Report on the RHM activities in AEVUS PT

Participating scientists from RHM: Dr. Mikhail Varentsov, Dr. Inna Rozinkina, Dr. Gdaly Rivin, Denis Blinov, Dr. Alexander Kirsanov

Additional contributions: Dr. Timofey Samsomov (Lomonosov Moscow State University, Faculty of Geography) – performing the GIS-based processing of OpenStreetMap data in order to obtain the used external parameters for TERRA_URB scheme; Dr. Irina Repina and Arseniy Artamonov (A.M. Obuhov Institute of Atmosperic Physcics RAS) – maintaining the observations of the MTP-5 profiler in Moscow downtown; Dr. Vladislav Yushkov (Lomonosov Moscow State University, Faculty of Physics) – participating in the data analysis for a considered case of extreme frosts in Moscow in January 2017.

1. Results for subTask0: Installation and debugging of the beta COSMO version including TERRA_URB

Within the framework of RHM activities in AEVUS PT, the different versions of COSMO model including the TERRA_URB (COSMO 5.05g_urb1, COSMO 5.05g_urb2, COSMO 5.05g_urb3, COSMO 5.05g_urb4) were installed on the two Russian supercomputers, namely, on the supercomputer “Lomonosov-2” of Lomonosov Moscow State University and on the Cray-XC40 supercomputer of Roshydromet.

After the installation, the primary task was to investigate the presence of the bugs in the newest COSMO version including urban parameterization, and to compare the consistency of the simulation results with the results obtained with the previous version of the scheme included in climate version of the model (COSMO5.00_clm9_terraurb).

1.1. General setup of the simulations for Moscow megacity region

For the task of basic debugging, and for the most of the further simulations, we used a well-tested framework from the previous modelling studies for Moscow, which were carried out with using the older COSMO5.00_clm9_terraurb model version. This set of simulations is described in details in (Varentsov et al., 2018; 2019), and here we give just a basic description.

The model was applied for a three-step dynamic downscaling of ERA-Interim reanalysis data (Dee et al., 2011) for the chain of nested domains D1, D2 and D3 with horizontal grid spacing 12, 3 and 1 km respectively (Figure 1). The TERRA_URB scheme was used only for the final D3 domain with 1-km grid step (180x180 grid cells) in “URB” runs. In addition, “noURB” runs with TERRA_URB switched off were conducted, which allows to investigate the model response to switching on the TERRA_URB as a difference between “URB” and “noURB” runs. The external parameters, which are required to use the TERRA_URB scheme, ISA (impervious surface area), and AHF (anthropogenic heat flux) were clarified with the original technology of GIS-processing of open-access OpenStreetMaps data (Samsonov et al., 2015; Varentsov et al., 2017). This technology also provided the 2D fields for such variables as building height H, roof area fraction RF and street canyon aspect ratio H/W, which were introduced as additional external parameters to the code of COSMO5.00_clm9_terraurb model version.

Although in previous studies the simulations with COSMO5.00_clm9_terraurb were carried out for multiple summer and winter seasons, for further debugging of the new model versions we have selected a relatively short period of 1-15 May 2014. New simulations were carried out only for a finest domain D3, using the initial and boundary condition from previous simulations with COSMO5.00_clm9_terraurb for D2 domain.

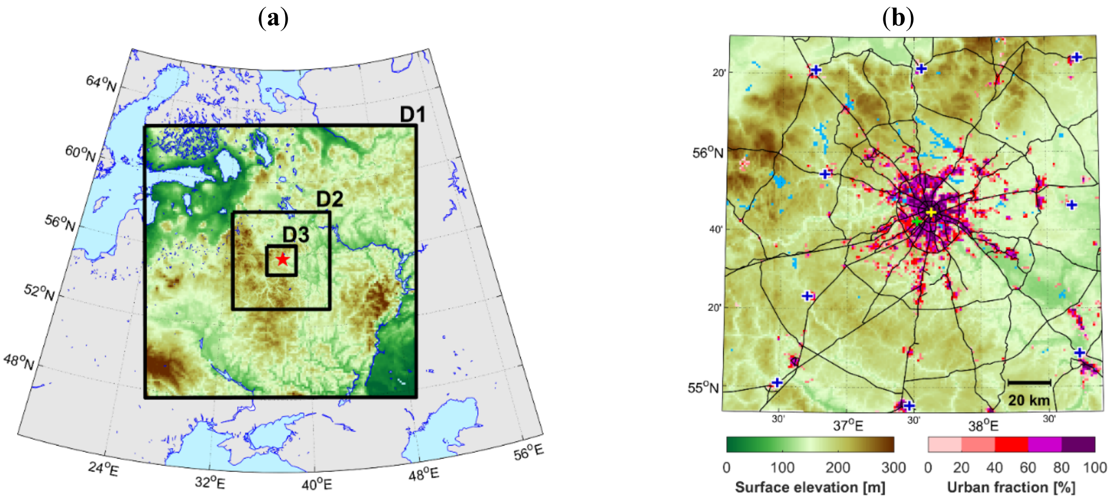

Figure 1. The configuration of the nested domains, used for simulations with the COSMO model, with surface elevation shown by the color scale, and water surfaces shown by the light-blue color (**a**). A detailed map of the finest D3 domain, used for the urban climate simulations with the COSMO-CLM model coupled to TERRA_URB, with urban fraction shown by an additional color scale (**b**). The location of the weather stations used for the estimation of the urban heat island (UHI) intensity is also shown (**b**). The yellow cross indicates Balchug station (considered as the city center), the green cross indicates MSU (Moscow State University) station, and blue crosses indicate the nine rural reference stations around Moscow. The black lines in (**b**) represent the primary road network.

1.2. The bug of the artificial heating of rural areas

A specific set of simulations was carried out in order to investigate the bug of the artificial heating in rural areas in case of switching the TERRA_URB scheme on, which was reportage by other participants of AEVUS PT just after the release of the COSMO 5.05_urb1 model version. This set consisted of two simulations. In the first one, “noURB” run, the TERRA_URB scheme was switched off (lterra_urb = .FALSE., ntiles = 0). In the second one, “EmptyURB” run, TERRA_URB scheme was switched on (lterra_urb = .TRUE., ntiles = 2)., but the values of ISA and AHF were set to zero all over the model domain. The model response to switching the TERRA_URB scheme on was further investigated as a difference between two runs. Since the city is not represented in ISA and AHF external parameters, such response is expected to be a zero for any place and variables, and it was a zero in similar simulations with the older COSMO5.00_clm9_terraurb model version.

However, such experiments with COSMO 5.05_urb1 model version has shown an inconsistency between two runs in various output fields, including the soil and air temperature, wind speed, heat fluxes, etc. (Figure 2). Such inconsistency indicated the presence of some bugs in the implementation of TERRA_URB scheme or a tile approach, which disturbed the model behavior despite the absence of any urban area in the whole domain.

The same problem was found in further versions 5.05urb2 and 5.05urb3. The problem was reported and discussed during AEVUS meetings with other PT participants and with Ulrich Schaettler. After an additional debugging, Ulrich Schaettler has provided the recent official update, 5.05urb4, where several bugs were found and fixed in order to solve this problem. The code changes affected different modules, including the implementation of the tile approach in turb_interface.f90. The most likely, the reason of the problem was related with this module (the explanation of Ulrich Schaettler is following *“The transfer-scheme turbtran also uses the ke-values of the variables tkvm, tkvh and tke, but only the values for ke1 are set in turbtran. The ke-values are only set in turbdiff (the atmospheric scheme). But turbdiff is not computed for all tiles, only for the averaged 0-tile. Therefore I do a copying of the 0-tile to the natural and the urban tile just for the ke-values”*)

Further tests for the Moscow case confirmed that the problem of artificial heating for rural areas is eliminated in the COSMO version 5.05urb4 (Figure 2). However, a slight inconsistency between the two runs is still observed in the version 5.05urb4. Specifically, the switching of the TERRA_URB scheme on affects the near-surface temperature (T_2M) above the lakes. The difference between the two runs is found in temperature, but is not found in surface temperature or fluxes (Figure 3). Hence, we could suggest that this problem affects only diagnostic variables and hence is not very critical, but should be investigated in further work.

(a) (b)

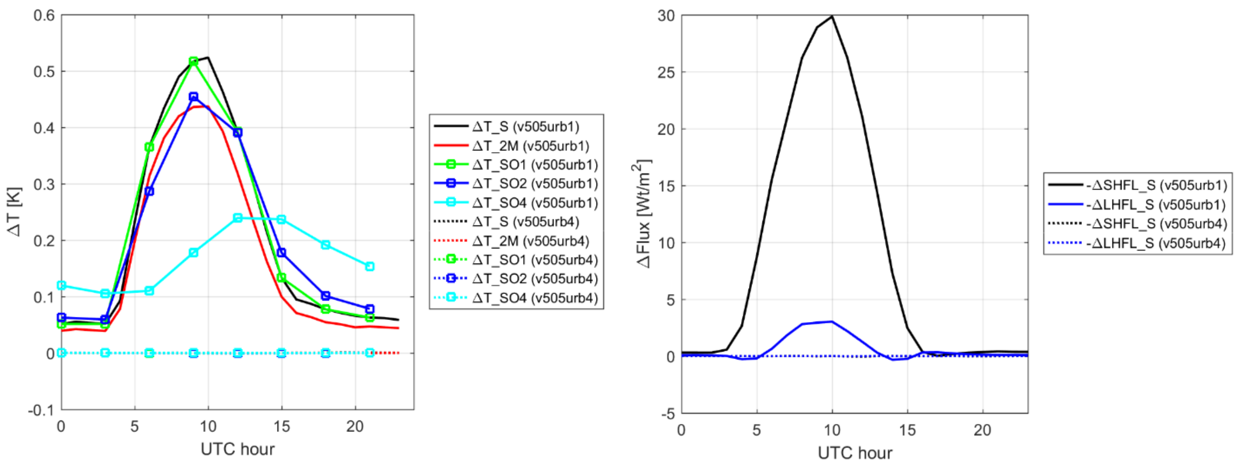

Figure 2. The diurnal variation of the model response in the fields of air, surface and soil temperatures (a) and surface heat fluxes (b) to switching the TERRA_URB scheme on, estimated as a difference between two runs, "EmtpyURB" and "noURB", for D3 domain, averaged over all land grid cells and over 15 days of simulation (1-15 May 2014).

1.3. The bug of the incorrect behavior of a skin-layer temperature scheme

The second important bug found in COSMO 5.05urb was related to the incorrect behaviors of a skin-layer temperature scheme (SLTS). The SLTS was originally developed by Dr. Jan-Peter Schulz in order to take into account the insulation effect of the vegetation canopy and to minimize the well-known problem of the underestimation of the diurnal temperature variation in COSMO (warm nocturnal bias and cold daytime bias for the air temperature, and vice versa for the temperature of top soil layers), see details in (Schulz & Vogel, 2017). The SLTS was implemented to the older COSMO5.00_clm9_terraurb model version. From the previous modelling studies (e.g. Wouters et al., 2017) this scheme was found to be very important for urban climate simulations, because the adequate reproduction of the temperature diurnal range is critical for correct simulation of the urban heat island (UHI) intensity. This is main argument why the SLTS was tested together with TERRA_URB scheme within the framework of AEVUS PT.

The expected effect from the switching on the SLTS is a decrease of a nocturnal temperate, a decrease of a daytime temperate, and a decrease of the diurnal temperature range. The amplitude of the effect should have an inversed dependence on the given skin-layer conductivity (SKC): the lowering of the SKC should increase the diurnal temperature rage.

However, opposite effects from the use of SLTS were found in preliminary test runs with the COSMO 5.05urb1-4 model versions. In order to investigate this problem in details, a specific set of the simulations was configured. We have analyzed the model response to the switching the SLTS scheme on as a difference between the control run (itype_canopy = 1) and a run with the SLTS switched on (itype_canopy=2 a constant SKC value, 10 or 30). TERRA_URB scheme was switched of in these runs. The simulations with the older model version, COSMO5.00_clm9_terraurb, show the expected response both for the air and soil temperatures, while the new model version, 5.05_urb4 shows the expected response for the soil temperature, but an opposing response for the air temperature (Figure 3).

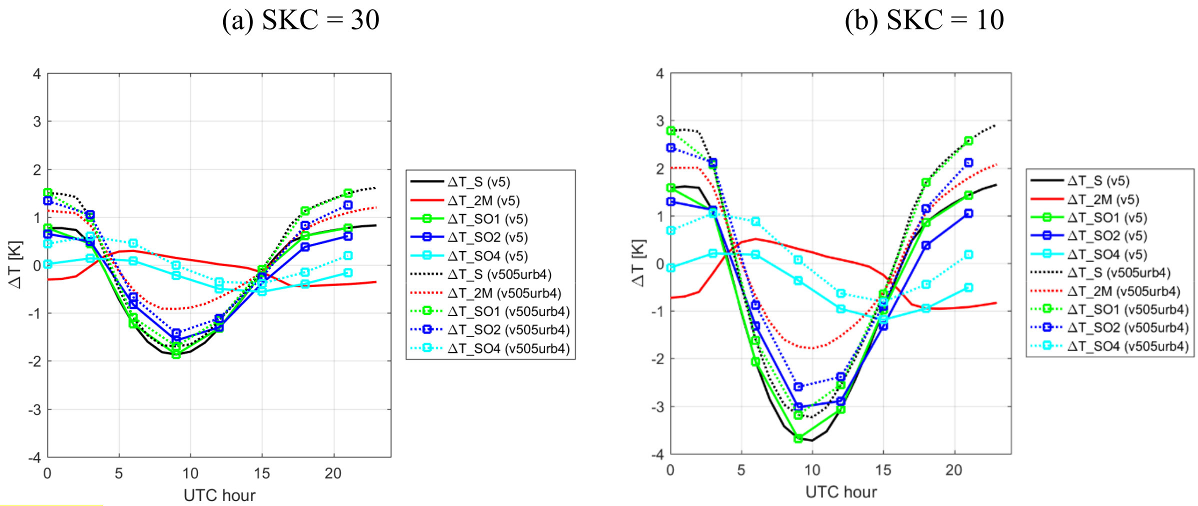

Figure 3. The diurnal variation of the model response in the fields of air, surface and soil temperatures to switching the SLTS on for COSMO 5.00_clm9_terraurb (v5) and COSMO 5.05urb4 (v505urb4) model versions. The SKC values is set to 30 (a) and 10 (b). The results are based on the simulations for D3 domain and averaged over all land grid cells and over 15 days of simulation (1-15 May 2014).

A further debugging of problem was based on the comparison between the model versions 5.05urb4 and 5.06a. The second one has a very similar code structure to 5.05urb4, but does not include the TERRA_URB scheme, and include the SLTS, which was implemented into the code completely independently from the implementation in 5.05urb versions. Finally, such approach allows to find a code bug in the 5.05urb4 in the sfc_utilities.f90, in the subroutine diag_snowfrac_tg (around line 249), where t_g variable was overwritten by t_soiltop instead of t_skin in case of using the SLTS. The corresponding conditional operator was added to the code in order to fix the bug:

```
IF (itype_canopy == 1) THEN
        IF (t_soiltop(ic) > t0_melt .AND. t_snow(ic) >= t0_melt - dbl_eps) t_g(ic) = t_soiltop(ic)
ELSEIF (itype_canopy == 2) THEN
        IF (t_skin(ic) > t0_melt .AND. t_snow(ic) >= t0_melt - dbl_eps) t_g(ic) = t_skin(ic)
END IF
```

After a fixing this bug, the two model versions, 5.05urb41 (5.05urb4 with a bug fix) and 5.06a show a similar response to switching on the SLTS, which corresponds to our expectations (Figure 4).

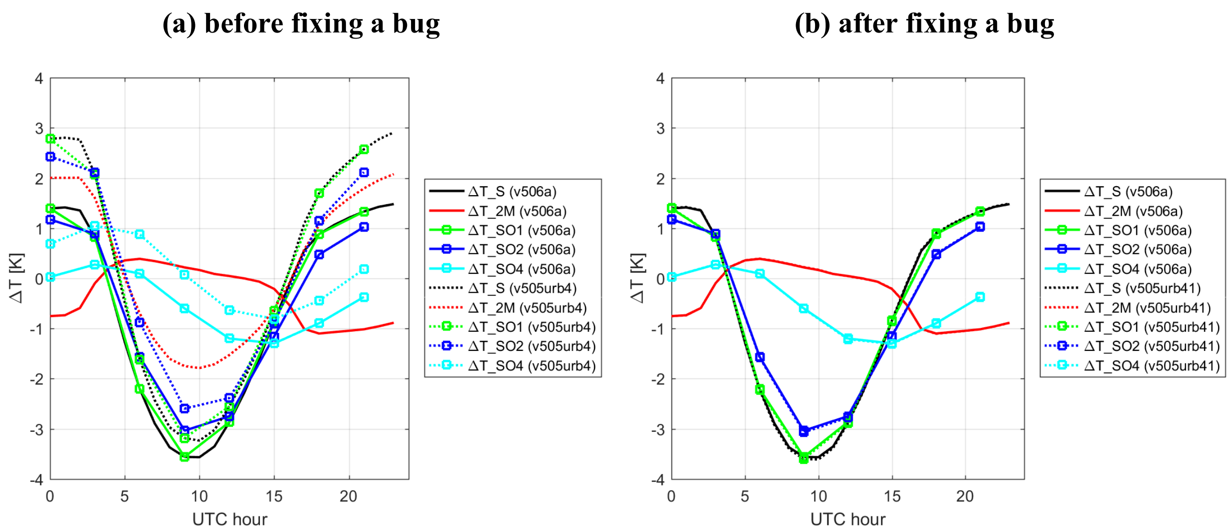

Figure 4 The diurnal variation of the model response in the fields of air, surface and soil temperatures to switching the SLTS on for COSMO 5.06a (v505a) and COSMO 5.05urb4 (v505urb4) before fixing a bug

(a) and after fixing a bug (b). The results are based on the simulations for D3 domain and averaged over all land grid cells and over 15 days of simulation (1-15 May 2014).

1.4. Other minor bugs

In addition to the two most important bugs, that were revealed and fixed during the work on the AEVUS PT, a number of other minor bugs were also found, but still not fixed. They are:

1) The problem of writing constants to the output files (**lffd*c.nc)**. In some cases, this problem is expressed in the model crash during writing the output, in another cases the model does not crash, but the unreal values of constants such as FR_LAND are written to the output file. The problem was observed both at the supercomputer "Lomonosov-2" of the MSU and at the Cray XC40 supercomputer of Roshydromet. In either case the Intel compiler was used.
2) The inconsistency related to the name of external parameter, which corresponds to impervious surface area. The model could read its values from the extpar variables called ISA (as it was COSMO 5.00_clm9_terraurb) and FR_PAVED, but only in case of usage FR_PAVED name, the actual values are recognized by the model correctly. In the case of use of ISA name, the model does not use the actual values from extpar file, but not error is thrown.

The listed minor bugs do not affect the model physics and hence do not prevent the using the new model version for the scientific and practical purposes, however in some cases they make the work with a model quite annoying. These bugs should be investigated and fixed during the further work.

2. Results for SubTask1: selection of case studies

Selection of case studies for model testing and for detailed verification of the modelling results for Moscow megacity was based on the following criteria:

1) Length of the period of case-study about 1-2 weeks;
2) Predominance of calm and clear weather conditions, which are favorable for the development of the urban heat island and other megacity-induced meteorological effects.
3) Availability of the observational data for the dense meteorological networks, that have been developed in the Moscow megacity since recently, including the network of the automatic weather stations (AWSs) of Roshudroment and the network of air pollution control stations of State Environmental Protection Institution Mosecomonitoring. The most detailed and reliable data from these two networks is available since 2014.
4) Availability of the observational data for the biggest number of sites among the network of microwave temperature profiles MTP-5, which operates in Moscow region and provides unique data in the vertical temperature profiles over the city and countryside. The description of the microwave temperature profiler could be found in (Ezau et al., 2013; Kadygrov & Pick, 1998; Yushkov, 2014), while previous data analysis for Moscow is described e.g. (Khaikine et al., 2006). The data on vertical temperature profiles allows to verify the modelling results not only for the surface layer, but also for a boundary layer of the atmosphere. The synchronous observations in the number of points (campus of Moscow State University, Central Aerological Observatory (CAO) in the northern suburb, Kosino site in the eastern suburb, Zvenigorod Scientific Station (ZZS) site in a rural area in 50 km to the west from Moscow) have being carried out only for a few recent years, since 2010th. The most detailed data is available since the beginning of 2017, when a new profiler started to work in a quasi-continuous mode just in a center of Moscow, at the roof of the A.B. Obukhov Institute of Atmospheric Physics (IAP site). Since its appearance, the data of MTP-5 network could be used for the verification of the vertical extent and 3-dimentional structure of the modelled UHI.

The location of the listed observational sites in Moscow city and its closes surrounding is shown in Figure 5.

Following the listed conditions, the several periods have been identified:

1) 17.05.2014 – 29.05.2014, the period of anomalously warm (for May), calm and clear weather which include several days with intensive anomalously UHI
2) 25.07.2014 – 10.08.2014, the period of anomalously warm and dry summer weather which include several days with intensive nocturnal UHI
3) 25.06.2015 – 05.07.2015, the typical period of calm and clear summer weather which include several days with intensive nocturnal UHI
4) 01.01.2017 – 15.01.2017, the winter period which includes a sub-period of the extremely cold weather from 6 to 10 of January, when temperature dropped below -35 ° in a countryside, and the intensive UHI was observed during more than one day under the conditions of strongly stable stratification of the atmosphere. MTP-5 data for a city center is available.
5) 10.05.2017 – 25.05.2017, the typical period of calm and clear May weather which include several days with intensive anomalously UHI. MTP-5 data for a city center is available.
6) 05.08.2017 – 20.08.2017, the typical period of calm and clear summer weather which include several days with intensive nocturnal UHI. MTP-5 data for a city center is available.

3. Results on SubTask2: simulation setup and runs

The simulations for the selected cases were performed using the same modelling framework that was used in the previous modelling studies for Moscow (Varentsov et al., 2018; 2019) and in the debugging tasks (see subsection 1.1). As described above, we used a chain of nested domains D3-D1 (Figure 1) for a dynamic downscaling of the ERA-Interim reanalysis data for Moscow region for the periods of selected case-studies (about 15 days). We use the same external parameters as in previous modelling studies, including the clarified datasets on ISA and AHF, obtained using OpenStreetMap data.

The simulations were aimed to the checking the consistence between new and old COSMO versions including TERRA_URB, and for detailed verification of the modelling results.

For each considered ase, three different simulations were performed. The older model version COSMO5.00_clm9_terraurb was used in the simulations called v5_REF and v5_MOD. In v5_REF simulations, the default values were used for the most of namelist settings. In the v5_MOD simulations, we used the namelist settings that were carefully tuned in the previous modelling studies for Moscow in order to minimize the systematic model errors, including the well-known nocturnal warm bias. The most important differences between the tuned and default setup include the changes of the minimum coefficients of turbulent diffusion (tkhmin and tkmmin) and the scale of the subgrid thermal inhomogeneity's (pat_len) according to (Cerenzia et al., 2014), the use of a new parameterization of bare soil evaporation (Schulz & Vogel, 2016) and a new skin-layer temperature scheme (Schulz & Vogel, 2017). The last set of simulations, v505_REF, was performed with a use of the new model version 5.05urb4. In general, the default namelist settings were used for v505_REF simulations, however, these settings are different from the default settings of the model version 5.0. It should be noted that it was not possible to run the simulations with new model version using the SLTS, because the bug of its incorrect behavior (see section 1.3) was not yet debugged and fixed when the simulations were performed. The key differences between namelist settings for v5_REF, v5_MOD and v505_REF simulations are given in Table 1. The namelists could be shared on a request.

Table 1. The key differences between namelist settings for v5_REF, v5_MOD and v505_REF simulations

Parameter	**v5_REF**	**v5_MOD**	**v505_REF**
PHYCTL namelist			
itype_rootdp	**1**	**2**	**2**
itype_evsl	**1**	**4**	**4**

itype_heatcond	**1**	**2**	**3**
itype_canopy	**1**	**2**	**1***
calamrur (skin-layer conductivity)	**-**	**30**	**-**
TUNNING namelist			
tkmmin & tkhmin	**0.4**	**0.1 or 0.05**	**0.75**
pat_len	**500**	**100 or 50**	**100**
DYNCTL namelist			
hd_corr_(t, u, p…)	**defaults**	**0.25 for all**	**defaults**

4. Results on SubTask4: evaluation and verification of the case studies

As indicated above in the section 2, the model verification was performed using the observational data from a dense network of the weather stations and air pollution control stations (more than 70 points in total within the D3 domain, the exact number slightly vary from one case to another), as well as the data from the network of microwave temperature profilers MTP-5. The location of the observational sites in Moscow city and its closest surroundings is shown in Figure 5.

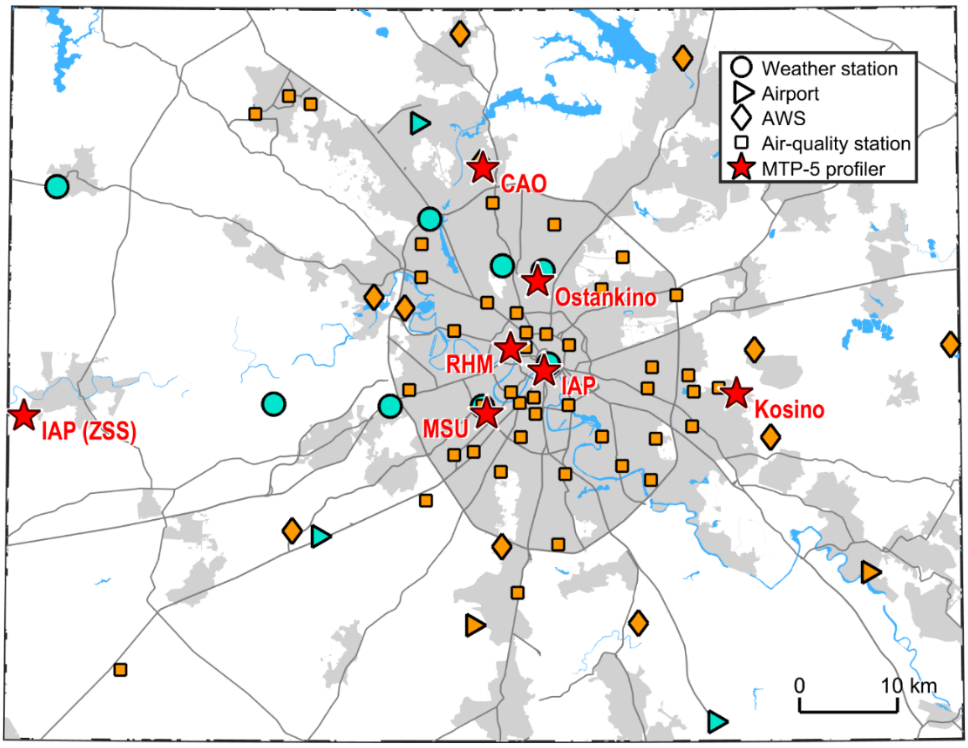

Figure 5. The location of the observational sites, used for the model verification for Moscow region. The orange color indicates the relatively new observational sites; the cyan color indicates the sites with long-term observational series.

The verification was focused mainly on the rural temperature and the UHI intensity. The UHI intensity was defined as a temperature anomaly with respect to the mean rural temperature, which was averaged over the 9 rural stations around Moscow (blue crosses in Figure 1b). The most attention was paid to the UHI intensity in the city center, where the Balchug weather station is located (yellow cross in Figure 1b).

The comparison between the modelling results and observations has clearly shown the significant difference between RED and MOD simulations with an older model version 5.0_clm9_terraurb. For the summer and late spring conditions (on an example of the case #1), the REF simulations strongly overestimate the nocturnal temperature at rural areas and underestimate the UHI intensity, while in the MOD simulations the nocturnal temperature and UHI intensity are much closer to the observations (Figure 6). The new model version (v505_REF) simulates the rural temperate and UHI intensity almost as well as the old version with tuned settings (v5_MOD).

A comparison between the simulated vertical temperature profiles and observations of MTP-5 profiler at a rural site (Zvenigorod, 50 km to the west from Moscow) and a suburb site (CAO, northern suburb of Moscow) has clearly shown that the differences between the different simulations in field of the near-surface temperature are densely linked with the differences in vertical temperate profiles. v5_REF simulations strongly underestimate the strength of the nocturnal temperature ingestion, while v5_MOD and v505_DEF simulations reproduce it much closer to observations (Figure 7). In general, v505_DEF simulations still slightly overestimate the minimal nocturnal temperatures and slightly underestimate the maximum UHI intensity as well as the strength of nocturnal temperature invasion. However, the SLTS was not used in v505_DEF simulations, so we could expect that the use of SLTS in new model version will eliminate these biases. Figures 8 and 9 shows that v505_DEF simulation generally nicely captures the spatial structure of the nocturnal UHI of Moscow, as well as v5_MOD simulation.

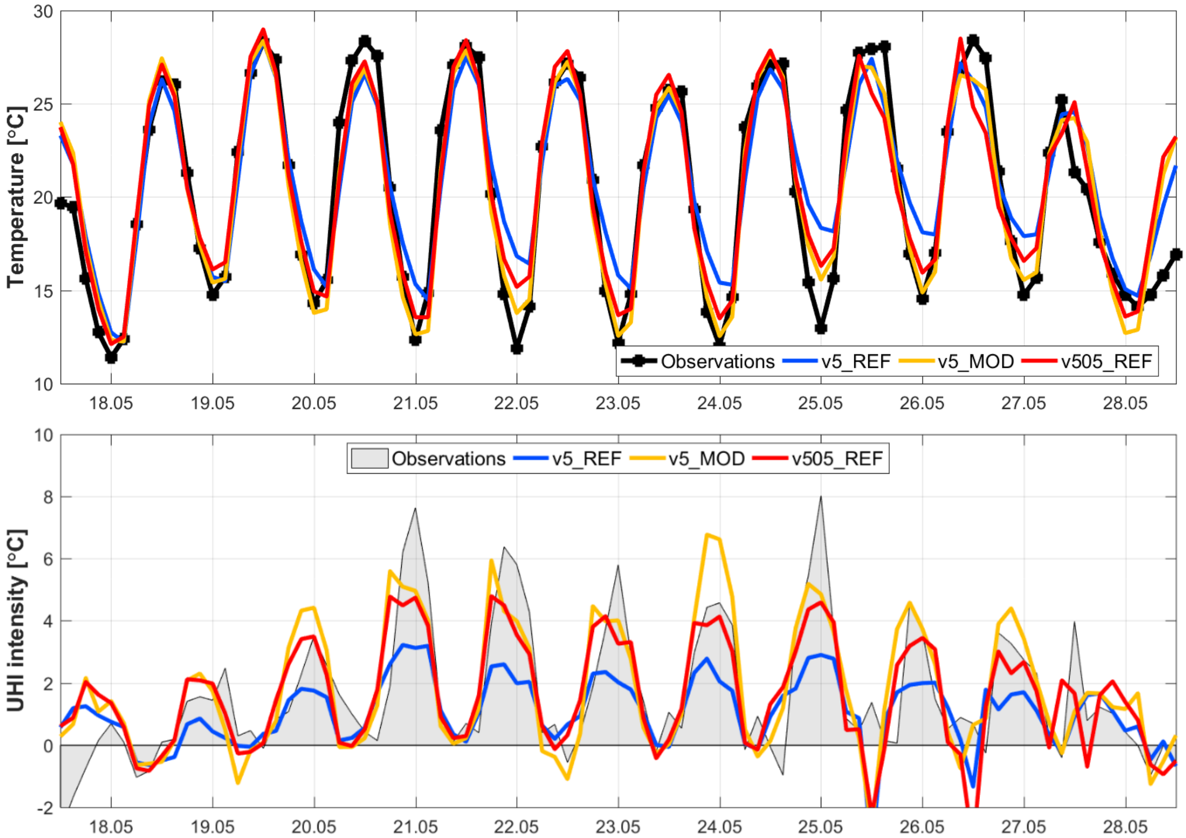

Figure 6. The variations of the mean rural air temperate and the UHI intensity for the city center (temperature difference between the value for Balchug weather stations and the mean rural value) according to observations and modelling results for case #1 (18-28 May 2014).

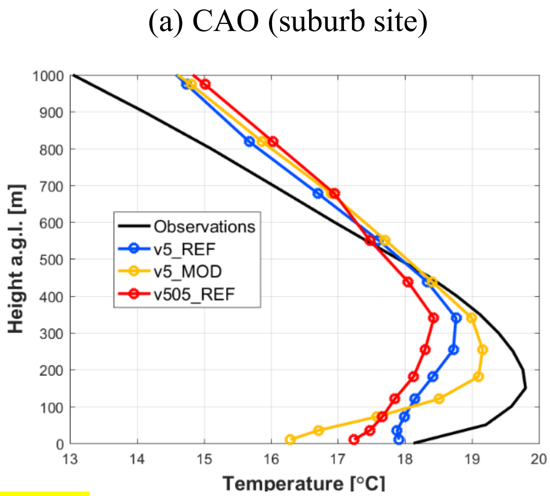

Figure 7. The observed and simulated nocturnal (0 UTC) vertical temperature profiles, averaged over the period of 20-27 May 2014 for CAO suburb site (a) and Zvenigorod rural site (b).

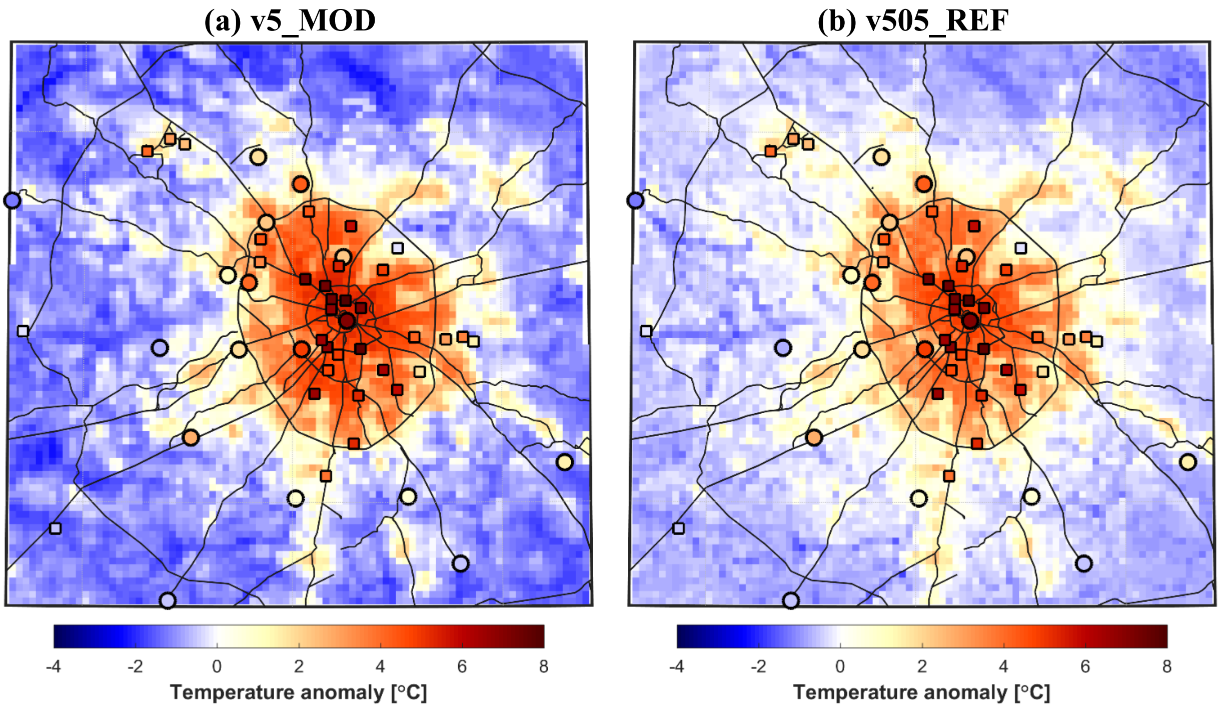

Figure 8. The spatial structure of the average nocturnal (0 UTC) urban temperature anomaly in Moscow region according to observations (colored squares and circles) and simulations v5_MOD (a) and v505_REF (b), shown as colored background. The averaging is performed over 20-27 May 2014. The temperature anomaly is defined as a deviation from the mean rural value, averaged over 9 rural reference weather stations (see Figure 1).

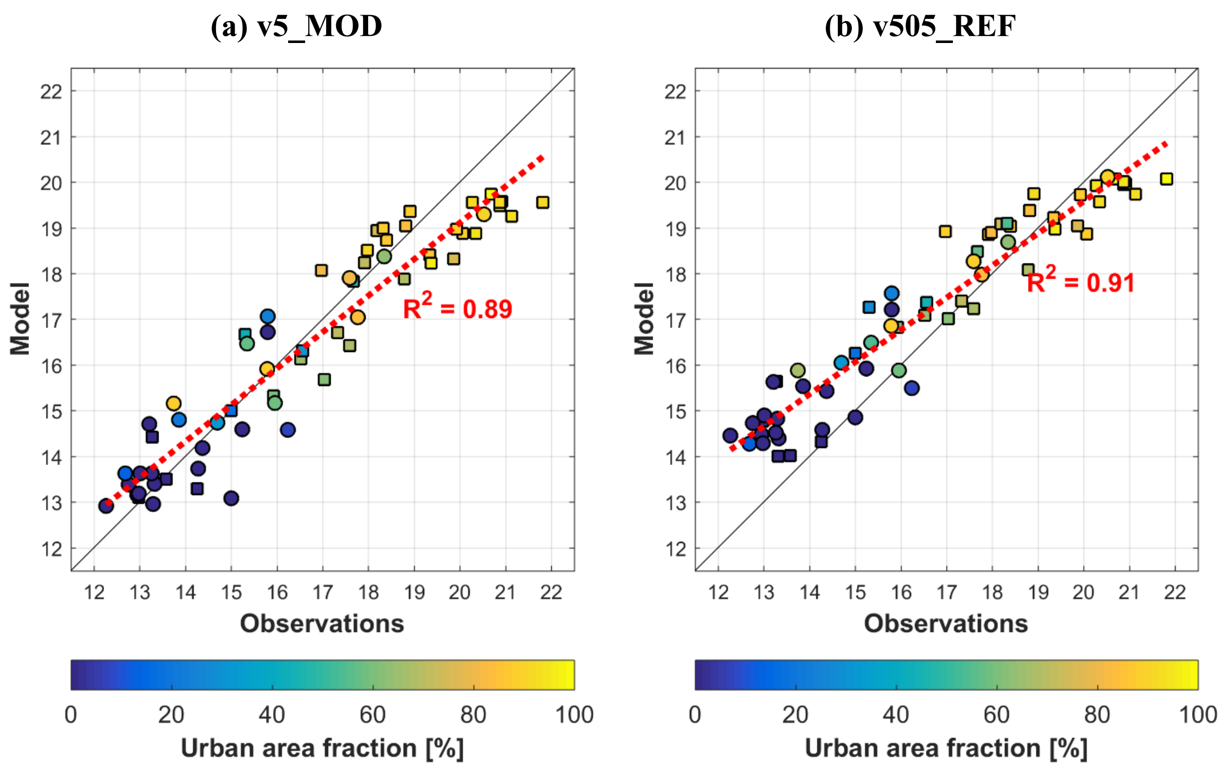

Figure 9. The dependence between the observed and modelled values of the mean nocturnal (0 UTC) temperature for v5_MOD (a) and v505_REF (b) simulations. The averaging is performed over 20-27 May 2014. Each point corresponds to a different weather station (circles) or air-quality control stations (squares), the color of the point represents the urban area fraction for corresponding model grid cell.

Especially interesting are the results for the winter case #4, which include a period of extremely cold weather with a temperature drop below -35 °C in a countryside area of Moscow region. All of the considered model runs generally nicely simulate the temporal dynamics of the mean rural air temperature and the UHI intensity for the city center during this case (Figure 10). The simulation with the newest model version, 5.05urb, has a cold bias for the peak of cooling at 7th of January, but shows the best correlation with observations, especially after the peak of cooling. Despite a very simple approach used for the AHF definition in TERRA_URB, the simulations capture the dynamics of the UHI intensity quite nicely.

The considered case allows to verify the model ability to simulate the spatial structure of the UHI in different conditions. At 8th of January the UHI was shifted to the southwest by prevailing north-eastern wind, and at the 9th January the UHI was collocated with the urban areas under calm weather conditions. The model generally successfully captures these features, however the v505_REF simulation shows a lower agreement with observations than v5_MOD simulation (Figure 11).

The data from the network of MTP-5 profiles gives a unique possibility to evaluate the vertical temperature profiles in the rural and urban sites during the period of frosty weather. All of the model runs successfully simulate the intensive temperature inversion in the lower atmosphere, that was observed during the last day of the frosty period and promoted the development of the UHI (Figure 12). The model run with old model version without tuning, v5_REF, underestimates the strength of inversion and overestimates the near-surface temperatures. The tuned model run with the old version, v5_MOD, captures the observed vertical temperature profile the best. The model run with the new version, v505_REF, also captures the near-surface temperatures and the inversion strength, but overestimates the height of inversion. All of the model runs successfully simulate the difference between rural and urban temperature profiles, including the UHI in the lowest 100 m above the ground, and a negative temperature anomaly over the city. Such anomaly corresponds to a so-called crossover-effect, which is known from the literature but is still poorly investigated (Duckworth & Sandberg, 1954; Khaikine et al., 2006; Lokoshchenko et al., 2016)

The key conclusion from the presented verification results is that the new version of COSMO model including TERRA_URB, 5.05urb4, in general successfully simulates the key features of the UHI of Moscow megacity for the considered cases, including the spatiotemporal variations of the UHI intensity. The results obtained with the new version (v505_REF runs) are generally consistent with the results obtained with the old version COSMO5.00_clm9_terraurb (v5_REF and v5_MOD runs). Moreover, even without any special tuning, the simulations with the new model version (v505_REF runs) show almost as good verification results as the carefully tuned simulations with the old model version (v5_MOD runs). Such result indicates the improvements that come from a use of the new ICON-based model physics in the new model version. However, in some cases the new model version is still not perfect, which is shown based on the example of the extreme winter frosts in Moscow.

Further improvements are expected from the tuning and calibration of the new model version, including the tuning for the namelist settings, the use of the skin-layer temperature scheme and the improvements of the external parameters for the TERRA_URB scheme.

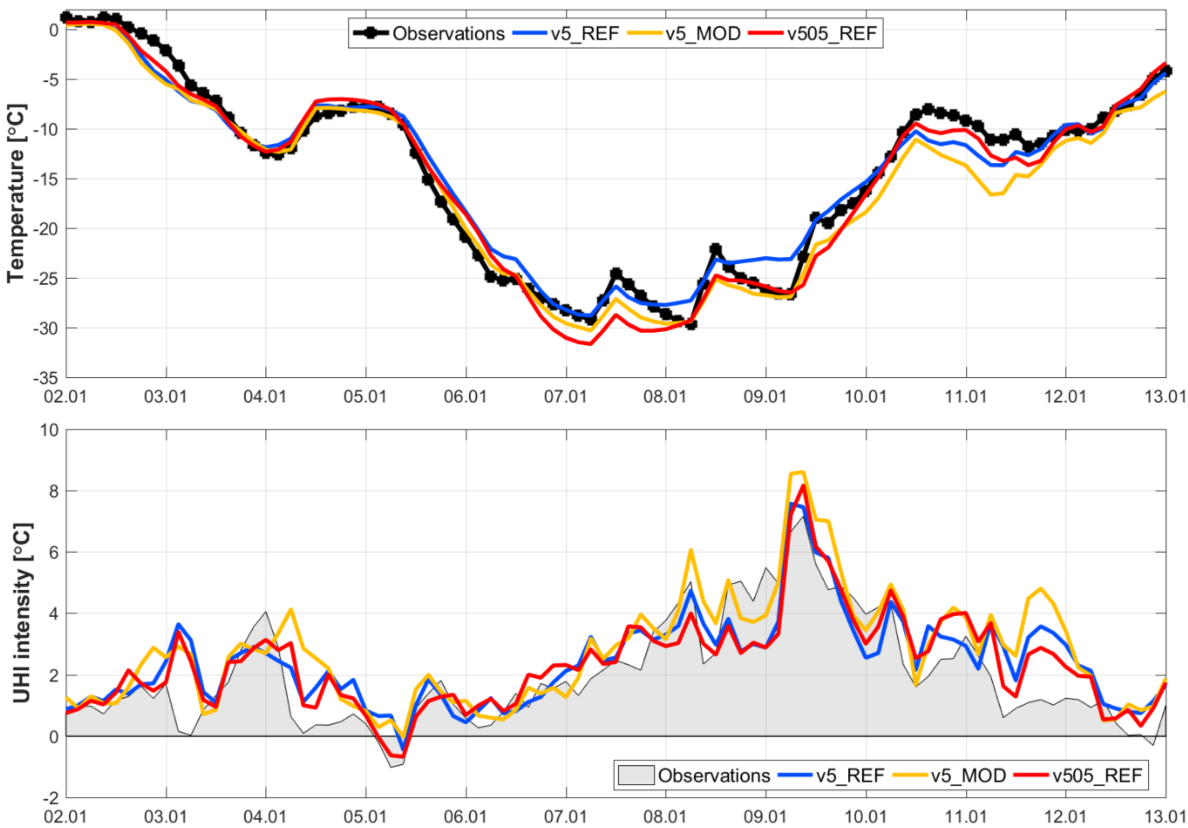

Figure 10. The variations of the mean rural air temperate and the UHI intensity for the city center (temperature difference between the value for Balchug weather stations and the mean rural value) according to observations and modelling results for case #4 (2-13 January 2017).

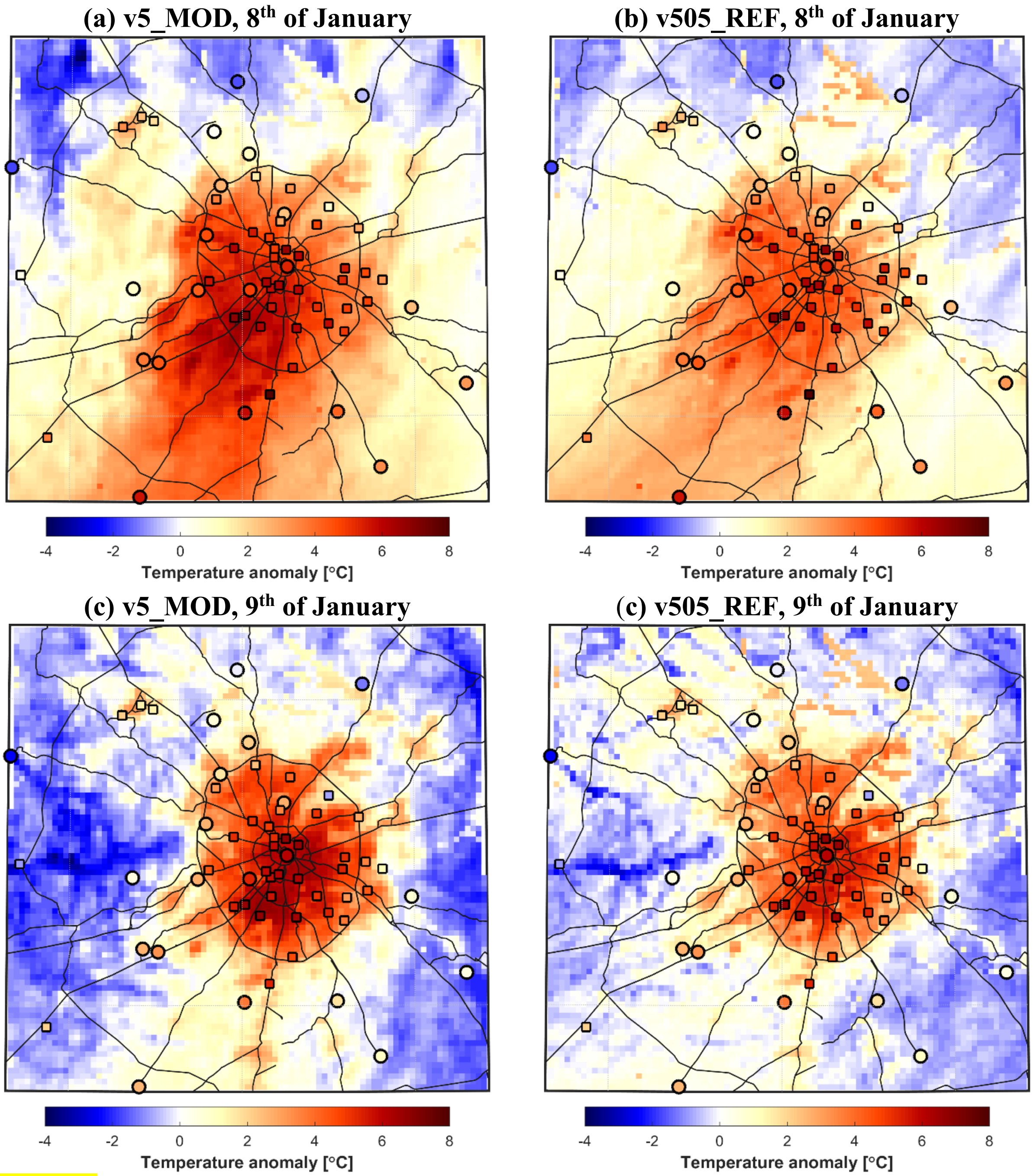

Figure 11. The spatial structure of the urban temperature anomaly in Moscow region according to observations (colored squares and circles) and simulations v5_MOD (a,c) and v505_REF (b,d), shown as colored background. The averaging is performed over the whole day of 8th of January 2017 (a, b) and 9th of January 2017 (c, d). The temperature anomaly is defined as a deviation from the mean rural value, averaged over 9 rural reference weather stations (see Figure 1).

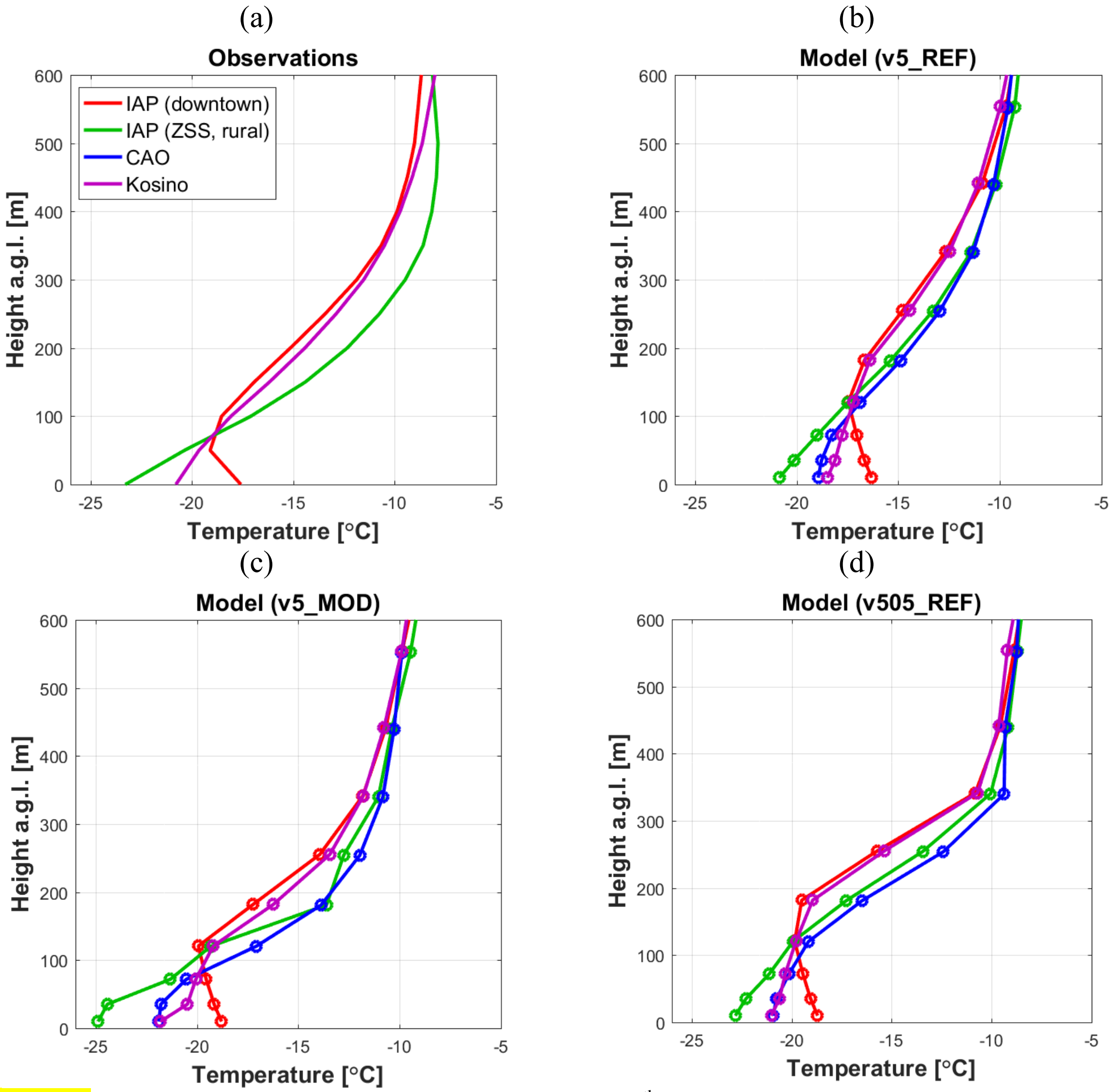

Figure 12. The vertical temperature profiles, averaged of 9th of January 2017, for four sites of Moscow region according to observations (a) and different model runs (b-d). The sites are: a city center (IAP site), rural area near Zvenigorod in 50 km to the west from Moscow (IAP ZSS site), Kosino site in the eastern suburb and CAO site in the northern suburb. The observations for CAO site are not available for the considered period**.**

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