SPECIAL PROJECT FINAL PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting Year:	Reporting period from July 2015 to December 2017
Project Title:	**EnviroAerosols on ECMWF** *(Enviro-HIRLAM/ HARMONIE model research and development for online integrated meteorology- chemistry/ aerosols feedbacks and interactions in weather and atmospheric composition forecasting)*
Computer Project Account:	SPDKSASS
Start Year - End Year :	Jul 2015 – Dec 2017
Principal Investigator(s)	Mr. Bent Hansen Sass (DMI) *Reported by Bent Hansen Sass & Alexander Mahura (University of Helsinki, UHEL)*
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Experience with the Special Project framework:

The project did not experience any problems with administrative issues such as application procedure for the proposal, preparation, submission and evaluation, annual reporting to ECMWF; access to forms and relevant documents etc.

Future plans:

As a continuation of this completed project, a new proposal Enviro-PEEX on ECMWF HPC (2018-2020)"Pan-Eurasian EXperiment (PEEX) Modelling Platform research and development for online coupled integrated meteorology-chemistry-aerosols feedbacks and interactions in weather, climate and atmospheric composition multiscale modelling" has been submitted for the evaluation procedure. The proposal is coordinated by Dr. Alexander Mahura (University of Helsinki, Finland).

Summary of project objectives

The overall objectives are to analyse the importance of the meteorology-chemistry/aerosols interactions and to provide a way for development of efficient techniques for on-line coupling of numerical weather prediction and atmospheric chemical transport via process-oriented parameterizations and feedback algorithms, which will improve both the numerical weather prediction and atmospheric composition forecasts.
Two main application areas of the on-line integrated modelling are considered: (i) improved numerical weather prediction with short-term feedbacks of aerosols and chemistry on formation and development of meteorological variables, and (ii) improved atmospheric composition forecasting with on-line integrated meteorological forecast and two-way feedbacks between aerosols/chemistry and meteorology. Modelling systems: Enviro-HIRLAM/HARMONIE

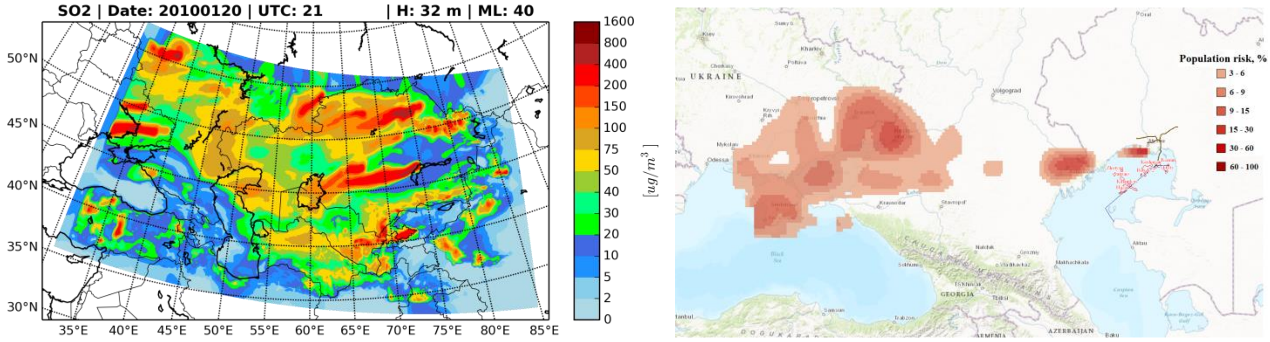
Summary of problems encountered (if any)

no problems observed

Summary of project results (from July 2015 to December 2017)

Based on recent Enviro-HIRLAM/HARMONIE (the latest overview of the model is given by *Baklanov et al., 2017*) scientific developments and working plan the following topics important for operational numerical weather prediction and atmospheric composition forecasting, were investigated with a close collaboration with the Universities and research organizations during the the project realisation 2015-2017 (note that summaries of the 1st and 2nd year reporting periods were presented in *Sass et al., 2016 & 2017:*
Jul 2015 – Jun 2016 --- https://www.ecmwf.int/sites/default/files/special_projects/2015/spdksass-2015-report2.pdf
Jul 2016 – Jun 2017 --- https://www.ecmwf.int/sites/default/files/special_projects/2015/spdksass-2015-report3.pdf)
of the Special Project:

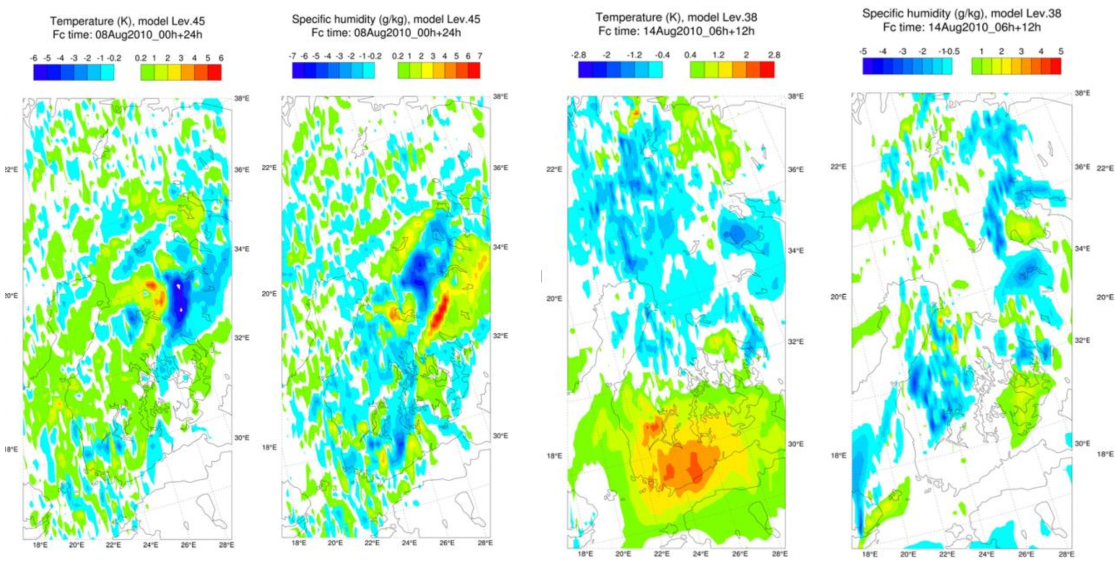
1. Study "On-line Meteorology-Chemistry/Aerosols Modelling and Integration for Risk Assessment: Case Studies". On regional level, and especially in areas with potential diverse sources of industrial pollutants, the risk assessment of impact on environment and population is critically important. During normal operations, the risk is minimal. However, during accidental situations, the risk is increased due to releases of harmful pollutants into different environments such as water, soil, and atmosphere where it is following processes of continuous transformation and transport. In study by *Bostanbekov et al. (2015, 2016)* the Enviro-HIRLAM model was adapted and employed for assessment of scenarios with accidental and continuous emissions of sulphur dioxide for selected case studies during January of 2010 (Fig. 1a). The following scenarios were considered: (i) control reference run; (ii) accidental release (due to short-term 1 day fire at oil storage facility) occurred at city of Atyrau (Kazakhstan) near the northern part of the Caspian Sea; and (iii) doubling of original continuous emissions from three locations of metallurgical enterprises on the Kola Peninsula (Russia). The implemented aerosol microphysics module M7 uses 5 types – sulphates, sea salt, dust, black and organic carbon; as well as distributed in 7 size modes. Removal processes of aerosols include gravitational settling and wet deposition. As the Enviro-HIRLAM model is the on-line integrated model, both meteorological and chemical processes are simultaneously modelled at each time step. The modelled spatio-temporal variations for meteorological and chemical patterns were analyzed for both European and Kazakhstan regions domains. The results of evaluation of sulphur dioxide concentration and deposition on main populated cities, selected regions, countries were analyzed with GIS tools (Fig. 1b). And finally, the modelling results for accidental release near the Caspian Sea were integrated into the RANDOM (Risk Assessment of Nature Detriment due to Oil spill Migration) system.



(a) (b)

Figure 1: (a) Example of Enviro-HIRLAM modelled (for 20 Jan 2010, 21 UTC) sulphur dioxide concentration fields over domain with focus on Kazakhstan; and (b) Results of GIS integration of modelled results and estimation of risks for population resulted from accidental release from oil refinery at city of Atyrau (Kazakhstan).

2. Studies "The sensitivity of precipitation simulations to the soot aerosol presence" & "The precipitation forecast sensitivity to data assimilation on a very high resolution domain". The role of aerosols in non-linear feedbacks on atmospheric processes is important, and in particularly, the importance of black carbon particles for evolution of physical weather including precipitation formation and release. In study by *Palamarchuk et al. (2015, 2016a)*, the HARMONIE-38h1.2 model with the AROME physics package was used to study changes in precipitation life-cycle under black carbon polluted conditions. A model configuration includes a radar data assimilation procedure on a high resolution domain covering the Scandinavia region. Model results showed that precipitation rate and distribution as well as other variables of atmospheric dynamics and physics are sensitive to aerosol concentrations (Fig.2a). The attention should also be paid to numerical aspects, such as a list of observation types involved in assimilation. The use of high resolution radar information allows to include mesoscale features in initial conditions and to decrease the growth rate of a model error with the lead time.

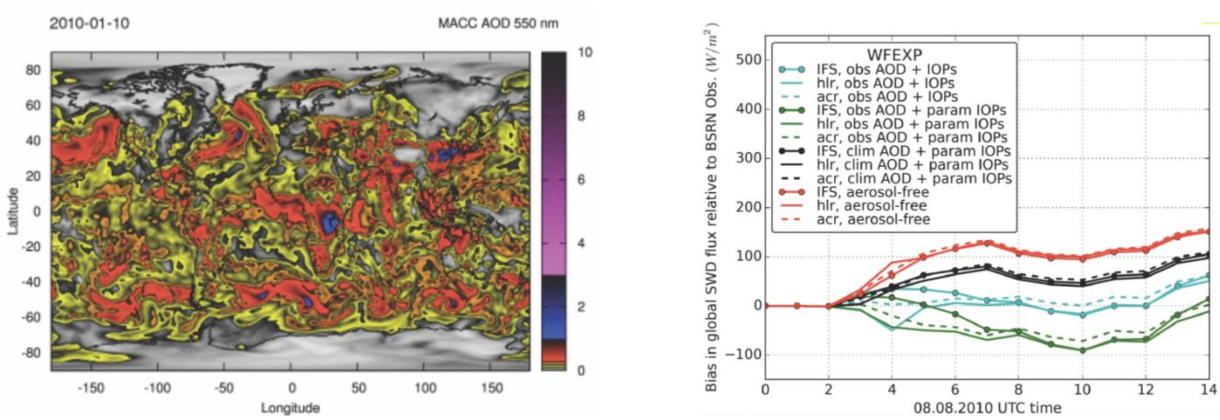


(a) (b) (c) (d)

Figure 2: Results of the HARMONIE model experiments with simulated differences (ab – with/without soot & cd – with/without data assimilation) fields for (ac) air temperature and (bd) specific humidity on (ab) 9 Aug 2010, 00 UTC and (cd) 14 Aug 2010, 18 UTC at about height /model level/ of (ab) 1 km /lev 45/ and (cd) 2 km /lev 38/.

Moreover, recent developments in computing technologies allow implementation of a very high resolution in NWP models which is crucially important in studies of precipitation including their life-cycle. New opportunities generate prerequisites to revise existing knowledge both in meteorology and numerics, and in particular, with formulation of initial conditions involving data assimilation (DA). Depending on applied techniques, observational data types and spatial resolution the precipitation prediction appears quite sensitive. In study by *Palamarchuk et al. (2016b)*, the impact of data assimilation on resulting fields is analysed using the HARMONIE-38h1.2 model with the AROME physics package. The numerical experiments were performed for the Nordic domain (with focus on Finland) with horizontal resolution of 2.5 km and 65 vertical levels for selected period in Aug 2010 (covering the BaltRad experiment). The initial conditions formulation included downscaling from the MARS archive and involving observations through 3DVAR data assimilation. The treatment of both conventional and radar observations in numerical experiments was used. The background error covariances required for the variational assimilation have already been computed from the ensemble perturbed analysis with the purely statistical balance. Deviations among the model runs started from the MARS, conventional and radar DA were complex (Fig.2b). The contribution from observed variables included in the control vector, such as humidity and temperature, was expected to be largest, but nevertheless, revealing of such impact is not so straightforward task. Major changes occur within the lower 3-km layer of the atmosphere for all predicted variables. However, those changes were not directly associated with observation locations, as it often shows single observation experiments. Moreover, the model response to observations with lead time produces weak mesoscale spots of opposite signs. Special attention was paid to precipitation, cloud and rain water, vertical velocity fields. A complex chain of interactions among radiation, temperature, humidity, stratification and other atmospheric characteristics resulted in changes of local updraft and downdraft flows and following cloud formation processes and precipitation release. One can assume that those features would arise due to both, atmospheric physics and numeric effects; the latter becomes more evident in simulations on very high resolution.

3. Study "Aerosol effects over China investigated with a high resolution convection permitting weather model". In study by *Nielsen et al. (2016)*, the aerosol effects was investigated in the operational high resolution (2.5 km) convection permitting non-hydrostatical weather model HARMONIE. Aerosol input from the global C-IFS model was downscaled and used (Fig. 3a). The impact of using realistic aerosols on both the direct and the indirect aerosol effects is studied and compared with default simulations that include only the direct aerosol effect of climatological aerosols. The study is performed for a selected region of China during months January and July 2010, where in particular January 2010 was characterized by several cases of high anthropogenic aerosol loads. The impact of accounting for realistic aerosol single scattering albedos and asymmetry factors in the simulations of the direct aerosol forcing was also investigated. In many studies only variations in the aerosol optical depth are accounted for. It is shown that this is to be inadequate, when the assumed aerosol types have different optical properties than the actual aerosols.



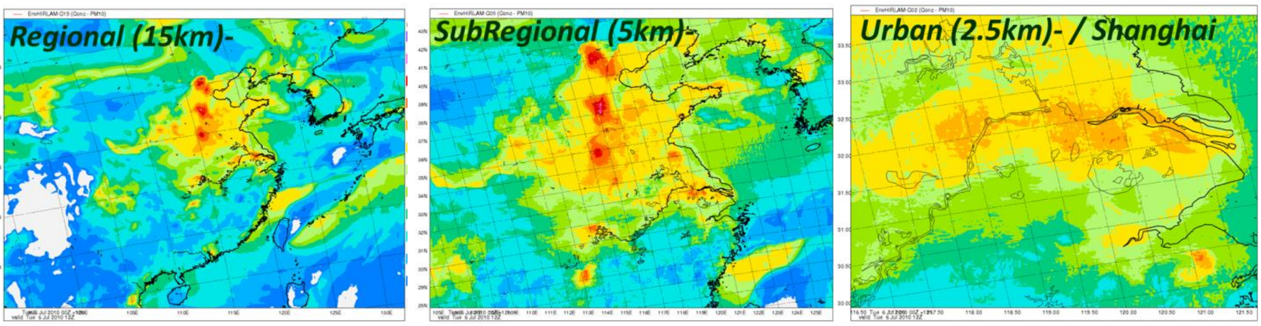
(a) (b)

Figure 3: Aerosol optical depth - AOD (a) at 550 nm from the MACC reanalysis data set from 1 Jan 2010; and (b) scaling sensitivity test results for HARMONIE /importance of the AOD scaling is just as large as getting the AOD at 550 nm right/.

4. Study "Effects of aerosols on clear-sky solar radiation in the ALADIN-HIRLAM NWP system". In study by *Gleeson et al. (2016)*, the direct shortwave radiative effect of aerosols under clear-sky conditions in the Aire Limitee Adaptation dynamique Developpement InterNational (ALADIN) –HIRLAM NWP system was investigated using three shortwave radiation schemes in diagnostic single-column experiments: the Integrated Forecast System (IFS), acraneb2 and the hlradia radiation schemes (the latter two are broadband schemes) (Fig.3b). The strengths and weaknesses of NWP system regarding aerosols were evaluated for use of real-time aerosol information. The experiments were run with focus on the Russian wildfires (Aug 2010). Each of 3 schemes accurately (within ±4 % at midday) simulated the direct shortwave aerosol effect when observed aerosol optical properties are used. When the aerosols were excluded from the simulations, errors of more than +15 % in global shortwave irradiance were found at midday, with the error reduced to +10 % when standard climatological aerosols were used. An error of −11 % was seen at midday if only observed aerosol optical depths at 550 nm, and not observation-based spectral dependence of aerosol optical depth, single scattering albedos and asymmetry factors, were included in the simulations. This demonstrates the importance of using the correct aerosol optical properties. The dependency of the direct radiative effect of aerosols on relative humidity was tested and shown to be within ±6 % in this case. By modifying the assumptions about the shape of the IFS climatological vertical aerosol profile, the inherent uncertainties associated with assuming fixed vertical profiles were investigated. The shortwave heating rates in the boundary layer changed by up to a factor of 2 in response to the aerosol vertical distribution without changing the total aerosol optical depth. Finally, we tested the radiative transfer approximations used in the three radiation schemes for typical aerosol optical properties compared to the accurate DISORT model. These approximations are found to be accurate to within ±13 % even for large aerosol loads.

5. Study "Impacts of the direct radiative effect of aerosols in numerical weather prediction over Europe using the ALADIN-HIRLAM NWP system". In study by *Toll et al. (2016),* the aerosol feedbacks were included in NWP in order to improve the accuracy of weather forecasts. The default set-up in the ALADIN-HIRLAM NWP system included monthly aerosol climatologies to account for the average direct radiative effect of aerosols. This effect was studied using the default aerosol climatology in the system and compared to experiments run using the more up-to-date Max-Planck-Institute Aerosol Climatology version 1 (MACv1), and time-varying aerosol data from the Monitoring Atmospheric Composition and Climate (MACC) reanalysis aerosol dataset. Accounting for the direct radiative effect using monthly aerosol climatologies or near real-time aerosol distributions improved the accuracy of the simulated radiative fluxes and temperature and humidity forecasts in the lower troposphere. However, the dependency of forecast meteorological conditions on aerosol dataset itself was found to be weak.

6. Study "Meteorological and chemical urban scale modelling for Shanghai metropolitan area". Urban air pollution is a serious problem in megacities and major industrial agglomerations of China. Therefore, air quality information is important for public. In study by *Mahura et al. (2016),* in particular, the Shanghai metropolitan area was studied as well-known megacity having severe air pollution episodes. The Enviro-HIRLAM model was applied for on-line integrated meteorology and atmospheric composition forecasting for this region of China. The model setup includes the urban Building Effects Parameterization module, describing different types of urban districts with its own morphological and aerodynamical characteristics. The model is running in downscaling chain from regional-subregional-urban scales (Fig. 4 a-b-c) for selected periods in summer and winter of 2010 having both elevated pollution levels as well as unfavorable meteorological conditions. For these periods, the effects of urbanization are analyzed for spatio-temporal variability of atmospheric and chemical/ aerosols patterns. The formation and development of meteorological (air and surface temperature, relative humidity, wind speed, cloud cover, boundary layer height) and chemical/aerosol patterns (concentration and deposition) due to influence of the metropolitan area was evaluated. The impact of Shanghai region on regional-to-urban scales as well as relationship between air pollution and meteorology was estimated.



(a) (b) (c)

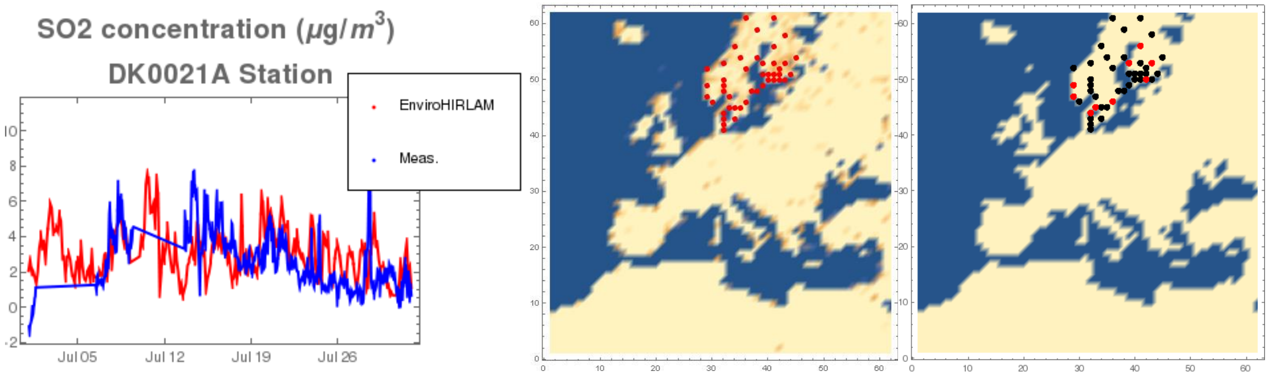
Figure 4: Example of Enviro-HIRLAM modelled PM10 concentration fields on 6 Jul 2010, 12 UTC for the downscaling chain at (a) regional - 15 km, (b) sub-regional - 5 km and (c) urban - 2.5 km resolution scales.

7. Study "Direct variational data assimilation algorithm for atmospheric chemistry data with transport and transformation model". Results of numerical experiments with chemical data assimilation algorithm of in situ concentration measurements on real data scenario are presented in studies by *Penenko et al. (2015ab).* The algorithm is based on the variational approach and splitting scheme. This allows avoiding iterative direct problems solution for transport and transformation model and the algorithm becomes a "real-time algorithm". In order to construct test scenario, meteorological data has been taken from Enviro-HIRLAM model output, initial conditions from MOZART model output and measurements from Airbase database.

Following classes of problems associated to the inverse modeling were considered: (i) Direct problems: system's behavior has to be forecasted and studied with a mathematical model and prescribed parameters; (ii) Inverse problems: model parameters must be adjusted to fit model forecasts to the corresponding measurement data. It may take to solve series of direct problems with various model parameters; and (iii) Data assimilation problems: a forecast has to be improved (on-line) by adjusting model parameters with incoming measurement data; it may take to solve series of inverse problems with various measurement data.

To construct a data assimilation algorithm, the following features were taken into account: (i) atmospheric composition is being changed rapidly, therefore current and future system state is of interest; (ii) stiff chemical kinetics equations (different time scales), various chemical mechanisms and their nonlinear behavior; (iii) uncertainties are not only in initial conditions but also in model coefficients (reaction rates) and in emission rates; (iv) high dimensionality ($\approx 10^7$) of modern atmospheric chemistry transport models due to high number of spatial variables and different species, imposes requirements to the computational performance; (v) relatively small number of chemical species in a small number of spatial points can be measured; (vi) data assimilation algorithms must be embedded in existing models; and (vii) multidisciplinary nature of the study.

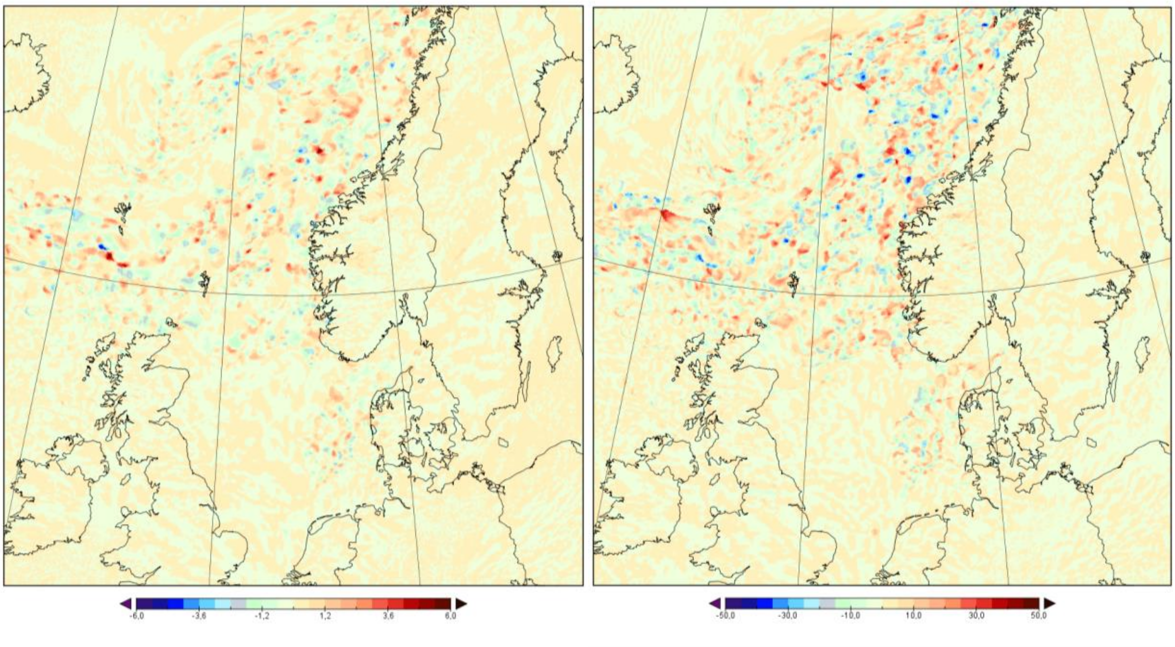
Combination of splitting and data assimilation schemes let us construct computationally effective algorithms for data assimilation of in situ measurements to convection-diffusion models. A complete data assimilation scenario has been compiled with meteorological data from Enviro-HIRLAM model, initial concentration data from MOZART model and in situ measurement data from Airbase (Fig. 5 a-b-c). We carried out series of numerical experiments in which we tested DA algorithms on different divisions of measurement data into assimilated and reference datasets. Data assimilation was able to improve modeling results with imperfect (approximate) models and model parameters. The advantage of data assimilation algorithm that includes chemical transformations was identified for ozone concentrations modeling. Among the future steps to improve data assimilation results we can identify: (i) inclusion of more realistic boundary conditions is required; (ii) additional tuning is essential for coefficients of chemical reactions; (iii) quality control of chemical data measurements at stations is recommended for excluding of "extreme" data; (iv) revision of implementation procedure/steps for chemical model is required; (v) additional evaluation of monthly and seasonal variability is needed.



(a) (b) (c)

Figure 5: (a) Example of Enviro-HIRLAM modelled vs. observation (at DK0021A station) time series for Jul 2010; (bc) Assimilated measurement sites locations (black dots) and reference measurement sites locations (red dots).

8. Study "Aerosol influence on High Resolution NWP HARMONIE Operational Forecasts". The main aim of *Edvardsson (2016)* study was to investigate the impact of sea salt aerosols on numerical weather prediction during low precipitation events. Two dates (also referred to as cases), one in winter (7 Dec 2014) and one in summer (31 May 2015) were selected. For the two cases, the HARMONIE NWP model was configured at the ECMWF HPC for a domain covering the northern European area. Model runs were made (for the full day with 6 hour spin-up) with and without sea salt aerosols. The modelling results were evaluated for changes in short wave solar radiation, air temperature and relative humidity on a diurnal cycle at the surface and at selected vertical levels within the atmosphere.

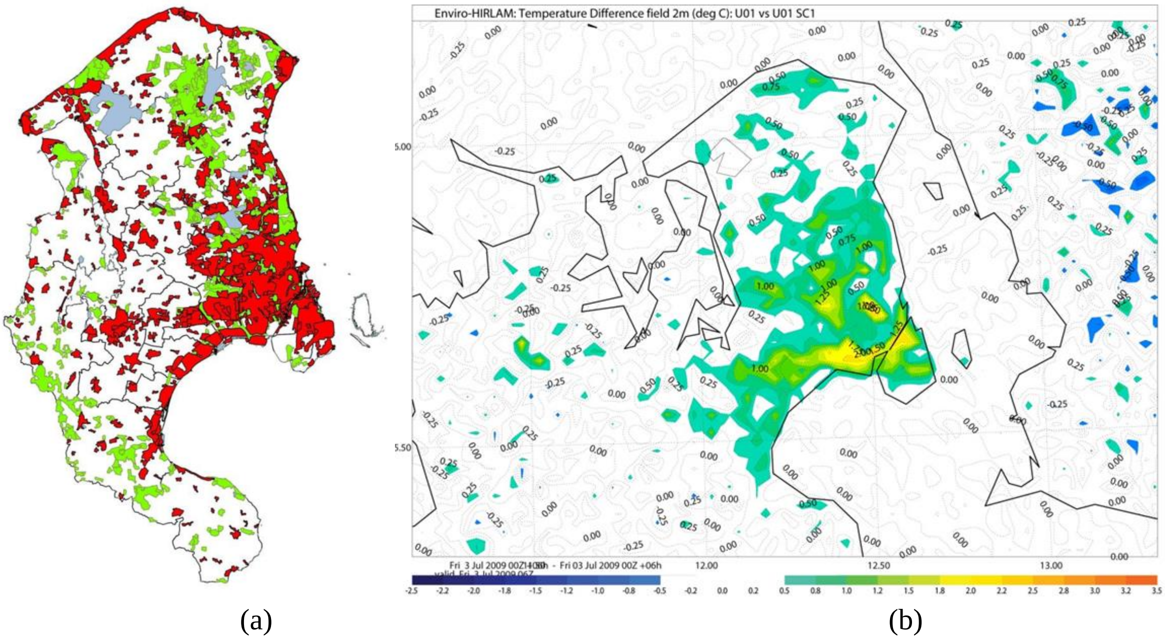


(a) (b)

Figure 6: Winter case study: example of HARMONIE modelled difference (control vs. sea salt aerosols excluded) fields for (a) air temperature (deg C) and (b) relative humidity (%) at 2m on 7 Dec 2014, 12 UTC.

In summary, variability in sea salt aerosol impact over the model domain was found for all meteorological parameters during both cases. In winter, the impact mainly occurred over sea-ocean areas, where the low pressure system was located. In the summer case, two low pressure systems were located in the area of study, one over the sea-ocean area and one over land, and the impact occurred in these two regions. The impact on air temperature in levels of the atmosphere was found to be the strongest in the PBL and the impact on relative humidity was found to be strongest at the levels of 850-500 hPa. The impact on air temperature and relative humidity was stronger during the winter case than in the summer case. Low pressure systems tend to be deeper in the winter compared to the summer. Deeper low pressure systems leads to higher wind speeds, causing more sea salt aerosols to be produced which is the reason for a stronger impact on air temperature and relative humidity during winter. Regarding short wave radiation flux, the impact was found to be stronger in the summer. The few hours of sunlight during winter is the reason for a lower impact on short wave radiation flux during winter compared with summer. This study showed importance of sea salt aerosol inclusion in numerical weather prediction. These aerosols are important for precipitation formation in both winter and summer conditions.

9. Study "Impact of regional afforestation on climatic conditions in metropolitan areas: case study of Copenhagen". As European metropolitan areas will face a range of climate–related challenges over the next decades that may influence the nature of urban life across the continent, under future urbanization and climate change scenarios the well-being and comfort of the urban population might become progressively compromised. In urban areas, the effects of climate change will be accelerated by a combination of urban heat island (UHI) effect and extreme heat waves. The land cover composition will be playing an important role in modulating local and regional climatic conditions, and to be vital factor in the process of adapting cities to warming climate. In study by *Stysiak (2015) & Stysiak et al. (2015, 2016)* the impact of forest and land-cover change on formation and development of temperature regimes in the Copenhagen Metropolitan Area (CPH-MA, Denmark) was studied. Potential to modify the UHI effect in CPH-MA was estimated. Using 3D meteorological data and up-to-date 2012 high resolution land-cover CORINE dataset, the Enviro-HIRLAM model was run to simulate air temperature at 2 meter for a selected period in July 2009. The influence of different afforestation (Fig. 7a) and urbanization scenarios (with new forests being placed following the Danish national afforestation plan, proximity to the city center, dominating wind characteristics, and urbanization taking place as densification of the existing conurbation) was investigated. It was found that temperature difference (Fig. 7b) can be up to 3.25°C (for extreme urbanization scenario), and decrease in spatial extent of temperature fields up to 68%, depending on selected scenario. Performed simulations demonstrated that well-positioned and well-sized afforestation at the regional scale can significantly affect the spatial distribution, structure and intensity of the air temperature field. This study points to vegetation having practical applications in urban and regional planning for modifying local climatic conditions.

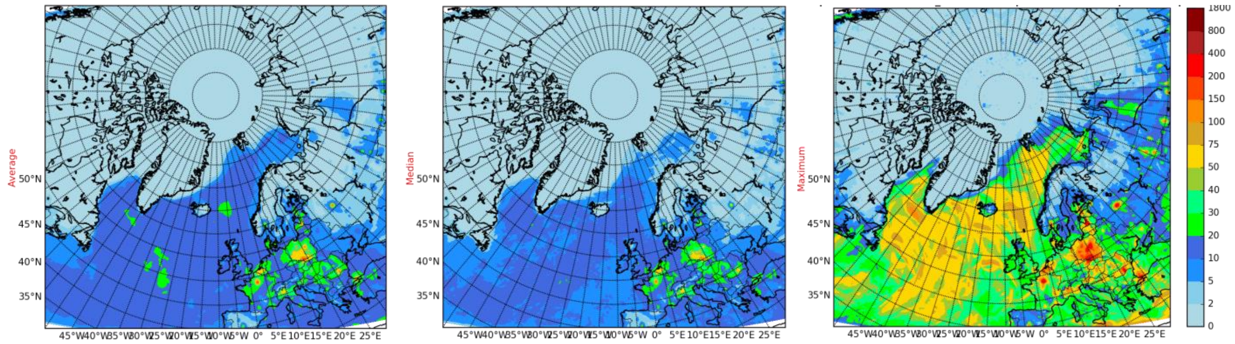


(a) (b)

Figure 7: (a) Spatial representation of the Copenhagen Metropolitan Area and surroundings (baseline scenario: red – urban, light green – forest, blue - water bodies) on a Zealand Island of Denmark; and (b) Enviro-HIRLAM modelled difference in air temperature field at 2m (°C) for 3rd of July 2009 at 06 UTC for the baseline scenario.

10. Study "Spatio-temporal variability of aerosols in the Arctic and boreal regions".

Aerosols have influence on weather, air quality and climate. Multi-scale modelling, and especially long-range atmospheric transport, dispersion, and deposition of aerosols from remote sources is especially challenging in northern latitudes. It is due to complexity of meteorological, chemical and biological processes, their interactions and especially within and above the surface layer, linking to climate change, and influence on ecosystems. The online integrated meteorology-chemistry-aerosols model Enviro-HIRLAM (Environment – High Resolution Limited Area Model) was employed. The model setup covers domain having 510 x 568 grids of latitude vs. longitude, horizontal resolution of 0.15 deg (appx 15 km), 40 vertical hybrid levels, time step of 360 sec, 6 h meteorological surface data assimilation. In particular, the focus was on studying spatio-temporal distribution of the concentration and deposition patterns of the particular matter (PM2.5 and PM10) for the winter and summer months (an example is shown in Figure 8). The model was employed in 4 modes: the reference run (e.g. without aerosols influence on meteorology) and 3 modified runs (direct aerosol effect (DAE), indirect aerosol effect (IDAE), and both effects DAE and IDAE included). The differences between the reference run and the runs with mentioned aerosol effects are statistically estimated on a day-by-day, monthly and diurnal cycle bases over the domain (*Mahura et al., 2017ab*).



(a) *(b)* *(c)*

***Figure 8**: Spatio-temporal distribution of the PM2.5 concentration field at 12 UTC - (a) average, (b) median, and (c) maximum for the Enviro-HILRAM long-term run for the month of January 2010 / at the 1st model level, 32 m/.*

11. Study "Aerosols regional influence in North-West Russia"

In 21st century, the industrial development has reached the higher levels. In particular, almost all cities of Russia have own industrial enterprises. These produce large amounts of anthropogenic emissions. For megacities, there are several sources of such emission such as transport, energy and heating production from combustion, etc. St. Petersburg is one of such megacities. In this study the evaluation of pollutants influence (on example of the North-West Russia /NWRu/ as well as St. Petersburg megacity) has been realized through the online integrated modelling (employing the Enviro-HIRLAM model) of aerosols influence on regional and megacity scales and analysis of their influence on meteorological patterns, For NWRu region in focus, for episode 10-12 Jul 2010 and summer month of August 2010, four runs of the model were performed: CTRL (or control/ reference run, e.g. without any aerosols effects included), DAE (direct aerosols effects), IDAE (indirect aerosols effects) and DAE+IDAE (combined effects of both direct and indirect aerosols effects included). The analysis focused on evaluation of influence on key meteorological parameters such as air temperature at 2 m (T2m) and total cloud cover (TCC) (*Nerobelov, 2017; Nerobelov et al., 2017*). As an example, the monthly averaged T2m and TCC for the studied region as well as difference fields between the reference and direct/ indirect aerosol effects for the Enviro-HIRLAM model runs are shown in Figures 9-10.

For IDAE, for the short-term episode, on average, the TCC had changed by increasing up to 10-20% on a regional outlook. For the St. Petersburg megacity such change was about 3-6%. For the August 2010, this change was about 6-9% (with local maxima up to 20%) over NWRu in focus. For T2m, such aerosol effect was not well seen. In general, the IDAE led to changes of 0.4-1°C on regional scale in the northern and south-eastern territories of NWRu, and up to 1.2°C for the megacity. For DAE, the influence had the opposite effect than the IDAE for the case study. On regional scale, the TCC had reduced by 10-20%, as well as decreased on the boundaries of the megacity and surroundings. For August, the change was small in general, although in the western territories of NWRu it was showing a decrease up to 12%. For T2m, the DAE effect was more visible and stronger. It has been reflected in decrease of temperature by 2-3°C (for case study with unfavorable conditions) and by 2-2.5°C (for August). The combined effect (DAE+IDAE) for the case study, showed more influence on a regional scale, and the area of its influence is clearly depends on merging and overlapping areas of independent influence of indirect and direct effects, where changes are observed over larger size territories and the value of such changes became also larger by magnitude.

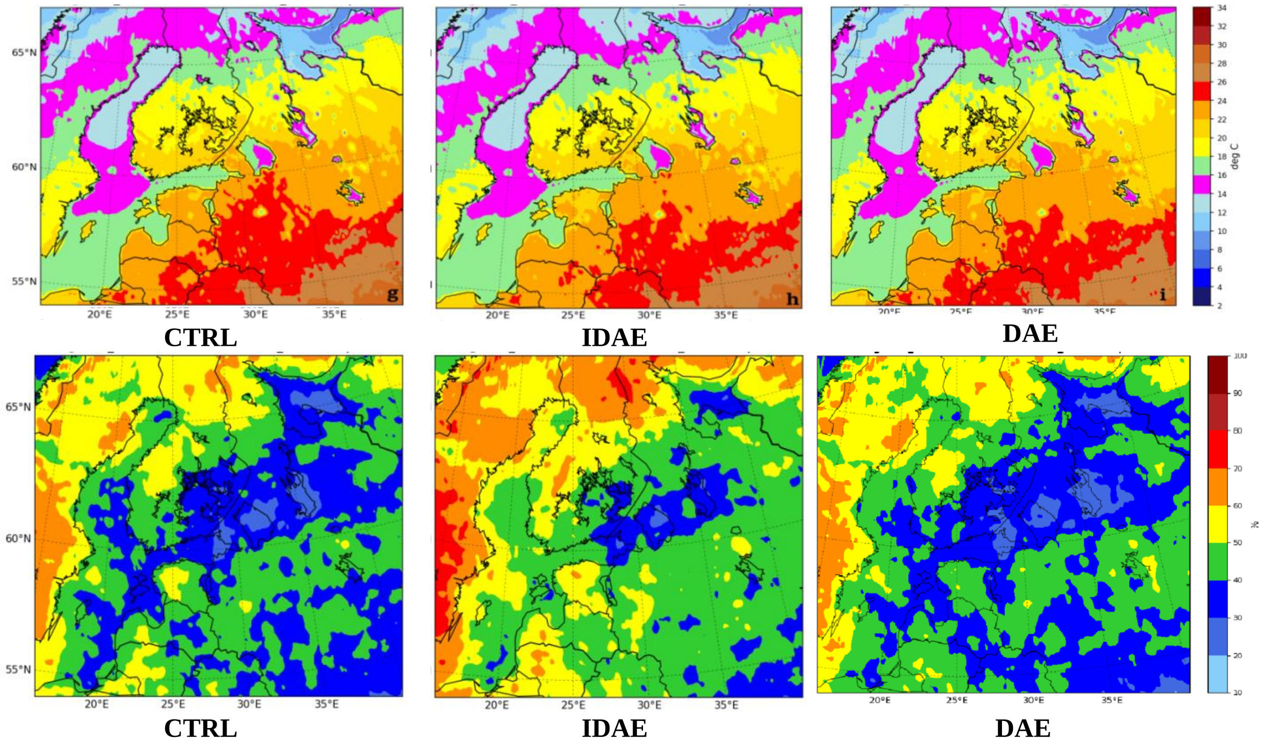
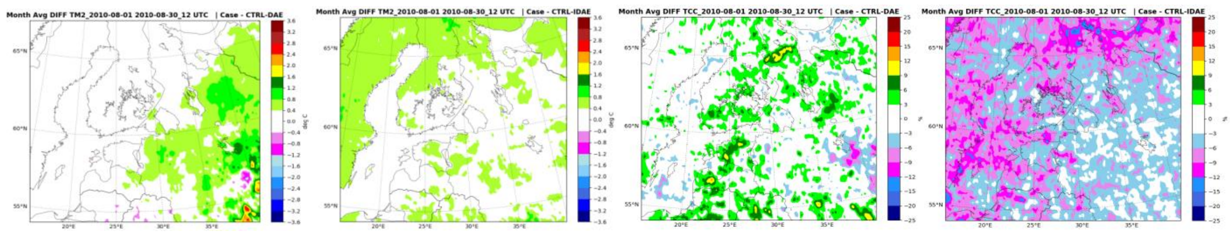


Figure 9: *Monthly averaged (at 12 UTC) (top) air temperature and (bottom) total cloud cover fields for - (left) CTRL, (middle) IDAE, and (right) DAE - Enviro-HIRLAM model runs.*



(a) *(b)* *(c)* *(d)*

Figure 10: *Difference fields (at 12 UTC) for monthly averaged air temperature (a,b) and total cloud cover (cd) for the Enviro-HIRLAM model runs (a,c) CTRL vs. DAE and (b,d) CTRL vs. IDAE over 30 day period (1-30 Aug 2010).*

12. Study “Atmospheric transport and deposition patterns of sulphates on the Kola Peninsula”

The Kola Peninsula (Murmansk region, Russia) has several sources of continuous emissions. Among such sources are the enterprises “Severonickel” (city of Monchegorsk) and “Pechenganickel” (cities of Nickel and Zapolayrnyy). These emit substantial amounts of sulphur dioxide (SO_2) and other chemical species, which are transported though the atmosphere, dispersed, and deposited on underlying surface. This study has been realized through Enviro-HIRLAM modelling and GIS evaluation of SO_2 pollution over the Kola Peninsula for episode 22-24 Jan 2010 and month of January 2010. For that, only the reference run was performed, and the analysis focused on evaluation of atmospheric concentration and deposition patterns for SO_2. For this study, the Enviro-HIRLAM modeling results (concentration and deposition fields) were also integrated into the GIS environment (using QuantumGIS) for further planned analysis of potential impact on environment and population (*Sedeeva, 2017; Nerobelov et al., 2017*). The spatio-temporal distribution of the averaged concentration and deposition patterns is shown on examples in Figure 11: for the episode and January 2010.

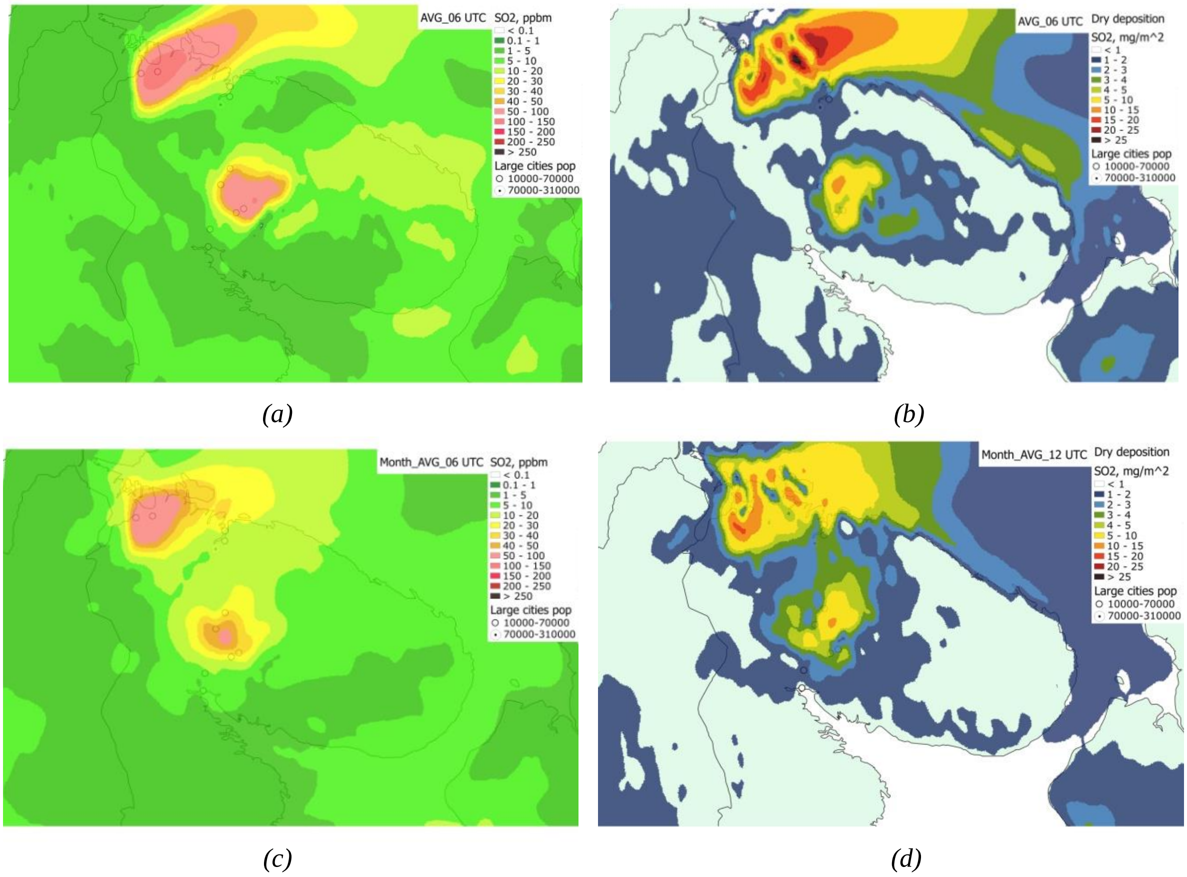


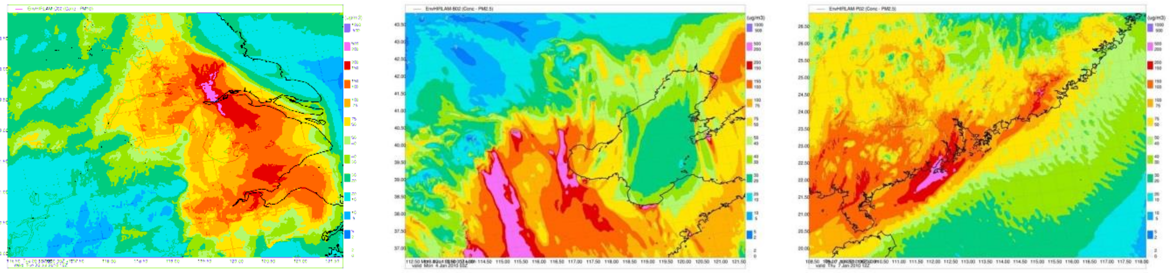
Figure 11*: Examples of the spatio-temporal distribution of SO2 averaged (a,c) concentrations and (b,d) deposition patterns for the (ab) case study/ episode 22-24 Jan 2010 and (cd) full month of January 2010.*

Analysis of short-term episode with unfavorable meteorological and air pollution conditions showed that averaged concentration of SO_2 was about 141 and 89 ppbm for the Nickel-Zapolayrnyy and Apatity-Kirovsk settlements (populated areas), respectively. The maximum on a diurnal cycle was observed at 12 UTC (15 pm of local time). The dry deposition were about 21 and 14 ug/m^2 for the first and the second areas mentioned above, respectively, with elevated values during the daytime. For Jan 2010, the daily averaged concentration was about 100 and 55 ppbm for the Nickel-Zapolayrnyy and Apatity-Kirovsk (cities located to S-E from the "Severonickel" smelters) settlements, respectively. The deposition was higher during 06-18 UTCs period, and it was higher for the first area compared with the second: 87 vs. 50 mg/m^2).

13. Study "Enviro-HIRLAM downscaling to metropolitan areas"

The most serious air pollution events occur in cities where there is a combination of high population density and air pollution. The pollutants can lead to serious human health problems. Due to constantly increasing supercomputer power modern nested numerical meteorological and air pollution models realize model nesting/down-scaling from the global to urban scale and approach the necessary horizontal and vertical resolutions to provide weather and atmospheric composition forecasts for urban scales. It will bring strong support for continuous improvement of the forecast modelling systems for weather and air quality worldwide, and underline clear perspectives for future multi-scale air quality core-downstream services for end-users.

In studies by *Mahura et al. (2017cd)*, the evaluation of formation and development of meteorological and chemical/aerosol patterns due to influence of the metropolitan areas is performed employing the urbanized version of the Enviro-HIRLAM. For urbanization of this model, several options are used such as modifications of the anthropogenic heat flux and roughness, building effects parameterisation (BEP), modified soil model for urban areas having improved urban heat and water budgets, and others. In particular, the BEP module was implemented in the model and used in several studies with a focus on metropolitan areas. The downscaling approach is useful for both research and operational forecasting tasks. In particular, originally, the model is running at a low resolution, and then the same model (but with urbanization included) is running at the finer scale (using generated 3D fields from the outer model runs). The model is run at regional, sub-regional and urban scale (at resolutions of 15, 5, and 2.5 km). Examples of Enviro-HIRLAM runs at the urban scale for selected Chinese metropolitan areas are shown in Figure 12.



(a) *(b)* *(c)*

Figure 12: *Examples of Enviro-HILRAM urban scale forecast for atmospheric composition (PM10 and PM2.5) to selected metropolitan areas of (a) Shanghai, (b) Beijing, and (c) Perl River Delta of China.*

Finer scale resolution modelling allows to simulate influence of metropolitan areas on both meteorological and chemical patterns: (i) on meteorology - these effects are more visible at low wind conditions and above/ closer downwind distances to urban areas; (ii) on chemistry - higher concentrations of maxima at finer resolutions and more complex non-homogeneous structure of pollutant plumes are both observed. The effects of urbanization are important for atmospheric transport, dispersion, deposition, and chemical transformations, in addition to better quality emission inventories (in especially, within the urban areas). Such forecasting is important for metropolitan areas, where formation and development of meteorological and chemical/aerosol patterns are especially complex. It also provides information for evaluation impact on selected megacities as well as for investigation relationship between air pollution and meteorology on urban scales. Tested downscaling modelling system for regional-meso-urban scales can be applied for advanced planning safety measures, post-accidental analysis and health/environment impact assessment, and operational forecasting and emergency preparedness, and others.

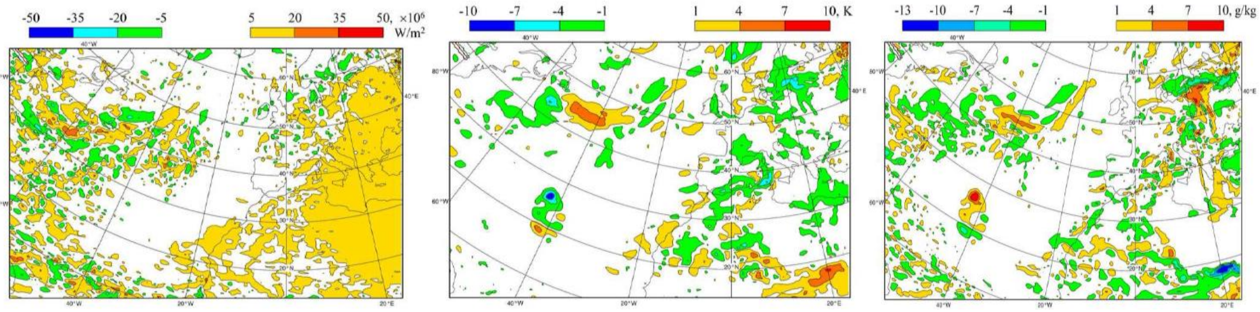
14. Study "Influence of aerosols on atmospheric variables in the HARMONIE model"

The mesoscale HARMONIE model is used to investigate the potential influence of aerosols on weather forecasts (*Palamarchuk et al., 2017*). The study considers three numerical experiments over the Atlantic - Europe - Northern Africa region during 11-16 August 2010 with the following configurations: (a) no aerosols, (b) only the sea aerosols, and (c) the four types of the aerosols: sea, land, organic, dust aerosols. The spatio-temporal analysis of forecast differences highlights the impact of aerosols on the prediction of main meteorological variables such as air temperature, humidity, precipitation, and cloud cover as well as their vertical profiles. The variations occur through changes in radiation fluxes and microphysics properties. The sensitivity experiments with the inclusion of climatological aerosol concentrations demonstrate the importance of aerosol effects on weather prediction.

Numerical experiments with the HARMONIE model have shown the considerable aerosol influence on most atmospheric variables (Figure 13). The impact occurred through a complex chain of interactions between physical variables, where aerosols played the role of a trigger. However, they worked in a different manner depending on a type of aerosols and synoptic pattern. Major changes occurred in the planetary boundary layer and along the frontal zone of high gradients at all levels. The perturbations appeared in a form of mesoscale cells growing with the leading time, while domain averaged deviations were oscillating around zero values.

In particular, the largest differences in air temperature and specific humidity have been observed near

the top of PBL. The temperature discrepancies reached up to ± 5 K at single cells depending on geographical region and vertical level. The domain average differences were less pronounced and showed the increase in air temperature by 0.2 K in the aerosol-polluted troposphere. The opposite effect, when the clean atmosphere is warmer than polluted, is revealed in the PBL for the "SEA" experiment. Relative humidity varied from 10% for the “NO-YES” experiments to 30% for the “NO-SEA” experiments. Specific humidity differences demonstrated the model tendency to reproduce more humid atmosphere in the presence of aerosols (at 0.05-0.1 g/kg) for the domain-averaged value, while locally they varied at about ±8-10 g/kg. Short-wave radiation increased at the top of the model atmosphere by extra 100 W/m^2, while near the surface it decreased by 200 W/m^2. Long-wave radiation was less sensitive to aerosol, with the exception of frontal zones and cloudy regions. Aerosols have affected mainly weak rates of precipitation by changing their formation and life-time. In particular, in the aerosol scenario the larger water amount in the atmosphere was accumulated and the precipitation was postponed.



(a) *(b)* *(c)*

***Figure 13**: Fig. 2 – Difference fields (no aerosols – climate aerosols) of the (a) short-wave radiation near the surface, (b) air temperature and (c) specific humidity at 925 hPa level simulated by the HARMONIE model on 16 Aug 2010, 06 UTC.*

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