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HABILITATION THESIS

Uncertainties in Climate Model Outputs

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CONTENTS

ABSTRACT

Global and regional climate models, i.e., numerical representations of processes in the Earth's climate system, have become the most commonly used instruments for contemporary climatology. These models are being employed for numerous different purposes. However, there are still large uncertainties connected to climate model outputs. Therefore, it is crucially important to assess these uncertainties carefully before the outputs of the models are used in any applications, including assessments of future climate evolution and possible impacts of expected climate change in different sectors. This thesis presents how different aspects of climate model outputs and their uncertainties can be treated using various methods and approaches to their analysis. Specifically, the issues investigated include (i) evaluation of climate model performance, (ii) construction of climate change scenarios, and (iii) analysis of the influence of driving GCM on nested RCM simulation. Further, foreseen future research directions are outlined.

LIST OF ABBREVIATIONS

RCM	Regional Climate Model
GCM	Global Climate Model
ICV	Internal Climate Variability
WCRP	World Climate Research Programme
ESM	Earth System Model
CORDEX	Coordinated Regional Climate Downscaling Experiment
FOCI	Non-CO_2 Forcers And Their Climate, Weather, Air Quality And Health Impacts
CMIP	Climate Model Inter-comparison Project
KTC	Koeppen-Trewartha Climate Classification
FFT	Fast Fourrier Transform
KZ	Kolmogorov-Zurbenko Filter
GWL	Global Warming Level
PERUN	Prediction, Evaluation, and Research for Understanding National sensitivity and impacts of drought and climate change for Czechia

INTRODUCTION

Uncertainty estimate has to accompany the results of any scientific method (Strommen et al., 2019); global and regional climate models, i.e., numerical representations of processes in the Earth's climate system, are no exception from this rule. These models have become the most commonly used instruments for contemporary climatology. They are employed for various purposes, including studies focused on the dynamics of the climate system, past climate evolution, and future climate projections. However, there are still large uncertainties connected to climate model outputs due to limitations in (i) our understanding of processes in the climate system, (ii) our ability to describe the already well-understood processes, (iii) computational methods, (iv) scarcity of observed data, and due to (v) finite predictability of the climate system due its non-linear and chaotic behavior (Abramowitz et al., 2019). Therefore, it is crucially important to assess these uncertainties carefully before the outputs of the models are used in any applications, including assessments of future climate evolution and possible impacts of expected climate change in different sectors, both human societies and natural ecosystems (Tebaldi and Knutti, 2007).

I have devoted a significant part of my research work to the topic of uncertainties in climate model outputs, starting already during my Ph.D. studies (the results described, e.g., in Holtanová et al., 2010; Holtanová et al., 2014). Since then, I have studied different aspects of climate model outputs and applied various methods and approaches to their analysis. The issues I have investigated can be divided into three topical groups:

I. Evaluation of climate model performance
II. Climate change scenarios
III. Analysis of the influence of GCM on RCM simulation

In the next chapter, I describe the basic concepts of climate models and the sources of uncertainties in their outputs. In the following chapters, 2 - 4, I summarize studies in which my co-authors and I dealt with the abovementioned themes. I also explain how my published work contributed to the research field. In the last chapter, I describe possible future research directions, specifying my ongoing research activities. The papers discussed in Chapters 2 – 4 are enclosed in the Appendix of this thesis. I have contributed significantly to all of them, including their design, calculations, interpretation, and discussion of the results.

Chapter 1

GLOBAL AND REGIONAL CLIMATE MODELS

1.1 GLOBAL CLIMATE MODELS

Global climate models (GCMs) represent numerical three-dimensional representations of the components of the real climate system, i.e., mainly the atmosphere, ocean, cryosphere, and solid surface. They comprise a solution of a series of differential equations describing the movement of energy, momentum, and various chemical components (e.g., water vapor in the atmosphere and salt in the oceans) and the conservation of mass. Due to computational limitations resulting in a relatively coarse spatial resolution, small-scale sub-grid processes cannot be described explicitly. Instead, some parameterizations have to be implemented, which brings about an unavoidable source of uncertainty. Nevertheless, the parametrized processes (e.g., cloud formation, precipitation, soil moisture transfer) play a vital role in forming the Earth's climate (McGuffie and Henderson-Sellers, 2001).

The outputs of GCMs are the basis for decision-making about adaptation and mitigation strategies. The experiments with them are coordinated under the framework of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP, Taylor et al., 2012; Eyring et al., 2016). A new generation of CMIP GCM simulations is produced every five to seven years. GCMs in each new CMIP generation evince improvements and progress in various aspects. These include finer horizontal resolution and an increasing variety of physical processes included in the models. Most recently, some GCMs have implemented detailed representations of biogeochemical processes, which enable the simulation of a complete carbon cycle. Such GCMs are usually called Earth System Models (ESMs). However, despite these new achievements and vast investments in computational capacity, the GCMs still suffer from many deficiencies and uncertainties (see Section 1.4 below).

1.2 REGIONAL CLIMATE MODELS

One aspect of deficiencies in GCMs relates to their coarse spatial resolution. The horizontal resolution of the atmospheric part in the GCMs contributing to the last CMIP generation ranges from 0.5° - 4.5° of latitude/longitude. Thus, the model outputs are not applicable on regional and local scales. Therefore, some of the downscaling techniques need to be applied. One commonly used approach is dynamical downscaling, using regional climate models (RCMs). RCMs represent numerical models analogous to the atmospheric component of global models that operate on a limited integration domain. Boundary conditions provided to the RCMs come from their driving GCM or reanalysis (resulting in "perfect boundary simulations” that are convenient for model evaluation). The horizontal resolution of the state-of-the-art RCMs ranges from 50 km to 1 km. The basic assumption underlying the use of RCMs is that they better represent surface details (e.g., orography, coastlines, vegetation, and soil characteristics) and small-scale meteorological processes than coarser resolution GCMs (Giorgi, 2019). RCMs with a resolution finer than 3 km are operated in “convection-permitting“ mode, allowing for explicit simulation of deep convection and improved representation of regional climatic features (Lucas-Picher et al., 2021). Generally, a more pronounced added value of RCM simulations is foreseen in regions with complex orography and along coastlines (Prommel et al., 2010).

Similarly to CMIP, experiments with RCMs conducted in different modeling centers worldwide are coordinated by WCRP, resulting in the CORDEX initiative (Coordinated Regional Climate Downscaling Experiment, https://cordex.org/).

1.3 MODEL EXPERIMENTS AND CLIMATE CHANGE SCENARIOS

Among a wide variety of experiments conducted with GCMs and RCMs, two are most relevant for the research topics dealt with in the present thesis. The first is the historical experiment conducted with forcings affecting the climate system according to observed evolution in a chosen period, most commonly starting around 1850 in the case of GCMs and about 1950 in the case of RCMs. The historical simulations serve for model validation, i.e., they are compared to observations, and the ability of the model to reproduce the basic climatic features is evaluated. Moreover, they deliver a basis for future climate change scenarios. Further, the scenario runs carried out with external forcings prescribed according to a chosen socio-economic and emission scenario play a crucial role in the research described in the following chapters. The scenario simulations within the newest CMIP6 GCMs cover the period of 2015-2100, with an optional extension until 2250 (Tebaldi et al., 2020).

The first step in estimating future climate change is to determine the possible evolution of the factors that influence climate. The magnitude of both external and internal forcings can be assessed by the "radiative forcing". It is defined as the effect of the considered forcings on the radiative balance at the top of the atmosphere (Forster et al., 2007). It is given in W/m^2. A positive radiative forcing implies an increase in the radiative balance and, therefore, a warming of the climate system. The future evolution of anthropogenic forcings depends on highly uncertain developments in technology, the economy, lifestyle, and politics. Therefore, scenarios of possible socio-economic pathways are used to estimate potential climate change impacts. Several sets of socio-economic and emission scenarios have been formulated in recent decades. Most recently, shared socio-economic pathways (Meinshausen et al., 2020) that classify diverse societal options and approaches to climate change adaptation and mitigation have been adopted.

The construction of a climate change scenario based on the outputs of climate models can be achieved in various ways (e.g., IPCC-TGICA, 2007). When selecting a particular procedure, it is necessary to consider the purpose for which the scenario is being created (region, time period, variables of interest). The simplest approach is the “delta-method” – the difference of long-term climatic characteristics (e.g., monthly mean air temperature or precipitation) between the scenario and historical reference periods represents the projected climate change. In this way, the simulation biases in reference and future time periods do not have to be considered. Some more advanced procedures belong to the family of “bias-correction” techniques, where the known errors and biases are directly treated. Statistical distributions of the variable of interest in model outputs and observations are compared. A correction function is designed for the reference period and then applied for the scenario period. The main idea behind all bias-correction methods is that the model errors are constant over time. Therefore, the correction adjustment for the reference period will also be valid and sufficient for future periods. An additional drawback of most of these methods is that the corrections are determined and applied for each variable separately. This threatens to break the physical relationships between the meteorological elements. This issue is partly addressed by new procedures that account for the multidimensional nature of meteorological data (Canon, 2018).

1.4 UNCERTAINTIES IN CLIMATE MODEL OUTPUTS

Inevitable uncertainties in GCM outputs stem from two main sources: the uncertain response of the climate system to a given forcing, and the magnitude and nature of internal climate variability (Hawkins and Sutton, 2009). The former is closely linked to the magnitude of climate sensitivity, that is, the change in global mean temperature after doubling carbon dioxide concentration. The second arises from unavoidable differences between the real and modeled climate system, e.g., the reduced model complexity. Abramowitz et al. (2019) distinguishes between “epistemic” and “aleatory” uncertainty. The first “relates to our knowledge and understanding of the climate system, and so encompasses uncertainties that are thought to be reducible with more information or knowledge” (Abramowitz et al., 2019). Contrarily, aleatory uncertainty relates to stochasticity and chaotic behavior of the real climate system and thus limited predictability.

From a practitioner's point of view, it is convenient to differentiate between the uncertainty connected to initial conditions, boundary conditions, parameterizations, and structure of the models (Tebaldi and Knutti, 2007). Boundary conditions play a crucial role, especially in the case of RCMs; the uncertainty can be sampled using simulations driven by different driving GCMs. The uncertainty related to internal climate variability can be assessed using ensembles of single GCM simulations with perturbed initial conditions (e.g., Deser et al., 2020). A partial evaluation of the parameterization uncertainty can be done when simulations with perturbations in selected parameters are employed (e.g., Yamazaki et al., 2021). The estimate of the overall structural uncertainty is commonly based on the spread of available multi-model ensembles. Nowadays, there are more than sixty GCMs, differing to some extent in their architecture, especially in choices regarding spatial and temporal resolution, grid point structure, numerical methods, and parameterization schemes. However, even if we significantly increased the number of GCMs, it would only be possible to sample a fraction of structural uncertainty. One of the striking concerns regarding the CMIP multi-model ensemble is the inter-dependency of individual models, which needs to be considered when processing their outputs (e.g., Knutti et al., 2010; Merrifield et al., 2023).

Chapter 2

EVALUATION OF MODEL PERFORMANCE

The general assumption underlying the applicability and usability of climate model outputs for any purpose is that the models are able to depict the basic features of observed climatic conditions in a selected reference period. Even though good performance in a reference period does not automatically guarantee reliable simulation of future climate (e.g., Merrifield et al., 2023; Knutti, 2008), poor performance definitely lowers our trust in the model outputs. Model errors and biases depend on many aspects, e.g., climatic variables, geographical area, timescale, and metrics used for the assessment (e.g., Maraun et al., 2015; Holtanová et al., 2012; Crhová et al., 2014). Therefore, applying complex approaches suited for a given purpose is necessary for proper model evaluation.

The main outcomes of the studies of Holtanová et al. (2012), Belda et al. (2015), and Crhová and Holtanová (2019), which all deal with the evaluation of model performance, are described below. Some results of Holtanová et al. (2022) that relate to model evaluation are also mentioned.

In Belda et al. (2015), we paid attention to evaluating concurrent GCMs. The evaluated CMIP5 GCMs represented the most up-to-date GCM simulations available at the time of the study. The assessment of model performance was based on the application of the Koeppen-Trewartha climate classification (KTC) scheme (Belda et al., 2014), which combines the aspects of the annual course of air temperature and precipitation that belong to the main drivers of vegetation distribution over land areas. Unlike conventional methods of model performance evaluation focused on single variables, KTC provides an aggregated complex assessment metric. The study employed different perspectives of model performance evaluation, including comparing the continental area covered by KTC climate types, relative error and overlap metrics, and hierarchical cluster analysis. One of our results was no clear performance improvement with finer spatial resolution. Further, in accordance with other studies (e.g., Knutti et al., 2013), we showed that the resemblance of the GCMs is, to a large extent, given by the GCM "family", i.e., that the GCMs operated in the same modeling center or sharing the same components are more similar. The influence of internal climate variability on performance evaluation was also assessed, and the perturbed initial condition ensemble of one of the GCMs (CSIRO-Mk3.6.0) was analyzed. Its analysis showed that the influence of internal climate variability on climate type distribution is relatively small, at least concerning the chosen reference period of 1961-1990. Another point was that contrary to some of the previous studies (e.g., Weigel et al., 2008), the multi-model mean did not outperform individual members of the multi-model ensemble. This can be explained by the fact that unlike traditional evaluation techniques based on a single variable, the KTC scheme combines various aspects of both air temperature and precipitation, which precludes a simple cancellation of errors.

In Holtanová et al. (2012), we evaluated the performance of a suite of RCMs over the Czech Republic. We focused not only on frequently studied average values of basic meteorological elements but also on the characteristics of temporal and spatial variability of air temperature and precipitation. One of the main conclusions of this study was that the performance of RCMs differs with different evaluation criteria, and therefore, it is impossible to choose the "best" model. Instead, combining information from various models using available multi-model ensembles is necessary. Generally, simulated precipitation fields are often associated with larger errors than temperature fields. To this end, the study pointed to the fact that a part of the studied RCMs was more successful in simulating temporal variability of precipitation than mean precipitation amounts. Further, the potential influence of horizontal resolution on RCM performance was also investigated. We found a slight enhancement with finer resolution in some characteristics, but the effect could not be generalized to all studied cases.

The model evaluation by Crhová and Holtanová (2019) focused entirely on the temporal variability of simulated near-surface air temperature and precipitation over eight selected regions distributed around Europe from western Germany to eastern Poland and from Serbia to northern Germany. Four simulations of two different RCMs driven by two GCMs, together with their driving simulations, were analyzed using the decomposition of time series into three temporal scales. The simulated variability on each scale was compared between individual simulations and observations. The temporal scale decomposition was done using two methods: Fast Fourier transformation (FFT) and Kolmogorov–Zurbenko (KZ) filtering. The results gained by the two methods were very similar, which implied the robustness of the results. Even though some model simulations failed to represent the total variability, its separation into the three temporal components was quite successful. Considerable shortcomings of simulated variability features were found over the Alps; however, the analysis was hindered by issues connected to the availability of good quality observed data over this orographically complex mountainous region. Further, southeastern Europe represents another region where the climate models fail to simulate the air temperature and precipitation variability, especially regarding short-term and seasonal components. This finding was in accordance with previous studies (e.g., Jacob et al., 2007; Farda et al., 2010; Crhová et al., 2018) and can be explained by the fact that this region has a very complex topography and is subject to changing influence of air masses of different origins. These features are difficult to depict in climate model simulations.

A part of the analysis by Holtanová et al. (2022) also dealt with the evaluation of model performance with a focus on the mean annual cycle of mean, maximum, and minimum air temperature and precipitation and their inter-annual variability. These characteristics are crucial for different sectors of human activities and natural ecosystems. One of the goals was to assess the differences between CMIP5 and CMIP6 GCM multi-model ensembles. We concluded that there are no large differences in the resemblance with observed values between CMIP5 and CMIP6 when the whole multi-model ensembles are analyzed. On the other hand, a simple comparison of selected CMIP5-CMIP6 pairs showed a tendency towards better performance in the new CMIP6 generation.

Chapter 3

CLIMATE CHANGE SCENARIOS

As described in Chapter 1.3, the climate change scenarios are conventionally based on the comparison between model projections for selected socio-economic scenarios and historical model simulations. This chapter describes the main outcomes of two papers that dealt with the topic of climate change scenarios. In Belda et al. (2017), the follow-up of Belda et al. (2015), we analyzed projected changes in the global geographical distribution of Koeppen-Trewartha climate types. Holtanová et al. (2022) dealt with projected changes in the mean annual cycle of air temperature and precipitation and their inter-annual variability over Central Europe.

Belda et al. (2017) employed projections of 30 CMIP5 GCMs under two socio-economic scenarios for the 21st century. The expected changes were described using a multi-model median and an uncertainty estimate based on the spread between the 10th and 90th percentiles of the multi-model ensemble. The study showed that the coldest climate types, i.e., ice cap climate, tundra, and boreal climate, were projected to decline. In contrast, temperate, dry, and savanna climates were expected to expand. These conclusions are in agreement with the foreseen increase of near-surface air temperature throughout the course of the 21st century. Considering the model errors in the reference period as a benchmark for projected changes, the projected decline of boreal climate and tundra was robustly pronounced, as well as the expansion of continental temperate climate. Other projected changes were less distinctly expressed. Further, our analysis did not confirm any unequivocal relationship between the model performance and the magnitude of expected changes.

In Holtanová et al. (2022), we employed a suite of CMIP5 and CMIP6 GCMs to analyze projected changes in mean temperature and precipitation annual cycle over Central Europe. Attention was also paid to the inter-annual variability of these climatic elements. Our results indicated considerable future changes in the shape of the annual cycle of both air temperature and precipitation, implying changes in thermal and ombric continentality of climate over Central Europe. Combined with increasing mean air temperature, such changes could profoundly affect many sectors of our society and natural ecosystems. Further, our study highlighted the increasing probability of dangerous dry periods and heat waves during summer, and floods during spring and winter. Additionally, our results emphasized that the uncertainty of projected changes over central Europe connected to internal climate variability cannot be neglected. Another striking outcome of Holtanová et al. (2022) was that we pointed to a higher projected air temperature increase in CMIP6 compared to the previous generation of CMIP5, especially in summer.

Chapter 4

INFLUENCE OF THE DRIVING GCM ON NESTED RCM SIMULATION

This chapter concentrates on issues connected to the dynamical downscaling of GCM outputs using RCMs. The focus is on potential interactions between the driving and nested models and the differentiation of their influence on simulated climatic conditions. In Holtanová and Mikšovský (2016), we analyzed the range of uncertainty in projected air temperature changes simulated by a suite of RCMs and the differences in the uncertainty range among different tropospheric vertical levels, European regions and time periods. In Crhová and Holtanová (2019), also included in Chapter 3, we paid attention to the influence of RCM and driving GCM on model performance in simulating air temperature and precipitation variability. In Crhová and Holtanová (2018), we evaluated the influence of RCM and driving GCM on the simulated relationship between near-surface air temperature and precipitation over Europe. Holtanová et al. (2019) introduced an innovative approach for the analysis of multi-model ensembles based on a functional data analysis approach. The last study belonging to this chapter, Holtanová et al. (2024), evaluates the GCMs over the boundaries of the RCM integration domain, concentrating on variables used as the RCM boundary conditions.

Holtanová and Mikšovský (2016) showed that the influence of the driving GCM increases with increasing height of the vertical level under consideration. Regarding the RCM-simulated near-surface air temperature changes over Europe in summer, the GCM influence decreases from west to east, so in central and eastern Europe, the RCM influence prevails. In contrast, the GCM influence is stronger over the whole continent in winter. A possible explanation is that in summer, local radiative processes governed by RCM mainly control the air temperature. In winter, on the other hand, the large-scale circulation dictated to a large extent by driving GCM is the main factor.

The results of Crhová and Holtanová (2019) indicated that the total variance of both air temperature and precipitation was influenced more by the driving GCM than by the RCM. Regarding the separation of the total variance into the three temporal components (short-term, seasonal, long-term), our results were somewhat inconclusive as we could not generalize whether the influence of RCM and GCM is more important.

Crhová and Holtanová (2018) showed that the nested RCM influences the simulated relationship between air temperature and precipitation over Europe more than the driving GCM. This conclusion is especially important for impact studies dealing with events where the relationship between air temperature and precipitation plays an important role, for example, in the analysis of possible drought events evolution. It points to the necessity of emphasizing the uncertainties related to the choice of RCMs in these studies.

Holtanová et al. (2019) introduced an innovative methodology for analyzing the structure of multi-model ensembles and the mutual relationships between their members. We illustrated the approach in a case study assessing the EURO-CORDEX multi-model ensemble complemented by the driving CMIP5 GCM simulations. We specifically focused on the relationship between the driving GCM and nested RCM simulations regarding the temporal development of simulated temperature and precipitation changes over two selected European regions. Unlike previously used methods, the new approach considers the character of the whole simulated temporal development of the studied variables, thanks to the generalization of similarity between two time series to functional similarity. Concerning the interpretation of the results, the higher similarity between an RCM and its driving GCM points to a strong GCM forcing and relatively low influence of RCM. Besides the method itself, we further presented an illustrative way of visualization of the mutual distances between the members of a multi-model ensemble based on a network spatialization algorithm. The data points corresponding to individual models can be ordered on a two-dimensional plane employing the layout graphs, enabling an unambiguous interpretation.

One of the goals of Holtanová et al. (2024) was to analyze the links between GCM performance regarding RCM boundary conditions and the near-surface variables inside the potential RCM integration domain (over the Czech Republic in this case). We employed an ensemble of CMIP6 GCMs. The evaluation over the domain center focused on the mean annual cycle of air temperature, precipitation, relative humidity, and global radiation, which are relevant to sectors of agriculture and hydrology. Our results showed that the skill of studied CMIP6 GCMs to simulate the upper air atmospheric parameters (commonly serving as RCM boundary conditions) is only weakly related to GCM performance over the inner domain. Considering the results of Rocheta et al. (2020) regarding the reduced influence of bias correction of the driving GCM data on the RCM simulation, we formulated a hypothesis that good (or bad) performance of the driving GCM does not automatically imply better (or worse) performance of the dynamical downscaling. The hypothesis relies on the fact that the errors might be partly handled by the nested regional model. However, the resulting errors cannot be generally anticipated, as individual combinations of driving GCM and nested RCM can behave differently.

Chapter 5

CONCLUDING REMARKS AND FUTURE OUTLOOKS

Despite recent intense advances in climate model complexity, unavoidable uncertainties remain and need to be assessed and analyzed. This thesis consists of 9 papers that show different approaches to this issue. This last chapter describes the topics that remain open or showed up during the work presented above.

Currently solved project PERUN – “Prediction, Evaluation and Research for Understanding National sensitivity and impacts of drought and climate change for Czechia”, funded by the Technology Agency of the Czech Republic, aims to update climate change scenarios for the Czech Republic. Uncertainty estimate is an integral task within the project. The updated scenarios will be based on high-resolution simulations of RCM Aladin-Climate/CZ, operated by the Czech Hydrometeorological Institute, and other available most up-to-date global and regional climate models. The most recent CMIP6 GCMs, also to be employed, are a considerable step forward in the model development. However, an issue that arose recently is a distinct (and potentially unrealistic) increase in climate sensitivity in some CMIP6 GCMs, which results in higher projected changes in global mean temperature (Forster et al., 2021). A regional manifestation of this “hot model problem” (Hausfather et al., 2022) was also pointed out by Holtanová et al. (2022), i.e., the inter-generation shift between CMIP5 and CMIP6 in projected air temperature changes. Understanding the reasons and consequences of higher climate sensitivity and formulation of a physically based constraint (Hall et al., 2019) is essential for greater confidence in future climate change projections and is a major challenge for current climate research. As potential constraints have been investigated mainly on a global scale (e.g., Brunner et al., 2020; Tokarska et al., 2020), their impact in Central Europe remains to be assessed. In this regard, we have recently been exploring ways of constraining the projected changes for Central Europe to enable narrowing the uncertainty estimate.

Alternative approaches to climate change scenarios exist, including, for example, global warming levels (GWL), where the attention is not paid to a specific future time period but to regional changes projected for a chosen value of expected global temperature change (James et al., 2017). This framework provides a convenient way of handling the hot model problem without discarding more sensitive models automatically. Some European countries have recently adopted the GWL approach for their updates of national climate change scenarios (e.g., Switzerland, personal communication). We will explore this pathway in cooperation with colleagues from the University of Vienna, who are engaged in developing the new Austrian reference climate scenarios (https://klimaszenarien.at/).

A prominent feature of the climate system, its internal variability (ICV), closely relates to uncertainties in climate model outputs. This topic will be investigated in the project proposed for support by the Czech Grant Agency in cooperation with Masaryk University in Brno. We will explore the nature and magnitude of ICV over Europe. We will also assess to what extent this variability is linked to large-scale variability modes and what the differences in internal variability patterns between observed and simulated data are. Planned results will represent valuable enhancement and deepening of our knowledge about regional climate. Further, the project results will provide the basis for increasing the robustness of climate change projections for Europe and suggested adaptation strategies (ICV represents a useful benchmark for evaluating climate model performance and projected changes). Furthermore, better knowledge of the ICV role may significantly improve our understanding of past climate variability, which was evolving under natural conditions. In this sense, the project's results may further contribute to a more precise characterization of the role of anthropogenic forcing in recent and future climate with respect to natural climate variability. As a first step, we have done a preliminary evaluation of the ICV magnitude as modeled by CMIP6 GCMs over Central Europe in Randriatsara and Holtanová (2023).

In cooperation with the Department of Atmospheric Science at Colorado State University, we will investigate the relationship between ICV, climate sensitivity, global mean temperature increase, and changes in the occurrence of temperature extremes. The focus will be on mid-latitude continental regions in the Northern Hemisphere. Very long GCM simulations available within the LongRunMIP initiative (Rugenstein et al., 2019), stored at Colorado State University, will be employed. The results of our joint research will increase our ability to (i) estimate the uncertainty of future climate changes, (ii) evaluate the magnitude of variations in hot and cold extremes induced by internal climate variability and by externally forced climate change, and (iii) understand how the internal climate variability interferes with forced climate changes. The cooperation will be initiated in connection to the research stay supported by the Fulbright Scholarship for Scholars and Researchers 2024/2025.

To analyze in more detail the changes in the mean annual cycle of air temperature revealed by Holtanová et al. (2022), we have been working on a follow-up study in cooperation with colleagues from Masaryk University and the University of Vienna. We have implemented an innovative technique based on a functional data approach (in continuity of Holtanová et al., 2019) to quantitatively describe the changes in the air temperature mean annual cycle shape. We have been analyzing CMIP6 GCM simulations over many different regions covering the whole globe. The results will contribute to the discussion of the potential impacts of the revealed changes on diagnosing the changes in air temperature extremes (Brunner and Voigt, 2024).

Another topic we have been working on in cooperation with doctoral student Herijaona Hani-Roge Hundilida Randriatsara is the analysis of the impacts of projected climate change over Madagascar. This country, one the poorest in the world, has already experienced the effects of ongoing climate changes with recurring drought having severe impacts. We are working on a study analyzing the observed and future projected drought and its impact on the vegetation cover. This research is a follow-up of Ms. Randriatsara's recent papers (Randriatsara et al., 2022a, 2022b, 2023).

Further, in 2022, the project FOCI (Non-CO2 Forcers And Their Climate, Weather, Air Quality And Health Impacts), an international project co-funded by the European Union within the call HORIZON-CL5-2021-D1-01 coordinated by our department, started. The partners include universities and research institutes from 10 countries, as well as several international institutions. The project will produce a large number of model simulations. We will work on their analysis, focusing again on the uncertainty assessments.

Additionally, our department's team has been involved in an international initiative of the Euro-CORDEX (Jacob et al., 2014). A new phase of Euro-CORDEX, aimed at downscaling the CMIP6 simulations, is just about to be launched. We have already participated in its previous phases, and our engagement will continue. We plan to contribute with our RCM simulations and an analysis of the whole multi-model ensemble.

REFERENCES

Abramowitz, G., Herger, N., Gutmann, E., Hammerling, D., Knutti, R. et al. (2019): ESD reviews: Model dependence in multi-model climate ensembles: Weighting, sub-selection and out-of-sample testing. Earth System Dynamics 10(1): 91-105. doi: 10.5194/esd-10-91-2019

Belda, M., Holtanová, E., Halenka, T., Kalvová, J., 2014. Climate classification revisited: From Köppen to Trewartha. Climate Research 59: 1–13. doi: 10.3354/cr01204

Belda, M., Holtanová, E., Halenka, T., Kalvová, J., Hlávka, Z. (2015): Evaluation of CMIP5 present climate simulations using the Köppen-Trewartha climate classification. Climate research 64: 201–212. doi: 10.3354/cr01316

Belda, M., Holtanová, E., Kalvová, J., Halenka, T. (2017): Global warming-induced changes in climate zones based on CMIP5 projections. Climate Research 71: 17– 31. doi: 10.3354/cr01418

Brunner, L. Voigt A. (2024): Pitfalls in diagnosing temperature extremes. Nature Communications 15: 2087. doi: 10.1038/s41467-024-46349-x

Brunner, L., Pendergrass, A. G., Lehner, F., Merrifield, A. L., Lorenz, R., Knutti, R. (2020): Reduced global warming from CMIP6 projections when weighting models by performance and independence. Earth System Dynamics 11(4): 995-1012. doi: 10.5194/esd-11-995-2020

Canon (2018): Multivariate quantile mapping bias correction: an N-dimensional probability density function transform for climate model simulations of multiple variables. Climate Dynamics 50:31–49. doi: 10.1007/s00382-017-3580-6

Crhová, L., Holtanová, E. (2018): Simulated relationship between air temperature and precipitation over Europe: sensitivity to the choice of RCM and GCM. International Journal of Climatology 38 (3): 1595–1604. doi: 10.1002/joc.5256

Crhová, L., Holtanová, E. (2019): Temperature and precipitation variability in regional climate models and driving global climate models: Total variance and its temporal scale components. International Journal of Climatology 39 (3): 1276 - 1286. doi: 10.1002/joc.5876

Crhová, L., Holtanová, E., Kalvová, J., Farda, A. (2014): Performance of ALADIN-CLIMATE/CZ over the area of the Czech Republic in comparison with ENSEMBLES regional climate models. Studia Geophysica et Geodaetica 58: 148-169. doi: 10.1007/s11200-013-1107-0

Crhová, L., Holtanová, E., Kalvová, J., Farda, A. (2018): Changes in air temperature means and interannual variability over Europe in simulations by ALADIN-Climate/CZ: dependence on the size of the integration domain. Theoretical and Applied Climatology 131 (1–2): 363–376. doi 10.1007/s00704-016-1962-z

Deser, C., Lehner, F., Rodgers, K. B., Ault, T., Delworth, T. L. et al., (2020). Insights from Earth system model initial-condition large ensembles and future prospects. Nature Climate Change, 10(4): 277-286. doi: 10.1038/s41558-020-0731-2

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B. et al. (2016): Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development 9 (5): 1937–1958. doi: 10.5194/gmd-9-1937-2016

Farda, A., Déqué, M., Somot, S., Horányi, A., Spiridonov, V., Tóth, H. (2010): Model ALADIN as regional climate model for Central and Eastern Europe. Studia Geophysica et geodaetica 54: 313-332. doi: 10.1007/s11200-010-0017-7

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R. et al. (2007): Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L. (2021): The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi: 10.1017/9781009157896.009.

Giorgi, F. (2019): Thirty years of regional climate modeling: Where are we and where are we going next? Journal of Geophysical Research: Atmospheres 124: 5696–5723. doi: 10.1029/2018JD030094

Hall, A., Cox, P., Huntingford, C., Klein, S. (2019): Progressing emergent constraints on future climate change. Nature Climate Change 9(4): 269-278. doi: 10.1038/s41558-019-0436

Hausfather, Z., Marvel, K., Schmidt, G. A., Nielsen-Gammon, J. W., Zelinka, M. (2022): Climate simulations: Recognize the 'hot model'problem. Nature 605(7908): 26-29. doi: 10.1038/d41586-022-01192-2

Hawkins, E., Sutton, R. (2009): The potential to narrow uncertainty in regional climate predictions. Bulletin of the American Meteorological Society 90: 1095–108. doi: 10.1175/2009BAMS2607.1

Holtanová, E., Belda, M., Crespo, N.M., Halenka, T. (2024): On the relation of CMIP6 GCMs errors at RCM driving boundary condition zones and inner region for Central Europe region. Climate dynamics. doi: 10.1007/s00382-024-07216-z.

Holtanová, E., Belda, M., Halenka, T. (2022): Projected changes in mean annual cycle of temperature and precipitation over the czech Republic: Comparison of CMIP5 and CMIP6. Frontiers in Earth Sciences. 10:1018661. doi: 10.3389/feart.2022.1018661

Holtanová, E., Kalvová, J., Mikšovský, J., Pišoft, P., Motl, M. (2010) Analysis of uncertainties in regional climate model outputs over the Czech Republic. Studia Geophysica et Geodaetica 54: 513-528. doi: 10.1007/s11200-010-0030-x

Holtanová, E., Kalvová, J., Pišoft, P., Mikšovský, J. (2014): Uncertainty in regional climate model outputs over the Czech Republic: the role of nested and driving models. International Journal of Climatology 34(1): 27–35. doi: 10.1002/joc.3663

Holtanová, E., Mendlik, T., Koláček, J., Horová, I., Mikšovský, J. (2019): Similarities within a multi-model ensemble: functional data analysis framework. Geoscientific Model Development 12: 735-747. doi: 10.5194/gmd-12-735-2019

Holtanová, E., Mikšovský, J. (2016): Spread of regional climate model projections: vertical structure and temporal evolution. International Journal of Climatology 36: 4942–4948. doi: 10.1002/joc.4684

Holtanová, E., Mikšovský, J., Kalvová, J., Pišoft, P., Motl,. M. (2012): Performance of ENSEMBLES regional climate models over Central Europe using various metrics. Theoretical and Applied Climatology 108: 463-470. doi: 10.1007/s00704-011-0542-5

IPCC-TGICA (2007): General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment. Version 2. Prepared by T.R. Carter on behalf of the Intergovernmental Panel on Climate Change, Task Group on Data and Scenario Support for Impact and Climate Assessment, 66 pp.

Jacob, D., Petersen, J., Eggert, B. Alia, A., Christensen, O.B. et al. (2014): EURO-CORDEX: new high-resolution climate change projections for European impact research. Regional Environmental Change 14: 563–578. doi: 10.1007/s10113-013-0499-2

Jacob, D., Bärring, L., Christensen, O.B., Christensen, J.H., de Castro, M. *et al. (2007):* An inter-comparison of regional climate models for Europe: model performance in present-day climate. *Climatic Change* **81** (Suppl 1): 31–52. doi: 10.1007/s10584-006-9213-4

James, R., Washington, R., Schleussner, C. F., Rogelj, J., Conway, D. (2017): Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets. Wiley Interdisciplinary Reviews: Climate Change 8(2): e457. doi: 10.1002/wcc.457

Knutti, R. (2008): Should we believe model predictions of future climate change? Philosophical Transactions of the Royal Society A. 3664647 – 4664. doi: 10.1098/rsta.2008.0169

Knutti, R., Masson, D., Gettelman, A. (2013): Climate model genealogy: generation CMIP5 and how we got there. Geophysical Research Letters 40: 1194−1199. doi: 10.1002/grl.50256

Knutti, R., Furrer, R., Tebaldi, C., Cermak, J., Meehl, G. A. (2010): Challenges in combining projections from multiple climate models. Journal of Climate, 23(10): 2739-2758. doi: 10.1175/2009JCLI3361.1

McGuffie, K., Henderson-Sellers, A. (2001): Forty years of numerical climate modelling. International Journal of Climatology 21(9): 1067-1109. doi: 10.1002/joc.632

Maraun, D., Widmann, M., Gutiérrez, J.M., Kotlarski, S., Chandler, R.E. et al. (2015): VALUE: A framework to validate downscaling approaches for climate change studies. Earth's Future 3: 1–14. doi: 10.1002/2014EF000259

Meinshausen, M., Nicholls, Z. R., Lewis, J., Gidden, M. J., Vogel, E. et al. (2020): The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geoscientific Model Development 13 (8): 3571–3605. doi:10.5194/gmd-13-3571-2020

Merrifield, A. L., Brunner, L., Lorenz, R., Humphrey, V., & Knutti, R. (2023). Climate model Selection by Independence, Performance, and Spread (ClimSIPS v1. 0.1) for regional applications. Geoscientific Model Development, 16(16), 4715-4747. doi: 10.5194/gmd-16-4715-2023

Prömmel, K., Geyer, B., Jones, J. M., Widmann, M. (2010): Evaluation of the skill and added value of a reanalysis-driven regional simulation for Alpine temperature. International Journal of Climatology: A Journal of the Royal Meteorological Society 30(5): 760-773. doi: 10.1002/joc.1916

Randriatsara, H. H. R. H., Holtanová, E. (2023): Magnitude of Internal Climate Variability Based on Pre-industrial CMIP6 Models over Central Europe. In WDS'23 Proceedings of Contributed Papers — Physics (eds. J. Šafránková and J. Pavlů), Prague, Matfyzpress, pp. 125–134.

Randriatsara, H. H. R. H., Hu, Z., Xu, X., Ayugi, B., Sian, K. T. C. L. K. et al. (2023): Performance evaluation of CMIP6 HighResMIP models in simulating precipitation over Madagascar. International Journal of Climatology, 43(12): 5401-5421. doi: 10.1002/joc.8153

Randriatsara, H. H. R. H., Hu, Z., Ayugi, B., Makula, E. K., Vuguziga, F., Nkunzimana, A. (2022a): Interannual characteristics of rainfall over Madagascar and its relationship with the Indian Ocean sea surface temperature variation. Theoretical and Applied Climatology 148(1-2): 349-362. doi: 10.1007/s00704-022-03950-8

Randriatsara, H. H. R. H., Hu, Z., Xu, X., Ayugi, B., Sian, K. T. C. L. K. et al. (2022b): Evaluation of gridded precipitation datasets over Madagascar. International Journal of Climatology 42(13): 7028-7046. doi: 10.1002/joc.7628

Rugenstein, M., Bloch-Johnson, J., Abe-Ouchi, A., Andrews, T., Beyerle, U. et al. (2019): LongRunMIP: motivation and design for a large collection of millennial-length AOGCM simulations. Bulletin of the American Meteorological Society. 100(12): 2551-2570. doi: 10.1175/BAMS-D-19-0068.1

Strommen, K., Christensen, H. M., MacLeod, D., Juricke, S., Palmer, T. N. (2019): Progress towards a probabilistic Earth system model: examining the impact of stochasticity in the atmosphere and land component of EC-Earth v3.2. Geoscientific Model Development 12: 3099–3118. doi: 10.5194/gmd-12-3099-2019

Taylor, K., Stouffer, R. J., Meehl, G. A. (2012): An overview of CMIP5 and the experiment design. Bulletin of American Meteorological Society 93: 485–498. doi:10.1175/BAMS-D-11-00094.1

Tebaldi, C., Debeire, K., Eyring, V., Fischer, E., Fyfe, J. et al. (2020): Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. Earth System Dynamics 12: 253–293. doi: 10.5194/esd-12-253-2021

Tebaldi, C., Knutti, R. (2007): The use of the multi-model ensemble in probabilistic climate projections. Philosofical Transactions of Royal Society A, 365, 2053–2075. doi: 10.1098/rsta.2007.2076

Tokarska, K. B., Stolpe, M. B., Sippel, S., Fischer, E. M., Smith, C. J., Lehner, F., et al. (2020). Past warming trend constrains future warming in CMIP6 models. Science Advances 6 (12): eaaz9549. doi: 10.1126/sciadv.aaz9549

Rocheta E, Evans JP, Sharma A (2020) Correcting lateral boundary biases in regional climate modeling – The effect of the relaxation zone. Clim Dyn 55: 2511–2521. https://doi.org/10.1007/s00382-020-05393-1

Weigel, A. P., Liniger, M. A., Appenzeller, C. (2008): Can multi-model combination really enhance the prediction skill of probabilistic ensemble forecasts? Quarterly Journal of the Royal Meteorological Society 134(630): 241-260. doi: 10.1002/qj.210

Yamazaki, K., Sexton, D. M., Rostron, J. W., McSweeney, C. F., Murphy, J. M., Harris, G. R. (2021): A perturbed parameter ensemble of HadGEM3-GC3. 05 coupled model projections: part 2: global performance and future changes. Climate Dynamics 56(11-12): 3437-3471. doi: 10.1007/s00382-020-05608-5

APPENDIX

The appendix includes the full prints of the papers used in the present thesis. All these articles are subject to the copyright of their respective copyright holders.

The list of the papers:

Holtanová, E., Belda, M., Crespo, N.M., Halenka, T. (2024): On the relation of CMIP6 GCMs errors at RCM driving boundary condition zones and inner region for Central Europe region. Climate dynamics. DOI: 10.1007/s00382-024-07216-z. IF: 4.6

Holtanová, E., Belda, M., Halenka, T. (2022): Projected changes in mean annual cycle of temperature and precipitation over the czech Republic: Comparison of CMIP5 and CMIP6. Frontiers in Earth Science 10:1018661. DOI: 10.3389/feart.2022.1018661. IF: 2.9

Holtanová, E., Mendlik, T., Koláček, J., Horová, I., Mikšovský, J. (2019): Similarities within a multi-model ensemble: functional data analysis framework. Geoscientific Model Development 12:735-747. DOI: 10.5194/gmd-12-735-2019. IF: 5.2

Crhová, L., Holtanová E. (2019): Temperature and precipitation variability in regional climate models and driving global climate models: Total variance and its temporal scale components. International Journal of Climatology 39: 1276 - 1286. DOI: 10.1002/joc.5876. IF: 3.9

Crhová, L., Holtanová E. (2018): Simulated relationship between air temperature and precipitation over Europe: sensitivity to the choice of RCM and GCM. International Journal of Climatology 38: 1595–1604. DOI: 10.1002/joc.5256. IF: 3.6

Belda, M., Holtanová, E., Kalvová, J., Halenka, T. (2017): Global warming-induced changes in climate zones based on CMIP5 projections. Climate Research 71: 17– 31. DOI: 10.3354/cr01418. IF: 1.9

Holtanová, E., Mikšovský, J. (2016): Spread of regional climate model projections: vertical structure and temporal evolution. International Journal of Climatology 36: 4942–4948. DOI: 10.1002/joc.4684. IF: 3.8

Belda, M., Holtanová, E., Halenka, T., Kalvová, J., Hlávka, Z. (2015): Evaluation of CMIP5 present climate simulations using the Köppen-Trewartha climate classification. Climate research 64: 201–212. DOI: 10.3354/cr01316. IF: 1.7

Holtanová, E., Mikšovský, J., Kalvová, J., Pišoft, P., Motl,. M. (2012): Performance of ENSEMBLES regional climate models over Central Europe using various metrics. Theoretical and Applied Climatology 108: 463-470. DOI: 10.1007/s00704-011-0542-5. IF: 1.8