



Investigation of urban effects on Moscow megacity climate based on simulations with COSMO-CLM model and TERRA_URB scheme

Mikhail Varentsov^{1,2*}, Hendrik Wouters^{3,4}, Pavel Konstantinov¹

¹) Lomonosov Moscow State University, Russia

²) A.M. Obukhov Institute of Atmospheric Physics, Moscow, Russia

³) KU Leuven, Belgium

⁴) Ghent University, Department of Forest and Water Management, Belgium

* mvar91@gmail.com

**Presentation is based on the results of PhD thesis of Mikhail Varentsov titled
“Analysis and modelling of mesoclimatic features of Moscow agglomeration”**

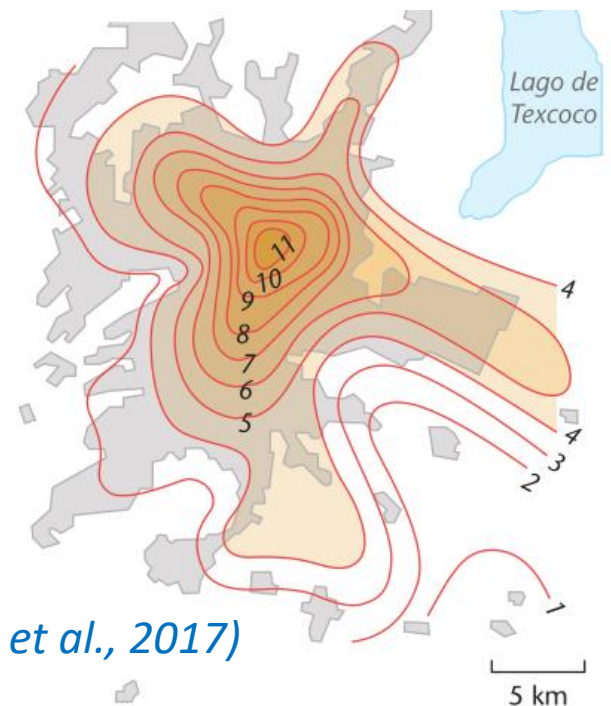
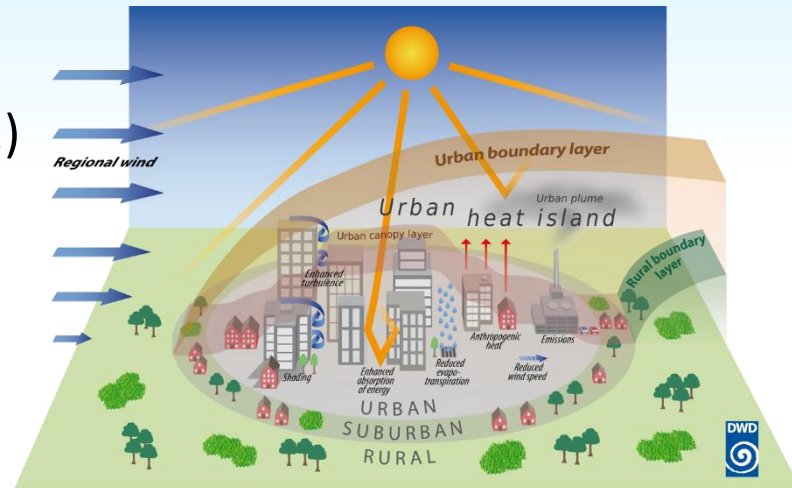


Motivation for research

Urbanization strongly modify the surface parameters (roughness, albedo, heat capacity, etc.) which determine the specific **urban climate features** – e.g. the urban heat island (UHI)

For **the megacities** the influence of urban surfaces is accumulated over tenth of kilometers, resulting in **mesoscale climate anomalies**, extending to the **ABL** and interacting with processes in lower troposphere (mesoscale circulations, convection, etc.)

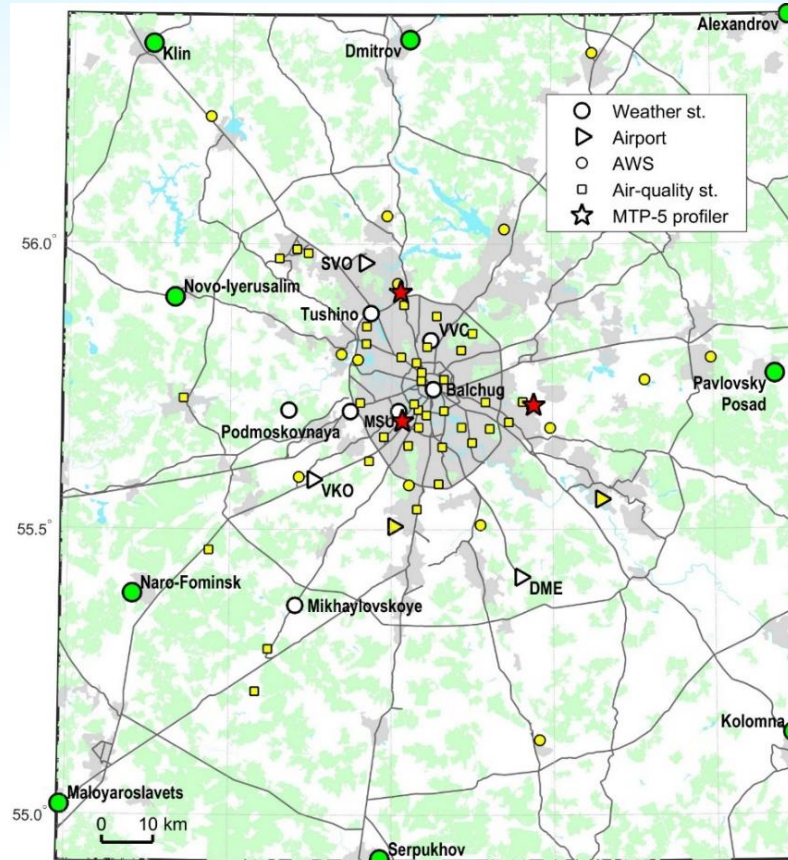
The most of the urban climate studies are focused on the canopy-layer UHI, while the knowledge about other urban-induced climate effects, especially in the ABL, is fragmented and insufficient for making climate-related conclusions



Moscow as test-bed for urban climate modelling

Key features of Moscow megacity as place of urban climate research:

- ✓ Biggest agglomeration in Europe ($\approx 17 \cdot 10^6$ people)
- ✓ Flat and homogenous landscape around the city
- ✓ Continental climate with warm summer and cold winter
- ✓ Strong UHI with mean intensity of $2\text{ }^\circ\text{C}$ and maximum intensity up to $13\text{ }^\circ\text{C}$ (Lokoschenko, 2014)
- ✓ Spatial building features (high-rise blocks of flats, etc.)
- ✓ **Good observation network**



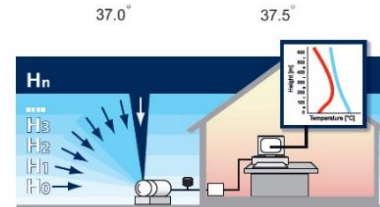
Meteorological observatory of Moscow University (MSU)



Balchug st. (city center)



Air-quality monitoring st.



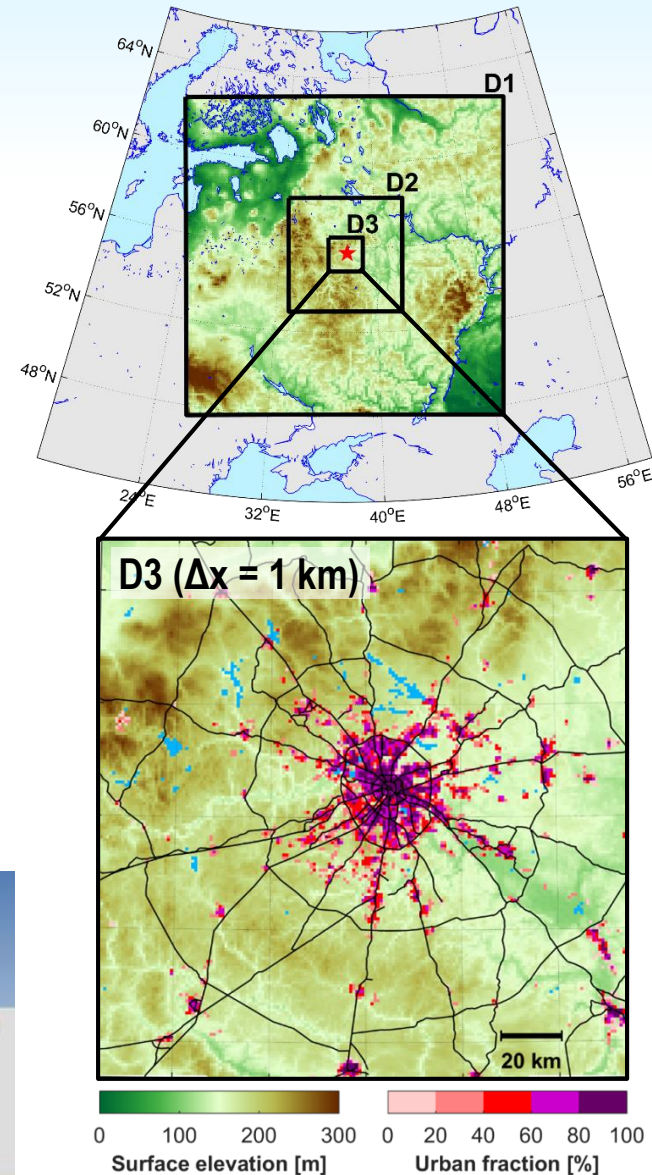
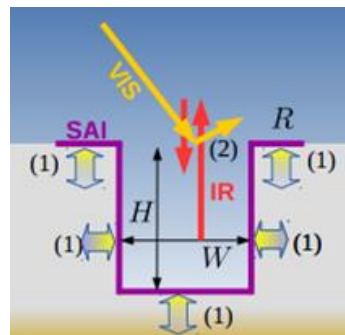
MTP-5 temperature profiler and its principle of operation



New AWS

Modelling framework

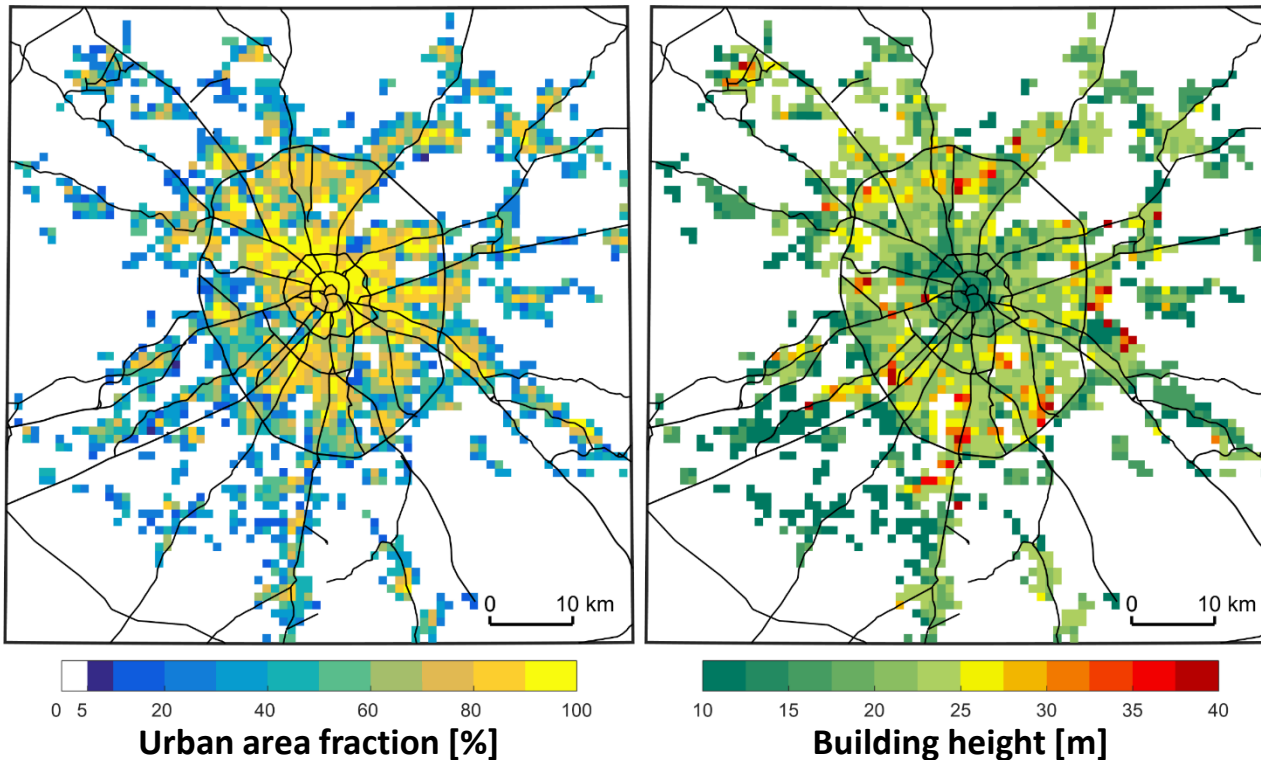
- ✓ **COSMO-CLM regional climate model**
- ✓ **Simulations for 10 summer seasons with 1 month of spin up, main focus further for summer 2014**
- ✓ **3 steps of dynamical downscaling (12 km → 3 km → 1 km)**
- ✓ **Boundary conditions for the first domain from ERA-Interim reanalysis + spectral nudging for U, V and T**
- ✓ **Tuned model configuration including reduced turbulent mixing in stable condition according (Cerenzia et al., 2014) [$tkhmin = tkmmin = 0.1$, $pat_len = 100$] and new evaporation & canopy schemes (Schulz, 2016; Schulz, Vogel, 2017) [$itype_evsl = 4$; $itype_canopy = 2$]**
- ✓ **TERRA_URB urban scheme (Wouters et al., 2015; 2016)**
 - SURY (Semi-empirical Urban canopy parameterization)
 - Tile approach for urban/rural area
 - Anthropogenic heat flux calculated from mean annual value with “climatological” annual and daily cycles according (Flanner, 2009)
- ✓ **Numerical experiments with urban scheme switched on (URB) and off (noURB)**



Urban canopy parameters

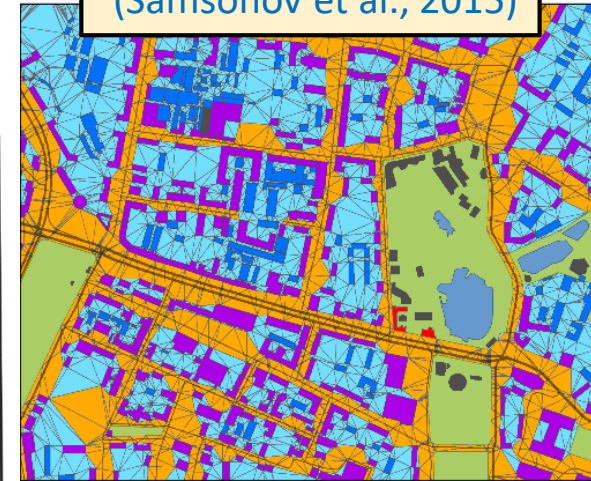
Required urban canopy parameters for TERRA_URB:

- Urban area fraction (= impervious surface fraction, ISA)
- Annual-mean anthropogenic heat flux (AHF)
- Building area fraction
- Building height H
- Street canyon aspect ratio (H/W)

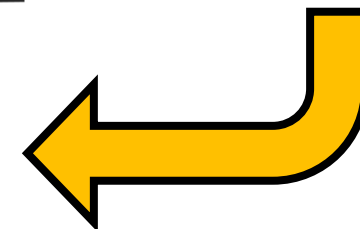


3) Calculation of the required parameters

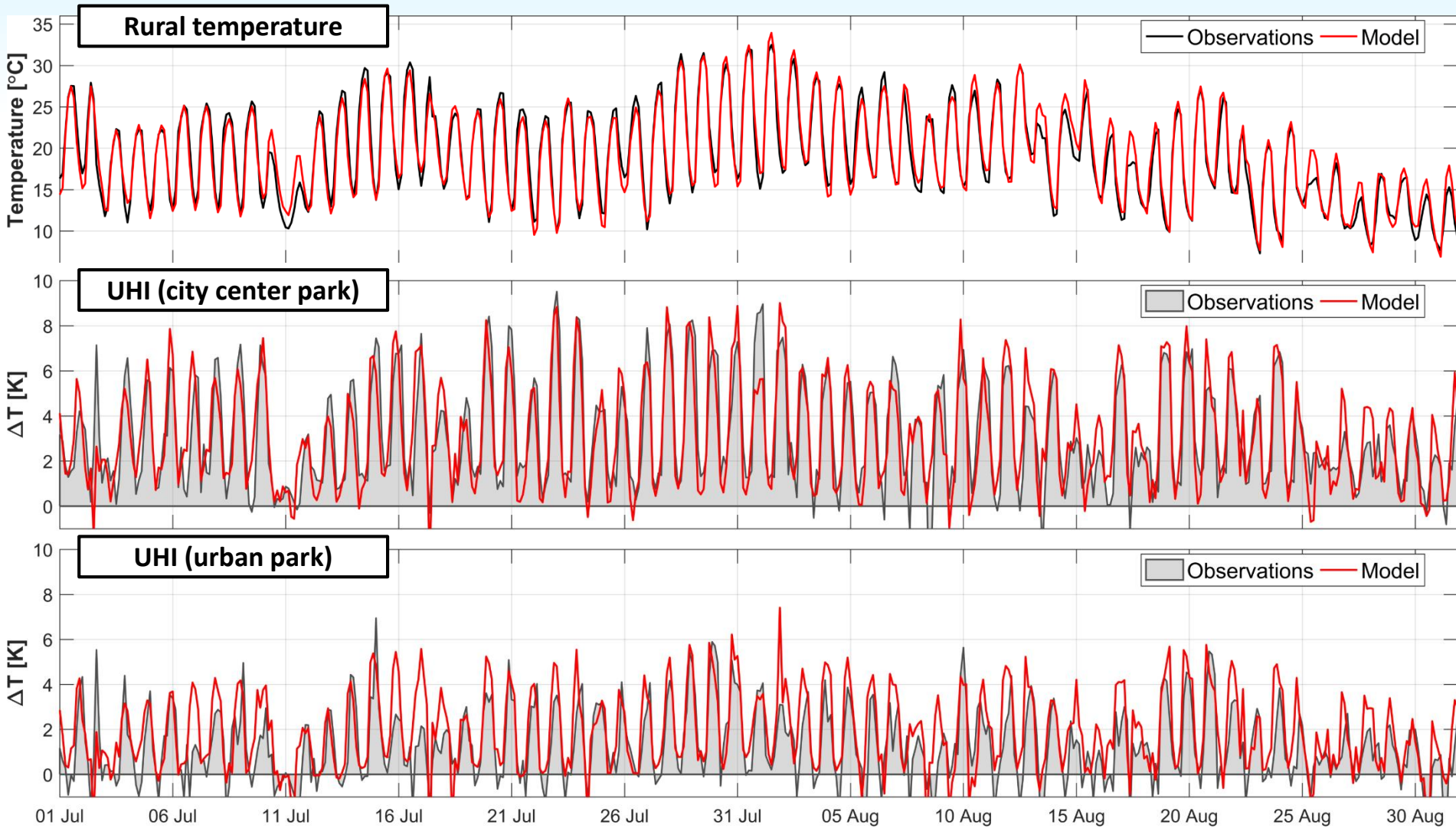
1) GIS-processing of
OpenStreetMaps data
(Samsonov et al., 2015)



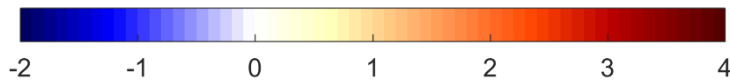
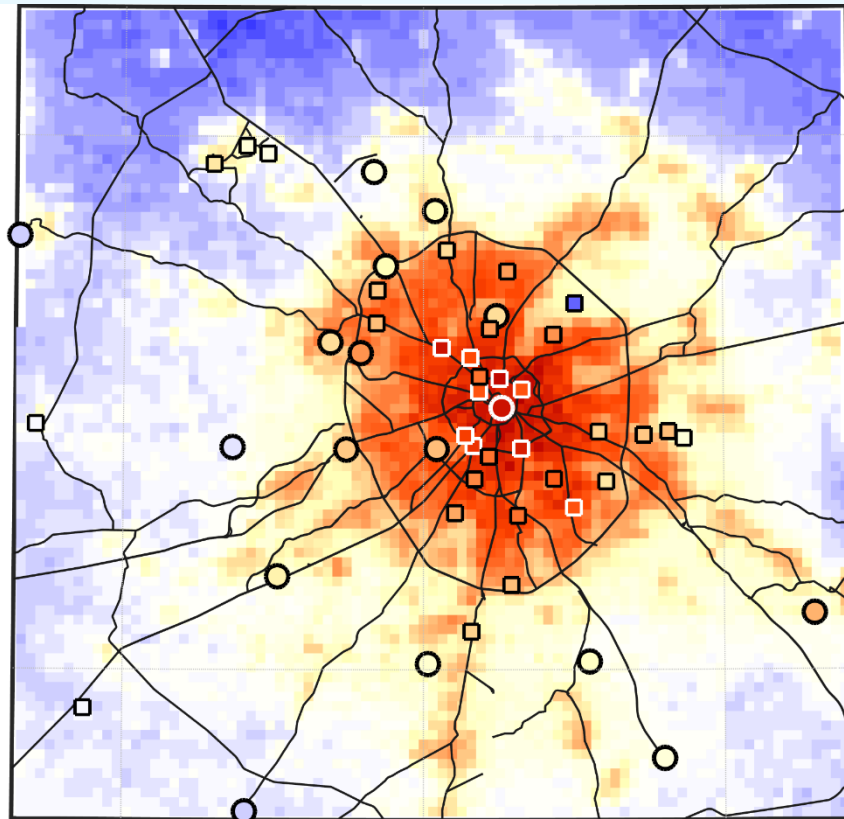
2) Averaging over given
model grid cells



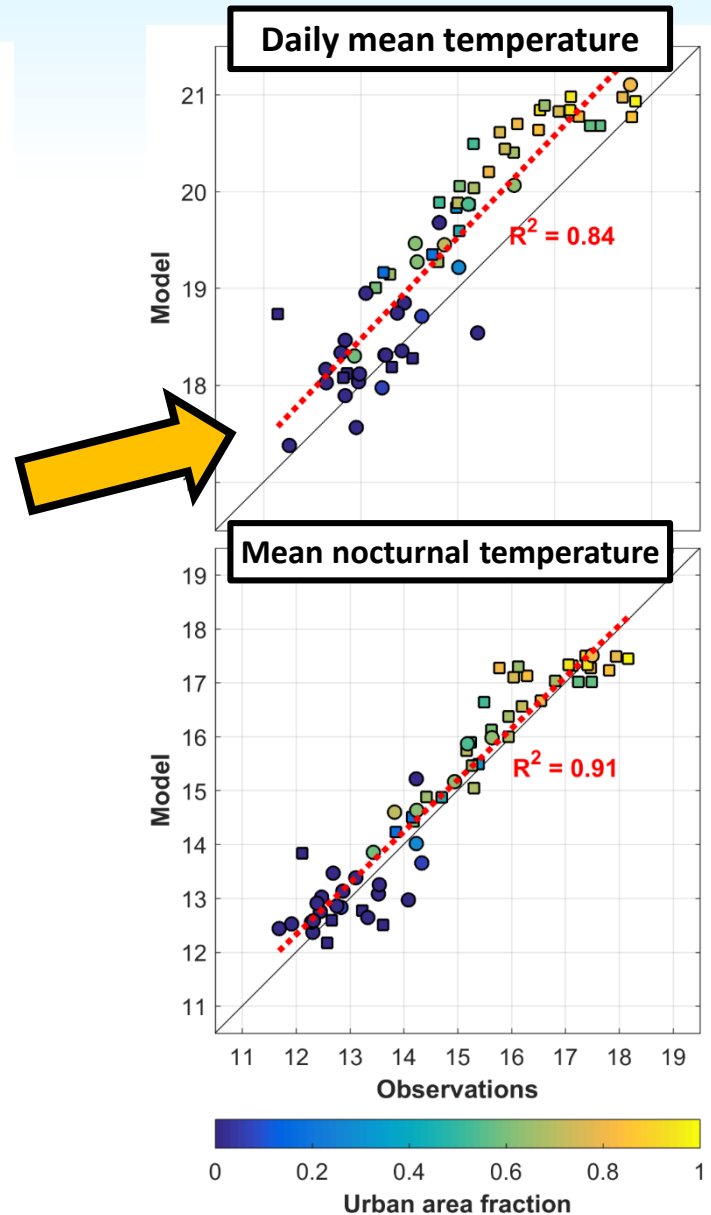
Model-to-observations comparison



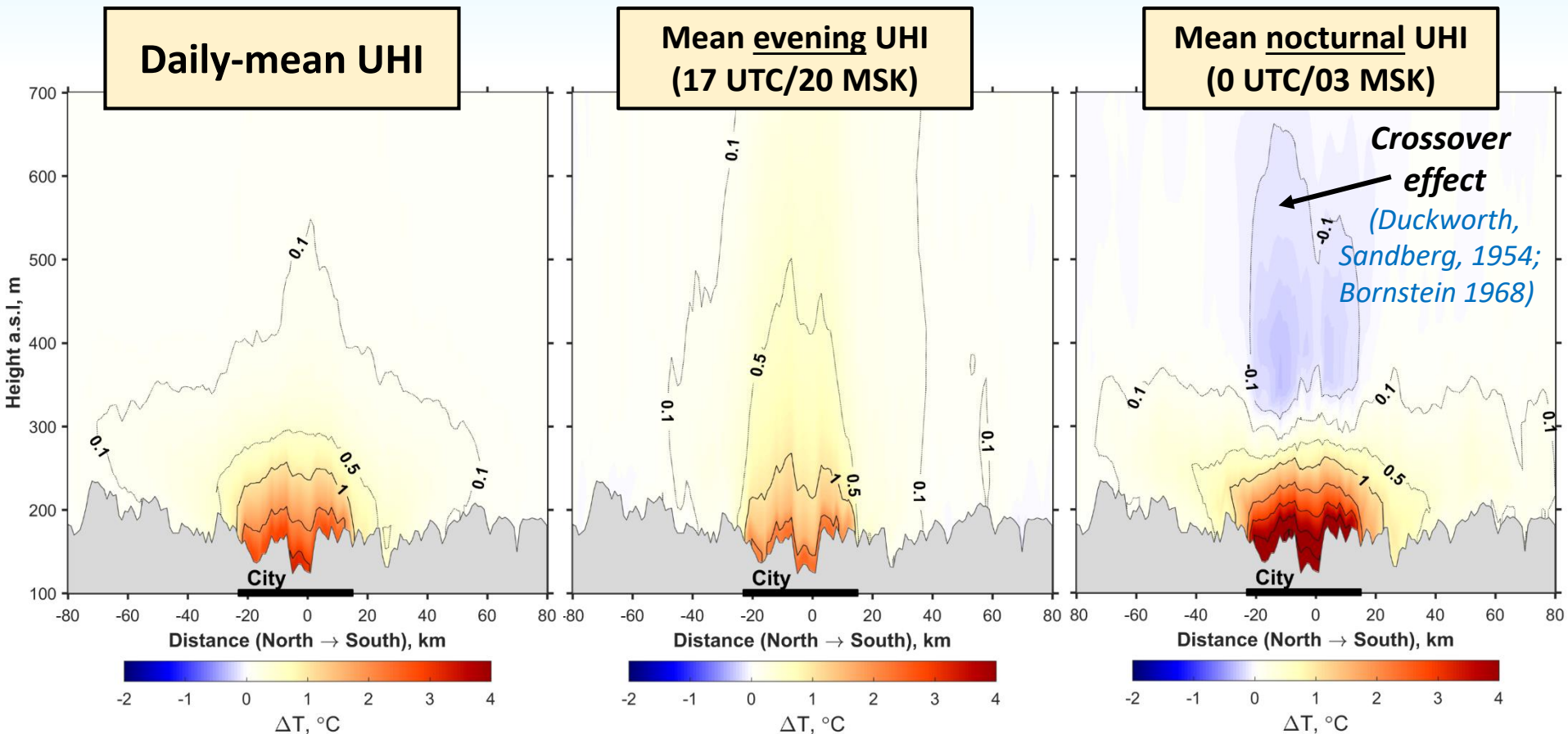
Model-to-observations comparison



Mean temperature anomaly for summer 2014
(deviation from mean rural value)
modelling (shading) and observations (colored circles)



Vertical structure of the UHI

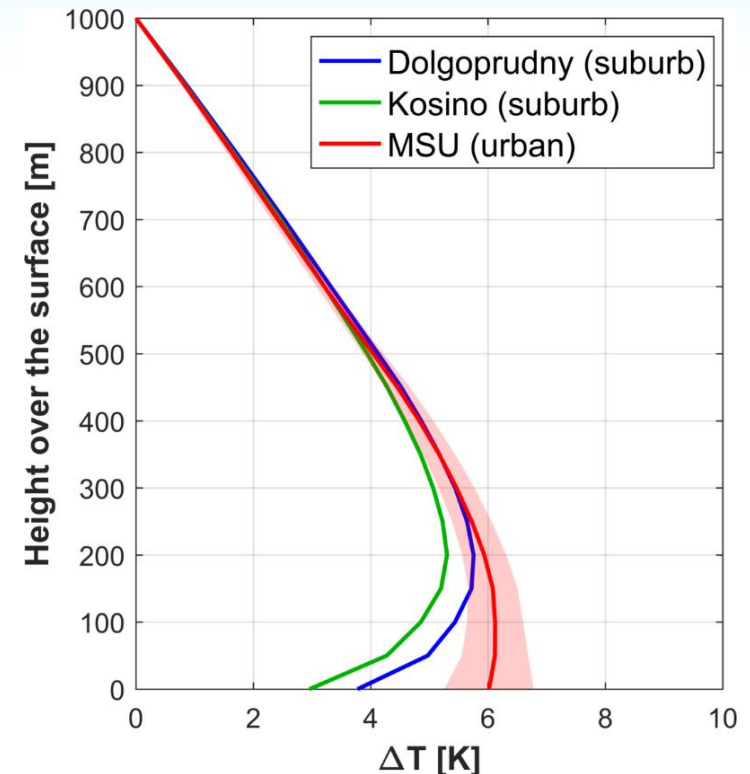
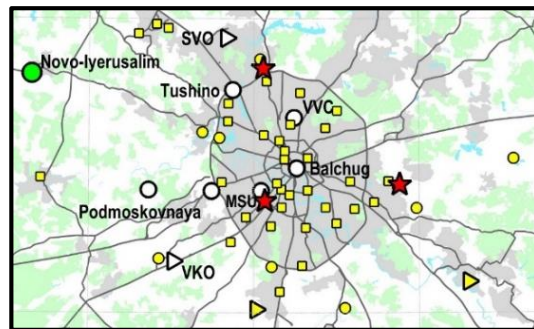
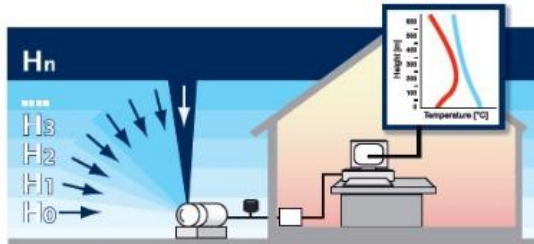


Modelling results qualitatively agrees with the estimates of Moscow UHI vertical extent based on **contact measurements** (Lokoshchenko et al., 2016), **remote sensing by ground-based temperature profilers** (e.g. Khaikine et al., 2006) and **satellite-based remote sensing data** (Gorlach et al., 2017; Kislov et al., 2017)

Vertical structure of the UHI

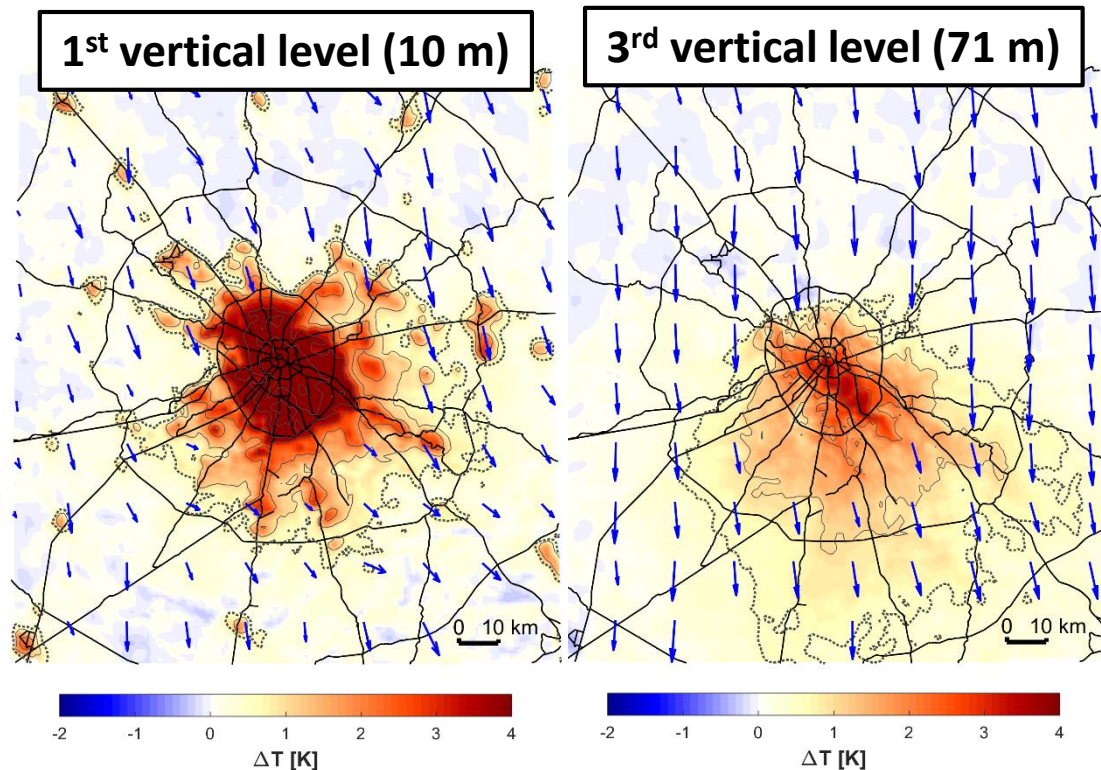
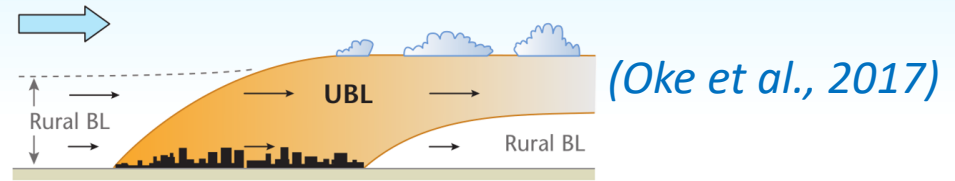
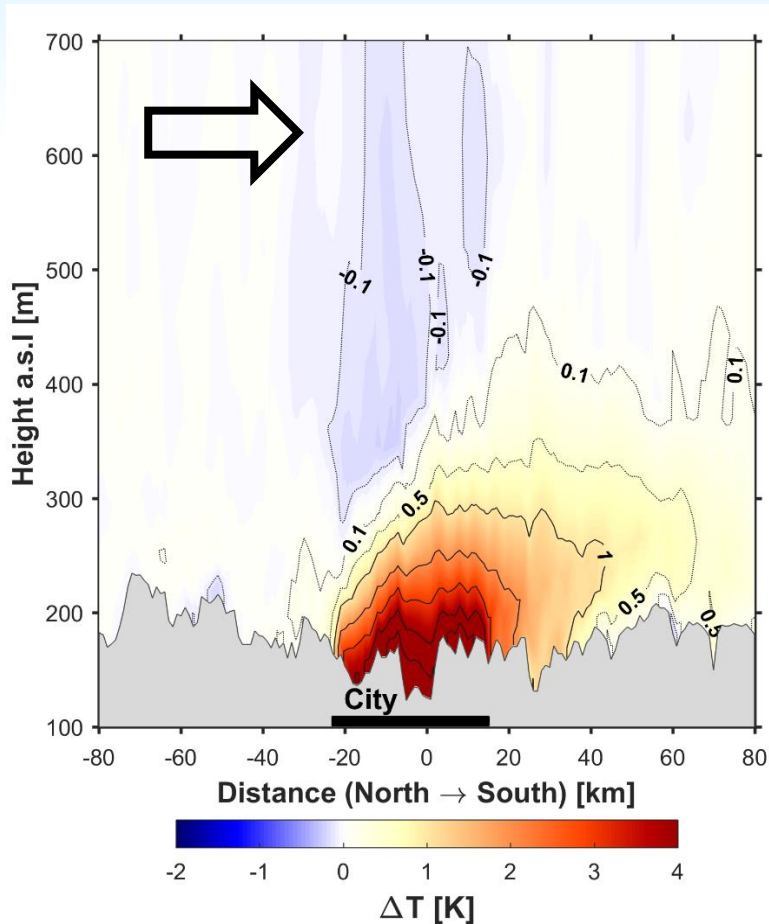
Recent experiment based on MTP-5 temperature profilers:

- Observations at three points (one urban and three suburban)
- Vertical range: **0 – 1000 m**
- Period of observations: **17 April – 3 July 2015**



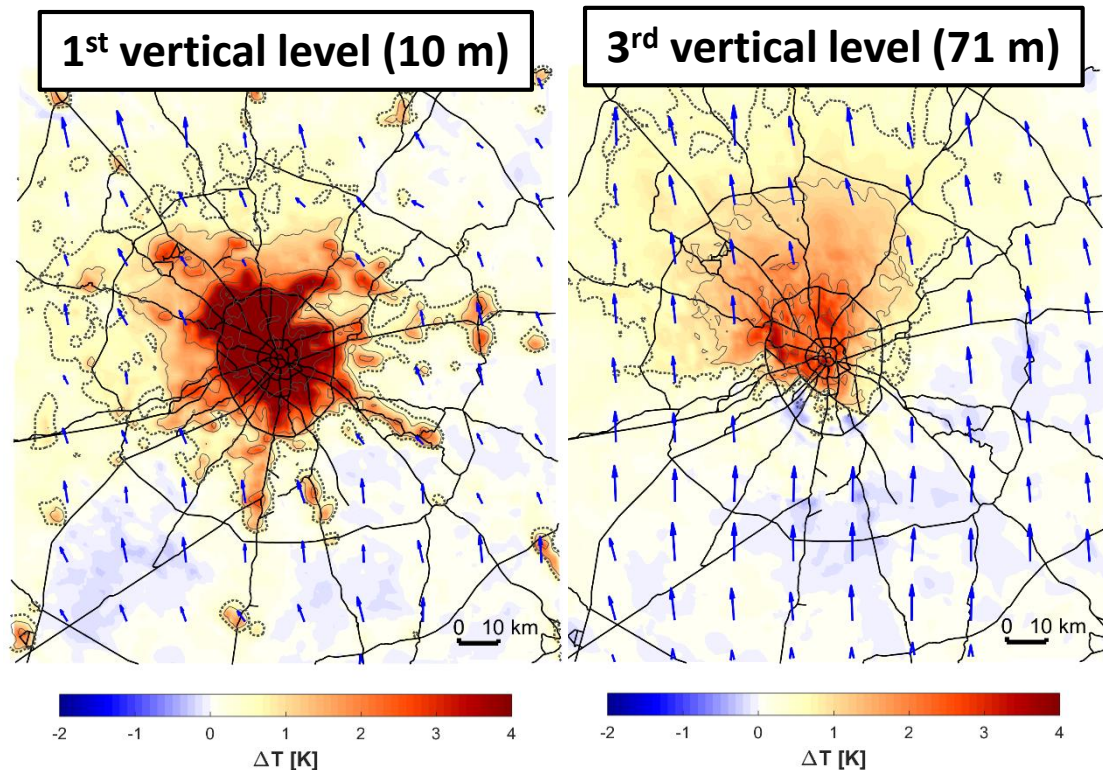
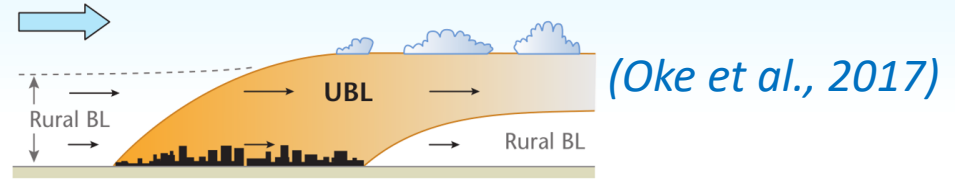
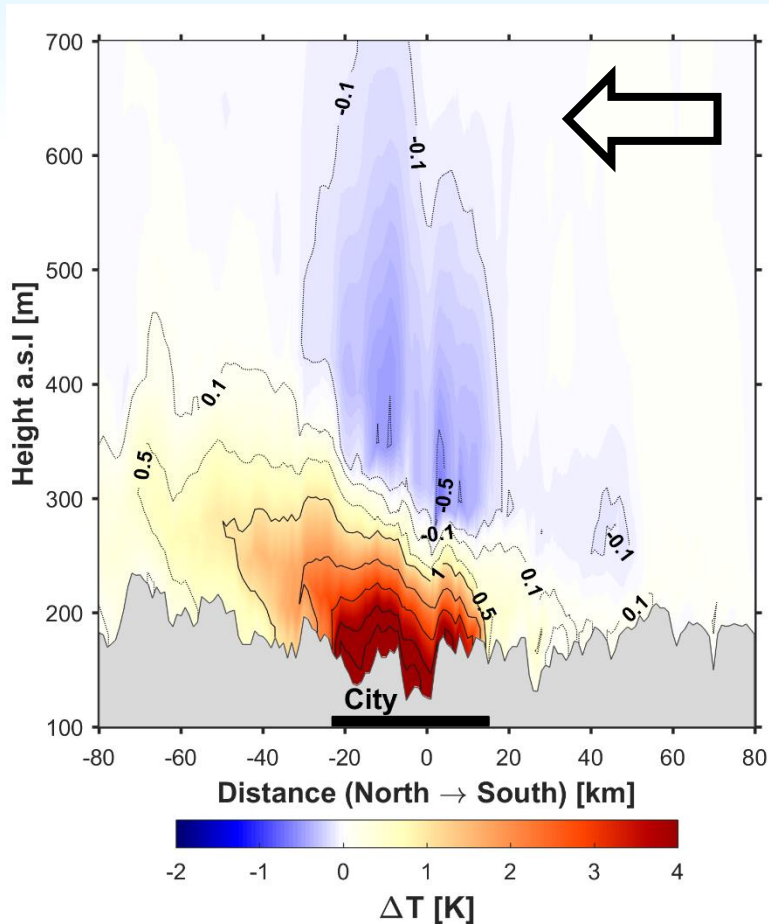
Vertical profiles of mean temperature deviation from the top level (ΔT) according to MTP-5 measurements **for nocturnal cases** with pronounced UHI during 17 April–3 July 2015

Urban heat plumes



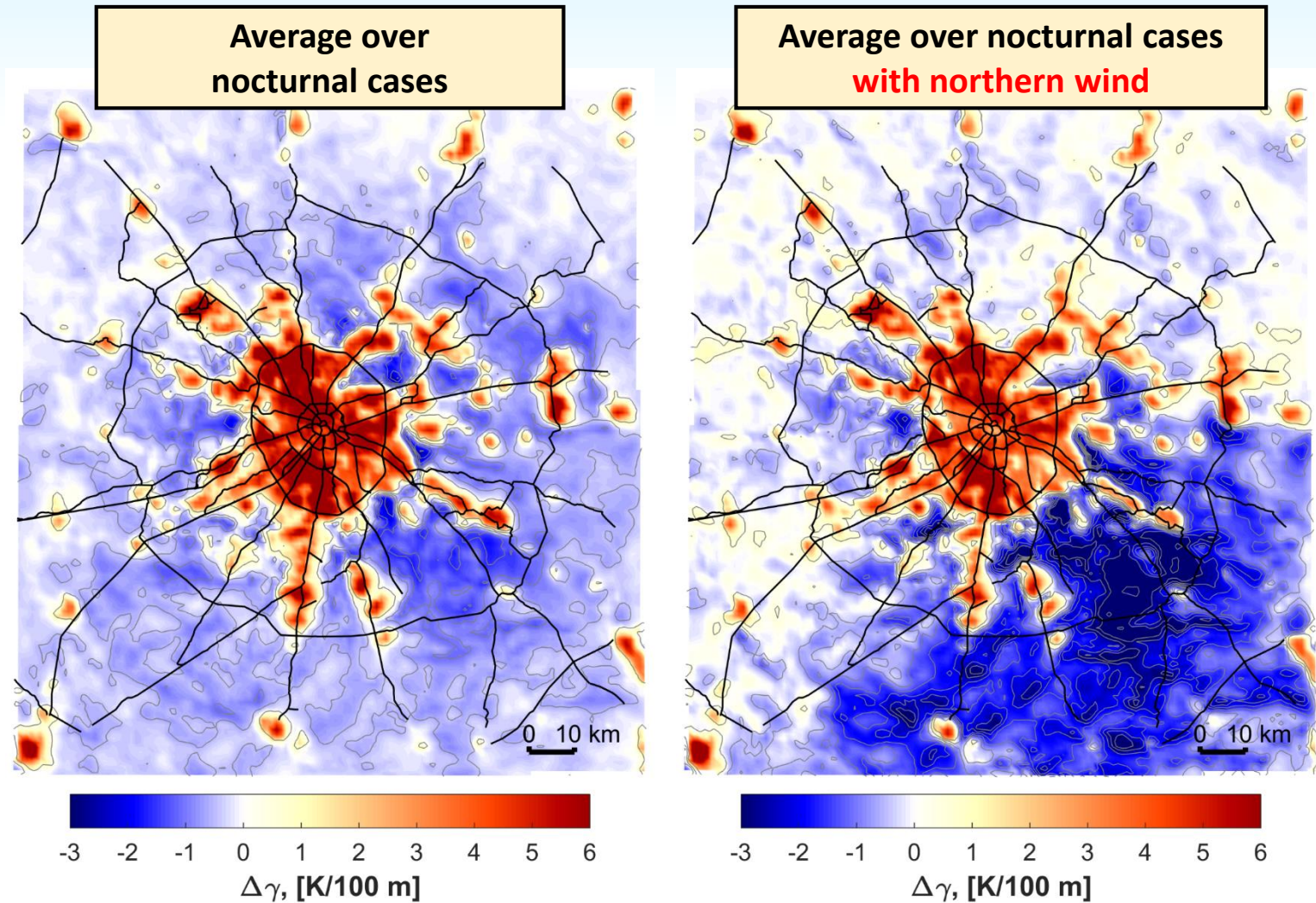
Vertical cross-section and maps for urban-induced temperature anomaly ($\Delta T = T_{\text{URB}} - T_{\text{noURB}}$) averaged over summer 2014, **for nocturnal hours** (1-2 UTC / 3-4 MSK) with prevailing **northern wind**

Urban heat plumes



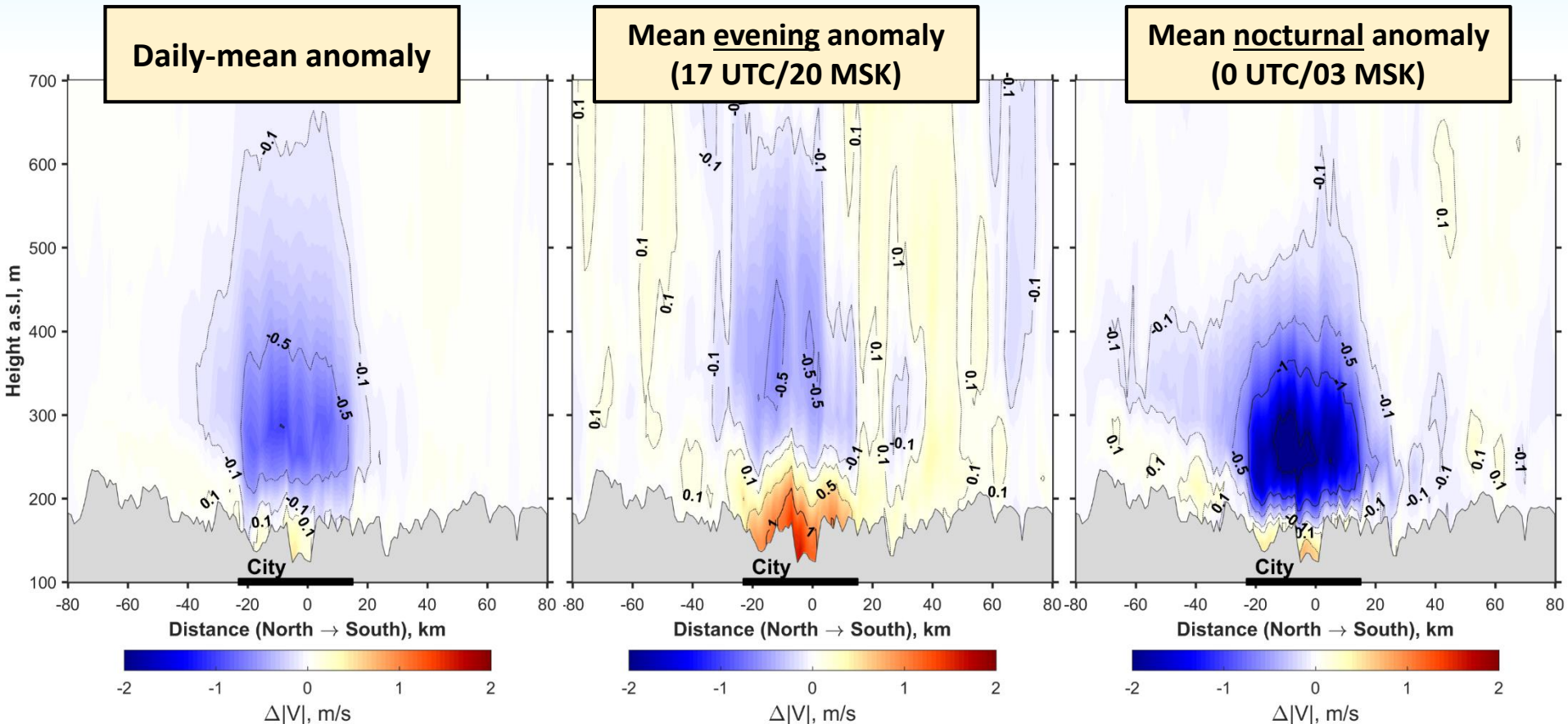
Vertical cross-section and maps for urban-induced temperature anomaly ($\Delta T = T_{\text{URB}} - T_{\text{noURB}}$) averaged over summer 2014, **for nocturnal hours** (1-2 UTC / 3-4 MSK) with prevailing **southern wind**

Urban effect on the lapse rate



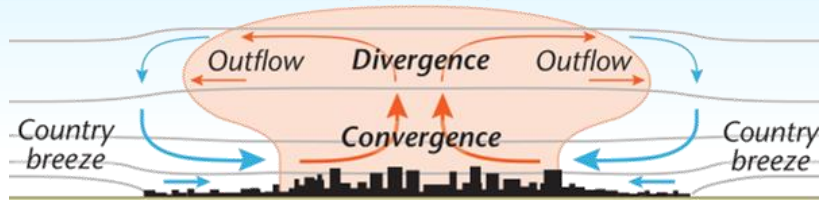
Urban-induced lapse rate anomaly $\Delta\gamma$ (where $\gamma = -dT/dz$) calculated between two lowest model levels (10 и 35 m), averaged over summer 2014 **for nocturnal hours** (1-2 UTC / 3-4 MSK)

Urban effect on the wind speed

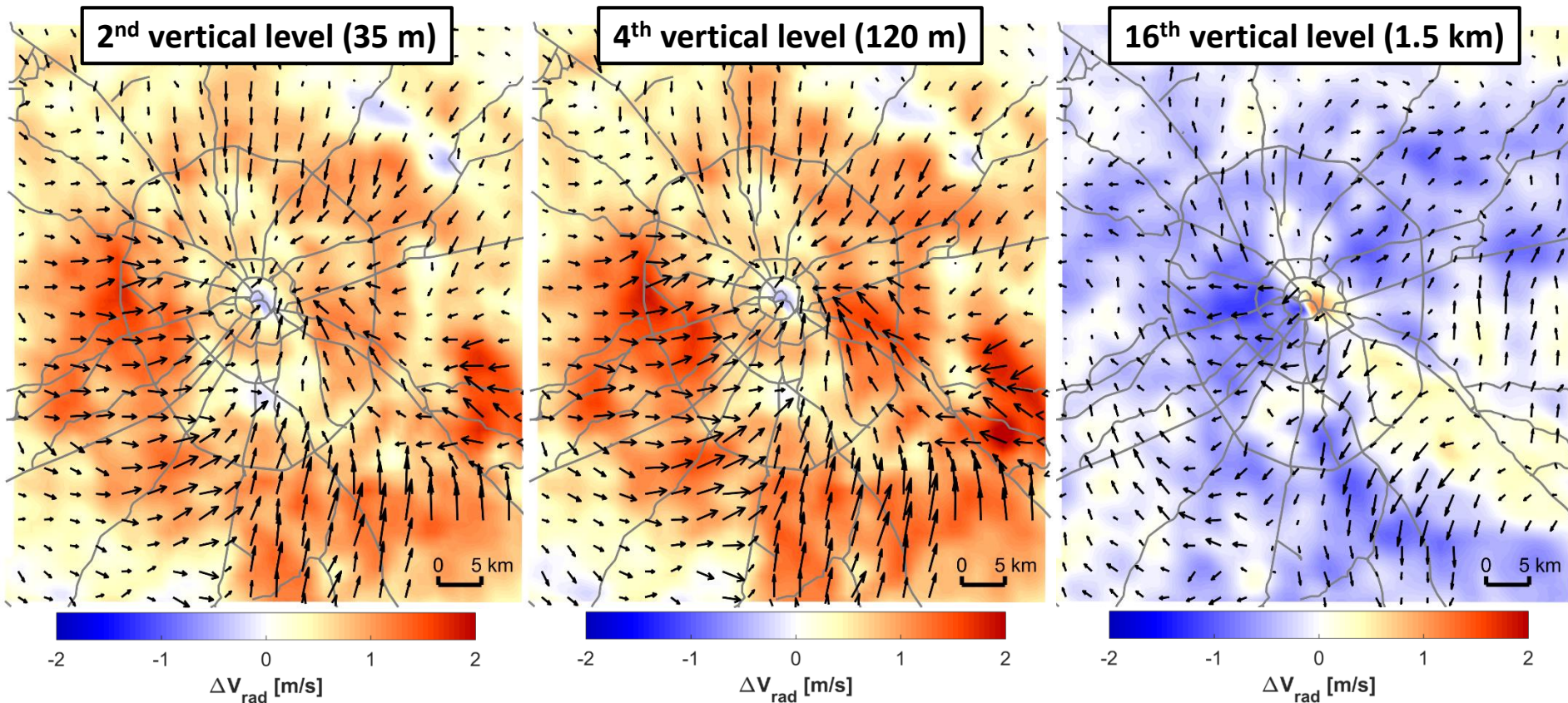


Vertical cross-sections of the urban-induced wind speed anomaly ($\Delta|V| = |V|_{\text{URB}} - |V|_{\text{noURB}}$) averaged over summer 2014 (for selection of days with $\text{UHI}_{\text{max}} > 4^\circ\text{C}$, approx. 78% of whole period)

Urban breeze effect (evening)

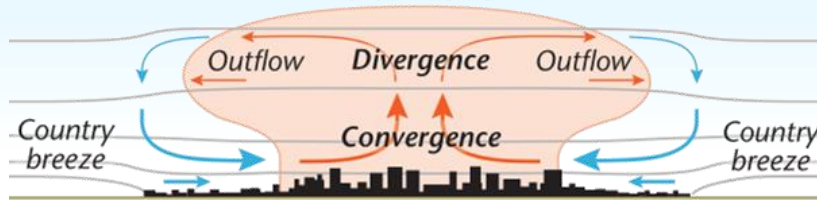


(Oke et al., 2017)

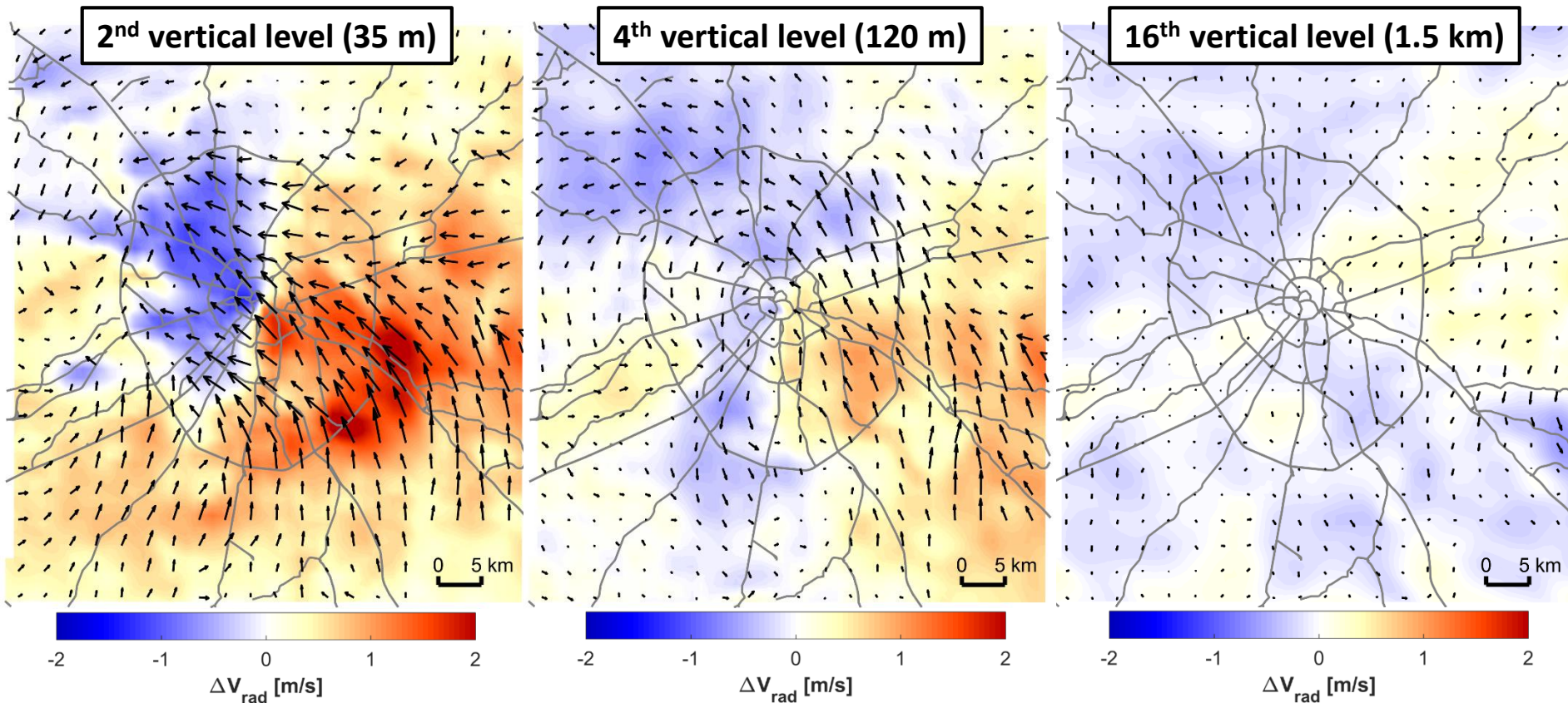


Urban-induced anomalies of the wind ($\Delta\vec{V}$, black arrows) and its radial component (ΔV_{rad} , arrows) averaged over summer 2014, **for evening hours** (15-16 UTC / 18-19 MSK) **with low wind speed**

Urban breeze effect (night)

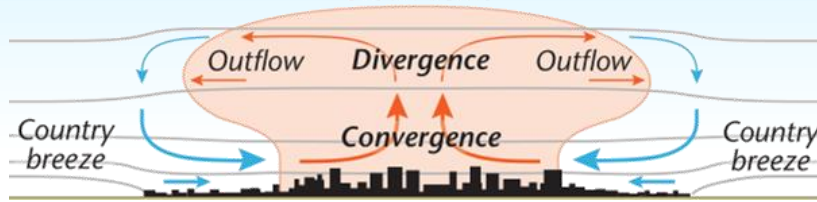


(Oke et al., 2017)

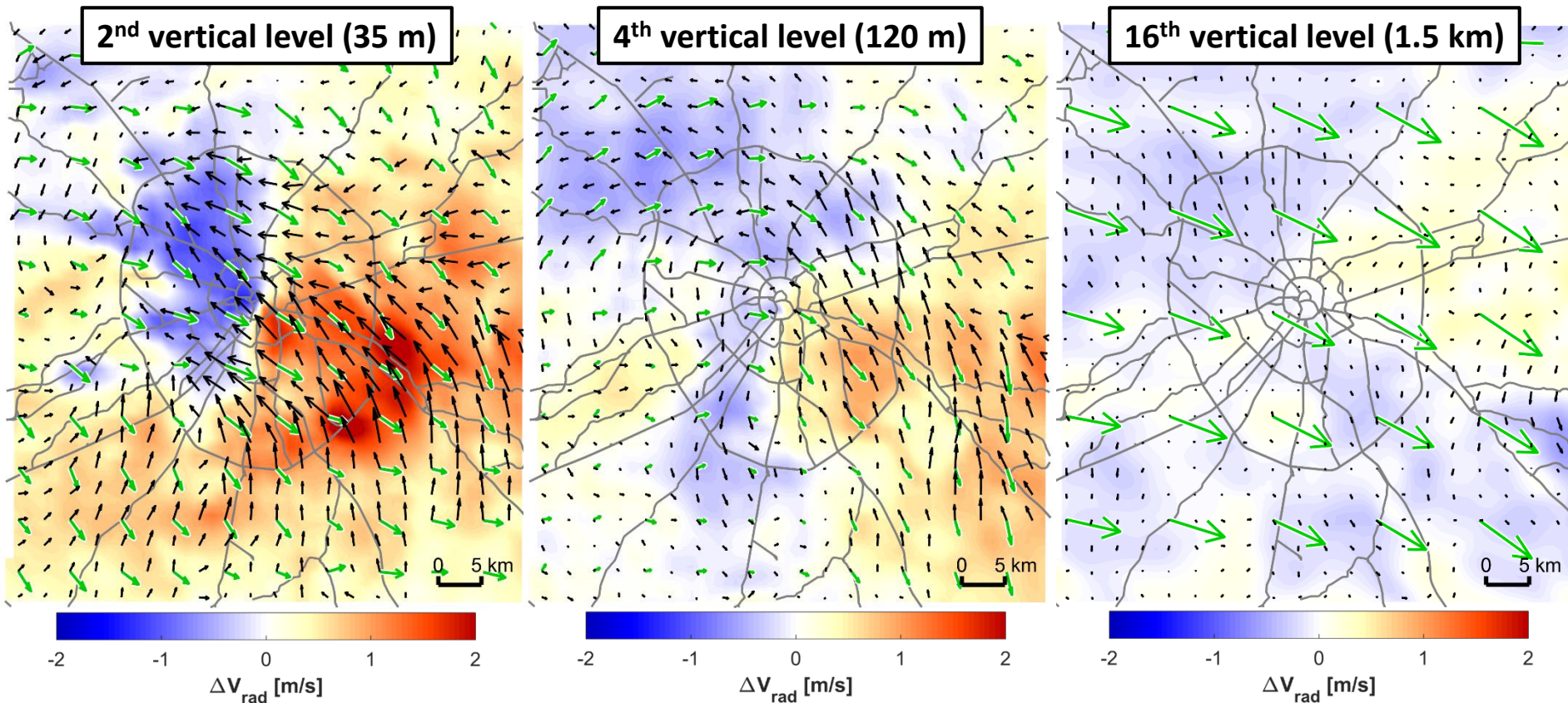


Urban-induced anomalies of the wind ($\Delta \vec{V}$, black arrows) and its radial component (ΔV_{rad} , arrows) averaged over summer 2014, **for nocturnal hours** (0-1 UTC / 3-4 MSK) **with low wind speed**

Urban breeze effect (night)



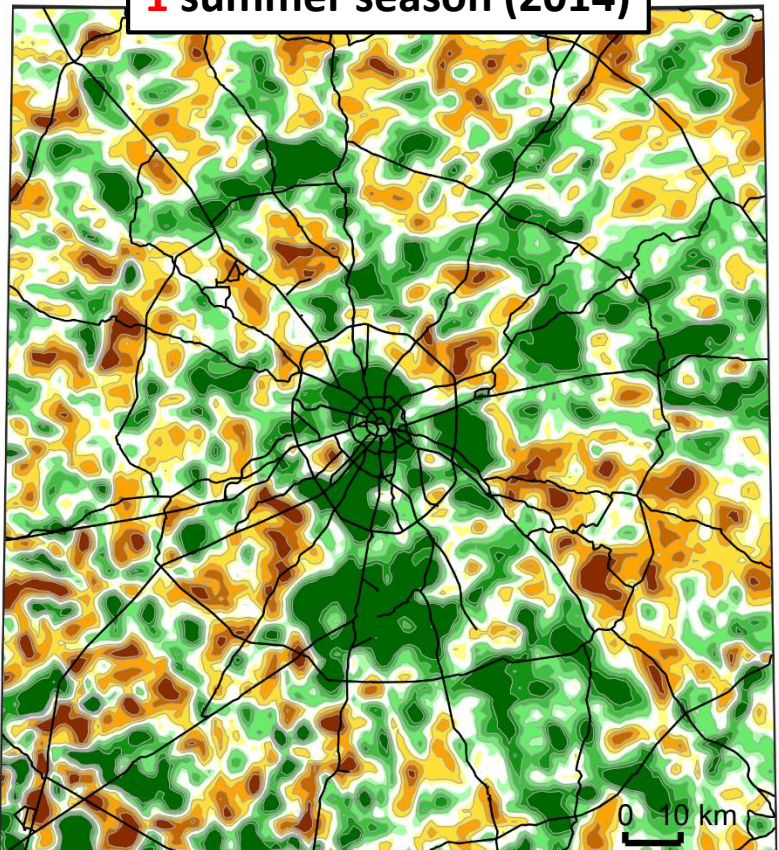
(Oke et al., 2017)



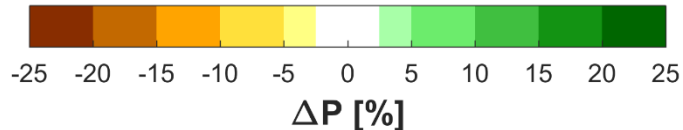
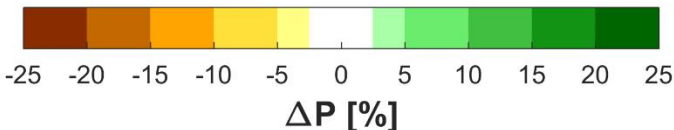
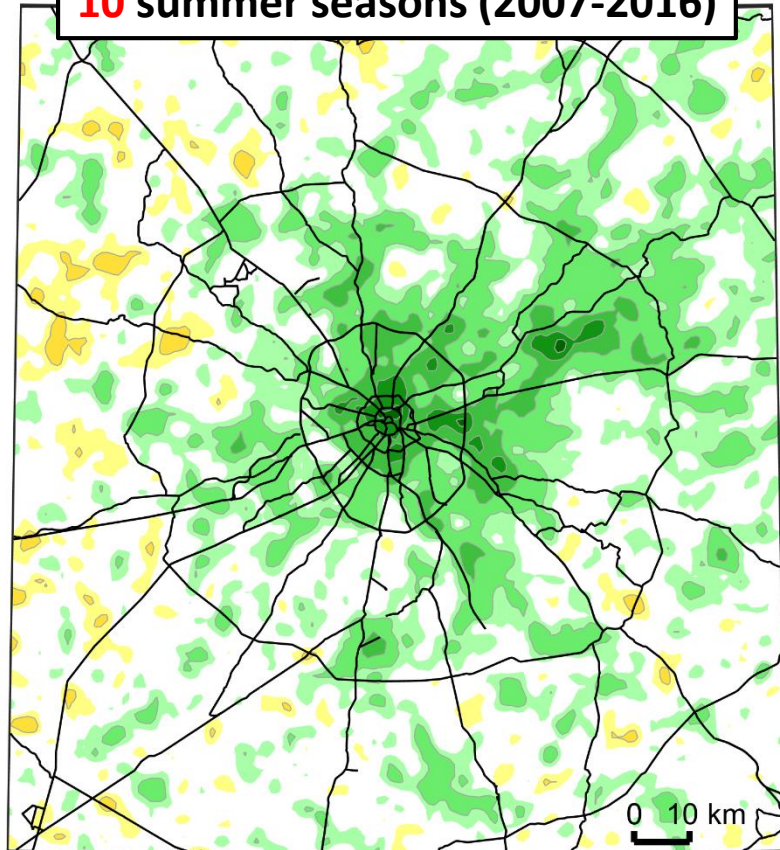
Urban-induced anomalies of the wind ($\Delta\vec{V}$, black arrows) and its radial component (ΔV_{rad} , arrows) averaged over summer 2014, **for nocturnal hours** (0-1 UTC / 3-4 MSK) **with low wind speed**

Urban effects on precipitation & cloudiness

1 summer season (2014)



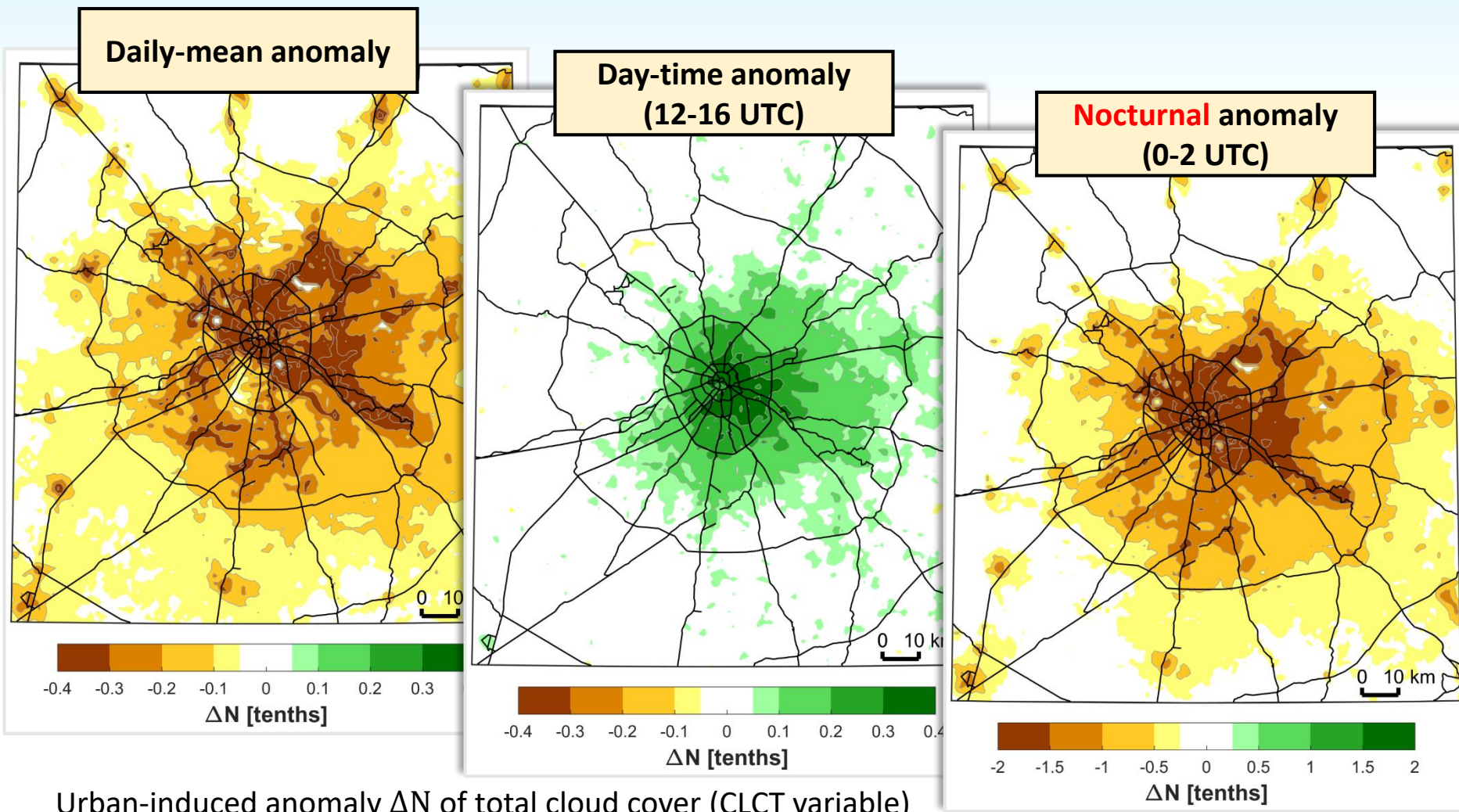
10 summer seasons (2007-2016)



Urban-induced anomaly of summer precipitation amount

$$\Delta P = 100 \cdot (P_{\text{URB}} - P_{\text{noURB}}) / P_{\text{noURB}}$$

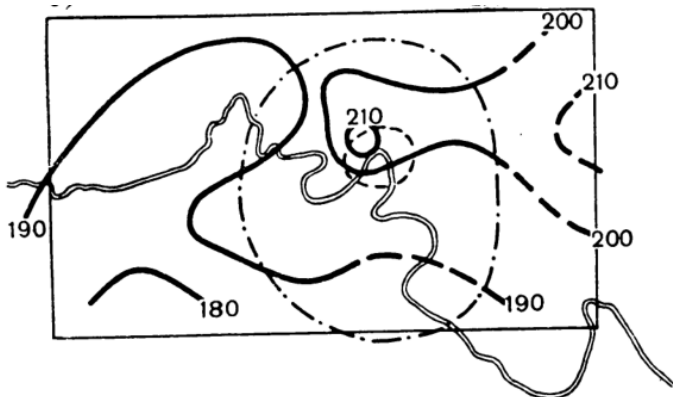
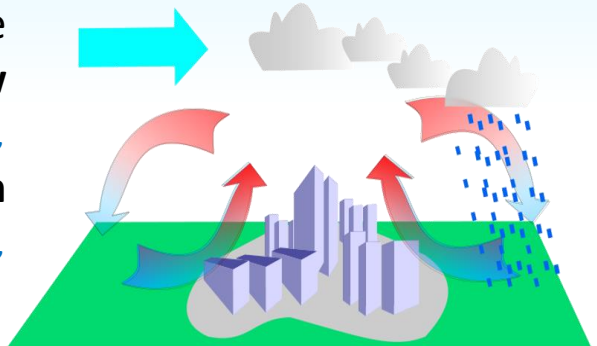
Urban effects on precipitation & cloudiness



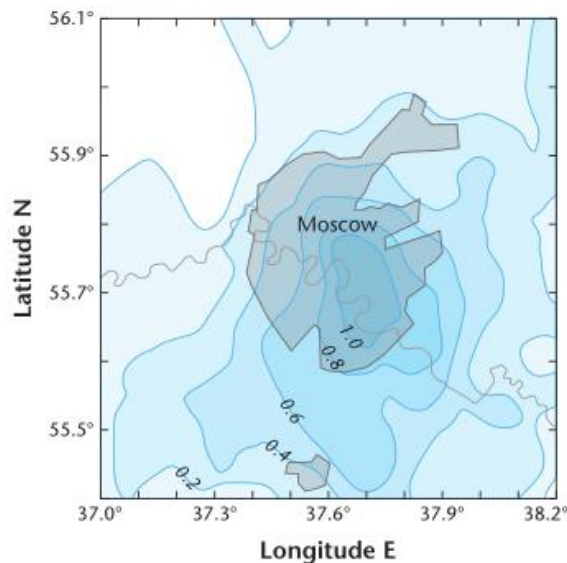
Urban-induced anomaly ΔN of total cloud cover (CLCT variable) in tenth (10 = total cloud cover) averaged over 10 summer seasons

Urban effects on precipitation & cloudiness

Modelling results for summer precipitation and daytime cloudiness are consistent with various observations for Moscow (*Climate of Moscow...*, 1969, in Russ.; Stulov, 1993; Romanov, 1999) and overall hypothesis of the urban-induced amplification of the moist convection (e.g. Bornstein, Lin, 2000; Dixon, Mote, 2003; Han et al., 2014; Zhu et al., 2017)



Summer precipitation amount in Moscow region according to the dense network of weather stations existed on 1950th (*Climate of Moscow...*, 1969, in Russ.)



Summertime daytime cloudiness anomaly according to satellite images (*Romanov, 1999; modified in Oke et al., 2017*)

References

Key references (for full list see our recent paper):

- Wouters et al., 2016. Efficient urban canopy parametrization for atmospheric modelling: description and application with the COSMO-CLM model for a Belgian Summer. *GMD*, 9, pp.3027–3054.
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atmosphere



Article

Megacity-Induced Mesoclimatic Effects in the Lower Atmosphere: A Modeling Study for Multiple Summers over Moscow, Russia

Mikhail Varentsov ^{1,2,*}, Hendrik Wouters ^{3,4}, Vladimir Platonov ¹ and Pavel Konstantinov ¹

- ¹ Faculty of Geography / Research Computing Center, Lomonosov Moscow State University, 1 Leninskiye Gory, Moscow 119991, Russia; vplatonov86@gmail.com (V.P.); kostadini@mail.ru (P.K.)
 - ² A.M. Obukhov Institute of Atmospheric Physics, 3 Pyzhevskiy Pereulok, Moscow 119017, Russia
 - ³ Department of Forest and Water Management, Ghent University, 9000 Ghent, Belgium; Hendrik.Wouters@ugent.be
 - ⁴ Division of Geography and Tourism, KU Leuven, 3001 Leuven, Belgium
- * Correspondence: mvar91@gmail.com

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Abstract: Urbanization leads to distinct meteorological features of urban environments, and one of the best-known is the urban heat island (UHI) effect. For megacities, these features become mesoscale phenomena (scale ≥ 10 km) that are amplified by the tropospheric feedbacks, and have substantial implications on human well-being. For the first time, a three-dimensional statistical description of the megacity-induced meteorological effects extending towards the lower troposphere for summer is acquired on a quasi-climatological timescale (a decade) based on high-resolution (1 km) simulations for Moscow with the COSMO-CLM model with and without its urban canopy model TERRA_URB. Our results confirm the features from previous observational and modeling studies, including the UHI itself, the cooling effect above established by the cross-over effect, the urban dry/moist islands and the urban breeze circulation. Particularly, the UHI shows a strong diurnal variation in terms of intensity and vertical extent between daytime (≈ 0.5 K/ ≈ 1.5 km) and nighttime (> 3 K/ ≈ 150 m). We have discovered a systematic veering in the downwind shift of the UHI spatial pattern established by the Coriolis effect, and an enhanced stable stratification of the rural surroundings established by the urban plumes further downwind. Finally, extending the analysis to multiple summers demonstrates a substantial increase in summer precipitation (up to +25%) over the city center and its leeward side. These urban-caused mesoclimatic effects need to be taken into account in weather and climate services, including the design of future megacities.

Keywords: urban climate; urban heat island; urban dry island; urban breeze; regional climate modeling; COSMO; crossover effect; urban plume; urban precipitation enhancement

Conclusion

- ✓ COSMO-CLM model, coupled to TERRA_URB urban scheme and supplied by realistic GIS-derived urban canopy parameters, **has successfully simulated summer UHI of Moscow megacity**, its spatiotemporal variability and its vertical structure.
- ✓ **The model has simulated a variety urban climate effects, known before from episodic and fragmented studies** - urban heat plumes, urban breeze circulation, urban effects on precipitation and cloudiness.
- ✓ Moreover, **the new urban climate effects were discovered**: the enhanced stable stratification downwind to the city and nocturnal anomaly of cyclonic vorticity over the city
- ✓ Modelling results allows to make possible the further investigation of the listed effects **with high spatial resolution towards to climatological timescales**.
- ✓ Presented results shown **the importance of the urban-induced mesoscale effects and the urban-troposphere feedbacks** (both “bottom-up” and “down-top”) in various applications, including the weather and air quality forecasts and design of the future megacities.
 - **This is a motivation for implementation of the urban canopy schemes to NWP COSMO model, COSMO-ART and ICON LAM**

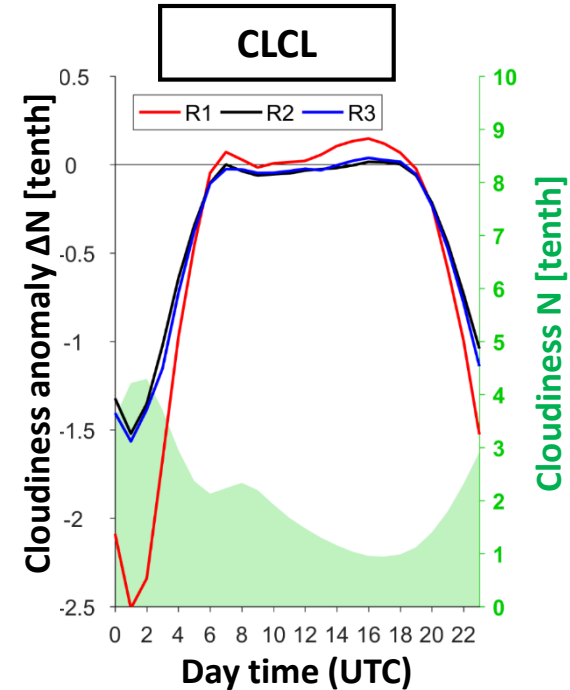
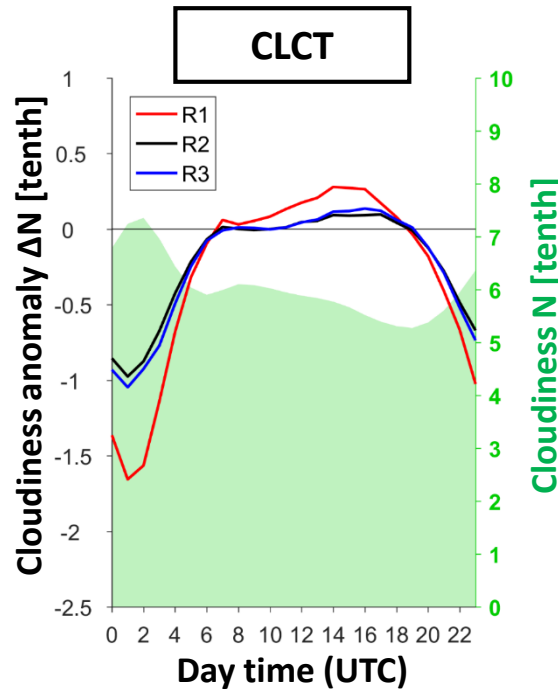
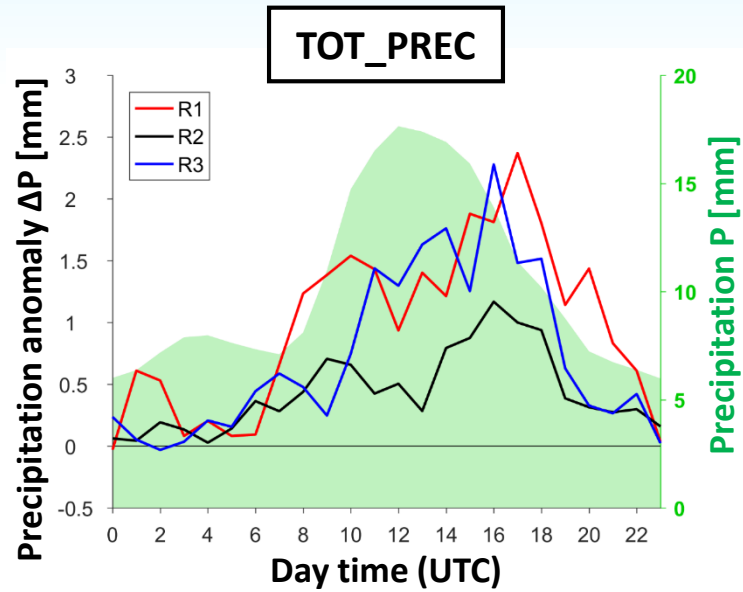
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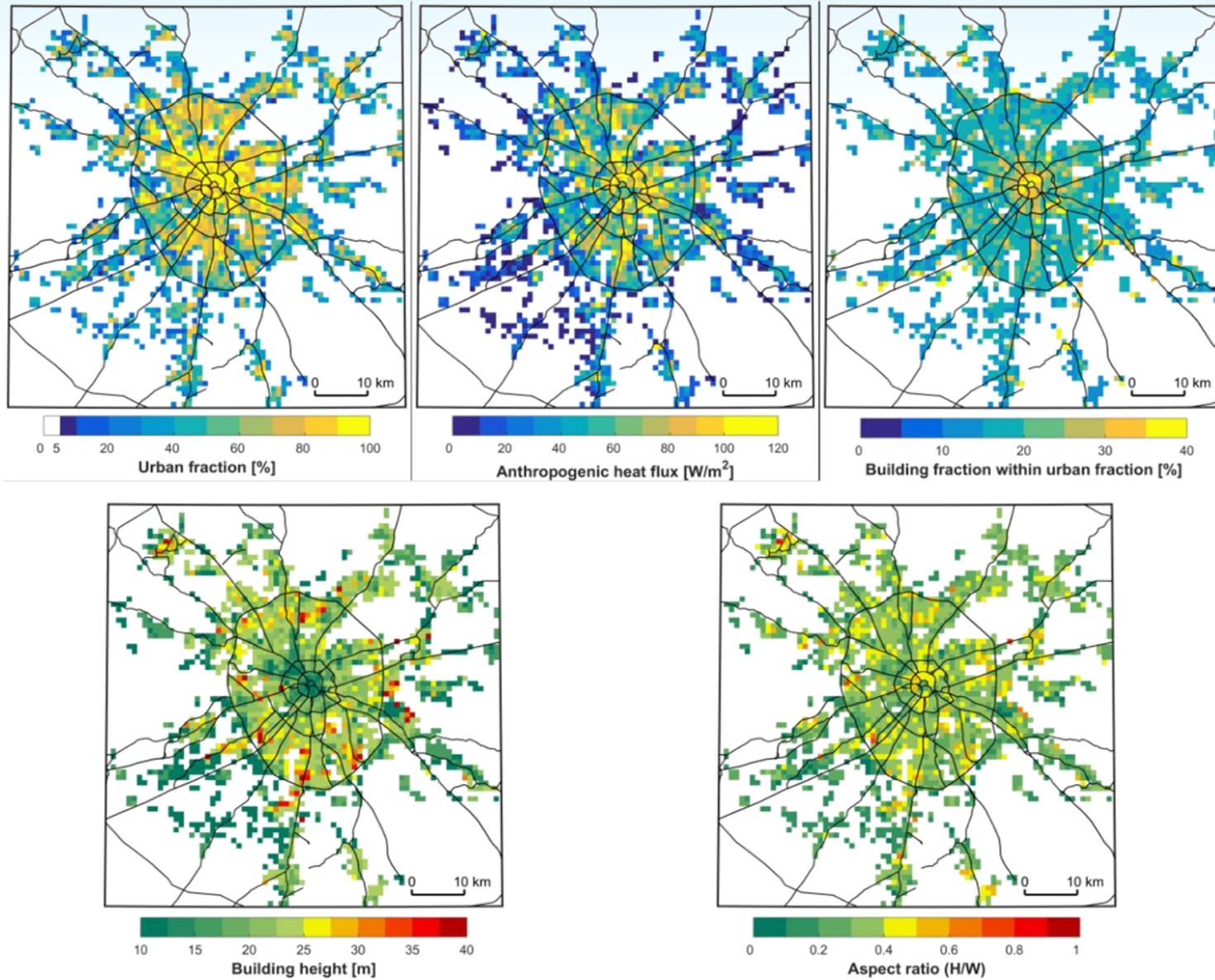
Additional slides



Urban effect on precipitation & cloudiness



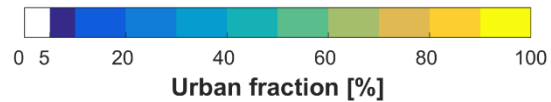
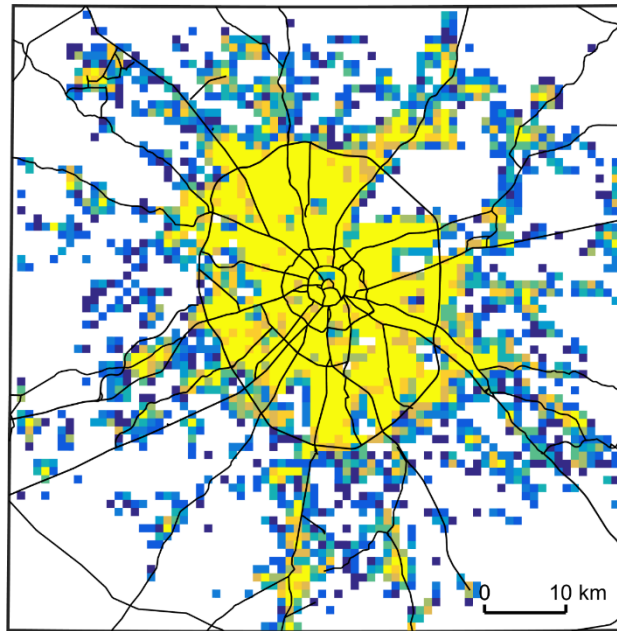
Input parameters of urban canopy



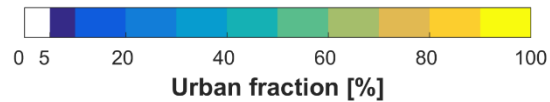
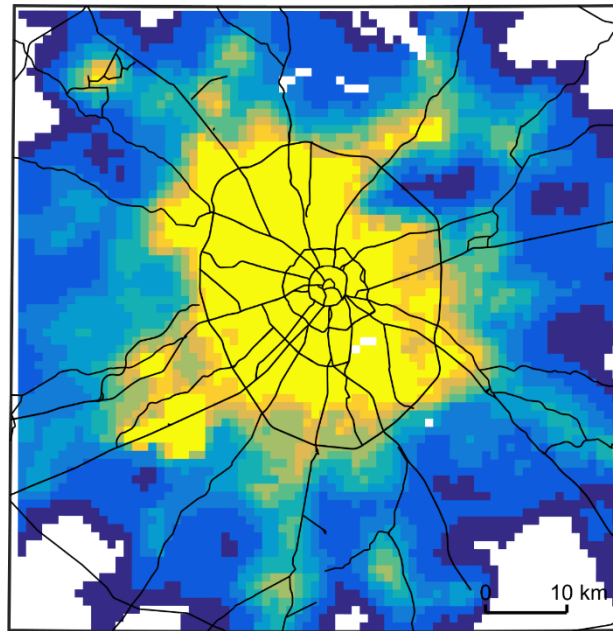
Input parameters of urban canopy

Urban fraction

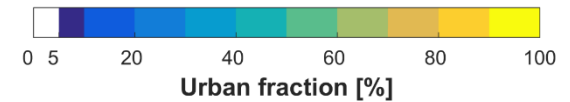
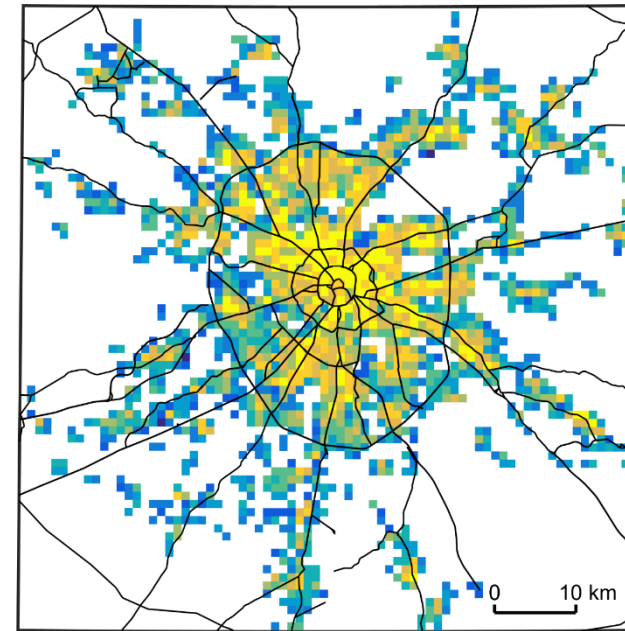
Urban fraction from
EXTPAR (Globcover)



ISA from EXTPAR
(fine resolution)

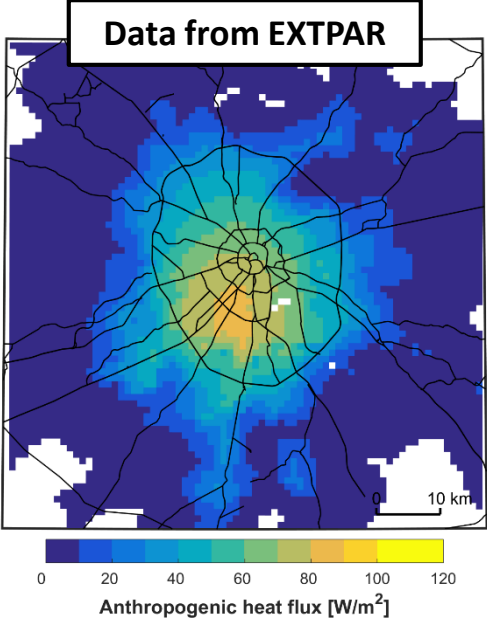
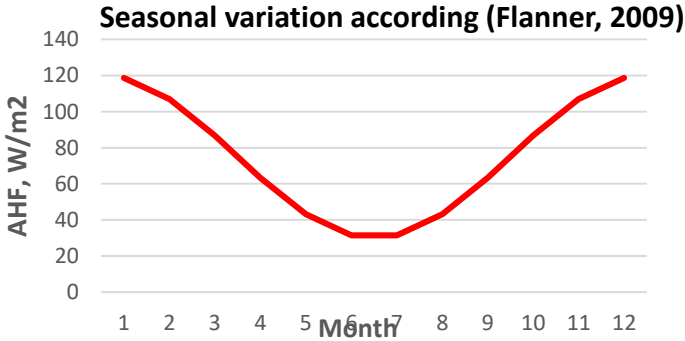
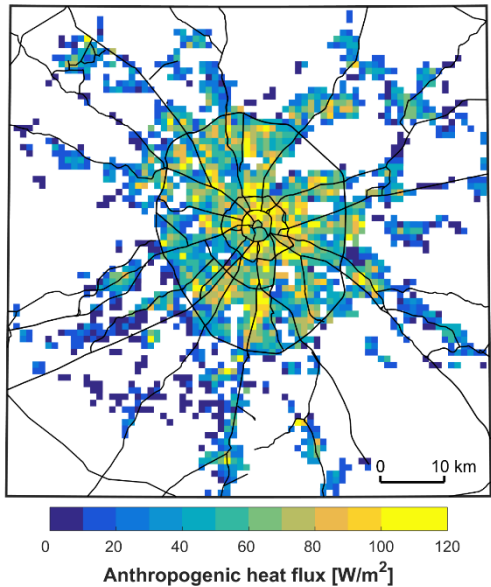
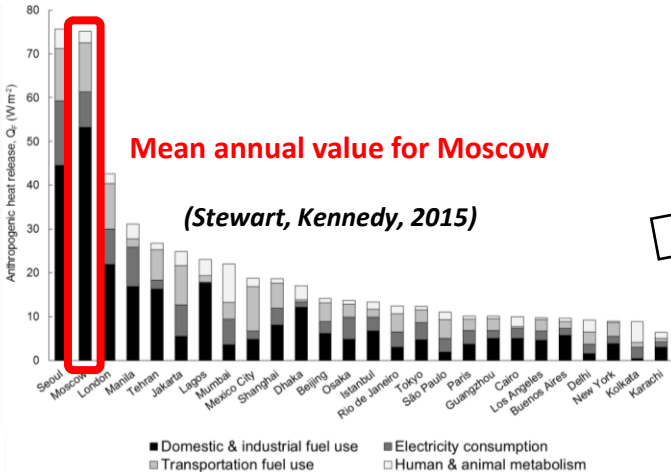


Urban fraction derived
from OSM data



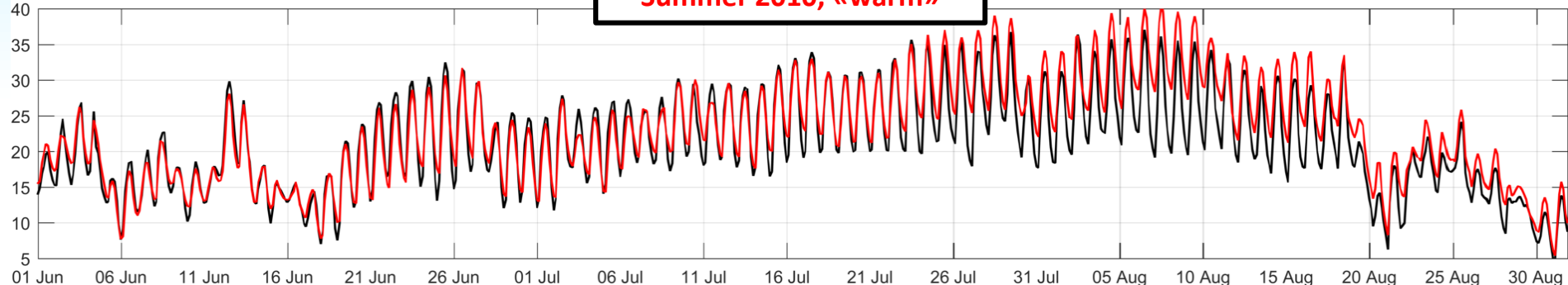
Input parameters of urban canopy

AHF

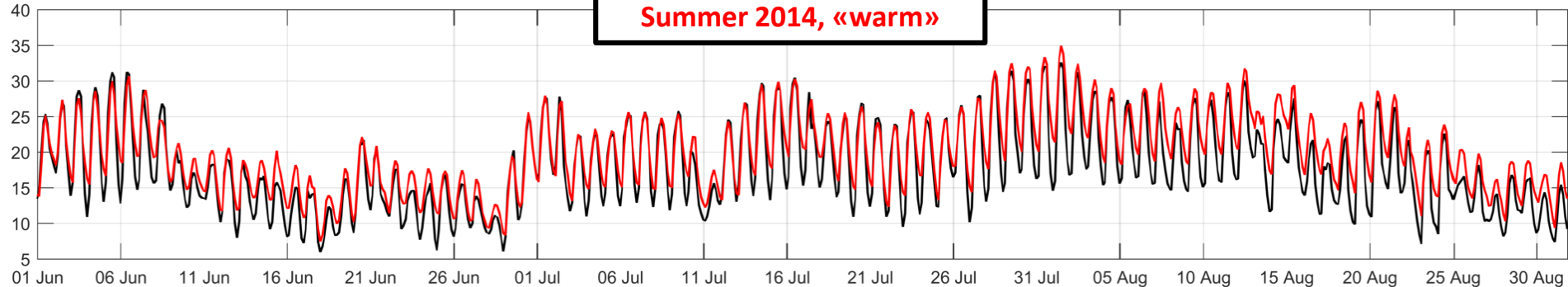


Model verification: standard options

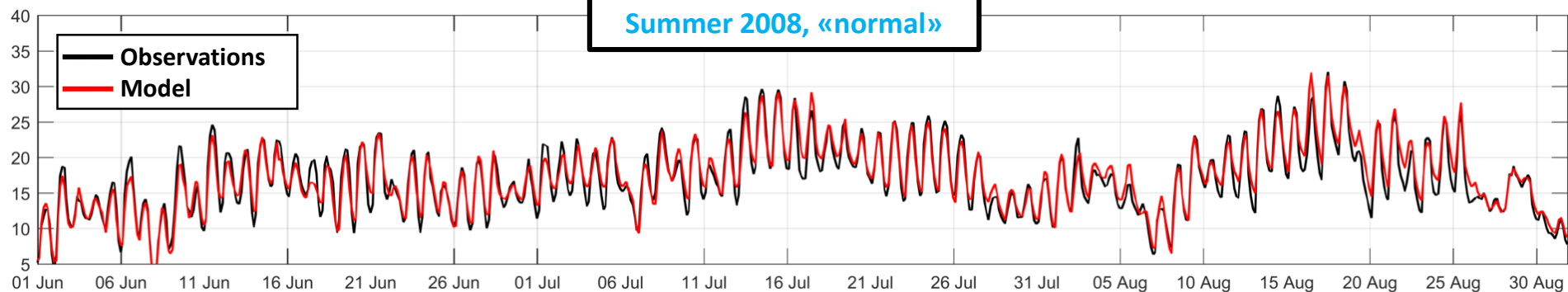
Summer 2010, «warm»



Summer 2014, «warm»



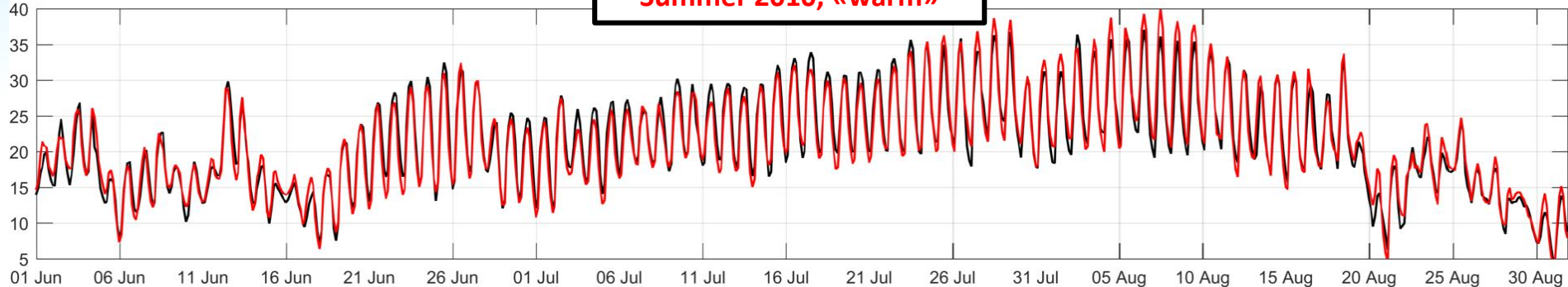
Summer 2008, «normal»



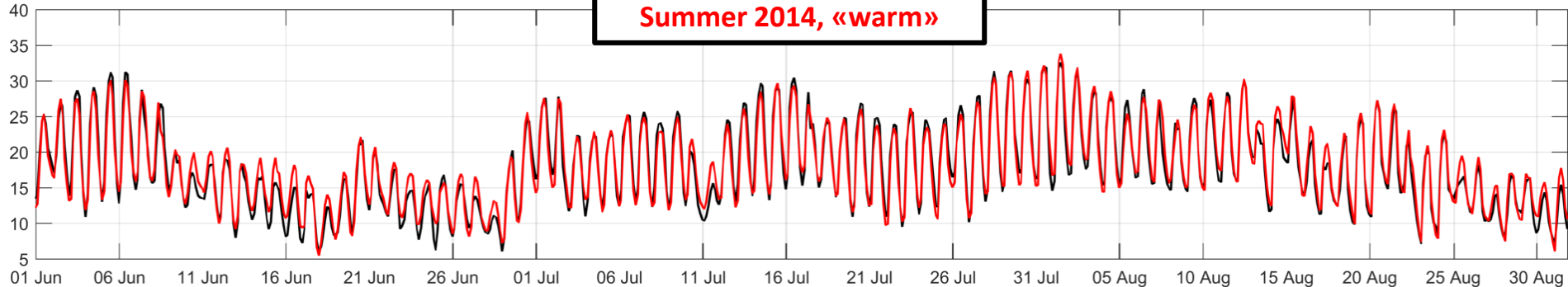
Temperature variations during 3 summer seasons

Model verification: tuned options

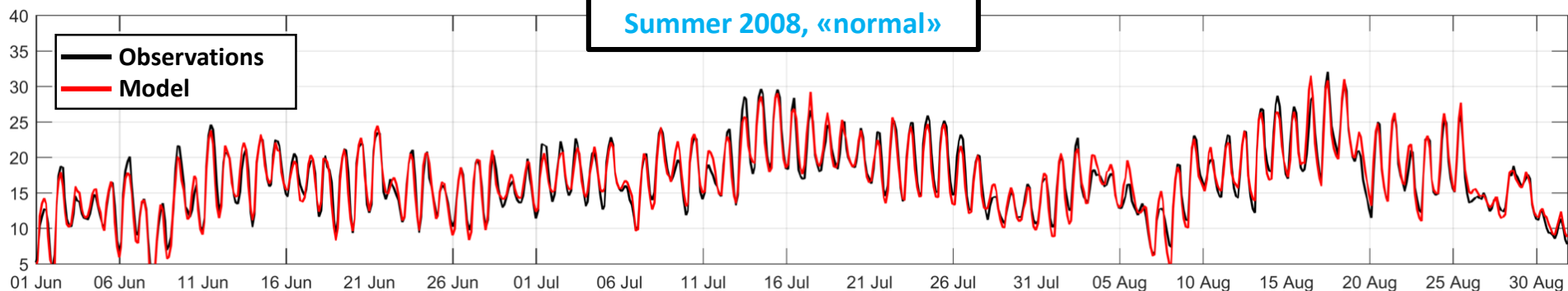
Summer 2010, «warm»



Summer 2014, «warm»



Summer 2008, «normal»



Temperature variations during 3 summer seasons