Atmospheric
Chemistry
and Physics

Dispersion of particulate matter (PM$_{2.5}$) from wood combustion for residential heating: optimization of mitigation actions based on large-eddy simulations

Tobias Wolf, Lasse H. Pettersson, and Igor Esau

Nansen Environmental and Remote Sensing Center, Jahnebakken 3, N-5007 Bergen, Norway

Correspondence: Igor Esau (igore@nersc.no)

Abstract. Many cities in the world experience significant air pollution from residential wood combustion. Such an advection–diffusion problem as applied to geographically distributed small-scale pollution sources presently does not have a satisfactory theoretical or modeling solution. For example, statistical models do not allow for pollution accumulation in local stagnation zones – a type of phenomena that is commonly observed over complex terrain. This study applies a Parallelized Atmospheric Large-eddy simulation Model (PALM) to investigate dynamical phenomena that control variability and pathways of the atmospheric pollution emitted by wood-burning household stoves. The model PALM runs at spatial resolution of 10 m in an urban-sized modeling domain of 29 km by 35 km with a real spatial distribution of the pollution source and with realistic surface boundary conditions that characterize a medium-sized urban area fragmented by water bodies and hills. Such complex geography is expected to favor local air quality hazards, which makes this study of general interest. The case study here is based on winter conditions in Bergen, Norway. We investigate the turbulent diffusion of a passive scalar associated with small-sized particles (PM$_{2.5}$) emitted by household stoves. The study considers air pollution effects that could be observed under different policy scenarios of stove replacement; modern woodstoves emit significantly less PM$_{2.5}$ than the older ones, but replacement of stoves is a costly and challenging process.

We found significant accumulation of near-surface pollution in the local stagnation zones. The simulated concentrations were larger than the concentrations obtained only due to the local PM$_{2.5}$ emission, thus indicating dominant transboundary contribution of pollutants for other districts. We demonstrate how the source of critical pollution can be at-

tributed through model disaggregation of emission from specific districts. The study reveals a decisive role of local air circulations over complex terrain that makes high-resolution modeling indispensable for adequate management of the urban air quality.

This modeling study has important policy-related implications. Uneven spatial distribution of the pollutants suggests prioritizing certain limited urban districts in policy scenarios. We show that focused efforts towards stove replacement in specific areas may have a dominant positive effect on the air quality in the whole municipality. The case study identifies urban districts where limited incentives would result in the strongest reduction of the population's exposure to PM$_{2.5}$.

1 Introduction

Residential wood combustion in households is a significant global air polluter. Even in developed countries, e.g., in Scandinavia, wood burning for residential heating is a dominant source of air pollution in cold winter days (Savolahti et al., 2019; Kukkonen et al., 2020). A low-temperature wood-burning process emits a considerable amount of particulate matter of less than 2.5 μm (micrometer) in size. Such particles are collectively abbreviated as PM$_{2.5}$. In fact, residential combustion is the largest PM$_{2.5}$ emitter in the Nordic countries, including Norway (Im et al., 2019). Studies reveal that PM$_{2.5}$ concentrations attributed to residential wood combustion in Oslo may reach 60 % of the total annual average concentrations of this pollutant (Kukkonen et al., 2020). The attributed fraction of PM$_{2.5}$ can be even larger in smaller cities

(Hedberg et al., 2006). In the short run, air pollution during cold winter days can result in reduced visibility and a pervasive smoky smell in the air. The highest levels of pollution are found in the most densely populated central urban districts where wood burning is used in apartments of multistory houses. The $PM_{2.5}$ concentrations exceeding $40\,\mu g\,m^{-3}$ can lead to an increased number of health issues in exposed populations. About 2000 annual premature mortality cases have been attributed to $PM_{2.5}$ pollution in Norway alone (Im et al., 2019). Overall, non-industrial wood combustion in Europe contributes to about 10 % of the total health cost of air pollution (Brandt et al., 2013). These numbers, as well as persistent public pressure and regulations from environmental protection agencies, are pushing many countries in the world, including Nordic municipalities, to introduce policy measures fostering reduction of residential emissions.

To be effective and efficient, policy measures must be supported by science. Atmospheric pollution caused by small-scale spatially distributed emitters is a non-trivial advection–diffusion problem that does not have a general solution. It is typically dealt with using numerical modeling. However, the most common Gaussian statistical models are unable to represent pollution aggravation in local stagnation zones. This problem is related to the fact that pollution dispersion models use only a diffusion operator to calculate the concentrations along the pollution transport pathways. The worst air quality is typically observed in atmospheric conditions of weak turbulent mixing where horizontal advection dominates over lateral diffusion. In such conditions, pockets of highly polluted air can be transported over long distances, eventually exacerbating the air quality problems in remote stagnation zones downstream. It is important to emphasize that local emission in the stagnation zones may be less significant, so those zones are not identified by statistical models as being vulnerable to air quality hazards. Turbulence-resolving atmospheric models have been found to be a proper and general tool to study passive scalar dispersion over complex terrain (Gousseau et al., 2015; Zhong et al., 2016). Such models simulate turbulence diffusion and pollution transport on the basis of air flow dynamics. Up to now, however, realistic studies with the turbulence-resolving models were limited as they require significant computing resources. This study is one of the first that assesses air quality and supports policy development for the whole urban municipality with hydrodynamical simulations that resolve all significant buildings.

Air quality is controlled by near-surface turbulent mixing and local winds. We treat small smoke particles ($PM_{2.5}$) as passive scalars emitted to the atmosphere at actual locations of household chimneys. Each chimney creates high $PM_{2.5}$ concentrations only in its immediate vicinity. A statistical model adds up these local emissions making the total concentrations roughly proportional to the chimney density and the local emission rates (Zhong et al., 2016). With our turbulence-resolving model, we aim to understand contributions from the dynamical component of turbulent diffusion and transport in spatial variability of the observable $PM_{2.5}$ concentrations. In realistic urban domains, such as in Bergen, Norway, concentrations are patchy and follow intricate patterns of local wind convergence and stagnation zones (Wolf et al., 2020). Such microscale climate information must be considered in air quality impact studies (Bai, 2018; Chandler, 1976). A challenge is, however, related to modeling of local winds and turbulence patterns. A turbulence-resolving model must be run with a realistic inventory of household emission sources and with correct topography in a sufficiently large domain.

One might argue that a dense network of low-cost meteorological and air quality sensors can do the job when it is combined with statistical models (Schneider et al., 2017) or machine learning (Venter et al., 2020). That is likely to be true. Policy makers, however, would benefit from the model-based approach as it provides quantitative evaluations of the impact of proposed measures, even in the case when those measures are changing configurations and intensities of emission sources. Ultimately, as we will demonstrate in this study, the models can help to identify urban areas vulnerable to air pollution and to justify more optimal policies complying with targeted air quality levels. Locked within a silo (i.e., vertically integrated) approach to environmental management, Nordic municipalities are reluctant to explore advanced modeling approaches (Leiren and Jacobsen, 2018). In such circumstances, a realistic case study is beneficial to demonstrate the added value of turbulence-resolving modeling for air quality management. We chose a domain of the Bergen municipality for such a prototype demonstration study.

Actionable policy scenarios must reflect the complex physico-geographical context of urban areas. Hence, the models of atmospheric chemistry and physics must include effects of local topography and spatial distribution of population and pollution sources. A specific interest for research is related to long-range pollution transport where the strongest air quality effects are observed further away from the source of emission. The long-range transport in a local sense is transport over a few hundred to thousands of meters. Such effects are typical in valleys or in complex coastal areas with significant local circulations (Fernando et al., 2010). Numerical weather prediction models with their typical geographical resolution of 1 km or coarser cannot represent this complex environment (Baklanov et al., 2017a; Køltzow et al., 2019). In addition, large buildings, road systems and other infrastructure objects modify winds and turbulent dispersion, shading some places or aggravating pollution in others (Gousseau et al., 2015). A growing body of literature suggests that turbulence-resolving or at least turbulence-permitting large-eddy simulation (LES) models are needed to deal with the urban pollution issues (Baklanov et al., 2017b; Brötz et al., 2014; Grimmond et al., 2020; Kurppa et al., 2018; Stoll et al., 2020). Fine-scale LES is a computational fluid dynamics technique that becomes affordable with growing perfor-

mance of massively parallel computers. The LES models resolve the most energetic and dispersive turbulent eddies in the stratified lower atmosphere over realistically complex surfaces.

The LES models have already been used to simulate turbulent flows and atmospheric pollution in several smaller urban areas (e.g., Castillo et al., 2009; Cécé et al., 2016; Gronemeier et al., 2017; Keck et al., 2014; Letzel et al., 2008; Park et al., 2015; Resler et al., 2017). Our study further extends LES modeling of the air quality transport and diffusion problem to a whole municipality. We run the model with real surface boundary conditions, atmospheric meteorological conditions, and actual distribution and effect of emission sources. In this configuration, the modeling results could be used in policy scenario evaluation and decision-making processes. We use the Parallelize Atmospheric Large-eddy simulation Model (PALM) described by Maronga et al. (2015, 2019b) with minor own modifications as described by Wolf-Grosse et al. (2017a) and Wolf et al. (2020). Furthermore, we investigate a set of plausible mitigation policy scenarios, which were proposed to reduce emissions from the residential wood combustion sources – the household stoves. The central policy measure is to push for replacement of older stoves with less-polluting new stoves. This push is given through soft economic incentives – a limited cash refund of NOK 5000 per stove – and unconditional hard policy stipulating a ban on the use of the older stoves by 2021. The policy was designed primarily fire safety considerations in mind, as well as improving the air quality. However, its effect on air quality and people's exposure to high PM$_{2.5}$ concentrations have not been quantitatively evaluated before this study.

The article has the following structure. The next section describes the context, geography and datasets of this study. The third section describes PALM, setup of the simulations and our methodology. The fourth section presents the obtained results. The fifth section provides a broader discussion with generalizations of the methodology, data usage and potentials for policy implications. The final section summarizes the conclusions.

2 The Bergen case study: local context and datasets

Bergen is the second largest city in Norway. Its population is more than 275,000 people. It occupies over 465 km^2 divided into eight districts. Lower parts of hills and coastal valleys within the Bergen municipality are built up. Central urban districts and several neighborhoods around large shopping malls are densely populated and include high-rise residential and administrative buildings. The central urban districts have a population of more than 75 000. They occupy a narrow Bergen valley, which opens on both sides towards large sea inlets (fjords). Topographic sheltering (Jonassen et al., 2013) by surrounding mountains up to 643 m height, together with maritime boreal climate at 60.4° N, favor persistent winter-

time surface temperature inversions capping cold air pools in the lowest parts of relief (Lareau et al., 2013). The temperature inversions, typically about 250 m height, can last over several days. They are robustly associated with clear sky, calm and cold-weather conditions (Wolf et al., 2014).

As in many Nordic cities, westerly winds bring clean air into Bergen from the Atlantic Ocean. The main local permanent PM$_{2.5}$ sources are ships in the harbor and road traffic (Wolf et al., 2020). In winter months, however, households actively use wood-burning stoves as a secondary heating source. The household stoves considerably contribute to the PM$_{2.5}$ pollution in Bergen in November through April. Accurate inventory of the residential PM$_{2.5}$ emission is nevertheless problematic as we will discuss later in our study. Ample use of wood burning frequently leads to high ambient concentration of PM$_{2.5}$ that in several urban districts exceeds a threshold of 40 µg m^{-3} set by the environmental protection agency (Høiskar et al., 2017; Wolf et al., 2020). A large fraction of PM$_{2.5}$ emission comes out from household wood-burning stoves installed before 1998, hereafter referred to as older stoves. These older stoves have much higher emissions of particulate matter per unit volume of wood, and they are less combustion and energy efficient than more modern "clean-burning" stoves, which we will refer to as new stoves. There is a strong anticorrelation between air quality and air temperature in Bergen (Wolf and Esau, 2014). Low air temperatures are associated with calm weather periods when residential wood burning is enhanced and when the emitted particles are trapped in the urban canopy due to weak vertical turbulent diffusion in the strongly, often inversely stratified lower atmosphere (Wolf et al., 2014). Although turbulent diffusion is weak, local near-surface micro-circulations (local winds) develop within this highly heterogeneous urban domain (Wolf-Grosse et al., 2017a). The local winds aggravate air pollution in convergence and stagnation zones. Thus, a general advection–diffusion problem translates in the Bergen context into the concrete modeling task of identification of urban districts with elevated PM$_{2.5}$ concentrations given a realistic distribution of household stoves, emission scenarios and weather conditions.

This study addresses the following questions. What is the spatial distribution of PM$_{2.5}$ concentrations in the city during critical air pollution episodes? What is the impact of emissions in each district on the (overall) air quality in the most polluted parts of the city? What would be the effect of replacing the existing older stoves with only clean-burning (new) stoves in the entire city or in some of its districts? These research questions were formulated by scientists. Policy makers and stakeholders might enrich the study by providing different opportunities and stove replacement strategies. The study benefits from communication with the Bergen municipality and other interested parties. Many Nordic cities are suffering from similar challenges, and this is today an active field of research (Simpson et al., 2018).

3 The model and method

3.1 The large-eddy simulation model PALM

We simulate the lower atmosphere (up to 2.2 km) over the whole Bergen municipality with the LES model PALM. PALM version 5.0 (revision 3063) is an atmospheric large-eddy simulation model developed by the PALM group at the Leibnitz University Hannover, Germany (Maronga et al., 2015). The model solves primitive hydrodynamic and thermodynamic equations for incompressible, Boussinesq fluids. PALM explicitly resolves a part of relevant three-dimensional atmospheric dynamics as well as turbulence–flow interactions with complex surface geometry. These features give some advantages to the LES-based approach as compared to a more traditional meso-meteorological modeling in the urban areas. Our reader shall, however, observe that we do not claim accurate simulations of details of such interactions. We only expect that PALM is robust for the dominant scales of the relief (hundreds of meters in Bergen), which are well resolved by the model grid.

Our own user code in PALM aims to improve treatment of the complex surface and environmental conditions. This user code includes a routine to relax the mean vertical temperature profile in the computational domain towards a given input profile. In this way, the model preserves the temperature inversion that traps the emitted pollutants within the urban canopy. The user code allows for mixed-type boundary conditions for the surface temperature; the von Neumann constant flux boundary conditions are set over land, and the Dirichlet constant temperature conditions are set over water. Our user code also recalculates temperature and concentrations of pollutants in a terrain-following coordinate system from the model output provided on the rectangular grid. For this, a linear extrapolation is conducted if the specified height above the ground is not a multiple of the grid height at the given grid point or simply the variable at the correct grid height is given.

Pollutants are treated as passive scalars. Chemical reactions are not simulated. Household chimneys are not resolved in the model. To compensate for variable heights of the houses and their chimneys, the user code allows for emission at any height above the surface. The emission height is then given as input to the model as an array of numbers for each horizontal grid point. The passive scalar is assumed being instantaneously mixed within the entire grid cell of emission. We apply a methodology of artificial pollutants prescribing emission of an independent pollution specimen at each district of choice. Thus, pollution from each district remains independent and traceable over the whole domain. The lateral boundary conditions do not allow for recirculation and inflow of passive scalars into the model domain through any boundary. The three first methodologies are described in Wolf-Grosse et al. (2017a) and Wolf et al. (2020) and the last one has been developed for this study.

3.2 The model setup for the Bergen case study

The model setup for the Bergen case study is discussed in details in Wolf et al. (2020), where it has been applied to study air pollution from a mixture of diverse (localized and spatially distributed) emission sources. Only a short summary and important differences are presented below. The computational domain includes Bergen and parts of the surrounding municipalities (see Fig. 1). The total domain size is 28 800 m and 34 560 m in the zonal and meridional directions, respectively. The simulations run with horizontally periodic lateral boundary conditions for wind, pressure and temperature. Therefore, this domain includes buffer zones with a width of 1000 m each, which are needed for linear interpolation between the opposing periodic boundaries. The horizontal grid resolution is 10 m. It gives a mesh of almost 1 million grid cells at each model level – the largest achieved urban simulations so far. The vertical grid resolution is 10 m up to 660 m height. Above that the vertical grid space increases by 1 % for each additional grid level. The total domain height is 160 levels or 2239 m. Thus, the model domain top is found well above the highest hill (640 m) in the area of simulations. The surface in the model is approximated with cubes of 10 m × 10 m × 10 m. The topographic data for the approximation are taken from a laser-scan digital elevation model (DEM) of 1 m resolution provided by the Norwegian mapping authority (Statens Kartverk, 2018). At this resolution, the DEM includes all buildings and trees in the city. DEM was delivered to us in the GeoTIFF format. We use the ArcGIS© software to process the data and to create a complete topography dataset of the required 10 m horizontal resolution. We fill in small gaps in the original DEM using the standard linear interpolation.

Water bodies have a distinct impact on boundary layer circulations, also in urban areas (Ronda et al., 2017; Wolf-Grosse et al., 2017a). This impact is accounted for in simulations by prescribing a constant negative surface heat flux of $-20\,\mathrm{W\,m^{-2}}$ over land. Constant surface temperature of 275.65 K (equal to 2.5 °C) is applied over sea water; temperature of 273.15 K (equal to 0 °C) is applied over freshwater bodies (lakes). This setup reflects conditions of winter temperature inversions with radiative surface cooling over land and warmer sea surface temperatures.

3.3 Weather scenarios

Damaging levels of air pollution are almost exclusively observed during persistent calm and cold-weather episodes. We have already identified typical meteorological conditions that correspond to the pollution episodes (Wolf et al., 2014). Analysis of such conditions produced two influential meteorological scenarios, i.e., two sets of vertical profiles, one for temperature (from the meteorological temperature profiler in Bergen) and another for wind (from the ERA-Interim reanalysis) that correspond to the observed high concentrations of
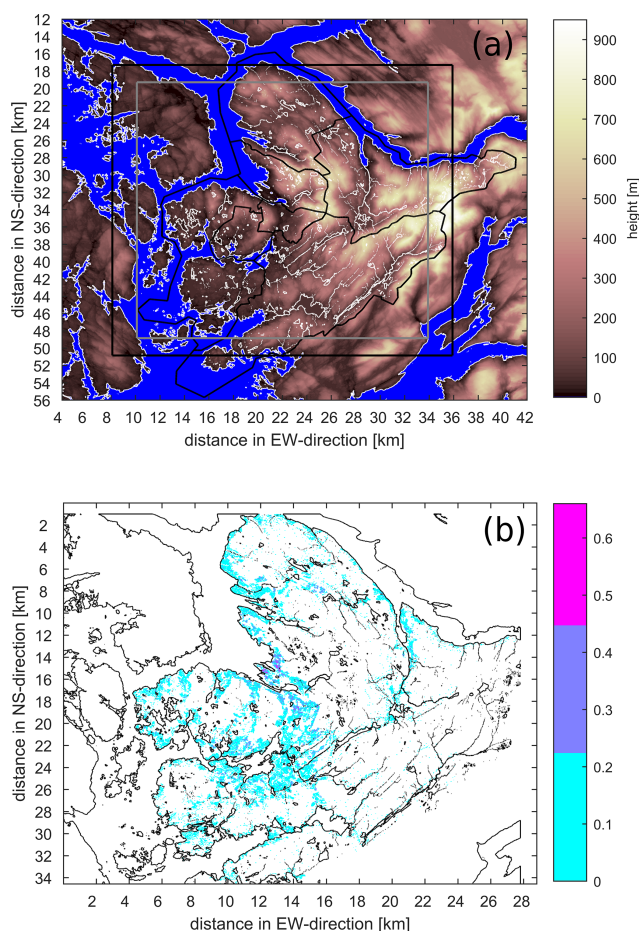
Figure 1. (a) Topographic map of the Bergen municipality. The color shading indicates elevations of the land surface area. Water surfaces are marked with blue color shading. The black curved lines indicate district boundaries. The black rectangle indicates the full extent of the model simulation domain. Buffer zones are not included. The grey rectangle indicates the part of the model domain that is selected for the analysis. **(b)** Map with the locations of wood-burning stoves in Bergen. The color shading indicates the number of households with registered stoves per $10 \times 10\,\mathrm{m}^2$ grid box (averaged over 3×3 boxes). Black lines indicate waterfront. Data sources are the Bergen municipality and the Bergen Fire Brigade.

PM$_{2.5}$. The first scenario is for the most typical winter conditions with high air pollution. This scenario is determined by the southeasterly geostrophic wind, which is used to force the model simulations, and by the fjord surface water temperature of 2.5 °C, which is used as the surface boundary condition in the model. In this scenario, the local winds transport polluted air from land to the city fjord through the densely populated central urban valley. The second meteorological scenario has the easterly geostrophic wind of slightly higher speed and the fjord surface water temperature of 0 °C, which is still above the freezing point for salt water. Both scenarios are described in detail in Wolf et al. (2020) under the abbreviations ws01_wd01_ft01 and ws03_wd02_ft03. Model

forcing and surface temperatures are fixed in both scenarios for the complete duration of the model runs. The runs are initialized with 12 h long precursor runs. At this point, most meteorological parameters do not show any significant drift. Simulations with different configurations of emission sources are then conducted following the precursor runs for another 6 h.

Positive turbulent sensible heat fluxes over water and negative fluxes over land are not in balance and do not cancel each other within the model domain. This imbalance, if not treated, would erode the stable stratification of the atmosphere in the upper layers of the model domain. We resolve the problem by relaxing the mean temperature profile to the initially prescribed profile using nudging. Nudging corrects the temperature at every grid point and time step by a weighted difference between the actual domain-averaged temperature and that at the model initialization. The weight is given by the relaxation timescale set to 43 200 s at elevations below 400 m, which effectively gives no nudging in the lower layers of the model domain. The relaxation timescale linearly decreases till 1800 s at 600 m and higher elevations. Nudging is not applied at the first grid point above the surface.

We run PALM with real spatial configuration of small-scale emission sources in the case study domain that is provided to us by the Bergen Fire Brigade (Bergen brannvesen). Overall, there were 80 506 household stoves registered in Bergen in June 2018. The new clean-burning stoves constitute 45.8 % or 36 864 stoves. Most of them were installed in recent years. Since 1995, only new stoves are allowed. We have aggregated and averaged the number of stoves within 3×3 grid cells plots ($90\,\mathrm{m}^2$) to emulate emission dispersion immediately after exhaust from chimneys. Figure 1 (bottom) shows the geographical distribution of the resulting emission source density. Concentrations are set to zero at starting both the scenario and sensitivity runs. In this study, we apply the same fixed emission height of 15 m (the second model level) above the ground everywhere in the model domain as it corresponds to the most typical building height in Bergen. Plausible effects of different emission heights are considered in a sensitivity study that is included in the Supplement.

The Bergen Fire Brigade has also provided us with stipulated emission rates per stove. The new, clean-burning wood-stoves have a relative emission rate of 7 g kg^{-1}. This number shall be understood as 7 g of PM$_{2.5}$ per kg of burned wood. The older stoves have a relative emission rate of 30 g kg^{-1}. With the given mix of the new and older stoves, the average relative emission rate is 19.42 g kg^{-1}. To obtain the actual emission rates, one must know consumption of wood per unit time per stove and frequency of using the stoves, i.e., parameters that characterize burning habits in the city. Felius et al. (2019) published an updated study of the wood-burning habits in Norway. It reveals that about 80 % of households use stoves only during the afternoon and evening hours, while 90 % of households still use wood burning as a sig-

nificant (primary and secondary) heating source. The typical average usage time is 4 to 10 h. Shorter usage time (2.5 to 3.5 h) is reported by Wyss et al. (2016) in a study of relations between indoor $PM_{2.5}$ concentrations and wood-burning habits in Norwegian households. Emission rates also depend on the wood quality, wetness and tree species in the wood supply (Hellén et al., 2008). These numbers are not available, so we estimated them using a small sampling study that is based on our social networks. We assume that each stove is used to burn approximately 11 kg wood per day and that the wood consumption is 1.25 kg h^{-1} (Solli et al., 2009). We arrived at 8.8 h of wood burning, primarily between 15:00 and 24:00 LT (local time); 90 % of all aerosol exhaust comes out as $PM_{2.5}$. Taken together, these assumptions and estimations result in the average $PM_{2.5}$ emission rate of 0.7647 g s^{-1} per stove. This number is about 10 times smaller than it has been assumed earlier by the Bergen Fire Brigade, but simulations with this emission rate show good agreement between computed $PM_{2.5}$ concentrations and the concentrations measured in the city. During the second week of February 2021, a persistent cold-weather situation similar to our first scenario was observed in Bergen. The maximum simulated (observed on 11 February 2021) $PM_{2.5}$ concentrations were 76.7 µg m^{-3} (81.2 µg m^{-3}) at Danmarksplass, 53.4 µg m^{-3} (59.2 µg m^{-3}) at Klosterhaugen in the city center and 26.1 µg m^{-3} (18.6 µg m^{-3}) at Rådal. This agreement demonstrates reasonably good capture of the spatial variability and accumulation of $PM_{2.5}$ in the scenario simulations despite the accepted simplifications, assumptions, and uncertainties.

4   Results

Air pollution in urban areas is patchy. As one might expect, simulations reveal higher concentrations of $PM_{2.5}$ in more densely populated districts. This pattern is, however, significantly distorted by the intricate interplay of local air circulations and turbulent diffusion in the lower parts of the atmosphere. Although there is an overall near-surface air flow towards the fjord, pollution tends to concentrate in some stagnation zones on the way. Thus, the study allows for certain generalizations. Our results reveal that the highest $PM_{2.5}$ concentrations are created by long-distance horizontal air advection into stagnation zones. Gradual accumulation and convergence of the polluted air is more important than the local dispersion over emission sources. A considerable fraction of pollution in the stagnation zones is advected from upstream urban districts. Figure 2 shows the near-surface wind and temperature fields in the actual boundaries of the Bergen municipality for the two predefined weather scenarios. This area is sufficiently distant from the model boundary zone, which is shown as a grey rectangle in Fig. 1 (top panel).

Our simulations represent two weather scenarios. Scenario 1 has higher water temperature (Fig. 2, top panel).
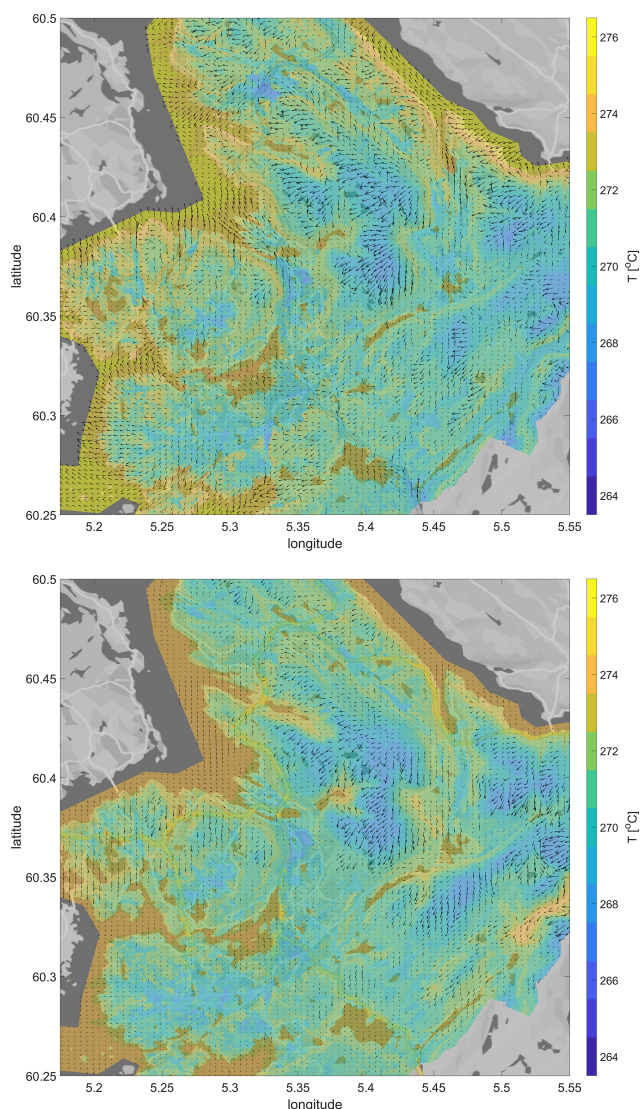
Figure 2. Surface-layer meteorology obtained from PALM simulations for scenarios 1 (top) and 2 (bottom). The color shading represents the surface air temperature at 2 m above the ground (terrain-following temperature field). Vectors represent the surface-layer wind at 10 m. Data overlay the grayscale map from © Google Maps 2019.

It represents the conditions with strong water–land surface temperature difference. Warmer water forces stronger wind convergence over the fjord and increases the outflow from the central valley. In some more general sense, it can be seen as a scenario with effective urban ventilation with local breeze. The increased wind convergence is also observed over smaller or medium-sized water bodies. We found that these surface-layer breeze-like circulations, which are driven by the horizontal temperature differences, are to a large degree autonomous, existing independently and in many places in opposition to the upper air winds. Scenario 2 has lower water temperature (Fig. 2, bottom panel). Weaker convergence

of the near-surface winds produces different configuration of the local air flows and therefore different pollution pathways. This scenario describes a situation when local surface heterogeneity is not strong enough or not well organized to increase urban ventilation. Its most pronounced effect is in the formation of air stagnation in the central urban districts. Stronger upper-layer winds do not break this stagnation. Thus, this stagnation zone is robust, which is an important result from the citizens and stakeholders' point of view.

A combination of uneven distribution of emission sources with an intricate pattern of local air circulations produces a patched picture of the pollution concentrations. Our simulations identify the pathways of pollution in the surface layer. In both scenarios, the high concentrations are found not only in the areas with the highest emission rates but also in other areas where local winds advect the pollutants and concentrate them in converge zones. Figure 3 presents the map of the PM$_{2.5}$ concentrations near the surface. It is simulated using the current distribution of new and older stoves. Both weather scenarios reveal high concentrations in cold air pools designating the effect and importance of topographic sheltering.

## 4.1 Implications of pollution advection across municipal districts

Now, we shall look at the role of long-distance pollution advection and convergence in different municipal districts. It is perhaps not surprising that the highest concentrations are found in the central, densest urban districts as, e.g., just south and upward in the central Bergen valley. More detailed analysis, however, suggests that a considerable fraction of the concentration shall be attributed to advection of polluted air from other upstream districts. Bergen has eight administrative districts. Figure 4 shows the simulated near-surface concentration obtained for emission sources (stoves) that are active only in the central district (Bergenhus) and in the most populated district (Årstad). We plot both the absolute and relative concentrations. The high concentrations in Årstad are determined by the stagnant cold air pool in a local topographical shelter and the high concentration of small apartments in old houses, each having an individual wood-burning stove. In addition, local wind convergence adds to increase the concentration even in the most polluted districts. Here, 80 % to 90 % of the total concentrations are of the local origin within the district itself. The non-local advection adds up to 60 % to the concentrations in the most central district of Bergenhus (see Fig. 4, top panel). This district is built-up by modern high-rise buildings where stoves are not in use. Nevertheless, the PM$_{2.5}$ concentrations are relatively high there. The pollution in this district is advected from the upstream Årstad district following the circulation pathway along the northern slope of the Bergen valley. By contrast, emissions within the city center have almost no impact on other districts as the area is located downstream in the Bergen valley and next to the waterfront (Byfjorden). Scenarios 1 and 2 are very sim-
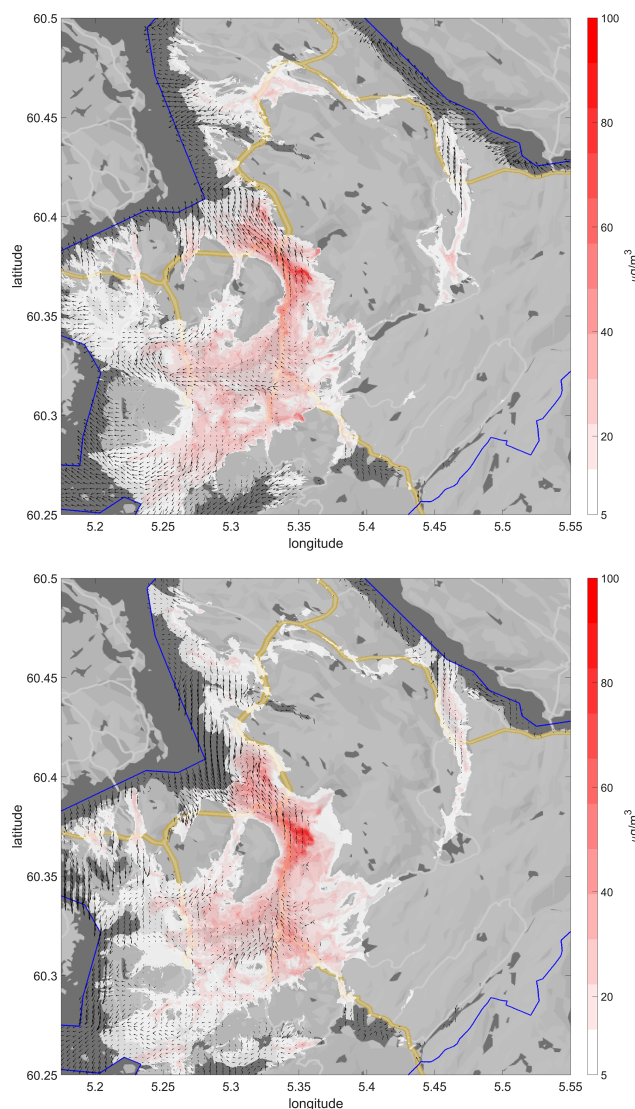
Figure 3. Simulated concentrations at 5 m above the ground (the surface-layer concentrations) of PM$_{2.5}$ for scenarios 1 (top) and 2 (bottom). Vectors show the surface wind at 10 m. The simulations use the current distributions of the wood-burning stoves and the current fraction of the new and older stoves in Bergen. Data overlay the grayscale map from © Google Maps 2019.

ilar to each other with respect to the pollution transboundary transport and non-local contribution of district's emission sources. Scenario 2 leads to lower local contribution (not shown), while the effects on the other areas remain similar. Since we want to identify the conditions with severe impact on the population, we will focus on details of the scenario 1 simulations.

Looking at the three districts located further south in the municipality, we clearly see the effect of the downstream and down-valley transport towards the city center. The main polluter, both locally (80 %) and downstream (up to 60 %), is the Årstad district. The pollution trapped in the surface layer
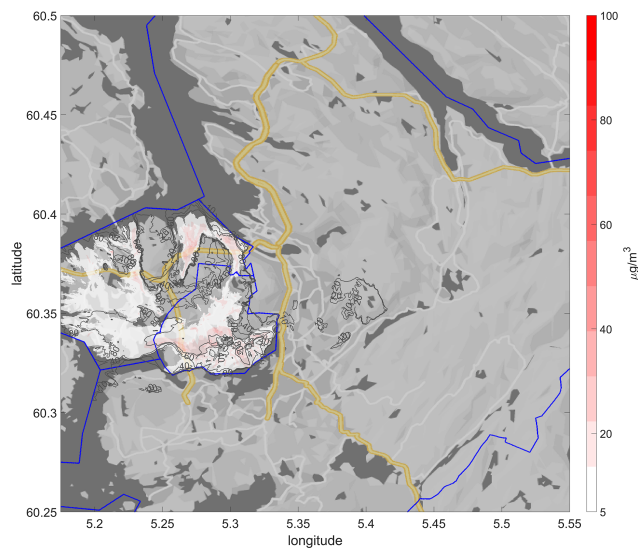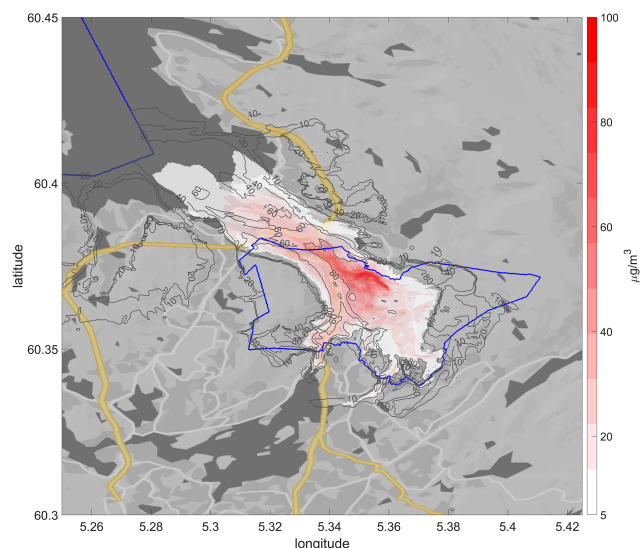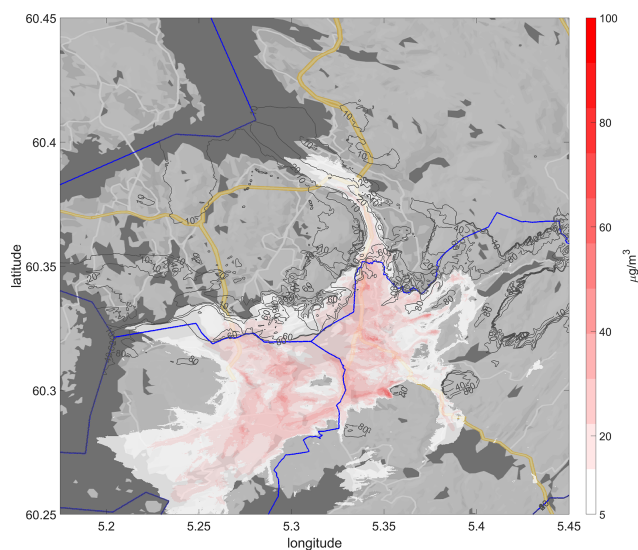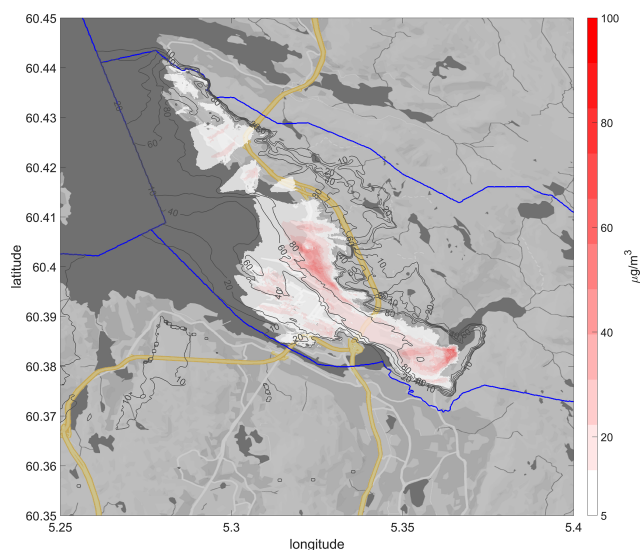
Figure 4. The simulated surface-layer concentrations of PM$_{2.5}$ for scenario 1 (shown in Fig. 3, top panel) but for emissions only from stoves within the Bergenhus (top) and Årstad (bottom) districts. The simulations use the current distributions of the number and types of stoves. The blue lines show the district boundaries. Thin grey isolines indicate the fraction of the total pollution that was caused by the emissions within the respective district. Data overlay the grayscale map from © Google Maps 2019.

Figure 5. Same as Fig. 4 but for the emissions within the districts Fana and Ytrebygda (top) and Laksevåg and Fyllingsdalen (bottom). Data overlay the grayscale map from © Google Maps 2019.

central valley, thus having no impact on the concentration of air pollutants. The local concentrations in these peripheral districts are less significant, due to different local topographic steering of the near-surface air masses.

4.2 Assessment of mitigation actions to reduce emissions from residential wood combustion

is, however, transported over long distances within the municipality. According to our simulations (see Fig. 5), the two southernmost districts (Fana, Ytrebygda) add up to 20 % to the concentrations in the city center, while standing for near 100 % of their own local pollution with their districts. The picture is very different when western (Fyllingsdalen, Laksevåg) and eastern (Åsane, Arna) urban districts are considered. Those districts are located behind mountains and water areas looking from the central Bergen perspective. Due to this, surface-layer pollution will not be transported to the

The most environmentally friendly clean air mitigation action is to place bans on all emissions from private woodstoves. However, the need for heating during cold winter days implies that more realistic policy actions must be considered. Moreover, active use of the wood-burning stoves could be an effective retrofitting measure, helping to save electricity and fossil fuels (Felius et al., 2019). Therefore, a

massive transition to new stoves is deemed necessary both from political and environmental points of view. The results of our simulations impose two important constrains on plausible retrofitting measures. First, we argue and demonstrate with model runs that there is a tight connection between weather conditions and exceedance of the concentration thresholds in particular districts. We found that PM$_{2.5}$ readings in one district, say Åsane, may tell little about the concentrations in another district or even over smaller neighborhoods. So, the measures need to be constrained by physico-geographical boundaries, which in turn could be determined only through high-resolution atmospheric simulations (or analysis of dense observations if they are available). Second, if the target is not to cross a certain concentration threshold, the measures must account for the developing local atmospheric circulations and not so much for dispersion of the very local emissions.

The presented simulations and many additional sensitivity simulations suggest that unavoidable inaccuracies and uncertainties of emissions should not be overdriven in mitigation measures. Indeed, there are many uncertainties associated with the current usage and replacement of the stoves, which includes uncertainties related to the emission factor (Seljeskog et al., 2017). But, however high or low the specific emission factor is, the spatial redistribution and aggravation of pollutants is robustly simulated with stagnation (high-concentration) zones found over the identified areas. In particular, the convergence zone related to the breeze inflow and land outflow is of general interest as it might be found in many coastal cities. Hence, limiting economic incentives for stove replacement to just certain districts could be a cost-effective measure. We however acknowledge that other, e.g., political, factors may render such an efficiency suboptimal. In our model simulations, we can alter the configurations and rates of emission sources in specific districts to estimate effects of different mitigation actions on the local and total level of urban pollution.

Plausible alternatives for the total and district-wise replacement of stoves with cleaner burning technology are presented in Fig. 6. We change the current distribution of the older and new stoves in two clusters of four districts each. First, we replace all stoves in the Bergen valley (the Bergenhus, Årstad, Fana and Ytrebygda districts) with the new stoves only. The simulations result in strongly improved air quality with the highest concentrations being almost eliminated. Concurrently, the moderate and low concentrations are not markedly lower determining the baseline level of pollution from the new stoves – all stoves will pollute. Then, we replace stoves in other districts (Laksevåg, Fyllingsdalen, Åsane and Arna). This results in further reduction of concentrations in the total accumulated concentrations of over the entire municipality.

We summarize the effect of mitigation actions in Fig. 7 and Table 1. The national regulators set the concentration threshold of 40 µg m^{-3} for PM$_{2.5}$ as the delimiter of high and low
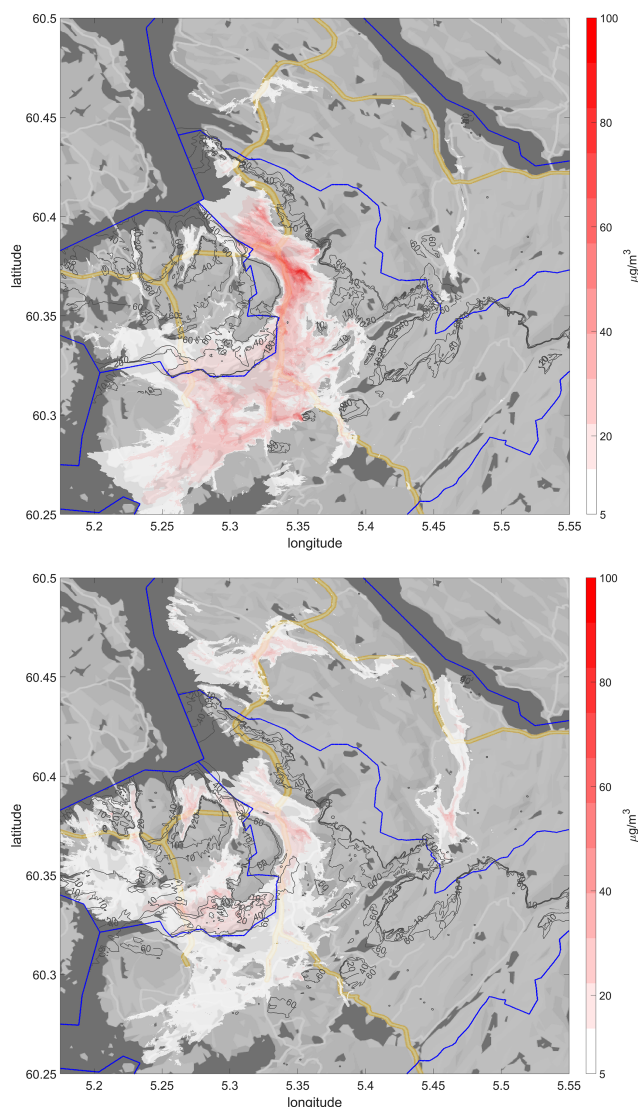
Figure 6. The same as in Fig. 4 but for the emissions expected when all older stoves have been replaced with the new stoves in Bergenhus, Årstad, Fana and Ytrebygda districts (top) or in Laksevåg, Fyllingsdalen, Åsane and Arna districts (bottom). The boundaries of the districts are highlighted with the blue lines. Thin grey isolines indicate the fraction of the total pollution that was caused by the respective districts, when compared to the total pollution distribution in Fig. 3 (top). Data overlay the grayscale map from © Google Maps 2019.

air pollution. The simulations reveal that the majority (respectively, 17 818 and 17 243) of the exposed households are exposed only to low air pollution in both scenarios. Nevertheless, a total of 4031 (scenario 1) and 5986 (scenario 2) households are still exposed to high air pollution under the current distribution of stoves. Switching to the new stoves in the entire city results in elimination of high-air-pollution exposure. We discover that a very similar effect could be obtained with more modest but better targeted efforts fo-
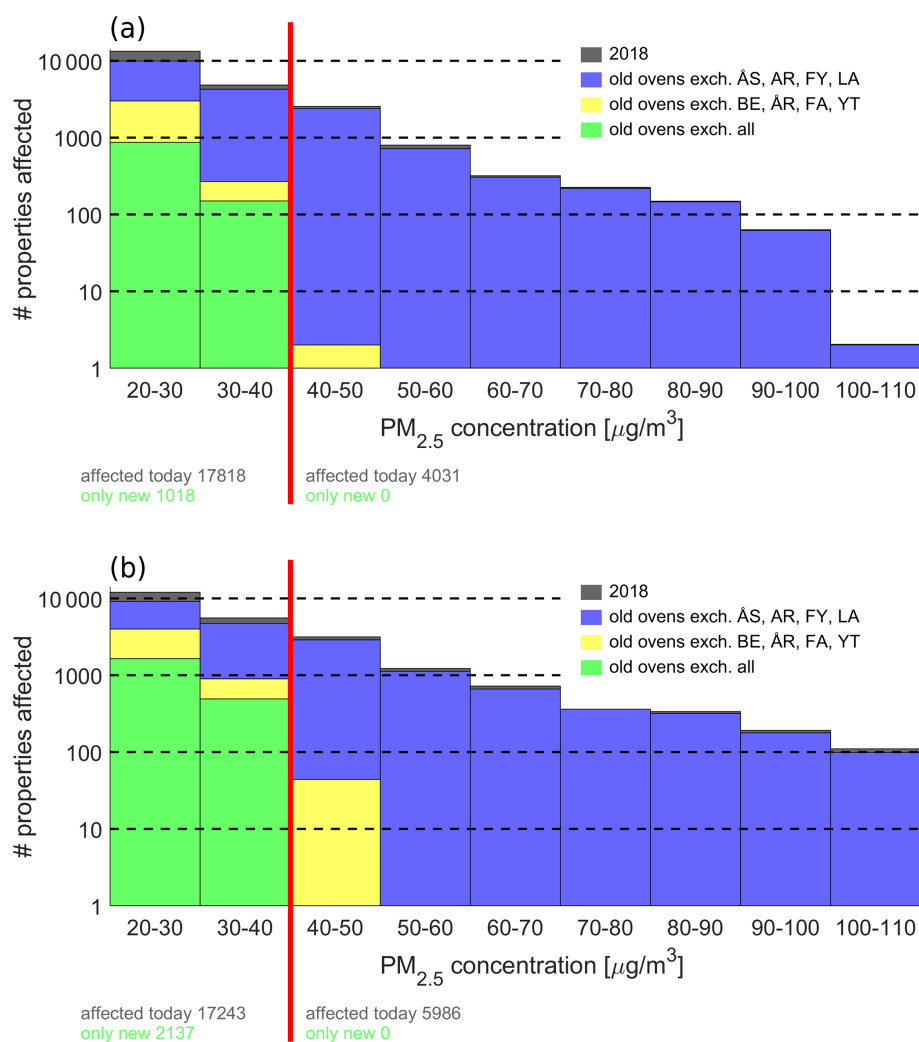
Figure 7. Histogram of the accumulated number of households (number of properties on the *y* axis given in logarithmic scale) in Bergen that were exposed to different concentrations (the binned concentration intervals on the *x* axis) for scenarios 1 **(a)** and 2 **(b)**. The "2018" (upper part of all columns) means the exposure from the simulations with the current mix of older and new stoves, and "old stoves exch." means a complete replacement with the new stoves in various subsets of districts (as shown in Fig. 6). The impact of the complete replacement in Åsane (ÅS), Arna (AR), Fyllingsdalen (FY) and Laksevåg (LA) (Fig. 6, bottom) is shown as blue columns; the same in Bergenhus (BE), Årstad (ÅR), Fana (FA) and Ytrebygda (YT) (Fig. 6, top) is shown as yellow columns, and the same in all districts as green columns. The threshold of 40 µg m^{-3} for PM$_{2.5}$ concentrations is indicated with a vertical red line.

cused on replacement of stoves in the central Bergen valley (Bergenhus, Årstad, Fana and Ytrebygda districts). Only 2 (scenario 1) and 44 (scenario 2) households are still exposed to high air pollution in the simulations. By contrast, 3848 and 5636 households, respectively, remain exposed when the stoves are installed only in peripheral districts (Laksevåg, Fyllingsdalen, Åsane and Arna). That corresponds to the relative exposure reductions by 5 % and 6 % of households only. At the same time, the whole 95 % of households will continue to be exposed to high air pollution wish such policy action.

5 Discussion and conclusions

Despite the frequent depiction of residential wood burning as clean energy, urban air data clearly associate wood combustion with elevated concentrations of the particulate matter (PM$_{2.5}$) in cities. These particles are extremely harmful to humans, because their small size allows them to reach the lungs and to deliver toxic contaminants. The World Health Organization attributed 61 000 of the premature deaths in 2010 alone in Europe to outdoor PM$_{2.5}$ pollution from residential wood combustion, whereas in Denmark estimations suggested that up to 30 %–40 % or the premature deaths should be attributed to this type of air pollution (Cincinelli

Table 1. Summary of the total simulated effect of the suggested mitigation actions.

Air pollution level	Weather scenario 1: winter temperature inversion		Weather scenario 2: winter temperature inversion and stagnation	
	Medium	Strong	Medium	Strong
PM$_{2.5}$ concentration range (μg m^{-3})	20–40	40–110	20–40	40–110
The present-day situation: the total number of exposed households	17 818	4031	17 243	5986
Reduction in the number of the exposed households when transition to the new stoves is completed in Åsane, Arna, Fyllingsdalen and Laksevåg districts	20 %	5 %	20 %	6 %
Reduction in the number of the exposed households when transition to the new stoves is completed in Bergenhus, Årstad, Fana and Ytrebygda districts	82 %	100 %	72 %	99 %
Reduction in the number of the exposed households when transition to the new stoves is completed in the whole Bergen municipality	94 %	100 %	88 %	100 %

et al., 2019). Residential wood combustion has its immanent importance for air quality not only in the Nordic cities where it contributes up to 82 % of the total particulate matter in Northern Sweden (Krecl et al., 2008) but also elsewhere in Europe (up to 60 % in southern Germany; Bari et al., 2009). Even in subtropical cities, e.g., Santiago, Chili (Mazzeo et al., 2018), the impact of residential wood combustion could be critical for urban health, so its modeling is in high demand. Due to these factors, there is a persistent interest and concentrated efforts to include the particulate matter into an urban integrated system (UIS) modeling approach (Grimmond et al., 2020). The UIS approach combines meteorological and air quality modeling with socio-economic and policy scenarios. It has been, however, recognized that integration of high-resolution models in existing systems still requires further development. In this study, we described a perspective UIS approach that has emerged from our co-production efforts with local policy makers.

PALM has been proposed as a perspective model that would allow for resolving urban dispersion from highly localized pollution sources (Esau et al., 2021; Heinze et al., 2017; Maronga et al., 2019b; Zhang et al., 2021). PALM simulations were evaluated in several case studies, but so far, this study is the first model application for policy and meteorological scenario development at the level of the whole administrative unit – an urban municipality. In this sense, our study sets up methodology and presents perspective ways to utilize the large-eddy simulation models in the UIS. This modeling is advantageous for population-weighted exposure estimates that are still missing the high-resolution meteorological component (Savolahti et al., 2019). We demonstrate what such a modeling component could contribute for such expose estimates (Fig. 7).

The UIS studies benefit from co-production with local policy actors. Our case study in Bergen was co-designed with city managers to select the most relevant scenarios and tar-

gets. The Bergen city council has banned firing of the older stoves since 1 January 2021. To facilitate a transition to the new stoves, financial incentives of NOK 5000 (Norwegian krones, about EUR 500) per stove have been allocated. The total allocated amount is NOK 50 million or just 25 % of the amount needed to support the total replacement of the older stoves in the municipality. So, it is not surprising that, by 2021, Bergen still has more than 30 000 older stoves. Our simulations, however, suggest that targeted incentives might be sufficient to cover the stove replacement in the most critical urban districts. We show that such a selective replacement could have a major effect on pollution reduction below the threshold of 40 μg m^{-3} of PM$_{2.5}$ for almost all households in Bergen municipality. Thus, we conclude that turbulence-resolving atmospheric modeling has a potential to contribute to the design of more efficient policy and scenarios than those presently applied. Analysis of simulation scenarios may not only increase the effects of limited incentives, which is desired per se, but can also assure that "no one is left behind", or in other words, that all households will experience positive effects of the proposed policy measures; no district would remain unnecessarily polluted or even with worse air quality.

There are available other modeling approaches and more comprehensive studies of residential wood combustion, notably, applications of the Norwegian modeling system based on the MetVed emission model, the EPISODES air quality model and AROME weather model (Grythe et al., 2019; Grythe and Lopez-Aparicio, 2020). Both the data graining (250 m) and atmospheric model resolution (1000 m) in this modeling system are much coarser than in the present study (30 and 10 m correspondingly). Kukkonen et al. (2018) presented PM$_{2.5}$ simulations in Helsinki, Finland, at higher resolution (100 m) with the SILAM modeling system. This system relies on the Gaussian (downgradient) approach and hence cannot resolve aggregation of polluted air. Emission inventory analysis and modeling results for different sys-

tems were presented in a study in four cities (Oslo, Helsinki, Copenhagen and Umeå) (Kukkonen et al., 2020). It considers the mean concentrations and the city-scale level and does not discuss relevant meteorological conditions. Our study is less model and site specific. Its focus is on explicit modeling of the turbulent dispersion and influential meteorological scenarios. Our simulations represent a moderate to strong impact of the atmospheric stability on the concentration exceedance. The leading effect of atmospheric stability have been found in our other studies (Wolf et al., 2014, 2020) as well as by other authors concerned with urban wood combustion (Grange et al., 2013). We show that the resolution and methodological differences do matter. Although the overall effect of the stove replacement programs on the emission reduction in the city could be moderate, the replacement in certain sensitive districts helps to dramatically reduce the population expose. In this sense, our study supports the conclusions of Lopez-Aparicio and Grythe (2020) (in Oslo, Norway) that the current indiscriminate subsidy programs are ineffective.

Concluding the modeling study of urban pollution dispersion, we observe that local winds within the turbulent boundary layer can transport polluted air over long distances in the urban areas. Convergence and accumulation of pollution from distributed small-scale emission sources, such as the considered household stoves, deteriorate air quality in stagnation zones where the local emissions are not sufficient to maintain such high concentrations. We simulated only the worst-case scenarios for wintertime air pollution, which are associated with the coldest weather and most frequent use of woodstoves for heating. Therefore, our concentrations considerably exceed the mean values given by other studies (Grythe et al., 2019; Kukkonen et al., 2020). Other weather regimes produce less severe air pollution, which might, however, contribute over the whole heating season. The weather conditions favorable for air quality deterioration in Bergen are considered in our other work (Wolf et al., 2020; Wolf and Esau, 2014). Two studies by Wolf-Grosse et al. (2017b) and Wolf et al. (2014) specifically consider co-variability between the temperature inversions and weather regimes in Bergen as the main control factors of the local atmospheric pollution. Emission scenario testing like the one highlighted here can be an important step of such a reasoning.

The methodology of this study is experimental. It requires further development and integration with other physical and chemical components of the urban environment. Such efforts are on the way (Maronga et al., 2019b). More specifically, the quality of the PALM simulations needs assessment against in situ observations of concentrations as well as against more constraining laboratory and other model results (Gronemeier et al., 2017, 2021). The input datasets ought to be more constrained too (Heldens et al., 2020; Masson et al., 2020). Uncertainty in emissions and surface boundary conditions currently impede fine tuning of the simulations. Societal uncertainties could be also influential (Felius et al., 2019; Wyss et

al., 2016). Heating patterns and habits are poorly constrained. Concerns that the new stoves will be used more and therefore retard the effect on air pollution have been also raised by stakeholders. A broader study of societal effects is out of the scope of this work. Finally, PALM is under extensive development now to allow for more realistic and comprehensive urban meteorological studies. It will include a block for improved surface boundary conditions (Maronga et al., 2019a, b; Resler et al., 2017) and connection with the regional model COSMO (Fröhlich and Matzarakis, 2020).

Code availability. The PALM code is available from the PALM group from https://palm.muk.uni-hannover.de/trac/wiki/doc/install. The model is free to download and to use upon registration. The scripts for data analysis and visualization are written in MATLAB and available from the Nansen Center FTP server at ftp://ftp.nersc.no/igor/ (Wolf et al., 2021).

Data availability. Availability conditions for the collection of datasets to setup and run the model and weather scenarios are described in Wolf et al. (2020). A selection of modeling results and processed data (smaller data files) are available from the Nansen Center FTP server at ftp://ftp.nersc.no/igor/ (Wolf et al., 2021). Data from new model simulations (larger data files) for this study are available upon request to the corresponding author.

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/acp-21-12463-2021-supplement.

Author contributions. TW was responsible for the data acquisition, setting and running the model PALM, data analysis scripts, and visualization routines. He contributed to writing the article and interpretation of the modeling results. LHP was responsible for contacts with data providers and end users, design of scenarios, interpretation, and communication of the results. He contributed to writing the article. IE was responsible for the conceptual design of the study, methodology of numerical simulations and data analysis. He wrote the article and connected the results of the study with the need of end users.

Competing interests. The authors declare that they have no conflict of interest.

Disclaimer. Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Special issue statement. This article is part of the special issue "Pan-Eurasian Experiment (PEEX) – Part II". It is not associated with a conference.

References

Bai, X.: Advance the ecosystem approach in cities, Nature, 559, 7, https://doi.org/10.1038/d41586-018-05607-x, 2018.

Baklanov, A., Smith Korsholm, U., Nuterman, R., Mahura, A., Nielsen, K. P., Sass, B. H., Rasmussen, A., Zakey, A., Kaas, E., Kurganskiy, A., Sørensen, B., and González-Aparicio, I.: Enviro-HIRLAM online integrated meteorology–chemistry modelling system: strategy, methodology, developments and applications (v7.2), Geosci. Model Dev., 10, 2971–2999, https://doi.org/10.5194/gmd-10-2971-2017, 2017a.

Baklanov, A., Brunner, D., Carmichael, G., Flemming, J., Freitas, S., Gauss, M., Hov, Ø., Mathur, R., Schlünzen, K. H., Seigneur, C., and Vogel, B.: Key Issues for Seamless Integrated Chemistry–Meteorology Modeling, B. Am. Meteorol. Soc., 98, 2285–2292, https://doi.org/10.1175/BAMS-D-15-00166.1, 2017b.

Bari, M. A., Baumbach, G., Kuch, B., and Scheffknecht, G.: Wood smoke as a source of particle-phase organic compounds in residential areas, Atmos. Environ., 43, 4722–4732, https://doi.org/10.1016/j.atmosenv.2008.09.006, 2009.

Brandt, J., Silver, J. D., Christensen, J. H., Andersen, M. S., Bønløkke, J. H., Sigsgaard, T., Geels, C., Gross, A., Hansen, A. B., Hansen, K. M., Hedegaard, G. B., Kaas, E., and Frohn, L. M.: Contribution from the ten major emission sectors in Europe and Denmark to the health-cost externalities of air pollution using the EVA model system – an integrated modelling approach, Atmos. Chem. Phys., 13, 7725–7746, https://doi.org/10.5194/acp-13-7725-2013, 2013.

Brötz, B., Eigenmann, R., Dörnbrack, A., Foken, T., and Wirth, V.: Early-Morning Flow Transition in a Valley in Low-Mountain Terrain Under Clear-Sky Conditions, Bound.-Lay. Meteorol., 152, 45–63, https://doi.org/10.1007/s10546-014-9921-7, 2014.

Castillo, M. C. L., Kanda, M., and Letzel, M. O.: Heat ventilation efficiency of urban surfaces using large-eddy simulation, Annu. J. Hydraul. Eng., 53, 175–180, 2009.

Cécé, R., Bernard, D., Brioude, J., and Zahibo, N.: Microscale anthropogenic pollution modelling in a small tropical island during weak trade winds: Lagrangian particle dispersion simulations using real nested {LES} meteorological fields, Atmos. Environ., 139, 98–112, https://doi.org/10.1016/j.atmosenv.2016.05.028, 2016.

Chandler, T. J.: Urban Climatology and its Relevance to Urban Design, WMO technical note no. 149, WMO, Geneva, Switzerland, 76 pp., 1976.

Cincinelli, A., Guerranti, C., Martellini, T., and Scodellini, R.: Residential wood combustion and its impact on urban air quality in Europe, Curr. Opin. Environ. Sci. Heal., 8, 10–14, https://doi.org/10.1016/j.coesh.2018.12.007, 2019.

Esau, I., Bobylev, L., Donchenko, V., Gnatiuk, N., Lappalainen, H. K., Konstantinov, P., Kulmala, M., Mahura, A., Makkonen, R., Manvelova, A., Miles, V., Petäjä, T., Poutanen, P., Fedorov, R., Varentsov, M., Wolf, T., Zilitinkevich, S. and Baklanov, A.: An enhanced integrated approach to knowledgeable high-resolution environmental quality assessment, Environ. Sci. Policy, 122, 1–13, https://doi.org/10.1016/j.envsci.2021.03.020, 2021.

Felius, L. C., Thalfeldt, M., Georges, L., Hrynyszyn, B. D., Dessen, F., and Hamdy, M.: Wood burning habits and its effect on the electrical energy demand of a retrofitted Norwegian detached house, IOP Conf. Ser. Earth Environ. Sci., 352, 012022, https://doi.org/10.1088/1755-1315/352/1/012022, 2019.

Fernando, H. J. S. S., Zajic, D., Di Sabatino, S., Dimitrova, R., Hedquist, B., and Dallman, A.: Flow, turbulence, and pollutant dispersion in urban atmospheresa), Phys. Fluids, 22, 051301, https://doi.org/10.1063/1.3407662, 2010.

Fröhlich, D. and Matzarakis, A.: Calculating human thermal comfort and thermal stress in the PALM model system 6.0, Geosci. Model Dev., 13, 3055–3065, https://doi.org/10.5194/gmd-13-3055-2020, 2020.

Gousseau, P., Blocken, B., Stathopoulos, T., and van Heijst, G. J. F.: Near-field pollutant dispersion in an actual urban area: Analysis of the mass transport mechanism by high-resolution Large Eddy Simulations, Comput. Fluids, 114, 151–162, https://doi.org/10.1016/j.compfluid.2015.02.018, 2015.

Grange, S. K., Salmond, J. A., Trompetter, W. J., Davy, P. K., and Ancelet, T.: Effect of atmospheric stability on the impact of domestic wood combustion to air quality of a small urban township in winter, Atmos. Environ., 70, 28–38, https://doi.org/10.1016/j.atmosenv.2012.12.047, 2013.

Grimmond, S., Bouchet, V., Molina, L. T., Baklanov, A., Tan, J., Schlünzen, K. H., Mills, G., Golding, B., Masson, V., Ren, C., Voogt, J., Miao, S., Lean, H., Heusinkveld, B., Hovespyan, A., Teruggi, G., Parrish, P., and Joe, P.: Integrated urban hydrometeorological, climate and environmental services: Concept, methodology and key messages, Urban Clim., 33, 100623, https://doi.org/10.1016/j.uclim.2020.100623, 2020.

Gronemeier, T., Raasch, S., and Ng, E.: Effects of Unstable Stratification on Ventilation in Hong Kong, Atmosphere, 8, 168, https://doi.org/10.3390/atmos8090168, 2017.

Gronemeier, T., Surm, K., Harms, F., Leitl, B., Maronga, B., and Raasch, S.: Evaluation of the dynamic core of the PALM model system 6.0 in a neutrally stratified urban environment: com-

parison between LES and wind-tunnel experiments, Geosci. Model Dev., 14, 3317–3333, https://doi.org/10.5194/gmd-14-3317-2021, 2021.

Grythe, H. and Lopez-Aparicio, S.: MetVed v2.0 model and application, NILU tech. report 19/2020, 33 pp., Oslo, Norway, 2020.

Grythe, H., Lopez-Aparicio, S., Vogt, M., Vo Thanh, D., Hak, C., Halse, A. K., Hamer, P., and Sousa Santos, G.: The MetVed model: development and evaluation of emissions from residential wood combustion at high spatio-temporal resolution in Norway, Atmos. Chem. Phys., 19, 10217–10237, https://doi.org/10.5194/acp-19-10217-2019, 2019.

Hedberg, E., Johansson, C., Johansson, L., Swietlicki, E., and Brorström-Lundén, E.: Is Levoglucosan a Suitable Quantitative Tracer for Wood Burning? Comparison with Receptor Modeling on Trace Elements in Lycksele, Sweden, J. Air Waste Manage. Assoc., 56, 1669–1678, https://doi.org/10.1080/10473289.2006.10464572, 2006.

Heinze, R., Moseley, C., Böske, L. N., Muppa, S. K., Maurer, V., Raasch, S., and Stevens, B.: Evaluation of large-eddy simulations forced with mesoscale model output for a multi-week period during a measurement campaign, Atmos. Chem. Phys., 17, 7083–7109, https://doi.org/10.5194/acp-17-7083-2017, 2017.

Heldens, W., Burmeister, C., Kanani-Sühring, F., Maronga, B., Pavlik, D., Sühring, M., Zeidler, J., and Esch, T.: Geospatial input data for the PALM model system 6.0: model requirements, data sources and processing, Geosci. Model Dev., 13, 5833–5873, https://doi.org/10.5194/gmd-13-5833-2020, 2020.

Hellén, H., Hakola, H., Haaparanta, S., Pietarila, H., and Kauhaniemi, M.: Influence of residential wood combustion on local air quality, Sci. Total Environ., 393, 283–290, https://doi.org/10.1016/j.scitotenv.2008.01.019, 2008.

Hiskar, B. A. K., Sundvor, I., Johnsrud, M., Haug, T. W., and Nr, N. P.: Tiltaksutredning for lokal luftkvalitet i Bergen, NILU tech. report, 15/2017, 122 pp., Oslo, Norway, 2017.

Im, U., Christensen, J. H., Nielsen, O.-K., Sand, M., Makkonen, R., Geels, C., Anderson, C., Kukkonen, J., Lopez-Aparicio, S., and Brandt, J.: Contributions of Nordic anthropogenic emissions on air pollution and premature mortality over the Nordic region and the Arctic, Atmos. Chem. Phys., 19, 12975–12992, https://doi.org/10.5194/acp-19-12975-2019, 2019.

Jonassen, M. O., Ólafsson, H., Valved, A. S., Reuder, J., and Olseth, J. A.: Simulations of the Bergen orographic wind shelter, Tellus A, 65, 19206, https://doi.org/10.3402/tellusa.v65i0.19206, 2013.

Keck, M., Raasch, S., Letzel, M. O., and Ng, E.: First Results of High Resolution Large-Eddy Simulations of the Atmospheric Boundary Layer, J. Heat Isl. Inst. Int., 9, 39–43, 2014.

Køltzow, M., Casati, B., Bazile, E., Haiden, T., and Valkonen, T.: An NWP Model Intercomparison of Surface Weather Parameters in the European Arctic during the Year of Polar Prediction Special Observing Period Northern Hemisphere 1, Weather Forecast., 34, 959–983, https://doi.org/10.1175/WAF-D-19-0003.1, 2019.

Krecl, P., Hedberg Larsson, E., Ström, J., and Johansson, C.: Contribution of residential wood combustion and other sources to hourly winter aerosol in Northern Sweden determined by positive matrix factorization, Atmos. Chem. Phys., 8, 3639–3653, https://doi.org/10.5194/acp-8-3639-2008, 2008.

Kukkonen, J., Kangas, L., Kauhaniemi, M., Sofiev, M., Aarnio, M., Jaakkola, J. J. K., Kousa, A., and Karppinen, A.: Modelling of the urban concentrations of PM$_{2.5}$ on a high resolu-

tion for a period of 35 years, for the assessment of lifetime exposure and health effects, Atmos. Chem. Phys., 18, 8041–8064, https://doi.org/10.5194/acp-18-8041-2018, 2018.

Kukkonen, J., López-Aparicio, S., Segersson, D., Geels, C., Kangas, L., Kauhaniemi, M., Maragkidou, A., Jensen, A., Assmuth, T., Karppinen, A., Sofiev, M., Hellén, H., Riikonen, K., Nikmo, J., Kousa, A., Niemi, J. V., Karvosenoja, N., Santos, G. S., Sundvor, I., Im, U., Christensen, J. H., Nielsen, O.-K., Plejdrup, M. S., Nøjgaard, J. K., Omstedt, G., Andersson, C., Forsberg, B., and Brandt, J.: The influence of residential wood combustion on the concentrations of PM2.5 in four Nordic cities, Atmos. Chem. Phys., 20, 4333–4365, https://doi.org/10.5194/acp-20-4333-2020, 2020.

Kurppa, M., Hellsten, A., Auvinen, M., Raasch, S., Vesala, T., and Järvi, L.: Ventilation and Air Quality in City Blocks Using Large-Eddy Simulation – Urban Planning Perspective, Atmosphere, 9, 65, https://doi.org/10.3390/atmos9020065, 2018.

Lareau, N. P., Crosman, E., Whiteman, C. D., Horel, J. D., Hoch, S. W., Brown, W. O. J., and Horst, T. W.: The Persistent Cold-Air Pool Study, B. Am. Meteorol. Soc., 94, 51–63, https://doi.org/10.1175/BAMS-D-11-00255.1, 2013.

Leiren, M. D. and Jacobsen, J. K. S.: Silos as barriers to public sector climate adaptation and preparedness: insights from road closures in Norway, Local Gov. Stud., 44, 492–511, https://doi.org/10.1080/03003930.2018.1465933, 2018.

Letzel, M. O., Krane, M., and Raasch, S.: High resolution urban large-eddy simulation studies from street canyon to neighbourhood scale, Atmos. Environ., 42, 8770–8784, https://doi.org/10.1016/j.atmosenv.2008.08.001, 2008.

Lopez-Aparicio, S. and Grythe, H.: Evaluating the effectiveness of a stove exchange programme on PM$_{2.5}$ emission reduction, Atmos. Environ., 231, 117529, https://doi.org/10.1016/j.atmosenv.2020.117529, 2020.

Maronga, B., Gryschka, M., Heinze, R., Hoffmann, F., Kanani-Sühring, F., Keck, M., Ketelsen, K., Letzel, M. O., Sühring, M., and Raasch, S.: The Parallelized Large-Eddy Simulation Model (PALM) version 4.0 for atmospheric and oceanic flows: model formulation, recent developments, and future perspectives, Geosci. Model Dev., 8, 2515–2551, https://doi.org/10.5194/gmd-8-2515-2015, 2015.

Maronga, B., Knigge, C., and Raasch, S.: An Improved Surface Boundary Condition for Large-Eddy Simulations Based on Monin–Obukhov Similarity Theory: Evaluation and Consequences for Grid Convergence in Neutral and Stable Conditions, Bound.-Lay. Meteor., 174, 297–325, https://doi.org/10.1007/s10546-019-00485-w, 2019a.

Maronga, B., Gross, G., Raasch, S., Banzhaf, S., Forkel, R., Heldens, W., Kanani-Sühring, F., Matzarakis, A., Mauder, M., Pavlik, D., Pfafferott, J., Schubert, S., Seckmeyer, G., Sieker, H., and Winderlich, K.: Development of a new urban climate model based on the model PALM – Project overview, planned work, and first achievements, Meteorol. Z., 28, 105–119, https://doi.org/10.1127/metz/2019/0909, 2019b.

Masson, V., Heldens, W., Bocher, E., Bonhomme, M., Bucher, B., Burmeister, C., de Munck, C., Esch, T., Hidalgo, J., Kanani-Sühring, F., Kwok, Y. T., Lemonsu, A., Lévy, J. P., Maronga, B., Pavlik, D., Petit, G., See, L., Schoetter, R., Tornay, N., Votsis, A., and Zeidler, J.: City-descriptive input data for urban climate models: Model requirements, data sources and challenges, Urban

Clim., 31, 100536, https://doi.org/10.1016/j.uclim.2019.100536, 2020.

Mazzeo, A., Huneeus, N., Ordoñez, C., Orfanoz-Cheuquelaf, A., Menut, L., Mailler, S., Valari, M., Denier van der Gon, H., Gallardo, L., Muñoz, R., Donoso, R., Galleguillos, M., Osses, M., and Tolvett, S.: Impact of residential combustion and transport emissions on air pollution in Santiago during winter, Atmos. Environ., 190, 195–208, https://doi.org/10.1016/j.atmosenv.2018.06.043, 2018.

Park, S.-B., Baik, J.-J., and Han, B.-S.: Large-eddy simulation of turbulent flow in a densely built-up urban area, Environ. Fluid Mech., 15, 235–250, https://doi.org/10.1007/s10652-013-9306-3, 2015.

Resler, J., Krč, P., Belda, M., Juruš, P., Benešová, N., Lopata, J., Vlček, O., Damašková, D., Eben, K., Derbek, P., Maronga, B., and Kanani-Sühring, F.: PALM-USM v1.0: A new urban surface model integrated into the PALM large-eddy simulation model, Geosci. Model Dev., 10, 3635–3659, https://doi.org/10.5194/gmd-10-3635-2017, 2017.

Ronda, R. J., Steeneveld, G. J., Heusinkveld, B. G., Attema, J. J., and Holtslag, A. A. M.: Urban Finescale Forecasting Reveals Weather Conditions with Unprecedented Detail, B. Am. Meteorol. Soc., 98, 2675–2688, https://doi.org/10.1175/BAMS-D-16-0297.1, 2017.

Savolahti, M., Lehtomäki, H., Karvosenoja, N., Ville-Veikko, P., Korhonen, A., Kukkonen, J., Kupiainen, K., Kangas, L., Karppinen, A. and Hänninen, O.: Residential wood combustion in Finland: PM$_{2.5}$ emissions and health impacts with and without abatement measures, Int. J. Environ. Res. Pub. He., 16, 2920, https://doi.org/10.3390/ijerph16162920, 2019.

Schneider, P., Castell, N., Vogt, M., Dauge, F. R., Lahoz, W. A., and Bartonova, A.: Mapping urban air quality in near real-time using observations from low-cost sensors and model information, Environ. Int., 106, 234–247, https://doi.org/10.1016/j.envint.2017.05.005, 2017.

Seljeskog, M., Goile, F., and Skreiberg, Ø.: Recommended Revisions of Norwegian Emission Factors for Wood Stoves, Enrgy. Proced., 105, 1022–1028, https://doi.org/10.1016/j.egypro.2017.03.447, 2017.

Simpson, W., Law, K., Schmale, J., Pratt, K., Arnold, S., and Mao, J.: Alaskan Layered Pollution And Chemical Analysis (ALPACA) White Paper, the International Global Atmospheric Chemistry (IGAC) Project, Boulder, CO, 2018.

Solli, C., Reenaas, M., Strømman, A. H., and Hertwich, E. G.: Life cycle assessment of wood-based heating in Norway, Int. J. Life Cycle Assess., 14, 517–528, https://doi.org/10.1007/s11367-009-0086-4, 2009.

Statens Kartverk: Hydedata, available at: https://hoydedata.no/LaserInnsyn/ (last access 17 August 2021), 2018.

Stoll, R., Gibbs, J. A., Salesky, S. T., Anderson, W., and Calaf, M.: Large-Eddy Simulation of the Atmospheric Boundary Layer, Bound.-Lay. Meteorol., 177, 541–581, https://doi.org/10.1007/s10546-020-00556-3, 2020.

Venter, Z. S., Brousse, O., Esau, I., and Meier, F.: Hyperlocal mapping of urban air temperature using remote sensing and crowdsourced weather data, Remote Sens. Environ., 242, 111791, https://doi.org/10.1016/j.rse.2020.111791, 2020.

Wolf, T. and Esau, I.: A proxy for air quality hazards under present and future climate conditions in Bergen, Norway, Urban Clim., 10, 801–814, https://doi.org/10.1016/j.uclim.2014.10.006, 2014.

Wolf, T., Esau, I., and Reuder, J.: Analysis of the vertical temperature structure in the Bergen valley, Norway, and its connection to pollution episodes, J. Geophys. Res.-Atmos., 119, 10645–10662, https://doi.org/10.1002/2014JD022085, 2014.

Wolf, T., Pettersson, L. H., and Esau, I.: A very high-resolution assessment and modelling of urban air quality, Atmos. Chem. Phys., 20, 625–647, https://doi.org/10.5194/acp-20-625-2020, 2020.

Wolf, T., Pettersson, L. H., and Esau, I.: Scripts for data analysis and visualization, modeling results and processed data for "Dispersion of particulate matter (PM$_{2.5}$) from wood combustion for residential heating: optimization of mitigation actions based on large-eddy simulations", Nansen Center FTP [code and data set], available at: ftp://ftp.nersc.no/igor/, last access: 17 August 2021.

Wolf-Grosse, T., Esau, I., and Reuder, J.: Sensitivity of local air quality to the interplay between small- and large-scale circulations: a large-eddy simulation study, Atmos. Chem. Phys., 17, 7261–7276, https://doi.org/10.5194/acp-17-7261-2017, 2017a.

Wolf-Grosse, T., Esau, I., and Reuder, J.: The large-scale circulation during air quality hazards in Bergen, Norway, Tellus A, 69, 1406265, https://doi.org/10.1080/16000870.2017.1406265, 2017b.

Wyss, A. B., Jones, A. C., Bølling, A. K., Kissling, G. E., Chartier, R., Dahlman, H. J., Rodes, C. E., Archer, J., Thornburg, J., Schwarze, P. E., and London, S. J.: Particulate Matter 2.5 Exposure and Self-Reported Use of Wood Stoves and Other Indoor Combustion Sources in Urban Nonsmoking Homes in Norway, PLoS One, 11, e0166440, https://doi.org/10.1371/journal.pone.0166440, 2016.

Zhang, Y., Ye, X., Wang, S., He, X., Dong, L., Zhang, N., Wang, H., Wang, Z., Ma, Y., Wang, L., Chi, X., Ding, A., Yao, M., Li, Y., Li, Q., Zhang, L., and Xiao, Y.: Large-eddy simulation of traffic-related air pollution at a very high resolution in a mega-city: evaluation against mobile sensors and insights for influencing factors, Atmos. Chem. Phys., 21, 2917–2929, https://doi.org/10.5194/acp-21-2917-2021, 2021.

Zhong, J., Cai, X. M., and Bloss, W. J.: Coupling dynamics and chemistry in the air pollution modelling of street canyons: A review, Environ. Pollut., 214, 690–704, https://doi.org/10.1016/j.envpol.2016.04.052, 2016.