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Localized real-time information on outdoor air quality at kindergartens in Oslo, Norway using low-cost sensor nodes

Nuria Castell*, Philipp Schneider, Sonja Grossberndt, Mirjam.F. Fredriksen, Gabriela Sousa-Santos, Mathias Vogt, Alena Bartonova

NILU – Norwegian Institute for Air Research, Kjeller, Norway

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ABSTRACT

In Norway, children in kindergartens spend significant time outdoors under all weather conditions, and there is thus a natural concern about the quality of outdoor air. It is well known that air pollution is associated with a wide variety of adverse health impacts for children, with greater impact on children with asthma.

Especially during winter and spring, kindergartens in Oslo that are situated close to streets with busy traffic, or in areas where wood burning is used for house heating, can experience many days with bad air quality. During these periods, updated information on air quality levels can help the kindergarten teachers to plan appropriate outdoor activities and thus protect children's health.

We have installed 17 low-cost air quality nodes in kindergartens in Oslo. These nodes are smaller, cheaper and less complex to use than traditional equipment. Performance evaluation shows that while they are less accurate and suffer from higher uncertainty than reference equipment, they still can provide reliable coarse information about local pollution. The main challenge when using this technology is that calibration parameters might change with time depending on the atmospheric conditions. Thus, even if the sensors are calibrated a priori, once deployed, and especially if they are deployed for a long time, it is not possible to determine if a node is over- or under-estimating the concentration levels. To enhance the data from the sensors, we employed a data fusion technique that allows generating a detailed air quality map merging the data from the sensors and the data from an urban model, thus being able to offer air quality information to any location within Oslo.

We arranged a focus group with the participation of local administration, kindergarten staff and parents to understand their opinion and needs related to the air quality information that was provided to the participant kindergartens. They expressed concern about the data quality but agree that having updated information on the air quality in the surroundings of kindergartens can help them to reduce children's exposure to air pollution.

1. Introduction

The prevalence of childhood asthma has increased over the past decades, making it the most common chronic illness in children and the leading cause of pediatric hospitalization worldwide (Anandan et al., 2010; World Health Organization, 2008). Simultaneously, air pollution is a growing environmental concern, responsible for approximately 2 million premature deaths per year worldwide (World Health Organization, 2008). Children are particularly vulnerable to airborne pollutants because of their narrower airways and because they generally breathe more air per body weight than adults, increasing their exposure to air pollution. Children are particularly susceptible not only because their lungs are still developing, but because they are also often very active outdoors and have very different ventilatory parameters compared to adults that facilitate deeper and greater lung deposition of particles and gas/cell membrane interactions (Ciencewicki et al., 2008; Gasana et al., 2012). Children often breathe through their mouth especially when they exercise. Mouth-breathing bypasses the natural filtering of air pollutants by the nose and allows larger volumes of polluted air to affect the more sensitive areas of children's lungs which are still developing (Gasana et al., 2012). Therefore, they can be subject to oxidant-induced injury to the lungs, which can lead to permanent lung changes (Gilliland et al., 1999).

Numerous studies have indicated that exposure to traffic-related air pollution is associated with the increase in the incidence of childhood asthma or the development of asthma symptoms (Brauer et al., 2002; Gauderman et al., 2005; Gehring et al., 2002; McConnell et al., 2006; Zmirou et al., 2004). Results show that living or attending schools near

* Corresponding author.
E-mail address: ncb@nilu.no (N. Castell).

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high traffic density roads exposes children to higher levels of motor vehicle pollutants, and increases the incidence and prevalence of childhood asthma and wheeze (Gasana et al., 2012). Experimental studies indicate that chemicals found in diesel vehicle exhaust may actually trigger allergic reactions and aggravate respiratory conditions (Delfino et al., 2009). Traffic pollution has also been positively associated with the development of obesity in children aged 5–11 years (Jerrett et al., 2014). Other research indicates that exposure to air pollution may operate through inflammatory pathways to initiate metabolic processes contributing to diabetes formation (Brook et al., 2008; Krämer et al., 2010).

In the BREATHE study, indoor and outdoor air quality was assessed in 39 schools in Barcelona (Rivas et al., 2014). The authors found that the outdoor NO_2 concentration was 1.2 times higher at schools than at urban background sites, suggesting the proximity of some schools to road traffic. The indoor levels were similar to those detected outdoors, indicating easy penetration of atmospheric pollutants. To monitor NO_2, the authors employed passive dosimeters, obtaining weekly-averaged NO_2 concentrations. The limitation of dosimeters is the impossibility of offering real-time data, thus not being suitable for activity planning in the kindergartens.

Wichmann et al. (2010) monitored the relationship between indoor and outdoor air pollution levels in 6 schools and 10 pre-schools in Stockholm. They found that the indoor and outdoor NO_2 levels were strongly associated, indicating that the indoor environments occupied by children offer little protection against combustion-related pollutants. In the study, NO_2 was measured using diffusive samplers and averaged over 14 days. This type of monitoring offers a good understanding of the air quality situation at the place, but it cannot offer the necessary time resolution to change day-to-day activities in real-time to protect children's health.

During the last decade, the development of low-cost monitoring platforms has seen significant growth (Castell et al., 2013). Low-cost sensor nodes have a lower price than reference instrumentation and have the advantage over other traditional methods as diffusive samplers that they can monitor at high temporal resolution. This enables observations at high spatial resolution in near-real-time (Van den Bossche et al., 2016; Castell et al., 2015; Hasenfratz et al., 2015; Kumar et al., 2015) and provides an opportunity to continuously monitor air quality at places of interest like kindergartens.

However, low-cost sensor nodes have associated technological challenges. The most significant of these is the reliability of the measured air pollution data. Although the data quality of the novel low-cost monitoring devices have already improved drastically since their early days, it is not yet as reliable as that obtained at traditional reference measuring stations (Fishbain et al., 2016; Spinelle et al., 2017). Results show that some of the novel sensor nodes are capable of offering coarse information about air quality that easily indicates if the air quality is good, moderate or bad (Borrego et al., 2016; Castell et al., 2017). This type of indicative information on current air quality conditions can help kindergartens to plan their activities accordingly and thus protect children's health.

In Norway, children in kindergartens spend much time outdoors in all weather, and smaller children often sleep outdoors in their stroller. There is thus a natural concern about the quality of outdoor air. In the framework of the EU FP7 project CITI-SENSE (http://co.citi-sense.eu), we have mounted 17 units in kindergartens in Oslo to see to what extent we can provide air quality information to kindergartens that is useful for them. Together with the data from the low-cost nodes, we also have developed an air quality map using a data fusion method allowing to merge an average concentration field with the real-time data gathered by the sensors. In order to evaluate to what extent this information is useful for the kindergartens, we organized focus groups at the end of our study with the local administration in charge of the public kindergartens, kindergarten staff and parents.

2. Material and methods

2.1. Study area

The study was carried out in the city of Oslo, Norway (658390 inhabitants in 2016). The municipality of Oslo has an area of 130 km^2, and it is situated at the northernmost end of the Oslo fjord. While the fjord lies to the south of the city, in all other directions Oslo is surrounded by wooded hills and mountains. Oslo has a humid continental climate, which is highly influenced by the warm Gulf Stream, thus making the climate milder than at similar northern latitudes elsewhere over the globe. In summer, the daily mean temperature is around 16 °C, and during winter it is around −4 °C (climate data for Oslo-Blindern for the period 1961–1990). In January, three out of four days are below 0 °C, and on average one out of four days is colder than −10 °C.

Traffic, especially exhaust from heavy-duty vehicles and private diesel vehicles and dust resuspension from studded tyres, together with wood burning in winter, are the main sources of pollution in Oslo. Emissions from the harbour also contribute to the pollution levels.

During winter, on cold, clear days with low or no wind, Oslo often experiences the formation of thermal inversions, with a reversal of the normal decrease of air temperature with altitude. The warm air on the top holds down the cool air and prevents pollutants from rising and dispersing. The inversion layer can persist for several days, causing an increase in the pollution levels, exceeding, in some occasions, the air quality thresholds defined for human health protection.

Norway, as part of the European Economic Area, is obliged to comply with the European air quality regulations (e.g., Directive 2008/50/EC) and ensure clean air. Nevertheless, Oslo exceeded both the annual and hourly NO_2 threshold for health protection defined in the Directive 2008/50/EC (EU, 2008) in 2015.

2.2. Monitoring sites: kindergartens and reference stations

The low-cost sensor nodes were installed in 17 kindergartens in Oslo. Fig. 1 shows the location of the low-cost sensors and the reference stations. The monitoring campaign was performed from the 1st to the 31st of January 2016. The sensor nodes were located outdoors, on the playground of the kindergarten, at heights of around 2.5 − 3 m (Fig. 1, red circles). Additionally, 6 sensor nodes were installed in streets in Oslo (Fig. 1, green squares).

During January 2016, NO_2 concentrations were monitored at 9 reference stations in Oslo (Fig. 1, yellow stars). These stations are equipped with certified reference instruments for measuring regulatory pollutants. They are also subject to strict routines of maintenance and calibration of their instruments to ensure high quality data. During the campaign, a low-cost sensor node, identical to the one employed in the kindergartens, was co-located at the reference traffic station of Kirkeveien (Fig. 1, yellow cross). We classified the traffic intensity in the neighbourhood of the kindergartens, employing the average daily traffic (ADT) given by the Norwegian road authorities:

- Super traffic locations: ADT > 50,000 vehicles/day
- High traffic locations: 20,000 < ADT < 50,000 vehicles/day
- Medium traffic locations: 5000 < ADT < 20,000 vehicles/day
- Low traffic locations: 500 < ADT < 5000 vehicles/day
- Urban background sites: ADT < 500 vehicles/day

Following that classification, within a radius of 50 m, 9 kindergartens are situated in urban background, 2 in low traffic and 6 in medium traffic. If we expand the radius to 100 m, 10 of the kindergartens are in medium traffic locations with an ADT between 8000 and 19,000 vehicles per day. For a radius of 200 m, 12 of the kindergartens are in medium traffic locations, 2 in high traffic locations and one in a super traffic location. The high traffic locations have and ADT of 20,200 veh/day and 48,700 veh/day and the super traffic location has an ADT of 82,100 veh/day.

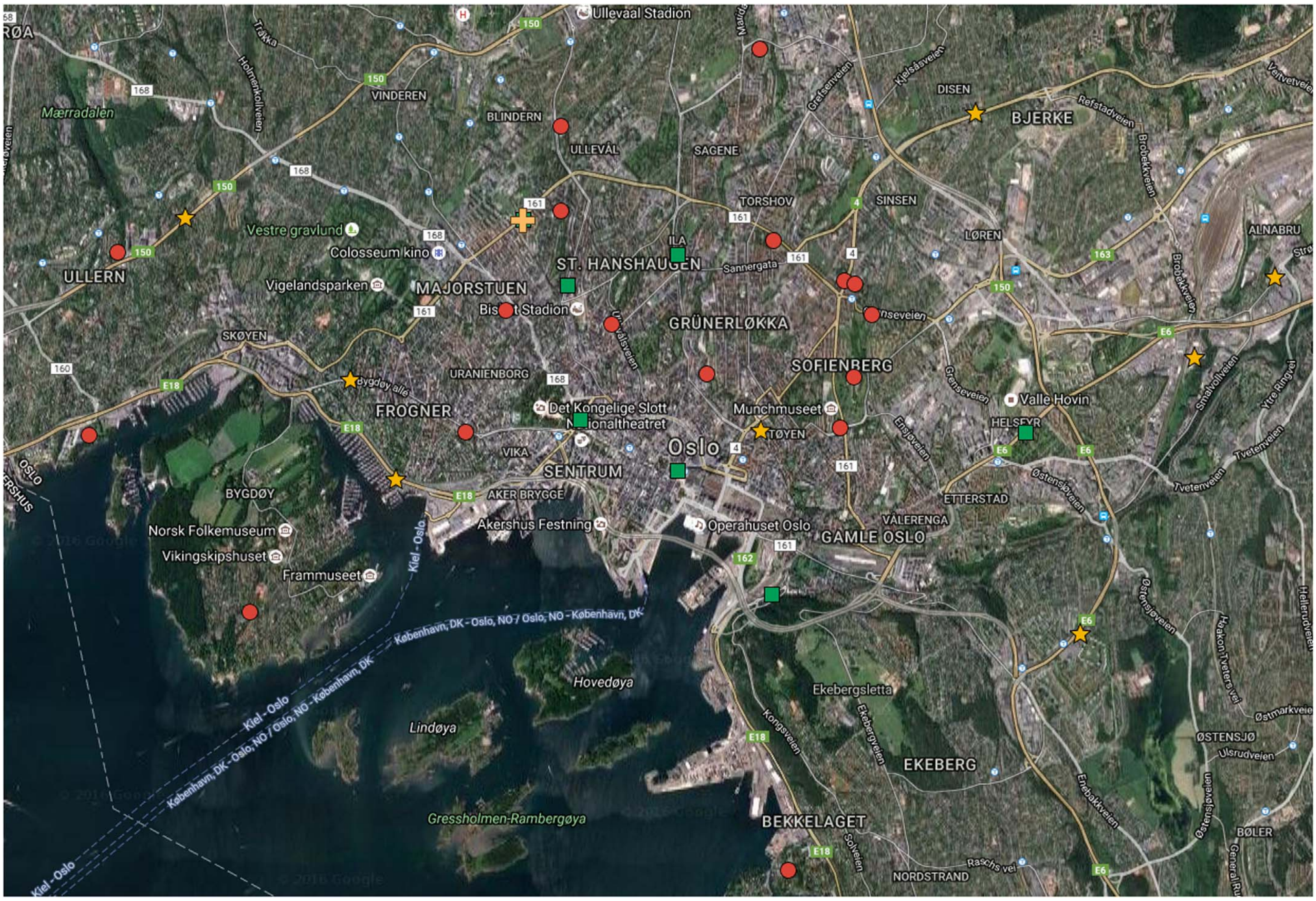

Fig. 1. Location of the (i) low-cost sensor nodes at kindergartens (red circles) and streets (green squares) and (ii) reference stations monitoring NO_2 (yellow stars). The yellow cross is the reference station of Kirkeveien where one of the low-cost node was co-located during January 2016.

2.3. Air quality data

2.3.1. Air quality monitoring using low-cost sensors

Air quality in the kindergartens was monitored during January 2016 employing the commercial low-cost platform AQMesh v3.5 (provided by Environmental Instruments Ltd, UK, www.aqmesh.com). The AQMesh nodes are battery driven stationary platforms which measure four gaseous components (CO, NO, NO_2 and O_3), particle number, temperature, relative humidity and atmospheric pressure. A proprietary algorithm is used to post-process the data gathered by the gas sensors with the aim to correct cross-interferences and the effect of temperature and relative humidity. In this study, we focus on the analysis of the NO_2 concentrations. The NO_2 sensor employed in the AQMesh v3.5 is an electrochemical sensor provided by Alphasense (NO2-B42F) that incorporates a filter to eliminate cross-sensitivity issues with O_3. The low-cost sensor nodes provided air quality information at a temporal resolution of 1 h.

2.3.2. Air quality modelling using EPISODE dispersion model

EPISODE is a 3-D Eulerian/Lagrangian dispersion model that provides urban and regional-scale atmospheric pollutant concentrations such as NO_2. The model is an Eulerian grid model with embedded subgrid models for computing the pollutant concentrations originating from area-, point- and line-based emission sources. EPISODE employs schemes for advection, turbulence, deposition and chemistry. The model can be run at horizontal spatial resolutions down to 100 m. EPISODE has a temporal resolution of 1 h. The model uses as input the emissions from an official inventory and the meteorology is provided by a meteorological model. The EPISODE model does not use data from the low-cost nodes. A more detailed description of the model can be found in Slørdal et al. (2003).

2.3.3. Air quality mapping using data fusion techniques

In order to provide near-real time high-resolution spatial maps of air quality, we developed an approach based on data fusion techniques, which allow for combining low-cost sensor hourly observations (representing temporal variability) with a characterization of spatial distribution derived from the EPISODE model (Lahoz and Schneider, 2014; Schneider et al., 2017).

The EPISODE model provided a base map (i.e., characterization of the spatial distribution of the concentrations) representing the NO_2 annual average concentration field for 2013 (Fig. 2). This gives detailed spatial pattern in the model area. We then combine the map with real-time hourly data collected by the low-cost nodes using data fusion techniques (Schneider et al., 2017). In this way, we obtain a real-time map for every hour of the monitoring period, reflecting short-term variability.

2.4. Air quality visualisation portal

We developed a web portal to visualise the data from the sensor nodes in real-time, as part of visualisation of all information collected by the CITI-SENSE project (CITI-SENSE, 2016). The web portal showed the location of each sensor node on Google Maps© and provided real time information on the measured air quality levels (Fig. 3). Air quality information was displayed using a 5-colour scale (Air Pollution

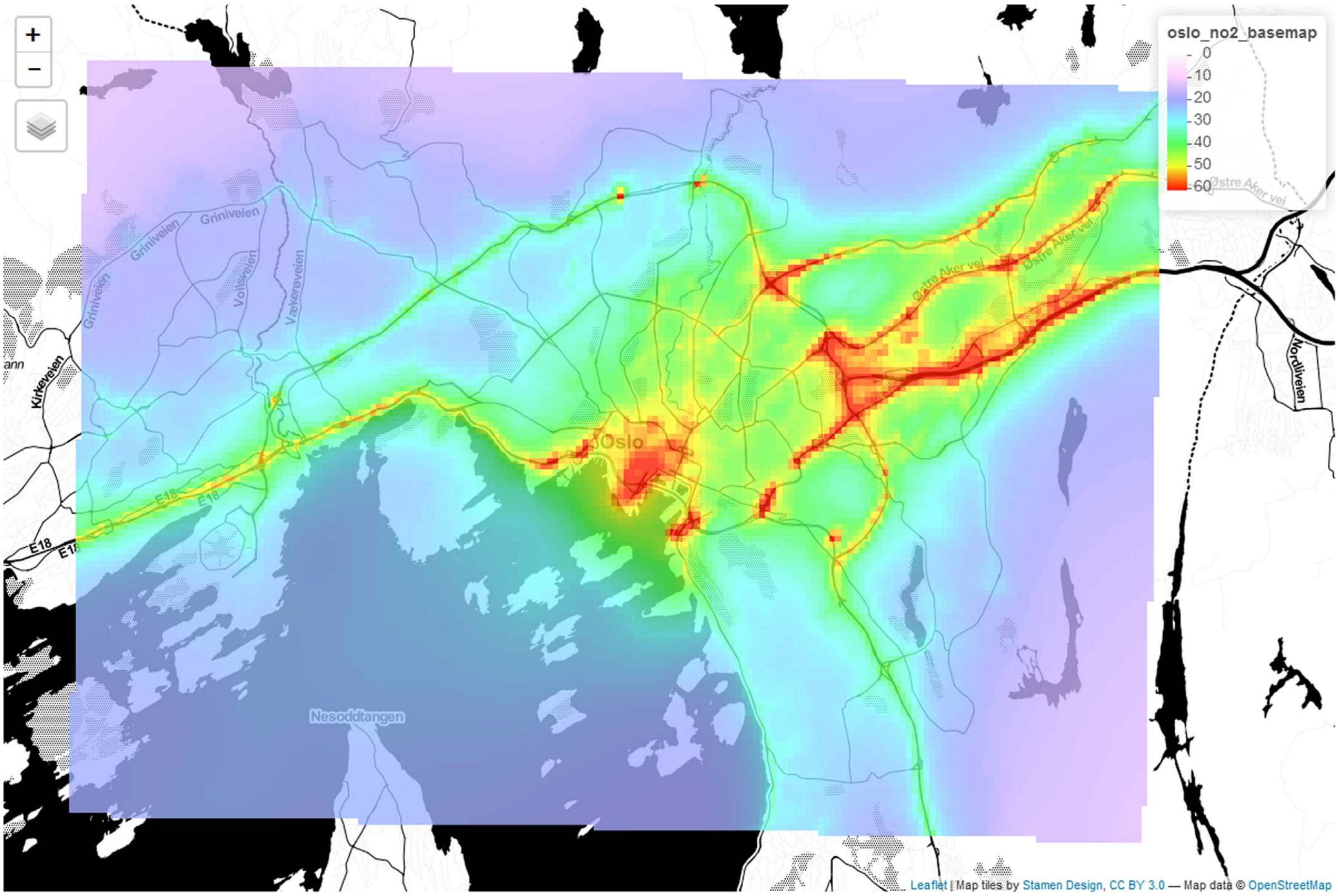

Fig. 2. Air quality base map for NO_2 employed in the data fusion technique. The map was obtained with the EPISODE model and represents the NO_2 yearly average concentrations for 2013 in units of $\mu g/m^3$.

Indication, APIN), indicating if the air pollution is very low, low, rather low, rather high or very high. The thresholds were based in the Common Air Quality Index (CAQI) for hourly values. The CAQI was proposed to facilitate the comparison of air quality in European cities in real-time (Van den Elshouta et al., 2014).

The user could choose a specific period to see the air quality over time. By clicking on a specific sensor node, additional information on its current data would be available (e.g., APIN values for the last 24 h). A summary graph would also indicate air quality measured by all sensor units and provide an overall APIN for the whole city. The user could also see the air quality map generated in real time. The kindergarten staff received information about the web portal and the URL with instructions on how to use it.

2.5. Focus groups

We made use of focus groups in order to obtain feedback from local administration, kindergarten staff and parents about their need related to air quality information in kindergartens and specifically about their opinion on the air quality data generated in this study.

Focus groups are a well-established method in both marketing and research (especially social and health sciences) and have been applied for more than 50 years (Galloway Research Service, 2016). A focus group is a dynamic interaction process with an open discussion on given topics to identify the perceptions, opinions, needs or attitudes of a defined group. This setting allows for obtaining more in-depth knowledge from the participants through exchange not only with the facilitator, but also amongst the participants (Kitzinger, 1995). Ideally, each group consists of four to eight participants and a facilitator/moderator.

Focus groups within social sciences are a well-established instrument to obtain in-depth information on certain topics from both educational staff, the children themselves or the parents. The topics of concern are manifold, ranging from nutrition to inclusion, health related issues, to child abuse (e.g., Frerichs et al., 2016, Starr et al., 2016, Heary and Hennessy, 2000, Feng et al., 2009).

At the end of the CITI-SENSE project, we had two focus groups with user-groups, one with parents (3 attendees) and one with kindergarten staff (6 attendees). In both of them we had one representative of the local administration in charge of the public kindergartens in Oslo. The goal of the focus groups was to assess if the information provided in the visualisation portal was clear and meaningful for the participants and how it can be improved. The participants were asked to what extent outdoor air quality information at kindergartens was useful for them, what and how this information could help them to do better and what were the opportunities, barriers and conditions that should be met to take actions based on the air quality information. The focus groups had a duration of approximately 2 h. We recorded and transcribed the discussions for their posterior analysis.

3. Results

3.1. Comparison of the low-cost node output and a reference monitor data

Before the sensor nodes were deployed in the kindergartens, they were all co-located at the Kirkeveien traffic air quality monitoring station in Oslo for the period between April and June 2015. The goal of the co-location was to test the performance of the sensor nodes, and correct possible biases by applying a field calibration. The results of the

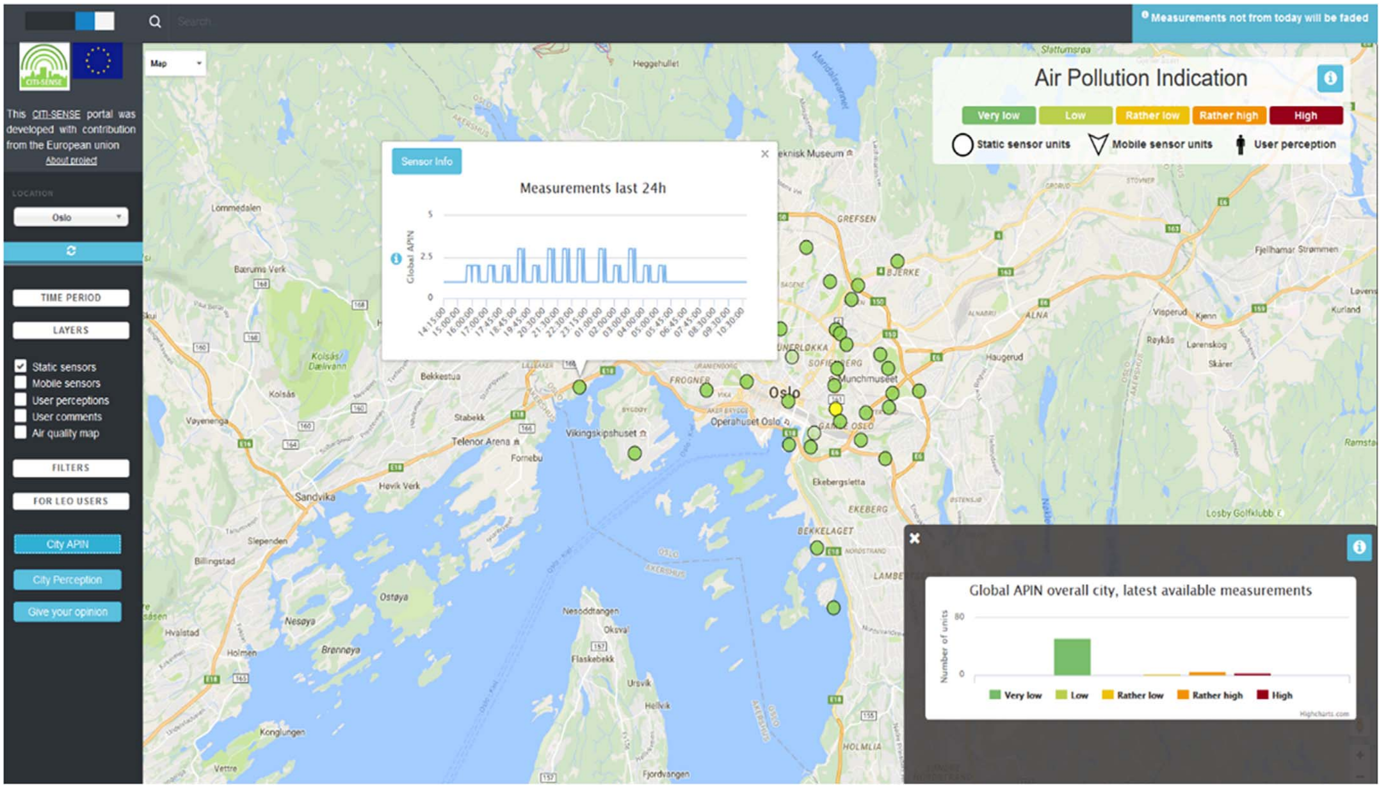

Fig. 3. Data visualisation portal displaying the air quality information collected by the AQMesh sensor nodes deployed in kindergartens and streets in Oslo.

co-location showed that the AQMesh nodes presented low accuracy for regulatory purposes, but they can provide relative and aggregated information about the observed air quality indicating if the air pollution is low, medium or high (Castell et al., 2017). The main challenge is that the field calibration parameters might change with the meteorological conditions and the location. It is therefore not possible to fully ensure that the sensor will not suffer from biases once deployed (Castell et al., 2017).

During the campaign in January 2016, one of the nodes remained co-located at the traffic reference station at Kirkeveien. The results for the co-location show a good performance for NO_2 with a correlation (r) of 0.95, a mean bias (MB) of −8 ppb and a root mean square error (RMSE) of 14 ppb (see Fig. 4). However, the slope during January is 0.5, indicating that the field calibration applied with the values from April to June 2015 is no longer accurate. This is an example of the change in the calibration factors due to different environmental conditions in January (deployment campaign) and in April-June (calibration campaign). The fact that the calibration factors might change with the environmental conditions is one of the main challenges of low-cost sensors, as it is not possible to know if the concentrations will be over or underestimated once the nodes are deployed in the field.

Fig. 5 shows that the AQMesh node captures the increase in the NO_2 concentrations on the 5th of January and during the pollution episode between the 19th and 21st of January. However, the node underestimates the NO_2 concentrations. The main challenge of low-cost sensors is that they suffer from chemical interference and are affected by environmental conditions (Aleixandre and Gerboles, 2012; Castell et al., 2017). Field calibration of low-cost sensors still represents a challenge, but new investigations suggest that the introduction of supervised learning techniques can reduce the measurement error (Spinelle et al., 2015, 2017).

3.2. Comparison of the data fusion output and a reference monitor data

The results for January 2016 show a good agreement between the

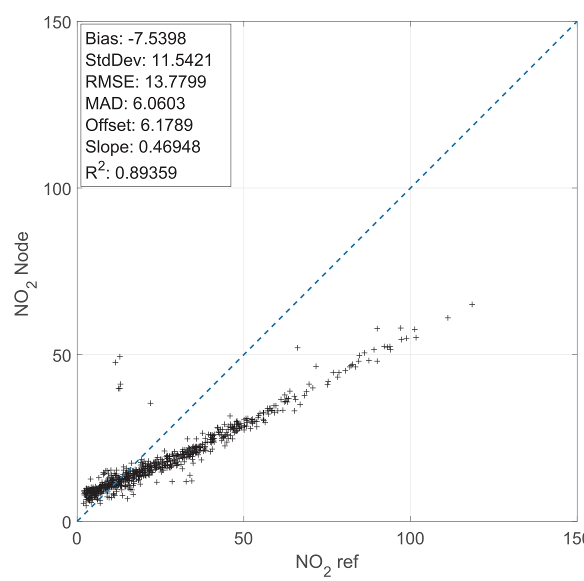

Fig. 4. Correlation plot for NO_2 monitored by the AQMesh node and the reference monitor for January 2016. NO_2 concentrations are in ppb.

NO_2 concentrations obtained using the data fusion technique and the reference data, with a correlation (r) of 0.9. The MB is −5 ppb and the RMSE is 11 ppb (Fig. 6). When employing the data fusion technique the bias and errors are reduced compared to only using low-cost sensors. The correlation is slightly lower than only using data from low-cost node (Fig. 4), probably due to the fact that we are missing local events measured only by the sensor located on the top of the station and not by the other nearby sensors.

Fig. 7 shows the hourly concentrations for January 2016. During the episode between the 19th and 21st of January, the concentrations obtained with the data fusion technique are underestimated but are closer

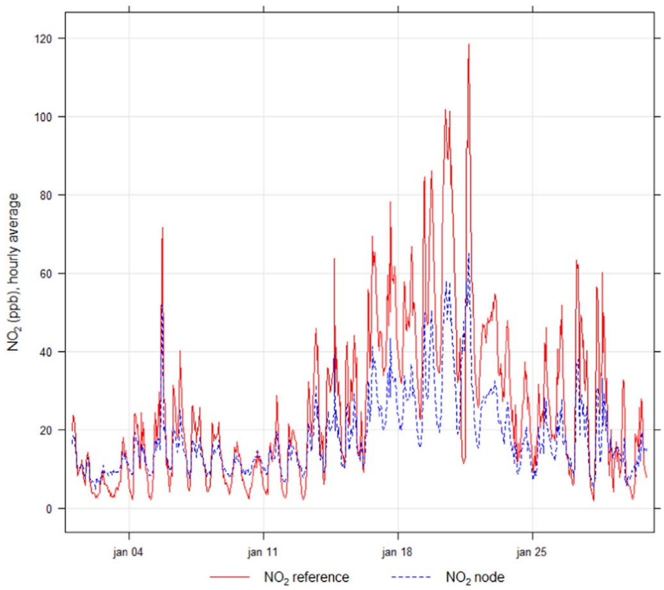

Fig. 5. NO_2 hourly concentrations measured at Kirkeveien monitoring station by the reference monitor and by the AQMesh node.

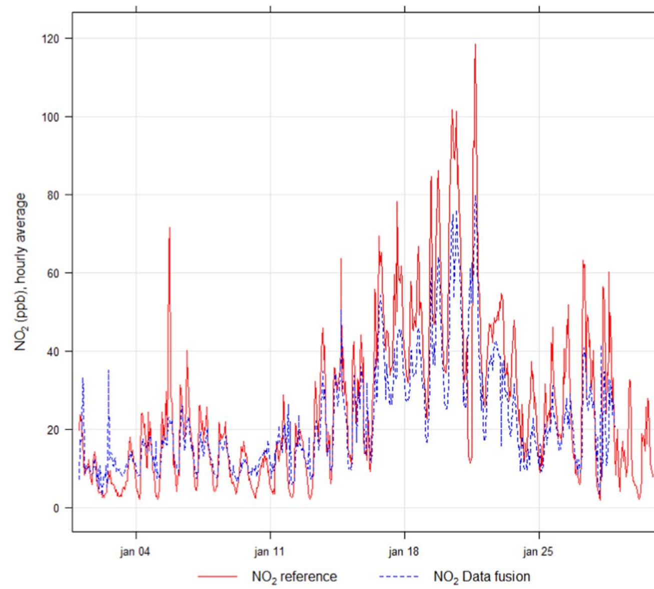

Fig. 7. NO_2 hourly concentrations measured at Kirkeveien monitoring station by the reference monitor and obtained using the data fusion technique.

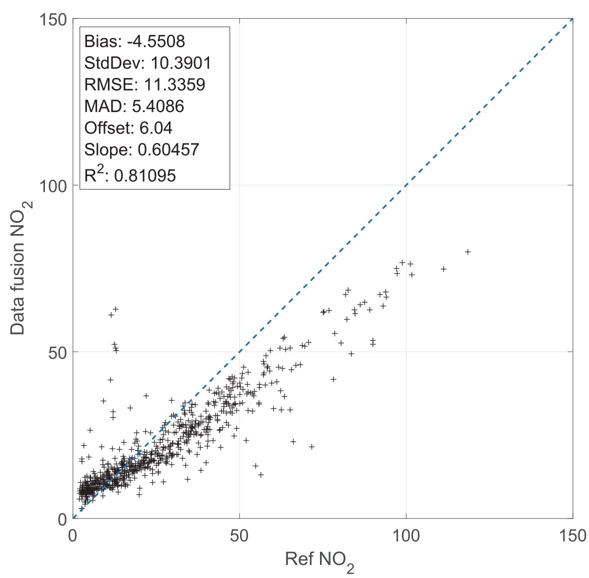

Fig. 6. Correlation plot for NO_2 obtained using the data fusion technique and measured by the reference monitor at Kirkeveien station for January 2016. NO_2 concentrations are in ppb.

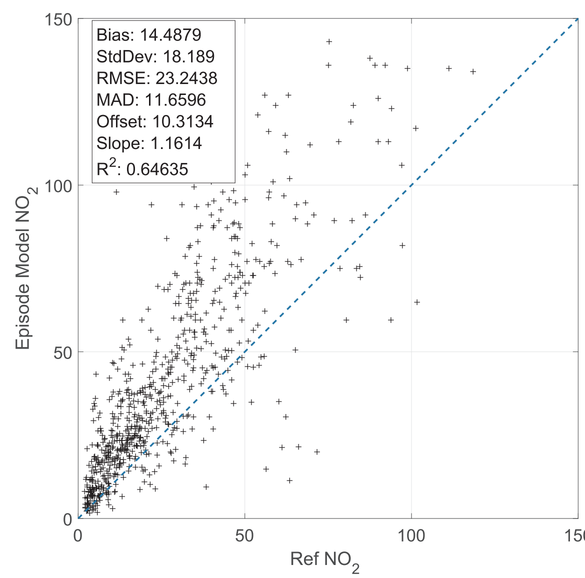

Fig. 8. Correlation plot for NO_2 modelled by the EPISODE model and measured by the reference monitor at Kirkeveien station for January 2016. NO_2 concentrations are in ppb.

to the ones measured by the reference monitor than if we only use the data from the low-cost node. However, we miss the peak on the 5th of January. The reason is that the peak was caused by a local event that was not monitored by the nodes nearby.

3.3. Comparison of the EPISODE model output and a reference monitor data

We ran the EPISODE model hour-for-hour for January 2016 and compared the results of the model with the data measured at the Kirkeveien reference station. The results show that the model and the reference data have a correlation (r) of 0.8, and RMSE of 23 ppb and a MB of 15 ppb (see Fig. 8). The RMSE obtained with the EPISODE model is higher than the one obtained with the low-cost node. The correlation using the EPISODE model is lower than using low-cost sensor nodes and the data fusion techniques, this can be due to the fact that the model does not use any real-time data, and therefore cannot capture specific events (e.g. roads closed due to an accident).

Fig. 9 shows that the EPISODE model captures the rise in NO_2 concentrations between the 19th and 21st of January but it does not capture the NO_2 peak on the 5th of January. Contrary to the low-cost sensor node and the data fusion method, the EPISODE model overestimates the NO_2 concentrations. This might be caused by modelling errors, due mainly to errors in the input data, as for instance meteorology, pollutant emissions and background conditions. The meteorology is obtained with a meteorological model, and can under- or overestimate the wind speed, temperature or have errors in the wind direction. The pollutant emissions are based on annual averages that are spatially distributed according to the location of the sources (i.e., roads, house heating, industry) and temporally distributed according to an average temporal pattern depending on the type of source (Slørdal, 2003). Due to uncertainties, emissions can have biases in the total amount assigned to each location. In our case, the model

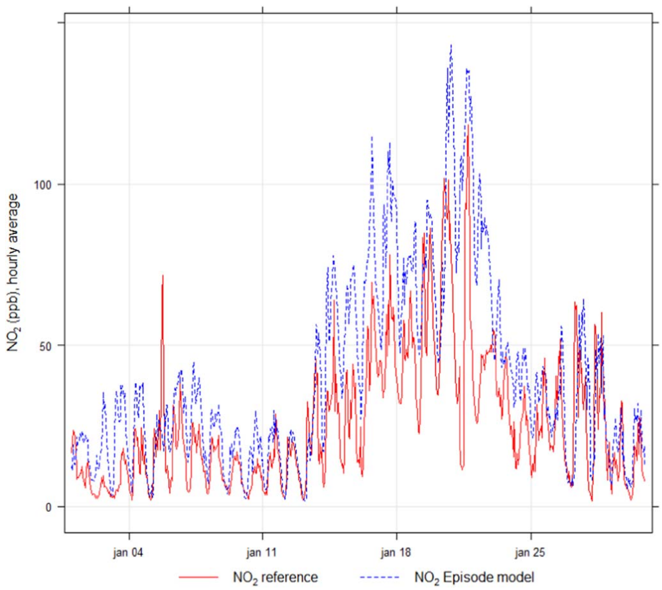

Fig. 9. NO_2 hourly concentrations measured at Kirkeveien monitoring station by the reference monitor and modelled by EPISODE.

overestimation is more probably caused by the background concentrations. We employed as regional background concentrations the NO_2 levels measured at a reference station located in the roof of a building (25 m high) in the centre of Oslo. The station can still be influenced by the local sources, especially during thermal inversion conditions, resulting in an overestimation of the concentrations. The use of regional background concentrations instead of urban background concentrations will help to improve the model outputs. Unfortunately, regional NO_2 background concentrations were not available for January 2016.

3.4. Air quality information for the Oslo kindergartens

Our main goal was to provide localized real-time air quality information to the kindergartens. We analysed the benefits and challenges of employing three different sources of information: (1) data from low-cost sensors deployed in the playground of the kindergarten, (2) data obtained using an air quality model (EPISODE) and (3) data obtained employing a data fusion technique, merging a static base map and real-time data from the sensors.

Table 1 shows the average and standard deviation of the NO_2 concentrations in January 2016 at the 17 kindergartens and at the Kirkeveien reference station. The results show that depending on the source of information the reported concentration is different. For example, the EPISODE model gives higher concentrations than the AQMesh node or the data fusion. The monthly average and standard deviation measured by the reference equipment at Kirkeveien is 26 ± 21 ppb. The data fusion technique is the one closer to the concentrations from the reference station (22 ± 14 ppb). The AQMesh nodes underestimate the monthly average concentrations (18 ± 10 ppb). The node at location Grünerhagen Barnehage has a large bias, showing unrealistic readings (monthly NO_2 average concentration of 244 ppb). When employing the data fusion method, the concentration values at Grünerhagen are more realistic, with a monthly average concentration of 23 ppb. When merging the data from a node, the data fusion method not only considers the data from that node but also the concentrations from the nearby nodes. If the concentrations measured by the nearby nodes are lower, that will result in lower concentrations. In that sense, the data fusion helps to tackle the calibration issues that the low-cost sensors experience when deployed in the field.

The Air Quality Directive 2008/50/EC (AQD) (EU, 2008)

Table 1
NO_2 average concentrations and standard deviation (in ppb) at the 17 kindergartens measured by the AQMesh nodes, modelled by the EPISODE air quality model and obtained with the data fusion technique. The average daily traffic (ADT) is the maximum in a radius of 100 m of the kindergarten.

Location	ADT at 100 m (veh/day)	AQMesh node	EPISODE	Data fusion
Badebakken barnehage	10,000	8 ± 4	36 ± 29	21 ± 14
Barnas hus barnehage	19,000	16 ± 7	44 ± 33	24 ± 15
Bellevue Samisk Gård barnehage	0	23 ± 6	42 ± 32	22 ± 14
Bergebo barnehage	4000	17 ± 5	36 ± 31	20 ± 13
Hasselkroken Kanvas barnehage	4000	19 ± 5	36 ± 30	16 ± 10
Fagerborg Menighetsbarnehage	2250	14 ± 7	39 ± 31	21 ± 14
Grünerhagen barnehage	4000	244 ± 157	44 ± 33	23 ± 14
Heibergløkka barnehage	17,300	13 ± 6	46 ± 33	26 ± 16
Hjelmsgate barnehage	11,000	11 ± 6	39 ± 32	20 ± 11
Melkeveien barnehage	11,400	22 ± 8	42 ± 33	22 ± 13
Nedre Bekkelaget barnehage	500	14 ± 4	32 ± 26	18 ± 10
Ola Narr barnehage	9000	8 ± 6	44 ± 33	24 ± 15
Sognsveien barnehage	11,200	11 ± 5	38 ± 31	20 ± 13
Sophies hage barnehage	16,000	24 ± 8	46 ± 33	25 ± 16
Stiftelsen Hydroparken barnehage	8000	16 ± 4	41 ± 33	21 ± 12
Støperiet barnehage	2200	23 ± 7	43 ± 33	25 ± 16
Værkerø gård barnehage	9032	18 ± 8	42 ± 31	27 ± 18
Kirkeveien reference station	20,200	18 ± 10	40 ± 30	22 ± 14

establishes health-based standards and objectives for a number of pollutants. For NO_2, the AQD establishes an hourly limit value of 200 µg/m^3 that should not be exceeded more than 18 times per year. The reference station of Kirkeveien registered an exceedance of the hourly limit value on the 21st of January for 2 h, at 16:00 and 17:00. The EPISODE model registered that exceedance. However, the AQMesh node and the data fusion method did not show any exceedance on the 21st of January 2016.

Fig. 10 shows the hourly NO_2 concentrations during the pollution episode in Oslo between the 19th and 21st of January. The

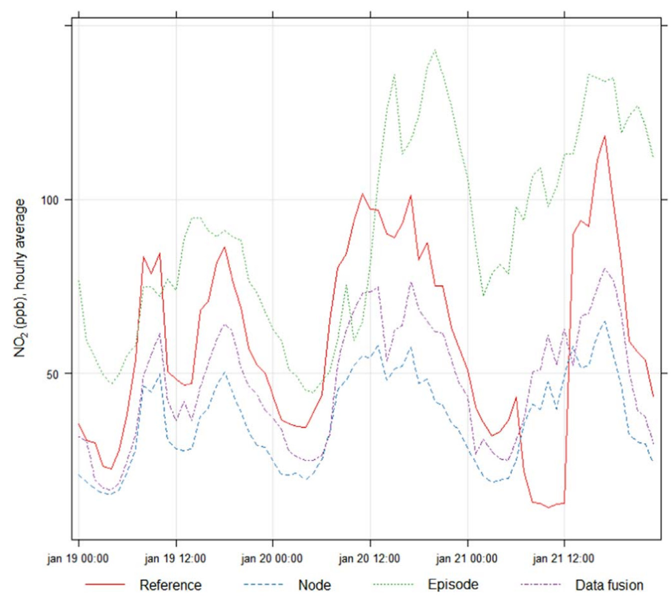

Fig. 10. NO_2 concentrations measured by the reference instrument, by the AQMesh node, modelled by the EPISODE model and obtained with the data fusion technique in Kirkeveien station between 19th January and 21st January 2016.

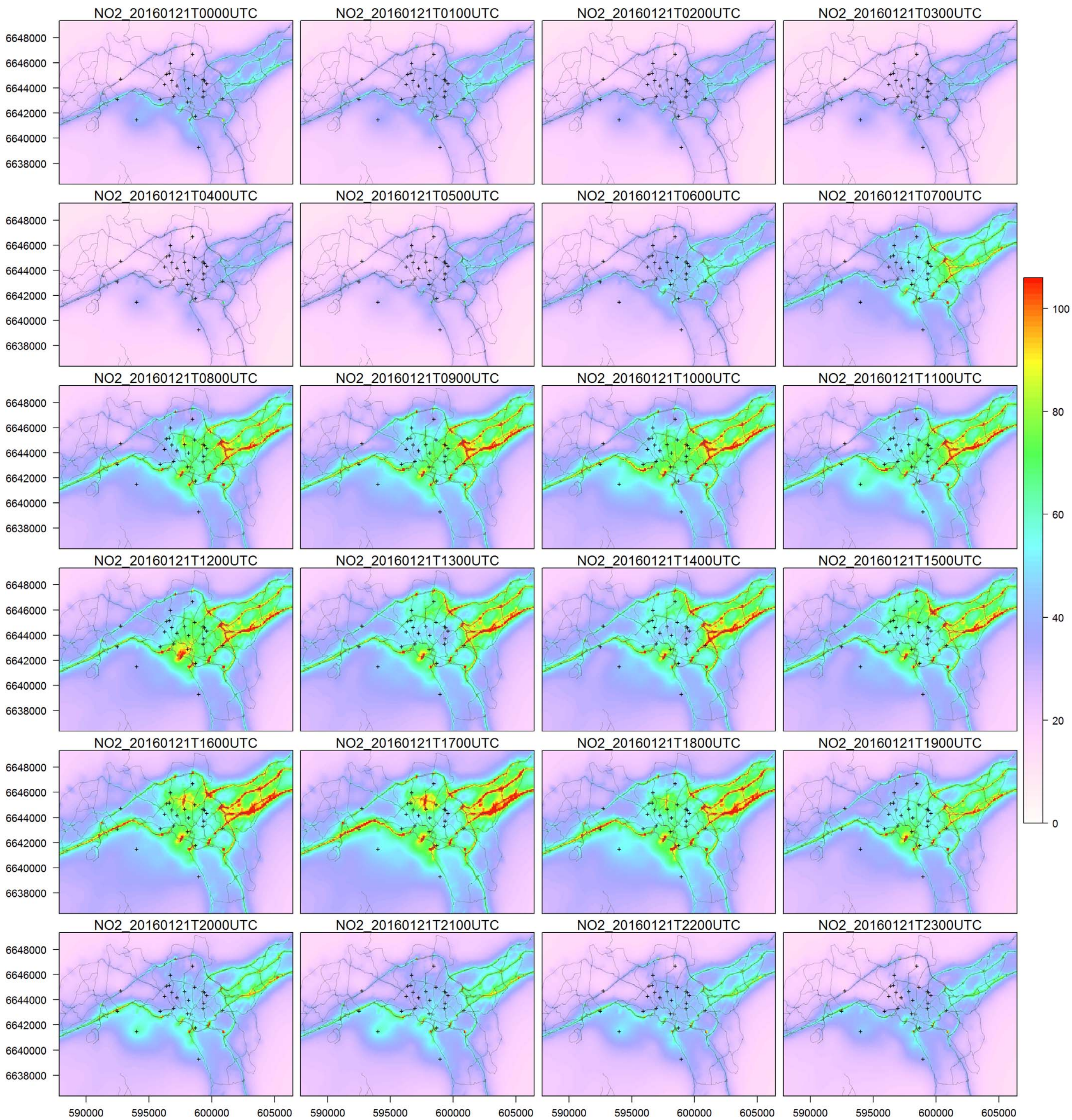

Fig. 11. Air quality NO_2 map for the city of Oslo created by merging the data from the static sensors and the annual average NO_2 concentrations from an air quality model. The results are for the 21st of January 2016 from 00:00 to 23:00. The map shows NO_2 concentrations in ppb. The dots represent the location of the 24 AQMesh nodes.

meteorological conditions were favourable to the formation of a thermal inversion with cold temperatures and low wind speed. The NO_2 concentrations show an increasing trend with the highest concentrations on the 21st of January (see Fig. 10, Reference). The EPISODE model shows also a clear increasing trend although the highest concentrations are registered on the 20th of January. The data fusion and the node also shows an increasing trend, capturing the temporal pattern and the occurrence of the NO_2 peaks.

Fig. 11 shows an example of the air quality map generated with the data fusion technique for the 21st of January 2016. The map shows that air pollution is higher along the main roads and during the times when there is more traffic. By fusing the data of the sensor nodes with the air quality model, we are able to visualise air quality patterns. An advantage of the data fusion technique is that we are able to offer real-time air quality information not only to the kindergartens that have low-cost sensors installed, but also to any location in Oslo. This offers great opportunities for raising public awareness and protecting children's health.

3.5. Findings from the focus groups

We held two focus groups, one with parents (3 attendees) and one with kindergarten staff (6 attendees). A representative of the local administration working with air pollution in Oslo attended both focus groups. The aim of the focus groups was not only to obtain information about the functionality and user friendliness of the data visualisation web portal, but also the respondents' view on the information need related to air quality information in kindergartens in Oslo.

Overall, the participants expressed that they are very interested in receiving air quality information and rated the web portal as a useful tool to receive information on air quality. For example, one father commented that receiving updated information on air quality could help him to plan the medication of his asthmatic child. Kindergarten staff commented that localized real-time information could help them to plan outdoor activities according to air pollution levels. In this context, additional health related information would be much appreciated by the users. One topic that has been discussed was the communication of air quality levels. This information should be communicated in an easy to understand way so that people without any scientific background can understand what the air quality levels mean for their health and how they should behave in each situation. The participants agreed that this might also be a way to motivate people that are generally less interested in air quality issues to become more engaged, because they see the potential impacts on their or their children's health. In the long run, information on air quality could eventually be used by citizens' groups to put pressure on local administration or policy makers to implement measures for improving air quality.

Although the data visualisation portal has been rated as quite useful overall, the participants also admitted that the uncertainty of the data at this point would rather limit their actions based on the air quality information obtained from the visualisation portal. If the actions were too costly, such as moving away from a more polluted to a less polluted area, this would also limit the participants' possible actions.

4. Discussion

There is clearly a need to empower the kindergarten staff to take actions to minimize children's exposures to harmful air pollutants while at the kindergarten. Such actions could be based on accurate and timely locally specific air quality information in real time. We investigate information that can be provided by the combination of low cost sensors representing temporal patterns and a base map representing spatial patterns, and compare this also to high resolution dispersion modelling that in Oslo is used for short-term (days) air quality predictions.

Real-time air quality maps can be generated using an air quality dispersion model such as e.g., EPISODE. However, not all cities have a suitable air quality model in place, as this is demanding in terms of availability of the necessary input data and expensive in expert time needed to run the model. The advantage of the data fusion technique is that the base map can be generated employing also less demanding techniques than dispersion modelling, as long as they capture the spatial correlation with air pollutants. Such alternative techniques to generate the base map are land use regression or simply using spatial proxy datasets such as distance to roads or similar. In this way, the data fusion technique can be implemented also in smaller cities.

The quality of the resulting high-resolution map depends on the quality of the sensor data as well as the quality of the base map. While the data fusion method is capable of dealing with erroneous measurements to some extent by using data from the entire deployed sensor network, it is still necessary to ensure that the data from the individual sensor nodes is of good quality and that the biases are as low as possible. The low-cost sensors can capture local events that cannot be captured by an urban dispersion model as it employs emissions that are usually derived from annual inventories. However, the calibration parameters of the low-cost nodes might change with the environmental conditions resulting in wrong readings. Data fusion techniques provide a way of merging both datasets, constraining the data from the urban model with real-time data from sensors. The quality of the data fusion map depends on the quality of the input data. If we use an urban model based on good quality high-resolution emission information that also accounts well for described background conditions, and combine this with data from low-cost sensors calibrated with regard to real atmospheric conditions, the data fusion results can considerably improve. In addition, this method has the advantage of being computationally less demanding than a real-time high resolution dispersion modelling.

5. Conclusions

We installed 17 nodes monitoring NO_2 in the playground kindergartens in Oslo and one node in the top of a reference air quality monitoring station. The results showed that low-cost sensors can provide an indication of the air pollution levels, being capable to reproduce the trends during a high pollution episode.

We identified that the main challenge in the use of low-cost sensors is that calibration parameters might change with time depending on the atmospheric conditions. Thus, even if the sensors are calibrated a priori, once deployed, and especially if they are deployed for a long time, it is not possible to determine if a node is over- or under-estimating the concentration levels. More research is needed in order to improve sensor technology as well as to develop field calibration techniques that allow bias correction on the spot.

We investigated the use of data fusion techniques to produce air quality maps using the data from the low-cost sensors. The results showed that this method provides good results and is able to fill the gaps between measurements. This would enable us to offer air quality information to all kindergartens in Oslo and not only to those that have low-cost sensors installed.

The focus groups with parents, kindergarten staff and the local administration showed that there is an increasing interest in receiving personalized air quality information to change kindergarten practices to protect children's health. The outlook for low-cost sensor nodes is promising and we have demonstrated the big potential that lies within this new technology to provide localized real-time air quality information, especially when combining it with data fusion techniques.

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