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EVALUATION OF NO_x EMISSION AND DISPERSION FROM MARINE SHIPS IN KLAIPEDA SEA PORT

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Abstract. The aim of the presented research was to assess the NO_x emission and dispersion from marine ships in Klaipeda sea port. NO_x emissions from ships operating in Klaipeda sea port were calculated using the Lloyd's Register detailed ship movement method, after collecting the information about technical characteristics of each marine ship visiting the port and the time spent staying in the port. After calculating the emission, the modelling using AERMOD software was completed and the dispersion of pollutants over different seasons of the year was determined. When performing the evaluation of NO_x emissions it was estimated, that most of these pollutants enter the atmosphere from stationary vessels moored to quays with active auxiliary motors; this accounts even for up to 72% of the total NO_x emission from marine ships in Klaipeda port. It was calculated that a total of 945.6 tons of NO_x compounds enter the air basin from ships which operate in Klaipeda port. It was determined that the seasonality and meteorological conditions are a significant factor affecting the dispersion of pollutants. During winter time, a higher dispersion of pollutants is typically found at the source of contamination, and in the summer pollutants are decomposed more quickly and their concentrations as formed above the port are 30% lower**,** however, 40–50% higher concentrations are formed over the Klaipeda city residential districts.

Keywords: Klaipeda port, atmospheric pollution, ships, nitrogen oxides.

Introduction

Concerns regarding the air quality in the port cities due to the pollutants emitted by ships are increasing all over the world; increasingly more attention is paid to evaluation and control of air pollution caused by ships. The impact on the city air basin made by growing number of ships, entering the port is assessed. Ways to reduce the negative environmental impact of sea navigation were searched. It is searched for ways to reduce the negative environmental impact of sea navigation (Corbett *et al.* 2007, 1999; Cooper 2003; Wang *et al.* 2007; Georgakaki *et al.* 2005; Saxea, Larsena 2004).

Growth in demand for transport services is inseparable from the country's overall economic growth. When the gross domestic product of the country grows by 2.5%, the demand for transport services increases by 2.7%. The official EU rules state, that the policy of the transport development must be an integral part of environmental policy. Transportation means in Lithuania emit approximately 500 thousand tons of pollutants each year (Baltrėnas *et al.* 2004). In port cities the economic activities and the associated atmospheric pollution is mostly concentrated in the coastal areas. Due to the growing global trade the flow of goods by maritime transport is also increasing. The diesel combustion process results in the highest atmospheric pollution; particulate matter and nitrogen oxides are one of the main components of pollution. The road transport is the main source of nitrogen oxides (NO_x), where about a half of amount of the nitrogen oxides is emitted in the Europe. Therefore, the highest concentrations of NO and NO_2 are formed in cities where the traffic is the most intense. Other important sources of pollution are: thermal power plants, industrial processes and shipping (Bailey, Solomon 2004; Isakson *et al.* 2001; Lonati *et al.* 2010; Luke *et al.* 2010; Schreier *et al.* 2006). In ships, the energy producing machinery that burns fuel oil is important regular source of air pollution emissions; it includes propulsion and auxiliary engines and steam boilers. The composition

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of fuel combustion products emitted by them is well-researched and can be readily evaluated according to chemical composition of the fuel, air and fuel ratio in the cylinder and combustion conditions (Smailys *et al.* 2003).

Various atmospheric pollution components exist in gases that are emitted by ships when combusting fuel. According to Eyring *et al.* (2009), the combustion of 1 kilogram of diesel fuel results in 3170 g of CO_2, 77 g of NO_x, 40 g of SO_2, 7.4 g of CO and 5.5 g of PM emitted into the atmosphere. Thus, the largest emissions into the atmosphere from ships include carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulfur dioxide (SO_2). Due to the large emissions of these pollutants into the air basin, the environmental requirements are being elevated. This fact is receiving increasing attention during design of new vessels and chemical composition of fuel used in ships.

The age of ships visiting the port plays an important role in the emissions of NO_x, since engines are more sophisticated in newly built ships, which leads to significantly lower emissions. Accomplished studies have shown that the new ship engines manufactured since 2005, meet the requirements of the Technical Code for NO_x emissions better by 17% than the older ones. However, the engine life time is approximately 25 years, and the fleet composition typically remains stable for a long time, so it was estimated that over the period of 5 years the fleet is supplemented with only 4% of new vessels (Trozzi *et al.* 1995).

The amount of nitrogen and sulphur oxides (NO_x and SO_x), entering the atmosphere from ships, is increasing (Deniz, Durmusoglu 2008). It is forecasted, that by 2020 the emissions of NO_x will increase by two-thirds, and SO_x emissions – nearly twice (Eyring *et al.* 2009). Meanwhile, the emission limitations are especially tightened during implementation of international law regulations, such as MARPOL 73/78 convention Annex VI, regulating the prevention of air pollution from ships. NO_x emissions are limited by the special conditions provided in MARPOL 73/78 Annex VI, which depend on the ship engine speed. UN sets new standards for ship engines in order to reduce the amount of NO_x emitted into atmosphere. NO_x emission limits should be reduced by 20% per kWh for marine engines manufactured after 2011, i.e. from 7.7 to 14.4 g/kWh, depending on engine speed. And the NO_x emissions should be decreased by as much as 80% (from 2.0 to 3.4 g/kWh, depending on the ship engine speed) for ships built after the year 2016 (McCarthy 2009).

The Baltic Sea is an area extensively used for short sea shipping. At one time there are more than 2000 different ships sailing in the Baltic Sea. Methods for calculating emissions from ships are based on the number of vessels, distance travelled, power of ship engines and (or) fuel consumption (Endresen *et al.* 2003; Dalsoren *et al.* 2009; Miola, Ciuffo 2010; Cooper 2003). In some studies the emission calculations are performed based on the amount of fuel purchased in the country. However, when using this method, it is difficult to assess the amount of emissions within a defined territory, let alone to determine the contribution of ship pollutants to overall air basin in the port and port area.

Due to pollutants emitted into atmosphere, the urban air quality deteriorates, and acidity of soil and surface water increases, eutrophication takes place; it also contributes to the formation of the greenhouse effect and formation of ground level ozone. This has a negative effect firstly on human health, agricultural productivity, biodiversity and condition of forests (Oke 2004). Due to the air contamination, the number of people with asthma and other respiratory diseases and cardiovascular conditions increases; lung cancer morbidity rate and early mortality is influenced. It is therefore necessary to take measures to reduce this pollution (Bailey, Solomon 2004; Krozer *et al.* 2003).

One of the most important features of port city of Klaipeda is the fact that the city is narrow, on average not wider than 2.5–3 km, and is 11–12 km long, extending from north to south along the port; the nearest residential areas of the city are located not more than 250–300 meters from port quays. When dominant west winds blow, the entire city is trapped inside the dispersion trail of port air pollutants, which has a significant impact on the formation of sanitary condition of city air basin (Smailys *et al.* 2003). The influence of maritime transport is stronger in the cities which are located near lagoons than in other coastal areas, thus the air pollution monitoring and evaluation of contaminants formed via the main transportation channels becomes necessary (Premuda *et al.* 2011). The aim of these studies is to assess the NO_x emissions from marine ships and dispersion of pollutants in Klaipeda port, on the basis of analysis of arriving ships.

1. Research method

In order to calculate the emissions from ships operating in Klaipeda port the Lloyd's Register detailed ship movement method was selected, which is typically recommended when the detailed movement data of the vessels and their technical information is known. The calculations of NO_x emissions were performed considering that the ships use diesel, because black oil in the port area is forbidden. When performing the investigation, the data collected in 2009 about the ships which visited the Klaipeda port was used. Since the fleet composition varies insignificantly, and the age of ships does not exceed 24 years, this data may retain its representative character for a long time.

When calculating NO_x emissions from ships stationed at the quays and ships sailing inside the port, and

Table 1. Subdivision of Klaipeda port area

Part of port	Companies	Quays
I	SC "Klaipėdos Jūrų krovinių kompanija" KLASCO (northern part); SC "Klaipėdos nafta"; SC "Krovinių terminalas"	1–7
II	SC "Klaipėdos Jūrų krovinių kompanija" KLASCO (southern part); SC "Klaipėdos laivų remontas"; SC "Laivitė"; SC "Vakarų Baltijos laivų statykla"	8–64
III	Joint-stock stevedoring company "Klaipėdos Smeltė" (northern part); UAB "Klaipėdos keleivių ir krovinių terminalas"; SC Klaipėdos jūrų krovinių kompanija "Bega"	65–88
IV	SC "Senoji Baltija"; Jūrų keltų terminalas; Karinės jūrų pajėgos; Joint-stock stevedoring company "Klaipėdos Smeltė" (southern part); Mažųjų žvejybos laivų prieplauka; SC "Klaipėdos hidrotechnika"	89–126; 146–151; 121A–123A
V	SC "Vakarų laivų gamykla"; SC "Klaipėdos konteinerių terminalas"; SC "Malkų įlankos terminalas"	127–144; 131A–138A

also when evaluating the pollution dispersion, the Klaipeda port area was subdivided into 5 equal sections, each 2,4 km long. In this way it was attempted to ensure the precision of the research results. Table 1 shows what companies are located here and which quays are included into particular sections of the port.

In order to assess the total emission of NO_x, the ship sailing and stationary time (h) while staying in the port has to be matched against the emission rates (kg/h). The emission was evaluated separately for all five sections of the port. Ship sailing distance is considered to be equal to the distance from the port gates to the respective area of the port. In Klaipeda port aquatory the ship movement speed is limited to 6 knots. Consequently, after assessing the permissible ship speed inside the port and sailing distances, durations of sailing of each ship to the respective quay were estimated. Each ship stationary time was calculated in accordance to the data regarding arrival and departure time of ships (accuracy in minutes), provided by Klaipeda port direction.

Data on the main and auxiliary ship engine power ratings were collected from the database of Lloyd's Register, according to the IMO (International Maritime Organization) number of each ship, i.e. the ship identification number issued by International Maritime Organization. Emission rates are calculated separately for main and auxiliary engines.

During 2009, a total of 7529 vessels visited the Klaipeda port. Only sea ships were analysed, since they contain more powerful engines compared to the transport of internal waters, and they emit the largest quantities of pollutants. In total, the data about 1890 marine ships which visited the Klaipeda port during 2009 was collected. They entered the port 6837 times and their total stationary time while moored with active auxiliary engines accounted for 14668 days.

The AERMOD model was selected to evaluate the dispersion of NO_x pollutants in Klaipeda port. ISC-AERMOD View is a complete and powerful Windows air dispersion modelling system which seamlessly incorporates three models into one interface: ISCST3, AERMOD and ISC-PRIME. AERMOD is the next generation air dispersion model designed for short-range (up to 50 kilometers) dispersion of air pollutant emissions from stationary industrial sources. AERMOD is a steady-state plume model. The basis of the model is the straight-line, steady-state Gaussian plume equation (Petraitis 2010; Kowalski, Tarelko 2009).

NO_x emissions from marine ships operating in Klaipeda port were calculated using detailed ship movement method. Emissions from sailing and stationary ships were calculated separately for five sections of the port, therefore, when evaluating the pollution dispersion, each area of the port was considered as a separate area source of pollution. In order to assess the impact of seasonality on pollution dispersion, the modelling was carried out for months of April, August and December, and also the time duration from 2006 to 2009 was selected. In this way the dispersion of NO_x components was determined for selected months, according to prevailing four-year meteorological conditions; this ensures higher reliability of the results. During modelling of pollutant dispersion in Klaipeda port, NO_x concentrations at 1.5 meter height were determined. Average daily concentrations of pollutants from stationary and sailing ships in Klaipeda port were calculated; other nitrogen oxide emission sources and background pollution were not considered. Concentration areas matching the coordinate grid of Klaipeda city plan were formed with aim to assess the pollutant concentrations. Using the model, concentrations are calculated at the points of created grid; 150 meter calculation step was selected and values at 2911 points were modelled.

1.1. NO_x analysis method

The passive measurement method with diffusive samplers was used for analysis NO_x concentration. Diffusion samplers were located in the port area as shown in Figure 1. Eleven places have been chosen for the exposition. The diffusive samplers have been exposed for the period of seven days during different seasons of the year- during the spring and autumn seasons. In the selected locations the samples were hung at a height approximately 3.5 meters. NO_x concentration accumulated in samplers was determined (Smailys *et al.* 2009) using naphtylethylendiamino-dihydrochloride with spectrophotometer (JENWAY 6300, λ = 540 nm).

Fig. 1. Map of diffusive samplers' exposure on Klaipeda's streets

2. Results and their discussion

2.1. Analysis of ships visiting the Klaipeda port

Ships of medium and small tonnage visit Klaipeda port most often. Most part of tonnages of arriving ships fall into range between 1000 and 4999 t or is smaller than 500 t. Ships of large tonnage (larger than 50000 t) arrive in rare cases.

Ships of different tonnage are distributed in different areas of the port unevenly (Fig. 2). Port section II differentiates in particularly small tonnage ships; they comprise 71% of total number of small tonnage ships which visited Klaipeda port. There are a lot of tugboats and fishing boats in this area of the port with tonnage up to 500 t. Number of visiting vessels with tonnage from 1000 to 4999 t is similar in all areas of the port; none of the port sections distinguishes by number of ships with tonnage 500–900 t and these vessels are evenly distributed over entire port.

Even 53% of ships with tonnage 10000–49999 t belong to port section IV and 21% belong to section I. Even though the smallest number of arriving ships is characteristic to the port area I, it distinguishes by ships of largest tonnage. 22 visits of ships with tonnage 50000 t and larger were observed in Klaipeda port, and 16 of them were made in port section I; tankers and bulk carriers arrive here most often.

2.2. Analysis of sailing and stationary times of marine ships operating in Klaipeda port

Number of ship visits in separate areas of the port varied from 721 to 2456, while the calculated total stationary time of the ships staying at the quays in different areas of the port varied from 946.6 to 5801.3 days. Most ship visits (even 41% from total number) belong to port area II; respectively, the ship stationary time while staying at the quays is also longest in this section of the port. According to number of visits and total stationary time duration, the port area which was attributed to section IV does not fall far behind. It has 23% of ship visits and 27% of stationary time, compared to the overall result of Klaipeda port. The smallest number of ship visits and the shortest vessel stationary time is characteristic to the port area I.

It can be noted that in separate areas of the port number of visits and stationary time at the quays are directly proportional. When the larger number of ship visits is present in respective area of the port, the total ship time spent at the quays with auxiliary engines active will be also longer (Fig. 3).

In Klaipeda port ship sailing time until respective quays is reached will be directly proportional to the distance to port gates, since in port aquatory the speed is limited to 6 knots for all vessels. Therefore, the ships entering the first area of the port, the distance of which to the port gates is approximately 2.4 km, will take 0.22 hours. The longest sailing time (1.08 hours) belongs to ships which sail to the port area V, since the distance from the quays located in this

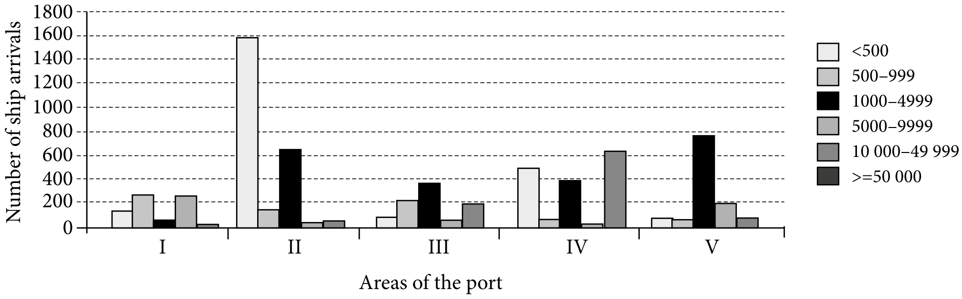

Fig. 2. Number of ship arrivals according to tonnage in separate areas of the port

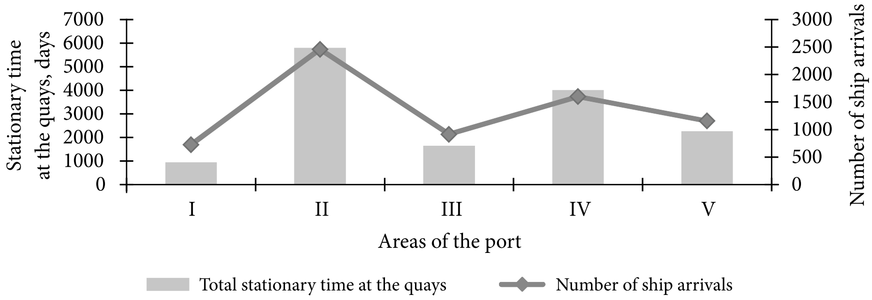

Fig. 3. Relation between number of ship arrivals and their total stationary time at the quays

section to the port gates is approximately 12 km.

2.3. NO_x emissions from ships operating in Klaipeda port

The emission of NO_x pollutants from ship sailing in Klaipeda port over one hour reaches from 0.95 kg to 358.8 kg, and from 0.1 kg to 28.5 kg over one hour from stationary ship with active auxiliary engines. Although sailing ships emit the amount of NO_x pollution components over one hour about 10 times larger than those stationed at quays, the total NO_x emission from stationary ships in Klaipeda port is higher (Table 2).

Relative distribution of overall NO_x emission in different areas of the port indicates, that the largest amount of these pollutants enter the atmosphere from the port area IV, which is responsible for 27% of total NO_x emission, and the smallest pollution is characteristic to the port section I, from which 12% of NO_x components from the total sum of port emissions enter the air basin.

The emission depends not only on the ship stationary time duration. Data presented in Fig. 4 shows, that the NO_x emission in the port area II is smaller by 65.3 t/year compared to the port section IV, and smaller by 53.7 t/year compared to the port section V, even though the ship stationary time while moored at the quays is the longest and the number of visits is the largest. Visits of ships with small power engines dominate in this area of the port.

Although the distance to the port gates in the port area II is 4.8 km, the total time of ships sailing into this area reaches 1056 hours due to the large number of arriving ships, and the NO_x emission from ships sailing to the quays in this section is one of the smallest, 20.8 t/year, and exceeds only emissions in the port area I. Most of NO_x is emitted in the port area IV, since it has both the largest number of arriving ships and also ships with large tonnage and powerful engines; furthermore, the distance from the quays in this section to the port gates is 9.6 km.

Thus, the calculated annual emission of NO_x components in Klaipeda port reaches 945.62 tons. This data matches calculations accomplished by Smailys *et al.* (2003), where during the year 1995 approximately 981 tons of NO_x components entered air basin from ships.

Table 2. Total NO_x emission (t/year) from ships operating in Klaipeda port

Port area	Emission from ships sailing from port gates to quays and back, t	Emission from stationary ships, t	Total NO_x emission in separate areas of the port, t	Relative distribution of overall NO_x emission
I	11.31	60.14	113.77	12%
II	32.19	137.28	190.91	20%
III	41.72	86.45	140.08	15%
IV	119.37	202.59	256.23	27%
V	63.57	191.01	244.64	26%
Total:	268.16	677.46	945.62	

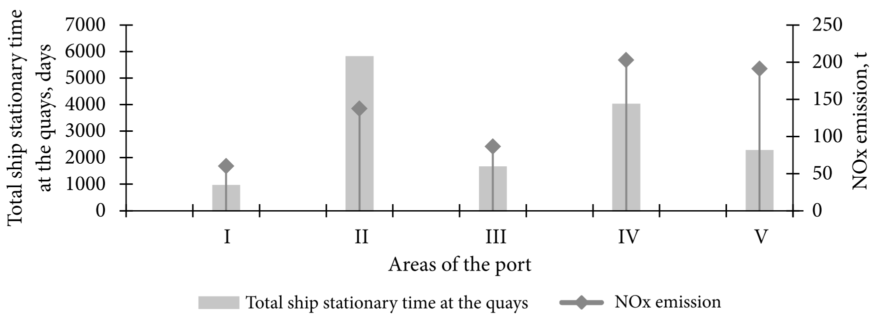

Fig. 4. Dependency between total ship stationary time at the wharves and NO_x emission from the ships

In 2000 the European Commission study estimated the emissions from ships in European ports. In ports which are significantly larger than the port of Klaipeda the NO_x emissions were even 3 times higher; these ports include Rotterdam (Netherlands), where annual NO_x emission reaches up to 3800 tons, and Hamburg (Germany), were estimated annual port emission constitutes 2000 tons. In slightly smaller ports the determined pollution emissions are more similar to values obtained for Klaipeda port; for example in port of Gothenburg (Sweden) the annual NO_x emission reaches 1500 tons (Isakson *et al.* 2001; European Commission... 2002).

2.4. Results of NO_x pollution dispersion evaluation using the AERMOD model

After completing the calculations of NO_x emissions from ships, it was determined what amount of pollutants is emitted in each area of the port, and that a total of 945.62 t of NO_x components is emitted from marine ships in Klaipeda port into the air basin of Klaipeda city.

We can see from figures (Figs 5, 6, and 7), in which the average daily concentrations are presented, that the highest dispersion of pollutants is characteristic to the southern area of the port (port section V), where concentration reaches up to 60 μg/m³. Highest dispersion of pollutants and lowest concentrations were determined in April and August, when 20–30 μg/m³ of NO_x components is found in Klaipeda city, and the 30–40 μg/m³ concentration zone extends through entire port territory. Meanwhile, in December significantly higher pollution concentrations were determined both above the port and in adjacent territories. In April and August pollutants are mostly transferred into the Klaipeda city area, while in December the NO_x pollutants are more displaced to the western side, above the sea, especially in the southwestern part, where 40–60 μg/m³ NO_x concentrations were determined; however the pollution concentrations in residential districts of Klaipeda city are considerably lower.

Similar studies (Matthias *et al.* 2010; Lonati *et al.* 2010) were conducted in the North Sea regions, where the dispersion of pollutants was modelled for summer and winter seasons. The obtained results coincide with the results of the modelling accomplished in this work. In both cases higher concentrations of nitrogen oxides were determined in winter than in summer. Results could be influenced by the fact that during the warm season of the year the chemical reactions taking place in the air are faster due to higher ambient temperatures, and pollutants are degraded more

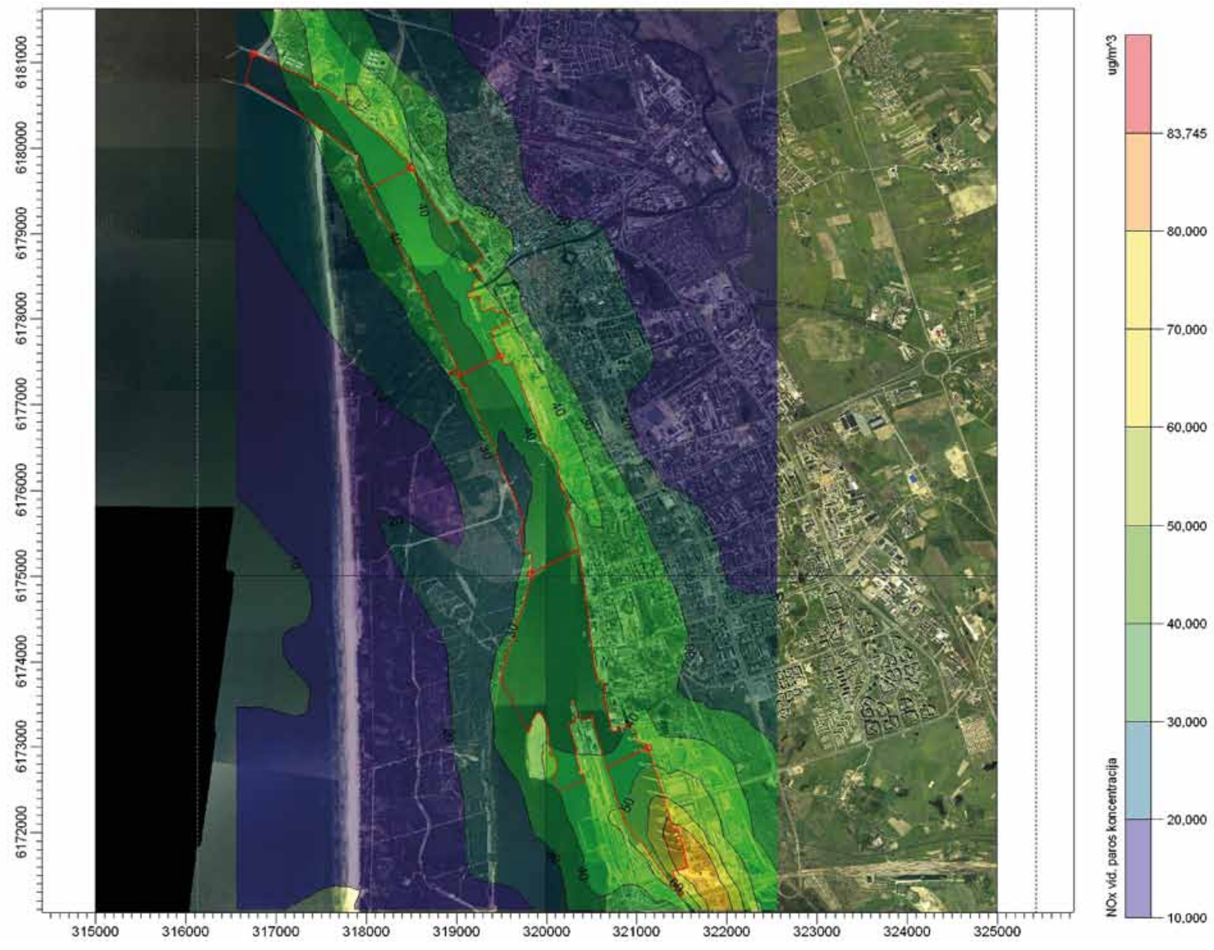

Fig. 5. Average daily concentrations of NO_x (μg/m³) due to emissions from ships in April

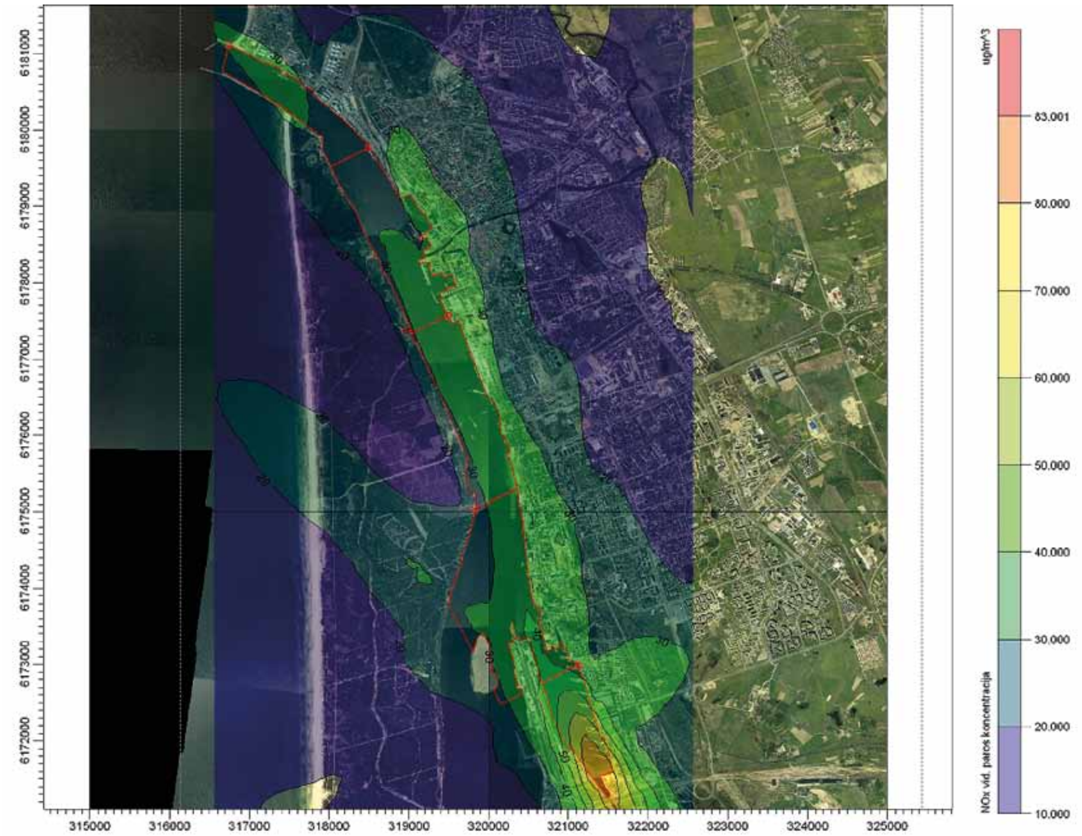

Fig. 6. Average daily concentrations of NO_x ($\mu g/m^3$) due to emissions from ships in August

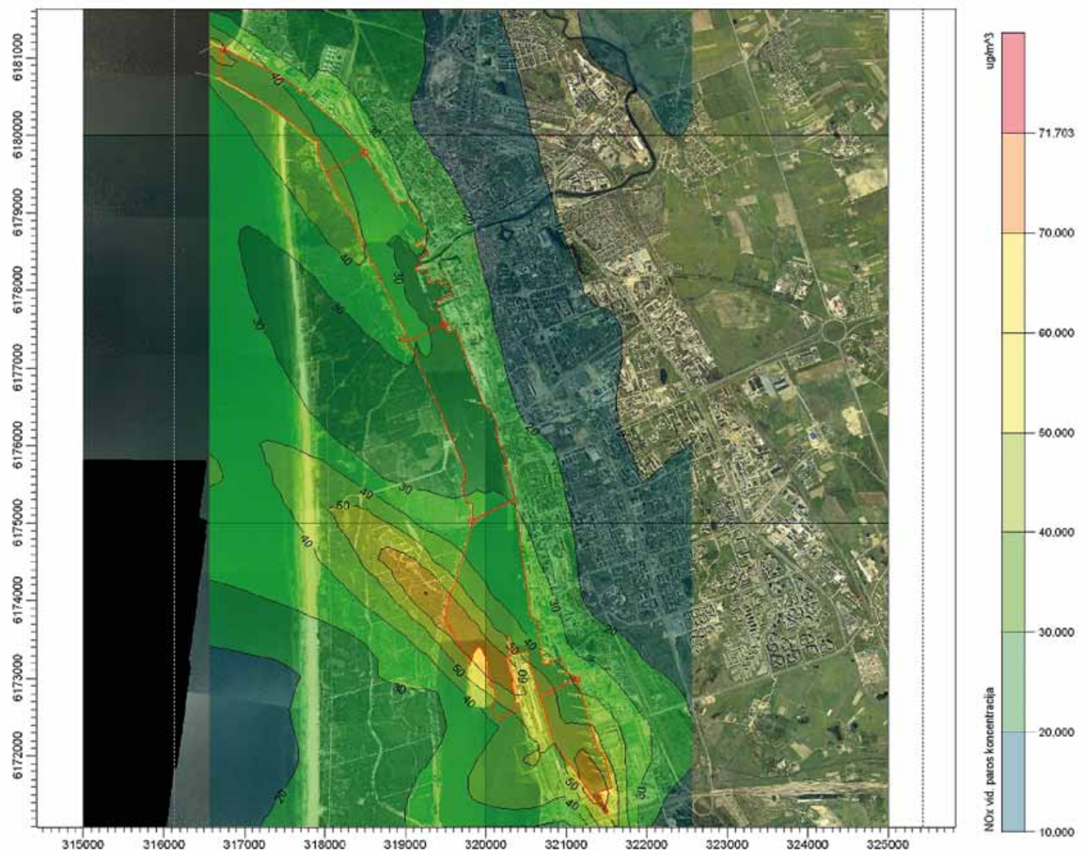

Fig. 7. Average daily concentrations of NO_x ($\mu g/m^3$) due to emissions from ships in December

quickly; additionally, stronger vertical mixing of atmospheric layers is typical for summer, which also determines faster dispersion of pollutants and lower accumulation of pollutants in the near-ground atmosphere layer.

Analysis of diffusive samplers data was carried out and the change of average concentration of NO_x was determined during the months of April and August, at the same time as the ships' pollution dispersion modelling was being performed (Fig. 8).

In the Figure 8, it is shown the comparison of NO_x concentrations found by modelling and diffusive samplers in the selected locations. Similar tendencies of concentration ranges are observed in spring. The least NO_x concentrations are found in the 1st point in both cases by using diffusive samplers and by modelling. The highest concentrations of both cases are found in 8, 9, and 10th points. Direct comparison of received concentrations is impossible due to reason that research using samplers was provided in 2010 while summarized meteorological data in model was used. Also some inaccuracies maybe originate due to impact of buildings. Moreover, it is impossible to exclude an influence of auto transport if measure NO_x concentrations by using diffusive samplers. However average NO_x concentrations determined by both methods allow finding what city place in what time is more affected by ships entering to Klaipeda seaport. The similar conclusion was made by Smailys *et al.* (2013). It was noticed that in most cases the emissions from ships are estimated using theoretical calculations and include total amounts of pollutants and it is difficult to compare this amounts with experimental data.

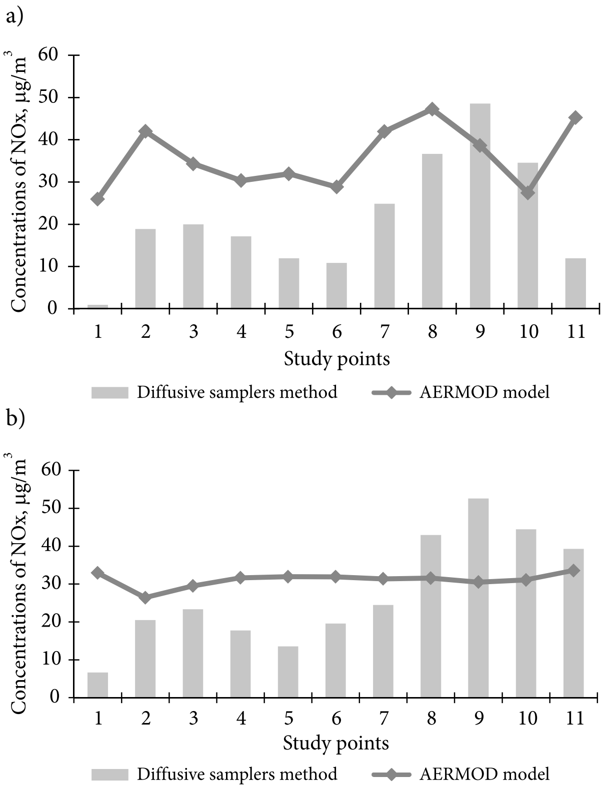

Fig. 8. Comparison of research of diffusive samplers conducted in: a) April; b) August and modelling results

Conclusions

1. After completing the analysis of ships operating in Klaipeda port, during which their types, tonnage, engine power and time while staying in port were assessed, it was determined, that these vessels accomplished 6837 arrivals and the total stationary time while moored to quays was 14668 days. It was estimated that the most part of NO_x enters the atmosphere from moored ships with active auxiliary engines; it forms 72% of the total NO_x emission from marine ships in Klaipeda port. It was calculated that a total of 945.6 tons/per year of NO_x components enter the air basin from ships operating in Klaipeda port.

2. After the modelling of pollutant dispersion was completed, it was determined that during winter time a higher dispersion of pollutants is typically observed near the pollution source, and during summer time pollutants are degraded more quickly and their concentrations less by up to 30% are formed above the port, but the concentrations above the residential districts of Klaipeda city become 40–50% higher. Higher input of NO_x pollutants into the air basin of Klaipeda city was observed during summer, when the dispersion of pollutants was wider, and during the cold time of a year pollutants were concentrated above the port and their mass extended towards the western direction, to the sea.

3. After evaluation of NO_x emission from marine ships and dispersion of pollutants in Klaipeda port, it was estimated, that pollutants from ships concentrate more in the southern part of the port during all seasons of a year. Highest NO_x pollution emissions from ships were determined in the southern part of the port, which contains the port sections IV and V. The section IV also distinguishes by the number of arriving ships and overall ship stationary time in the port; these numbers comprise 23% and 27% of the total result of the port, respectively; all this could have had some impact on formation of higher pollutant concentrations in this side of the port.

4. Average NO_x concentrations determined by both – passive measurement method with diffusive samplers and pollution dispersion modelling allow finding what city place in what time is more affected by ships entering to Klaipeda seaport.

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