An enhanced integrated approach to knowledgeable high-resolution environmental quality assessment

Esau, Igor

2021-08

Esau , I , Bobylev , L , Donchenko , V , Gnatiuk , N , Lappalainen , H K , Konstantinov , P , Kulmala , M , Mahura , A , Makkonen , R , Manvelova , A , Miles , V , Petaja , T , Poutanen , P , Fedorov , R , Varentsov , M , Wolf , T , Zilitinkevich , S & Baklanov , A 2021 , ' An enhanced integrated approach to knowledgeable high-resolution environmental quality assessment ' , Environmental Science & Policy , vol. 122 , pp. 1-13 . https://doi.org/10.1016/j.envsci.2021.03.020

http://hdl.handle.net/10138/339709
https://doi.org/10.1016/j.envsci.2021.03.020

Environmental Science and Policy 122 (2021) 1–13

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

An enhanced integrated approach to knowledgeable high-resolution environmental quality assessment

Igor Esau[a,*], Leonid Bobylev[b], Vladislav Donchenko[c], Natalia Gnatiuk[b], Hanna K. Lappalainen[d,e], Pavel Konstantinov[f], Markku Kulmala[d], Alexander Mahura[d], Risto Makkonen[d,g], Alexandra Manvelova[c], Victoria Miles[a], Tuukka Petäjä[d], Pyry Poutanen[d], Roman Fedorov[e,j], Mikhail Varentsov[f,i], Tobias Wolf[a], Sergej Zilitinkevich[d,e,g,†], Alexander Baklanov[h]

[a] Nansen Environmental and Remote Sensing Center / Bjerknes Center for Climate Research, Thormohlensgt. 47, 5006, Bergen, Norway
[b] Nansen International Environmental and Remote Sensing Centre, 14th Line 7, Office 49, Vasilievsky Island, 199034, St. Petersburg, Russia
[c] St. Petersburg Federal Research Center of the Russian Academy of Sciences, 39, 14 Line, St. Petersburg, 199178, Russia
[d] Institute for Atmospheric and Earth System Research, University of Helsinki, Gustaf Hällströmin katu 2a, FI-00560, Helsinki, Finland
[e] Tyumen State University, 625003, 6 Volodarskogo Str., Tyumen, Russia
[f] Lomonosov Moscow State University, Faculty of Geography / Research Computing Center, Leninskie Gory 1, Moscow, 119991, Russia
[g] Finnish Meteorological Institute, P.O. Box 503, FI-00101, Helsinki, Finland
[h] World Meteorological Organization, Geneva, Switzerland
[i] A.M. Obukhov Institute of Atmospheric Physics, 119017, Pyzhyovskiy pereulok, 3, Moscow, Russia
[j] Institute of the Earth Cryosphere SB RAS, 625026, 86 Malygina Str., Tyumen, Russia

ARTICLE INFO

Keywords:
Environmental impact assessment
Meteorological integrated modeling
Urban remote sensing
Urban air quality scenarios

ABSTRACT

Sustaining urban environmental quality requires effective policy measures that integrate local monitoring and contextualized high-resolution modelling with actionable scenarios. Knowledgeable decision making in this field can nowadays be supported by an array of atmospheric models, but their transfer into an Integrated Urban hydrometeorological, climate and environmental Services (IUS) remains challenging. Methodological aspects that are beyond pure technicalities of the model-to-model coupling are still poorly explored. Modeling downscaling chains lack their most user-relevant link – urban-to-neighborhood scale observations and models. This study looks at a socio-environmental context of the high-resolution atmospheric modeling in the case study of the Arctic urban cluster of Apatity and Kirovsk, Russia. We demonstrate that atmospheric dynamics of the lowermost, turbulent air layers is highly localized during the most influential episodes of atmospheric pollution. Urban micro-climates create strong circulations (winds) that are sensitive to the local environmental context. As the small-scale turbulence dynamics is not spatially resolved in meteorological downscaling or statistical modeling, capturing this local context requires specialized turbulence-resolving (large-eddy simulation) models. Societal acceptance of the urban modeling could be increased in the IUS with horizontally integrated modeling driven by localized scenarios. This study presents an enhanced integrated approach, which incorporates a large-eddy simulation model PALM into meteorological downscaling chains of a climate model (EC-EARTH), a numerical weather prediction – atmospheric chemical transport model (ENVIRO-HIRLAM) and a regional-scale meteorological model (COSMO-CLM). We discuss how this approach could be further developed into an environmental component of a digital “smart city”.

---

[*] Corresponding author.
E-mail address: igore@nersc.no (I. Esau).
[†] Deceased.

https://doi.org/10.1016/j.envsci.2021.03.020
Received 25 September 2020; Received in revised form 16 February 2021; Accepted 31 March 2021

1. Background

1.1. Public discourse on integrated urban services

Public discourse on environmental quality frequently lacks detailed, concrete data to inform decision making process. Heat and controversy of debates could be very intense in urban areas where societal costs of decisions are high. Recognizing the challenge, the Integrated Urban hydrometeorological, climate and environmental Services (IUS) initiative has been launched by the World Meteorological Organization (WMO) to support sustainable, resilient and climate adopted cities (Baklanov et al., 2018; WMO, 2019; Grimmond et al., 2020). As in many other places, the Russian northern cities – such as Apatity and Kirovsk (Murmansk region, Kola Peninsula) in our case – experience wicked societal, environmental, and economic challenges; some of them are specific to the Arctic environment. Distinct to many other places, the Arctic cities have received much less attention from international research agendas. Observational networks here are sparce, and environmental modeling is less detailed. Urban planning in the Arctic cities is often conceived in big administrative centers that can be located thousands of kilometers away (Petrov et al., 2016; Shiklomanov et al., 2017; Taylor et al., 2016). Their stakeholders operate non-concrete, non-localized and non-contextualized environmental information (Dale, 2016; Laruelle, 2019; Laruelle et al., 2019). Destructive consequences of such planning decisions might overwhelm environmental management after a few decades of urban development (Hagner and Rigina, 1998; Streletskiy et al., 2012). Rethinking approaches to obtain and use local environmental knowledge is clearly needed to aid a sustainable development paradigm in the global Arctic.

Apparent underuse of local environmental information cannot be explained only by lack of technologies to operate high-resolution observations and models. High barriers are created by a tendency to work within vertically-integrated organizational frameworks, known as siloed structures or simply as the silos (Leiren and Jacobsen, 2018; Fan et al., 2018). Invisible normative barriers in the silos restrict horizontal data sharing, knowledge transfer and acceptance of model downscaling chains. Moreover, local details that concern the stakeholders might face vigorous opposition and even denial from involved local actors (Biesbroek et al., 2014). For example, Eliasson et al. (see Eliasson, 2000; and Svensson and Eliasson, 2002) studied barriers to utilize the urban climate information by stakeholders in Sweden. They found that despite active interest to get a more accurate information, this information is infrequently utilized in actual decision making due to rigidity of the administrative routines. We have drawn similar conclusions from interviews with stakeholders in Hammerfest and Alta (Norway)[1], and more recently in the Russian sub-Arctic city of Nadym (Fedorov et al., 2021). The stakeholders emphasized deficit of expertise and time to work with the local environmental information. In such circumstances, a large weight in decision-making is given to regional environmental features while more influential local features are omitted or overlooked.

The known integrated services rely on centralized providers of weather, air quality, and other environmental information. New urban services have generally been developed from existing prediction systems, which undervalue the local needs. Attempts to increase end-user participation in such services have been disappointing (Kolstad et al., 2019). It was recognized that IUS is an iterative process where actionable information ought to be co-produced through dialogue, integration, and contextualization.

1.2. Barriers to a horizontally integrated approach

What barriers to overcome becomes clearer from analysis of delegation of responsibilities. Cohen et al. (1972) demonstrated that the siloed organizations produce sub-optimal decisions if incoming information is pre-selected. Inconvenient or simply incompatible information is ignored or even eliminated. Lower administrative levels are inclined to wait for instructions and policy from above while the higher authorities are reluctant to fully account for the local context and tend to rely on less relevant but certified information sources (Leiren and Jacobsen, 2018). How might this local context be overlooked by certified information sources? A physical reason for this comes from required "representativeness" of the certified observations. Observations must characterize a typical environment, whereas each local environment is unique by definition. The locally influential phenomena may not be seen at higher decision levels as such details would be considered as peculiar and redundant. At the same time, the lack of robust local context has been recognized as an issue leading to chaotic, non-resolving managerial decisions (Cohen et al., 1972). For example, the local "meandering flows" (Mortarini et al., 2019) are driven by local balances (Mahrt, 2011) and do not make imprints above a blending height – a layer of a few hundred meters, which smooth all local horizontal differences (Baklanov et al., 2011). Wolf-Grosse et al. (2016) shows that local circulations driven by small-scale horizontal temperature differences may deteriorate air quality in the most populous urban districts at significant distances from emission sources.

Reflecting the global tendencies (Bai et al., 2017), emerging civil society of northern cities gradually voices stronger demand for localized and integrated environmental assessment (Nilsson et al., 2017; Reckien et al., 2015). The post-Soviet socio-economic adaptation temporary reduced the societal demand to environmental quality. Several studies (e.g., Johansen and Skryzhevska, 2013; Dushkova and Krasovskaya, 2018) noted that the municipalities on the Kola Peninsula (Murmansk region, Russia; Fig. 1) still underappreciate impact of climate change and environmental pollution; but an important swing has been observed. Nilsson et al. (2017) reported that environmental and natural conditions with respect to socio-economic development pathways constitute the most significant (mentioned by 23 % of respondents) issue in Kirovsk. The public attention to the local climate conditions is debated in research studies such as those dealing with anthropogenic (Varentsov et al., 2018) or natural (Demin, 2019) origin of an urban heat island – the phenomenon of persistent warmer temperatures within urban limits. The urban heat island intensity is a convenient and accessible proxy for many other indicators of environmental quality (Li et al., 2018) and even social justice (Voelkel et al., 2018).

Inspired by this progress, strong efforts are now directed towards multi-scale seamless modeling and data analysis (Baklanov et al., 2007; Reichstein et al., 2019). Still, the full enhanced IUS implementation remains challenging; methodological problems of the system integration at local scales persist. The essential components, such as dense observation networks and databases, high-resolution models across different time scales, are rather being run together than integrated. Using public subsidies, environmental agencies prone to suppress independent market-oriented solutions, thus, delaying maturity of the IUS and impeding engagement with different sectors. A study of sub-Arctic cities (Ebrahimabadi et al., 2015) concluded that tools for microclimate analysis are still insufficiently user friendly. The urban stakeholders need methods that combine analyses and offer a complete targeted assessment. Methods of data fusion may help in increasing data density (Johansson et al., 2015; Varentsov et al., 2020), especially in connection with the seamless model integration (Baklanov et al., 2018).

This study includes descriptions of monitoring (Section 2) and modeling (Section 3) components of the horizontally integrated approach. Section 4 discusses multi-, inter- and trans-disciplinary implications of the enhanced IUS. It also surveys issues related to administrative and policy implications of the enhanced integrated approach. Finally, Section 5 outlines conclusions and recommendations.

---

[1] The interviews were conducted by L. Iversen in 2015–2016 for the Belmont Forum project HIARC (unpublished).

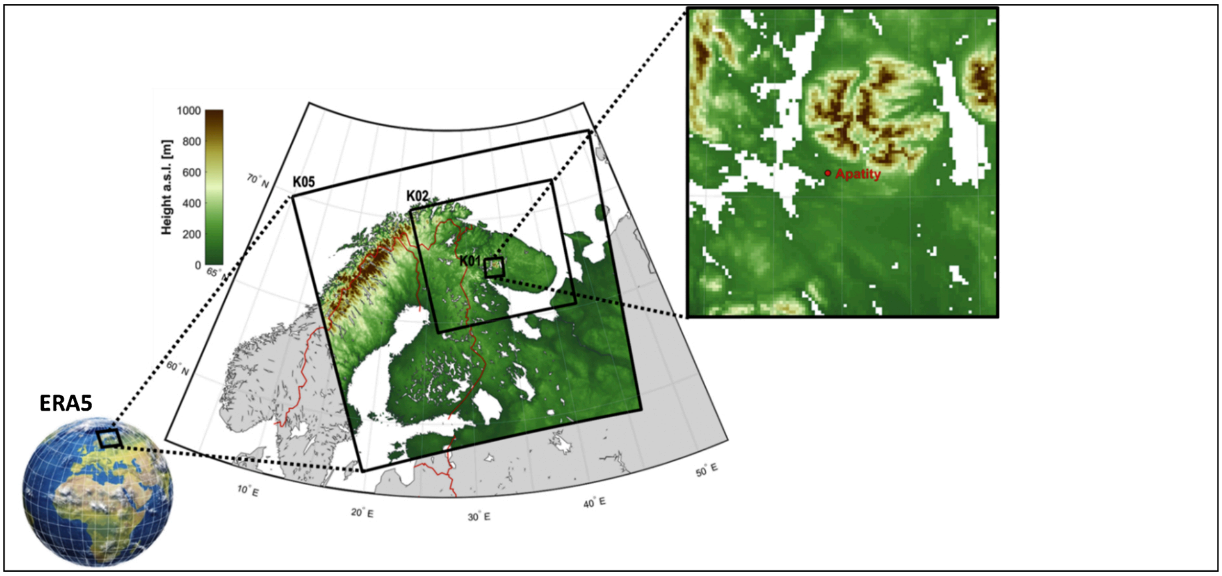

Fig. 1. The Apatity-Kirovsk study area on the Kola peninsula, Murmansk region, Russia. The scheme shows the downscaling chain and three nested domains K05, K02 and K01, used for simulations with the COSMO-CLM model. The right subplot shows the relief of the finest domain K01 at the grid resolution of 1 km.

2. Integrated monitoring at the local scales

The World Urban Database and Access Portal Tool (WUDAPT) identifies four data criteria for successful data application in the urban studies (Ching et al., 2018): (1) surface descriptions must permit models to resolve the temporal/spatial characteristics of the urban boundary layer, including properties at local scales; (2) data sets must meet highly specialized requirements of the urban models; (3) for worldwide applicability, data sets should be consistent and reliable; and (4) coarse models must represent unresolved variations of atmospheric quantities. Generation of data and model results should be practicable and achievable over a reasonably short time frame to adopt a pragmatic approach. Below, we consider these criteria in more details as implemented in our study area.

2.1. The case study area and climate

Following the WUDAPT requirements, we adopt a pragmatic approach in a concrete context for monitoring and data collection. Extensive literature review is used to generalize the key elements of the study. Apatity at 67.57 °N, 33.38 °E, 170 m above sea level (asl) and Kirovsk at 67.62 °N, 33.67 °E, 380 m asl constitute an Arctic urban cluster that we selected to this case study. The cluster is located above the Arctic circle in the center of the Kola Peninsula between the lake Imandra and the Khibiny mountains. The winter season here is rather long (7–8 months) with snow cover up to 250 days. The mean monthly air temperature in Apatity is −14 °C in January and +15 °C in July. The polar night in this region lasts from December 15 until 28; the polar day – from May 29 until July 15. The area is characterized by contrasting land cover types.

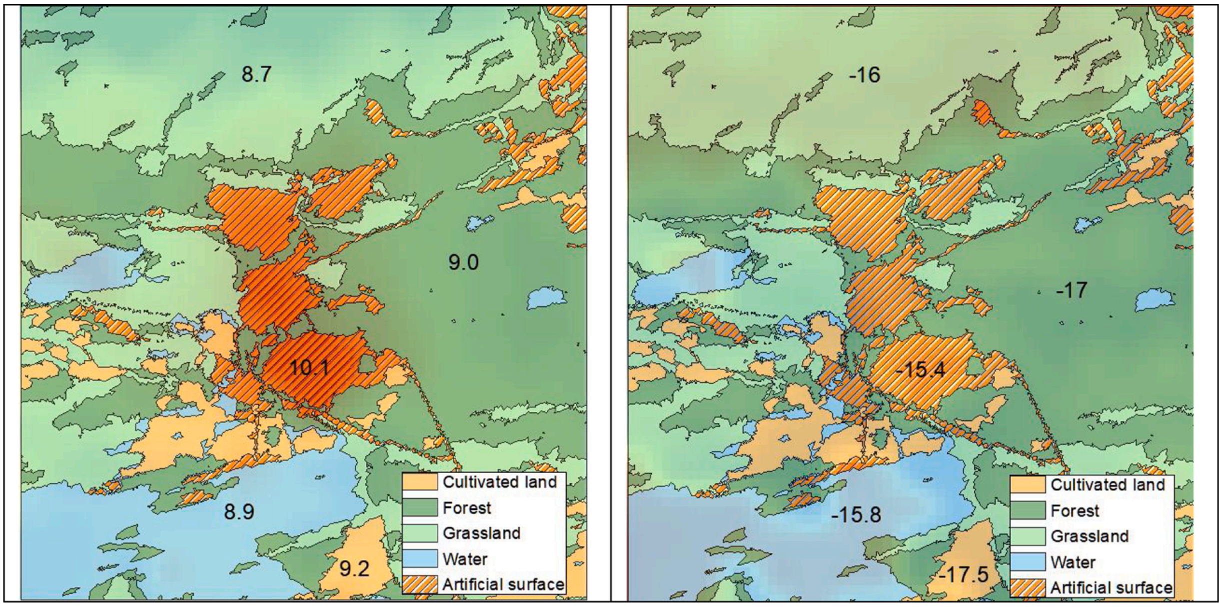

Fig. 2. The mean summer and winter land surface temperatures and the corresponding relative urban temperature anomalies (surface urban heat island – UHI) proper for different land use – land cover types found around Apatity during: (left panel) the summer months June, July, August; (right panel) the winter months December, January, February. Averaging is performed over the day- and nighttime datasets.

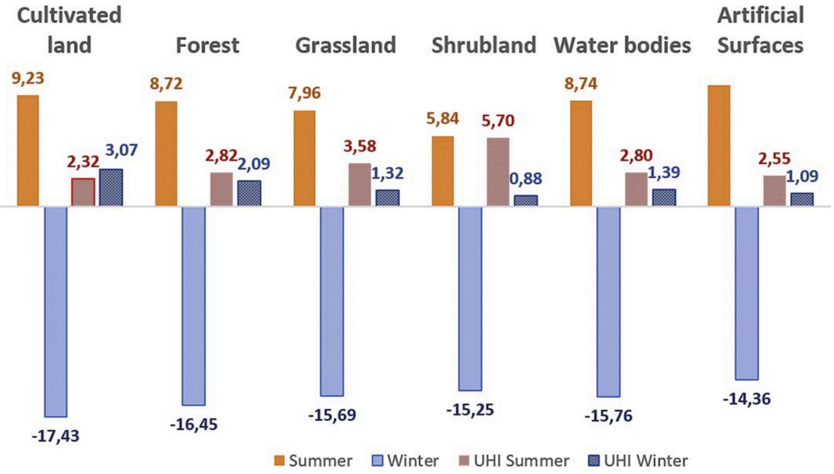

Fig. 3. Urban-rural temperature differences over 2000-2018. The LULC types are taken from Apatity and surrounding area as in Fig. 2. Summer (orange) and winter (blue) bars show the mean land surface temperature for the summer and winter seasons over the given LULC type. UHI bars show the seasonally average temperature differences between the given LULC type and the urban type.

2.2. *Surface description resolving local climate and environment*

We use satellite remote sensing of land use – land cover (LULC) to associate local climate anomalies with the surface types (Esau and Miles, 2018) and biological productivity (Miles and Esau, 2016). Fig. 2 shows the LULC surface types in the area. The map is combined with the analysis of the average land surface temperature. The analysis is based on the MODIS data products (2000–2018). The urbanized surface area of Apatity is significantly warmer than the surrounding natural landscapes. This temperature anomaly is created by dryer urban surfaces in summertime and intense anthropogenic heat release in wintertime (Varentsov et al., 2018). In wintertime, local temperature variations reflect differences in the surface elevation as temperature inversions are frequently observed (Demin et al., 2016). The accepted criterion that advocates for a careful selection and distinction of urban and rural observations (Stewart, 2011) looks less sound when patchiness and diversity of the natural LULC types are taken into account (Esau and Miles, 2018). Therefore, the surface description shall account for interconnections and feedbacks between the LULC types and climatic variables. Fig. 3 reveals these persistent relationships. Urbanized surface is warmer in all seasons. Forested and cultivated land are warmer than open wet-, shrub and grassland in summer, but colder in winter enhancing the apparent UHI.

Differences in the local LULC heat budget may drive atmospheric circulations at local and larger scales. In situ observations could be misleading in heterogeneous environment. Baldocchi et al. (Baldocchi et al., 2000) showed that partitioning between sensible and latent fluxes alone can create differences in the surface heat budget that influence the atmospheric boundary layer. The latent flux constitutes 65 % of the total absorbed radiation in coniferous forest in Norunda, Sweden (60.5 °N, 17.29 °E; Composition: *Pinus sylvestris, Picea abies, Vaccinium myrtillus L.*; Canopy height: 23 m; Tree age: 100 years), but its share reduces to 25%–45% over open wetland.

The published data might have indicated an underappreciated positive micro-climatic feedback that links increased surface roughness, which leads to increased canopy heat storage, with climatically significant redistribution of heat in space and time; the redistribution that sustains higher temperatures in the areas of generally negative surface energy balance. Driving local atmospheric circulations, the LULC differences can translate and couple to regional weather patterns. An effect of in-land snow breezes in the boreal forest zone has been already noted (Taylor et al., 1998) as well as climatic feedbacks of the surface energy modification between open and forest patches at larger scale (Beringer et al., 2005). This multi-scale atmospheric dynamics makes the integrated approach necessary for local meteorological models.

2.3. *Low-cost urban meteorological networks*

The Arctic cities lack representative meteorological and other environmental data that are collected by WMO certified stations inside the urbanized area. A typical weather station of the Russian Hydrometeorological Service (Roshydromet) is located outside the city, frequently near its airport. Hence, low-cost local meteorological networks are needed to monitor the diversity of micro-climatic conditions as well as their different response on changing weather patterns. Such networks are common in temperate cities, e.g., in Helsinki (Johansson et al., 2015) or in Oslo (Schneider et al., 2017; Venter et al., 2020), but rather unique for the Arctic settlements (Klene et al., 2013). Apatity is one of the Russian Arctic cities, where the Urban Heat Island Arctic Research Campaign (UHIARC) network is deployed (Konstantinov et al., 2018; Varentsov et al., 2018). Observations in Apatity are conducted with an automatic weather station (AWS) in the city center and numerous temperature sensors (*iButton* loggers) distributed over the whole area. Fig. 4 shows configuration of the temperature sensors in the 2017–2018 winter measurement campaign.

Meteorological variables, such as anomalies of the surface air temperature in the urban heat island (UHI), are less difficult to monitor at spatial high resolution than air quality of socio-environmental indicators. Therefore, e.g., UHI is frequently used as a reasonably accurate but inexpensive proxy for air pollution (Li et al., 2018) or even population health (Gasparrini et al., 2015). The UHI in Apatity is also related with environmental quality indicators. A strong UHI in Apatity was found during the intensive observation and modeling period in December 26, 2017. The central urban area was up to 6.1 °C warmer than an open land area at the neighboring hill; and by almost 10.0 °C warmer than the lower open lake shore (Fig. 4). Such large local temperature differences are created by persistent clear-sky, anti-cyclonic weather conditions with very calm winds and intense surface temperature inversions. The regular WMO station at the lake Imandra reports 9.0 °C lower temperature than that in the city (Fig. 5). Calm winds enhance the role of local circulations that are driven by the large horizontal temperature gradients. We argue in this study that those circulations are captured only by a turbulence-resolving model capturing local circulations in the boundary layer.

2.4. *High-cost detailed monitoring*

High quality, and high-cost, labor-intensive monitoring is needed to

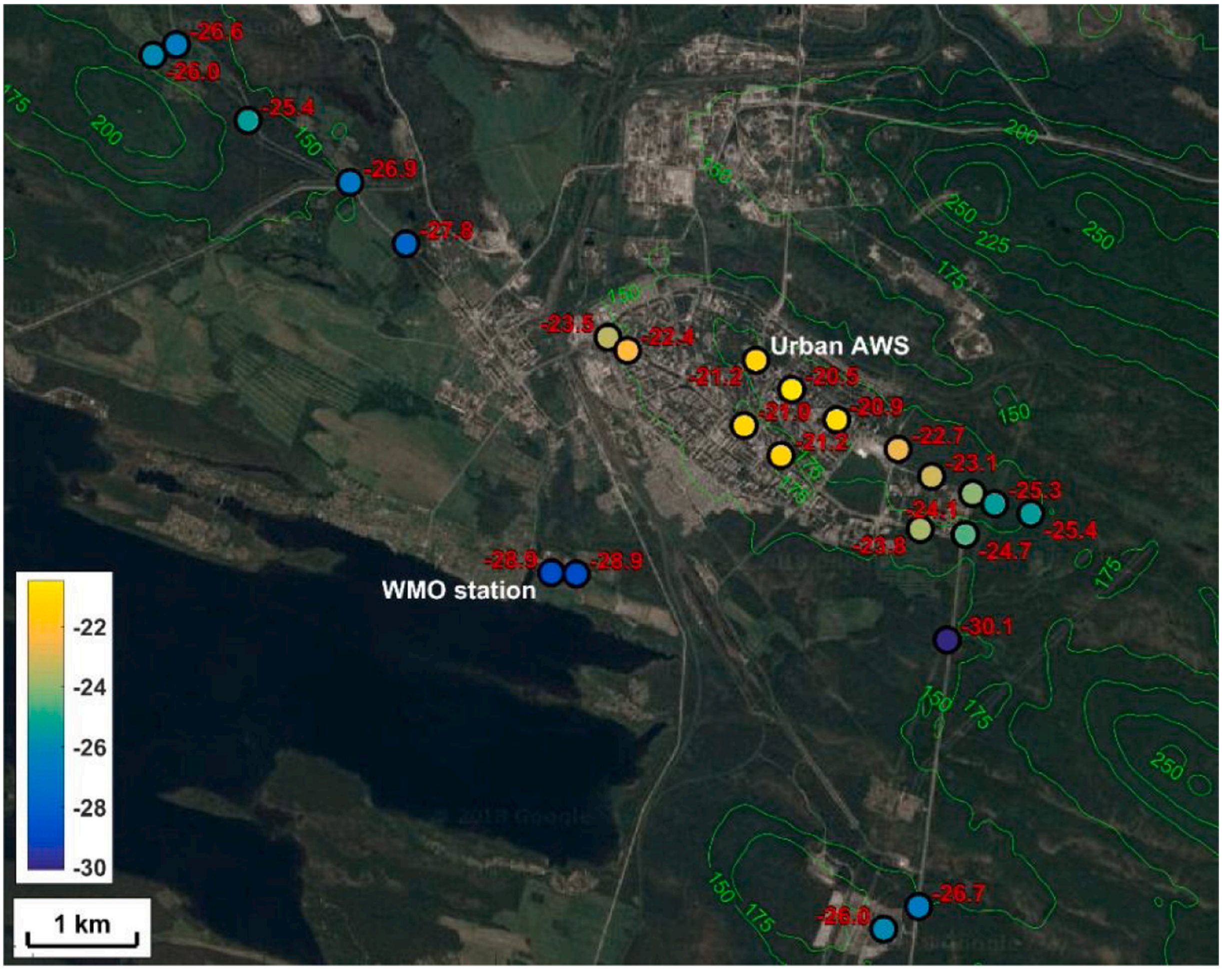

Fig. 4. Spatial distribution of the mean air temperature, averaged over 26 December 2017 according to extended UHIARC observations. Elevation is shown using green contour lines, which are indicated every 25 m.

interconnect dynamical, physical, and chemical processes on small spatial and temporal scales. Current observational networks are siloed so that each discipline, research team or monitoring authority designs and builds stations to suit their own purposes. Integration of these networks into a coherent information supply chain have proved to be difficult. Integration with models is difficult as well. Each agency pushes for its own modeling systems. To mitigate this challenges more comprehensive and coherent monitoring systems are necessary (Kulmala, 2018). Such systems may resolve processes, fluxes, or traces ofhundreds of compounds of interest in the atmosphere. These needs require an integrated approach (Petäjä et al., 2016, 2020) that includes data collected by the Station for Measuring Ecosystem-Atmosphere Relations (SMEAR) installations (Hari et al., 2016; Hari and Kulmala, 2005). Atmospheric mass spectrometers, cloud radars, lidars and other high accuracy instruments are collocated to observe more than 1200 parameters[2] . Here, we use data from two Finnish stations: SMEAR-I (boreal forest in Värriö; in operation since 1991; 67°46′ N, 29°36′ E, 390 m asl.; Hari et al., 1994); and partially SMEAR-III (urban environment, Helsinki; Järvi et al., 2009) stations. Observations are web-online available and can be downloaded for independent analysis[3] .

3. Integrated modeling approach extended to the local scales

Presently, the focus of integrated approaches is undisputedly on sustaining environmental quality under progressive global warming. There is a challenge to localize and contextualize global climate change projections as well as scenarios. The climate models provide projections of large-scale anthropogenic and natural climate forcing for a hundred years ahead. However, they have little to tell about regional projections, especially in those areas and for those variables that are sensitive to small-scale atmospheric dynamics (Shepherd, 2014). Such modeling frameworks that include the regional COSMO-CLM model, urban models and personal environmental quality indices are under development in several European projects (Reinwald et al., 2019). The most influential small-scale dynamics in our study area is related to the air pollution and its impact on environmental quality. Both local and long-range transport pollution must be considered simultaneously (Arnold et al., 2016; Schmale et al., 2018). Local Arctic air pollution is severe in many places, impairing public health and affecting ecosystems. In Apatity, 66.5 % of population were concerned with water quality and 54.1 % with air quality in 2008[4] . Although the accumulated environmental impact is considerable in the Monchegorsk-Apatity-Kirovsk triangle (Hagner and Rigina, 1998), high pollution episodes were infrequent in Apatity (0.03 % - 0.18 % of the total number of samples) and Kirovsk (0.04 % - 0.16 %)

---

[2] The complete SMEAR description is available from https://www.atm.helsinki.fi/SMEAR.

[3] The data are available from https://www.atm.helsinki.fi/SMEAR/index.php/online-observations and can be downloaded from https://avaa.tdata.fi/web/smart/smear/download.

[4] According to the site https://eco-apatity.jimdofree.com; last accessed 08.02.2021

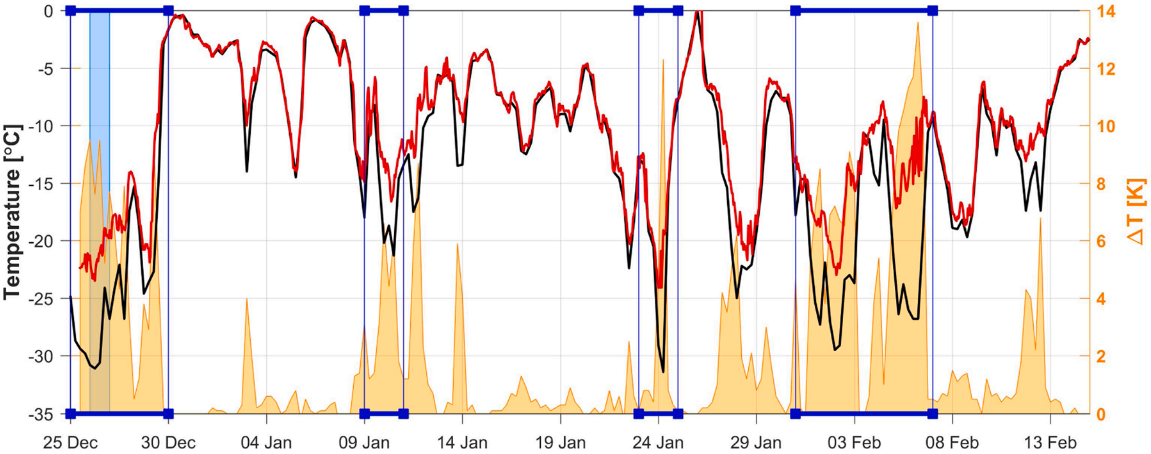

Fig. 5. Variations of the surface air temperature at the urban AWS site (red line) and at the regular WMO station (black line) for 2017-2018 winter observational campaign (25 Dec – 15 Feb). Orange shading indicates the temperature difference ΔT between two sites. Blue rectangles indicate the typical periods with the pronounced urban-rural temperature contrasts and stable stratification of the lower atmosphere. Blue shading indicates the cold period of 26th of December, selected for the modeling study scenario.

in 2014–2017 (Anon, 2018). In wintertime, however, pollution can accumulate under lower atmospheric inversion layers. Localization of such events makes them particularly difficult to resolve in regional models. Moreover, present-day inventories show a large spread in the amount and location of emissions increasing uncertainty of model predictions and deviations from observations (Schmale et al., 2018).

3.1. Global- and regional-scale components of the downscaling chain

The following components are included in the enhanced integrated model downscaling chain (Fig. 1) and Table 1. The global scales were represented by the European Community Earth System Model, EC-EARTH (Hartung et al., 2018). The historical observations were taken from the ERA-5 archive at the European Centre for Medium range Weather Forecast (ECMWF). The details on the regional level were added through downscaling (zooming) model chains with the COSMO-CLM (Rockel et al., 2008) and Enviro-HIRLAM (Baklanov et al., 2017b) models. The local or urban level of details was coupled through the turbulence-resolving model PALM (Maronga et al., 2015). To initialize and run the simulations we use remote-sensing data collections (Miles and Esau, 2020). The in-situ UHIARC data (Konstantinov et al., 2018) is used to verify the results. Table 2 provides information about access to the described modeling components.

The EC-EARTH historical and climate change simulations provide statistics of weather conditions, which are critical for the air quality monitoring. Using two thresholds for daily mean precipitation (0.01 mm and 0.1 mm) and daily mean surface wind speed (3 m s^{-1} and 5 m s^{-1}), the number of days was found when these thresholds were met in the region. Fig. 6 shows that typical wintertime days are not completely calm and dry. The atmospheric conditions favorable for the air pollution episodes and strongly localized heat anomalies are observed 4–6 times over the winter season. The average winter temperature and number of days with precipitation are increasing towards the end of the 21st century in the climate change simulations. That should reduce both frequency and severity of the air quality hazards in the region. Indeed, such trends seems to be observed in the air quality data in the study area (Anon, 2018) as well as across other parts of the region, e.g., in Bergen (Wolf-Grosse et al., 2017).

A regional air pollution transport is provided by the Environment – High Resolution Limited Area Model (Enviro-HIRLAM). Enviro-HIRLAM is a fully online integrated numerical weather prediction and atmospheric chemical transport multi-scale modelling system (Baklanov et al., 2017b). It includes modules for gas-phase chemistry and aerosol microphysics; urbanization (anthropogenic heat flux and roughness, building effect parameterization, others); natural, biogenic and anthropogenic emissions; different aerosol processes, etc. The model runs are organized in a downscaling chain with 3 enclosed domains of 15, 5 and 2 km horizontal resolutions and 40 vertical levels. Fig. 7 shows characteristics obtained in the downscaling chain of the Enviro-HIRLAM model centered over Kola Peninsula. The model is forced by the ERA-5 reanalysis data but does not integrate additional observational information from local observational networks. The model includes effects of

Table 1
Summary of the model tools in the integrated approach.

Purpose/Model	Domain/Resolution	Output	Time Scales
Climate projection and impactful scenarios:	Global domain	Climate projections for the historical and several representative pathway scenarios; data for assessment of influencial weather regimes, their frequency and persistence	Days (for pollution trajectories) to decades (climate change model runs)
EC-EARTH (combines IFS, LPJ-GUESS, NEMO, TM5)	Model resolutions for the atmosphere of about 80 km and for the ocean of 1 degree		
Forecast and scenario assessment:	Limited-area domains; downscaling chain with the model runs at 15, 5, 2 km (40 levels); boundary conditions from GTOPO30, GLCC, ECOCLIMAP, and CORINE data sets at 5, 2, 1 km (50 levels); spectral nudging to prescribed initial and boundary conditions		Hours to days in the weather forecast runs
Enviro-HIRLAM		Meteorology (based on ERA-Interim), chemistry and aerosol transport	
COSMO-CLM		Meteorology (based on ERA-Interim and ERA5)	
Local scenario assessment:	Local domains		Minutes and up to one day
PALM	Resolution of 5 m (urban districts) to 25 m (entire urban area)	Boundary layer meteorology, pollution concentrations and local air flows	

Table 2

Access to the components of the LES-enhanced integrated approach.

Product/set	Access mode	Status/ Notes	Web site
UHIARC data	Open access after registration	Available	http://urbanreanalysis.ru
SMEAR data	Open access	Available	https://www.atm.helsinki.fi/SMEAR/index.php/online-observations https://smear.avaa.csc.fi/
PALM code	Open access after registration	Available	https://palm.muk.uni-hannover.de/trac
COSMO-CLM code	Open access after registration	Available	https://www.clm-community.eu/
Enviro-HIRLAM code	Open access after registration	Available	Request for agreement should be submitted to alexander.mahura@helsinki.fi (Alexander Mahura)
Transboundary pollution web Atlas	Open access	Available	http://www.atm.helsinki.fi/peex/webatlas/WEBATLAS.html

the urban surfaces as well as accounts for both the direct and indirect aerosol effects.

Enviro-HIRLAM downscaling has a significant added value. We observe emergence of locally high concentrations of black carbon around Apatity-Kirovsk (the 3rd column in Fig. 7; increasing resolution of the model output from the top to bottom rows). In the considered winter period, the winds are calm in central areas of the Kola Peninsula. Major pollution transport routes are better localized at finer scales. At high resolutions, the model underestimates influence of local and turbulent winds that are unresolved in its single-column physical organization.

3.2. Regional- and local-scale components of the downscaling chain

3.2.1. Large-eddy simulation (LES) enhancement of the downscaling chain

Integration with a turbulence-resolving model is needed to overcome difficulties of transition from single-column to fully three-dimensional turbulence dynamics. The LES-enhanced downscaling is a rapidly developing research line that aims to close the scale gap between meteorological and turbulence-resolving models. One-way model coupling is a popular approach. In this approach, the LES is driven by the meteorological model but does not feed back to it. The Weather Research and Forecasting (WRF) model is used in several important studies on the subject. For instance, LES-enhanced simulations were reported that span the resolution range of four orders of magnitude (from 111 km to 0.0082 km) in studies of stably stratified atmospheric conditions (Muñoz-Esparza et al., 2017). These simulations demonstrated high fidelity in reproduction of wind and temperature profiles throughout the entire diurnal cycle

At present, a consensus from the LES-enhanced downscaling studies is emerging indicating more accurate results on somewhat intermediate LES resolutions (10 m–100 m) as resolving climatic external factors but damping upscaling of errors from small structures. One study (Bauweraerts and Meyers, 2019) found that modelling errors decrease with grid coarsening, as both chaotic divergence and subgrid-scale error sources decrease. This counterintuitive result owes to stronger suppression of the numerical noise at coarse meshes while accuracy degradation at larger scales is still under control. Mirocha et al. (Mirocha et al., 2014) demonstrated that small hills and valleys improve the turbulence representation in under-resolving LES as large-scale motions and meandering flows are reproduced better than small-scale turbulence. There are also promising results of the LES-enhanced downscaling evaluated with respect to particulate matter measurements (Joe et al., 2014). The LES-enhancement improves average and maximum hourly contributions from all sources by nearly a factor of 2, particularly in extreme pollution episodes. Finally, a more conceptual study (Zhou et al., 2014) concludes that having the model mesh in the transition range of scales between two- and three-dimensional turbulence (0.1 km–5 km) should be avoided as the natural scales of instability resonate with the numerical instability on the grid scales. This argument justifies the leap over the scale gap directly to the LES scales.

3.2.2. Enhancement with the COSMO and PALM models

We argue in this study that the local model enhancement is not only a technicality of environmental monitoring and assessment but an essential addition to include information inaccessible on higher levels of

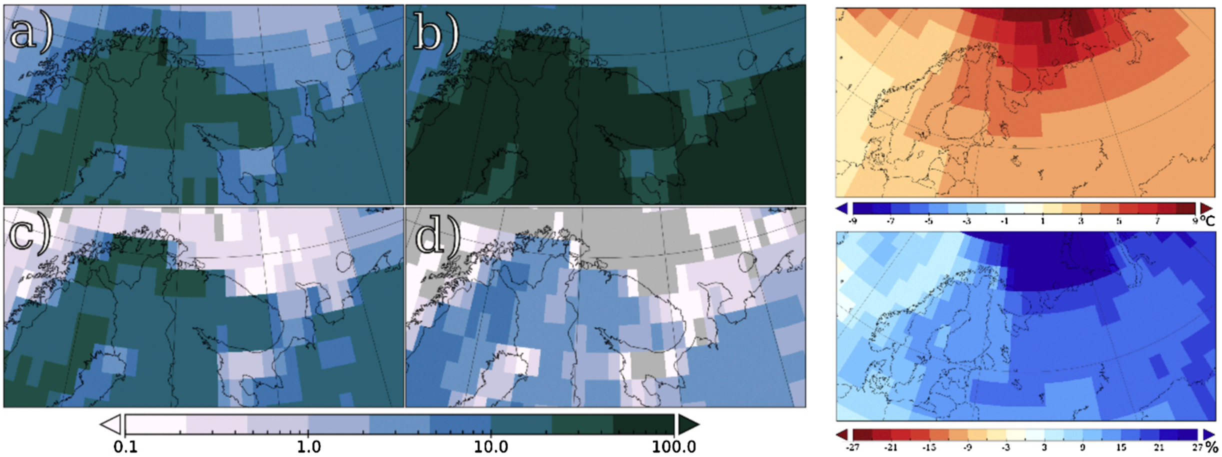

Fig. 6. Fraction of winter (Dec-Jan-Feb; 2005-2015) days when the selected meteorological thresholds are met: (a) daily precipitation < 0.1 mm; (b) daily average wind-speed < 5 m/s; (c) both conditions are met; (d) precipitation <0.1 mm and wind-speed < 3 m s^{-1} and changes in wintertime (e) 2-meter temperature (^{o}C) and (f) precipitation (%) during the 21 st century (present-day climatology is averaged over years 1981-2010 and end-of-century climatology over 2070-2099).

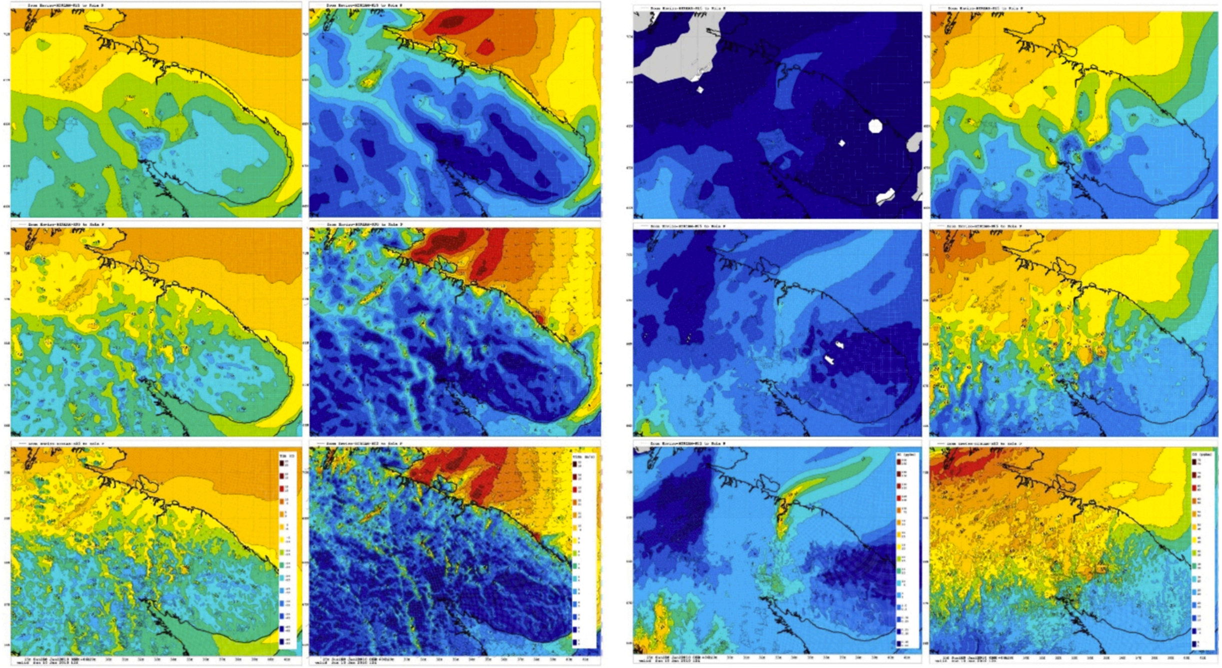

Fig. 7. Localization of the meteorological and air quality characteristics with the Enviro-HIRLAM model downscaling chain. The top row shows the model runs at the horizontal resolution of 15 km; the middle row – 5 km; and the bottom row - 2 km. The first (left) column shows air temperature at 2 m; the second column – wind speed at 10 m; the third column – black carbon concentration; and the fourth (right) column – ozone concentration. The zoomed area is centered over the Kola Peninsula.

environmental protection hierarchy. The critical environmental physics is related to the localized turbulent mixing processes near the surface that lack universality required by their schematic representation in coarse resolution models and sparce monitoring data. We will demonstrate now that implementation of the model downscaling without turbulence-resolving simulations – a kind of the mainstream approach – does not resolve critically important details to be used in decision-making.

The proposed enhanced approach requires integration of COSMO and PALM models. The downscaling chain with these two models was tried and favorably evaluated in several studies (Heinze et al., 2017b; Reinwald et al., 2019). There were also attempts to extend the COSMO model with runs at 500 m and 250 m resolution in Zurich (Mussetti et al., 2020). COSMO-CLM was used for dynamical downscaling of the ERA-Interim and ERA5 (fragments) retrospective meteorological analyses (Hersbach and Dee, 2016). The COSMO-CLM model has been already applied to Apatity-Kirovsk studies (Varentsov et al., 2018). It was found that the model performance deteriorates under calm weather conditions in winter, which results in a persistent positive temperature bias during cold air spills. The bias is well known, but poorly understood; its effect is traced to the breakdown of the turbulence closure schemes under stably stratified atmospheric conditions (Atlaskin and Vihma, 2012; Fay and Neunhauserer, 2006). Here, we look in more detailed into this key drawback impeding the seamless model downscaling.

We compare the results of the older COSMO-CLM 5.0 version (Varentsov et al., 2018), and the newer version 5.05. The newer version has improved boundary-layer physics, which is based on an ICON (ICOsahedral Nonhydrostatic) unified modeling system for global numerical weather prediction and climate studies (Dipankar et al., 2015; Heinze et al., 2017a). In addition, we replace lakes (open water surface type) with snow-covered surface. The COSMO-CLM is initialized with the ERA5 reanalysis data. The observed cold spells are simulated adequately only in the high-resolution (the horizontal resolution of 2 km or finer) domains with the COSMO-CLM 5.05. The warm bias of up to +10 °C is found during the coldest period in both model versions running at 5 km mesh (Fig. 8). Similar warm bias is found for the ERA Interim reanalysis data.

The bias is related to underestimation of the surface inversion strength. Although interests of the regional weather forecast and long-range pollution transport are not strongly sensitive to this modeling drawback as the surface layer fluxes are diagnostic in the model, the interests of local environmental management and warning systems are critically connected to the representation of the surface layer balances and mixing. Thus, there is disparity of priorities of siloed and horizontally integrated approaches. The former admits that local model disadvantages could be compensated by advantages in other areas or situations; the later requires high local modelling quality, plausibly on expense of its performance in other locations. As a spatial correlation scale is smaller near the surface, the performance of the model schemes in the atmospheric boundary layer becomes critical for the horizontally integrated approaches. The high spatial resolution of models is a necessary, but not sufficient for an adequate simulation of stably stratified atmosphere and related polluted periods.

We enhance the downscaling chain of the COSMO-CLM with the Parallelized Atmospheric Large-eddy simulation Model (PALM[5]) described in (Maronga et al., 2015). To assess sensitivity of the local high-resolution modeling, we initialize PALM with two different driving forcings. The run A is initialized through wind and potential temperature profiles taken directly from ERA-Interim data. The run B is initialized through the COSMO-CLM output in the K02 run. The used profiles correspond to the mean profiles over December 26, 2017. The initial wind profile serves also as geostrophic wind forcing in the PALM runs. The potential temperature is nudged towards its initial profile. The total domain size of the PALM simulations is 46.07 × 34.55 km^2 with a 10 m isotropic resolution. The observed land surface temperature is used as the surface temperature in the model. It is taken from the MODIS LST product (1 km resolution) (Varentsov et al., 2018) and interpolated to

---

[5] The model code is freely available from https://palm.muk.uni-hannover.de/trac.

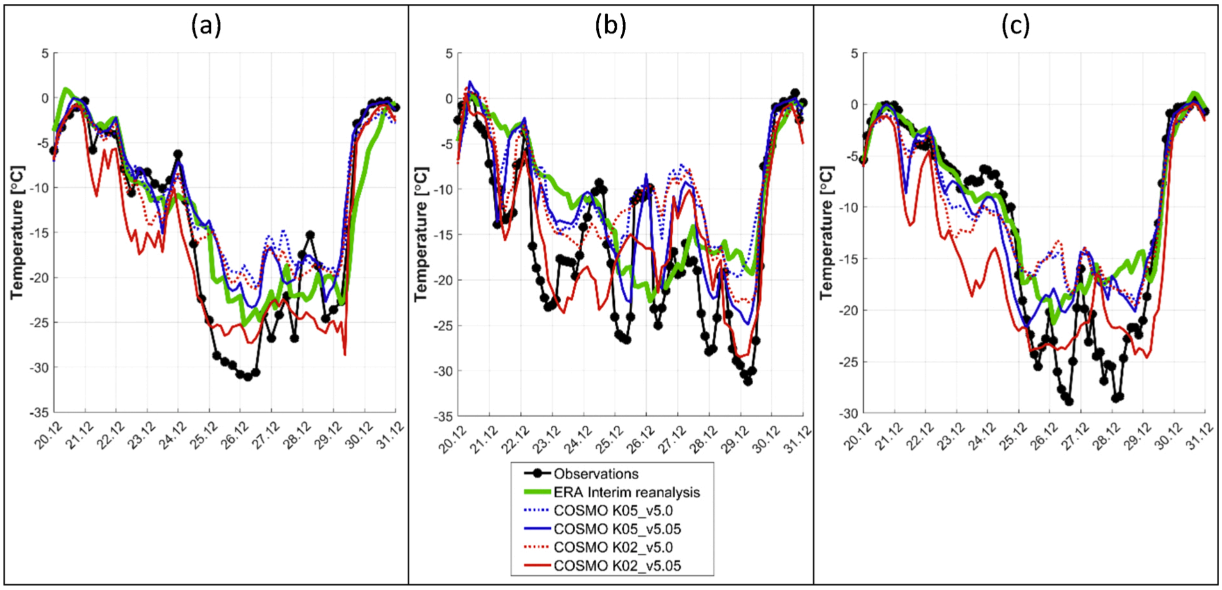

Fig. 8. Comparison of the air temperature at 2 m. Blue lines represent the COSMO-CLM model runs of the version 5.0 (dotted) and 5.05 (solid) in the domain with 5 km horizontal resolution (K05); red lines – in the domain with 2 km horizontal resolution (K02). The green line represents the ERA-Interim reanalysis data in the corresponding locations. Three panels show the comparison for the following locations: (a) the Apatity weather station (WMO ID 22213); (b) Lovozero (WMO ID 22127); (c) Krasnoshchelye (WMO ID 22235). The data observed at the WMO stations are given by black line and dots.

the 10 m grid resolution.

Our PALM runs further detail and localize the meteorological and air quality patterns in the turbulent atmospheric boundary layer. Meandering local circulations develop in shallow stably-stratified boundary layers (Mahrt et al., 2001) that are sensitive to details of the vertical wind and temperature profiles and surface heterogeneity (Mahrt, 2000). These essentially three-dimensional motions are not captured in the single-column dynamics parametrizations of regional meteorological models. Hence, making further grid refinement without LES enhancement would be unjustified. Fig. 9 illustrates this sensitivity. The run A uses the wind profile from the reanalysis, i.e., the coarse resolution data without the local effect of mountains. This kind of coarse data is typically used by statistical, Gaussian plume or Lagrangian models to project pollution plume's trajectories and concentrations. The plume (given by gray shading) propagates in the north-western direction away from the urbanized area. The run B uses the wind profile from the COSMO-CLM K02 run. The wind profile in the lower atmosphere accounts for the mountains. A low-level jet at about 200 m above ground develops. The wind direction changes by 40°. These changes are moderate, so that in the K02 run itself the urbanized areas remain largely unaffected by the pollution plume. LES enhancement by PALM transforms these moderate changes into critically different boundary layer circulation. The polluted plume in the run B propagates directly over the urbanized area.

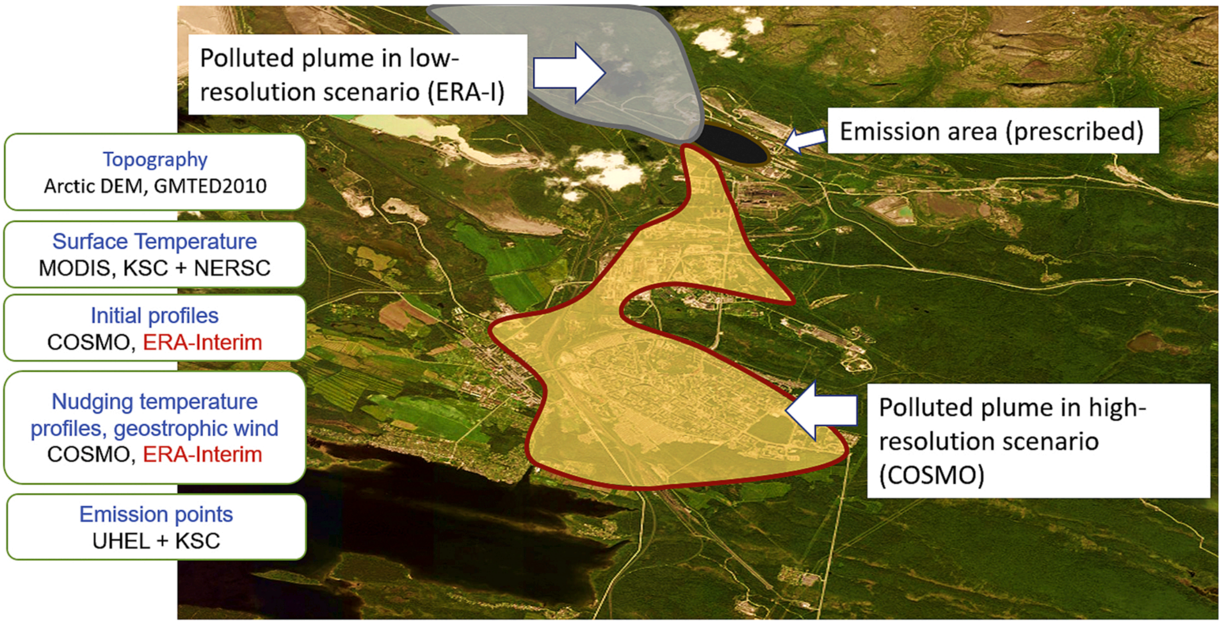

Fig. 9. Comparison of two PALM runs for different initial wind profile scenarios: Gray shading shows the polluted air plume in the run A (see description in the text) driven by the low-resolution ERA-Interim reanalysis; Yellow shading shows the polluted air plume in the run B driven by the high-resolution COSMO-CLM downscaling; Black shading shows the area where emission source is in the model.

4. Discussion

4.1. Selection of local scenarios

A local adaptation to climate change is challenging. Urban planning needs to assess the environmental quality not only in relation to climate but also in relation to social, economic, and political changes that affect the capacity for adaptation or otherwise play a role in decision making (Nilsson et al., 2017). The scenario methodology is promising and therefore we applied this approach in our study.

We selected a scenario of an anti-cyclonic situation favorable to pollution trapping and transport in the surface atmospheric layer. Recent, alarming, dynamics of population health in the Apatity-Kirovsk urban area reveals 2.3 times increase of the number of medical cases in Apatity; and by 44.4 % in Kirovsk (Nikanov et al., 2019). Respiratory diseases are common. The same study has robustly attributed the cases to the atmospheric pollution from particulate matter (dust). We adopted the weather conditions observed on December 26, 2017 (Fig. 5), as a scenario for our case study modeling. The downscaling chain is initiated with atmospheric conditions (vertical profiles of wind and temperature) from the reanalysis. The spatial differences in the observed temperature were significant (Fig. 4) to drive local circulations. The coldest places are located in the lowland near the coast of the lake Imandra (-28.9 °C) and at a local depression to the east from the lake (-30.1 °C), while the elevated sites, including the urban area, are significantly warmer (typically −26 °C or warmer). The urban area of Apatity was significantly warmer (typically -21 °C) than the non-urbanized part of the same hill to the east of the city (−25 °C), and warmer than two other hills in the north-west.

4.2. Appreciation of the local integrated approach

The environmental legislation in Russian Federation set the environmental quality management under the joint jurisdiction of federal and regional authorities, but the local authorities nevertheless enjoy considerable room for maneuver. Being pressed by public concerns – more than 50 % of the population are concerned with air and water quality – the local regulators publish environmental quality indicators that are provided by the centralized agencies, e.g., by Roshydromet. However, their policy actions normally do not extent beyond this point; environmental taxes and fees received by the municipal budget are diverted from supporting environmental protection actions to other purposes (Klyuchnikova, 2008). Correspondingly, air quality protection is not included in the municipal programme for environmental protection for 2021−2023.

As argued by Salmi and Hukkinen (2007), this obvious misfit between environmental concerns and actions has its roots in setting priority to production capacity increase. Such an increasing production is expected to bring along a reduced pollutant emission per unit of current production, whereas pollution from the accumulated waste, in our case dust from tailings impoundments, are not counted. It was recognized "… the familiar tendency of downplaying the current industrial emissions against those in the past as a key source of government reluctance in engaging in environmental problems." We revealed that observations from a sparce network cannot provide information for full appreciation of such a localized impact. The existing siloed approach to environmental monitoring and modeling failed to call for actions and thus is used rather for information than for decision making. In these circumstances, we see a potential of the proposed enhanced approached as it identifies smaller geographical areas of higher priority for interventions of policy makers. Being unable to solve this wicked socio-environmental problem at the municipal level, more technically oriented solutions could be found on micro-levels. For example, one might be able to control pollution sources that affect most of the population. This approach has gradually found its way. "Apatit" company (the main polluter in the area) spent significant funding (3.3 billion rubles over 2015-2017[6]) to research (2 million rubles) and develop more effective environmental protection measures through identification of the most impactful pollution sources.

Air quality and green-house gas emission are the most frequently referred issues to be addressed with IUS. In a narrow sense, which is better reflecting the current state-of-knowledge, the integrated approach comprises a downscaling chain of meteorological–chemical models (Baklanov et al., 2018). The presented IUS enhancement aims to shift the current focus from large spatial and time scales to societally influential local scales. Such efforts are known for our case study area but approached with simpler local-scale models (Amosov et al., 2020), also in the frameworks of the Integrative and Comprehensive Understanding on Polar Environments (iCUPE), see Petäjä et al. (2020). Hourly-to-decadal time scales, regional-to-local geographic scales and seamless coupled coarse-to-fine scale models are considered as essential components. Such models are enabled by diverse fine-resolution observational data (González et al., 2018) and have greatly evolved in the recent years (Baklanov et al., 2017a). Elements of such an integrated approach have been successfully demonstrated in the Enviro-HIRLAM (Baklanov et al., 2017b) and COSMO-CLM (Varentsov et al., 2018) modeling systems. They however lack an urban-scale model, and therefore, we enhanced the downscaling chain with the turbulence-resolving model PALM. A way of integration of different technological elements of the approach seems to be important (Pulver et al., 2018).

Although science has much to provide for stakeholders, three major integration challenges are still waiting for a better resolution. The first challenge is related to data misrepresenting the local climatic conditions. Fig. 2 makes clear that local climate diversity could be rather large, whereas the local climate changes could be divergent and sensitive to the land cover types. The second challenge is related to mismatch of scales. Interests of stakeholders are typically more localized than environmental data provided to inform decision making. In Apatity, the interests are highly concentrated within urban and industrial zones (less than 20 km across) where the role of meso-scale atmospheric flows are significant. Fig. 9 demonstrates that the pollution plume cannot be directly related to the large-scale winds or stably reproduced without knowledge of local surface heterogeneity.

The third challenge is related to information dissemination routines and standards. A co-production approach has been widely referred to as a panacea for effective progress in wicked socio-environmental issues. The problem however is that co-production interweaves facts and beliefs, whereas facts are frequently pre-selected and contested to re-affirm the beliefs. It has been noted (van der Sluijs et al., 2008) that the observed "facts" do not necessarily entail a unique, correct and commonly accepted policy decision. Experience in the co-production actions reveal that presenting uncertainties and unresolved issues, particularly in the case of the model output, is often used to excuse non-acting rather than to create a plausible envelope for acting. Dissemination of detailed and localized environmental model output and observations can meet stakeholder's opposition. We run a set of seminars for local stakeholders in Apatity. The discussion revealed stiff constraints for local information dissemination. Environmental protection agencies and weather services heavily rely on their siloed approach and internal data flow. Efficient in concrete problem solving, they impede adoption of the truly integrated approach and limit diversity of problems they intended to deal with.

---

[6] Rossijskaja Gazeta, available from https://rg.ru/2017/12/12/reg-szfo/murmanskie-gorniaki-zanialis-zashchitoj-ekologii-kraia.html

5. Conclusions and recommendations

The Integrated Urban Services (IUS) connect climate, weather, and pollution transport models that run across wide range of spatial and time scales. The models at different resolutions serve different needs as it is specified in Table 1. The global-scale models provide information about weather and climate phenomena. The regional-scale models localize this information, including effects of the surface heterogeneity and long-term pollution transport. The local-scale models contextualize and enhance the information including turbulence effects and local circulations. We conclude that LES-enhanced downscaling chains require dense representative observational local networks to constrain the simulations. Moreover, our results (Fig. 9) clearly suggest that statistical or index-based localization of the meteorological information – the most popular approach to date – could be misleading as it would necessarily misrepresent the local atmospheric phenomena.

Although the modelling and data collection technologies are mature and readily accessible (Table 2), horizontally integrated urban hydro-meteorological and environmental services meet considerable organizational barriers when increasing local context of observations and model simulations is to be included. The siloed environmental agencies are not interested in deployment, maintenance, and collection of the local information as this activity is not within their mandate. Local actors are interested but lack resources and expertise to contextualize the IUS.

A holistic approach to vulnerability, resilience and sustainable development is recommended by both research and end-user communities in the Pan-Eurasian Experiment (PEEX) (Lappalainen et al., 2016) and in the Northern Eurasia Earth Science Partnership Initiative (NEESPI) (Groisman and Bartalev, 2007). This consensus makes the choice of solutions to deviate from a paradigm of siloed monitor-and-forecast or reactive-action services. The latter has become increasingly popular in the world of abundant data and cheap model simulations. Negative consequences of reactive actions that ignore sectoral interconnections are repeatedly reported in urban nexus studies (Creutzig et al., 2019; Gago et al., 2013; Wilson and Stammler, 2016).

In the final word, we note that combination and integration of mathematical modelling and statistical analysis approach convey a spurious impression of precision, prediction and control. Involving non-conventical measurements and non-certified models directly out of the research domain redistributes a good deal of responsibility from information providers to decision-makers. The uncertain and uncertified knowledge that is not prescribed by normative policy is usually excluded from decision making. (Saltelli and Giampietro, 2017) wrote: "*When using evidence-based policy … alternative frames become a kind of 'uncomfortable knowledge' which is de facto removed from the policy discourse. All the more so when the analysis is supported by extensive mathematical* modelling".

CRediT authorship contribution statement

Igor Esau: Conceptualization, Writing - original draft, Writing - review & editing, Funding acquisition. **Leonid Bobylev:** Project administration. **Vladislav Donchenko:** Conceptualization, Methodology, Resources. **Natalia Gnatiuk:** Investigation. **Hanna K. Lappalainen:** Methodology, Supervision, Project administration. **Pavel Konstantinov:** Data curation, Validation. **Markku Kulmala:** Supervision, Conceptualization, Resources. **Alexander Mahura:** Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Risto Makkonen:** Software, Validation, Visualization. **Alexandra Manvelova:** Investigation. **Victoria Miles:** Data curation, Validation. **Tuukka Petäjä:** Supervision, Conceptualization, Data curation. **Pyry Poutanen:** Investigation. **Roman Fedorov:** Methodology. **Mikhail Varentsov:** Software, Validation, Visualization, Investigation, Writing - original draft, Writing - review & editing. **Tobias Wolf:** Software, Validation, Visualization, Investigation, Writing - original draft. **Sergej Zilitinkevich:** Supervision, Conceptualization, Methodology. **Alexander Baklanov:** Supervision, Conceptualization, Methodology, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was mainly supported by the PECC project TRAKT-2018. The authors acknowledge the support from: ERA-PLANET (Grant Agreement: 689443); the Belmont Forum projects HIARCand SERUS (no. 1729, NFR 311986); the Russian Foundation for Basic Research, project No. 20-55-71004; the Norwegian Ministry of Environment project ReSiS; the Academy of Finland grant 314 798/799. The completed project and its results are actively promoted through the activities of the Pan-Eurasian EXperiment (PEEX) programme. We are grateful to Dr. V. Gornyy for insightful discussion of satellite data; Dr. Victoria Sinclair and Dr. Ella-Maria Duplissy for discussions of the SMEAR station data.

References

Amosov, P.V., Baklanov, A.A., Makarov, D.V., Masloboev, V.A., 2020. Estimating air pollution levels by numerical simulation depending on wind flow speed and dust source area. News of the Higher Institutions. Min. Ind. J. 5, 80–89. https://doi.org/10.21440/0536-1028-2020-5-80-89.

Anon, 2018. Report of the State of Envirnment in Murmansk Region in 2017. МурМанск.

Arnold, S.R., Law, K.S., Brock, C.A., Thomas, J.L., Starkweather, S.M., von Salzen, K., Stohl, A., Sharma, S., Lund, M.T., Flanner, M.G., Petäjä, T., Tanimoto, H., Gamble, J., Dibb, J.E., Melamed, M., Johnson, N., Fidel, M., Tynkkynen, V.-P., Baklanov, A., Eckhardt, S., Monks, S.A., Browse, J., Bozem, H., 2016. Arctic air pollution: challenges and opportunities for the next decade. Elem. Sci. Anthr. 4, 000104 https://doi.org/10.12952/journal.elementa.000104.

Atlaskin, E., Vihma, T., 2012. Evaluation of NWP results for wintertime nocturnal boundary-layer temperatures over Europe and Finland. Q. J. R. Meteorol. Soc. 138, 1440–1451. https://doi.org/10.1002/qj.1885.

Bai, X., McPhearson, T., Cleugh, H., Nagendra, H., Tong, X., Zhu, T., Zhu, Y.-G., 2017. Linking urbanization and the environment: conceptual and empirical advances. Annu. Rev. Environ. Resour. 42, 215–240. https://doi.org/10.1146/annurev-environ-102016-061128.

Baklanov, A., Hänninen, O., Slørdal, L.H., Kukkonen, J., Bjergene, N., Fay, B., Finardi, S., Hoe, S.C., Jantunen, M., Karppinen, A., Rasmussen, A., Skouloudis, A., Sokhi, R.S., Sørensen, J.H., Ødegaard, V., 2007. Integrated systems for forecasting urban meteorology, air pollution and population exposure. Atmos. Chem. Phys. 7, 855–874. https://doi.org/10.5194/acp-7-855-2007.

Baklanov, A.A., Grisogono, B., Bornstein, R., Mahrt, L., Zilitinkevich, S.S., Taylor, P., Larsen, S.E., Rotach, M.W., Fernando, H.J.S., 2011. The nature, theory, and modeling of atmospheric planetary boundary layers. Bull. Am. Meteorol. Soc. 123–128. https://doi.org/10.1175/2010BAMS2797.1.

Baklanov, A., Brunner, D., Carmichael, G., Flemming, J., Freitas, S., Gauss, M., Hov, Ø., Mathur, R., Schlünzen, K.H., Seigneur, C., Vogel, B., 2017a. Key issues for seamless integrated chemistry–Meteorology modeling. Bull. Am. Meteorol. Soc. 98, 2285–2292. https://doi.org/10.1175/BAMS-D-15-00166.1.

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

Baklanov, A., Grimmond, C.S.B., Carlson, D., Terblanche, D., Tang, X., Bouchet, V., Lee, B., Langendijk, G., Kolli, R.K., Hovsepyan, A., 2018. From urban meteorology, climate and environment research to integrated city services. Urban Clim. 23, 330–341. https://doi.org/10.1016/j.uclim.2017.05.004.

Baldocchi, D., Kelliher, F.M., Black, T.A., Jarvis, P., 2000. Climate and vegetation controls on boreal zone energy exchange. Glob. Chang. Biol. 6, 69–83. https://doi.org/10.1046/j.1365-2486.2000.06014.x.

Bauweraerts, P., Meyers, J., 2019. On the feasibility of using large-eddy simulations for real-time turbulent-flow forecasting in the atmospheric boundary layer. Boundary-Layer Meteorol. 171, 213–235. https://doi.org/10.1007/s10546-019-00428-5.

Beringer, J., Chapin, F.S., Thompson, C.C., McGuire, A.D., 2005. Surface energy exchanges along a tundra-forest transition and feedbacks to climate. Agric. For. Meteorol. 131, 143–161. https://doi.org/10.1016/j.agrformet.2005.05.006.

Biesbroek, G.R., Termeer, C.J.A.M., Klostermann, J.E.M., Kabat, P., 2014. Analytical lenses on barriers in the governance of climate change adaptation. Mitig. Adapt. Strateg. Glob. Chang. 19, 1011–1032. https://doi.org/10.1007/s11027-013-9457-z.

Ching, J., Mills, G., Bechtel, B., See, L., Feddema, J., Wang, X., Ren, C., Brousse, O., Martilli, A., Neophytou, M., Mouzourides, P., Stewart, I., Hanna, A., Ng, E., Foley, M., Alexander, P., Aliaga, D., Niyogi, D., Shreevastava, A., Bhalachandran, P., Masson, V., Hidalgo, J., Fung, J., Andrade, M., Baklanov, A., Dai, W., Milcinski, G., Demuzere, M., Brunsell, N., Pesaresi, M., Miao, S., Mu, Q., Chen, F., Theeuwes, N., 2018. WUDAPT: an urban weather, climate, and environmental modeling infrastructure for the anthropocene. Bull. Am. Meteorol. Soc. 99, 1907–1924. https://doi.org/10.1175/BAMS-D-16-0236.1.

Cohen, M.D., March, J.G., Olsen, J.P., 1972. A garbage can model of organizational choice. Adm. Sci. Q. 17, 1. https://doi.org/10.2307/2392088.

Creutzig, F., Lohrey, S., Bai, X., Baklanov, A., Dawson, R., Dhakal, S., Lamb, W.F., McPhearson, T., Minx, J., Munoz, E., Walsh, B., 2019. Upscaling urban data science for global climate solutions. Glob. Sustain. 2 https://doi.org/10.1017/sus.2018.16.

Dale, B., 2016. Governing resources, governing mentalities. Petroleum and the Norwegian integrated ecosystem-based management plan for the Barents and Lofoten seas in 2011. Extr. Ind. Soc. 3, 9–16. https://doi.org/10.1016/j.exis.2015.10.002.

Demin, V.I., 2019. Role of antropogenic and natural drivers in estimation of urban heat island. . Sovrem. Probl. distantsionnogo Zo. Zemli iz kosmosa 16, 25–33. https://doi.org/10.21046/2070-7401-2019-16-5-25-33.

Demin, V.I., Kozelov, B.V., Elizarova, N.I., Menshov, Y.V., Konstantinov, P.I., 2016. The role of relief in the heat island phenomenon in the city of Apatity. Fundam. Appl. Climatol. 2, 95–106. https://doi.org/10.21513/2410-8758-2016-2-95-106.

Dipankar, A., Stevens, B., Heinze, R., Moseley, C., Zängl, G., Giorgetta, M., Brdar, S., 2015. Large eddy simulation using the general circulation model ICON. J. Adv. Model. Earth Syst. 7, 963–986. https://doi.org/10.1002/2015MS000431.

Dushkova, D., Krasovskaya, T., 2018. Post-Soviet single-industry cities in northern Russia: movement towards sustainable development. Belgeo. https://doi.org/10.4000/belgeo.27427.

Ebrahimabadi, S., Nilsson, K.L., Johansson, C., 2015. The problems of addressing microclimate factors in urban planning of the subarctic regions. Environ. Plan. B Plan. Des. 42, 415–430. https://doi.org/10.1068/b130117p.

Eliasson, I., 2000. The use of climate knowledge in urban planning. Landsc. Urban Plan. 48, 31–44.

Esau, I., Miles, V., 2018. Exogenous drivers of surface urban heat islands in northern West Siberia. Geogr. Environ. Sustain. 11, 83–99. https://doi.org/10.24057/2071-9388-2018-11-3-83-99.

Fan, P., Chen, J., Ouyang, Z., Groisman, P., Loboda, T., Gutman, G., Prishchepov, A.V., Kvashnina, A., Messina, J., Moore, N., Myint, S.W., Qi, J., 2018. Urbanization and sustainability under transitional economies: a synthesis for Asian Russia. Environ. Res. Lett. 13, 95007. https://doi.org/10.1088/1748-9326/aadbf8.

Fay, B., Neunhauserer, L., 2006. Evaluation of high-resolution forecasts with the non-hydrostatic numerical weather prediction model Lokalmodell for urban air pollution episodes in Helsinki, Oslo and Valencia. Atmos. Chem. Phys. 6, 2107–2128.

Fedorov, R., Kuklina, V., Sizov, O., Soromotin, A., Esau, I., Krasnenko, A., Pechkin, A., Lobanov, A., Prihodko, N., 2021. Zooming in on Arctic Urban Nature: Green and Blue Space in Nadym, Siberia, accepted for publication in Environmental Research Letters. Article reference: ERL-110495.

Gago, E.J., Roldan, J., Pacheco-Torres, R., Ordóñez, J., 2013. The city and urban heat islands: a review of strategies to mitigate adverse effects. Renewable Sustainable Energy Rev. 25, 749–758. https://doi.org/10.1016/j.rser.2013.05.057.

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S., Rocklöv, J., Forsberg, B., Leone, M., De Sario, M., Bell, M.L., Leon Guo, Y., Wu, C., Kan, H., Yi, S.-M., Coelho, M., Saldiva, P., Honda, Y., Kim, H., Armstrong, B., 2015. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Lancet 386 (9991), 369–375.

González, C.M., Ynoue, R.Y., Vara-Vela, A., Rojas, N.Y., Aristizábal, B.H., 2018. High-resolution air quality modeling in a medium-sized city in the tropical Andes: assessment of local and global emissions in understanding ozone and PM10 dynamics. Atmos. Pollut. Res. 9, 934–948. https://doi.org/10.1016/j.apr.2018.03.003.

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., Joe, P., 2020. 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.

Groisman, P.Y., Bartalev, S.A., 2007. Northern Eurasia earth science partnership initiative (NEESPI), science plan overview. Glob. Planet. Change 56, 215–234. https://doi.org/10.1016/j.gloplacha.2006.07.027.

Hagner, O., Rigina, O., 1998. Detection of forest decline in Monchegorsk Area. Remote Sens. Environ. 63, 11–23. https://doi.org/10.1016/S0034-4257(97)00113-2.

Hari, P., Kulmala, M., 2005. Station for measuring ecosystem-atmosphere relations (SMEAR II). Boreal Environ. Res.

Hari, P., Aalto, P., Hämeri, K., Kulmala, M., Lahti, T., Luoma, S., Palva, L., Pohja, T., Pulliainen, E., Siivola, E., Vesala, T., 1994. Air pollution in eastern Lapland : challenge for an environmental measurement station. Silva Fenn. 28, 29–39. https://doi.org/10.14214/sf.a9160.

Hari, P., Petäjä, T., Bäck, J., Kerminen, V.-M., Lappalainen, H.K., Vihma, T., Laurila, T., Viisanen, Y., Vesala, T., Kulmala, M., 2016. Conceptual design of a measurement network of the global change. Atmos. Chem. Phys. 16, 1017–1028. https://doi.org/10.5194/acp-16-1017-2016.

Hartung, K., Svensson, G., Struthers, H., Deppenmeier, A.-L., Hazeleger, W., 2018. An EC-Earth coupled atmosphere-ocean single-column model AOSCM.v1 EC-Earth3 for studying coupled marine and polar processes. Geosci. Model. Dev. Discuss. 11, 4117–4137. https://doi.org/10.5194/gmd-11-4117-2018.

Heinze, R., Dipankar, A., Henken, C.C., Moseley, C., Sourdeval, O., Trömel, S., Xie, X., Adamidis, P., Ament, F., Baars, H., Barthlott, C., Behrendt, A., Blahak, U., Bley, S., Brdar, S., Brueck, M., Crewell, S., Deneke, H., Di Girolamo, P., Evaristo, R., Fischer, J., Frank, C., Friederichs, P., Göcke, T., Gorges, K., Hande, L., Hanke, M., Hansen, A., Hege, H.-C., Hoose, C., Jahns, T., Kalthoff, N., Klocke, D., Kneifel, S., Knippertz, P., Kuhn, A., van Laar, T., Macke, A., Maurer, V., Mayer, B., Meyer, C.I., Muppa, S.K., Neggers, R.A.J., Orlandi, E., Pantillon, F., Pospichal, B., Röber, N., Scheck, L., Seifert, A., Seifert, P., Senf, F., Siligam, P., Simmer, C., Steinke, S., Stevens, B., Wapler, K., Weniger, M., Wulfmeyer, V., Zängl, G., Zhang, D., Quaas, J., 2017a. Large-eddy simulations over Germany using ICON: a comprehensive evaluation. Q. J. R. Meteorol. Soc. 143, 69–100. https://doi.org/10.1002/qj.2947.

Heinze, R., Moseley, C., Böske, L.N., Muppa, S.K., Maurer, V., Raasch, S., Stevens, B., 2017b. 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.

Järvi, L., Hannuniemi, H., Hussein, T., Junninen, H., Aalto, P.P., Hillamo, R., Mäkelä, T., Keronen, P., Siivola, E., Vesala, T., Kulmala, M., 2009. The urban measurement station SMEAR II: continuous monitoring of air pollution and surface-atmosphere interactions in Helsinki, Finland. Boreal Environ. Res. 14.

Joe, D.K., Zhang, H., DeNero, S.P., Lee, H.-H., Chen, S.-H., McDonald, B.C., Harley, R.A., Kleeman, M.J., 2014. Implementation of a high-resolution source-oriented WRF/Chem model at the Port of Oakland. Atmos. Environ. 82, 351–363. https://doi.org/10.1016/j.atmosenv.2013.09.055.

Johansen, H., Skryzhevska, Y., 2013. Adaptation priorities on Russia's Kola Peninsula: climate change vs. Post-Soviet transition. Polar Geogr. Geol. 36, 271–290. https://doi.org/10.1080/1088937x.2013.788577.

Johansson, L., Epitropou, V., Karatzas, K., Karpinen, A., Wanner, L., Vrochidis, S., Bassoukos, A., Kukkonen, J., Kompatsiaris, I., 2015. Fusion of meteorological and air quality data extracted from the web for personalized environmental information services. Enviromental Model. Softw. 64, 143–155. https://doi.org/10.1016/j.envsoft.2014.11.021.

Klene, A.E., Nelson, F.E., Hinkel, K.M., 2013. Urban–rural contrasts in summer soil-surface temperature and active-layer thickness, Barrow, Alaska, USA. Polar Geogr. Geol. 36, 183–201. https://doi.org/10.1080/1088937X.2012.706756.

Klyuchnikova, E.M., 2008. Ecological and economical challenges of sustainable development on the municipal level (Apatity). Problems Modern Econ. 2 (26) in Russian, available on. http://www.m-economy.ru/issue_e.php?num=26.

Kolstad, E.W., Sofienlund, O.N., Kvamsås, H., Stiller-Reeve, M.A., Neby, S., Paasche, Ø., Pontoppidan, M., Sobolowski, S.P., Haarstad, H., Oseland, S.E., Omdahl, L., Waage, S., 2019. Trials, errors, and improvements in coproduction of climate services. Bull. Am. Meteorol. Soc. 100, 1419–1428. https://doi.org/10.1175/BAMS-D-18-0201.1.

Konstantinov, P., Varentsov, M., Esau, I., 2018. A high density urban temperature network deployed in several cities of Eurasian Arctic. Environ. Res. Lett. 13, 075007 https://doi.org/10.1088/1748-9326/aacb84.

Kulmala, M., 2018. Build a global Earth observatory. Nature 553, 21–23.

Lappalainen, H.K., Kerminen, V.-M., Petäjä, T., Kurten, T., Baklanov, A., Shvidenko, A., Bäck, J., Vihma, T., Alekseychik, P., Andreae, M.O., Arnold, S.R., Arshinov, M., Asmi, E., Belan, B., Bobylev, L., Chalov, S., Cheng, Y., Chubarova, N., de Leeuw, G., Ding, A., Dobrolyubov, S., Dubtsov, S., Dyukarev, E., Elansky, N., Eleftheriadis, K., Esau, I., Filatov, N., Flint, M., Fu, C., Glezer, O., Gliko, A., Heimann, M., Holtslag, A. A.M., Hõrrak, U., Janhunen, J., Juhola, S., Järvi, L., Järvinen, H., Kanukhina, A., Konstantinov, P., Kotlyakov, V., Kieloaho, A.-J., Komarov, A.S., Kujansuu, J., Kukkonen, I., Duplissy, E.-M., Laaksonen, A., Laurila, T., Lihavainen, H., Lisitzin, A., Mahura, A., Makshtas, A., Mareev, E., Mazon, S., Matishov, D., Melnikov, V., Mikhailov, E., Moisseev, D., Nigmatulin, R., Noe, S.M., Ojala, A., Pihlatie, M., Popovicheva, O., Pumpanen, J., Regerand, T., Repina, I., Shcherbinin, A., Shevchenko, V., Sipilä, M., Skorokhod, A., Spracklen, D.V., Su, H., Subetto, D.A., Sun, J., Terzhevik, A.Y., Timofeyev, Y., Troitskaya, Y., Tynkkynen, V.-P., Kharuk, V. I., Zaytseva, N., Zhang, J., Viisanen, Y., Vesala, T., Hari, P., Hansson, H.C., Matvienko, G.G., Kasimov, N.S., Guo, H., Bondur, V., Zilitinkevich, S., Kulmala, M., 2016. Pan-Eurasian Experiment (PEEX): towards a holistic understanding of the feedbacks and interactions in the land–atmosphere–ocean–society continuum in the northern Eurasian region. Atmos. Chem. Phys. 16, 14421–14461. https://doi.org/10.5194/acp-16-14421-2016.

Laruelle, M., 2019. The three waves of Arctic urbanisation. Drivers, evolutions, prospects. Polar Rec. (Gr. Brit). 1–12. https://doi.org/10.1017/S0032247419000081.

Laruelle, M., Esau, I., Miles, M., Miles, V., Kurchatova, A.N., Petrov, S.A., Soromotin, A., Varentsov, M., Konstantinov, P., 2019. Arctic cities as an anthropogenic object: a preliminary approach through urban heat islands. Polar J. 00, 1–22. https://doi.org/10.1080/2154896X.2019.1685171.

Leiren, M.D., Jacobsen, J.K.S., 2018. 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.

Li, H., Meier, F., Lee, X., Chakraborty, T., Liu, J., Schaap, M., Sodoudi, S., 2018. Interaction between urban heat island and urban pollution island during summer in Berlin. Sci. Total Environ. 636, 818–828. https://doi.org/10.1016/j.scitotenv.2018.04.254.

Mahrt, L., 2000. Surface heterogeneity and vertical structure of the boundary layer. Boundary-Layer Meteorol. 96, 33–62. https://doi.org/10.1023/A:1002482332477.

Mahrt, L., 2011. The near-calm stable boundary layer. Boundary-Layer Meteorol. 140, 343–360. https://doi.org/10.1007/s10546-011-9616-2.

Mahrt, L., Moore, E., Vickers, D., Jensen, N.O., 2001. Dependence of turbulent and mesoscale velocity variances on scale and stability. J. Appl. Meteorol. Climatol. 40, 628–641. https://doi.org/10.1175/1520-0450(2001)040<0628:DOTAMV>2.0.CO;2.

Maronga, B., Gryschka, M., Heinze, R., Hoffmann, F., Kanani-Sühring, F., Keck, M., Ketelsen, K., Letzel, M.O., Sühring, M., Raasch, S., 2015. 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. Discuss. 8, 2515–2551. https://doi.org/10.5194/gmd-8-2515-2015.

Miles, V.V., Esau, I., 2016. Spatial heterogeneity of greening and browning between and within bioclimatic zones in northern West Siberia. Environ. Res. Lett. 11, 115002 https://doi.org/10.1088/1748-9326/11/11/115002.

Miles, V., Esau, I., 2020. Urban Climate Surface urban heat islands in 57 cities across different climates in northern Fennoscandia. Urban Clim. 31, 100575 https://doi.org/10.1016/j.uclim.2019.100575.

Mirocha, J., Kosović, B., Kirkil, G., 2014. Resolved turbulence characteristics in large-eddy simulations nested within mesoscale simulations using the weather research and forecasting model. Mon. Weather Rev. 142, 806–831. https://doi.org/10.1175/mwr-d-13-00064.1.

Mortarini, L., Cava, D., Giostra, U., Costa, F.D., Degrazia, G., Anfossi, D., Acevedo, O., 2019. Horizontal meandering as a distinctive feature of the stable boundary layer. J. Atmos. Sci. 76, 3029–3046. https://doi.org/10.1175/JAS-D-18-0280.1.

Muñoz-Esparza, D., Lundquist, J.K., Sauer, J.A., Kosović, B., Linn, R.R., 2017. Coupled mesoscale-LES modeling of a diurnal cycle during the CWEX-13 field campaign: from weather to boundary-layer eddies. J. Adv. Model. Earth Syst. 9, 1572–1594. https://doi.org/10.1002/2017MS000960.

Mussetti, G., Brunner, D., Allegrini, J., Wicki, A., Schubert, S., Carmeliet, J., 2020. Simulating urban climate at sub-kilometre scale for representing the intra-urban variability of Zurich, Switzerland. Int. J. Climatol. 40, 458–476. https://doi.org/10.1002/joc.6221.

Nikanov, A.N., Dorofeev, V.M., Talykova, L.V., Sturlis, N.V., Gushin, I.V., 2019. Adult incidence in the russian european arctic with developed mining and metallurgical industry. Russ. Arct. 15–21. https://doi.org/10.24411/2658-4255-2019-10063.

Nilsson, A.E., Bay-Larsen, I., Carlsen, H., van Oort, B., Bjørkan, M., Jylhä, K., Klyuchnikova, E., Masloboev, V., van der Watt, L.-M., 2017. Towards extended shared socioeconomic pathways: a combined participatory bottom-up and top-down methodology with results from the Barents region. Glob. Environ. Chang. 45, 124–132. https://doi.org/10.1016/j.gloenvcha.2017.06.001.

Petäjä, T., O'Connor, E.J., Moisseev, D., Sinclair, V.A., Manninen, A.J., Väänänen, R., von Lerber, A., Thornton, J.A., Nicoll, K., Petersen, W., Chandrasekar, V., Smith, J.N., Winkler, P.M., Krüger, O., Hakola, H., Timonen, H., Brus, D., Laurila, T., Asmi, E., Riekkola, M.-L., Mona, L., Massoli, P., Engelmann, R., Komppula, M., Wang, J., Kuang, C., Bäck, J., Virtanen, A., Levula, J., Ritsche, M., Hickmon, N., 2016. BAECC: a field campaign to elucidate the impact of biogenic aerosols on clouds and climate. Bull. Am. Meteorol. Soc. 97, 1909–1928. https://doi.org/10.1175/BAMS-D-14-00199.1.

Petäjä, T., Duplissy, E.-M., Tabakova, K., Schmale, J., Altstädter, B., Ancellet, G., Arshinov, M., Balin, Y., Baltensperger, U., Bange, J., Beamish, A., Belan, B., Berchet, A., Bossi, R., Cairns, W., Ebinghaus, R., El Haddad, I., Ferreira-Araujo, B., Franck, A., Huang, L., Hyvärinen, A., Humbert, A., Kalogridis, A.-C., Kontantinov, P., Lampert, A., MacLeod, M., Magand, O., Mahura, A., Marelle, L., Masloboev, V., Moisseev, D., Moschos, V., Neckel, N., Onishi, T., Osterwalder, S., Ovaska, A., Paasonen, P., Panchenko, M., Pankratov, F., Pernov, J., Platis, A., Popovicheva, O., Raut, J.-C., Riandet, A., Sachs, T., Salvatori, R., Salzano, R., Schröder, L., Schön, M., Shevchenko, V., Skov, H., Sonke, J., Spolaor, A., Stathopoulos, V., Strahlendorff, M., Thomas, J., Vitale, V., Vratolis, S., Barbante, C., Chabrillat, S., Dommergue, A., Eleftheriadis, K., Heilimö, J., Law, K., Massling, A., Noe, S., Paris, J.-D., Prévôt, A., Riipinen, I., Wehner, B., Xie, Z., Lappalainen, H., 2020. Integrative and comprehensive understanding on Polar Environments (iCUPE): the concept and initial results. Atmos. Chem. Phys. 1–62. https://doi.org/10.5194/acp-2019-1217.

Petrov, A.N., BurnSilver, S., III, F.S.C, Fondahl, G., Graybill, J., Keil, K., Nilsson, A.E., Riedlsperger, R., Schweitzer, P., 2016. Arctic sustainability research: toward a new agenda. Polar Geogr. Geol. 39, 165–178. https://doi.org/10.1080/1088937X.2016.1217095.

Pulver, S., Ulibarri, N., Sobocinski, K.L., Alexander, S.M., Johnson, M.L., McCord, P.F., Dell'Angelo, J., 2018. Frontiers in socio-environmental research: components, connections, scale, and context. Ecol. Soc. 23 https://doi.org/10.5751/ES-10280-230323 art23.

Reckien, D., Flacke, J., Olazabal, M., Heidrich, O., 2015. The influence of drivers and barriers on urban adaptation and mitigation plans—an empirical analysis of European cities. PLoS One 10, e0135597. https://doi.org/10.1371/journal.pone.0135597.

Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., Prabhat, 2019. Deep learning and process understanding for data-driven Earth system science. Nature 566, 195–204. https://doi.org/10.1038/s41586-019-0912-1.

Reinwald, F., Ring, Z., Kraus, F., Kainz, A., Tötzer, T., Damyanovic, D., 2019. Green Resilient City - A framework to integrate the Green and Open Space Factor and climate simulations into everyday planning to support a green and climate-sensitive landscape and urban development. IOP Conf. Ser. Earth Environ. Sci. 323, 012082 https://doi.org/10.1088/1755-1315/323/1/012082.

Rockel, B., Will, A., Hense, A., 2008. The regional climate model COSMO-CLM (CCLM). Meteorol. Zeitschrift 17, 347–348. https://doi.org/10.1127/0941-2948/2008/0309.

Salmi, O.H., Hukkinen, J.I., 2007. Cultural contextualization of indicators of human-environment interaction: the case of the Kola mining network. Environ. Sci. 4 (4), 209–228.

Saltelli, A., Giampietro, M., 2017. What is wrong with evidence based policy, and how can it be improved? Futures 91, 62–71. https://doi.org/10.1016/j.futures.2016.11.012.

Schmale, J., Arnold, S.R., Law, K.S., Thorp, T., Anenberg, S., Simpson, W.R., Mao, J., Pratt, K.A., 2018. Local arctic air pollution: a neglected but serious problem. Earth's Futur. 6, 1385–1412. https://doi.org/10.1029/2018EF000952.

Schneider, P., Castell, N., Vogt, M., Dauge, F.R., Lahoz, W.A., Bartonova, A., 2017. 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.

Shepherd, T.G., 2014. Atmospheric circulation as a source of uncertainty in climate change projections. Nat. Geosci. 7, 703–708. https://doi.org/10.1038/ngeo2253.

Shiklomanov, N.I., Streletskiy, D.A., Grebenets, V.I., Suter, L., 2017. Conquering the permafrost: urban infrastructure development in Norilsk. Russia. Polar Geogr. 40, 273–290. https://doi.org/10.1080/1088937x.2017.1329237.

Stewart, I.D., 2011. A systematic review and scientific critique of methodology in modern urban heat island literature. Int. J. Climatol. 31, 200–217. https://doi.org/10.1002/joc.2141.

Streletskiy, D.A., Shiklomanov, N.I., Nelson, F.E., 2012. Permafrost, infrastructure, and climate change: a GIS-Based landscape approach to geotechnical modeling. Arctic Antarct. Alp. Res. 44, 368–380. https://doi.org/10.1657/1938-4246-44.3.368.

Svensson, M.K., Eliasson, I., 2002. Diurnal air temperatures in built-up areas in relation to urban planning. Landsc. Urban Plan. 61, 37–54. https://doi.org/10.1016/s0169-2046(02)00076-2.

Taylor, C.M., Harding, R.J., Pielke, R.A., Vidale, P.L., Walko, R.L., Pomeroy, J.W., 1998. Snow breezes in the boreal forest. J. Geophys. Res. Atmos. 103, 23087–23101. https://doi.org/10.1029/98JD02004.

Taylor, A., Carson, D.B., Ensign, P.C., Huskey, L., Rasmussen, R.O., Saxinger, G. (Eds.), 2016. Settlements at the Edge: Remote Human Settlements in Developed Nations (New Horizons in Regional Science Series). Edward Elgar Pub.

van der Sluijs, J.P., Petersen, A.C., Janssen, P.H.M., Risbey, J.S., Ravetz, J.R., 2008. Exploring the quality of evidence for complex and contested policy decisions. Environ. Res. Lett. 3, 24008. https://doi.org/10.1088/1748-9326/3/2/024008.

Varentsov, M., Konstantinov, P., Baklanov, A., Esau, I., Miles, V., Davy, R., 2018. Anthropogenic and natural drivers of a strong winter urban heat island in a typical Arctic city. Atmos. Chem. Phys. 18, 17573–17587. https://doi.org/10.5194/acp-18-17573-2018.

Varentsov, M., Esau, I., Wolf, T., 2020. High-resolution temperature mapping by Geostatistical Kriging with external drift from large-eddy simulations. Mon. Weather Rev. 148, 1029–1048. https://doi.org/10.1175/MWR-D-19-0196.1.

Venter, Z.S., Brousse, O., Esau, I., Meier, F., 2020. 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.

Voelkel, J., Hellman, D., Sakuma, R., Shandas, V., 2018. Assessing vulnerability to urban heat: a study of disproportionate heat exposure and access to refuge by socio-demographic status in Portland, Oregon. Int. J. Environ. Res. Public Health 15, 640. https://doi.org/10.3390/ijerph15040640.

Wilson, E., Stammler, F., 2016. Beyond extractivism and alternative cosmologies: arctic communities and extractive industries in uncertain times. Extr. Ind. Soc. 3, 1–8. https://doi.org/10.1016/j.exis.2015.12.001.

WMO, 2019. Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services. Volume 1: Concept and Methodology, WMO-No. 1234. Online. https://library.wmo.int/doc_num.php?explnum_id=9903.

Wolf-Grosse, T., Esau, I., Reuder, J., 2016. Sensitivity of local air quality to the interplay between small- and large-scale circulations: a Large Eddy Simulation study. Atmos. Chem. Phys. Discuss. 1–29. https://doi.org/10.5194/acp-2016-892.

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

Zhou, B., Simon, J.S., Chow, F.K., 2014. The convective boundary layer in the Terra Incognita. J. Atmos. Sci. 71, 2545–2563. https://doi.org/10.1175/JAS-D-13-0356.1.