# Enviro-HIRLAM Downscaling Setup towards Fine Scale Modelling

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To demonstrate the seamless/ on-line integrated meteorology-chemistry-aerosols modelling system Enviro-HIRLAM (*Environment – HIgh Resolution Limited Area Model*), the downscaling chain (with 3 enclosed domains) was setup to perform fine-resolution simulations over territories of the Kola Peninsula and northern Finland and Norway in focus. The selected domains (with geographical boundaries) are shown in Figure 1. The basic parameters (horizontal resolution, number of grid-points along the latitude and longitude, number of passive boundary points, S-W-N-E boundaries of the domain in the rotated system of coordinates with positioning of the pole, time step, and number of vertical levels) for these model domains are given in Table 1. The ECWMF boundary conditions (BCs) are used to drive the Enviro-HIRLAM-K15 model runs. Then, meteorological and atmospheric composition output generated by the outer models (i.e. –K15 and –K05) is used as BCs for the inner models (i.e. –K05 and –K02, respectively) simulations.


***Figure 1.*** *Geographical boundaries of model domains for the Enviro-HIRLAM subsequent downscaling at regional (K15) – subregional (K05) – urban (K02) scales.*

Note that the Enviro-HIRLAM model is developed as a fully online integrated numerical weather prediction (NWP) and atmospheric chemical transport (ACT) model for research and forecasting of joint meteorological, chemical (and biological weather in case of pollen) at multi-scales (*Baklanov et al., 2017*). And the selected online/ seamless and downscaling approaches are jointly able to handle and study major existing processes and interactions at multi-scales (i.e. regional-subregional-urban) which are difficult to investigate using the off-line modelling approach.

At initialisation, the physiographic data are pre-processed. In each grid cell of the modeling domains the elevation is calculated as mean, and land cover classes are transformed in accordance to the ISBA land surface scheme requirements. The climate generation procedure for the model uses a set of different data sources, including GTOPO30, GLCC, ECOCLIMAP, and CORINE (where it is available for European countries).

| DOMAIN-NAME | K15 | K05 | K02 |
|---|---|---|---|
| RESOLUTION (deg) | 0.15 | 0.05 | 0.02 |
| RESOLUTION (km) | 15 | 5 | 2 |
| # boundary points | 10 | 10 | 10 |
| NLON (grid-points) | 310 | 442 | 460 |
| NLAT (grid-points) | 188 | 340 | 340 |
| SOUTH | -27.527 | -21.527 | -15.357 |
| WEST | -31.325 | -16.025 | -7.025 |
| NORTH | 0.523 | -4.577 | -8.577 |
| EAST | 15.025 | 6.025 | 2.155 |
| POLAT | -10.0 | -10.0 | -10.0 |
| POLON | 40.0 | 40.0 | 40.0 |
| Time step (sec) | 240 | 120 | 60 |
| # vertical levels | 40 | 40 | 40 |

***Table 1.*** *Summary of the basic parameters for the selected model domains.*

The NWP-components include the digital filtering initialization, semi-Lagrangian advection scheme, and a set of physical parameterizations such as the Savijaervi radiation, STRACO condensation, CBR turbulence and ISBA schemes, etc (see more in *Baklanov et al., 2017*). The Enviro-components include modules for aerosol microphysics M7, gas-phase chemistry CBMZ, urbanization, emissions, nucleation, coagulation, condensation, deposition, etc. (see more in *Uden et al., 2012*). The emissions are also pre-processed and include anthropogenic, biogenic, and natural.

Although the Enviro-HIRLAM model can be setup (*signing of the code transfer and use agreement is required*) and run at personal LUNIX/UNIX-oriented environment computer, for this study, the model runs are realised at the Sisu supercomputer (for each model setup 256 procs, with 16 nodes and 16 tasks per node are allocated). Sisu is the part of the CSC (IT Center for Science Computing; https://research.csc.fi/home) infrastructure, and it is the most powerful supercomputer in Finland. Sisu's Cray XC40 system architecture is designed for massively parallel applications (& include Xeon E5-2690v3 12C 2.6GHz, with 40608 cores and peak performance 1.7 PFlop/s; according to https://www.top500.org).

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## Analysis of Atmospheric composition at SMEAR I station in December 2017

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Air masses are often categorized by using temperature and humidity as the key characteristics. However, when measurements of aerosol particles and atmospheric trace gases are available, atmospheric composition can act as even better identifier of air mass. Lifetime of aerosols and gases in the atmosphere vary from hours to months. Sulfur dioxode ($SO_2$) and nitrogen oxides (NOx) both have a lifetime of a few days, so the pollution source must be relatively close, usually within some hundreds of kilometers, to detect traces of these gases. Carbon monoxide (CO) has a lifetime of several weeks, so it is harder to determine source of it. One important anthropogenic source of CO is biomass burning. In Finland, especially in winter, wood is an important source of energy in households so if an air mass is coming from a populated area, CO concentration is likely to increase. Concentration of ozone ($O_3$) near surface is typically low, but it is a product in photochemical smog, where NOx acts as a precursor of $O_3$.

SMEAR I station in Värriö, Finnish Lapland was constructed in 1991-1992 and $SO_2$, NOx and $O_3$ concentrations have been measured since then (Hari et al. 1994). More variables were included during the following years and currently continuous observations include measurements of tens of meteorological variables and atmospheric gases. Differential Mobility Particle Sizer (DMPS) has been measuring aerosol particle number size distribution since 1997 and in August 2017 Airmodus A20 PSM was installed to allow detection of particles down to diameter of 1.1 nm.

SMEAR I station is located in very scarcely populated area. Air quality at the station is very good, especially in wintertime natural sources of aerosol particles and trace gases are weak. Land is covered in snow and incoming solar radiation greatly decreases which means that photo-chemistry is very limited. In Värriö, polar night starts on December 13th and ends on December 31st. However, several significant local pollution sources in Kola peninsula are within 200 kilometers from the station (Paatero et al. 2008). When wind direction is favourable, $SO_2$ and NOx concentrations can peak very high (fig. 1).

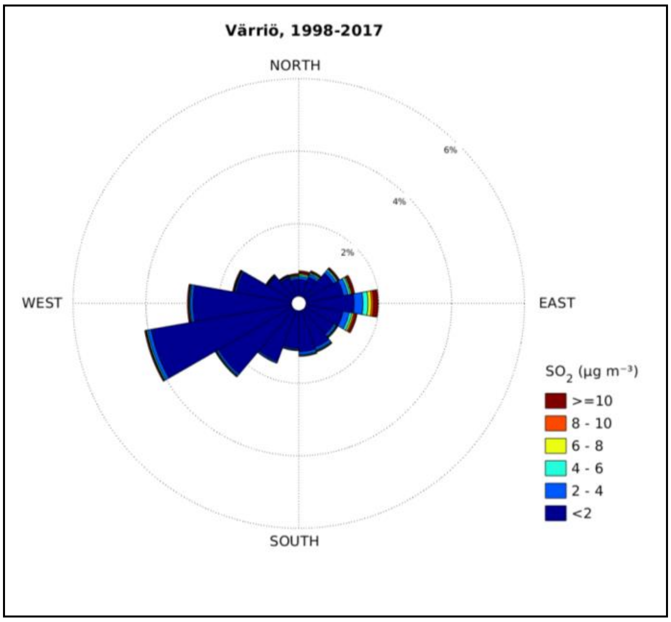


***Figure 1.*** *Hourly averaged wind direction and $SO_2$ concentration at SMEAR I station in 1998-2017.*

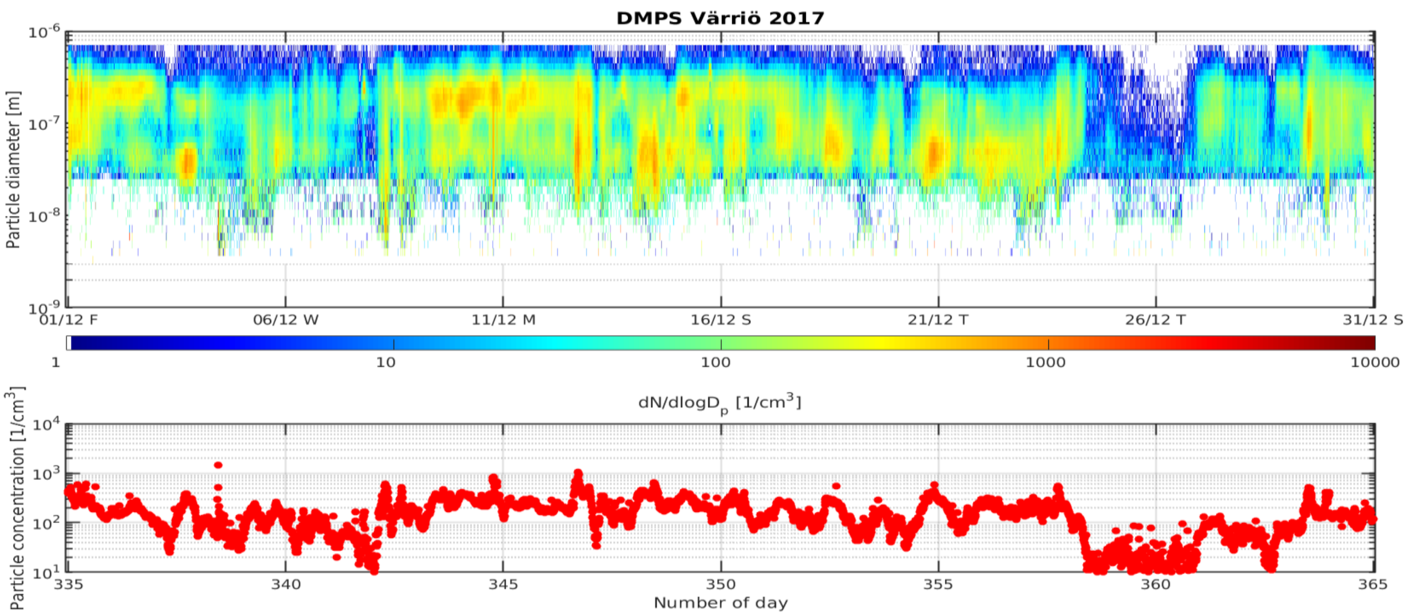


***Figure 2.*** *Number size distribution at SMEAR I station in December 2017.*

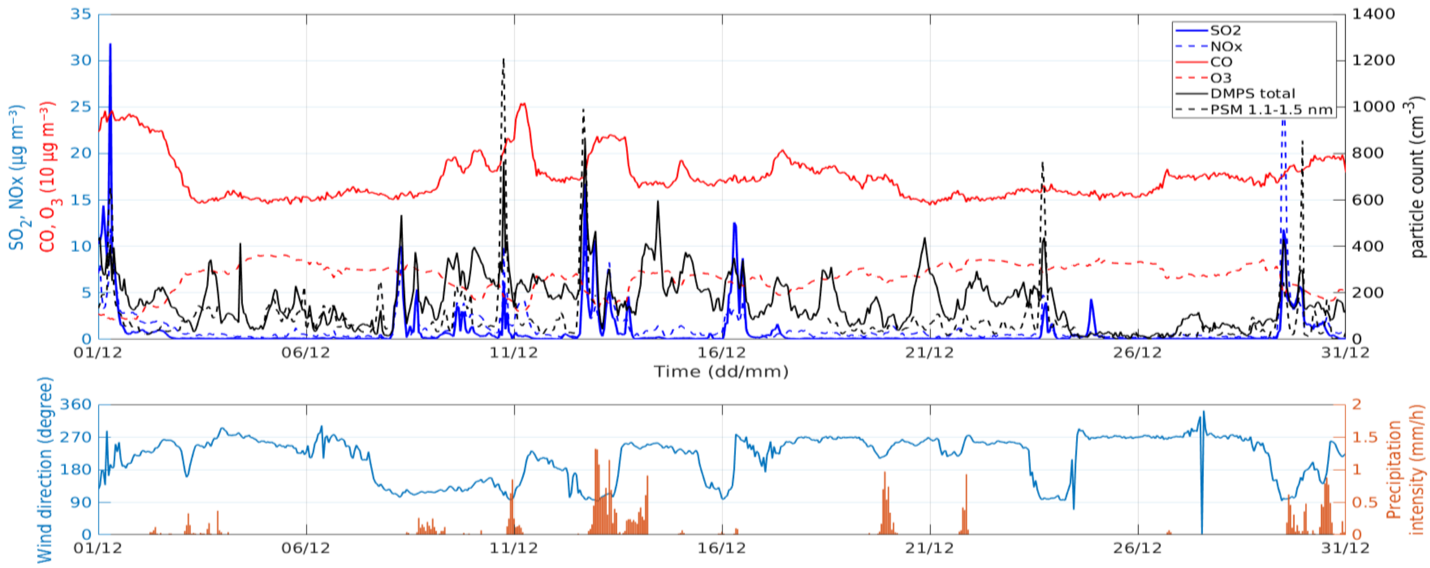


***Figure 3.*** *Air quality (top), and wind direction and precipitation intensity (bottom) at SMEAR I station in December 2017.*

Analysis of DMPS data (fig. 2) shows that number concentration of aerosol particles in Värriö during December 2017 was very low with a mean of 163 $cm^{-3}$. Clear cases of new particle formation events were not observed. High $SO_2$, NOx and CO concentrations coincide well with easterly wind direction (fig. 3).

Two cleaner periods took place: first one from 3rd to 8th and the second one, much more pronounced case from 24th to 29th. During the latter time period aerosol particle number concentration as low as 10-100 $cm^{-3}$ was frequently measured. A closer look at the clean time period suggests that the period can further be divided to an extremely clean period (25th-26th) with mean aerosol particle number concentration of 20 $cm^{-3}$ and a more typical clean period (27th-28th) with mean aerosol particle number concentration of 63 $cm^{-3}$.

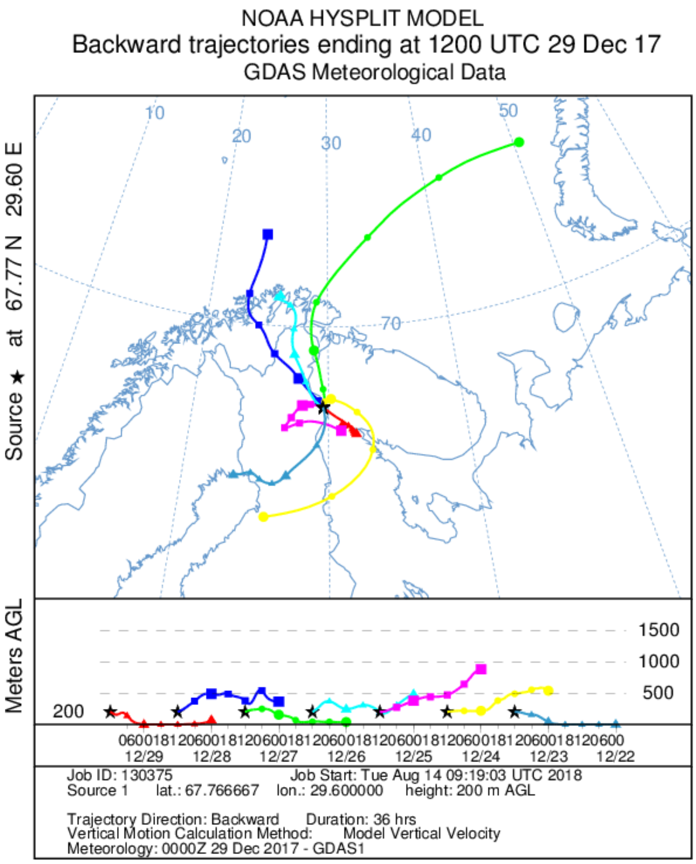


***Figure 4.*** *Backward atmospheric trajectories for seven arrival times from 23th to 29th of December 2017.*

Local wind direction observation at the station is often not sufficient to determine origin of an air mass. Wind can be strongly influenced by terrain, which is also the case in Lapland where several fjeld ranges exist. Thus, for this study, HYSPLIT backward atmospheric trajectories were also used to explain atmospheric composition (fig. 4).

Trajectory model reveals that origin of air mass during these days indeed changed even though wind direction was nearly constant. Just before the clean period air masses formed south and were transported to Värriö via Kola peninsula. On the evening of 24th wind direction suddenly changed from easterly to westerly. For the next two days wind speed was low and air that arrived to Värriö had circulated over the scarcely populated boreal forest of northern Scandinavia. No significant aerosol particle or trace gas sources contributed to the composition of the air mass. Then, on 27th of December wind speed increased again and arctic air mass arrived from the arctic sea. It is likely that the particles observed at size range of 50-300 nm originated from the sea. On the 29th wind direction changed again in a way that arriving air mass was transported via Kola peninsula industrial sites, which can be observed as an increase of $SO_2$, NOx and aerosol particle concentrations.

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## *Analysis of meteorological conditions at SMEAR I station in December 2017*

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SMEAR I station in Värriö, Finland (67°46′N, 29°36′E) is situated 390 meters above sea level in close proximity to Värriö fjeld range, pine forest and swamps (Hari et al. 1994). Several meteorological variables are measured at the station. Measured variables include air temperature, humidity, air pressure, wind speed and direction, visibility, precipitation, radiation and more. Most of these variables have been continuously measured for over 20 years, in this study December 2017 was studied. In addition to station data (available for download at: https://avaa.tdata.fi/web/smart/smear/download), UK Met Office synoptic weather charts (http://www1.wetter3.de/archiv_ukmet_dt.html) and HYSPLIT model backward atmospheric trajectories (http://ready.arl.noaa.gov/hypub-bin/trajtype.pl?) were used to study the synoptic meteorology during the study period.

Weather in Scandinavia in December is typically characterized by cyclonic activity. Cyclogenesis often occurs in Northeast Atlantic during early winter months, and from there cyclones propagate northeast. By the time they approach Värriö, they have often reached a mature, occluded stage. Air masses are usually maritime polar or arctic. Nearly all precipitation comes as snowfall, though most of the time water content of air is low due to low temperature, even when relative humidity is high. Still, snow depth can reach over 1 meter during winter months. Due to the northern location of SMEAR I station, the amount of incoming radiation is very low during winter months. Polar night lasts almost three weeks, from December 13th to December 31st.

In 2017, December begun with an almost occluded front passing Värriö on the 3rd, with only narrow zone of warmer, polar air between the warm and cold fronts. Rapidly intensifying cyclone formed just south of Iceland on the 6th and begun moving east, reaching its highest intensity on the coast of Norway. There it remained stationary for several days, gradually weakening and associated occluded fronts reached Värriö on the 9th and 11th, causing moderate precipitation. Meanwhile, over Bay of Biscay, north of Spain, a cyclone formed and begun to move northeast. The cyclone swept over the length of Finland from south to north and it reached Lapland on the 13th, bringing precipitation to Värriö from two rain bands following each other. On the 20th, an occluded front associated with a cyclone over the Arctic Sea briefly brought warm air and precipitation to Värriö, before a

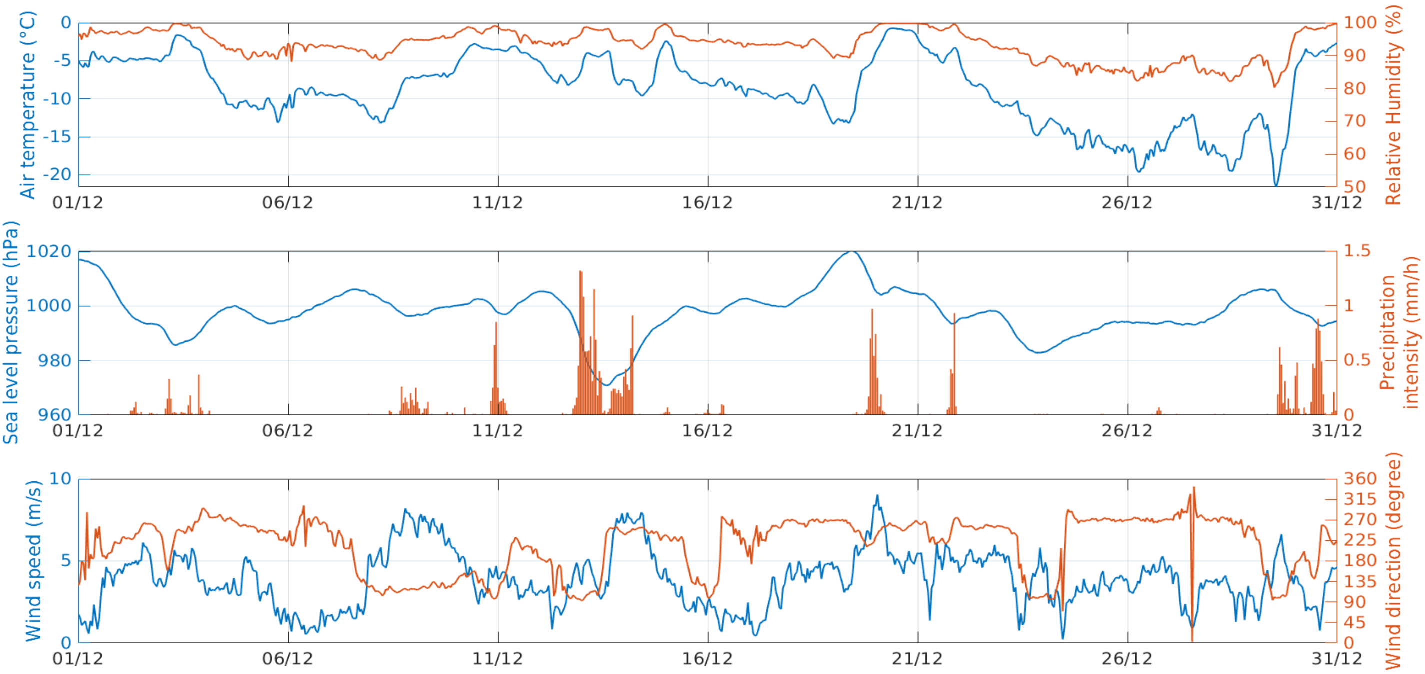


***Figure 1.*** *Hourly averages of air temperature and relative humidity (top), Sea level pressure and precipitation intensity (middle), and wind speed and direction (bottom) measured at SMEAR I station in December 2017.*

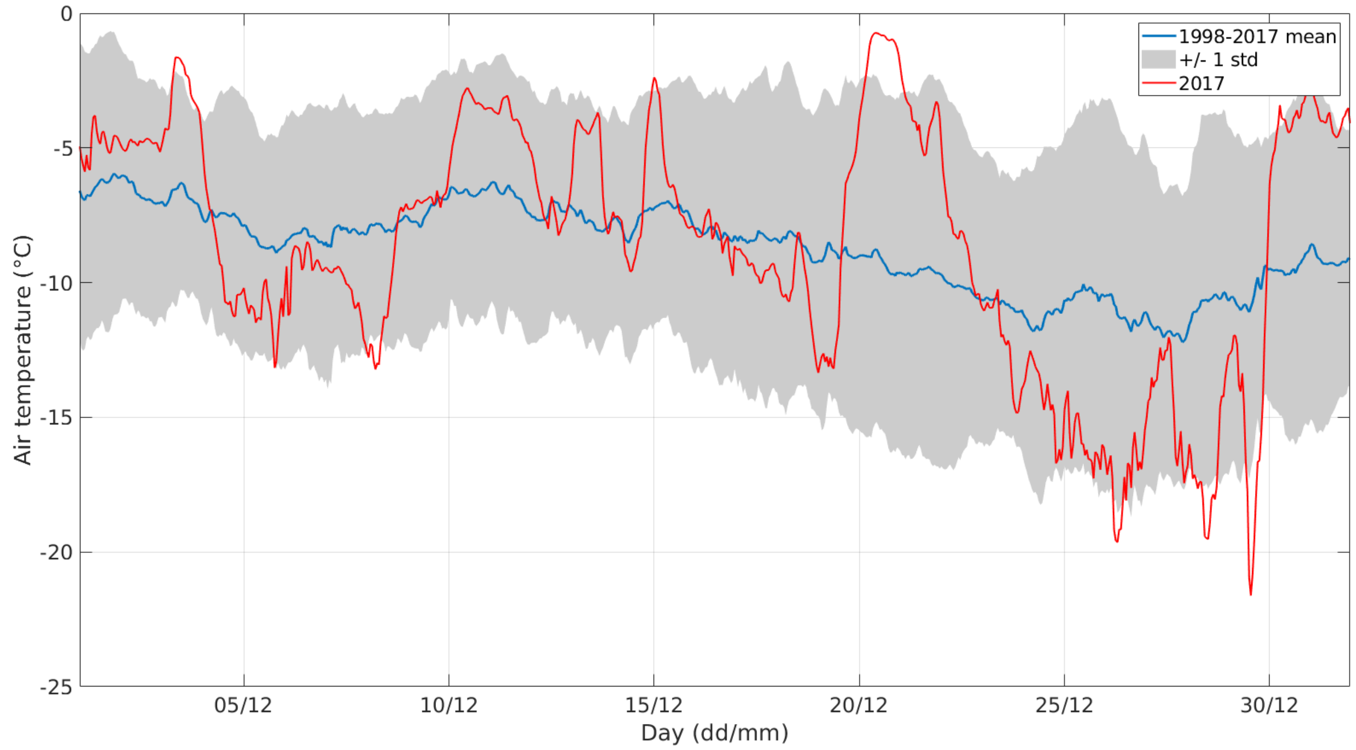


***Figure 2.*** *Hourly average air temperature at SMEAR I station. Blue curve represents 1998-2017 mean and shading +/- 1 standard deviation from it. Red curve is 2017 observations.*

cold arctic air mass arrived on the evening of 21st. For the next few days, cyclone tracks were south of Lapland so that conditions remained stationary and temperature gradually decreased. The cold period ended with the arrival of warm front on the 29th, which brought snowfall and caused rapid increase of temperature (16.0 °C in 12 hours).

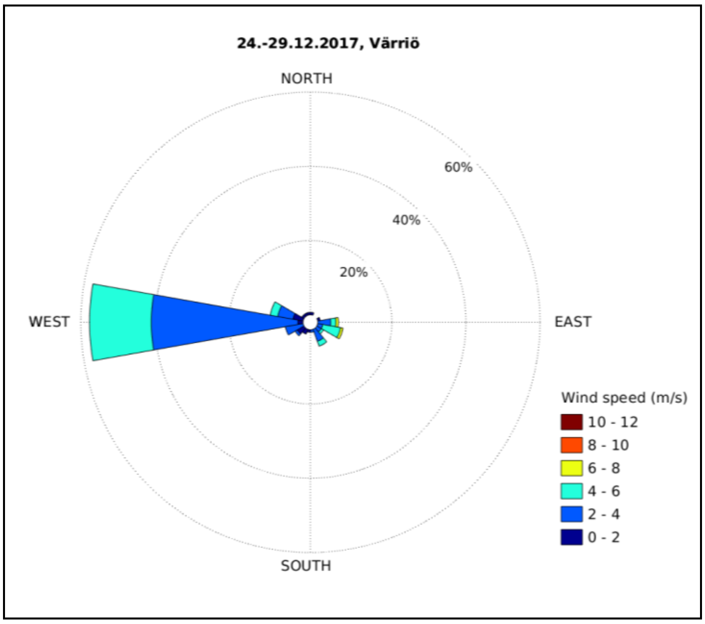


***Figure 3.*** *Wind rose with colour resembling wind speed of hourly averages from 24th to 29th of December 2017 measured at SMEAR I station.*

The coldest period in Värriö, from 24th to 29th of December, was characterized by low temperature (fig. 2), westerly wind direction, low wind speed (fig. 3) and unusually low level of air pollution. Temperature was below 1998-2017 mean during that time and at times even below one standard deviation from past temperature measurements. December monthly mean temperature was -8.7 °C which is also the 1998-2017 December mean. Maximum temperature was -0.7 °C (Dec 20th) and minimum was -21.6 °C (Dec 29th). The cold period mean temperature was -15.6 °C and the maximum -10.3 °C.

At the station low wind speeds were measured and wind was mostly westerly. However, further analysis of wind trajectories showed that the air masses did not come from west, but from southeast until 25th and after that from the north. Thus, air masses were not being affected by Kola peninsula industrial sites (Paatero et al. 2008), which partially explains good air quality. Air pressure was quite stable during the time period. An increase in air pressure towards the end of the period increased visibility, however due to polar night, that only increased outgoing longwave radiation causing further cooling of the air mass.

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# *Seasonal impact due to sulphur emissions from Severonikel smelters*

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During the last decades the enterprises of various risks (nuclear, chemical, biological, etc.) are under permanent and critical view from the society. Large Russian industrial major enterprises such as the Norilsk Nickel, Pechenganikel and Severonikel are sources of continuous emissions (www.nornickel.com, www.kolagmk.ru). The investigation of impact on population of different regions (Figs 1-2) due to continuous emissions of sulphates from the Severonickel Cu-Ni smelters (city of Monchegorsk, Murmansk region, Russia) was performed employing the Lagrangian long-range transport model DERMA (*Sorensen, 1998; Baklanov et al., 2008*) in a long-term simulation mode and applying GIS tools for integrating and analysis of modeling results (*Mahura et al., 2018*).

It was found that over the model domain (covering Northern Hemisphere starting at 10°N) on annual scale, daily dry deposition is about 6 t with the highest (10 t) - in September. The wet deposition is 23 t (maximum 50 t - in February), and it is dominating in the total deposition. On average, about 33% of the emissions could be deposited on the surface during 10 days of the atmospheric transport from the smelters with the highest (65%) and lowest (14%) deposited amounts observed in February and July, respectively.

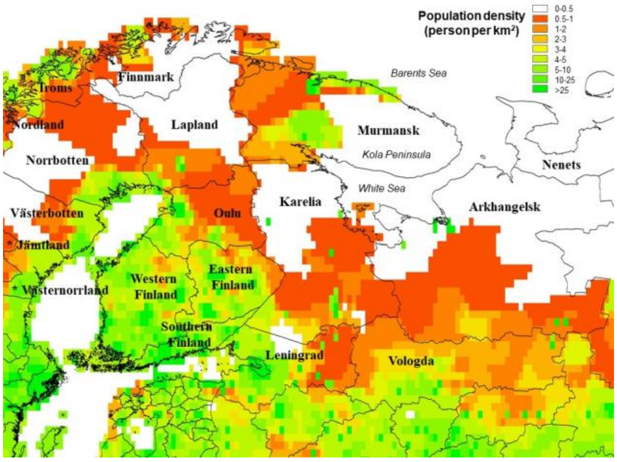


***Figure 1.*** *Geographical boundaries of administrative units (regions, provinces, counties, etc.) and population density (in persons per km²).*

The Murmansk region, where the smelters are located, is the most impacted, followed by the Karelia Republic and Arkhangelsk region (with the total deposition more than order of magnitude lower compared with the Murmansk region). Among administrative units of the Scandinavian countries, Lapland (Finland), Norrbotten (Sweden) and Finnmark (Norway) have the highest depositions. On average, it is higher in autumn for all three Scandinavian countries; and lower in summer (for Finland) and winter (for Norway).

For the Russian regions, on average, deposition is higher in spring (except, the Arkhangelsk and Nenets regions), and it is lower in summer and winter.

The maximum total deposition is observed for the northern, central, and southern territories of Finland in spring, autumn and winter, respectively. For Sweden, it occurs in autumn. For the northernmost part of Norway it takes place in spring, and for other territories – in autumn. For Russia, the largest maxima are linked with spring and autumn for the territories southerly and easterly of the Severonikel smelters, respectively.

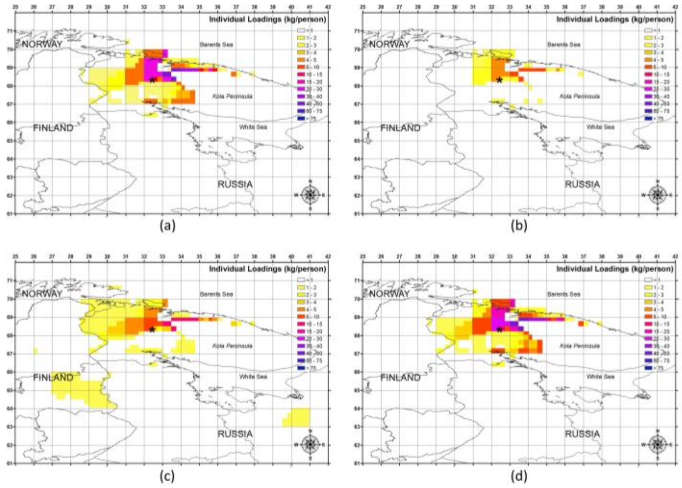


***Figure 2.*** *Seasonal individual loadings for population (in kg/person) from deposited sulphates resulted from the Severonikel smelters continuous emissions (mild scenario; * - location of the Severonikel plant): (a) spring, (b) summer, (c) autumn, and (d) winter.*

The yearly individual loading can be up to 120 kg/person for the most populated urban areas of the Murmansk region. For bordering territories with this region such loadings are less than 5 kg/person for territories of the eastern Finland, Karelia Republic, and Arkhangelsk region; and not greater than 15 kg/person – for the Finnmark county of Norway. There exists seasonal variability (with lowest loadings in summer), which is less pronounced for the Scandinavian countries. The percentage contribution into such loading is higher in winter-spring for Russia (in sum 85%), in spring for Norway (34%), in autumn for Finland and Sweden (32 and 41%, respectively). The yearly collective loading is the highest (2403 tonnes) for the Murmansk region. Both the Karelia Republic and Arkhangelsk region have the second largest loadings (83 and 77 t). For populated territories of the bordering countries with the Murmansk region such loadings are 140.4, 13, and 10.7 t for Finland, Norway and Sweden, correspondingly.

The results of this study are applicable for (i) evaluation of risks, vulnerability, and short- and long-term consequences due to airborne pollution on population, environment, and ecosystems; (ii) complex human health impact assessments taking into account social, economical, and other factors; (iii) support of decision-makers, adjustment of legislation at regional levels, control pollution exceedances; planning preventive measures, mitigation scenarios, etc.

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