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Report on the Habilitation Thesis "Modeling the Climate System Across Scales" by Dr. Michal Belda

Dear Prof. Zdeněk Doležal, dear Prof. Jakub Langhammer, honoured members of the committee,

the Habilitation Thesis by Dr. Michal Belda entitled "Modeling the Climate System Across Scales" consists of a 10 page-long summary and 9 attached papers (see overview in Table 1), which have been published in peer reviewed journals, 5 of the 9 by Dr. M. Belda as first author. The 9 published studies are grouped according to 3 different research topics (3 papers each), which correspond to the scale of applied model domains, namely the global scale, the regional scale, and the urban scale. As such, the selection of papers fits very well the chosen title of the thesis and also the summary nicely reflects this.
It is important to note that the (auto)plagiarism audit (Turnitin report) did not indicate scientific misconduct regarding copying.

The first part about the global scale is the most self-contained: all three papers are first author publications by Dr. Belda. The first one [1][1], a review of a revised climate classification based on pioneering work by Köppen and Trewartha, is highly cited (239 times). The authors clearly motivate the application of the climate classification as a combination of the climate parameters temperature and precipitation, linking climate states with vegetation zones. The classification is applied to a recent comprehensive dataset based on observations to illustrate the development of climate in the 20th century. In the second paper [2], Dr. Belda and co-authors apply the climate classification to evaluate the performance of global climate models participating in CMIP5 in representing the current climate state. Dr. Belda et al. defined different metrics and found quite some differences between the results of the different models, and interestingly that the multi-model mean does not outperform individual models (except for one metric). Moreover, no indication could be found that higher resolved models better represent the climate types. Last, but not least, in the third paper [3] Dr. Belda used the climate classification to analyse the climate projections of the models participating in CMIP5 for the RCP4.5 and RCP8.5 scenarios.

[1] References in [...] refer to the publications numbered in Table 1.

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Table 1: Overview of paper with number of citations according to Scopus (status of June 9, 2023).

	Authors	Title	Year	Cited by	
1	**Belda M.**, Holtanová E., Halenka T., Kalvová J.	Climate classification revisited: From Köppen to Trewartha	2014	239	
2	**Belda M.**, Holtanová E., Halenka T., Kalvová J., Hlávka Z.	Evaluation of CMIP5 present climate simulations using the Köppen-Trewartha climate classification	2015	18	
3	**Belda M.**, Holtanová E., Kalvová J., Halenka T.	Global warming-induced changes in climate zones based on CMIP5 projections	2016	33	290
4	Skalák P., Déqué M., **Belda M.**, Farda A., Halenka T., Csima G., Bartholy J., Caian M., Spiridonov V.	CECILIA regional climate simulations for the present climate: Validation and inter-comparison	2014	6	
5	**Belda M.**, Skalák P., Farda A., Halenka T., Déqué M., Csima G., Bartholy J., Torma C., Boroneant C., Caian M., Spiridonov V.	CECILIA regional climate simulations for future climate: Analysis of climate change signal	2015	13	
6	Jacob D., Teichmann C., Sobolowski S., Katragkou E., Anders I., **Belda M.**, et al.	Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community	2020	181	200
7	Resler J., Krč P., **Belda M.**, Juruš P., Benešová N., Lopata J., Vlček O., Damašková D., Eben K., Derbek P., Maronga B., Kanani-Sühring F.	PALM-USM v1.0: A new urban surface model integrated into the PALM large-eddy simulation model	2017	46	
8	Resler J., Eben K., Geletič J., Krč P., Rosecký M., Sühring M., **Belda M.**, Fuka V., Halenka T., Huszár P., Karlický J., Benešová N., Aoubalová J., Honzáková K., Keder J., Nápravníková Š., Vlček O.	Validation of the PALM model system 6.0 in a real urban environment: A case study in Dejvice, Prague, the Czech Republic	2021	12	
9	**Belda M.**, Resler J., Geletič J., Krč P., Maronga B., Sühring M., Kurppa M., Kanani-Sühring F., Fuka V., Eben K., Benešová N., Auvinen M.	Sensitivity analysis of the PALM model system 6.0 in the urban environment	2021	3	61

The strong point of this **first part** (with 3 peer-reviewed papers) is that it covers (1) the review and inter-comparison of a methodology (i.e. climate classification) including its application on observational data to provide a reference dataset for further analyses, (2) the application of the method (including the definition of adequate metrics) to analyse the performance of state-of-the-art climate models in representing the current climate, and (3) the application of the method to inter-compare climate projections based on state-of-the-art climate models and projected scenarios. As such, this first part clearly depicts an original and important scientific contribution for the assessment of climate change. It is a pity that the model spread analysed in [2] has not been further investigated in a follow-up-study, e.g. by analysing the simulated temperature and precipitation patterns in more detail. Moreover, it might have been helpful to include a recent reanalysis data set into the analysis of [2] as a potential 2nd reference in addition to the CRU dataset.

The second part of the thesis, about the regional scale, comprises one first-author and two co-authored papers by Dr. Belda. The first [4] is about a multi-model inter-comparison of the simulated current climate state of Central and Eastern Europe. Two regional models (in different flavours) at 10 km resolution have been forced at their lateral boundaries by ERA-40 reanalysis data over areas of selected European countries (Austria, Czech Republic, Hungary, Slovakia and Romania). The simulation results have been compared with results of the same (and other) models at 25 km resolution. It turns out that observed temperature patterns are better represented at higher resolution, whereas for precipitation patterns this is not necessarily the case. The authors discuss three major explanations: the role of scales in applied physical parameterisations, the rather coarse (primarily in time) forcing at the lateral model boundaries, and potential conceptual shortcomings of the observational dataset used for evaluation. In the second paper of this part [5], Dr. Belda and co-authors apply two such evaluated models to dynamically downscale IPCC climate projections of two global general circulation models (GCMs) over Central and Eastern Europe. The regional models retain

the large-scale patterns of the global GCMs, but add local information that is not solely related to orography, and therefore depict a basis for future climate assessments on the regional scale. Finally, Dr. Belda contributed to an overview paper [6] about the EURO-CORDEX community, its objectives, its organisation structure, and its major achievements.
The strong point of this **second part** is certainly the important contribution to the down-scaling efforts for climate assessment in Central and Eastern Europe. The fact that [5] basically ends with a mandate on further model development clearly shows the justification for the study, although it unfortunately remains unclear how this "further model development" is going to happen (it is well appreciated that this is not under the control of Dr. Belda and co-authors, though). The "weakest" contribution in terms of direct scientific output is [6], although it is very much recognized that the coordination of such major scientific efforts, aiming at an overall "robust" regional downscaling, is very beneficial, if not mandatory, to best utilize resources, both personal and computational. This is also reflected by the large number of citations of [6] (see Table 1). It needs to be noted that Dr. Belda is in the "alphabetical list" of co-authors, thus it would have been helpful to find more details about his role in the introductory summary of the thesis.

The third part, about the urban scale, comprises one first-author and two co-author papers by Dr. Belda. In [7], the authors implemented a new "urban surface model" into an existing Large Eddy Simulation (LES) model and evaluated its realism and impact (in the model context) by several sensitivity simulations and by comparing the results with observations of a comprehensive measurement campaign, which they conducted as part of that study. In a later study [8] the authors evaluated a further developed version of the LES model, again by performing simulations and comparing the results (meteorology, air quality, surface quantities) with observations from a specifically designed measurement campaign. One important lesson learned (among others) is the limitation imposed by the cartesian grid of the model, a finding that might trigger important changes in model design, not only for this specific urban model. According to the "authors contributions" of [8], Dr. Belda was deeply involved in various aspects of this study. As already found in [7] and [8], an important source of uncertainty of the results are boundary conditions that are required to be prescribed for such an urban model, such as the building and land-surface properties. To investigate their role, Dr. Belda et al. conducted further sensitivity analyses [9], subdivided in two sets: one addressing surface parameters (such as albedo, emissivity, surface roughness, thermal conductivity of walls, volumetric heat capacity, etc.), and a second focusing on potential urban heat island mitigation measures (such as changing of surfaces, urban greening, anthropogenic heat flux by air conditioning devices, etc.). Dr. Belda et al. [9] find albedo, emissivity, thermal conductivity of walls, and volumetric heat capacity to be most influential for the model results. They further critically assess the mitigation potential of white painting of surfaces and find urban vegetation to be the most effective mitigation measure, when considering reduction in both, physical and biophysical temperature indicators. Last, but not least, Dr. Belda et al. find an opposite behaviour of thermal comfort and air quality, yet under the limitation that no interactive photochemical scheme has been applied.
This **third part** is probably the most comprehensive part in terms of effort, because it involves model development [7], the execution of tailored, extensive measurement campaigns for model evaluation [7,8], and the detailed assessment of the role of required (uncertain) input data for the robustness of model predictions. As such, this contribution by Dr. Belda et al. can certainly be considered as pioneering work in modelling urban environments, not only for the applied model, but for the entire community. Such modelling capacities are an important prerequisite to assess urban mitigation potentials aiming to reduce the urban heat island effect in future heat waves and to improve air quality.

In summary: With the corresponding peer-reviewed publications of all three parts, on global, regional, and urban modelling, Dr. Belda contributed significantly to the corresponding research fields:

1. For analysing global scale models, Dr. Belda reviewed and established a climate classification system, which relates model simulated climate (here, temperature and precipitation) to

vegetation zones. This serves as an improved metric to assess the performance of global climate models in reproducing the current climate, and to assess climate change in model projections. Although the methodology as such is not entirely new, the application to results of state-of-the-art global model results is. This climate classification application (analysed for future scenarios) has the potential to be a more suitable information for stakeholders (e.g. policy makers, agriculture) compared to individual climate parameters.

2. The contribution of Dr. Belda to the regional climate modelling was mainly to first establish dynamical regional downscaling of climate projections for countries in Central and Eastern Europe, and second, to lay the basis for improvements, i.e. further model development. The contributions by Dr. Belda are "incremental" (analysis of model results), but major scientific breakthroughs can hardly be expected in near future, thus the contribution of Dr. Belda is of importance, as also shown by the number of citations of [7] and [8]. The overall research topic requires a huge effort that needs coordinated activity from an entire community. Dr. Belda got involved into such a coordinated effort, the EURO-CORDEX community.
3. In the field of urban modelling, Dr. Belda contributed pioneering work, with the development of new model components, the in-depth evaluation of an urban model by means of dedicated, specifically designed measurement campaigns, and the analysis of uncertainties in model simulations. Since such comprehensive undertakings are rare (because the efforts are huge) and not much comparable development seems to be ongoing, the most recent paper [9] is not yet often cited, although the findings by Dr. Belda and co-authors might impact similar model studies (and developments) for other cities as well. Dr. Belda et al. contributed significantly to eventually enable robust numerical assessments of mitigation options for cities facing more frequent heat waves under climate change.

All three topics Dr. Belda worked on and documented in this Habilitation thesis are centred around the analysis of simulated climate and model projections of climate change, on global, regional and local (urban) scale. The methods applied by Dr. Belda et al. are either re-visited and improved (in the case of climate classification), well established (in the case of the regional downscaling), or fundamentally advanced (in case of the urban scale modelling). Working on the three different scales (with the deepest involvement on the urban scale, followed by the regional and then global scale), Dr. Belda could gather quite some experience in different branches, which might provide a very good basis for teaching.

The weakest point of the thesis is that the three parts (the three different scales) are only loosely (if at all) connected, although the chosen topic "Modelling the climate system across scales" suggests something different ("on different" instead of "across" in the title would not have suggested this!). It is very well recognized that the corresponding research might have been largely driven by third-party funding (also documented in the acknowledgement sections of the papers), and the "jump" over scales was, at least partially, a side effect of these frame conditions. Nevertheless, the 10-pages thesis framing the 9 presented papers could have elaborated a bit more on a central theme, such as how the expected climate change shifts the climate classification over Central and Eastern Europe, whether the regional model results are consistent with this, and why it is therefore important to assess urban mitigation options for the city of Prague.

Disclaimer: The above report is based on my personal experience and does not reflect any official view of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) at which I am employed.
I hope my review will help you with your decisions.

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Patrick Jöckel