since 1961

Baltica

BALTICA Volume 26 Number 1 June 2013 : 51–56
doi:10.5200/baltica.2013.26.06

# Urbanization influence on meteorological parameters of air pollution: Vilnius case study

**Adomas Mažeikis**

Mažeikis, A., 2013. Urbanization influence on meteorological parameters of air pollution: Vilnius case study. *Baltica, 26 (1), 51–56*. Vilnius. ISSN 0067-3064.

Revised manuscript submitted 6 March 2013 / Accepted 7 May 2013 / Published online 20 June 2013.
*© Baltica 2013*

**Abstract** This study concerns on spatial and temporal effects of surface parameters on boundary layer meteorological fields in urban territories. Selected parameters (2-metre temperature, precipitation amount and intensity, wind speed) are important for evaluating air pollution dispersion. Study is done using Enviro-HIRLAM numerical weather prediction model with the modifications of surface parameters to reflect changes due to urbanization. The modifications were made to parameters that are directly influenced by urbanization: surface roughness, albedo and anthropogenic heat flux. Case study consists of three different dates with different conditions and two different modelling domains. Overall, nine simulation runs were done including the control ones. Comparison of control and modified model runs was used for evaluation of effects. Differences of wind speed and temperature between control and modified runs were detected and in some cases, they reach up to 1.4 °C and 2.7 m/s. In addition, spatial differences in precipitation meteorological field were observed.

***Keywords*** • *Urban territories • Boundary layer meteorology • Air pollution dispersion • Numerical weather prediction • Physical geography • Vilnius city • Lithuania*

✉ *Adomas Mažeikis (adomas@mazeikis.eu), Nature Research Centre, Institute of Geology and Geography, T. Ševčenkos Str. 13, LT-03223, Vilnius, Lithuania.*

## INTRODUCTION

Outdoor air pollution has negative effect on public health and this has been proved by numerous studies (Curtis *et al.* 2006). Public health discussions are more frequent and air quality standards are being tightened to fight increased mortality and morbidity rates due to high air pollution periods. Precise timing is crucial for effectiveness of measures taken to minimize air pollution influence on public health (Vuuren, Vries 2000). Air quality forecasts provide help for decision makers to evaluate the probability and scale of possible high pollution period. If the possibility is high enough – measures can be taken to minimize or avoid damage to population at the smallest expenses.

Recognition of typical patterns and values of meteorological parameters that lead to high air pollution periods are needed for the most primitive air quality forecasting. For this task, precise weather forecasts must be available. This study concentrates on main meteorological parameters (which are the most important ones in air pollution dispersion processes) sensitivity to urban areas surface parameters such as surface roughness, albedo and anthropogenic heat flux as the surface of urban areas differs from other territories in many parameters. These differences do have impact for boundary layer meteorological parameters (Mason 2006) which are especially important for dispersion of air pollutants (Daviesa *et al.* 2007) and more precise forecast of these parameters leads to better possibilities of recognizing and forecasting high air pollution periods.

Several major cities in Europe have been selected for studies of impact of urbanized areas on meteorological parameters. Studies performed in Paris region showed that urban heat island forms over city and it has an effect on primary and secondary regional pollutants (Sarrat *et al.* 2006). Copenhagen agglomeration is distributed over vast area and only low height buildings are allowed in it but it still has a measurable effect on meteorological parameters that influence air pollution (Baklanov *et al.* 2005). Vilnius agglomeration was selected for this study, as it is big urban area in Lithuania.

Chosen numerical weather prediction model was set up in a standard way – software settings, boundary conditions and basic configuration parameters such as dynamic time step, data assimilation type etc. were taken from operational model used daily by Lithuanian Hydrometeorological Service and later specific modifications were done. The main schemes and parameterizations of surface parameters used in a model and their impact to meteorological fields are known quite well, but the exact cases can differ from expected results because of overall complex of conditions such as meteorological situation on the modelling date and orography of the area etc. The most interesting cases are the extreme ones when the air pollution dispersion conditions are well (high wind), poor (calm wind conditions) and such events as heavy precipitation or stable atmosphere stratification occur. Different dates with different meteorological conditions were taken to test the setup.

This type of study was never performed for any areas in Lithuania in such high horizontal and vertical resolution. Moreover, basis of this study is a set of numerical weather prediction experiments and their results, which gives opportunity to evaluate patterns of meteorological parameters. Earlier only statistical analysis on meteorological station measurement data sets were performed. Interpolation between these stations did provide only rough approximations of meteorological parameter values (Turčinienė, Bukantis 2009) not taking into account specific properties of exact area (soil type, terrain, surface roughness etc.).

## METHODS AND MATERIAL

The survey version of numerical weather prediction (NWP) model Enviro-HIRLAM (Korsholm *et al.* 2008) was used to carry out this study. Enviro-HIRLAM is the urbanized online-integrated NWP-Atmosphere Chemical Transport Modelling version (ACTM) of HIRLAM NWP model. For this study ACTM module was switched off to exclude the chemistry effect on meteorological fields. The parameterization schemes used for simulation runs were: Tiedtke convection and Sundqvist condensation scheme; CBR turbulence scheme (Cuxart *et al.* 2000); ISBA (Interactions Soil-Biosphere-Atmosphere) land surface scheme (Noilhan *et al.* 1996); Savijarvi radiation scheme (Savijärvi, 1989). Calculations were carried out using 40 vertical levels. Additionally digital filtering initialization (DFI) was used to improve simulation results.

Different modelling domains are used with Vilnius agglomeration centred in domain areas. Main parameters of LT1 and LT3 domains are (Fig. 1):

- Longitude grid points: 250 and 150 latitude grid points for LT1, 298, and 220 accordingly to LT3 domain.
- Rotation of south pole with parameters Polon=10 and Polat= –40 were chosen to minimize grid cell irregularities for minimization of computational cost and improvement of precision for LT1 domain. Polon=0 and Polat= –30 for LT3 domain.
- Cell size was chosen 1.4x1.4 km (which is minimal cell size for this model version) for LT1 and 2x2 km – for LT3 domains.
- Number of boundary points used: 10 and 4 of them defined as passive boundary points.

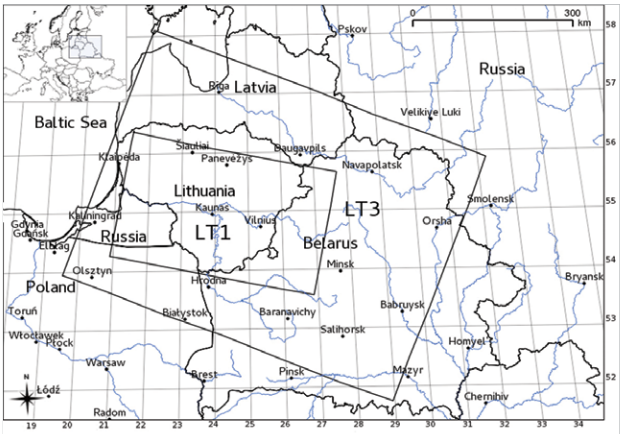

**Fig. 1** LT1 and LT3 NWP modelling domains.

Although boundary conditions are one of the most important parts of numerical modelling they are not provided in this article in any format due to an extremely high amount of data – high number of meteorological parameters, 40 levels, numerous time moments add up and to put them all would take thousands of map images (to show billions of data units).

Boundaries and climate generation files with urban fraction (Fig. 2) for LT1 domain simulation run (date: 2009 January 29) were prepared from Danish Meteorological Institute NWP model HIRLAM operational runs (initially resolution 15x15 km downscaled to 5x5 km). Boundaries and climate generation files with the

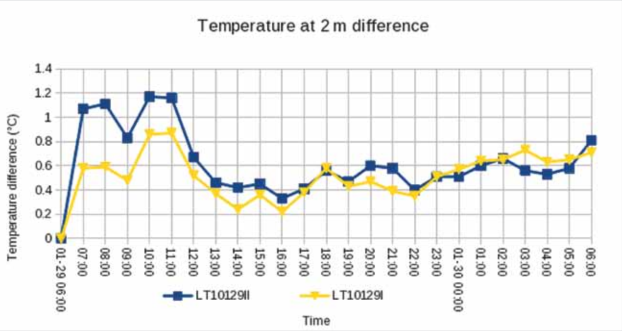

**Fig. 2** Temperature at 2 m difference between control and modified runs 2009-01-29 at Vilnius centre (54.70° N; 25.27° E).

urban fraction (Fig. 3) for LT3 domain (dates: 2009 March 14th and 2009 June 23rd) were prepared from operational Lithuanian Hydrometeorological Service NWP domain HLB8 (8x8 km).

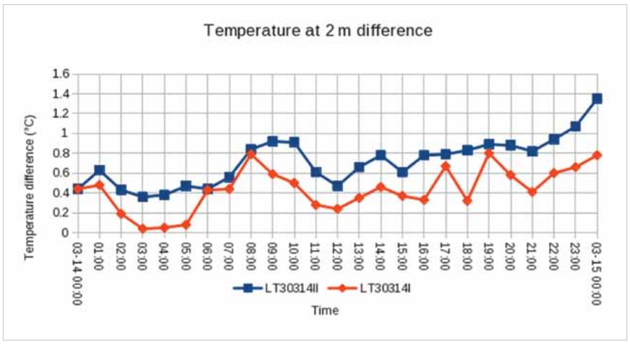

**Fig. 3** Temperature at 2 m difference between control and modified runs 2009-03-14 at Vilnius centre (54.70° N; 25.27° E).

The included urbanization is made by modifying the roughness, albedo and anthropogenic heat flux (Table 1) for the grid cells that have urban fractions. Urban fractions have dedicated class in ISBA surface scheme (where the modifications are made), but afterwards are transferred to Bare Soil surface class in Enviro-HIRLAM computations since there are 20 ISBA surface classes that must be simplified to 5 HIRLAM NWP surface classes.

The typical urban albedo of 0.15 was taken (15% of energy is reflected). It might be an extreme value for Vilnius since its agglomeration distinguishes itself as the one that has many forests, high, middle and low vegetation. However, the materials that are used for roof surfaces in Vilnius typically have lower albedo.

Surface roughness of 2 meters was taken as a standard surface roughness for Vilnius agglomeration area. It can be an extremely low value, but only the new downtown office buildings district can be taken with the higher values. Since the area of this district does not reach even one cell space – its impact can be measured and classified as a sub grid impact.

Anthropogenic heat flux can be described as the heat released from all human related activities (power generating, transport, heating, cooking, using home appliances etc.) including metabolism. It is one of the most underestimated parameters that influences urban heat island and in some extreme cases can be higher than the sum of the solar radiation (Ichinose T *et al.* 1999). In the simulated case of Vilnius agglomeration area, the anthropogenic heat values that were used are 100W/m$^2$ and 200W/m$^2$ in different cases. Such high values were taken, because Vilnius has vast districts of residential buildings that can be up to 20+ floors and in the cold season the energy amount used for heating or cooling in summer period can reach extremely high values.

The simulations were calculated using Lithuanian Hydrometeorological Service computing cluster consisting of 12 nodes with 24GB of RAM memory and 23 processors (most computational tasks in Enviro-HIRLAM are parallelized and can be distributed to all 12 nodes). Depending on modelling domain size, the computations of one experiment took 20–50 minutes using LHMS cluster. With the dynamical time step of 60s, the computations of one-step took 0.7–1.5 seconds excluding Input/output tasks.

## RESULTS AND ANALYSIS

As the main scope of study was identification of urban area surface characteristics influence on meteorological parameters comparison with observations is not included. Moreover, only two meteorological stations are nearby Vilnius, which are out of urban heat island territory: one in Vilnius International Airport (outskirts of the city) and another in Trakų Vokė district (suburb of Vilnius). None of these stations represent meteorological situation in Vilnius downtown area.

Two fields: temperature at 2 m and wind speed at 10 m were taken for comparing and the differences between control and two modified runs can be seen in the following (Figures 4 to 9). The provided plots

**Table 1** Definition of experiments.

| Case name* | Date | Domain | Modifications |
|---|---|---|---|
| LT10129C | 2009.01.29 | LT1 | No modifications |
| LT10129I | 2009.01.29 | LT1 | Roughness 2 m; AHF 100W/m$^2$; Albedo 0.15 |
| LT10129II | 2009.01.29 | LT1 | Roughness 2 m; AHF 200W/m$^2$; Albedo 0.15 |
| LT30314C | 2009.03.14 | LT3 | No modifications |
| LT30314I | 2009.03.14 | LT3 | Roughness 2 m; AHF 100W/m$^2$; Albedo 0.15 |
| LT30314II | 2009.03.14 | LT3 | Roughness 2 m; AHF 200W/m$^2$; Albedo 0.15 |
| LT30623C | 2009.06.23 | LT3 | No modifications |
| LT30623I | 2009.06.23 | LT3 | Roughness 2 m; AHF 100W/m$^2$; Albedo 0.15 |
| LT30623II | 2009.06.23 | LT3 | Roughness 2 m; AHF 200W/m$^2$; Albedo 0.15 |

*Note: First three characters in index of case name (LT1) mean domain used in experiment (see Fig. 1); next four characters – month and day of simulations (0129), and the last one indicates modification (C – control run, I and II – realistic and extreme scenario).

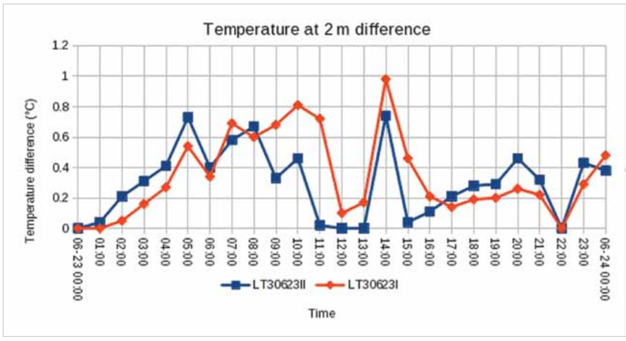

**Fig. 4** Temperature at 2 m difference between control and modified runs 2009-06-23 at Vilnius centre (54.70° N; 25.27° E).

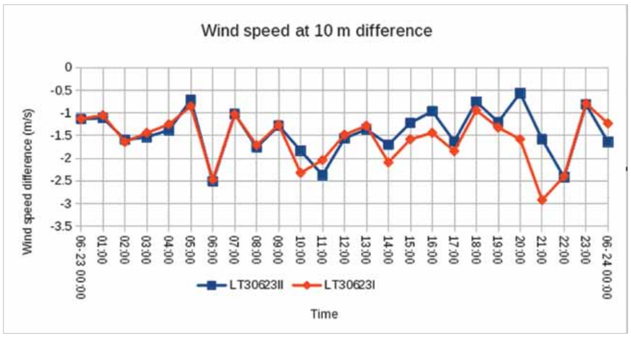

**Fig. 5** Wind speed at 10 m difference between control and modified runs 2009-06-23 at Vilnius centre (54.70° N; 25.27° E).

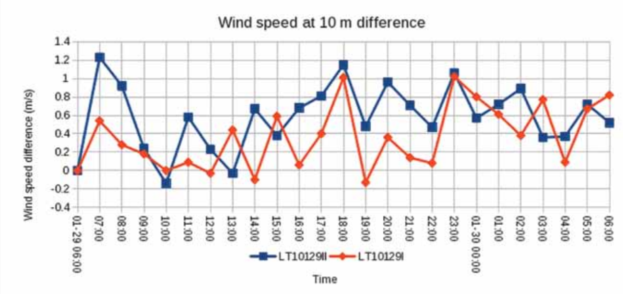

**Fig. 6** Wind speed at 10 m difference between control and modified runs 2009-01-29 at Vilnius centre (54.70° N; 25.27° E).

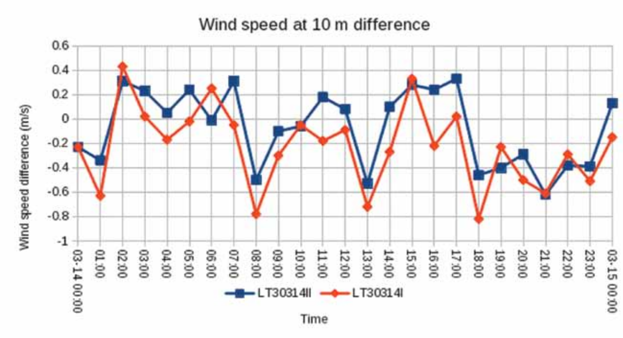

**Fig. 7** Wind speed at 10 m difference between control and modified runs 2009-03-14 at Vilnius centre (54.70° N; 25.27° E).

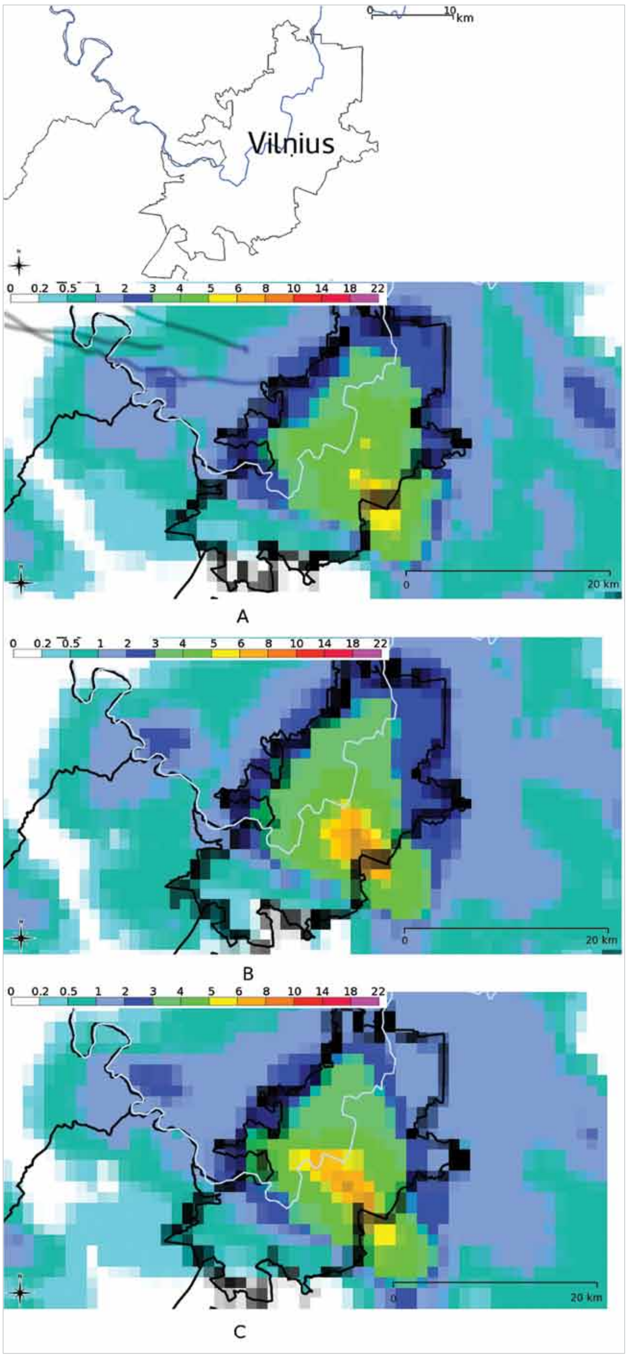

**Fig. 8** Precipitation field (mm/3 hours) A) LT30623C run results; B) LT30623I run results; C) LT30623II run results.

illustrate the difference in temperature and wind speed at the grid cell of Vilnius where the urbanization is the highest (that would be *Žvėrynas* district now). Vertical axis in figures 4 to 6 (measurement unit is t°C), temperature of modified runs – temperature of control run, so if less than 0 – control run temperature is higher (Figs 4 and 5). .It can be clearly stated, that in all cases the changes do affect the temperature by increasing it (except some hours on the 2009 June 23rd). The reason is clear – lower albedo means that more solar energy is absorbed.

Higher anthropogenic heat flux sums up to higher sensible heat flux and it means that the energy available for heating the near surface air is higher. Surface roughness means more drag which decreases airflow speed so the lower wind speed would be expected, but adding extra heat by increasing albedo and anthropogenic heat flux means that there is more energy for air parcel heating/lifting and it means air movements that can create turbulence as well.

By viewing the output, the fact that the urban effect is limited in area of the cells that contain urban fraction and the ones that have common borders with those, was verified. The effect is seen up to two cells (in LT1 domain it is 2x1.4=2.8 km) away from the heavy urbanized points. The same can be seen with the impact in height of the boundary layer. Already in the first layer (30–40 meters), the effect is near to zero (Figs 6 and 7).

Since the impact of urban territories on mentioned meteorological fields is not the same in all cases it might be difficult to evaluate the impact on dispersion conditions. However, in cases when the wind speed is higher, even though the effect is not very distinct in some cases it can show enormous effect on air pollution dispersion. For example, the 2009 January 29th case was with extremely calm wind conditions, so the air pollution dispersion condition were bad enough to trap the pollutants in city (Figs 8 and 9). The wind speed change of even 1 m/s when the measured speed is 3 m/s can mean big changes in pollutant concentration. However, the impact of urbanization can be negative too – the wind speed can become extremely low due to increased surface roughness.

Changes in spatial distribution of precipitation were also observed (Fig. 10). Results of modifications in experiment where AHF was set to 200W/m$^2$ showed more concentrated precipitation field over centre of urban heat island. A mechanism behind this effect is not directly connected to cloud condensation nuclei as CCN number is stable in this model configuration, so more research should be done to clear out the exact cause of such concentrated fallout of precipitation.

## CONCLUSIONS

The modifications of the surface parameters in urban territories have impact the meteorological fields that affect air pollution dispersion. However, the impact in different cases and time of day is different. The temperature at 2 m height is higher in modified simulation runs with urbanization included. The wind conditions can be higher in some cases and in some cases significantly lower (up to 2.7 m/s). The impact of urban territories in simulations is local (up to 2.8 km from heavily urbanized territories and up to 30–40 m height).

To study the sensitivity of meteorological fields to modifications of every single surface parameter a more detailed study should be carried out. The effect of several modifications at once can give positive feedback to meteorological fields in one case, but negative in other and the mechanisms that are responsible for the effect cannot be distinguished. However, the importance of net effect of urban territories should be studied using several modifications at once.

Urban areas have increased aerosol concentration. A joined experiment with an online-coupled numerical weather prediction–atmospheric chemistry transport model should be made to test if direct and indirect effects of increased concentration of aerosols do not extinguish the effect of urbanization on meteorological fields over urban areas.

## Acknowledgements

Author would like to thank Numeric Weather Prediction Group of Lithuanian Hydrometeorological Service for technical help on performing computational experiments. Thank is given to reviewers Dr. Hüseyin Toros (Istanbul) and Dr. Rimas Petrošius (Vilnius) who made valuable comments and suggestions to improve the article. As well, research teams of MEGAPOLI and TRANSPHORM projects for guidance and Danish Meteorological Institute together with MUSCATEN and NETFAM projects for possibilities to use computational resources.

## References

Baklanov, A., Mestayer, P., Clappier, A., Zilitinkevich, S., Joffre, S., Mahura, A., Nielsen, N. W., 2005. On the parameterisation of the urban atmospheric sublayer in meteorological models. *Atmospheric Chemistry and Physics Discussions 5 (6)*, 12119–12176. http://dx.doi.org/10.5194/acpd-5-12119-2005

Curtis, L., Rea, W., Smith-Willis, P., Fenyves, E., Pan, Y., 2006. Adverse health effects of outdoor air pollutants. *Environment International 32 (6),* 815–830. http://dx.doi.org/10.1016/j.envint.2006.03.012

Cuxart, J., Bougeault, P., Redelsperger, J.-L., 2000. A turbulence scheme allowing for mesoscale and large-eddy simulations. *Quarterly Journal of the Royal Meteorological Society 126*, 1–30. http://dx.doi.org/10.1002/qj.49712656202

Daviesa, F., Middletonb, D. R., Boziera, K. E., 2007. Urban air pollution modelling and measurements of boundary layer height. *Atmospheric Environment 41 (19)*, 4040–4049. http://dx.doi.org/10.1016/j.atmosenv.2007.01.015

Ichinose, T., Shimodozono, K., Hanaki, K., 1999. Impact of anthropogenic heat on urban climate in Tokyo. *Atmospheric Environment 33 (24)*, 3897–3909. http://dx.doi.org/10.1016/S1352-2310(99)00132-6

Korsholm, U. S., Baklanov, A., Gross, A., Mahura, A., Sass, B. H., Kaas, E., 2008. Online coupled chemical weather forecasting based on HIRLAM – overview and prospective of Enviro-HIRLAM. *HIRLAM Newsletter 54*, 151–168.

Masson, V., 2006. Urban surface modeling and the meso-scale impact of cities. *Theoretical and Applied Climatology* 84, 35–45. http://dx.doi.org/10.1007/s00704-005-0142-3

Noilhan, J., Mahfouf, J.-F., 1996. The ISBA land surface parameterization scheme. *Global and Planetary Change 13 (4)*, 145–159. http://dx.doi.org/10.1016/0921-8181(95)00043-7

Sarrata, C., Lemonsub, A., Massona, V., Guedaliac, D., 2006. Impact of urban heat island on regional atmospheric pollution. Atmospheric Environment 40 (10), 1743–1758. http://dx.doi.org/10.1016/j.atmosenv.2005.11.037

Savijärvi, H., 1990. Fast radiation parameterization schemes for mesoscale and short-range forecast models. *Journal of Applied Meteorology 29 (6)*, 437–447. http://dx.doi.org/10.1175/1520-0450(1990)029<0437:FRPSFM>2.0.CO;2

Turčinienė, J., Bukantis, A., 2009. Research of air temperature spatial field in Lithuania. *Geografija 45 (2)*, 131–138. [In Lithuanian].

Vuurena, D. P., Vriesa, H. J. M., 2001. Mitigation scenarios in a world oriented at sustainable development: the role of technology, efficiency and timing. *Climate Policy 1 (2)*, 189–210.