. An air quality measurement (AQM) station is located at 672,940 and 4,547,740 UTM coordinates in Kandilli. Its location is available on Fig. 5. The measurement data covered entire 2014. On the other hand, the measurement data was available only for the periods between 1 January and 1 April of 2021.

The third data was the meteorological variables. The data were gathered from two different meteorological stations. Surface meteorological data including wind speed and direction, atmospheric temperature, and cloud cover was taken from the station located 10 km southwest of the 1st point in Fig. 2 whereas radiosonde data was gathered from the station located 10 km southeast of the same point. All surface data was hourly, and the sounding data was twice a day. Suitable meteorology files for AERMOD were prepared by AERMET pre-processor. The wind rose plot is given in Fig. 3.

The prevailing wind direction in 2014 was NNE with nearly one-third of the whole distribution. NE and N was the directions with the second and the third highest blow counts. The counter flows were from SE, SSE, and S. The sum of the southerly wind ratios was 9.3%. The highest wind speed class was 0.5–2.1 m/s with 52%. The wind rose plot of 2021 was prepared by only using the meteorological variables between 1 January and 1 April, which is the boundary for the

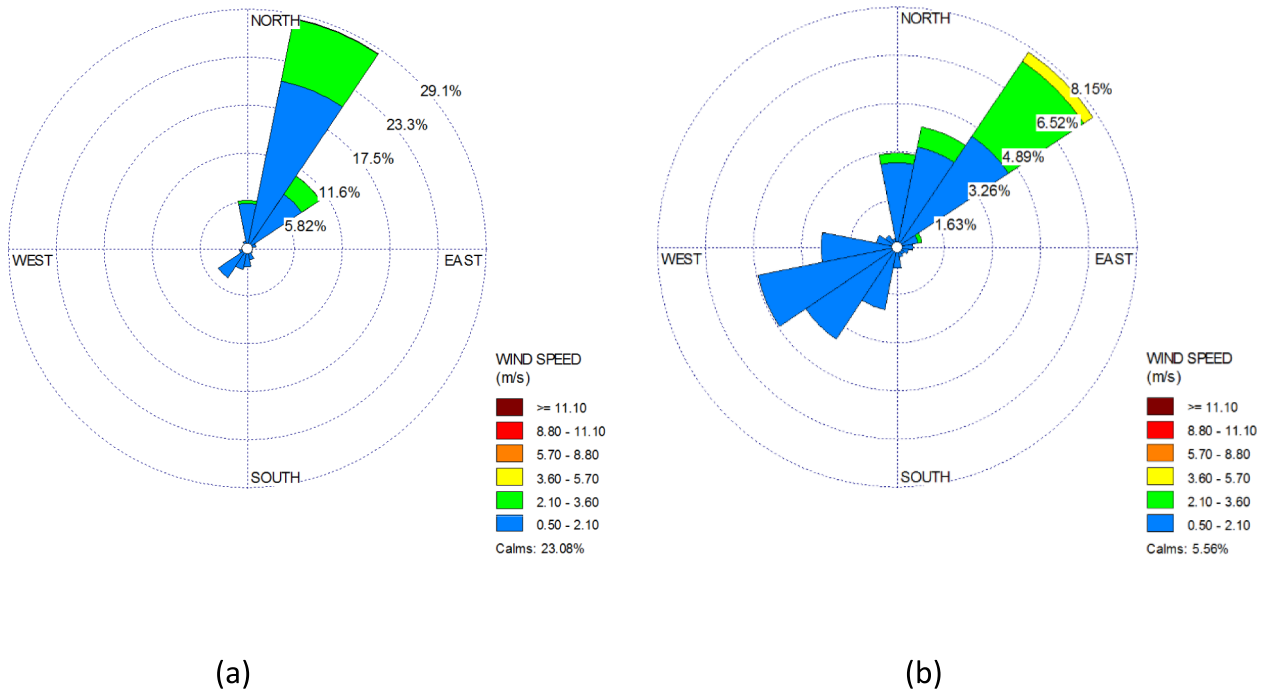


Fig. 3 Wind rose plots of the meteorological data that are used for the model inputs for the year of **a** 2014, **b** 2021

model input. The prevailing wind direction was NE. WSW and NNE had the highest second and the third highest blow counts. Although the prevailing wind direction in Istanbul is NE, number of winds blowing from SW direction increases in the spring season (Kuzu et al. 2013; Kuzu 2016). The vast majority of the wind speed was between 0.5 and 2.1 m/s.

Results and discussion

Pollutant emissions

Table 1 presents the distribution of ship types that traversed the Bosphorus during the study period, categorized by year. The 'Other' category encompasses ship types like motor yachts, fuel barges, fishing vessels, animal carriers, research vessels, and tugboats. Military vessels were excluded due to limitations in accessing their technical specifications.

Bulk carriers exhibited a gradual increase, rising from 7691 in 2014 to a peak of 9235 in 2021, with some fluctuations in between years. Container ship traffic experienced a slight initial decline from 2976 in 2014 to 2623 in 2015, followed by a fluctuating pattern with a modest rise to 2769 in 2021. General cargo ships showed a steady decrease, dropping from 23,558 in 2014 to 16,472 in 2021, with a significant decline between 2016 and 2017. The "Other" category displayed no clear trend, with numbers fluctuating throughout the study period. Tanker traffic remained relatively stable, ranging from 8260 in 2021 to 8730 in 2014 with minor variations. Passenger ships experienced a dramatic decline, plummeting from 651 in 2014 to just 42 in 2021. The COVID-19 pandemic in 2020 likely contributed significantly to this decrease. Finally, Ro-Ro ship traffic exhibited some fluctuations, starting at 497 in 2014, reaching a peak of 524 in 2020, and then slightly decreasing to 522 in 2021.

Figure 4 shows the variation of the amount of NO_x, SO_2, PM_{10}, and CO over the years.

2014 stands out as the year with the highest emissions for all pollutants. PM_{10} and SO_2 emissions remained within a small fluctuation between 385 and 413 tons/year for PM_{10} and 2957 and 3184 tons/year for SO_2. After the mandatory rules in 2020, the amount of these pollutants decreased. NO_x emissions were in a decreasing trend during the calculation period and CO emissions exhibited a fluctuating pattern. But the fluctuation was between 367 and 393 tons/year, which is approximately 7% according to the extreme values. NO_x has the highest emissions in terms of mass compared to other calculated pollutants. Nitrogen oxides are released due to the oxidation of atmospheric nitrogen, which is used in the combustion process of engines. We can infer that the reduction of NOx emissions is related to lower fuel consumption during the passage of Bosphorus strait. The reduction might have happen due to the decrease of total fuel consumption of the vessels. Additionally, PM_{10} emissions were halved and SO_2 emissions were reduced down to approximately one-fifth of their previous levels.

Ground-level concentrations

SO_2 concentrations were chosen due to their distinction from urban related emissions. SO_2 is expected to be more related to maritime emissions when compared to other gaseous or particle emissions. The widespread fuel for residential heating in Istanbul is natural gas (Kuzu 2019). Therefore, urban heating and traffic is not the source of SO_2 emissions. Annual plots of SO_2 concentrations are shown in Fig. 5 for the years of 2014 and 2021. The data for 2014 included the entire year. However, the data was missing in 2021. Hence, model was compared between 1 January and 1 April to be consistent with the measurement data.

The air quality measurement (AQM) station in Kandilli was selected as a comparison point for the model results. Location of the AQM is shown by black circle in the figures. The maximum concentration was 21 μg/m^3 in 2014. The modelled annual average SO_2 concentration at the AQM was 6.65 μg/m^3. The maximum concentration was 5.4 μg/m^3 in 2021 and the annual average was 1.48 μg/m^3. The measured annual average concentration was 9.73 and 6.3 μg/m^3 for 2014 and 2021, respectively. The modelled values only represent the contribution from shipping

Table 1 Ship types and quantities by year

Type/Year	2014	2015	2016	2017	2018	2019	2020	2021
Bulk Carrier	7691	7678	8032	8570	8908	9220	9045	9235
Container Ship	2976	2623	2769	2632	2568	2706	2700	2769
General Cargo	23,558	22,297	21,021	20,922	18,932	18,364	16,478	16,472
Other	865	1108	1002	978	1129	967	926	1004
Passenger Ship	651	466	300	337	367	250	51	42
Ro-Ro	497	369	343	437	328	414	524	522
Tanker	8730	8572	8668	8813	8576	8935	8430	8260
Total	44,968	43,113	42,135	42,689	40,808	40,856	38,154	38,304

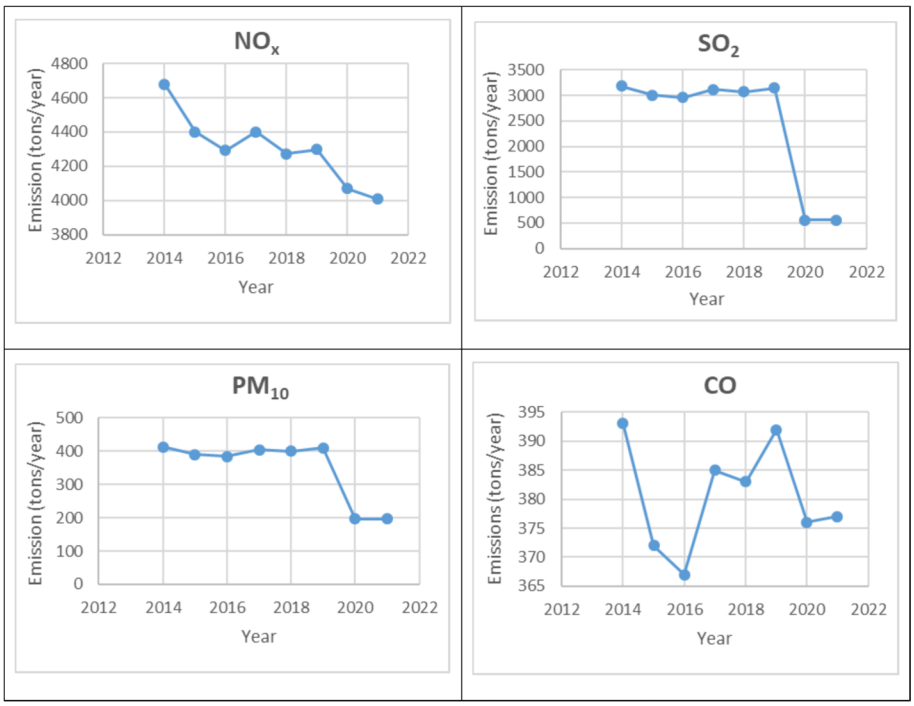
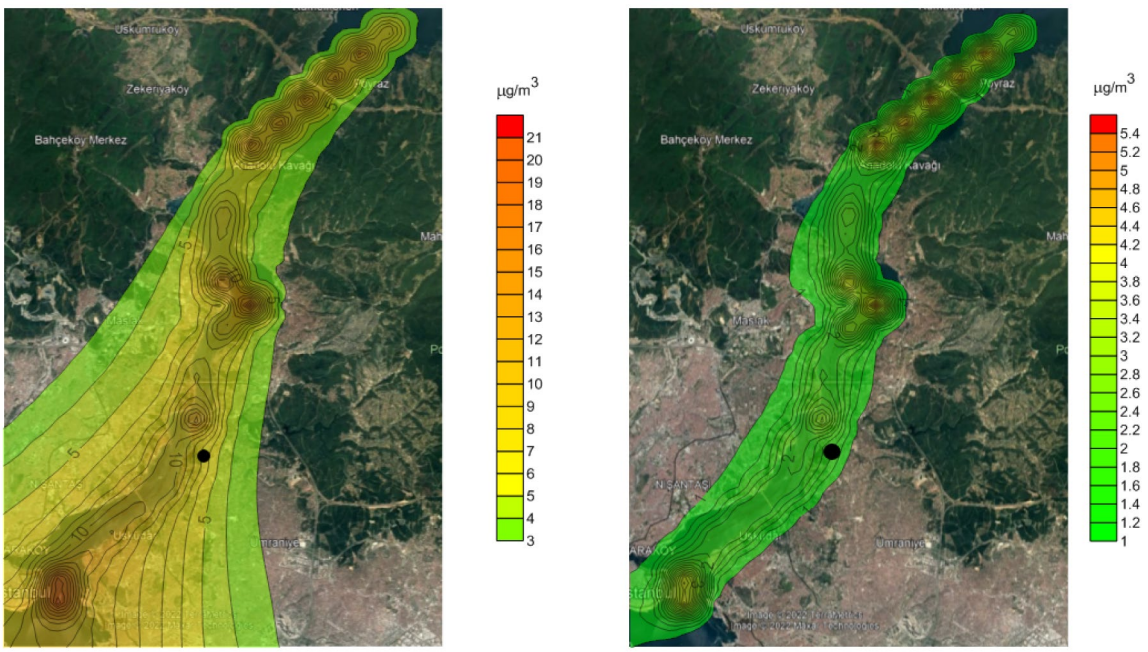


Fig. 4 Emissions of the pollutants between 2014 and 2021



(a) (b)

Fig. 5 **a** Annual mean SO_2 concentration of 2014, **b** Annual mean SO_2 concentration of 2021

emissions. However, the measured concentrations are the sum of shipping emissions and any other emissions that are already present in the atmosphere.

The shipping emissions made up more than half of the annual average SO_2 concentrations that is measured in the atmosphere in 2014. This value is consistent with the

expectations when the emission profile of the region is observed. SO_2 contribution primarily originates from the fuels which include sulphur in its composition. The region is surrounded by residential areas and the vast majority of the heating system is powered by natural gas. Only limited number of individual coal powered heating may be available. In 2021, both the measured and modelled concentrations decreased by the change of sulphur content in the maritime fuels. This result is important to show the impact of SO_2 emissions from maritime activities along Bosphorus.

Some studies have shown that SO_2 emissions from the combustion of high-sulphur fuels contribute to the formation of acid rain, smog, and fine particulate matter (Akkoyunlu and Erturk 2002). By reducing SO_2 emissions, the overall pollution load in the surrounding areas is decreased, leading to improved air quality. The health benefits of reducing SO_2 concentrations have also been well-documented. SO_2 is a known respiratory irritant that can cause or exacerbate respiratory conditions such as asthma, bronchitis, and other respiratory diseases (Manisalidis et al. 2020; Bronte-Moreno et al. 2023). SO_2 is also documented to lead low-birthweight (Lindgren 2021). Decreasing SO_2 concentrations can lead to reduced respiratory symptoms, improved lung function, and lower rates of respiratory illnesses, particularly in vulnerable populations such as infants, the elderly, and individuals with pre-existing respiratory conditions.

Conclusion

Given Istanbul's dense population and diverse industries, the emission concerns associated with Bosphorus crossings are significant. Therefore, determining and examining the environmental effects of shipping activities in this region in detail is of great importance for the people living in this region and for the protection of the ecosystem in the Marmara Sea, which is home to many aquatic life. Such studies can contribute significantly to establishing the Marmara Sea Basin as an Emission Control Area (ECA).

Understanding the scale of the emission risk is essential for implementing effective reductions. This necessitates the creation of a comprehensive emission inventory. Beyond traditional calculation methods, employing modern approaches that provide fast, user-friendly results with future projections would be highly beneficial. Such methods can enable cost-effective and efficient emission calculations.

This study also indicates that the reduction of the sulphur content within the maritime fuel makes a significant reduction in SO_2 concentrations measured in the city. In Kandilli station the estimated SO_2 concentration was 6.65 $\mu g/m^3$. Following the reduction of marine fuel sulfur content to 0.5%, the estimated SO_2 concentration by the air quality model was reduced to 1.48 $\mu g/m^3$ in Kandilli station. This finding also supports that decision makers should consider these findings in planning the future air quality projections in a city.

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Author contributions All authors contributed to the writing of this study. Araks Ekmekçioğlu was responsible for responsible for the designing, literature search and data analysis of the manuscript. Uğur Buğra Çelebi made the supervision of the study. Kaan Ünlügençoğlu gathered relevant information for the study. S. Levent Kuzu applied air quality model and reviewed the paper.

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Availability of data and materials Data used in the study is available upon request from corresponding author.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Ethics approval and consent to participate No ethical approval is required for this study. Informed consent was obtained from all individual participants included in the study.

Consent for publication Confirmation for publication of this article has been received from all participants.

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References

Akkoyunlu A, Erturk F (2002) Evaluation of air pollution trends in Istanbul. Int J Environ Pollut 18(4):388. https://doi.org/10.1504/IJEP.2002.003735

Bilgili L (2021) Life cycle comparison of marine fuels for IMO 2020 Sulphur Cap. Sci Total Environ 774:145719. https://doi.org/10.1016/j.scitotenv.2021.145719

Bilgili L, Celebi UB (2018) Developing a new green ship approach for flue gas emission estimation of bulk carriers. Meas J Int Meas Confed 120:121–127. https://doi.org/10.1016/j.measurement.2018.02.002

Bronte-Moreno O et al (2023) Impact of air pollution on asthma: a scoping review. Open Respir Arch 5(2):100229. https://doi.org/10.1016/j.opresp.2022.100229

Ekmekçioğlu A et al (2020) Assessment of shipping emission factors through monitoring and modelling studies. Sci Total Environ 743:140742. https://doi.org/10.1016/j.scitotenv.2020.140742

Ekmekçioğlu A, Ünlügençoğlu K, Çelebi UB (2019) Ship Emission Estimation For Izmir and Mersin International Ports: Turkey. J Therm Eng 5(6):184–195. https://doi.org/10.18186/thermal.654319

Ekmekçioğlu A, Ünlügençoğlu K, Çelebi UB (2021a) Container ship emission estimation model for the concept of green port in Turkey. Proc Inst Mech Eng Part M J Eng Maritime Environ. https://doi.org/10.1177/14750902211024453

Ekmekçioğlu A, Ünlügençoğlu K, Çelebi UB (2021b) Estimation of shipping emissions based on real-time data with different methods: A case study of an oceangoing container ship. Environ Dev Sustain. https://doi.org/10.1007/s10668-021-01605-8

ENTEC (2010) 'UK ship emissions inventory. Final report'. Available at: https://uk-air.defra.gov.uk/assets/documents/reports/cat15/1012131459_21897_Final_Report_291110.pdf

EPA - Office of Transportation Air Quality (2020) 'Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emission Inventories', (February), p. 202

EPA - Office of Transportation Air Quality (2022) Port Emissions Inventory Guidance: Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emissions (EPA-420-B-22–011, April 2022)

IHS Maritime database (2022)

Kılıç A et al (2020) Assessment of ship emissions through cold ıroning method for Iskenderun Port of Turkey. Environ Res Technol Environ Res Technol. https://doi.org/10.35208/ert.794595

Kutluk E (2018) İstanbul Boğazı'ndan Geçen Gemilerin Oluşturduğu Trafik Yükünün Çevresel Etkileri: Ro-Ro Gemileri Özelinde Bir İnceleme. Siyasal Bilimler Dergisi 6(1):285–310. https://doi.org/10.14782/marusbd.412651

Kuzu SL et al (2013) A detailed investigation of ambient aerosol composition and size distribution in an urban atmosphere. Environ Sci Pollut Res 20(4):2556–2568. https://doi.org/10.1007/s11356-012-1149-9

Kuzu SL (2016) Compositional Variation of PCBs, PAHs, and OCPs at Gas Phase and Size Segregated Particle Phase during Dust Incursion from the Saharan Desert in the Northwestern Anatolian Peninsula. Adv Meteorol 2016:1–12. https://doi.org/10.1155/2016/7153286

Kuzu SL (2018) Estimation and dispersion modeling of landing and take-off (LTO) cycle emissions from Atatürk International Airport. Air Qual Atmosp Health 11(2):153–161. https://doi.org/10.1007/s11869-017-0525-5

Kuzu SL (2019) Source identification of combustion-related air pollution during an episode and afterwards in winter-time in Istanbul. Environ Sci Pollut Res 26(17):16815–16824. https://doi.org/10.1007/s11356-016-7831-6

Kuzu SL, Bilgili L, Kiliç A (2021) Estimation and dispersion analysis of shipping emissions in Bandirma Port, Turkey. Environ Dev Sustain 23(7):10288–10308. https://doi.org/10.1007/s10668-020-01057-6

Lindgren S (2021) The coast is clear: Shipping emission standards, air quality and infant health. Transp Res Part D: Transp Environ 100:103067. https://doi.org/10.1016/j.trd.2021.103067

Mamoudou I et al (2018) Characteristics of PM2.5 from ship emissions and their impacts on the ambient air: a case study in Yangshan Harbor, Shanghai. Sci Total Environ 640–641:207–216. https://doi.org/10.1016/j.scitotenv.2018.05.261

Manisalidis I et al (2020) Environmental and health ımpacts of air pollution: a review. Front Public Health. https://doi.org/10.3389/fpubh.2020.00014

MarineTraffic – Global Ship Tracking Intelligence (2023)

Moreno-Gutiérrez J, Durán-Grados V (2021) Calculating ships' real emissions of pollutants and greenhouse gases: towards zero uncertainties. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2020.141471

Murena F, Prati MV, Quaranta F (2018) Assessment of the impact of ship emissions on the air quality in naples. Maritime Transp Harvesting Sea Resources 2:1037–1041

Nunes RAO et al (2017) Assessment of shipping emissions on four ports of Portugal. Environ Pollut 231:1370–1379. https://doi.org/10.1016/j.envpol.2017.08.112

Schwarzkopf DA et al (2021) A ship emission modeling system with scenario capabilities. Atmosp Environ X 12:100132. https://doi.org/10.1016/j.aeaoa.2021.100132

Simonsen M, Gössling S, Walnum HJ (2019) Cruise ship emissions in Norwegian waters: a geographical analysis. J Transp Geogr 78:87–97. https://doi.org/10.1016/j.jtrangeo.2019.05.014

Simonsen M, Walnum HJ, Gössling S (2018) Model for estimation of fuel consumption of cruise ships. Energies. https://doi.org/10.3390/en11051059

Toscano D et al (2021) Assessment of the impact of gaseous ship emissions in ports using physical and numerical models: the case of Naples. Build Environ. https://doi.org/10.1016/j.buildenv.2021.107812

Trozzi C (2010) Emission estimate methodology for maritime navigation. Co-leader of the Combustion & Industry Expert Panel

Trozzi C (2013) EMEP/EEA Emission Inventory Guidebook

Trozzi C, De Lauretis R (2016) EMEP/EEA air pollutant emission inventory guidebook: technical guidance to prepare national emission inventories. Eur Environ Agency 21:124. https://doi.org/10.2800/92722

Ünlü S, Oztürk B, Alpar B (2018) Oil Spill along the Turkish Straits Sea Area ; Accidents , Environmental Pollution , Socio-Economic Impacts and Protection, Turkish Marine Research Foundation (Tudav)

Yang L et al (2021) An AIS-based emission inventory and the impact on air quality in Tianjin port based on localized emission factors. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2021.146869