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HABILITATION THESIS

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Modeling the Climate System Across Scales

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Contents

Abstract

Climate system is one the most complex problems of contemporary physics with components and processes spanning multiple spatial and temporal scales. Throughout the history of climate research many different types of models have been employed ranging from simple conceptual models or statistical models based on observations of historical patterns to fully physically-based models. The state-of-the-art weather and climate models are derived from the basic principles of physics such as the description of motion in the form of the Navier-Stokes equations. However, due to our limited knowledge, these equations need to be solved only by using some form of numerical approximation. Successful application of these techniques was made possible with the advent of electronical computers in the late 1940s and thanks to the advances in computer science and information technology, modern models are able to represent most of the complexity of the climate system components and processes. On the other hand, even with the fastest supercomputers, the full range of scales cannot be covered in sufficient details. Models covering the entire globe are limited in their spatial resolution to typically a hundred kilometers or more and, on the other side of the spectrum, turbulence-resolving models can only be integrated on a limited area, e.g. covering a city quarter. This thesis presents studies based on various numerical modeling systems covering the global, regional and local scales showing examples of results and challenges numerical modeling offers in the applications ranging from global and regional climate scenarios to urban micro-climate. Included are 9 research articles on the assessment of global climate model simulations using the conceptual Köppen-Trewartha climate classification, evaluation of regional climate models in Europe and evaluation of LES model PALM in urban context in three case studies of urban heat island and air quality for Prague.

Introduction

Climate system behavior is one of the most complex problems of contemporary physics. Climate, as one of the main determinants of the biophysical environment on Earth, has in some way been studied throughout most of modern human history, creating more or less sophisticated models based mostly on observations of existing patterns. The idea of applying general principles of physics on atmospheric motions had been floating around since early 20$^{\text{th}}$ century starting with the groundbreaking works of Cleveland Abbe, Vilhelm Bjerknes or Lewis Fry Richardson (for a historical review see e.g., Lynch, 2007). However, only in the last couple of decades, with the advent of digital electronic computers, these techniques have been made into full-fledged modeling tools that are being used every day for weather forecasting and in extension for climate projections. In a broad sense, these models belong to the computational fluid dynamics family of models (CFD).

Although most of the rules governing the climate system's various components and processes can be described by known principles and equations of dynamics, thermodynamics or radiative transfer, there are still unknowns. Prime examples are the Navier-Stokes equations, governing climate system dynamics, for which an analytical solution is not known and approximate numerical methods must be used. However, as we know from the seminal work of Edward Lorenz, these methods brought about new challenges due to their inherently chaotic behavior.

All current methods of predicting the state of the climate system still contain considerable uncertainty. In the field of climate projections, this uncertainty stems from the unknown chemical composition of the atmosphere (specifically concentrations of greenhouse gases), internal variability of the system and the models describing it, but also from incomplete knowledge of all relevant processes. A part of the uncertainty cannot be avoided, typically the part coming from the boundary conditions. Some parts, however, can be reduced to a certain degree, for example, in individual models, by making improvements to the representation of relevant processes or increasing resolution. The internal variability of the models can be estimated by constructing ensembles of simulations produced by different models, models with different configurations, initial conditions, etc. The community efforts of the initiatives like the Coupled Model Intercomparison Project (CMIP) and the Coordinated Regional Climate Downscaling Experiment (CORDEX) help immensely in this regard.

In this work, 9 research articles published between years 2014 and 2022 are presented, showing examples of climate system modeling techniques on three separate scales going from global, through regional to the street-scale local modeling for urban applications. In these publications, I was a principal author of the articles on which chapter 1 is based, contributing to data processing, analysis of the results and formulating conclusions. In the articles of chapters 2 and 3, I was involved in all stages of the research, beginning with experiment design, running regional climate simulations with the RegCM model, development of the LES model PALM and post-processing tools for RegCM and PALM, data processing, analysis and preparation of the manuscript text.

1. Global Models

At the top of the hierarchy of the model family are models that in one way or another see the entire globe, i.e., global models. Loosely speaking, these can range from simple conceptual (e.g., climate zones), statistical, or lower-dimension physics-based models (e.g., Maher et al., 2019). However, in a strict sense, the climate community reserves the label global climate models (GCM; also general circulation models) for a set of models based on the general principles of fluid dynamics and thermodynamics (Stute et al., 2001). GCMs are a direct counterpart to the global numerical weather prediction models (NWP), sharing the basic principle of predicting the behavior of the climate system by solving the fundamental physical equations, providing the most detailed model view of the climate on the global scale.

The global view of the climate in these models brings about their most important drawback which is the insufficient level of detail a GCM can provide in terms of horizontal resolution. Operating these models meaningfully is only possible in the form of numerical integration on powerful supercomputers. The performance of such computers is inherently limited by hardware capabilities, thus setting a limit on the resolution of the climate models. Even though kilometer-scale global simulations exist, the bulk of state-of-the-art GCM scenario simulations in 2020s are produced on grids with horizontal resolution as low as 100 km or coarser. Processes whose typical scale is finer than that (e.g., convection, turbulence, etc.) need to be represented as parameterizations that are not always based on general principles but in many instances derived from observed statistical relations between large and fine scale.

Given all the limitations of the global models, it is only natural that before using these as tools for producing climate projections, one must test their performance on known climate conditions to prove model suitability. Tests like these are usually performed by comparing model simulations with observations of variables such as air temperature, precipitation, wind speed, etc., providing not only information about potential model deficiencies, but also giving the user a set of data that can be used for adjusting the raw future scenario simulations by the means of various statistical methods usually referred to as “bias-correction” (technical term encompassing many techniques of adjusting bias but also other statistical properties).

This chapter is composed of a series of three research articles we published between 2014 and 2016 on the evaluation of GCM simulations from the CMIP5 project (Coupled Model Intercomparison Project Phase 5, simulations that served as the main input for the Intergovernmental Panel on Climate Change Assessment Report 5). In these articles, we provided a validation of the CMIP5 ensemble with respect to the observed data (Belda et al., 2015a) and a summary of future climate projections based on the CMIP5 ensemble (Belda et al., 2016). The underlining theme of the series was using a conceptual model of climate devised by Wladimir Köppen in the early 1900s (e.g., Köppen, 1923, 1936). The main idea behind this method is an observation of an existing link between the physical and biophysical realm, specifically the fact that the typical vegetation of an area is determined by the climatic conditions in that area. This conceptual model, although extremely simplistic compared to modern numerical models, proves to be useful in this task thanks to its comprehensive look at the climate. One of the challenges of numerical model evaluation is the observation that model performance is usually not uniform across either the physical or variable space. In simple terms, one model can be highly successful in representing e.g., mean temperature, yet fail in simulating correct precipitation patterns or vice versa. With the help of an aggregated metric such as the Köppen climate zone system, one can view the model outputs indeed as an interconnected system instead of a set of independent variables.

In our work, we used a revised version of the original Köppen scheme proposed by Glenn T. Trewartha hereafter named Köppen-Trewartha Climate Classification (KTC; Trewartha et al., 1980). This revised scheme introduced several adjustments for improvement of the correspondence with the observed boundaries, mainly in the North American context. Also, some vague formulations of the original Köppen scheme were improved upon, making this modification more suitable for model evaluation.

Even though the Köppen scheme and its various descendants have for many decades been a go-to tool in climatology taught in many a university course, while preparing the evaluation of CMIP5 ensemble, we found out that quite a large number of discrepancies appear in the existing literature concerning nomenclature but also climate zone definitions and numerical thresholds used in these definitions. This observation resulted in a review article that laid the foundation for the following two papers and was published as Belda et al. (2014).

2. Regional Models

The ultimate goal of climate modeling in terms of applications is to provide regional projections of potential climate system behavior in the future. Global climate models, however advanced, still lack the spatial detail that would allow to take the GCM outputs directly for producing such detailed regional climate scenarios, mainly due to computational costs associated with the numerical method employed. However, several techniques were developed to help with this problem that are usually referred to as regional climate downscaling (RCD). One of these methods is statistical downscaling (SD) which uses the approach of applying known statistical relationships between large-scale patterns and regional-to-local climate to the GCM outputs.

Contrary to the statistical methods, dynamical downscaling methods use the physically consistent approach of numerical integration of fundamental equations in higher resolution. In simple terms, regional climate models (RCM) are the same category of models as GCMs only integrated on a selected region. The technique, analogous to the use of limited-area numerical weather prediction models, was first explored in the seminal works of Dickinson et al. (1989) and Giorgi (1990) and has since evolved into a separate field with its own set of advantages and drawbacks.

In our work, we use the latter approach of limited-area nested regional climate models. The first two studies in this chapter present a validation and intercomparison of a small ensemble of regional climate models used in a CECILIA project that ran from 2006 to 2009 (http://www.cecilia-eu.org/). As with GCMs, their regional counterparts need to have a performance evaluation on known climate conditions before their simulations can be used for construction of future climate projections, which was performed in the Skalák et al. (2014) article. The analysis of the climate change signal in the scenario simulations of the CECILIA model ensemble was then presented in Belda et al. (2015b).

The multi-model ensemble approach that had long been represented by the CMIP project in the global modeling community was also adopted by the RCM world in a number of local projects. Starting in 2009, however, the CORDEX initiative was born with the goal to connect the fragmented RCM communities, devise a common protocol for a coordinated effort in model development, and ultimately produce regional climate scenarios for all continents. Our involvement in this initiative, specifically in the European branch (EURO-CORDEX) was a natural step from the regional projects such as ENSEMBLES or CECILIA. A review of the ten-year experience in this effort was presented in Jacob et al. (2020).

3. Local Models

As discussed in previous chapters, the CFD modeling method based on approximate numerical integration of the fundamental physical equations poses a limit on the resolution of the models. Even when run on the most advanced supercomputers of the 2020s, global and regional models are only able to reach a kilometer-scale resolution for shorter time periods (e.g., individual decades) and long-term simulations are usually only available in resolutions of tens to hundreds of kilometers. Smaller-scale processes that cannot be neglected must be parameterized in these models and, by definition, these models are not able to discern specific micro-climatic features.

In certain practical applications, it is necessary to have a model able to resolve features that are beyond what both global and regional models are capable of. Urban areas are one example of such environments that are at the forefront of interest in connection with climate studies for the changes these areas introduce to the micro-climate. The urban heat island phenomenon (UHI) or deterioration of air quality are among the most studied effects due to their direct influence on thermal comfort and health. The specific behavior of artificial surfaces comprising towns and cities pushes the limits of both global and regional climate simulations. The radiation balance and turbulent processes within the urban canopy can at best be represented by some form of a generalized urban scheme in mesoscale models.

On the other side of the model spectrum are models designed to resolve the microscale. To do that, the models must inevitably use a much finer computational mesh. The limited computer power obstacle standing before the lower-resolution models is multiplied here by the fact that the convergence of the numerical solution is conditioned by a certain ratio between the time step and model grid spacing known as Courant-Friedrichs-Lewy or CFL condition (Courant et al., 1928). The CFL criterion means that increasing model horizontal resolution necessitates choosing a shorter time step for the model to be stable. For example, doubling the model horizontal resolution, i.e., halving the model grid point distance, while keeping the same overall domain size, results in roughly eight times higher number of computational operations.

When attempting to explicitly resolve micro-climatic features such as those of city components (buildings, streets, pavements, etc.), the models must reach spatial resolution of less than tens of meters. In effect, the time step of such models can be as short as a fraction of a second. Reaching a sufficient model resolution for these applications then usually means that only very short case studies can be performed. However, even with such limits, meaningful experiments can be performed in this regard.

The articles selected for this chapter are based on simulations using the large-eddy simulation method (LES) in urban areas. The LES technique allows for explicit representation of large turbulent eddies by scale separation, parameterizing only the smallest eddies by subgrid-scale models. In our studies, we used the PALM model utilizing the computational power of massively parallel computer architectures (Maronga et al., 2015). The open architecture of the PALM model allowed for an implementation of complex urban surface treatment. The then-called Urban Surface Model (USM) was introduced in 2017 and an evaluation of a case-study simulation suite in a typical urban quarter Prague-Holešovice was presented in the first of the included articles (Resler et al., 2017). The improvements also included a newly developed radiative transfer model (RTM) within the urban canopy. Model performance was tested against infrared camera observations. The analysis also included a test of the sensitivity of the model simulation results with respect to domain size and the uncertainty in material parameters.

The results of the Resler et al. (2017) analysis served as a basis for further improvements of the urban surface model (later renamed to Building Surface Model – BSM) and also as a starting point for more comprehensive validation against observations obtained in an extensive observation campaign specifically designed for this purpose. The model performance was evaluated on a larger domain in the densely built-up part of the Prague-Dejvice quarter in several places covering most of the typical urban surface configurations and materials. The details of the observation campaign and model validation were published in Resler et al. (2021).

As a companion paper, an extensive sensitivity study was performed building upon the previous rudimentary evaluation of Resler et al. (2017). High-resolution modeling is not only dependent on the model's ability to be run on a finer grid, but also on providing input data of sufficient resolution and quality. In urban modeling, this means that detailed information about the physical properties of natural and artificial materials in the cities is required. Belda et al. (2021) analyzed a comprehensive set of simulations studying the model response to artificially introduced changes in physical parameters of surface materials (albedo, emissivity, etc.) to assess the model sensitivity to potentially erroneous setting of these parameters that are hard to obtain in adequate quality. The second set of experiments then analyzed model response to typically considered counter-UHI measures like introduction of urban greenery or changing urban surface configuration.

Topics introduced in this chapter have been the subject of a number of studies and are currently analyzed in more detail within the TURBAN project framework.

Conclusions

Numerical models are an indispensable tool in the modern-era climate research. Their uses range from pure research to applications in decision-making processes and as such, the models need to be properly evaluated. In this thesis, a compilation of 9 studies was presented spanning a large range of spatial and temporal scales.

First three articles explored the application of a “classical” conceptual model of bioclimatic zones for evaluation of GCM ensemble performance in historical and future climate scenarios. The important advantage of this technique is in the aggregation of several climatological variables and their statistics into one metric showing the overall model performance. Combined with the link the classification makes between the climate and biosphere, this method also proves useful as a simple impact model.

The second set of articles showed three studies based on the dynamical downscaling method by which the outputs of global models can be focused on a specific area in much higher resolution. The regional climate modeling, which has been explored for more than three decades now, brings new possibilites and new challenges. The added value of using meso-scale models by including processes that are beyond the resolution of the global models is an important aspect. Regional climate models are making their way into the forefront and with the growing community centered around the CORDEX initiative are subject to an extensive research.

Urban microclimate and the specific challenges in its modeling were explored in the last chapter consisting of three analyses based on the LES modeling technique. The model studies included here show an application of this method in two typical urban areas in Prague, showing both an validation of newly developed model components as well as scenarios of potential urbanistic changes and their effects on thermal comfort and air quality in the streets.

Altogether, all CFD model applications are conditioned by the availability of computational resources. Fortunately, the advances in the information technology over time have made it possible not only to use the models at all, but with the ever increasing computer performance also to make steady advances in the model resolution and complexity. How long this trend will continue remains to be seen.

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List of Abbreviations

BSM	Building Surface Model
CFD	Computational Fluid Dynamics
CFL	Courant-Friedrichs-Lewy condition
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
GCM	General Circulation Model; Global Climate Model
LES	Large Eddy Simulation
KTC	Köppen-Trewartha Climate Classification
NWP	Numerical Weather Prediction
PALM	Parallelized Large-Eddy Simulation Model
RCD	Regional Climate Downscaling
RCM	Regional Climate Model
RTM	Radiative Transfer Model
SD	Statistical Downscaling
UHI	Urban Heat Island
USM	Urban Surface Model

List of Publications

The presented thesis has been compiled from the following peer-reviewed publications:

Belda, M., E. Holtanová, T. Halenka, and J. Kalvová (2014). "Climate classification revisited: From Köppen to Trewartha". In: *Climate Research* 59(1), pp. 1–13. DOI: `10.3354/cr01204`.

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