English summary

Climate models, and in particular regional climate models (RCMs) find their origin in Numerical Weather Prediction (NWP) models. Important developments in NWP models have in the mid 1950's led to the first applications of Global Climate Models (GCMs). The current GCMs have a spatial resolution of around $100-200$ km, and are an essential tool to determine and correctly understand the large-scale mechanisms and phenomena in our climate system, such as the general atmospheric circulation. However, the coarse spatial resolution of the GCMs falls short to take into account many key regional and local aspects and underlying subgrid scale processes, such as for example extreme precipitation. To account for this scale difference between the large-scale information from the GCMs on the one hand, and the small-scale and local information which is extremely relevant for impact studies on the other, the downscaling technique has been introduced.

A frequently used downscaling technique, is the dynamical downscaling, and more specifically the nesting approach. In this approach large-scale meteorological fields from either a GCM or from analyses of observations are used to provide the initial and time-dependent meteorological Lateral Boundary Conditions (LBCs) for the high-resolution Limited Area Model (LAM) or RCM. Over the last decades, RCMs have undergone enormous improvements in their development, characterized by important advancements in their representation of landscape and surface features, in their description of subgrid-scale physical effects, and in their spatial resolution (down to 10 km). Nowadays, the RCMs have become a popular tool for regional climate modeling, in which multiyear simulations are carried out to study important regional and local climate processes, such as extreme events.

The ultimate aim of this thesis is to study in detail to what extent the operational NWP model of the Royal Meteorological Institute of Belgium (RMI) (i.e. ALARO-0) can be used for regional climate modeling in Belgium of (i) extreme precipitation, and of (ii) the unfavorable meteorological conditions for the dispersion of air pollution. Precipitation is one of the most important climate variables. Furthermore, the underlying precipitation processes play a crucial role in the state of the atmosphere and the regional and global climate. Hence, a correct description of the precipitation processes in the climate models is crucial. However, deficiencies in the parameterizations for precipitation, and in particular for deep convection, prevent the climate models to correctly simulate spatial and temporal variations, as well as the frequency and intensity of precipitation. The new physics parameterizations for deep convection and clouds in the ALARO-0 model were specifically designed in the context of NWP, and aimed to be used for the

mesoscale to the convection-permitting scales (i.e. so-called "gray-zone" scales). The multiscale aspect of the physics parameterizations, called Modular Multiscale Microphysics and Transport (3MT), has indeed been demonstrated through consistent and realistic weather forecasts at spatial resolutions ranging from 10 km up to high resolutions of 4 km.

In the research department of the RMI, the ALARO-0 model is since 2010 used for regional climate simulations. Although, a detailed regional climate modeling study for Belgium is since then not carried out. The first aim of this thesis is therefore to carry out a detailed description and validation of the model and its new physics parameterizations in a climate context. For precipitation, and more specifically extreme precipitation, the validation of the downscaling results is executed for a wide range of spatial and temporal resolutions. As a second goal, this allows us to explore to what extent the model adds valuable fine-scale temporal and spatial details to its driving coarse-resolution global model. The downscaled model results generally consist of multiple sources of uncertainties which are related to (i) model formulation, (ii) uncertainties in the anthropogenic climate forcing factors, and (iii) natural variability. A multi-model ensemble which allows to quantify these uncertainties and the spread of the model results, requires sufficient computing capacity, which is impossible for a small institute such as the RMI. Hence, the last and third goal of this thesis is to assess the uncertainties of the regional downscaling results in a qualitative manner. This qualitative assessment is done through comparison of our downscaled future climate model results w.r.t. other RCM climate projections, which ideally use the same scenario of natural and anthropogenic forcing.

The above objectives are addressed by two main research steps. In a first step the Belgian ALARO-0 NWP model is validated for climatological time scales, by driving the model with "perfect boundary conditions" coming from global reanalyses. In a following step, the model is applied for a climate projection under the A1B scenario as described by the Intergovernmental Panel on Climate Change (IPCC), in which a global climate change simulation is dynamically downscaled using the ALARO-0 model. In this thesis, the ALARO-0 simulations with a vertical resolution of 46 model levels, are carried out up to high spatial resolutions of 4 km, corresponding to the finest atmospheric (micro)scales. Furthermore, this horizontal and vertical resolution is much higher than the state-of-the-art GCM and RCM resolutions of roughly $100-200$ km and 12 km as used in international initiatives such as the Model Intercomparison Project Phase 5 (CMIP5) and the EURO-CORDEX project.

A comparison of the different options in the radiation and surface parameterizations demonstrates that the combination of the radiation scheme ACRANEB and the surface scheme ISBA is an acceptable configuration for the simulation of precipitation with the ALARO-0 model.

Overall, the results of the validation of extreme daily and subdaily precipitation show that the ALARO-0 model is able to consistently and correctly reproduce the relevant precipitation characteristics, and this for a wide range of atmospheric and corresponding temporal scales varying from the micro- to the mesoscale. The validation of daily precipitation in Belgium demonstrates that the new 3MT parameterization, and its multiscale character, are responsible for a correct simulation of extreme summer precipitation at multiple horizontal resolutions, ranging from 40 km to 4 km resolution. Subsequently it is investigated to what extent the ALARO-0 model is able to simulate several subdaily precipitation characteristics at different temporal as well as spatial resolutions. The results of this validation suggest that the multiscale character of the ALARO-0 model as apparent in the simulation of the daily precipitation climatology, is not valid for the simulation of subdaily precipitation. Compared to the low-resolution simulations, the high 4-km model results demonstrate a significant added value in the description of the daily precipitation cycle, very high precipitation amounts, and important scaling properties.

These positive results from the validation allow us to apply the model in a next step for the calculation of a climate projection. The future changes in extreme precipitation and the meteorological conditions which are unfavorable for winter smog episodes, as a consequence of increased greenhouse gas (GHG) concentrations described by the A1B scenario of the IPCC, are investigated in the second and last part of this thesis. The validation of the control simulation reveal significant biases, which can be attributed to model errors that are present in the driving GCM CNRM-CM3. The future changes are explored through a sensitivity of the model for changes in the climate forcing, in which the differences between the future scenario and the control simulation are quantified.

When it comes to the extreme winter precipitation, we can expect, taking into account the model biases and the projection results from other modeling studies, to some level of confidence a future increase in the hourly precipitation amounts. However, for summer precipitation the negative changes in extreme and hourly precipitation are more uncertain. The negative changes are not significant and smaller than their respectively biases, and the negative response is in disagreement with the modeling results for western- and central Europe from previous studies. These disagreements can be attributed to the transition zone in which Belgium is located, and the strong dependency of the parameterizations, and in particular the parameterizations for deep convection, which are an important source of uncertainty in the projection of extreme summer precipitation.

To study the climate change impact on winter smog episodes in Brussels, two different stability indices are analyzed. Both indices, the transport index and the Pasquill stability classes, are based on the meteorological conditions determining the dispersion of air pollution. This methodology, in which the sensitivity of unfavorable conditions to the dispersion of winter smog pollutants under future climate conditions is explored through changes in the frequency of stability indices, is new and has to our knowledge never been used in previous studies. The biases which are present in the transport index obtained from the control simulation are taken into account by a bias correction directly applied on the transport lengths themselves. After the bias correction, the results show an acceptable deviation in the frequency of modeled transport lengths with respect to the observed ones. The same bias correction is applied on the transport lengths of the scenario simulation.

This allows to quantify the uncertainty in the future changes of the frequencies of low transport length values. Both the results of the changes in the frequency of low transport length values as well as in the frequency of stable Pasquill classes suggest a tendency towards more stable meteorological conditions, and hence a possible deterioration of the air quality during winter smog events in Brussels.

Based upon these results we conclude that the ALARO-0 model of the RMI can be used for regional climate modeling in Belgium, and in particular for the application of extreme precipitation and the meteorological conditions which are unfavorable for the dispersion of air pollution during winter smog episodes. This general conclusion allows us to state that the great potential of the high horizontal and vertical resolution of the downscaled model results provide relevant climate information that can be used as a forcing for impact studies on for example the Urban Heat Island effect (UHI), extreme precipitation, and the meteorological conditions which are unfavorable for the dispersion of air pollution.