Air pollution situation in small towns, including winter resorts: a comparative study of three cases in Northern Europe

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Abstract

In Europe, emissions of many air pollutants have decreased in recent decades, but there exist sites where concentrations of pollutants are still high and have become a public health problem. The air quality monitoring networks include urban stations in big cities and rural background stations. Main pollutants (SO_2, NO_x, CO, particulate matter) are measured automatically and reported on hourly basis, but there is very few research about air quality in small towns. The small towns are important transport nodes between cities and nowadays they are growing bigger, often being focused on seasonal tourism. In this paper, we try to understand the level of pollution in three small towns in Northern Europe, namely Otepää (Estonia), Lillehammer (Norway) and Saldus (Latvia) This research we point at seasonality of air pollution in towns related with winter sport activities, where the traffic flow increases in cold time simultaneously with heating season and higher prevalence of thermal inversions in atmospheric surface layer. Concentration peak of PM_{10} in Northern Europe appears in early spring, in snow thawing season and shortly after that. Even higher episodic concentrations may occur near unpaved streets in dry season. High seasonal variation of measured nitrogen dioxide concentrations was found in Lillehammer and Otepää, with remarkable contributions of traffic hotspots. This paper confirms that it is worth to study the air quality in small towns, furthermore, because air pollution levels and related public health concerns in small towns are not negligible.

Keywords Small town · NO_2 · PM · Residential heating · Seasonal variation · Transport

Introduction

In recent decades, urban air pollution (mainly from transport, local industrial enterprises, households) has become a public health problem around the world, causing hundreds of premature deaths in Estonia and hundreds of thousands in the European Union every year (EEA, 2020). In Europe, air quality remains poor in many areas, despite reductions in emissions and ambient concentrations (Coelho et al. 2021). Emissions of many air pollutants (economic and societal activities) have decreased but road transport, industry, power plants,

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households and agricultural activities still continue to emit significant amounts of air pollutants (Guerrerio et al. 2016).

Over the past 10 years, researchers, in cooperation with state institutions and municipalities, have analyzed the air quality of all European big cities (population larger than 90,000) and looked at how this affects people's health. On the other hand, there is a little research on small towns, although approximately 27% of the European population lives in small- and medium-sized towns (Servillo et al. 2017).

The effects of PM, NO_2 and SO_2 on human health and pollution sources have been examined in several studies (Curtis et al. 2006). Fine particles ($PM_{2.5}$) are particles of aerodynamic deametre less than 2.5 μm, formed mainly from the combustion products. The exhaust gases from diesel engines have a major impact on the amount of $PM_{2.5}$ in urban air due to the higher concentration of particulate matter in the exhaust gases of diesel engines. Springtime high concentrations of PM_{10} occur in North Europe due to wear-out of tyres and asphalt (by studded tyres in particular), in some sites wintertime sanding of roads plays a role. In addition, fine particles, emitted from firewood combustion

in domestic heating, is found to contain carcinogenic PAH benzo(a)pyrene in harmful amounts, exceeding European target value 1 ngm^{-1} at large areas, most notably in Eastern Europe (Guerreiro et al. 2016). Nitrogen oxides (NO$_x$) are emitted from fuel combustion, e.g. from industrial facilities and the road transport sector. NO$_x$ includes nitrogen oxide (NO) and dioxide (NO$_2$). NO makes up the majority of NO$_x$ emissions (EEA, 2020).

Sulphur dioxide is emitted to the atmosphere mainly from volcanoes. Main anthropogenic emissions originate from combustion of fossil fuels and from smelting of metals, such as copper and nickel. Sulphur dioxide is a precursor for one type of suspended particles, sulphate aerosols, which can affect the microphysical and optical properties of clouds—an effect that remains difficult to measure and is a large cause of uncertainty in climate models (Hansen, 2014). However, the emissions of sulphur dioxide have been reduced in Europe a lot in recent decades due to improving industrial prification systems. As an example, Sarnela et al. (2015) had pointed out an improved situation in Finland, where continuous SO$_2$ measurements apply since the 1970s. In the Kilpilahti industrial area in district Porvoo (population 50,000), nowadays the yearly average concentration of SO$_2$ is less than 2 μg.m^{-3}, which is ten times lower than 30 years ago.

European legislation on air quality is built on certain principles to control the ambient concentrations of air pollution in the EU. Pursuant to EU Directive 2016/2284/EU, Estonia has an obligation to reduce SO$_2$ emissions by at least 32% between 2020 and 2029 and 68% from 2030 onwards (reduction compared to 2005). The commitment to reduce NO$_x$ emissions by 2020–2029 is at least 18% and from 2030 it will be 30% (Tammekivi & Kaasik, 2021). Latvian obligation to reduce SO$_2$ emissions by at least 8% between 2020 and 2029 and 48% from 2030 onwards. Its commitment to reduce NO$_x$ emissions by 2020–2029 is at least 32% and from 2030 it will be 32%. For that the government has to understand the pollution sources and find ways to reduce the emissions.

In this study, the analysis was focused on three small towns, placed in three different countries, with different features. The aim of this research is to understand the air quality in winter resorts (popular places for events and visitors) in different countries of Northern Europe. Both measurement and modelling methods are used to study the concentrations of NO$_2$ and SO$_2$ in the air. In this research, every country has used different measuring and modelling methods, so it is interested to see how the methods match. The questionnaire study of inhabitants, aimed to quantify the emissions from residential heating, was provided. To our knowledge, no air quality study at comparable level of detail was carried out in this paper research area and other baltic countries (Latvia, Lithuania) before. This study work is intended partly to fill this gap and shows that small towns can contribute to improving the overall air quality of the country.

The joint study of University of Tartu and Estonian Environmental Research Centre has pointed out that air pollution affects public health in Estonian cities (Orru et al. 2009), but what about small towns?

Small towns are in some parts of the world considered inefficient, their development has often been neglected in policy making (Yin et al. 2021). However, in sparsely inhabited countries of Northern Europe, the small towns are much more important in national infrastructure, and thus deserve more attention in all aspects of human life.

For example, although 9 stations in Estonia may seem enough for a country of 45,000 km^2 by area, but the network is designed for quantifying the public health risks, rather than to understand the geographical spread of pollutants (Reis et al. 2013). In Estonia, ambient air quality monitoring takes place at national level in three background stations and six urban stations (Fig. 1), where main pollutants (SO$_2$, NO$_x$, CO, particulate matter) are measured automatically and reported on hourly basis. In the 2012–2014 heating period, the GLOBE Estonia environmental measurements programme with University of Tartu carried out SO$_2$ and NO$_2$ monitoring networks in different basic schools, where students could take passive samplers during for two-week measurement periods in 26 sites (Reis et al. 2013). Kaasik and Kinnel (2003) had pointed out that Estonia is a unique site for air quality research, where the transition from Soviet-time economy has resulted in enormously rapid changes in all economic activities, closing of a number of energy wasting and polluting enterprises, and rapid development of the transport system, reducing the emissions per vehicle tremendously, but growing rapidly the nmber on vehicles on the ohter hand.

The first goal of this research is to understand the level of pollution in small towns in Northern Europe (Fig. 1), which necessarily do not accommodate a permanent air quality monitoring station and constitute an indispensable part of the urban system, closely linked with rural areas (Yin et al. 2021). There is also a need and opportunity to improve the air quality in Otepää town, referring to the citizen's questionnaire.

The second goal is to point at seasonality of air pollution in towns related with winter sport activities, where the traffic flow increases in cold time, simultaneously with the heating season and higher prevalence of thermal inversions in atmospheric surface layers.

In North Europe, the majority of the population lives in urban areas, nearly a third of the population is concentrated in urban regions. The rest of people dwell in local centers, villages and dispersed settlement (Data on Estonia provided by Ahas et al. 2007). Here, in the first case study to clarify the origin and local sources of pollution in one of the most popular small towns in Estonia, a summer and winter resort Otepää was examined. The measurement data were collected
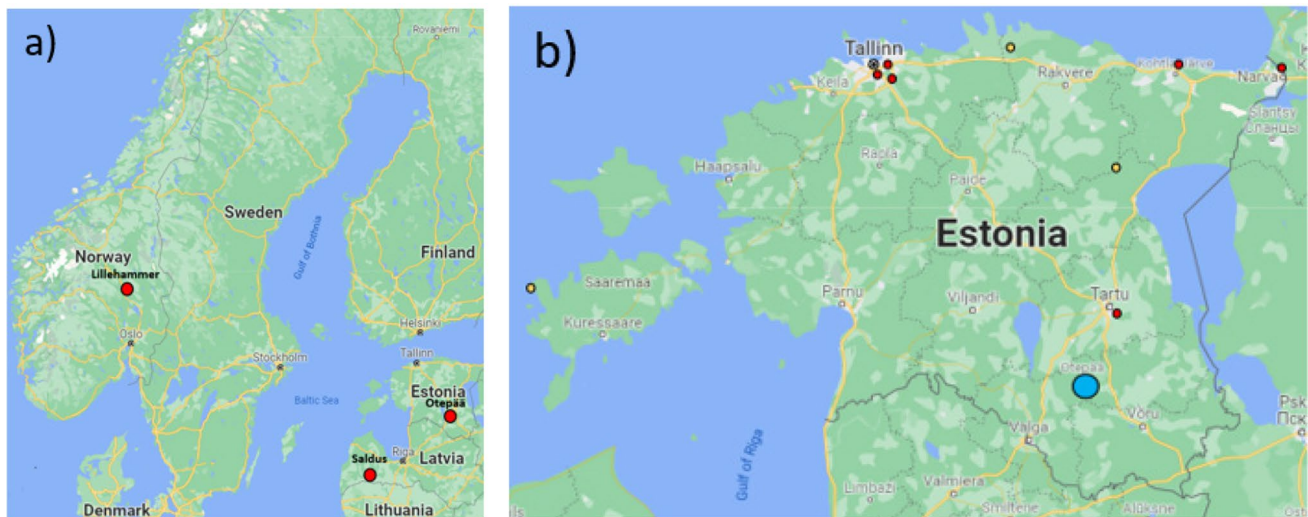
Fig. 1 **a**) Map of Northen Europe with research point. **b**) Estonia with major monitoring stations (urban stations in red, background stations in yellow and research town Otepää in blue).*base layer: Google maps*

during years 2017 and 2018, using passive samplers, a technique which is becoming increasingly popular in monitoring of air pollutants (Lis et al. 2021). In addition, there was used a local-scale air pollution dispersion model AEROPOL, to estimate the concentrations of $PM_{2.5}$, PM_{10}, NO_2 and SO_2 caused by local point sources, vehicles and residential heating.

Norway also shows similar patterns to the other northern European countries of a relatively high percentage of urban population, according to Statistics Norway (2022). The town of Lillehammer is located in Southern Norway, and is another medium-sized town that relies partially on seasonal tourism. The total area of the Lillehammer municipality is 477 km^2. Lillehammer is a winter sports center of worldwide prominence, which hosts many competitions, including the 1994 Winter Olympics and 2016 Winter Youth Olympics. Lillehammer also sits on an important highway connecting Oslo and Trondheim. The measurement data for NO_2, PM_{10} and $PM_{2.5}$ were collected during 2015 year using two stationary instrumental air quality monitoring stations .

Apart of winter resorts, the municipality of Saldus (10 km^2) is a typical small town in Baltic countries, placed in a relatively flat landscape, surrounded by sparsely inhabited rural landscape and forest patches in Latvia. A summertime field campaign in Saldus included detail measurements of particulate matter of different size fractions: PM_{10}, $PM_{2.5}$ and even PM_1 (particles with aerodynamic diameter less than 1 µm), which gives deeper insight into the aerosol of chemical origin, appart of coarse mode. The measurement data were collected during 2019 (02.06–07.09), using MOX sensors.

Thus, this research includes three case studies carried out in different years (yet in short and recent time interval, 2015–2019)

in different sites (yet in North European climate zone) and using different air quality models (yet proven suitable for urban scale), demonstrating the multitude of methods and approaches in use in the region and need for their harmonization.

We assess how much the pollution in small towns differs from bigger cities and how relevant the air quality of small towns can be in air quality directives, which give the guidelines to the Republic of Estonia to improve the air quality in next years. The author's goal is to quantify the concentrations of nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and to modelled the PM concentrations in the ambient air of small towns and, based on the performance data, to generally assess the quality of the town's ambient air.

No previous air pollution studies of comparable extent have been carried out in Otepää, Lillehammer and Saldus. In 2012–2014 the NO_2 and SO_2 concentrations have been measured with passive samples in Estonia: Palupera (12 km from Otepää), Põlva (38 km from Otepää) by basic school students within a project of GLOBE (Reis et al. 2013). Lillehammer is also isolated from other areas that have been studied in such detail, e.g. Brummundal (45 km from Lillehammer) was also studied as part of the NBV project and Oslo, which is the most studied site in Norway is over 100 km away from Lillehammer.

Models and methods

Otepää

The study at Otepää was made by group of atmospheric physics in Institute of Physics, University of Tartu, Estonia. The town of Otepää (nearly 2200 inhabitants in urban area)

is located in South Estonia, geographical coordinates 58.05° N, 26.49° E.

Measurements

Two 1-month measurement campaigns of SO_2 and NO_2 concentrations, for summer season (10.07. 2017–09.08.2017) and winter season (27.01.2018–26.02.2018), were carried out (Tammekivi & Kaasik, 2021). The measurements were made at 4 sites, using passive samplers of Ferm-IVL design (Ferm & Svanberg, 1998), which give the average concentration of sampling period only, as a result. Passive sampling techniques are becoming increasingly popular in monitoring of pollutants (Lis et al. 2021). Samplers were produced and analyzed after exposition by Estonian Environmental Research Centre (EERC). The samplers were installed at height of 2.4 m under a plastic shelter, nearly 20 cm in diameter (Fig. 2). The sampling sites were selected to represent different contexts: (1) the busiest street crossing, (2) a residential area close to a wood processing factory, (3) an area close to a secondary school and (4) a not built-up area near ski center and outdoor sports sites (Fig. 2) (Tammekivi & Kaasik, 2021).

Weather data

The weather data from Tartu-Tõravere station of Estonian Weather Service were used (23 km northwards of Otepää). During the summer measurement period, the average air temperature was 16°C and the precipitation was minimal. Warmest day was 28.07 with an average temperature of 20°C

and the coolest 20.07 with an average temperature of 13°C (Fig. 3).

During this period, southwestern and western winds were dominant at 0.2–8.2 m/s. The winter period (27.01 26.02.18) was much colder than the summer period. On a few days, the average daily air temperatures (27.01–29.1, 02.02.18) were above 0°C, and there was practically no precipitation throughout the period. The average temperature on the coldest days of the period was −15°C. During this period, southern, southeastern and northwestern winds were dominant, with speeds of 0.1–8.1 m/s.

Modelling

The AEROPOL model, version 5.3.2 was used for air pollution dispersion modelling. AEROPOL is a stationary Gaussian plume model developed in University of Tartu, Estonia. The model takes into account the reflection and partial absorption of the pollutant plume on the underlying surface, wet deposition and the initial thermal rise of the plume from the stack. The model is mainly used for environmental impact assessments and urban pollution dispersion calculations. In the past, a number of studies have been carried out for validation of the AEROPOL model (Kaasik & Kimmel, 2003, Geertsema & Kaasik, 2018), and it has been found that AEROPOL is a pretty reliable model for urban air quality assessment (Kaasik et al. 2019). In this research, the AEROPOL model was used to calculate the concentrations with grid resolution of 25–100 m and time frequency of 4 h, which served as base data to estimate the average for

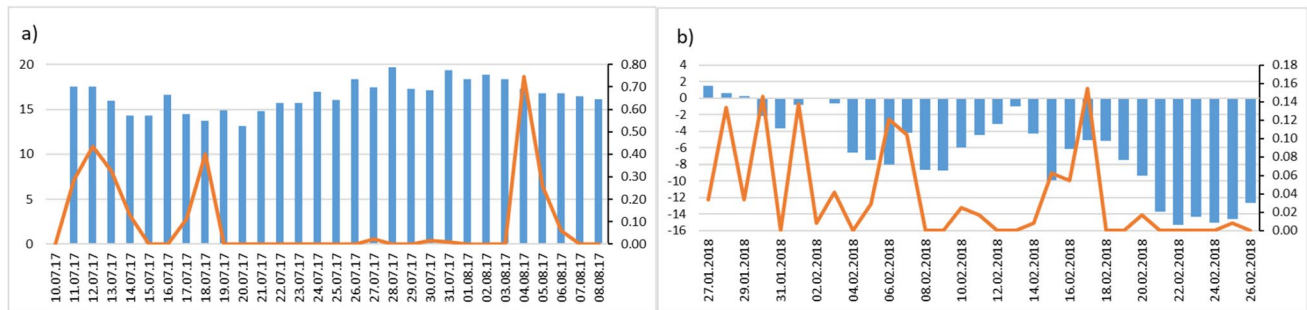**Fig. 2** **a**) Installation of passive samplers; **b**) in an area of one-family houses at Otepää

Fig. 3 **a**) Average air temperature (℃) in summer and **b**) winter period. The blue bars mark amount of precipitation (millimetres per day) and orange line marks temperatuure

Table 1 Emissions (tons per year) from Otepää

	SO$_2$	NO$_x$	PM$_{2.5}$	PM$_{10}$
Residential heating	1.08	6.20	19.04	19.77
Industries and district heating	5.68	30.07	40.89	40.89
Traffic	0.00	3.33	0.13	2.56
Total emissions	6.77	39.60	60.06	63.22

entire year 2017 and summer and winter sampling periods (see section "measurements") separately.

The single-point meteorological data for modelling originate from Tartu-Tõravere observation station (see "Weather" subsection). The street emission data are based on traffic counting, provided by Transport Administration of Republic of Estonia. The emission coefficients according to EURO vehicle categories were applied as reported by TU Graz (2009). Road transport, especially diesel cars, is one of the main contributors to urban air pollution. The emission data on boiler houses and small local industrial enterprises are based on governmental environmental licensing statistics. The emissions from 6 boiler houses were considered, where the highest emitting one is UPM-Kymmene boiler house (2.14 tons per year of SO$_2$ and 21.42 of NO$_x$). The emissions of NO$_x$ from all boiler houses are many times higher than SO$_2$ emissions, which certainly affects the concentrations in the air (Table 1).

To take into account the rural background, average concentrations measured during respective time intervals in Saarejärve regional monitoring station (75 km north of Otepää) were added to modelled values. As AEROPOL model does not consider chemical transformations of pollutants, the modelled concentrations of NO$_x$ were post-processed, applying the NO$_x$ to NO$_2$ regression formula developed for urban conditions, based on monitoring in Tallinn, Estonia (Kaasik et al. 2019).

Questionnaire study

For residential heating emissions (incl. saunas), a questionnaire on heating habits (35 respondents) was performed. It was found that by energetic value, 92% of used fuel is firewood, rest 8% consisting of peat and liquid fossil fuel. The emission factors from firewood are based on wood burning experiments made by Estonian Environmental Research Centre (Maasikmets et al. 2016). The estimated emissions were generalized for entire number of locally heated houses in the town, ca 600 houses in total, which were then treated as point sources in modelling.

Lillehammer

The study of Lillehammer was done in the scope of the "Nasjonalt Beregningsvektøy for Lokal Luftkvalitet" project (NBV, National modelling system for local air quality) that included the participation of the Norwegian Institute for Air Research (NILU) and the Norwegian Meteorological Institute . Lillehammer (about 27,000 inhabitants) is located in Southern Norway, coordinates of central part: 61.12° N, 10.46° E.

Measurements

There are two stationary instrumental air quality monitoring stations in Lillehammer: Bankplassen part and Barnehage in central part of urban area, at distance nearly 2 km from each other. Nitrogen oxides (NO and NO$_2$) and particulate matter (PM$_{2.5}$, PM$_{10}$) are measured on hourly basis in both stations. In this paper, the data from whole year 2015 are included—the year covered by modelling study.

Weather

Meteorological data was produced with the numerical weather prediction model AROME (Seity et al. 2011) coupled to the land surface model SURFEX (Masson et al. 2013), which are run together as part of the AROME-Met-CoOp operational weather prediction system (Müller et al. 2017). For 2015, data came from AROME-MetCoOp forecasts at 2.5 × 2.5 km horizontal resolution for all of Norway and then interpolated down to 1 × 1 km AROME is a limited area model, and it therefore relies on ECMWF's IFS meteorological forecast to provide forcing at its boundaries.

An evaluation of the results of AROME-MetCoOp for all Norway in 2015 (Denby & Süld, 2016) showed that for the synoptic meteorological parameters of 10 m wind speed, 2 m temperature and precipitation (12 h accumulated), the model showed low biases (as given by the mean error and mean absolute error in Table 2) relative to observations (50 to 70 measurement stations, depending on the variable); however, there were seasonal differences. Wind speeds were positively biased in winter and slightly negatively biased in summer, temperatures were slightly negatively biased throughout the year and precipitation had a slight negative bias in spring and autumn. Seasonally, there is higher model uncertainty (as given by the error standard deviation, see total statistics in Table 2) during the winter for wind speed and temperature but a higher uncertainty in precipitation during the summer and autumn. Higher uncertainty in wind and temperature during the colder winter months likely reflects the models decreased ability to reproduce the more stable stratification found then. A comparison of modelled and observed frequency distributions for wind speed, temperature and precipitation shows a very good statistical representation of these (Denby & Süld, 2016, pages 20&21).

Specifically for Lillehammer at the location of the meteorological station Sætherengen, Fig. 4 shows the time evolution in 2015 of variables air temperature at 2 m, wind speed at 10 m and hourly precipitation. There were no measurements for precipitation. Model and observations have good correlation for temperature. For wind speed, the model produces a much lower variability of results, not capturing the lower and the higher ends of the wind speed observations. The model shows higher precipitation in summer and lower in winter.

Seasonal variation

High seasonal variation of measured nitrogen dioxide concentrations was found in Lillehammer. The winter maximum in December to February is found about 2–4 times higher than summer minimum in June to August. Similar pattern exists in Otepää, too. However, the concentrations in Otepää are remarkably lower (Fig. 5). Notably, difference near main traffic street (Bankplassein in Lillehammer and site number 1 in Otepää) is in factor of 3–4 both in winter and summer.

Dispersion modelling

The dispersion modelling was carried out (for the reference year 2015) by NILU with the urban dispersion model EPISODE (Hamer et al. 2020). EPISODE is a 3D Eulerian model combined with Lagrangian sub-models, which allow to refine calculations close to sources. This is the case of the line source sub-model, which is a gaussian type model. EPISODE was developed specifically to answer questions regarding air quality legislative compliance and policy development in Norway (Sundvor and López-Aparicio, 2014; López-Aparicio et al. 2020; Sousa Santos et al. 2020). EPISODE calculates hourly average concentrations as gridded values and in a set of irregularly placed receptor points (which then were used to interpolate results to a regular grid of 100m×100 m horizontal resolution). In this study, the Eulerian grid had a 1 km × 1 km horizontal resolution over a domain of 37 km × 24 km with a south east origin of 570900, 6767500 in UTM coordinates (grid 32V). The Gaussian sub-grid models are used to calculate the dispersion emission sources that can be spatially confined to either point or line sources, e.g. emissions from individual road links. The meteorological input data (hourly) used was AROME-MetCoOp for Lillehammer, boundary concentrations from the Copernicus Atmospheric Monitoring Service ensemble reanalysis for 2015 (Marécal et al. 2015), and emissions for road traffic (line sources), off-road activities and residential heating. Input data for the emissions was for 2015, unless it was not available and then 2012/2013 were used. Exhaust emissions from traffic followed a bottom-up approach: traffic volumes came from the National Roads Database (Nasjonal VegDataBank). For the temporal variability of emissions, we used the same daily and hourly variation as used in previous
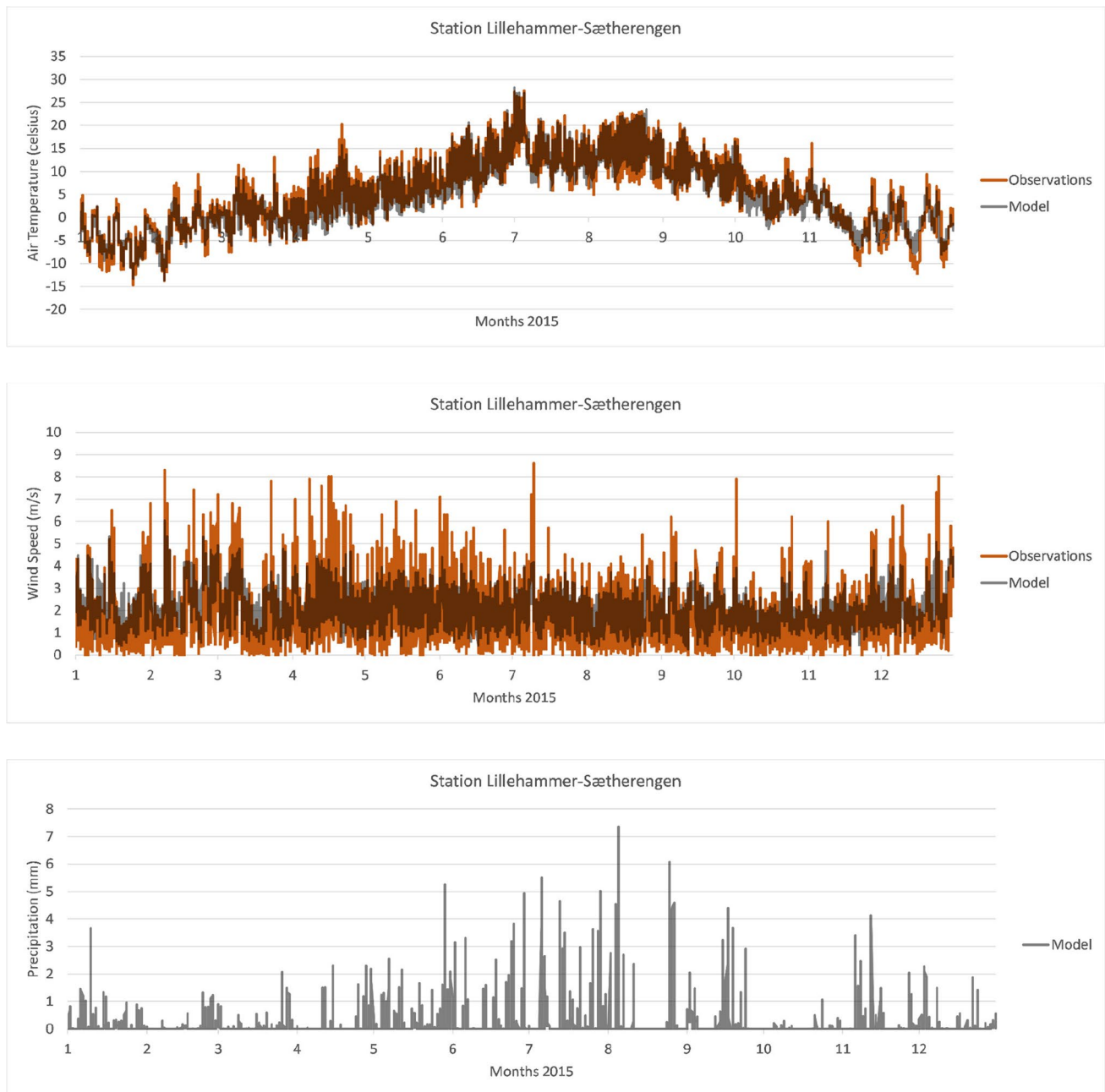
Table 2 Statistics for AROME-MetCoOp hourly results and for all Norway stations in 2015 (from Denby & Süld, 2016, page 19)

	Mean error	Mean absolute error	Root mean square error	Error standard deviation	Observations mean
2 m temperature (°C)	−0.54	1.24	1.56	1.36	7.17
10 m wind speed (m/s)	0.22	1.41	1.83	1.61	4.12
12h precipitation (mm in 12h)	0.01	1.26	2.83	2.83	2.18

Fig. 4 Observations (orange line) and model results (gray line—grid value) at the location of the meteorological station Sætherengen (Lillehammer) in 2015. Top to bottom: **a**) hourly air temperature at 2 m height (°C), **b**) wind speed at 10 m height (m/s), and **c**) hourly accumulated precipitation (mm)

studies for Oslo (Hamer et al. 2020) and flat weekly variation throughout the year. Resuspension of dust from the road surface is estimated based on a parameterisation by Tønnesen (2000). The parameterization relates emission to the percentage of studded tyres, the percentage of heavy duty traffic, to vehicles speed and volumes and road wetness (precipitation). Off-road activities (mobile sources and machinery from agriculture and forestry) and residential heating emissions came from the inventory developed in

NordicWelfair (https://projects.au.dk/nordicwelfair/). The residential heating inventory is based on wood combustion activity data compiled at county level by Statistics Norway. The county emission data was spatially distributed to a resolution of 1km × 1km using information on dwelling number and dwelling type (apartments and houses). Seventy percent of the wood consumption was allocated to houses and 30% to apartments. Due to very high modelled concentrations of $PM_{2.5}$ when compared with observations because of this
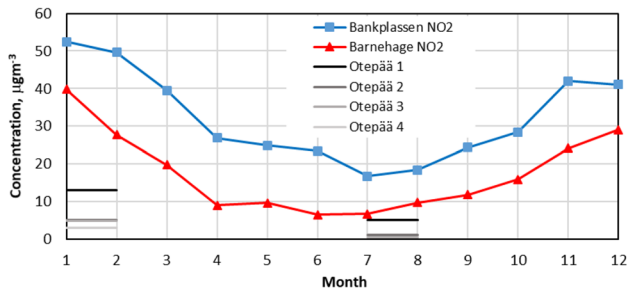
Fig. 5 Seasonal variation of concentrations of nitrogen dioxide measured in Lillehammer in 2015, compared to measured during winter and summer campaigns in Otepää in 2017

Table 3 Emissions (tons per year) from Lillehammer

Sources	NO_x	NO_2	NO	PM_{10}	$PM_{2.5}$
Offroad	76.75	7.68	69.07	5.18	5.10
Wood burning				194.00	194.00
Traffic	440.00	75.43	364.60	269.60	44.87
Total emissions	517	83	434	469	244

source, a scaling factor of 2 was at the end applied to the residential heating emissions. Overview of emissions is given in Table 3.

Considering the European Air Quality Directive 2008/50/EC, the yearly average concentrations (NO_2, $PM_{2.5}$ and PM_{10}) and short-term high concentrations (19th hourly highest concentration of NO_2 and 30th highest daily average concentration of PM_{10}) were calculated and mapped.

Full chemical-transport model EPISODE includes much more processes than Gaussian AEROPOL, most notably formation of chemical aerosol from gaseous admixtures. However, chemical aerosol, which typically remains in submicron accumulation mode, is usually not a big contributor to the total mass of $PM_{2.5}$ and PM_{10}.

Saldus

The study of Saldus was made by Department of Environmental Studies, University of Latvia. Saldus (about 9700 inhabitants) is located in Western part of Latvia, coordinates of central part: 56.66° N, 22.50° E. The study was initiated due to complaints of citizens on odour.

Measurements

The measurements in central part of Saldus were made during warm season of 2019 (02.06–07.09). Concentrations of H_2S, NH_3, CH_4, PM_1, $PM_{2.5}$ and PM_{10} were measured with MOX sensors, produced by Libelium. The original data series are with variable time step, about 1 min on average.

The data are aggregated to hourly averages. The data series of PM_1 is rather exceptional in a small town in Baltic countries, enabling an insight into lower end of particle size distribution, the chemically induced particles.

Weather

Temperature during the measurement period varied from +5 to +30°C, with average of 18°C. As typical for Baltic countries, the western and south-western winds prevailed, most of time the wind speed varied in range up to 5 ms^{-1} (95th percentile) with median value 2 ms^{-1}.

Modelling

The Aermod Gaussian plume model, developed by US Environmental Protection Agency, which is a steady-state plume model including air dispersion processes based on planetary boundary layer turbulence structure and scaling was used to produce the average maps of nitrogen dioxide and fractions of particulate matter. Information about stationary sources was obtained from national reporting system 2-Air where yearly data on sources (geometry, activity, fuels) are reported. Additionally, traffic flow counting results from the Latvian State Roads company were collected and emissions of NO_x and PM_x were calculated according to EMEP/CORINAIR methodology (2016). According to inventory, 119 of NO_x tons from industrial point sources and 1.58 from traffic sources per year were emitted. Total particulate matter emissions were 68.4 tons from industrial point sources and 1.18 tons per year from traffic. For modelling input data covering source activity within 2016, meteorological data from national meteorological service also was prepared. As a result yearly, maps of pollutants, based on 100 m resolution, were prepared for stationary (point and area) and mobile (traffic) sources, also national background concentrations were taken account from station Rucava (56,162° N, 21,173° E, near Baltic Sea coast about 100 km from Saldus; 18. above sea level) which is GAW/EMEP station and represents background and long-range air pollution for western part of Latvia.

Fractional composition of particulate matter

In Saldus, where three PM fractions (PM_{10}, $PM_{2.5}$ and PM_1) were measured separately, it appears that concentration of PM_1 fraction is almost determined by $PM_{2.5}$ (nearly 75% of PM_1 in $PM_{2.5}$), but ratio of PM_{10} to $PM_{2.5}$ varies in large extent: although more than two third of measured hourly values of PM_{10} include less than 50% of $PM_{2.5}$, a remarkable number of outliers have only 1–2% of $PM_{2.5}$ in PM_{10}, which hourly concentrations reach thousands of micrograms in cubic metre (Fig. 6). Very high episodic concentrations

Fig. 6 Dependence of finer PM fraction concentration on coarser fraction in Saldus: **a** PM_1 versus $PM_{2.5}$ and **b** $PM_{2.5}$ versus PM_{10}
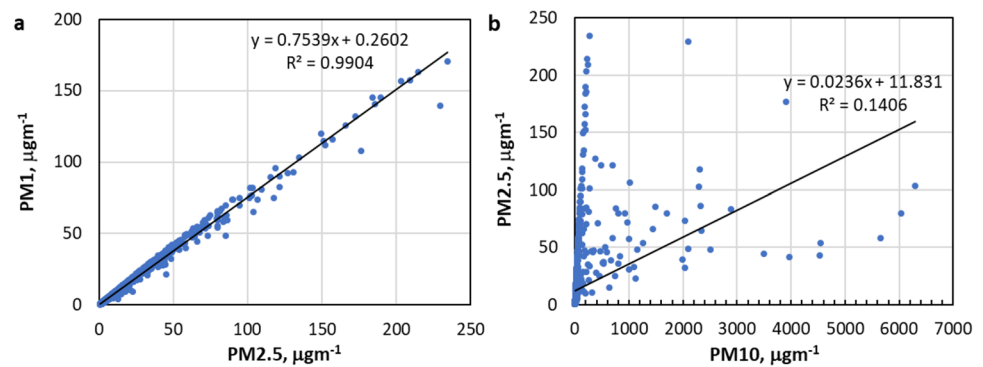
of PM_{10} originate most probably from an unpaved street next to the measurement site, which emits a lot of mineral erosion particles in dry weather, when vehicles pass on it. However, as measurements were made with low-cost sensor, the highers concentrations (more than 1000 µgm^{-3}) may be overestimated.

Similar pattern, composed of highly $PM_{2.5}$-determined particulate matter and outliers of low $PM_{2.5}$ content in PM_{10} is expressed in Lillehammer (Fig. 7). However, the peak concentrations of PM_{10} are much lower than in Saldus and share of $PM_{2.5}$ in PM_{10} is somewhat higher, respectively. Typically to the Northern Europe, the concentration peak of PM_{10} in Lillehammer appears in early spring, in snow thawing season and shortly after that (Fig. 8).

Results

Gaseous pollutants

Modelled and measured concentrations

Modelled annual average concentrations of NO_2 in Otepää and Lillehammer are presented in Fig. 9. The short-term high concentrations corresponding to the legislative norm, 19th highest hourly concentration, is shown in Fig. 10.

The highest 19th hourly concentrations of NO_2, range to 90 µg.m^{-3} in Otepää and more than 120 µg.m^{-3} in Lillehammer, a 13-fold larger town (Fig. 10), near busy

traffic streets and crossings in connection with stagnating boundary-layer condition and intense traffic during wintertime touristic season.

It is remarkable that in Lillehammer, in contrary to Otepää, both annual average and short-term high concentrations are underestimated by model. The possible reasons of underestimation in urban air range from underestimation of emissions to too fast modelled dispersion. As both average and short-term concentrations are underestimated less in urban background site Barnehage than in traffic hotspot Bankplassen, the overestimated dispersion speed is a likely reason, but more research is needed to clarify the issue.

The concentration statistics of nitrogen dioxide in locations of both monitoring stations in Lillehammer are given in Table 4: measured and modelled annual averages and short-term highs, correlation, bias and root mean square error (RMSE) between modelled and measured values.

Only for Otepää the concentrations of sulphur dioxide were modelled and respective passive sampler measurements were performed (Fig. 11). In summer campaign, all samplers resulted in concentrations below detection limit 0.7 µg.m^{-3}. Respective modelled values varied in range of 0.2–0.4 µg.m^{-3}. SO_2 measured in winter campaign varied in range of 1.4–2.4 and modelled 1.4–1.9 µg.m^{-3}. As the street emissions are expected not to contribute to SO_2, emissions from elevated point sources are distributed more evenly and residential emissions are spread on relatively large area, the concentration of SO_2 varies less than NO_2.

Fig. 7 Dependence of $PM_{2.5}$ versus PM_{10} fraction in Lillehammer: **a** Bankplassen and **b** Barnehage monitoring stations
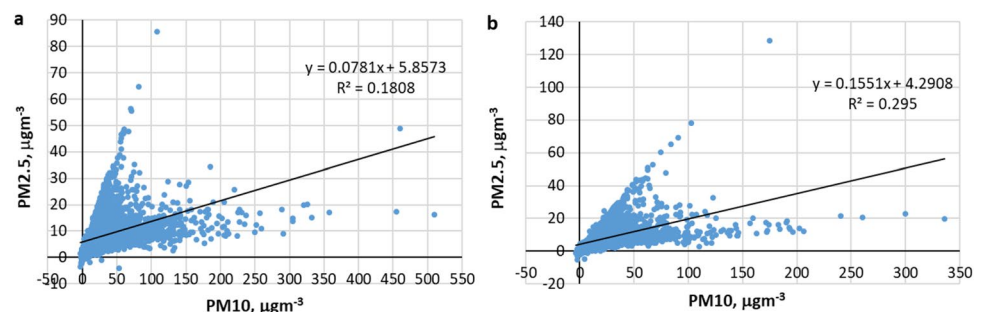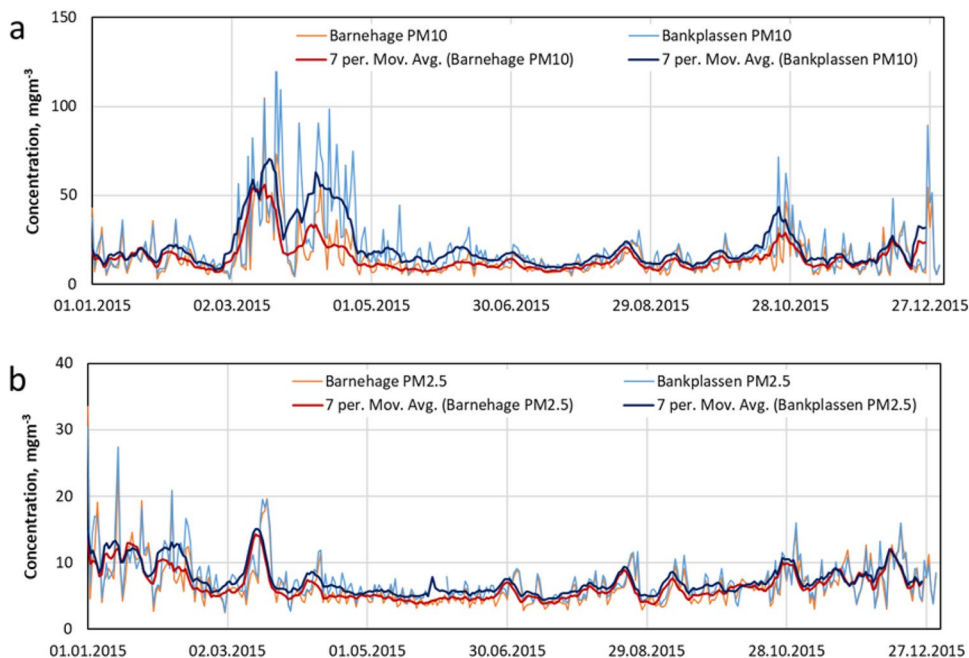
Fig. 8 Daily average and 7 day moving average measured concentrations of particulate matter: **a** PM$_{10}$ and **b** PM$_{2.5}$ in Lillehammer 2015

Particulate matter

Modelled and measured concentrations

Modelled annual average concentrations of PM$_{2.5}$ and PM$_{10}$ in Otepää and Lillehammer are presented in Figs. 7 and 12. The short-term high concentrations corresponding to legislative norms for the EU in Otepää and to Norwegian national legislation in Lillehammer. The 31st highest daily average in Lillehammer and nearly equivalent 91% percentile in Otepää are given in Fig. 12.The Norwegian national legislation in 2015 placed a stricter limit on the number of days with exceedances than the comparable EU legislation.

The areas of high concentrations of PM are located near the streets of highest traffic intensity. It is difficult to determine in municipal waste- how much and in what quantities people burns its at home. In 2013, an average of 0.921 kg/a was burned in a household of 3 member (Estonian

Fig. 9 Monthly average measured concentrations of particulate matter in Lillehammer (2015)

Environmental Research Centre). In Otepää, the share of residential heating (mainly wood combustion) is prevailing in PM$_{2.5}$. In Otepää, there are two main street and a traffic junction where the average daily number of cars passing through those streets exceeds 2000. There is also 6 working boiler houses in the town. In Otepää and Lillehammer the PM$_{2.5}$ average concentration extends to 10 µg.m^{-3}.

Figure 13 shows that PM$_{10}$ concentrations are higher than PM$_{2.5}$ in the main road. When at Otepää concentration of PM$_{2.5}$ reaches to 16 µg.m^{-3} and PM$_{10}$ concentration is up to 26 µg.m^{-3}, the similar difference appears in Lillehammer.

Measuring daily concentrations is important because they fix sudden emissions which may exceeded the daily limit, but not month and year. One example is the relaunch of the industry. In Fig. 14, it is shown that PM$_{10}$ highest daily concentrations are twice higher than annual average concentration and when at Otepää has the same roads, then in Lillehammer the daily highest concentrations shows only one main road (PM$_{10}$ concentrations higher than 50 µg.m^{-3}).

The concentration statistics of particulate matter fractions in locations of both monitoring stations in Lillehammer are given in Table 6: measured and modelled annual averages and short-term highs, correlation, bias and root mean square error (RMSE) between modelled and measured values.
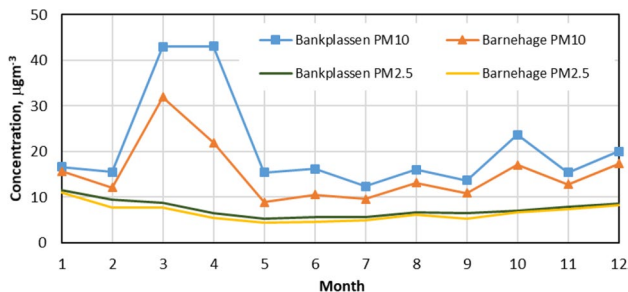
Model performance

The annual average concentrations of PM$_{2.5}$ in Lillehammer are modelled nearly perfectly, but both annual average and short-term high concentrations of PM$_{10}$ are underestimated by factor of 1.5–2. The factor of underestimation
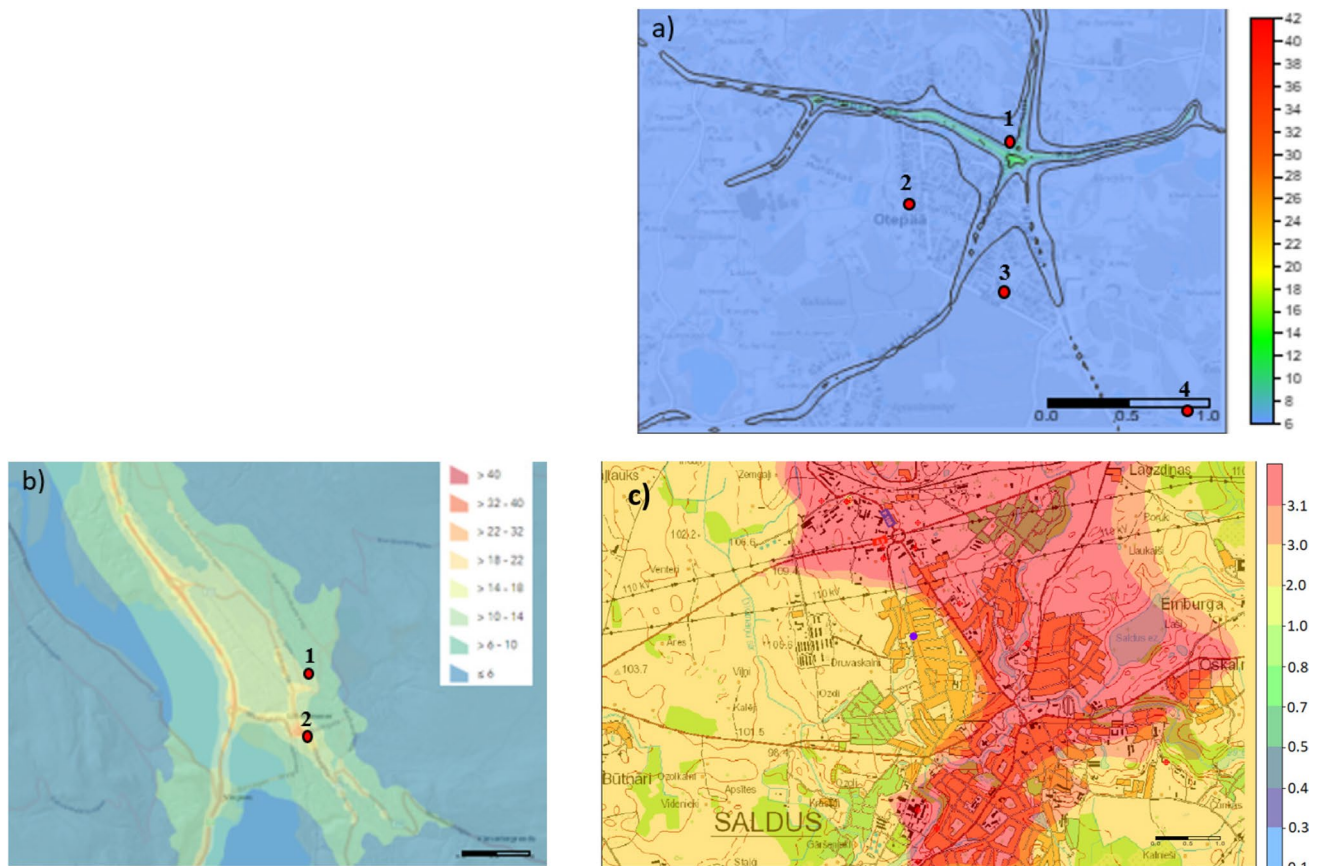
Fig. 10 **a**) Modelled annual average concentration of NO_2 in Otepää NO_2 (2017); **b**) modelled annual average concentration of NO_2 (2015) in Lillehammer (monitoring sites: 1- Barnehage, 2 -Bankplassen); **c**) modelled annual average concentration of NO_2 (2019) in Saldus

is bigger in Bankplassen station, where the impact of road transport is higher. Thus, most probably the model underestimates the effect of road dust. In Otepää, in contrary, the AEROPOL model tends to overestimate the concentrations of NO_2, but highest wintertime averages near

Table 4 Comparison of modelled and measures annual average and short-term (19th highest hourly) concentrations of NO_2 ($\mu g.m^{-3}$) in Lillehammer (2015)

	Bankplassen NO_2	Barnehage NO_2
Measured annual average	32.66	18.06
Modelled annual average	19.64	8.18
Correlation	0.66	0.59
Bias*	−13.27	−9.64
RMSE	21.77	16.93
Measured 19th highest hourly	124.48	88.15
Modelled 19th highest hourly	81.73	58.11

*Bias is not exactly same as difference between modelled and measured averages, because it is calculated pairwise, omitting the hours with gaps in measured values

the busiest crossing (site 1) is matched with accuracy of 15%. The AEROPOL model gave a realistic prediction of woodburning-driven wintertime SO_2 concentrations in Otepää: 1.5–2.0 $\mu g.m^{-3}$ modelled versus 1.4–2.4 $\mu g.m^{-3}$ measured. The summertime prediction 0.3–0.9 $\mu g.m^{-3}$ can be considered realistic, too, compared with all measured levels below detection limit of 0.7 $\mu g.m^{-3}$.

Future scenario for 2031–2050, the NO_2 levels are expected to decrease in central and northern Europe by nearly 0.6 $\mu g.m^{-3}$ on average, while in southern and southeast Europe NO_2 will increase by 1.0 $\mu g.m^{-3}$. A clear increase in the concentration of fine particles is projected in southern Europe (more than 2 $\mu g.m^{-3}$). $PM_{2.5}$ is expected to increase in southeastern Europe, decreasing or remaining constant in the rest of the areas (Guzmán et al. 2022).

In Otepää, the particulate matter was not measured, but modelled with AEROPOL, which resulted in hotspot concentrations about twice lower than in Lillehammer (Figs. 6 and 7). The AEROPOL model takes into account the engine emissions, brake, tyre and asphalt wear (Omstedt et al. 2005, Norman et al. 2016), including the peak levels in March and April, based on (Pirjola et al. 2010).
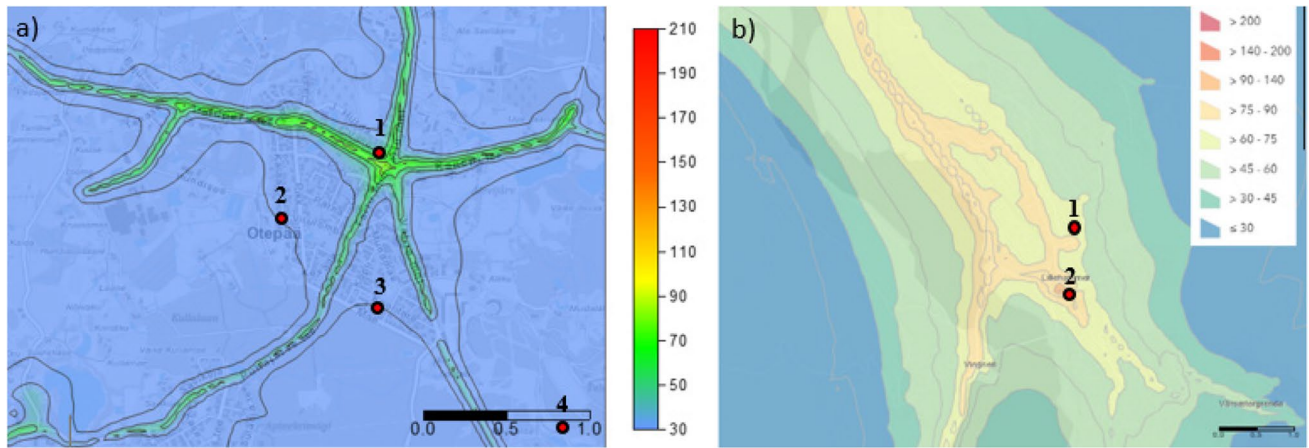
Fig. 11 **a**) Modelled 19th highest hourly concentration of NO_2 in Otepää NO_2 (2017); **b**) modelled 19th highest hourly concentration of NO_2 (2015) in Lillehammer (monitoring sites: 1- Barnehage, 2 - Bankplassen)
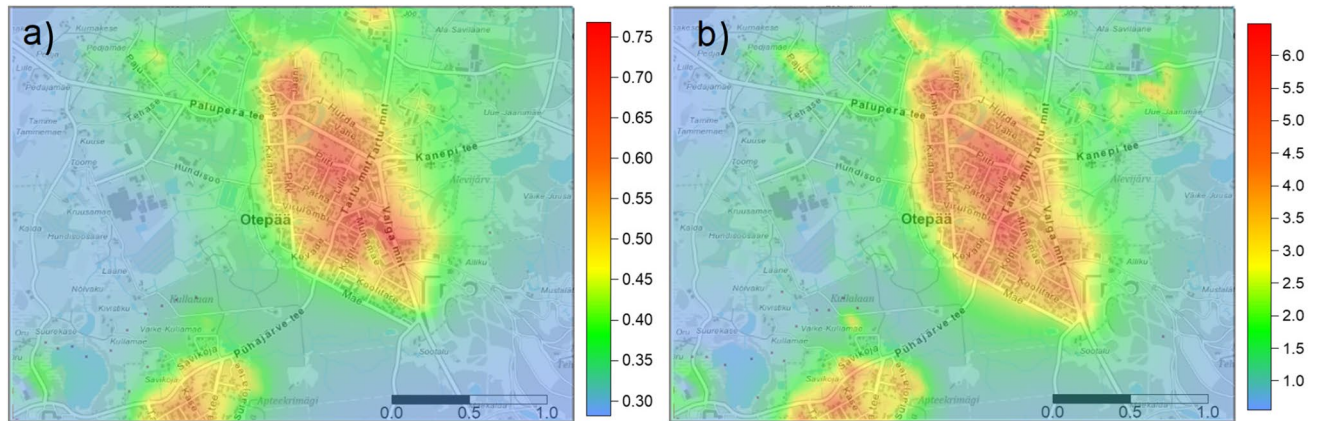

Fig. 12 Modelled average **a**) and hourly maximal **b**) concentrations in Otepää in 2017, $\mu g.m^{-3}$
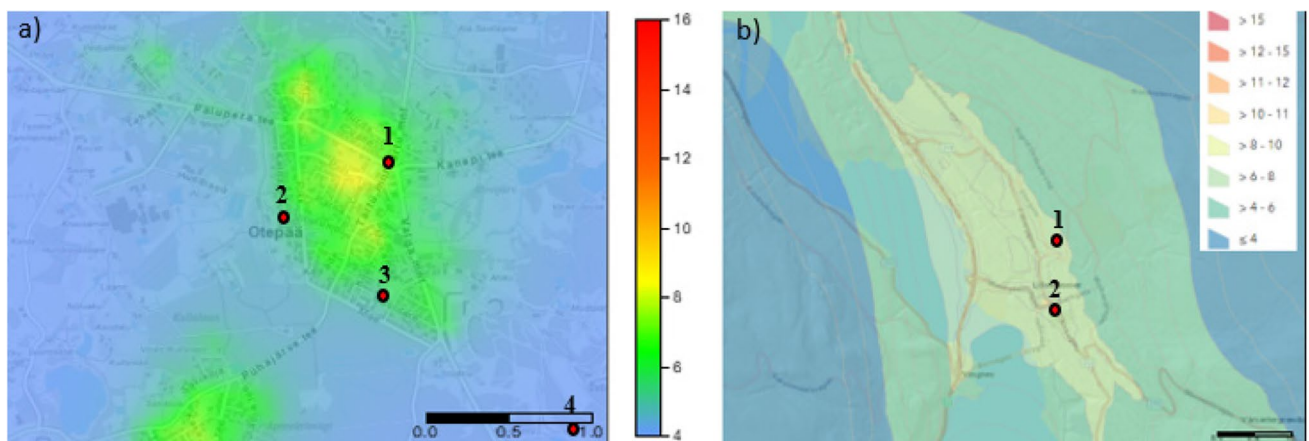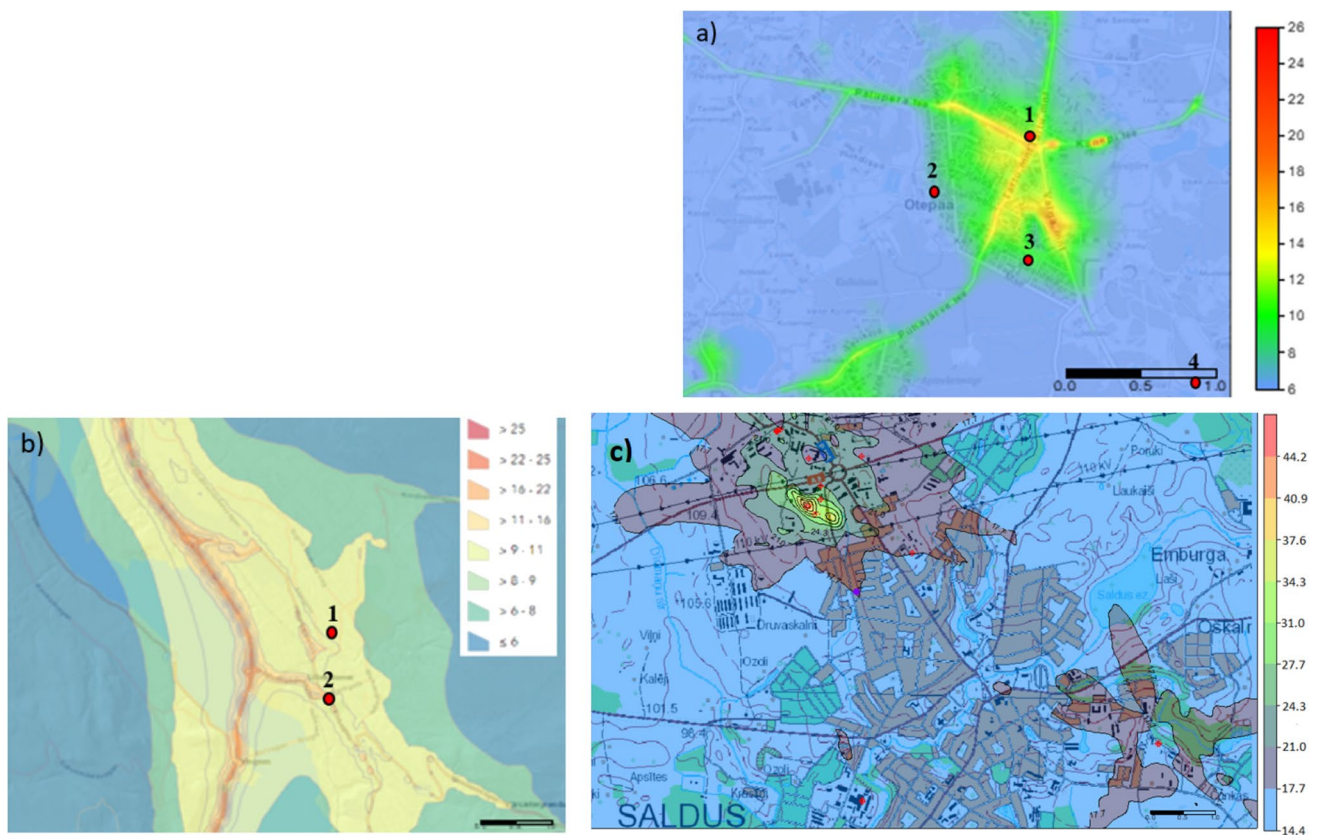

Fig. 13 **a**) Modelled annual average concentration of $PM_{2.5}$ in Otepää (2017); **b**) modelled annual average concentration of $PM_{2.5}$ in Lillehammer (2015, monitoring sites: 1- Barnehage, 2 - Bankplassen)

Fig. 14) Modelled annual average concentration average of PM$_{10}$ (2017) in Otepää; **b**) modelled annual average concentration of PM$_{10}$ in Lillehammer (2015, monitoring sites: 1- Barnehage, 2 - Bankplassen); **c**) modelled annual average of PM$_{10}$ (2019) in Saldus

Discussion

How polluted is the air in towns under consideration?

Gaseous pollutants

In recent decades in Europe in general, including Baltic and Nordic countries, the sulphur dioxide decreased due to diminishing combustion of coal and heavy oil products for heating and this tendency is continuing. Marginal, concentrations of SO$_2$, although slightly higher in heating season were measured in Otepää.

On the other hand, In Saldus, the emissions of nitrogen oxides tend to increase in many areas due to increasing traffic flows and consumption of natural gas, as emission reduction measures are not fully compensating the rapid increase. It is evident (Figs. 10 and 11) that in Otepää and Lillehammer, the highest concentrations of NO$_2$, both long-term average and short-term maxima, are formed near main traffic streets, as it is typical for cities and towns. However, both long-term and short-term concentration near biggest traffic congregations in Lillehammer are about three times higher than in

Otepää. It is evident that traffic is more intense in Lillehammer due to its more than ten-fold larger size and respectively busier ski tourism, which coincides with wintertime frequent thermal inversions in planetary boundary layer (PBL). The wintertime concentration of NO$_2$ in Lillehammer appears in urban center (Bankplassen) about by factor of 3 and in outskirts (Barnehage) even by factor of 5–6 higher than the summer low (Fig. 11). The sharper seasonal variation away from main traffic streets may occur due to different PBL stratification: In summertime, mostly, convective conditions the dispersion of pollutants upwards is more efficient, thus reducing the near-surface concentrations, when transported downwind the source. Seasonal variation of NO$_2$ in Otepää is less intense than in Lillehammer, as shown by winter and summertime sampling campaigns.

Compared to Estonian small small towns (Keila, Põlva, Rakvere, Saaremaa, Sindi, Valga, Viljandi) and a village Palupera, where passive probe sampling was carried out in a GLOBE project (Reis et al. 2013), Otepää is more polluted than Palupera (NO$_2$ 2.7 µg.m^{-3} and SO$_2$ 1 µg.m^{-3}), but almost same air quality as in Põlva (NO$_2$ 6 µg.m^{-3} and SO$_2$ 1.4 µg.m^{-3}) and smaller than in other measured small towns so Otepää have very good air quality.

Table 5 Measured and modelled average concentrations of nitrogen dioxide (µg.m^{-3}) in Otepää during summer (10.07.2017–09.08.2017) and winter (27.01.2018–26.02.2018) field campaigns; sampling sites, see Fig. 2

Sampling site no.		1	2	3	.4
Summer	Measured	5.1	1.2	0.6	-*
	Modelled	7.9	1.6	1.6	1.6
Winter	Measured	13.0	5.2	4.9	3.0
	Modelled	14.9	5.9	7.1	3.4

*Passive sampler was lost

Table 6 Comparison of modelled and measured concentrations of particulate matter (mg.m^{-3}) in Lillehammer (2015), based on hourly values

	Bankplassen		Barnehage	
	PM$_{10}$	PM$_{2.5}$	PM$_{10}$	PM$_{2.5}$
Measured annual average	21.04	7.51	15.23	6.64
Modelled annual average	13.22	7.36	8.81	5.76
Correlation	0.12	0.41	0.22	0.34
Bias*	−7.81	−0.05	−6.40	-0.86
RMSE	28.91	6.11	18.67	5.90
Measured 31th highest daily average	47.76	11.94	33.26	11.35
Modelled 31th highest daily average	22.80	12.22	15.64	10.03

*Bias is not exactly same as difference between modelled and measured averages, because it is calculated pairwise, omitting the hours with gaps in measured values

The annual average regulatory limits for NO$_2$ in EU, 40 µg.m^{-3} as annual average and 200 µg.m^{-3} as hourly average (the hour of 19th highest concentration within a year) are well met in all three towns under consideration in this study. However, the much stricter recommendation of World Health Organization (WHO, 2021), valid since September 2021, 10 µg.m^{-3} as annual average, seems narrowly met in Otepää (see winter and summer value in Table 5), but highly exceeded in Lillehammer. Modelled concentrations in Saldus (Fig. 10), which are rather similar to Otepää, suggest that considering even the normally higher levels in winter, most probably the guideline of WHO is met, too.

Particulate matter

Particulate matter measurements in small towns have been carried out in very few countries. In Poland, from 2017 to 2018, in small town (winter resort) (Janoszka et al. 2020) where we can see similar PM$_{10}$ concentrations with Lillehammer and in 2016 to 2017 in bigger town, where was also marked that the main PM$_{10}$ pollution source is residential heating, houses with individual heating system (Wiśniewska et al. 2019). With comparing our research data, we have to consider that in Poland, there is more continental climate than is in our research area. From Europe, there were not any researches about small towns air quality, but there was a lot of big cities (Italy from 2013 to 2016, Cesari et al. 2018, Estonia (Tallinn) from 2009, Orru et al. 2009).

It is evident that diffuse sources, residential heating in first order, prevail in concentrations of PM$_{2.5}$ (Fig. 5). In contrary, in annual average and short-term high concentrations the hotspots near main traffic streets and busy crossings are visible (Figs. 6 and 7). Most of time in the yearly course of particulate matter in Lillehammer (Fig. 9) the PM$_{2.5}$ constitutes 30–50% of PM$_{10}$ mass, except the springtime peak in March and April, when only 20–30% of PM$_{10}$ is in fraction of PM$_{2.5}$, as a possible indication of resuspension episode from streets after snowmelt and drying up the pavement (Pirjola et al. 2010). However, impact of a dust or sea salt episode due to long-range transport is not excluded. The peak is more clearly expressed for Bankplassen site, which has heavier street traffic nearby. The yearly course of PM$_{2.5}$ has decreasing tendency from winter to summer and increasing towards autumn again, which could be explained by impact of heating emissions.

The typical wintertime concentrations of of PM$_{10}$ in Lillehammer are 15–20 and summertime concentrations 10–15 µg.m^{-3} (Fig. 9), but due to high springtime peak the annual average is in range of 20–30 µg.m^{-3}. The modelled average annual in Otepää are up to 16 µg.m^{-3} summertime concentrations in Saldus 17 µg.m^{-3} (Fig. 6). In following, we provide some data from relatively small urban areas in Europe for comparison.

Concerning the regulatory annual average limit values in EU for PM$_{10}$ and PM$_{2.5}$, 40 and 25 µg.m^{-3} respectively, none of towns in this study (Lillehammer, Otepää, Saldus), neither Kynica discussed above, seems not having problem in respect to measured concentrations. However, the modelled concentrations in Lillehammer are highest not in the monitoring sites, but near the road passing the town northwards (see Figs. 12, 13 and 14). Keeping in mind the underestimation tendency by factor of 1.5–2 in Lillehammer (see Table 3), the limit values of PM$_{10}$ may be exceeded by a narrow margin in this hotspot.

The same is likely valid for hourly average concentration limit of 50 µg.m^{-3} for PM, which is allowed to exceed 35 times per year. However, since September 2021, WHO recommends much stricter limits (WHO, 2021) to fully avoid health damage: 15 µg.m^{-3} of PM$_{10}$ and and 5 µg.m^{-3} of PM$_{2.5}$ respectively as annual average and 45 and 15 µg.m^{-3} as hourly value respectively (number of permissible exceedances not specified). These limits are exceeded a lot in Lillehammer and narrowly in Otepää and Saldus. It is evident that nowadays a large majority of people in Europe are exposed to the concentrations higher than WHO recommendations. However, knowledge about exceedances out of big urban
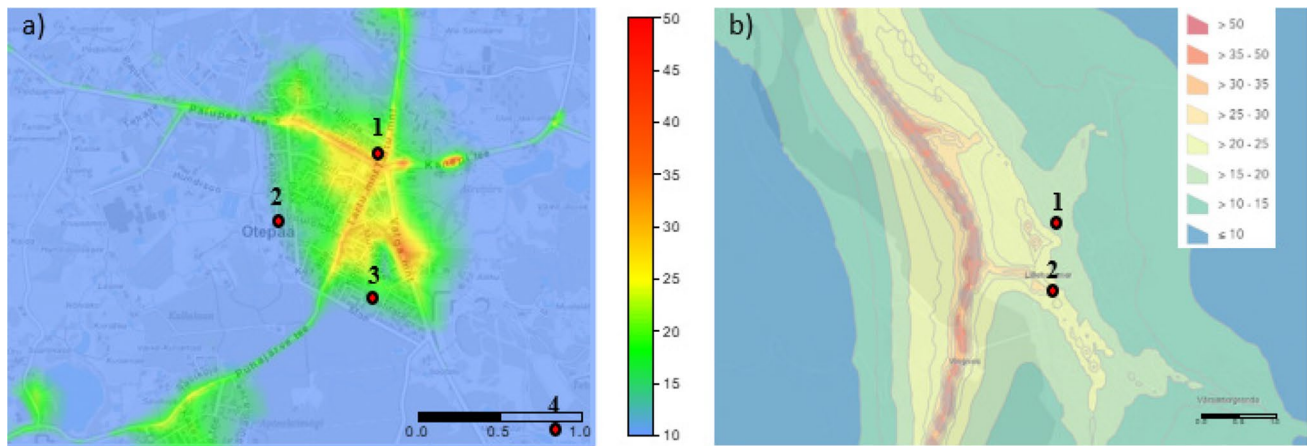
Fig. 15 **a**) Modelled 91% percentile of PM_{10} in Otepää (2017); **b**) modelled 31th highest daily average concentration of PM_{10} in Lillehammer (2015, monitoring sites: 1- Barnehage, 2 - Bankplassen)

congregations gives us deeper insight in air quality impact to public health and hints, how to mitigate it optimal way.

Fractional composition and possible origins of particulate matter

Both in Lillehammer (Fig. 15) and in Saldus (Fig. 8), the fraction of $PM_{2.5}$ in PM_{10} is highly variable, despite of most typical values of 30–50%. The snowmelt time dust episodes PM_{10} leave a long "tail" of occasions, when PM_{10} contains only a few per cent of $PM_{2.5}$. On the other hand, In Saldus such episodes, even much more remarkable, occur even in Summer.

In contrary, the PM_1 measured in Saldus correlates extremely well with $PM_{2.5}$ (Fig. 8), which is a clear evidence of common origin of PM_1 and coarser fraction of 1–2.5 µm of aerodynamic diameter, whereas as much as 75% of mass is concentrated in the finer fraction. Thus, there likely exist a well-defined aerosol model below 1 µm and a rather independent, highly variable mode of coarse particles with aerodynamic diameter 2.5–10 µm. The coarse mode is well-known as mechanically produced aerosols, whereas finer one is likely of chemical origin: soot and condensed burning and photooxidation products. It is worth further investigation, how extensively the $PM_{2.5}$, measured in many monitoring stations, can be used as a proxy of chemically produced aerosol and how much does vary the portion of even smaller fractions (e.g. PM_1) in it.

Conclusions

Based on three case studies in small towns in Northern Europe, it is evident that air pollution is a health concern of remarkable importance not only in big cities, but in rather small towns of population about 10,000. Although the EU air quality standards are met in small towns as a rule, the exceedances of WHO global guidelines, most remarkably of particulate matter, draw attention to public health impact that has to be studied at more detail level. Road transport is the main reason of air pollution hotspots, but mostly wood-based residential heating creates a remarkable urban background of particulate matter in winter.

The air pollution dispersion models, taking into account road transport, residential heating, industrial point sources and rural background, are useful to understand the spread of pollutants in small towns and contributions of different sources into it. However, more research is needed to model correctly the urban traffic hotspots and seasonal variation of PM_{10} from streets due to springtime resuspension of particulate matter accumulated in snow and ice during the winter. Unpaved streets, still existing in small towns in Eastern Europe, constitute a health concern due to dust emission episodes in dry season.

Unlike PM_{10}, the concentration of finer particulate matter fractions $PM_{2.5}$ and PM_1 is much more stable and less affected by dust events, referring to their combustion and chemical origin. It is worth to study further, whether rather stationary share of PM_1 in $PM_{2.5}$ (about 75%) found in Saldus in summer, is typical for ambient air in small towns.

This study reveals that more research on air quality in small towns is needed to better quantify the health impact for a remarkable segment of population.

Declarations

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