

**Alexander Mahura^{1*}, Iraxte Gonzalez-Aparicio², Roman Nuterman³,
Alexander Baklanov⁴**

¹ Institute for Atmospheric and Earth System Research (INAR) / Physics, Faculty of Science, University of Helsinki (UHESL)

² European Commission, DG-Joint Research Centre (EC, DG-JRC), Energy, Transport and Climate Directorate

³ University of Copenhagen (UCPH), Niels Bohr Institute

⁴ World Meteorological Organization (WMO), Research Department

* **Corresponding author:** alexander.mahura@helsinki.fi

SEASONAL IMPACT ANALYSIS ON POPULATION DUE TO CONTINUOUS SULPHUR EMISSIONS FROM SEVERONIKEL SMELTERS OF THE KOLA PENINSULA

ABSTRACT. This study is devoted to investigation of total deposition and loading patterns for population of the North-West Russia and Scandinavian countries due to continuous emissions (following “mild emission scenario”) of sulphates from the Cu-Ni smelters (Severonikel enterprise, Murmansk region, Russia). The Lagrangian long-range dispersion model (Danish Emergency Response Model for Atmosphere) was run in a long-term mode to simulate atmospheric transport, dispersion and deposition over the Northern Hemispheric’s domain north of 10°N, and results were integrated and analyzed in the GIS environment. Analysis was performed on annual and seasonal scales, including depositions, impact on urban areas and calculating individual and collective loadings on population in selected regions of Russia and Scandinavian countries.

It was found that wet deposition dominates, and it is higher in winter. The North-West Russia is more influenced by the Severonikel emissions compared with the Scandinavian countries. Among urban areas, the Russian cities of Murmansk (due to its proximity to the source) and Arkhangelsk (due to dominating atmospheric flows) are under the highest impact. The yearly individual loadings on population are the largest (up to 120 kg/person) for the Murmansk region; lower (15 kg/person) for territories of the northern Norway, and the smallest (less than 5 kg/person) for the eastern Finland, Karelia Republic, and Arkhangelsk region. These loadings have distinct seasonal variability with a largest contribution during winter-spring for Russia, spring – for Norway, and autumn – for Finland and Sweden; and the lowest during summer (i.e. less than 10 and 1 kg/person for the Russia and Scandinavian countries, respectively). The yearly collective loadings for population living on the impacted territories in Russia, Finland, Norway, and Sweden are 2628, 140.4, 13, and 10.7 tonnes, respectively.

KEY WORDS: atmospheric transport, dispersion and deposition modelling, sulphates, GIS analysis; individual and collective loadings

CITATION: Alexander Mahura, I. Gonzalez-Aparicio, Roman Nuterman, Alexander Baklanov (2018) Seasonal Impact Analysis On Population Due To Continuous Sulphur Emissions From Severonikel Smelters Of The Kola Peninsula. *Geography, Environment, Sustainability*, Vol.11, No 1, p. 130-144
DOI-10.24057/2071-9388-2018-11-1-130-144

INTRODUCTION

During the last decades the enterprises of various risks (nuclear, chemical, biological, etc.) are under permanent and critical view from the society. There is a number of important questions addressed as they are important because they are related to environmental issues and people's life. What are the potential impacts on the environment and on humans? Which geographical regions, countries, population groups etc. are under the largest influence when continuous emissions or accidental releases are taken place at different risk objects? Answers on such questions are, first of all, directly linked with investigation of atmospheric transport and deposition of pollution as well as estimation of their effects on population and environment.

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 two latter are located on the Kola Peninsula. Information about environmental and pollution situation in the Murmansk region of Russia is provided through annual state reports. A series of studies was performed as a part of the Russian state scientific-research programmes, Kola Science Center of the Russian Academy of Sciences projects, Arctic Monitoring and Assessment Programme activities, and others.

Many field campaigns taking meteorological and pollution measurements, soil and water samples were conducted in surroundings of the sources (Golubeva et al. 2010, Hansen et al. 2017). In addition, local and remote

continuous monitoring is carried out in order to evaluate influence on various ecosystems and people (Berglen et al. 2016, Reimann et al. 1999, Lappalainen et al. 2007).

Analysis of forest ecosystems of the Kola Peninsula, Karaban and Gutarsky (1995) revealed that within a 30-40 km radius from the emission sources the impact is the largest. Moreover, level of damage varies depending on a type of a forest (Gutarsky et al. 1997) and area of the forest decline is expanding (Hagner and Rigina, 1998). Microbial communities in polluted soils showed significant decrease in biomass and growth rate (Blagodatskaya et al. 2008). Following the smelters production and amount of toxic loading produced, Moiseenko et al. (2006) found that water ecosystem (the Imandra Lake near Severonikel) strongly affects a human's health. Higher altitude lakes in Khibiny mountains showed both contributions: from the local smelters and due to transboundary pollution (Dauvalter et al. 2003). Modelling of concentration and deposition patterns resulted from continuous and accidental releases (radionuclides, gaseous chemical species and aerosols) from potential sources of nuclear and chemical risks was performed in Mahura et al. (2006ab, 2007, 2008) and proved to be a reliable approach.

In this study, the influence of continuous emissions of pollutants (on example of sulphates) on population is evaluated taking into account available meteorological and emission data for the year 2000. For that long-term modelling of concentration and deposition patterns, their integration into the GIS environment and further analysis were performed. Results of analysis of temporal

and spatial variability of deposition patterns on annual and seasonal scales, impact on the most populated urban areas, individual and collective loadings on the population living within different geographical territories (with a focus on selected Russian regions and Scandinavian countries) are presented in this paper.

MATERIALS AND METHODS

Pollution from Cu-Ni Smelters

There are several major locations in the Russian Arctic associated with large amounts of sulphur dioxide (SO₂) and heavy metals emissions. These are known as Cu-Ni smelters having the largest environmental and health impacts. These are three Russian enterprises: Norilsk Nickel (Krasnoyarsk Krai), Pechenganickel (cities of Zapolyarny and Nikel, Murmansk region) and Severonikel (city of Monchegorsk, Murmansk region). Following the Kola Mining and Metallurgical Company (see more news at www.kolagmk.ru) activities and technological changes a substantial reduction of emissions was performed in recent years. For example, at the beginning of the last decade (year of 2000), the SO₂ emissions from the Severonikel and Pechenganickel enterprises reached 45300 and 151200 tonnes, respectively (Ekimov et al. 2001). Thus, calculated emission intensities of the Monchegorsk smelters are $1.433 \cdot 10^9$ µg/sec. In this study, hereafter, an analysis of impact due to the Severonikel smelters is based on the defined above intensities and considering so-called the "mild scenario" (i.e. about 31.6 thou. tonnes per year corresponding to about 86.4 tonnes per day). Such scenario was chosen according to dominating tendencies in reduction of emissions. Although not the entire released amount of SO₂ can be converted following chemical transformations into sulphates (SO₄⁻²) during long-range atmospheric transport, it was assumed that it occurred at maximal level (i.e. 82%; IPCC, 2001) in order to obtain the highest estimates for analysed parameters. I.e. we assumed that 82% of emitted SO₂ were converted to SO₄⁻², and then as aerosols were transported, dispersed and deposited.

Long-Term Modelling of Continuous Emissions

The modeling of atmospheric transport, dispersion and deposition of different pollutants is essential input for estimation of possible consequences on different scales ranging from hemispheric, regional, subregional, and transboundary to mesoscale and local scales. Generated model output is crucial for multi-level assessment of risk, vulnerability, impact, short- and long-term consequences for environment and population, which is living near-by or remotely from the sources of possible accidental releases and continuous emissions.

In this study, the long-term modeling of atmospheric transport, dispersion and deposition of pollution resulted from continuous emissions from the Severonikel Cu-Ni smelters was performed employing the Lagrangian-type Danish Emergency Response Model for Atmosphere (DERMA; Sorensen, 1998; Baklanov et al. 2008) in a long-term mode. The probabilistic approach, sensitivity of the model to meteorology and diffusion parameters, deposition processes, and other parameterizations are also described in more details by Baklanov and Mahura (2004), Sorensen (1998), Baklanov and Sørensen (2001). The European Centre for Medium-Range Weather Forecast (ECMWF) data archives were used as input meteorological 3D fields for the year 2000. The meteorological data are given at 1 x 1 degree resolution at every 6 hour time interval and covering the Northern Hemisphere starting 10°N. Only the emissions of sulphates were taken into account, although heavy metals are also linked with emissions from the smelters. The metals are mostly will be deposited at shorter distances from the sources, and hence, will have more influence on a local scale. As more detailed information about a technological cycle of the Severonikel production chain and hence, corresponding diurnal cycle of emissions, were not available on a daily basis, for the model runs it was assumed that the continuous emissions occurred daily at the constant rate (see Section @Pollution from Cu-Ni Smelters). Then, for each run, the

pollution plume originated near the source was transported through the atmosphere (as well as dispersed and deposited due to dry and wet deposition processes) during following 10 days. It should be noted that in general, levels of pollution can vary significantly depending on dominating meteorological conditions both within the boundary layer as well as free troposphere, and the most highest levels of pollution are generally observed in a vicinity of the sources.

The generated model output included: the air concentration, the time integrated air concentration (TIAC), the dry deposition (DD) and the wet deposition (WD) (see Fig. 1). Note that such output - if it is summed over a long period of time (for example: month, season, year) or if it is averaged over a short period of time (for example: day, period of accidental release) - can represent possible short- and long-term

effects and probabilistic characteristics of industrial pollution. In general, based on such available output, the geographical boundaries of potential influence due to continuous (or accidental) atmospheric releases of pollutants from different sources can be identified and possible impacts can be evaluated. An example of simulated summary and average TIAC, DD and WD patterns during 10 days of the atmospheric transport, dispersion and deposition for the month of April are shown in Fig. 1.

GIS Integration of Dispersion Modelling Results

The results of the long-term dispersion modelling were integrated into the Geographical Information System (GIS; ArcGIS geospatial processing software; www.gis.com) environment (Fig. 2) in order to assess the impact on population due to continuous anthropogenic emissions

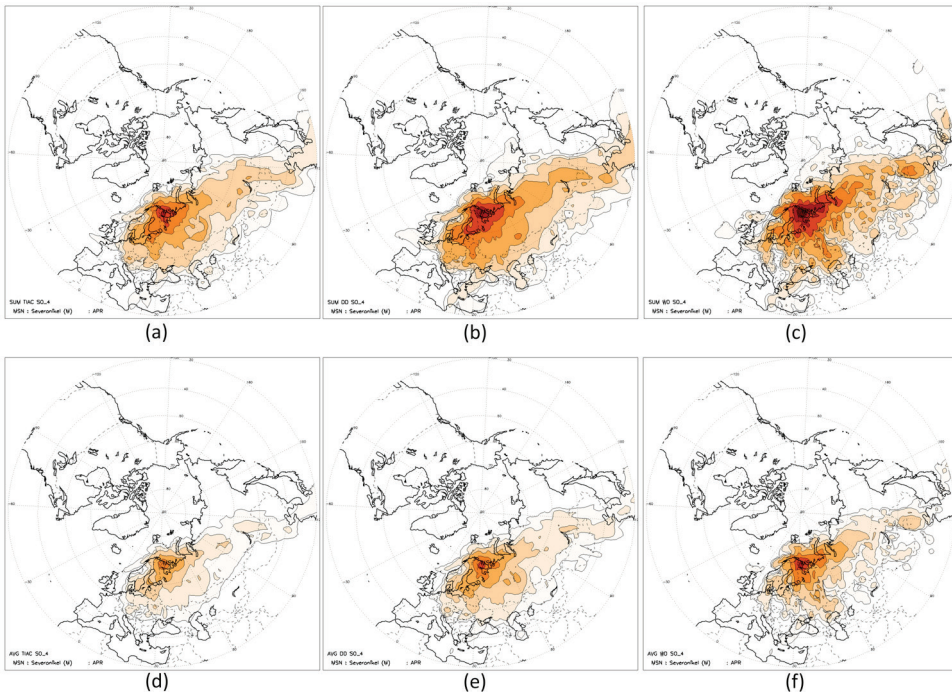


Fig. 1. Spatial patterns of the (abc) summary and (def) average - (ad) time integrated air concentration (TIAC), (be) dry (DD) and (cf) wet (WD) deposition - patterns during April due to continuous emissions of sulphates from the Severonikel smelters (deposition and concentration isolines are shown starting from the lowest $1e-2 \mu\text{g}/\text{m}^2$ and $1e-2 \mu\text{g}/\text{m}^3$, respectively; Δ MSN – location of the plant on the Kola Peninsula)

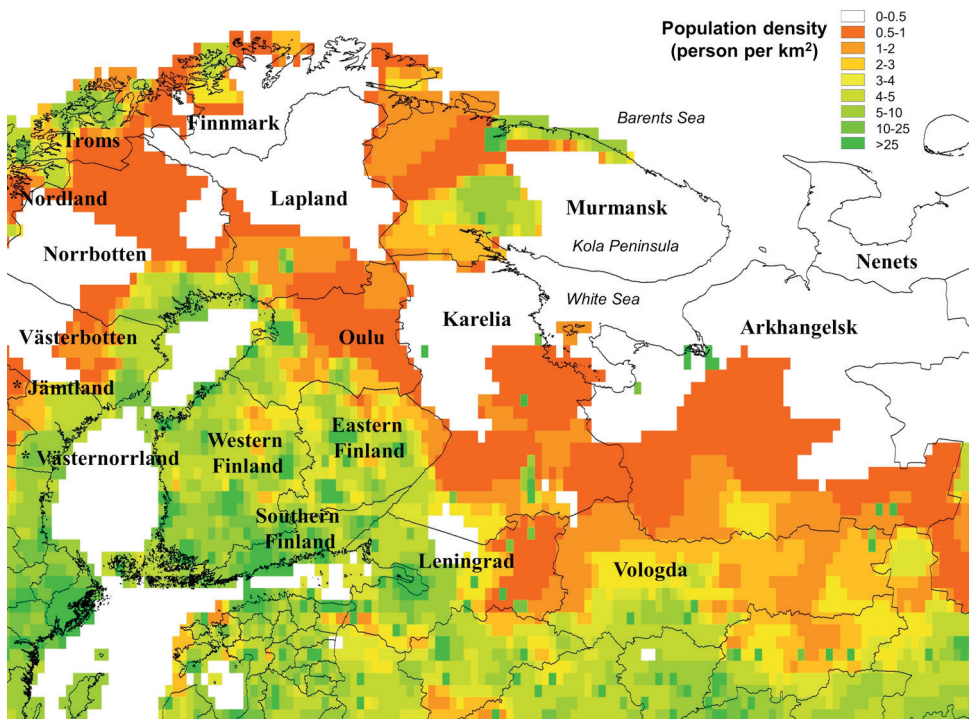
from the Severonikel smelters. For that, the ArcMap component of ArcGIS was applied. Note that ArcMap was used to geospatially view, edit, create, and analyze the integrated modelling data through exploring these results and creating maps. Moreover, note that the same coordinate system is required to work in ArcMap with different data-frames and layers. In particular, all data were converted into the Geographical Coordinate System GCS-WGS-1984. The WGS-1984 (World Geodetic Survey 1984) is a standard definition of a global reference system for a geospatial information, and is the reference system for the Global Positioning System (GPS).

At first, the countries and administrative units (regions/ oblast, provinces, counties) boundaries and population density of the European countries and Russia were loaded (see Fig. 2a; with interpolated population data). Data about administrative boundaries of the Russian regions (including Murmansk region) were extracted at gis-lab.info. Data about boundaries of the European countries and administrative units were downloaded from www.diva-gis.org. Data about the

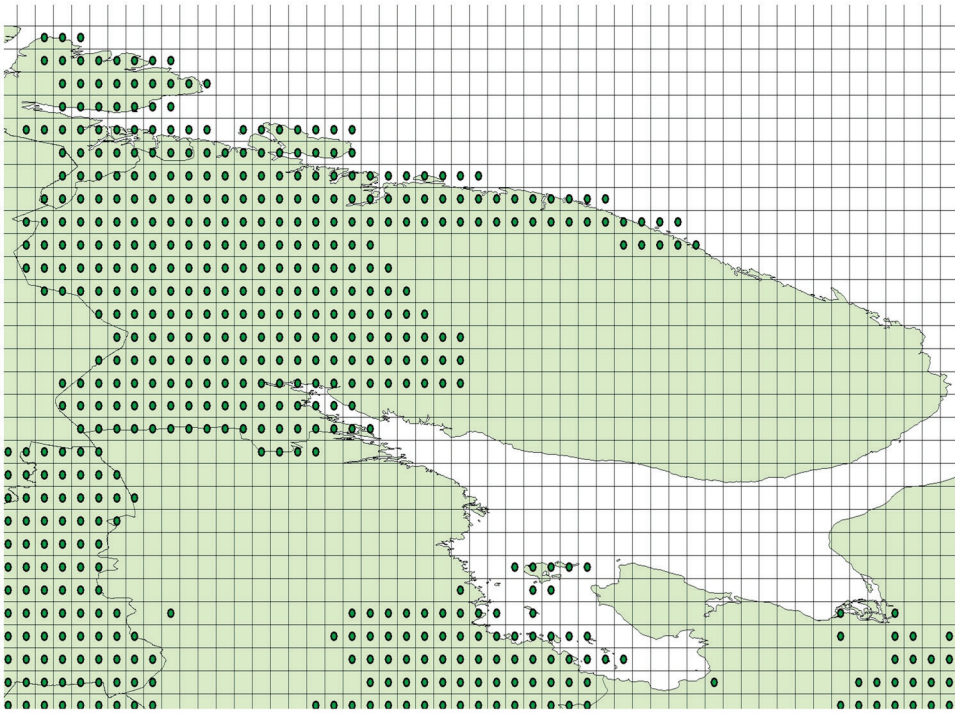
population density were obtained from the Center for International Earth Science Information Network (CIESIN; www.ciesin.org).

At second, the header (with information on number of grid points along latitude and longitude, south-west corner of modelling domain, and attribute for missing values) was added to the dispersion modelling output file, and it was needed for obtaining further information about spatial resolution and location. Then, the file was converted into the same GCS-WGS-1984 coordinate system.

At third, the raster centroids (centers of grid cells) were used to create the vector grid. For that, integrated raster data were converted into points and polygons. Because centroids were generated at regular grid, the Hawth tool (www.spatial ecology.com) was used to create a vector grid, where the resolution could be changed, in particular, increased. For a case of non-regular grid see González-Aparicio et al. (2010). The attribute table was used to transfer data from raster to vector grid based on spatial location. Subsequently,



(a)



(b)

Fig. 2. (a) Geographical boundaries of administrative units (regions, provinces, counties, etc.) and population density (in persons per km²), and (b) Example of extracted geographical region with overlapped layers of the total deposition, administrative boundaries and population density in order to calculate the impact on population exposed to emissions

new layers were created for different attributes taking into account grid cells with deposition greater than zero.

Finally, the overlapping (Fig. 2b) of the deposition layer with the administrative boundaries was performed in order to calculate the total deposition for selected regions and counties. The similar procedure (but in addition using the population density layer) was carried out to calculate the impact on population exposed to emissions. And then, these final results in a vector grid were converted into a raster format to visualise different levels of impact.

RESULTS AND DISCUSSIONS

Monthly Variability of Deposition

The simulation results on the Northern Hemispheric scale showed that a substantial value of deposition was observed not only

over the Kola Peninsula, but also on the regional scale. This includes contribution to Arctic regions (e.g. Arctic haze), transboundary atmospheric pollution transport between North-West Russia and Nordic countries, as well as to other geographical regions/ countries. As seen in Fig. 3, in particular, such influence is observed faraway on the Pacific region countries (Japan, China, and Korea). Due to irregularities of precipitation patterns, the isolated areas of the wet deposition is observed even along the western seashore of the North American continent (e.g. Canada and USA).

The supplementary materials – i.e. the animated web-based atlas of the modelled month-to-month variability of the averaged and summary TIAC, DD and WD patterns is available and plotted for the geographical domain covering the Northern Hemisphere

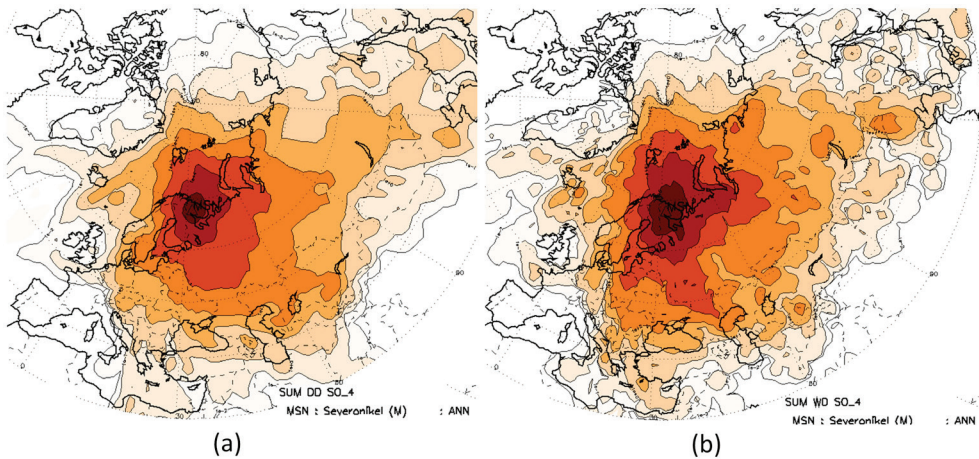


Fig. 3. Spatial patterns of the yearly (2000) summary (a) dry and (b) wet deposition due to continuous emissions of sulphates from the Severonikel smelters (isolines are shown starting from the lowest $1e-2 \mu\text{g}/\text{m}^2$; ΔMSN – location of the plant on the Kola Peninsula)

north of 30°N .

The simulated concentration and deposition fields allowed evaluating the spatial and temporal variability of resulted patterns on different scales. It has been found that for the “mild scenario emissions” (i.e. approx. 31.6 thou. tonnes), for the Severonikel smelters, the annual average daily dry deposition (DD) value is about 6 t. The highest average DD (10 t) is in September, and the lowest – less than 3 t – in April. The annual average daily wet deposition (WD) is about 23 t, and a strong month-to-month variability is seen compared with dry deposition (Fig. 4a). The highest average WD (more than 50 t) is in February although with the largest variability, and the lowest – about 6 t – in July. The WD is higher in magnitude and has more monthly variability compared with DD, and hence, WD is dominating in total deposition.

There are also differences in the total amount deposited from daily releases of the smelters (Fig. 4b). On an annual scale, on average, 33% of emitted amount could be deposited on the surface during 10 days of atmospheric transport from the sources. The highest deposited amount of 65% is observed in February and the lowest of 14% – in July. In general, during January–May the deposited amount is almost twice larger compared with June–October, but in November–December – it is close to the

annual average. Such identified pattern depends on dominated synoptic and large scale atmospheric transport as well as meso-scale circulation patterns over the Northern Hemisphere domain. Moreover, a larger amount of precipitation (and hence, the wet deposition) is taking place during winter and spring compared to summer and autumn months.

Regional Distribution of Deposition Patterns

A summary for total (as a sum of dry and wet) deposition characteristics for selected territories of the North-West Russia and Scandinavian countries is shown in Table 1. It includes analysis for total deposition (average and maximum) taking into account areas of grid cells enclosed by administrative boundaries of the selected regions/oblast, provinces and counties of selected countries. As seen, for the Murmansk region, where the source of emissions is located, on average, the deposition can reach up to $28 \mu\text{g}/\text{m}^2$ (with minimum of $14 \mu\text{g}/\text{m}^2$, and maximum of $122 \mu\text{g}/\text{m}^2$). The second most polluted Russian region is the Republic of Karelia followed by the Arkhangelsk region with average depositions, which are more than order of magnitude smaller compared with the Murmansk region. Among Finnish provinces, Lapland is the most polluted, and level of pollution is comparable with

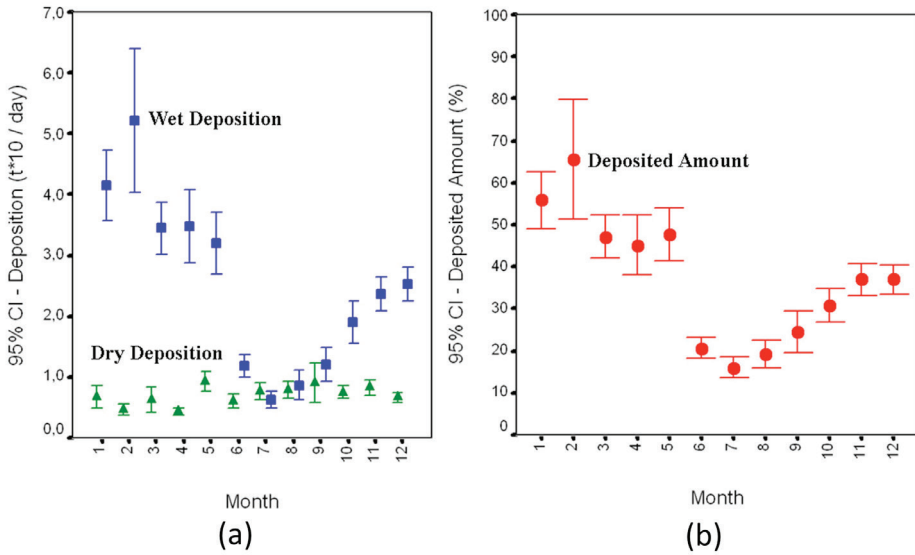


Fig. 4. Month-to-month variability at 95% confidence interval of averaged dry and wet deposition patterns (in tonnes per day) and (b) deposited amount (in %) resulted from the Severonikel continuous emissions

Karelia. The Swedish Norrbotten province has the highest deposition in the country. The Norwegian Finnmark county has also the largest deposition level, mostly due to its proximity to the source.

The analysis of the seasonal variability of the averaged total deposition (thereafter, ATD) showed, that for all Finnish provinces (except, Southern Finland) ATD is higher in autumn and it is the lowest in summer months. For the Norwegian counties, ATD is also higher in autumn (similarly for Finland and Sweden), but it is the lowest during winter. For the Russian regions considered, ATD is higher in spring; except, for the Arkhangelsk and Nenets regions (which are located easterly of the Kola Peninsula). Here, it is observed in autumn, similarly to the Scandinavian countries. The lower values of ATD are observed in summer and winter.

For the maximum total deposition (thereafter, MTD), on a seasonal cycle, it was found that for Finland, the MTD is the largest for the northern territories (Lapland province) in spring, for the southern territories (Southern Finland) – in winter, and for the rest (Oulu, Eastern and Western Finland provinces) – in autumn. The MTD is the lowest for all Finnish provinces in summer. For the Norwegian counties considered, the MTD is the largest

in spring (Finnmark) and autumn (Troms and Nordland); and MTD is the lowest – in winter and summer. For the Russian regions in focus, the largest maxima are linked with spring time, but for the easterly located regions (Arkhangelsk and Nenets) – in autumn. The lower maxima are more characteristic for summer compared with winter. For Sweden, the largest maxima are observed for all counties in autumn.

Individual and Collective Loadings on Population

Although sulphur deposition has ecological impacts, and first of all, on water and terrestrial ecosystems, in our study, the sulphates deposition effects on population were considered through contamination of the urban areas (e.g. those grid cells with a population fraction presented). Possible direct health effects on population might occur when the wet deposition process occurs with acidic pollutants in acid precipitation. Possible indirect effects might occur when the underlying urban surface (with soils and ground/surface waters) is contaminated due to both dry and wet deposition processes. In our study, these effects are combined through the loadings on the population.

Table 1. Regional distribution of total deposition (annual and seasonal) of sulphates due to continuous emissions of the Severonikel smelters

Country	Region/ County/ Province	Total Deposition ($\mu\text{g}/\text{m}^2$)									
		Spring		Summer		Fall		Winter		Year	
Statistics		Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max
Finland											
	Lapland	623	2263	230	571	940	2219	392	2117	2185	7170
	Oulu	282	792	61	180	802	1344	297	594	1442	2910
	Eastern Finland	70	122	21	38	316	698	160	354	567	1200
	Western Finland	30	40	8	17	131	573	37	64	205	640
	Southern Finland	42	73	9	18	48	105	85	137	183	332
Norway											
	Finnmark	826	3218	307	760	909	2242	197	889	2239	6730
	Troms	26	49	40	91	126	235	10	29	202	403
	NordLand	4	11	3	11	18	31	3	7	28	50
Russia											
	Murmansk	11228	56495	2279	7849	4369	11124	10406	46667	28282	122000
	Karelia	581	2181	198	611	542	1476	447	1677	1768	5050
	Arkhangelsk	112	578	115	1185	282	1651	42	148	551	3030
	Nenets	161	376	11	36	249	702	21	193	442	1250
	Vologda	107	391	26	216	66	243	15	47	214	864
	Leningrad	83	221	19	45	28	67	66	102	196	309
Sweden											
	Norrbotnen	16	67	19	75	92	268	11	65	138	397
	Vesterbotnen	2	7	1	2	15	31	12	29	30	69

The estimation of deposited amounts of sulphates with respect to population (thereafter, the loadings) for selected regions of Russia and Scandinavian countries was performed. At first, the yearly and seasonal deposition for the population density (in $\mu\text{g}\cdot\text{m}^{-2}$ / $\text{person}\cdot\text{km}^{-2}$) was calculated. At second, the yearly and seasonal individual loadings (in kg / person) were evaluated. At third, yearly collective loadings (in kg) for the entire population residing within the administrative boundaries of the studied regions/ counties/ provinces were also evaluated.

As seen in Fig. 5-6, for population residing in the central and northern territories (in urban settlements) of the Kola Peninsula the yearly individual loading can be more than 40 kg/person and up to 120 kg/person for most populated urban areas (located not far from the source of emissions) of the Murmansk region. For bordering territories with the Murmansk 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 northern Norway. There is also seasonal variability in

loadings, but it is less pronounced for the Scandinavian countries compared with the Russian regions. In particular, for all regions considered the loadings are the lowest in summer, i.e. less than 10 kg/person for Russia, and less than 1 kg/person for three considered Scandinavian countries. For the Russian regions the percentage contribution into the yearly individual loading is higher during winter-spring (in sum 85%) period compared with summer-autumn (15%). For Norway, such contribution is the largest in spring (34%) and the lowest – in summer (18%). For Finland, it is similar during all seasons, except autumn (32%). For Sweden, the contribution is similar during winter-spring period, the largest - in autumn (41%) and the smallest - in summer (11%). Such results are also in good correspondence with dominated deposition, and especially wet deposition, patterns in the studied geographical area.

During a year, about 33% of emissions (which is equivalent to 10.4 thousand tonnes for

the mild scenario emissions) were deposited on the underlying surface. But only a part of this process occurred over populated areas, the rest took place over non-populated territories including northern seas' aquatoria. In total, only 2792 tonnes (i.e. 27%, or less than 1/3) were deposited over the populated areas of the studied countries.

For the entire population residing on the territory of the Murmansk region the yearly collective loading is 2403 tonnes. Taking into account the total population of this region (according to 2002 Census – 892534 inhabitants), an average value of such loading is about 2.7 kg/person. Among all Russian regions, the Karelia Republic and Arkhangelsk region have the second largest loadings – 83 and 77 t, respectively. For the populated territories of bordering countries with the Murmansk region, the collective loading is 140.4 t for the entire Finland (with the largest contribution of 70.6 t from the Oulu province). For Sweden, this loading is about 10.7 t with the largest contribution

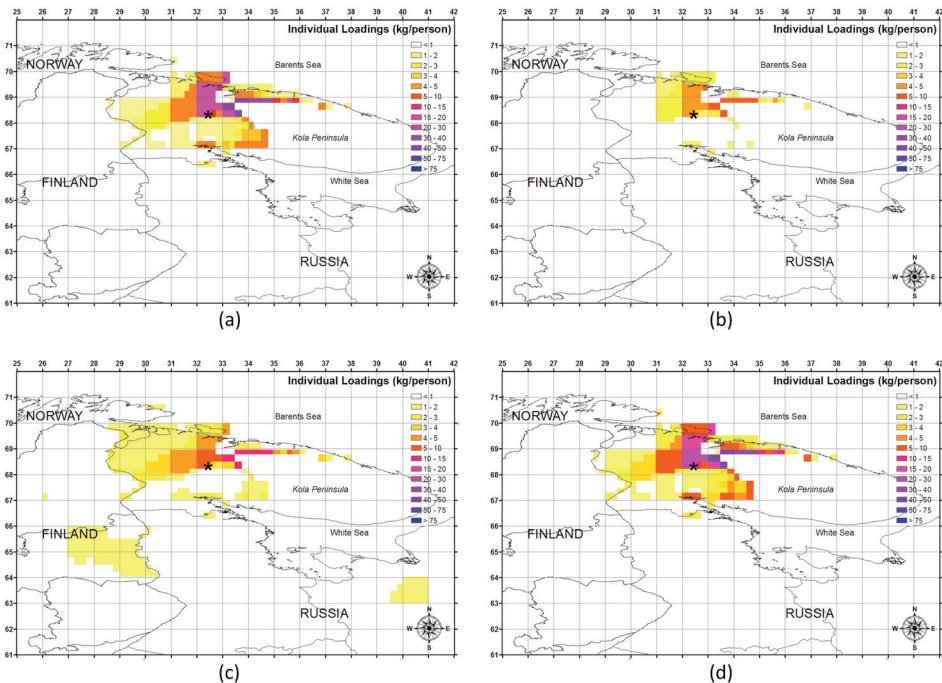


Fig. 5. Seasonal individual loadings for population (in kg/person) from deposited sulphates resulted from the Severonikel smelters continuous emissions (mild scenario; * - location of the Severonikel plant on the Kola Peninsula): (a) spring, (b) summer, (c) autumn, and (d) winter

(9.2 t or 87%) from the Norbotten county. For the northern Norway (Troms, Finnmark, and Nordland counties) it is about 13 t.

Note that the estimated magnitude of concentration and deposition patterns have limitations due to uncertainties in the modeling (based on lower horizontal resolution, boundary meteorological conditions, etc.) that would limit the magnitudes of the concentrations and deposition results. On a perspective, the online integrated meteorology-chemistry-aerosols Enviro-HIRLAM (Environment – High Resolution Limited Area Model) modelling system (Baklanov et al. 2017) in a downscaling chain (with running consequently at 15-5-2 km horizontal resolutions) is planned to be used for the domain of the North-West Russia and Scandinavian countries. Both the meteorological and atmospheric composition (including deposition patterns) at the same selected resolutions will be simulated, which will allow more in depth evaluation of loadings not only for population (associated with urban areas) but also with other ecosystems (such as

forest, soils, lakes, etc.) of the studied region in focus.

CONCLUSION

In this study, the investigation of impact on population due to continuous emissions of sulphates from the Severonikel Cu-Ni smelters (city of Monchegorsk, Murmansk region, Russia) was performed employing the Lagrangian long-range transport model DERMA in a long-term simulation mode and applying GIS tools for integrating and analysis of the dispersion modeling results.

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.

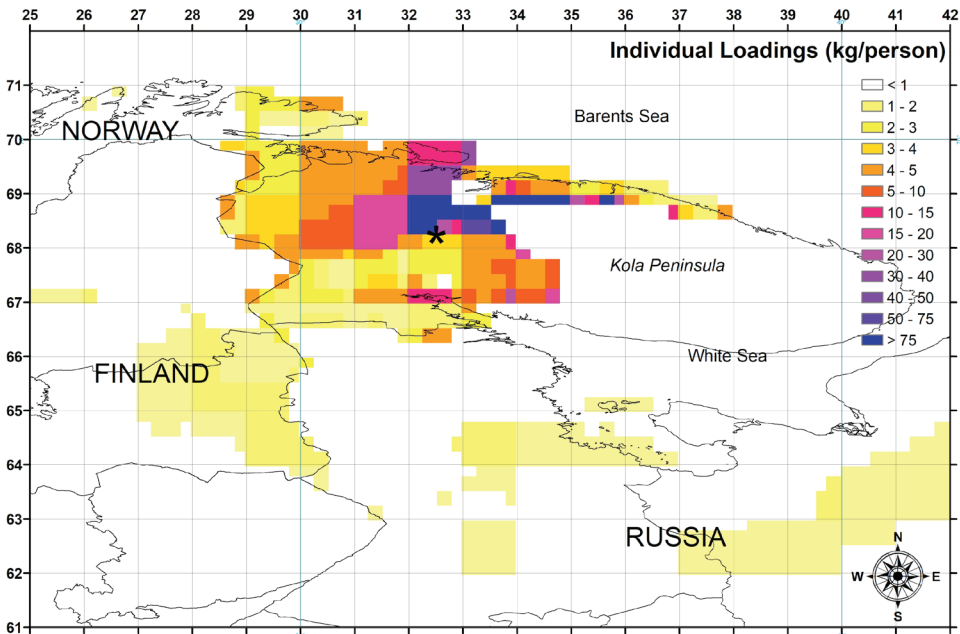


Fig. 6. Yearly individual loadings for population (in kg/person) from deposited sulphates resulted from the Severonikel smelters continuous emissions (mild scenario, * - location of the Severonikel plant on the Kola Peninsula)

The Murmansk region of Russia, 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.

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, economic, and other factors; (iii) support of decision-makers, adjustment of legislation at regional levels, control pollution exceedances; planning preventive measures, mitigation scenarios, etc.

ACKNOWLEDGEMENTS

This research received financial support from several projects including the Pan-Eurasian EXperiment (PEEX; www.atm.helsinki.fi/peex) Programme, NordForsk CRAICC-PEEX (CRyosphere-Atmosphere Interactions in a Changing Arctic Climate) and CRUCIAL-PEEX (Critical steps in understanding land surface – atmosphere interactions: from improved knowledge to socioeconomic solution) projects, and the FP6 EC Enviro-RISKS project (Enviro-RISKS - Man-induced Environmental Risks: Monitoring, Management and Remediation of Man-made Changes in Siberia; project.risks.scert.ru). The simulations were performed at CRAY-XC30 HPC supercomputer, and the ECMWF meteorological data archives were used in this study. Thanks to Drs. J.H. Sorensen (Danish Meteorological Institute, Copenhagen, Denmark) and O. Rigina (Kola Science Center, Apatity, Russia) for useful discussions. Thank you to anonymous reviewers for constructive and useful comments and suggestions to the manuscript. ■

REFERENCES

- Baklanov A. and Mahura A. (2004). Assessment of possible airborne impact from risk sites: methodology for probabilistic atmospheric studies, *Atmospheric Chemistry and Physics*, 4, pp. 485-495.
- Baklanov A. and Sørensen J. (2001). Parameterisation of radionuclide deposition in atmospheric long-range transport modelling. *Physics and Chemistry of the Earth: (B)*, 26(10), pp. 787-799.
- Baklanov A., Sørensen J., and Mahura A. (2008). Methodology for Probabilistic Atmospheric Studies using Long-Term Dispersion Modelling. *Environ. Model Assess.*, 13, pp. 541-552.
- Baklanov A., Korsholm U.S., Nuterman R., Mahura A., Nielsen K.P., Sass B.H., Rasmussen A., Zakey A., Kaas E., Kurganskiy A., Sørensen J., and González-Aparicio I. (2017). Enviro-HIRLAM online integrated meteorology–chemistry modelling system: strategy, methodology, developments and applications (v7.2), *Geosci. Model Dev.*, 10, pp. 2971-2999.
- Berglen T.F., Dauge F., Andersen E., Nilsson L.O., Svendby T.M., Tønnesen D., Vadset M. and Våler R.L. (2016). Air Quality Monitoring in the Border Areas of Norway and Russia-Progress Report April 2015–March 2016. NILU-Norsk Institut for Luftforskning; Kjeller, Norway: 2016-16. p. 112
- Blagodatskaya E.V., Pampura T.V., Bogomolova I.N., Koptsik G.N. and Lukina N.V. (2008). Effect of emissions from a Copper-Nickel Smelter on soil microbial communities in forest biogeocenoses of the Kola Peninsula. *Ecology*, 35 (2), pp. 202-210.
- Dauvalter V., Moiseenko T., and Kagan L. (2003). Global Change in Respect to Tendency to Acidification of Subarctic Mountain Lakes. *Advances in Global Change Research*, 9(2), pp. 187-194.
- Ekimov S.V., Samodova I.V., Petrov I.M., Troitsky V.V., and Burstein M.A. (2001). Russian smelter emissions, «Mining Journal», London, November 23, p 393.
- Golubeva N.I., Burtseva L.V., and Ginzburg V.A. (2010). Heavy metals in the atmospheric precipitation on the Barents Sea coast. *Russ. Meteorol. Hydrol.* 35: 333.
- González-Aparicio I., Nuterman R., Korsholm U.S., Mahura A., Acero J.A., Hidalgo J., and Baklanov A. (2010). Land-Use Database Processing Approach for Meso-Scale Urban NWP Model Initialization. DMI Scientific Report 10-02, 34 p. ISBN: 978-87-7478-593-4.
- Gutarsky M.L., Karaban R. T., and Nazarov I.M. (1997). On the Assessment of Sulphur Deposition on Forests Growing Over the Areas of Industrial Impact. *Environmental Monitoring and Assessment*, 48(2), pp. 125-137.
- Hagner O. and Rigina O. (1998). Detection of Forest Decline in Monchegorsk Area. *Remote Sensing of Environment*, 63 (1), 1998, pp. 11-23
- Hansen M. D., Nøst T. H., Heimstad E. S., Evenset A., Dudarev A.A., Rautio A., Myllynen P., Dushkina E.V., Jagodic M., Christensen G.N., Anda E.E., Brustad M. and Sandanger T.M. (2017). The Impact of a Nickel-Copper Smelter on Concentrations of Toxic Elements in Local Wild Food from the Norwegian, Finnish, and Russian Border Regions. *International Journal of Environmental Research and Public Health*, 14(7), 694.

IPCC (2001). *Aerosols, their Direct and Indirect Effects*// IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 302 p.

Karaban R. T. and M. L. Gutarsky (1995). Studies of precipitation contamination levels over the north-western forests of Russia subject to emissions from the two nickel smelters. *Water, Air, & Soil Pollution*, 85(4), pp. 2071-2076.

Lappalainen A., Tammi J. and Puro-Tahvanainen A. (2007). The effects of nickel smelters on water quality and littoral fish species composition in small watercourses in the border area of Finland, Norway and Russia. *Boreal Environ. Res.* (12), pp. 455-466.

Mahura A., Baklanov A. and Sørensen J.H. (2006a). Influence of long-range and long-term continuous and accidental anthropogenic emissions from Eurasian sources on Greenland environment. Proceedings of the International Conference «The Greenlandic Environment: Pollution and Solutions», 21-23 Feb 2006, Sisimiut in Greenland, pp. 15-22.

Mahura A., Baklanov A., Sorensen J.H. and Tridvornov A. (2006b). Long-term modelling for estimation of man-induced environmental risks. Abstracts of the European Geosciences Union (EGU) General Assembly, 2-7 April 2006, Vienna, Austria, EGU06-A-03781.

Mahura A., Baklanov A., Sørensen J.H., Svetlov A. and Koshkin V. (2007). Assessment of Long-Range Transport and Deposition from Cu-Ni Smelters of Russian North. In «Air, Water and Soil Quality Modelling for Risk and Impact Assessment», *Security Through Science, Series C - Environmental Security*. Eds. A. Ebel, T. Davitashvili, Springer Elsevier Publishers, pp. 115-124.

Mahura A., Baklanov A. and Sørensen J.H. (2008). *Enviro-RISKS: Overview of Applications for Short- and Long-Term Modelling and Assessment for Atmospheric Pollutants*. Abstracts of the International Conference on Environmental Observations, Modelling and Information Systems, ENVIROMIS-2008, 28 June – 5 July 2008, Tomsk, Russia, p.106.

Moiseenko T.I., Voinov A.A, Megorsky V.V., Gashkina N.A., Kudriavtseva L.P., Vandish O.I., Sharov A.N., Sharova Yu. and Koroleva I.N. (2006). Ecosystem and human health assessment to define environmental management strategies: The case of long-term human impacts on an Arctic lake. *Sci. Total Environ.*, 369(1-3), pp. 1-20.

Reimann C., Halleraker J.H., Kashulina G. and Bogatyrev I. (1999). Comparison of plant and precipitation chemistry in catchments with different levels of pollution on the Kola Peninsula, Russia. *Sci. Total Environ.*, 243, pp.169-191.

Sørensen J.H. (1998). Sensitivity of the DERMA long-range Gaussian dispersion model to meteorological input and diffusion parameters. *Atmospheric Environment*, 32 (24), pp. 4195-4206.

project.risks.scert.ru (2017). Official Website of the FP6 EC Enviro-RISKS project (Enviro-RISKS - Man-induced Environmental Risks: Monitoring, Management and Remediation of Man-made Changes in Siberia). [online] Available at: <http://project.risks.scert.ru/> [Accessed 11 Mar 2017].

www.atm.helsinki.fi/peex (2017). Official Website of the Pan-Eurasian EXperiment (PEEX) programme. [online] Available at: <https://www.atm.helsinki.fi/peex> [Accessed 11 Mar 2017].

www.nornickel.com (2017). Official Website of the Public Joint Stock Company "Mining and Metallurgical Company "NORILSK NICKEL" [online] Available at: www.nornickel.com [Accessed 11 Mar 2017].

www.kolagmk.ru (2017). Official Website of the Kola Mining and Metallurgical Company (Kola MMC) [online] Available at: <http://www.kolagmk.ru> [Accessed 11 Mar 2017] (in Russian).

www.gis.com (2017). Official Website of the ArcGIS geospatial processing software [online] Available at: <http://www.gis.com> [Accessed 11 Mar 2017].

gis-lab.info (2017). Website of the GIS-LAB independent online resource specializing in GIS and remote sensing [online] Available at: <http://gis-lab.info/projects/osm-export.html> [Accessed 11 Mar 2017] (in Russian).

www.diva-gis.org (2017). Website of the DIVA-GIS free computer program and data archives for mapping and geographic data analysis in GIS. [online] Available at: <http://www.diva-gis.org/Data> [Accessed 11 Mar 2017].

www.ciesin.org (2017). Website of the Center for International Earth Science Information Network with data and information products and resources [online] Available at: <http://www.ciesin.org/data.html> [Accessed 11 Mar 2017].

www.spatial ecology.com (2017). Website of the Hawth's analysis tools for ArcGIS [online] Available at: <http://www.spatial ecology.com/htools> [Accessed 11 Mar 2017].

Received on November 27th, 2017

Accepted on March 1st, 2018



Alexander Mahura, PhD (Phys&Math., Atm.Sci.), MSc (Env. Mod., Atm.Sci.), BSc. (Atm.Sci.); more than 25 years of research experience; fields of research are modelling of atmospheric processes and transport of pollutants (including radionuclides) on local-meso-regional-hemispheric scales, on-line integrated meteorology-chemistry-aerosols modelling at regional-urban scales, impact of urban areas on meteorology and atmospheric composition, atmospheric chemistry, atmospheric boundary layer processes, environmental impact and risk assessment, fine-scale road weather forecasting, birch pollen modelling, numerical weather prediction, statistics; consulting/co-advising students BSc/MSc/PhD on relevant research projects/theses; co-author of over 300 sci.-tech. publications, incl. 5 books and about 50 peer-reviewed papers.